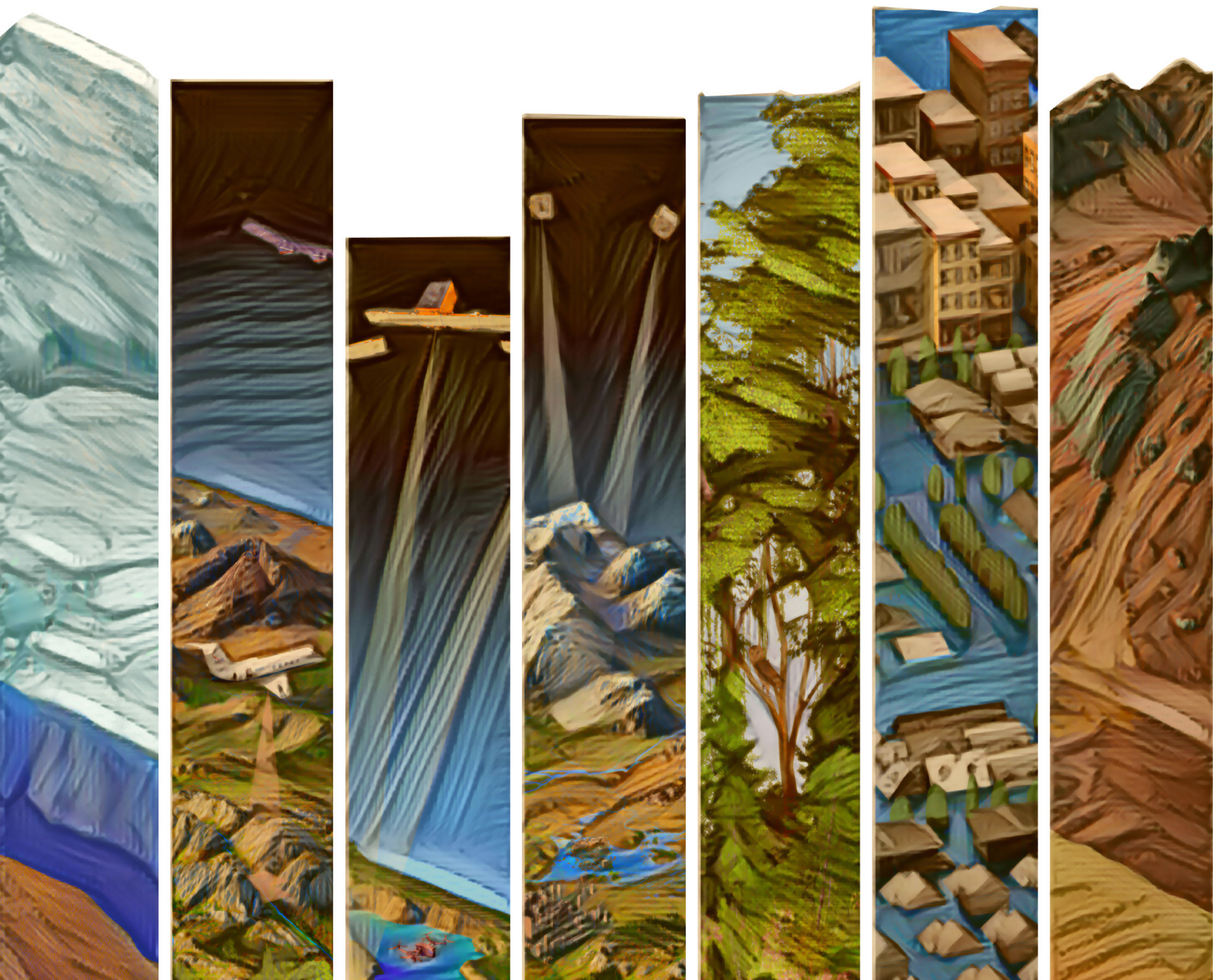
National Aeronautics and
Space Administration

OBSERVING EARTH'S CHANGING SURFACE TOPOGRAPHY & VEGETATION STRUCTURE

A FRAMEWORK FOR THE DECADE

NASA's Surface Topography
and Vegetation Incubation Study
Team Report
June 2021



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Minor corrections June 22, 2021

Dear Reader,

The Earth's surface is defined and shaped by forces acting on it from deep within the Earth to beyond its atmosphere. Tectonic forces, vegetation dynamics, weather, the sun, and humans change this interface between solid Earth and atmosphere or water. Understanding the structure of the surface, whether of geologic, vegetated, inundated, or built, is key to understanding a myriad of processes relevant to health and sustainability.

Earthquakes, volcanoes, landslides, subsidence, and other natural geologic hazards reshape the solid Earth. Vegetation and its structure create habitats, provide food and natural resources, and are deeply linked to a changing Earth and climate. The cryosphere provides fresh water, yet is rapidly changing and affecting climate, impacting sea level and transportation routes. Hydrological processes move water across the land in rivers and floods while wetland ecosystems are key to carbon cycling. Coastal processes are impacted by sea level change and shorelines change as coastlines erode and sediment is transported and deposited. Threaded throughout all of these disciplines are a number of applications. A common measurement of surface topography and vegetation structure would address numerous processes related to these science disciplines. Lidar, radar, and stereophotogrammetry deployed on a wide range of platforms, bound together by information systems can be matured and applied to meet the measurement needs.

In 2017 the Earth Science Decadal Survey recommended incubation of the Targeted Observable: Surface Topography and Vegetation. In 2019, in response, NASA formed a Surface Topography and Vegetation Incubation Study Team to further identify related needs and gaps. This Study Team Report is the product of that study conducted in just over a year and during the worst pandemic in a century. In the course of our deliberations the study team drew from the decadal survey and related study team reports, published literature, community workshops, and their own expertise. This entire incubation study occurred virtually and some team members have never yet met in person, yet the team discovered a common set of measurements could meet many of the community needs serving a wide array of disciplines. This Study Team Report provides the vision and framework to achieve surface topography and vegetation structure measurements in the coming decade to address key science and applications challenges for improved life on Earth.

Sincerely yours,

ANDREA DONNELLAN
STV Study Lead
June 2021

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EXECUTIVE SUMMARY

The 2017-2027 Earth Science Decadal Survey (DS) recommended high-resolution global surface topography and vegetation (STV) as a targeted observable (TO). The DS concluded that global topographic mapping from space with high spatial and temporal frequency poses a major technological challenge but is a necessary and logical next step that promises to transform understanding of landscape evolution and the interactions of processes that shape it. The DS assigned STV as an Incubation TO aimed at exploring measurement approaches and accelerating the readiness for cost effective flight implementation. In 2020 NASA's Earth Science Division competitively selected an STV incubation study team to identify methods and activities for improving the understanding of science and applications processes and priorities and for advancing the maturity of technologies applicable to the STV TO and its associated disciplines. STV observables include bare surface land topography, ice topography, vegetation structure, shallow water bathymetry, and snow depth. Solid Earth, Vegetation Structure, Cryosphere, Hydrology, and Coastal Processes are the key science disciplines and applications to benefit from global high-resolution Surface Topography and Vegetation observations. STV will provide the opportunity to make complementary, integrated observations of processes that transcend the boundaries of individual science disciplines and involve interfaces between cryospheric, aquatic and terrestrial systems, such as coastal geomorphology, boreal change, and wetland ecology. Relevant technologies include lidar, radar, stereophotogrammetry, and information systems.

FIGURE II-1. **STV objectives would be best met by new observing strategies that employ flexible multi-source and sensor measurements from a variety of orbital and suborbital assets. This flexible approach, coupling advancement of technology with modeling, simulation, and sensitivity studies would inform the design of a future STV observational system. Science and application objectives focusing on Solid Earth, Vegetation Structure, Cryosphere, Hydrology, and Coastal Processes would be best met by new, 3-dimensional observations from lidar, radar, and stereophotogrammetry.**

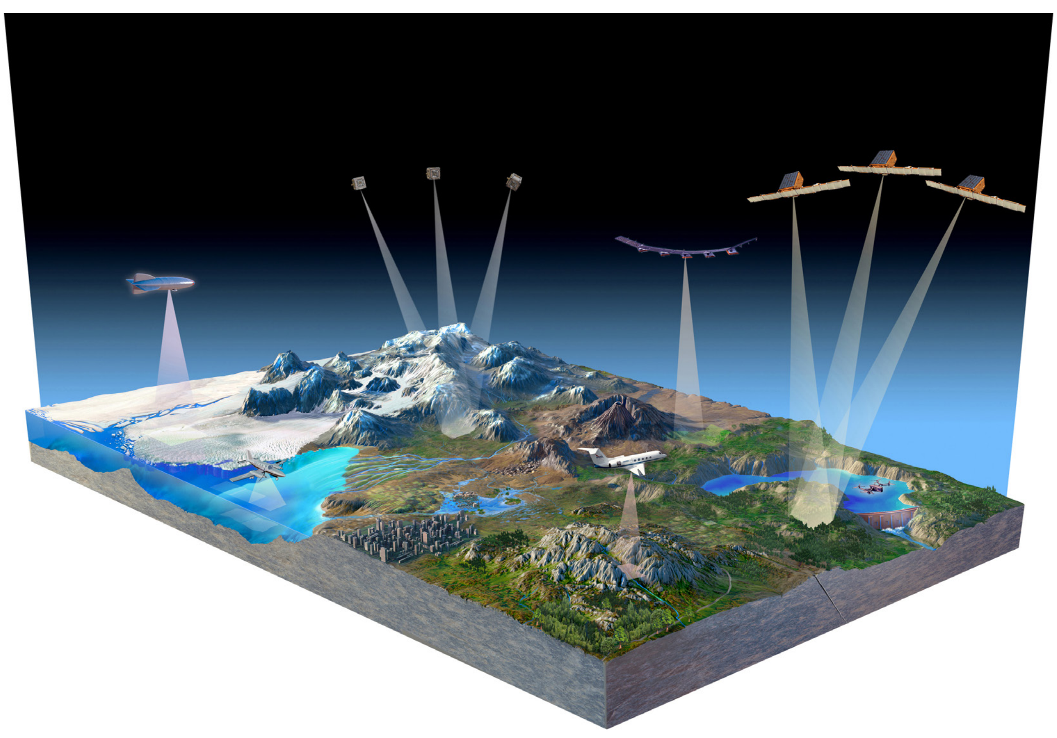
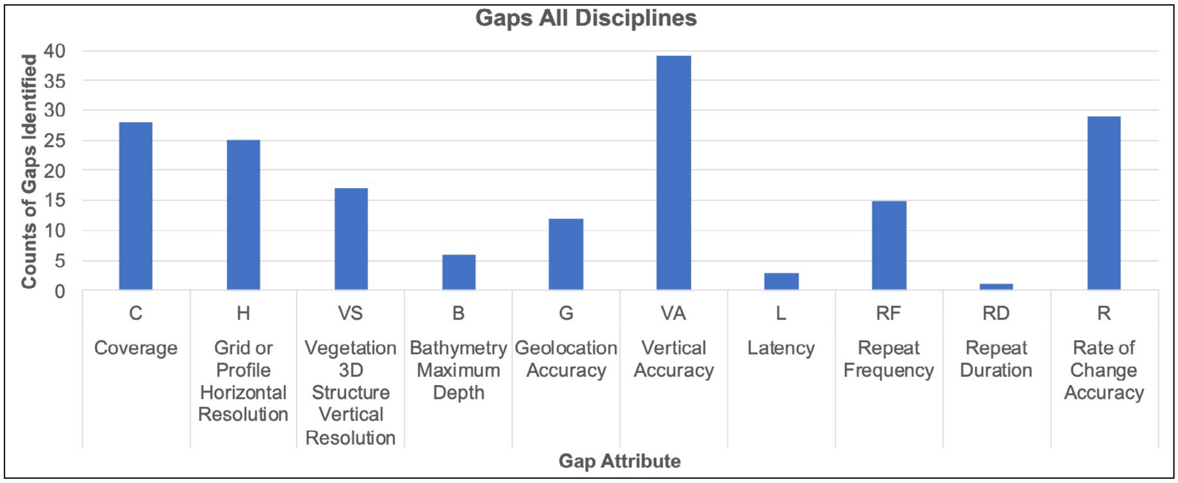


FIGURE II-2. Counts of gaps identified for all disciplines combined showing the need for accuracy, coverage, and ability to measure rates of change.



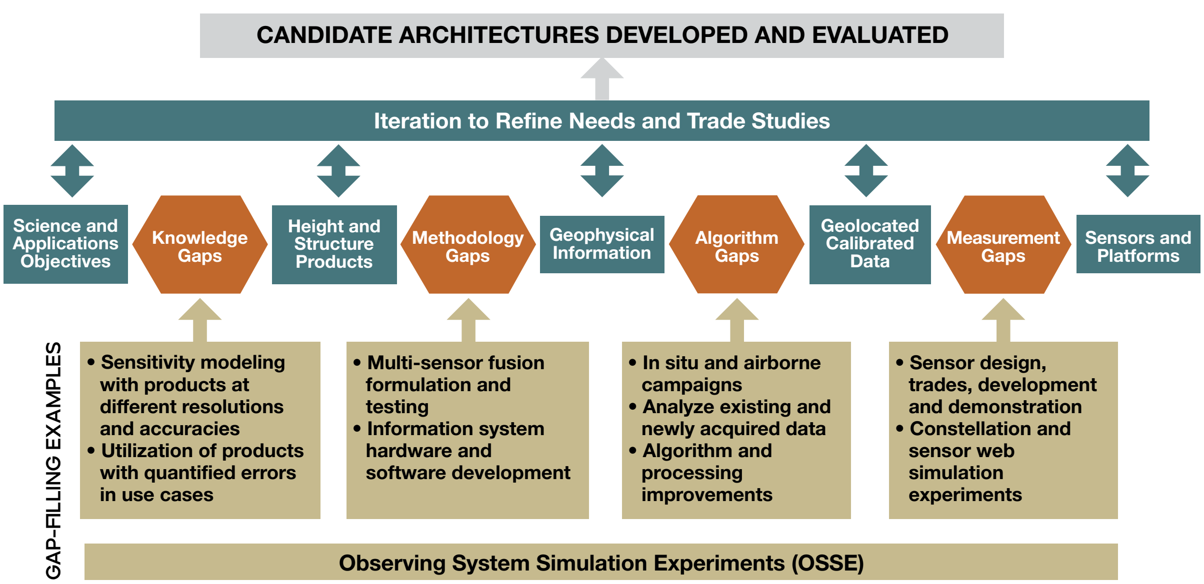
The STV incubation study team developed a preliminary Science and Applications Traceability Matrix (SATM), refined science and applications goals, reviewed current technologies, and identified gaps and gap-filling activities needed to mature STV observational capabilities in order to meet science and applications product needs. The DS served as the guiding document for the study. The broader STV community participated in this study through a plenary workshop and a series of breakout workshops focused on each of the science/applications and technology disciplines, a questionnaire to refine measurement needs, and development of quad charts describing new and emergent technologies. The study and findings were presented at a public town hall at the 2020 American Geophysical Union Fall Meeting and the community also reviewed and provided feedback on the draft STV study team report before it was finalized.

A key finding of this STV study is that an orbital observing system could meet a set of STV science and applications needs serving all STV disciplines. Further, an architecture of multiple platforms and sensors on orbital and suborbital assets would address STV needs more thoroughly than a single orbiter (Figure ii-1). The science and applications disciplines all need accurate repeat measurements to measure temporal changes, which are important for understanding processes as well as responding to events. A global baseline topographic map is needed followed by targeted repeated measurements. Vertical accuracy, rate of change accuracy, global coverage, horizontal resolution, vegetation 3D structure resolution, repeat frequency, geolocation accuracy, bathymetry maximum depth, and product latency are all gaps in current capability that should be closed to meet STV science and applications goals and objectives (Figure ii-2). Measurements that penetrate vegetation are essential to solid Earth, vegetation structure and ecosystem science and applications. An outcome of this study is that the preliminary STV SATM lists more detailed and stringent product needs than those specified in the DS. The increasing demand for data to support operational applications, e.g., critical infrastructure monitoring, disaster management, and commercial forestry, drives the most stringent aspirational product requirements. Low-latency, frequent products will enable rapid response to specific events such as disasters, while a long time series of observations will improve understanding of geophysical, ecological, and hydrological processes and their interrelationships through observations of subtle motion, long-term trends, and discrete changes. Long time series observations also serve the applications communities' needs for sustained observations. This would require at least two acquisition strategies: (i) global, frequent, systematic coverage, and (ii) rapid acquisition of high-resolution data for priority target areas. Targeted needs might be satisfied by suborbital observations but technology investments make meeting the needs from an orbiting platform more likely.

- An orbital observing system could meet a set of STV science and applications needs serving all STV disciplines
- An architecture of multiple platforms and sensors on orbital and suborbital assets would address STV needs more thoroughly
- All science and applications disciplines need accurate repeat measurements to measure temporal changes
- A global baseline topographic map is needed followed by targeted repeated measurements

Achieving high accuracy global topography drives the need for maturation of instrument, software technologies, and integrated observing systems to close existing gaps in product availability and technology capability. A framework for developing an STV architecture within the next decade includes integrated modeling, simulations, field campaigns, technology development, and trade studies (Figure ii-3). Geophysical process modeling and sensitivity studies and Observing System Simulation Experiments (OSSEs) will be informed by the SATM to help define an architecture that will meet science and applications objectives and product needs identified in this study. A preliminary roadmap identifies classes of technology maturation and gap-filling activities needed to advance knowledge and technology to address STV-related science and application objectives (Figure ii-4). Architecting and implementing this observational system to provide both global and targeted repeat high-resolution surface topography and vegetation measurements should be achievable in the next decade. The STV incubation activities, spanning in-situ and airborne campaigns to algorithm development and orbital constellation design, will enable an STV architecture with demonstrated capabilities by filling current STV gaps. These activities will pave the way to STV-focused missions that would fulfill urgent, well-documented product needs with high societal impact during the next decade.

FIGURE II-3. Framework for identifying gaps and gap-filling activities, with components necessary to accomplish STV objectives indicated in blue, gaps between those components indicated in red and examples of potential gap-filling activities indicated in green.



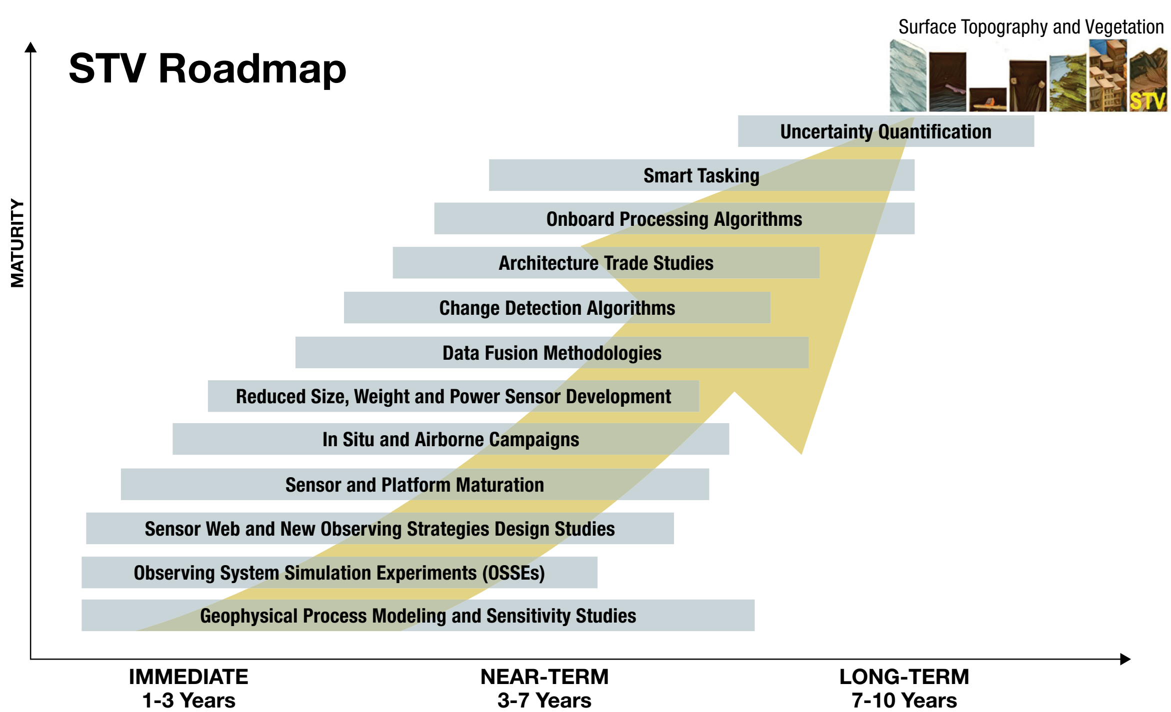
Knowledge gaps: the understanding of product quality needed to accomplish science and applications objectives is inadequate
Methodology gaps: the approaches to derive height products from geophysical information are inadequate
Algorithm gaps: the solutions to derive geophysical information from data are inadequate
Measurement gaps: the sensor and platform assets to acquire needed data are inadequate

TABLE II-1. Aspirational maturation activities for STV to attain by 2026.

Technology	Maturation Activity
Lidar	Beam scanning for mapping Size, weight, and power reduction
Radar	Multi-frequency and imaging trade study End-to-end TomoSAR and PolInSAR performance modeling and evaluation
Stereophotogrammetry	Systematic Multiview sensors Fixed point imaging
Information Systems	Multi-sensor fusion campaigns and algorithms Observing System Simulation Experiments
Platforms	Suborbital wide-area long-duration assets Optimized Small- and Large-Sat constellations

Key maturation activities achieved within the next five years will make STV poised to become achievable in the next decade (Table ii-1). This study team report describes a full set of activities to enable STV observations to meet science and applications community needs. Existing data should be identified and analyzed. Airborne campaigns should be established to characterize future STV performance, error sources, and quality. Earth science physical processes should be modeled to understand measurement thresholds required to improve scientific understanding and address application needs. Instruments should be simulated, developed, and matured. Performance of each instrument should be characterized. Ultimately, an integrated end-to-end OSSE would enable evaluation of how well STV instruments will perform and how science and applications needs will be addressed (Figure ii-3).

FIGURE II-4. Preliminary roadmap to mature Surface Topography and Vegetation technologies to enable an STV observational system within the next decade.

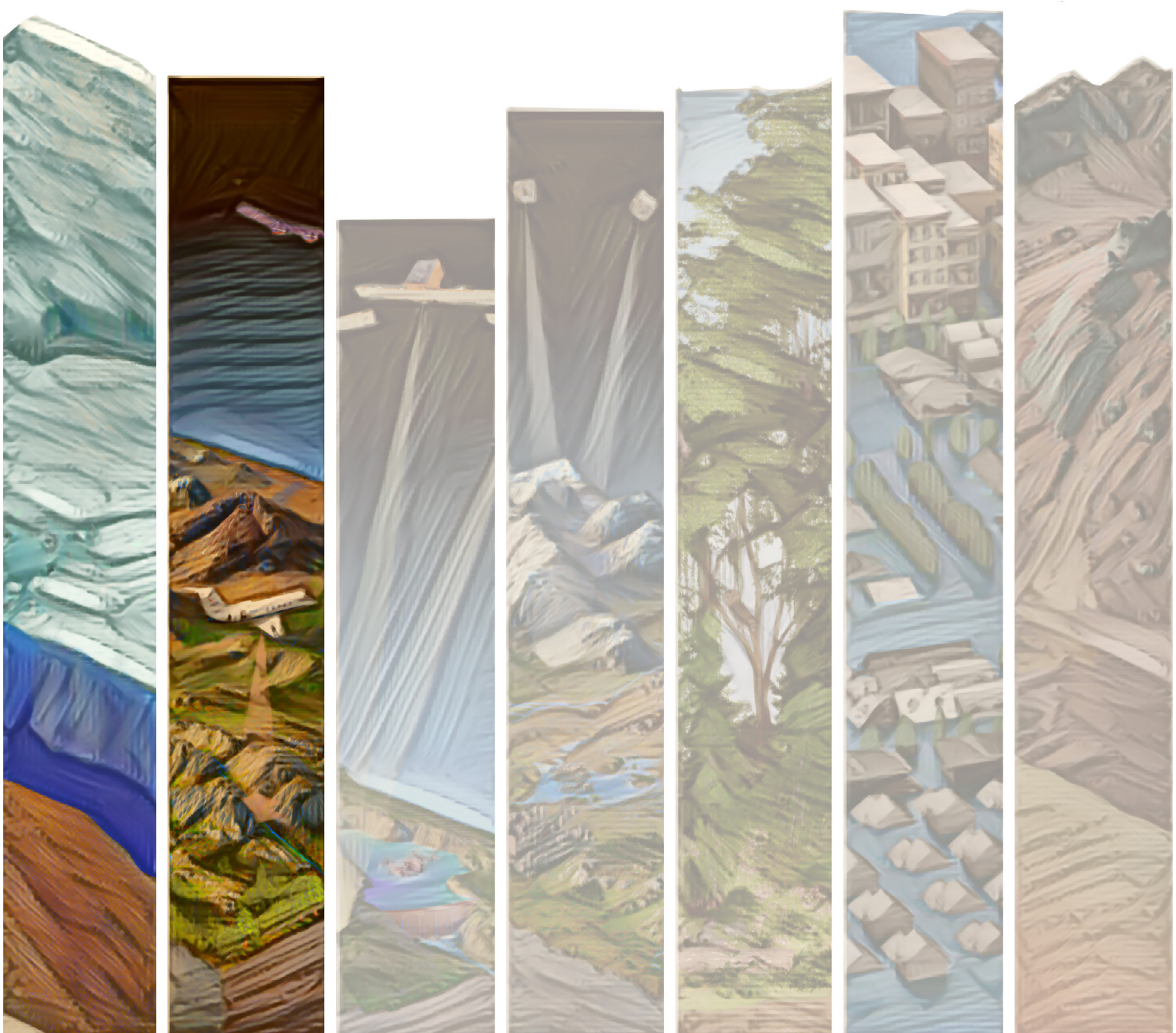


Defining a specific architecture to accomplish STV objectives is outside the scope of this study team report. The architecture that ultimately becomes the solution for STV will follow from the types of activities identified in this study team report to fill gaps in technical capabilities and in knowledge of how to best acquire and analyze remote sensing observations that meet the STV community's needs. More stringent needs within science disciplines and for the applications community could be met with suborbital components that complement an orbiting STV platform. Some disciplines and most applications need higher resolution products or rapid and repeated response, which might be satisfied by targeted suborbital observations that would complement systematic orbital observations or constellations of spaceborne instruments. Smart tasking could improve the usefulness of an orbital mission for lower latency or more frequent imaging of discrete events or disasters such as landslides, volcanic unrest, earthquakes, or flooding. A comprehensive set of vegetation structure and bare Earth measurements would best serve all of the science disciplines. Technology development will advance the ability of lidar, radar, or stereophotogrammetry to observe the various targets and reduce uncertainty in the measurement with an improved understanding of interactions between the target being measured and the instrument.

The incubation study team is confident that the STV roadmap of critical activities will mature technology sufficiently to make STV a feasible Designated Observable (DO) by 2028. The study clearly demonstrated that a well-architected STV will make complementary, vertical measurements of cryospheric, aquatic and terrestrial systems that will significantly improve our understanding of processes and allow applications with high socio-economic benefits. Continued development of the STV mission or observing system concept would benefit if STV maturation activities are carried out within the framework of an STV incubation team that works together to achieve STV objectives.

PART 1

STV SCIENCE & TECHNOLOGY OVERVIEW



CHAPTER 1

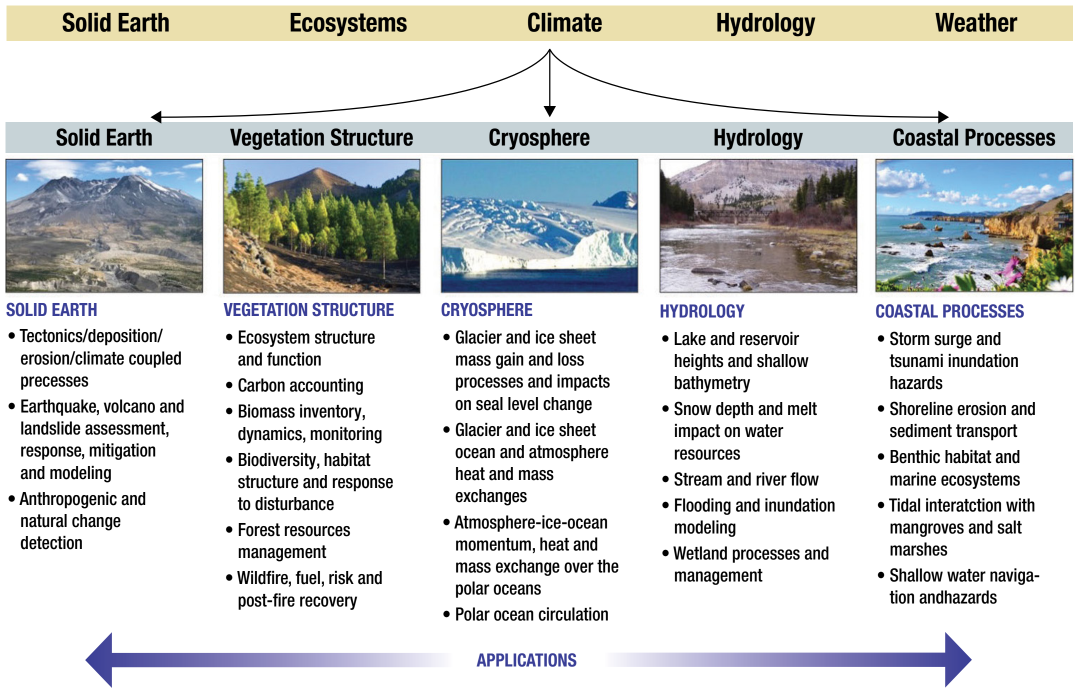
BACKGROUND

1.1 Introduction

The 2018 Decadal Survey (DS), Thriving on Our Changing Planet: A Decadal Strategy for Earth Observation from Space (2018, https://www.nap.edu/catalog/24938) by the National Academies of Sciences, Engineering, and Medicine (NASEM) recommended Surface Topography and Vegetation (STV) as a Targeted Observable (TO). A TO is a space-based observable common to a set of science objectives. The DS recommended the implementation of an incubation program intended to accelerate the readiness of high-priority TOs not yet feasible for cost-effective flight implementation. STV science and societal questions and goals call for exploring next-generation measurement approaches that could be ready for spaceborne implementation in about a decade. The DS recommends focused and sustained attention to these observables to establish the associated prospective scientific and other user communities, and to make progress towards maturing both measurement capabilities and implementation concepts within this decade. The DS calls for high-resolution global topography, including bare surface land topography, ice topography, vegetation structure, and shallow water bathymetry and identified radar or lidar as candidate measurement approaches. The five science disciplines identified by NASA as being relevant to STV were solid Earth, ecosystems, climate, hydrology, and weather. In 2020 NASA established a competitively selected STV study team (Table 1-1) to develop a preliminary Science and Applications Traceability Matrix (SATM) and to identify gaps that when filled would mature the technologies to enable STV observation from remote sensing platforms that are currently not possible. The study was broadened to include shallow water bathymetry as a measurement product and stereophotogrammetry as a measurement approach.

The DS recognizes that NASA should integrate science and applications with equal footing prior to and during the mission formulation phase and we do so in this STV study. The inaugural DS published in 2007 was organized around the theme of Earth science for societal benefit, and the 2017 DS continued that theme but went much further in connecting the science with broader benefit to the society as a whole in their priorities for "Societal and Science Questions/Goals." The survey acknowledges that there is a growing portion of Earth science that is user-inspired and directly addresses pressing questions with vast implications for society, most notably perhaps in their discussion of climate change but encompassing and cross cutting all disciplines. Significantly, the report addresses the "valley of death," the void into which scientific results fall before achieving societal relevance when there is not a close connection between researchers and end-users of the information. In this study we integrated applications and the science disciplines and also address separately additional applications for which agencies have an operational mandate related to STV.

FIGURE 1-1. DS science disciplines (top line) and STV Science disciplines (second line) with focus within each discipline. Applications are integrated throughout the science disciplines. The disciplines were derived from the DS highlighted in yellow at the top.



An initial step in organizing the STV Incubation Study was to identify and link the science disciplines supported by the primary STV observables of topography, vegetation structure, and shallow water bathymetry. The two key considerations in this step were: 1) to ensure representation from the widest possible range of scientific disciplines with strong, documented needs for STV observables, and 2) to identify natural linkages between these fields, such that they could be consolidated under broad science headings and, thus, keep the number of subgroups and breakout sessions manageable. The end result of this process was a remapping of DS science disciplines to STV disciplines (Figure 1-1).

1.2 Goals and Objectives of this STV Study

The goal of this STV Incubation Study is to identify methods and activities for improving the understanding of and advancing the maturity of the technologies applicable to STV. The DS states that "topographic mapping from space on a contiguous and high-resolution grid poses a major technological challenge, it is a necessary and logical next step that promises to transform understanding of landscape evolution and the interactions of processes that shape them. ….. Space-based, global coverage remains an important but unrealized goal at present." STV incubation activities to seek observing system architectures utilizing emerging sensors that will allow for the development of contiguous, high-resolution, bare-surface land topography, ice topography, vegetation structure, and bathymetry data products with global coverage and seasonal interannual repeat cycles. As described above, this STV study team defined the relevant science categories as: solid Earth (SE), vegetation structure (VS), cryosphere (C), hydrology (H), and coastal processes (CP; Figure 1-1). Embedded within and cutting across these science disciplines are applications objectives and needs (A). The team defined the technology categories to consider as radar (R), lidar (L), stereophotogrammetry (SP), and information systems (IS).

The objectives of this STV team were to:

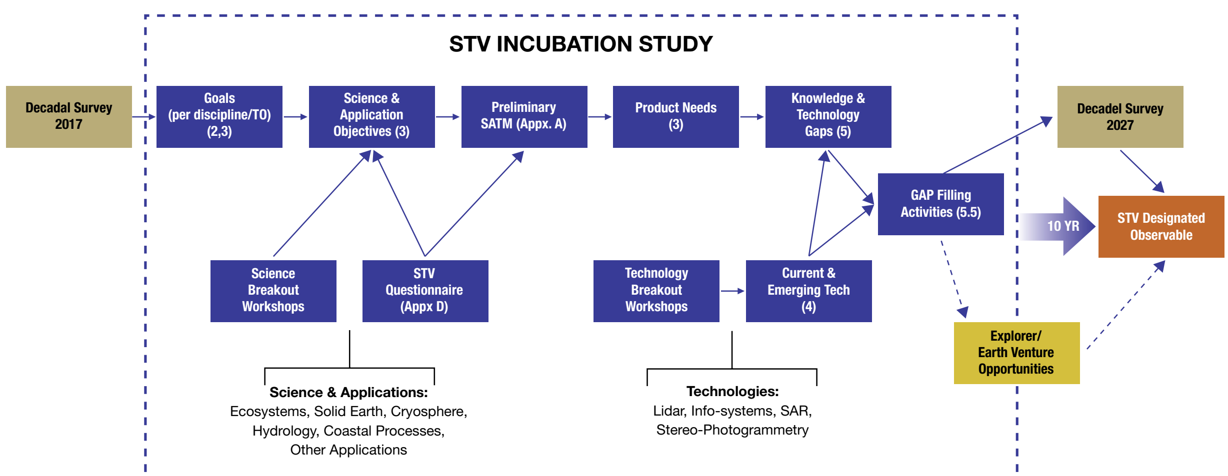
1. Develop a preliminary SATM and use it to identify gaps and flow down goals to technology and approaches
2. Justify the SATM with references, models, simulation, and analysis
3. Identify emerging lidar, radar, and stereophotogrammetry concepts
4. Identify data acquisition or integration strategies to advance STV science and applications

1.3 STV Study Process and Deliverables

The team carried on deliberations and obtained input from the community through workshops, questionnaires, and soliciting current and emerging technology quad charts (Figure 1-2). The team refined the science and applications goals and objectives relevant to STV, defined product needs, reviewed current technologies, identified gaps that should be filled in order to architect a future global STV mission, and identified approaches that could fill those gaps. The team related existing capabilities and technologies to the science and application goals and objectives identified by the team and community to identify the gaps. Science and application goals and objectives for each discipline were adopted from the DS, but refined and expanded where necessary based on team deliberations and community inputs. The communities of the respective science disciplines, associated applications, and technologies were engaged through workshops, questionnaires, and soliciting current and emerging technology quad charts. The team defined product needs derived from the science and application objectives, within a preliminary SATM, reviewed current technologies, identified gaps that should be filled in order to architect a future global STV mission, and identified approaches that could fill those gaps.

Deliverables of the STV team are this study team report and a preliminary SATM, which we present in abbreviated form and comprehensively. In the SATM and study team report the team outlines potential future methods and activity areas, which include Observing System Simulation Experiments (OSSEs), field campaigns, and potential observing system architectures utilizing emerging sensor and information technologies. The study team report and SATM define the relevant societal or science questions, geophysical observables, and possible draft concepts of associated measurement approaches, expanding on the DS.

FIGURE 1-2. Flowchart of STV Incubation study process. Relevant sections of the STV study team report are indicated in parentheses for each component.



1.4 Relation to NASA's Program of Record and DS Observables

Prior, existing, and planned missions in NASA's Program of Record (POR) provide global topographic, vegetation structure, shallow water bathymetry and water level mapping, although not at the needed spatiotemporal coverage or accuracies identified by this STV incubation team. This began with the NASA/DoD Shuttle Radar Topography Mission (SRTM), a single-pass Interferometric synthetic aperture radar (InSAR) flown in 2000 that produced a 30 m DEM from 56°S to 60°N, achieving an absolute elevation accuracy with 4 m RMSE for bare ground (Rodriguez et al., 2006a; Rodriguez et al., 2006b). The 30 m GDEM is a similar product generated using satellite stereo imaging acquired by the JAXA/NASA ASTER instrument, which operated from 2000 to 2011. GDEM covers ±83°, achieving 8 m RMSE absolute accuracy for bare ground (Hengl and Reuter, 2011). The SRTM result was combined with global lidar profiles acquired by the Ice, Cloud, and Land Elevation Satellite (ICESat) mission to produce the enhanced NASADEM. ICESat, operating from 2003 to 2009, was the first lidar in space acquiring altimeter measurements of ice sheet elevation change, sea ice freeboard, vegetation height, and topography. It was followed by the multi-beam ICESat-2 mission, launched in 2018, which is acquiring profiles with much greater coverage, resolution, and accuracy. ICESat-2 provides a unique capability to measure shallow-water bathymetry in coastal areas and some inland lakes. Elevation accuracy for ICESat and ICESat-2 is a few centimeters RMSE, necessary to observe ice elevation change on seasonal to interannual time periods (Brunt et al., 2019). Also, currently in operation, the multibeam Global Ecosystem Dynamics Investigation (GEDI) profiling lidar is acquiring data from the International Space Station at equatorial to mid-latitudes (Dubayah et al., 2020). Its focus is on forested regions to improve understanding of carbon cycle dynamics and biomass change. The team was directed to determine the potential to leverage ICESat-2, GEDI, Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO), Aeolus, and/or other existing spaceborne lidar data to reduce gaps in existing or planned STV activities. Activities are ongoing to fuse ICESat-2 and GEDI profiles with InSAR elevation mapping data from DLR's TanDEM-X mission to produce global topography and vegetation structure products. Additional activities are identified in later sections to advance readiness for STV that include incorporation of existing satellite and airborne lidar data. The upcoming Surface Water and Ocean Topography (SWOT) mission scheduled to launch in 2022 will provide measurements of inland river, lake and reservoir heights, water storage and river discharge. It will contribute to improved understanding of the terrestrial water cycle and management of water resources.

Although not a part of NASA's POR, commercial high-resolution imaging satellites operated by DigitalGlobe (now Maxar) have been acquiring stereoscopic images used for targeted production of DEMs beginning in 2007. Through an agreement with DoD/NGA, NSF and academic partners, those data have been used to produce ArcticDEM (https://www.pgc.umn.edu/data/arcticdem/) and REMA (https://www.pgc.umn.edu/data/rema/) which provides topographic and ice sheet elevation data at high latitudes. Spatial resolution and vertical accuracy are a few meters, where vegetation is absent. That program has been expanded, and production of NGS EarthDEM is ongoing, with the objective of complete global mapping; the horizontal posting will be submeter to 2m and vertical accuracy will generally be better than ±4m. Several commercial providers are implementing constellations to expand availability of stereo imaging. Maxar is deploying the WorldView Legion constellation in 2021 which will be able to target locations for stereo imaging on a daily basis. A CNES/Airbus partnership is scheduled to launch the CO3D constellation in 2023 to conduct continuous stereo imaging for global topographic mapping.

1.5 Relation to 2017–2027 DS Missions/Observables

The STV TO, that was designated as Incubation Observable, shares many objectives with several 2017 DS Designated and Explorer Observables. In particular, those are the Designated Surface Deformation and Change (SDC) Observable and the Explorer Ice Elevation, Terrestrial Ecosystem Structure, and Snow Depth and Snow Water Equivalent Observables. The SDC focus is Earth surface dynamics, such as earthquakes, land ice flow, biomass, and permafrost freeze/thaw. The three Explorer Observables will target components of the STV mandate, but are not expected to achieve comprehensive, high-resolution, global mapping of surface elevation and vegetation structure of the kind envisioned for STV.

The DS Surface Deformation and Change (SDC) designated observable and STV targeted observable are complementary. Combined measurements from both SDC and STV will provide a richer understanding of land surface, ecological, and hydrological processes. SDC is currently the subject of a five-year Designated Observable study that will conclude in 2023. The study team will start the SDC architecture assessment phase in March 2021. STV is the subject of a one-year incubation study to develop a study team report outlining science and applications objectives and needs, identify technology gaps, and provide a preliminary SATM. Additional incubation studies will follow the study team report to inform the next DS and a future STV mission architecture.

The SDC mission's focus is on Earth surface deformation measured in a line-of-sight component from the ground to the instrument. SDC addresses solid Earth, geohazards, cryosphere, hydrology and ecosystems disciplines. The DS mandated that SDC provide geodetic measurements of the solid earth surface and for assessing ice sheet stability and the potential for ice sheets to make large rapid contributions to sea-level rise. NASA HQ expanded that mandate to include SAR imaging, enabling hydrology (soil moisture, surface water extent, aquifers), ecosystems (biomass, disturbance), and radiometric applications (oil spills, agriculture, infrastructure monitoring). The modes in which SDC and STV complement each other depend on the final, to-be-determined architectures of each. Different architectures result in different capabilities, such as line-of-sight vector diversity for three-dimensional deformation mapping, tropospheric phase removal, different radiometric accuracy, and targeted increases in temporal sampling. The architectures are developed to address the DS goals and community inputs, resulting in a wide spectrum of potential applications. The SDC launch window is anticipated to be in the late 2020s to early 2030s.

The focus of STV is on surface topography, vegetation structure, and changes to both. SDC and STV both address surface elevation change. SDC is targeting regular global measurements at about 10m or coarser spatial resolution with mm/y accuracy. SDC measures deformation, but large disturbances or abrupt changes are difficult to measure as phase correlation between two passes breaks down. STV targets regular global measurements of surface elevation at decimeter to submeter 3D resolution providing a direct measurement of surface and vegetation structure enabling geomorphological and other analyses. Vertical and horizontal motions can be measured by differencing the 3D structure. STV aims to provide the vertical structure of vegetation from which both the top of canopy and ground elevations can be derived. STV will measure tree height and 3D structure, providing more accurate biomass estimates over the full range of global biomass stocks. STV would also observe snow covered, snow-free surfaces, and shallow water bathymetry.

In the DS, objectives for the Explorer Ice Elevation, Terrestrial Ecosystem Structure and Snow Depth and Snow Water Equivalent Observables which relate to observations of surface heights are also associated with STV. The objectives common to those three Explorers and STV are C-1c (ice sheet mass balance), C-8f (permafrost thaw), E-1b (3D structure of vegetation), E-1e (species diversity), H-2b (water quality and quantity), H-3c (plant evapotranspiration), H-4b (controls on flooding), S-3a (sea level change), S-4a (geologic landscape change), S-4b (hydrologic landscape change), S-4c (ecosystem response to landscape change) and W-3a (energy, water and momentum cycling). Observations to serve these common objectives could begin as Explorer missions and then be continued and expanded globally via STV. Those objectives not addressed in Explorer missions would be served when STV commences.

The STV Incubation study has bearing on the relevant Explorer class missions in the following three ways: 1) This STV incubation study helps identify product gaps and needs and provides detailed product requirements in the preliminary SATM. This study could be used for any Explorer mission that draws on those requirements. 2) STV reviews the gaps and maturity of relevant sensing technologies providing an overview that could be used in Explorer. 3) The STV Study Team Report suggests activities to mature specific technologies over the next decade. Proposers could use the study team report to justify Explorer proposals, particularly in later cycles where STV incubation technology maturity has occurred.

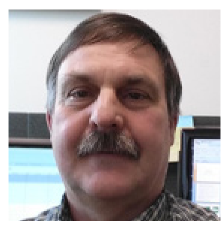
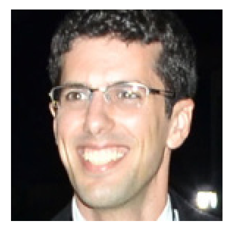
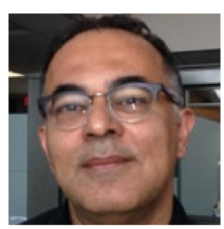
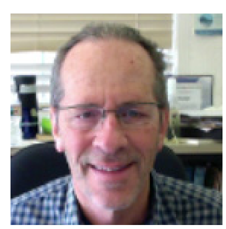
1.6 Expected Outcomes

This study and study team report identify technology and knowledge gaps that need to be addressed and identify focused technology investments, trade space analyses, mission architecture studies and measurement demonstrations that could make substantial advances toward meeting the challenging STV objectives. This study team report and follow-on work will inform the next DS expected to begin in the mid-2020s. The STV Team intends this study team report to provide the framework to further the STV incubation goals outlined in the DS, which are to:

- Improve understanding of measurement needs, including multi-platform scenarios, through modeling and mission concept studies, to define which can be addressed with state-of-the-art technology and which require further development.
- Identify which measurement needs can be obtained through suborbital means and which require a space-based component. Identify those ready to compete in Venture-class opportunities.
- Identify any proposed components that could be ready for Earth System Explorer opportunity, for consideration by Midterm Assessment.
- Consider appropriate split between global observations from space and potentially less expensive and higher resolution airborne measurements.
- Scope cost, benefits and limitations of obtaining commercial data to meet needs.
- Define a pathway to ensure any identified spaceborne component matures toward flight in the following decade.

This study team report is broken into two parts followed by appendices. Part I provides a high-level summary of the STV observables, science needs, and sensor, platforms, and information science. Part I then identifies gaps, potential gap-filling activities, and key findings. Part II provides a more detailed discussion of the science and applications that STV observables address, and current and emerging sensors, platforms, and information systems. The final STV mission solution may consist of one or more sensor types, using lidar, radar, stereo photogrammetric and/or spectrometry methods, that are hosted in space and/or suborbitally on one or more platforms. Follow-on activities to this STV incubation study are likely to include sensitivity studies; OSSEs; data fusion development; spaceborne, airborne, and field experiments; technology maturation; and architecture trade studies. Follow-on activities would leverage existing data, missions, and activities, as well as data collected through new experiments that are specifically designed to provide data well-suited for STV incubation investigations.

TABLE 1-1. STV team members, roles, and institutions

 **LEAD** **Andrea Donnellan** NASA/JPL/Caltech	 **TECHNOLOGY LEAD** **David Harding** NASA/GSFC	 **SOLID EARTH** **Paul Lundgren** NASA/JPL/Caltech	 **VEGETATION STRUCTURE** **Konrad Wessels** George Mason University
 **CRYOSPHERE** **Alex Gardner** NASA/JPL/Caltech	 **HYDROLOGY** **Marc Simard** NASA/JPL/Caltech	 **COASTAL PROCESSES** **Christopher Parrish** Oregon State University	 **APPLICATIONS** **Cathleen Jones** NASA/JPL/Caltech
 **RADAR** **Yunling Lou** NASA/JPL/Caltech	 **LIDAR** **Jason Stoker** US Geological Survey	 **STEREOPHOTOGRAMMETRY** **K. Jon Ranson** NASA/GSFC	 **INFORMATION SYSTEMS** **Batu Osmanoglu** NASA/GSFC
 **TEAM MEMBER** **Marco Lavalle** NASA/JPL/Caltech	 **TEAM MEMBER** **Scott Luthcke** NASA/GSFC	 **TEAM MEMBER** **Sassan Saatchi** NASA/JPL/Caltech	 **TEAM MEMBER** **Robert Treuhaft** NASA/JPL/Caltech

CHAPTER 2

STV TARGETED OBSERVABLES

2.1 Introduction

The DS recommended STV as a Targeted Observable (TO) and assigned STV to a new program element called "Incubation," intended to accelerate readiness of high-priority observables not yet feasible for cost-effective flight implementation. TOs are independent of specific implementation approaches. STV directly addresses at least one "Most Important" objective of four of the five interdisciplinary study panels of the DS (Hydrology, Marine and Terrestrial Ecosystems, Climate, Earth Surface and Interior), and one or more "Very Important" objective for Weather and Air Quality and Earth Surface and Interior panels. STV includes high-resolution global topography, including bare surface land topography, ice topography, vegetation structure, and shallow water bathymetry. STV addresses key priorities within and across disciplinary lines for five science disciplines and applications, as described in Chapter 3.

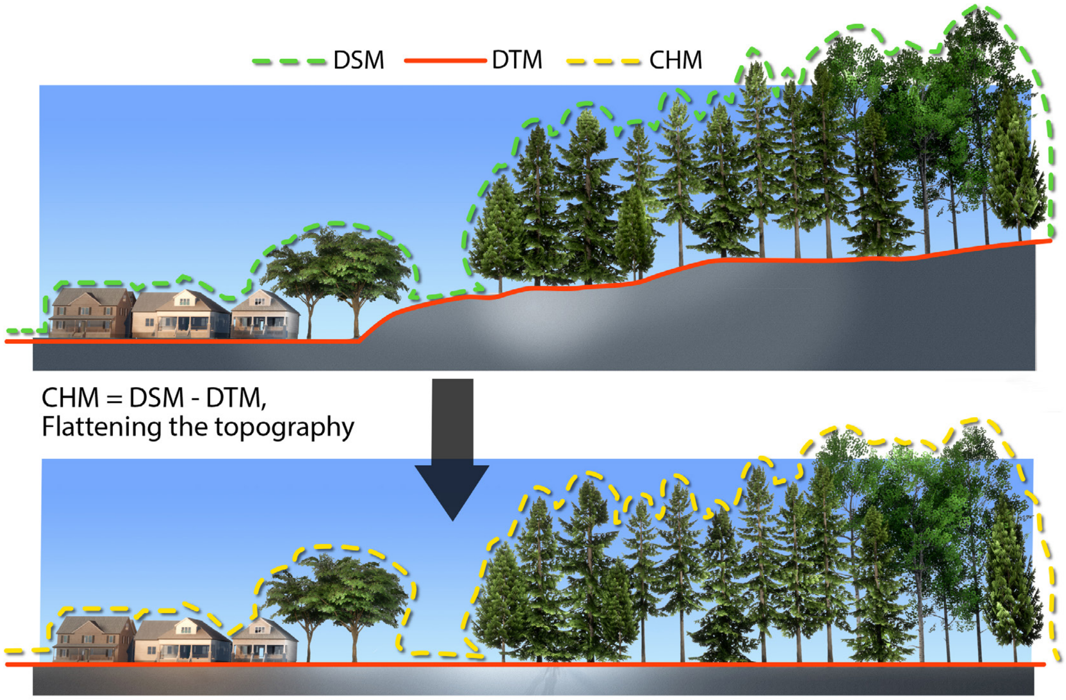
This science and technology interdisciplinary STV study team takes the first step in identifying benefits and trade-offs among different measurement approaches (Chapter 6). Here we describe the three main components of the STV TO: Topography, Vegetation Structure, and Shallow Water Bathymetry, and also include snow depth in the discussion.

2.2 Surface Topography

Topography is the measurement of surface elevation variations, which may include height of the ground, ice, snow, water surface, vegetation canopy and built environment. In this document, we adopt distinct definitions of topographic data structures. A digital elevation model (DEM) is a generic term for gridded (raster) elevation measurements. A digital surface model (DSM) is the elevation of the reflective surface which may include the height of elements above the bare earth elevation such as vegetation and infrastructure. Over vegetated surfaces, a DSM specifically containing height of canopy above ground or above datum is termed a canopy height model (CHM). A digital terrain model (DTM) is the elevation of bare Earth above datum where all elements or features above the bare Earth have been removed (Figures 2-1 and 2-2). The difference between DSM and DTM is the height of the reflective surface and CHM for vegetated surfaces that may be subject to large uncertainty depending on the remote sensing technique on how well DSM and DTM values are quantified.

The DS states that *"characterizing surface topography with contiguous measurements ... will allow for detailed understanding of geologic structure and geomorphological processes, which in turn can provide new insights into surface water flow, the implications of sea-level rise and storm surge in coastal areas, the depth of off-shore water in near*

FIGURE 2-1. Profile depictions of elevation models relevant to the STV Observable, showing the DSM and DTM representing the highest and lowest surfaces respectively and the difference over vegetated surfaces showing the canopy height model (CHM) as a component of vegetation structure. Adapted from Mahadi et al., 2018.

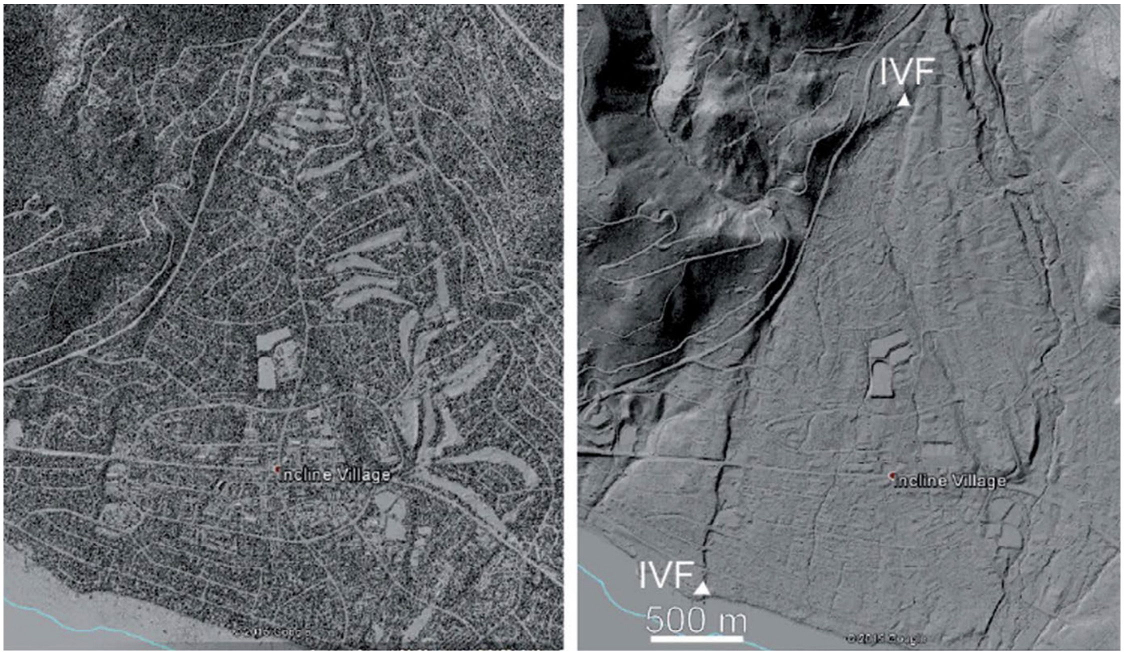


coastal areas, and more." Separating DSMs from DTMs will be key to improving geomorphic measurements. A common theme that emerged from this study and community input is the need for repeat topographic measurements in order to characterize change and improve understanding of solid Earth, land surface, ecological, cryospheric, hydrological, and coastal processes. Repeated measurements are also needed by the applications community to address changes in critical infrastructure, provide situational awareness for hazards or disasters, and support a wide range of services.

2.3 Vegetation Structure

Three-dimensional vegetation structure is defined as the vertical configuration of aboveground vegetation and its horizontal landscape variations (Brokaw and Lent, 1999), including tree and canopy height, canopy cover, leaf area density profile, stem diameter and their heterogeneity across the landscape. Depending on measurement techniques, vegetation structure is considered the distribution of foliage, branches, twigs, and stems with horizontal and vertical resolution sampling needs that may vary from 10s of centimeters to 10s of meters. Within three-dimensional resolution cells or voxels, vegetation components are observed as intercepted surfaces, volume, or mass of vegetation and expressed as vertical profiles (e.g., canopy, leaf area density) or estimates of structural quantities (e.g., height, stocking volume, biomass) depending on the wavelength (optical or microwave) and active (lidar and radar) or passive (stereophotogrammetry) remote sensing techniques.

FIGURE 2-2. Shaded relief of full feature (all lidar returns in left) and bare earth (right) of the area around Incline Village, Nevada, in the north Lake Tahoe area. Fault scarps and fluvial features along the Incline Village Fault (IVF) are marked by white triangles. Data provided by Tahoe Regional Planning Agency (http://dx.doi.org/10.5069/G9PN93H2; figure from Donnellan et al., 2016). High-resolution lidar-derived topographic data available from OpenTopography (www.opentopography.org; Crosby et al., 2011).



The DS states that "measurements of the three-dimensional (3D) physical structure of terrestrial vegetation particularly in forested ecosystems of the world, have a wide range of practical applications in addition to more fundamental understanding of the global carbon and water cycles." These applications vary from commercial forestry, watershed management, fire fuel load assessments at local and high spatial resolutions to national and regional greenhouse gas (GHG) inventory, and monitoring and verifying emission reduction programs for climate mitigation. Emerging themes from this study and the community inputs provide priorities for 3D vegetation structure observations for: 1) contiguous separation of horizontal and vertical structure of vegetation at landscape scales, and 2) repeated observations for quantifying changes of vegetation structure. Both science and application communities highlighted these priorities, though with different spatial and temporal scales.

2.4 Shallow Water Bathymetry and Surface Height

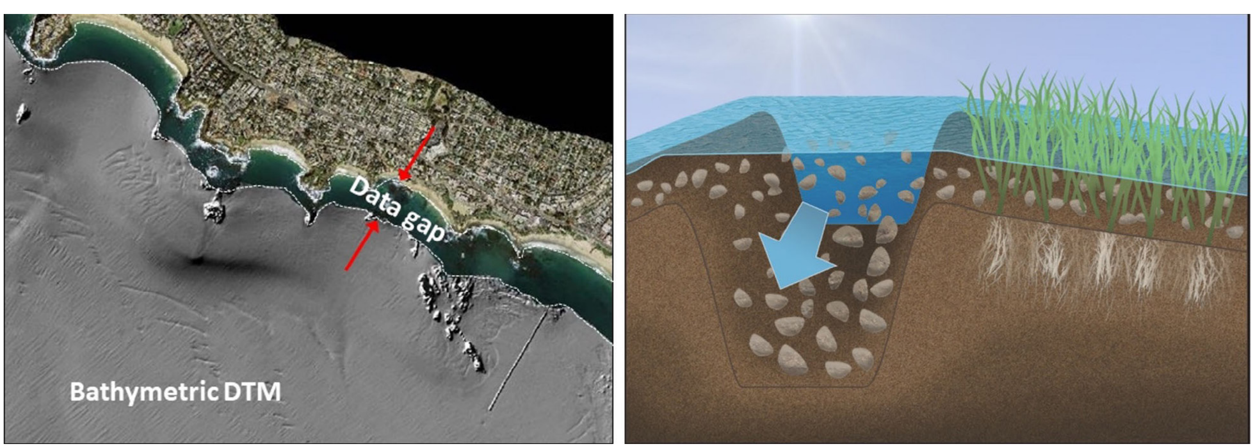
Water depths and snow depths are parameters of interest which require DSMs and DTMs. DTM generation is generally most challenging where the ground is submerged under water or snow. Underwater topography, known as bathymetry, modeled as a DTM, is needed for a range of science objectives in areas of the Earth covered by water (i.e., oceans, bays, lakes, reservoirs, rivers, wetland). River discharge, coral reef ecology, coastal inundation due to storms, safety of marine navigation, ice sheet and glacier hydrology, sea ice evolution, and study of wetlands are just a few of the science and application topics supported by accurate bathymetry. Bathymetric data are generally provided as either depths, representing the vertical distance from the water surface down to the submerged topographic surface, or heights of the submerged topographic surface above datum. In tidal areas, a third alternative is to use depths relative to a tidal datum, such as mean lower low water (MLLW), which serves as the chart datum for U.S. nautical charts supporting safety of marine navigation. Both water depth and snow depth can be derived from the difference of a DSM and a DTM.

For most of the science applications listed above, sparse spot measurements of bathymetry ("soundings") or DTMs along discrete transects are insufficient; study of the configuration of the ground elevation requires spatially-dense data to generate a continuous high-resolution DTM. While some studies require only bathymetric measurements, others require heights or depths of submerged aquatic vegetation, coral, and/or other underwater features. Currently there is a data gap near the coast where water is shallow and access by ships and boats is challenging or even dangerous (Figure 2-3). Measurement of bathymetry is logistically challenging, and generally feasible only in areas suitable to bathymetric (i.e., green) lidar in clear water or sonar surveys. These challenges have resulted in a significant data gap hindering the advancement of science and application in hydrology of rivers, reservoirs, lakes and wetlands, and particularly in coastal areas throughout the world (Figure 2-3). Therefore, in this paper, we discuss the data gaps and the requirements specific to the coast and inland hydrology in their respective sections, i.e., "Coastal Processes" and "Hydrology."

Over land, fluxes of water control lateral fluxes of carbon, sediment, nutrients and pollutants, and therefore require accurate estimates of flows to avoid error propagation into other variables. The total fluxes of water, along with their constituents, from the land surface into the global ocean are not well constrained and, if better known, would help to close the water and carbon cycles. In addition, high-frequency temporal variations are rarely known, and only measured *in situ* in a few large rivers. As such, constraining spatial and temporal variations in water fluxes across the landscape and to the ocean is needed to close the water cycle. This will require the ability to evaluate elevation change over time, either as a means of determining the drivers of change, or the impacts of the change.

An integrated hydrology system requires knowledge of land (DTM) and water surface elevation (DSM), as well as depth of seasonal land snow packs, to account for lateral fluxes of water across the land surface and the associated fluxes of carbon, sediment, nutrients and pollutants. These fluxes vary greatly in both space and time. Here, we note that while the SWOT mission addresses some components of surface hydrology, it does not meet all requirements discussed in this document, and also does not address components such as snow, wetlands and permafrost hydrology.

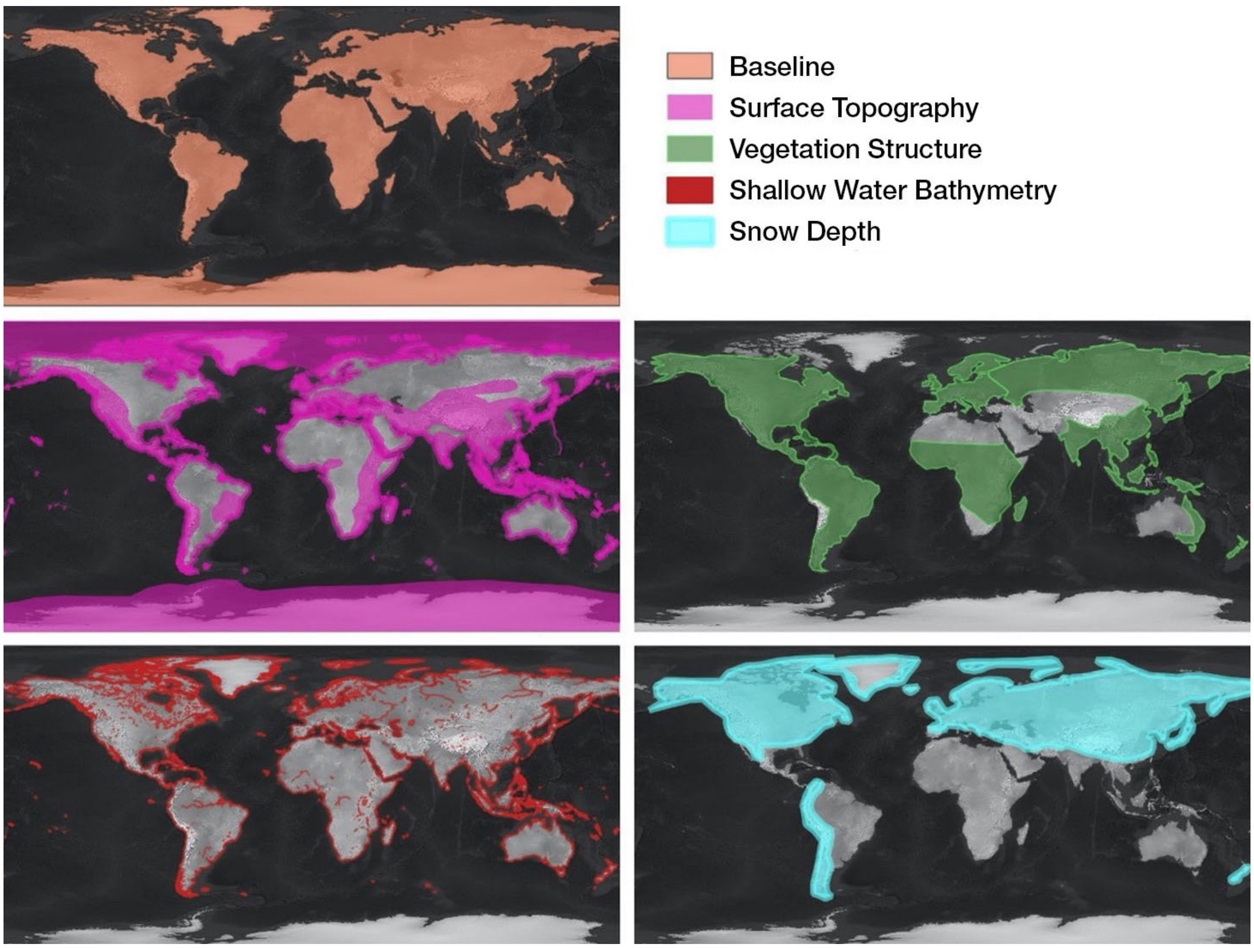
FIGURE 2-3. Examples of shallow water bathymetric data gaps, caused by the challenges associated with mapping these areas. Left: bathymetric DEM (shown as greyscale hill-shaded relief image) of Laguna Beach, California, showing data void adjacent to the shoreline and extending several hundred meters offshore. Right: Measurements of shallow bathymetry and water depth (or surface elevation) in rivers, reservoirs, lakes and the coastal seas are needed to understand the transport of water and transport of sediment, nutrients and pollutants. These flows have a profound impact on erosion, transport and deposition processes that shape the earth surface and ecosystems.

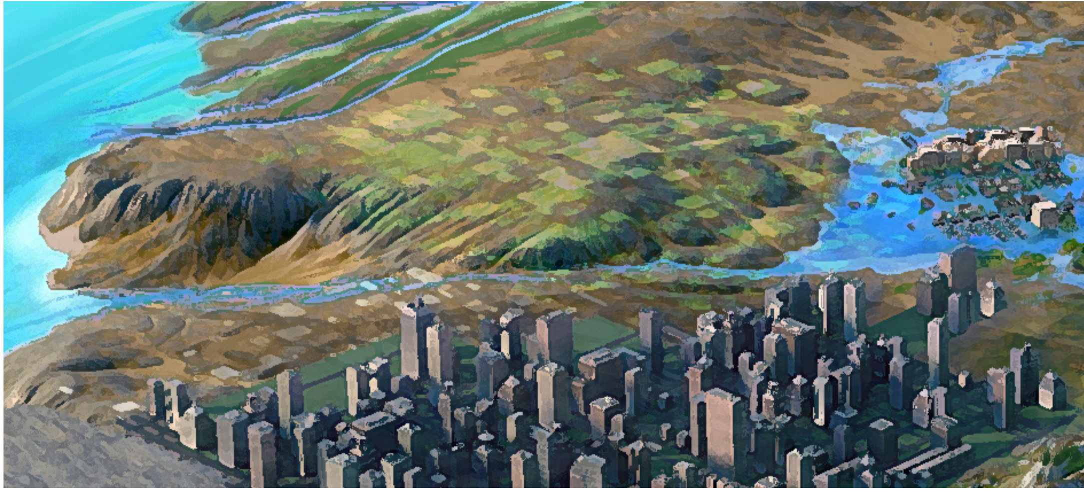


2.5 Summary

Science and applications needs are discussed in the chapters 3 and 8 of this study team report. Each observation type spans several disciplines identified by STV. The disciplines need global baseline measurements to achieve science and applications goals. Repeated measurements, also discussed in the next section, are needed at targeted regions and differ by observable (Figure 2-6).

FIGURE 2-6. Coverage maps for each observable within the STV Targeted Observable domain. Baseline topography is needed globally (top). Geographic regions needing repeat measurements are shown for surface topography (ST), vegetation structure (VS), shallow-water bathymetry (SWB), and snow depth (SD).





CHAPTER 3

SCIENCE AND APPLICATIONS GOALS, OBJECTIVES, AND PRODUCT NEEDS

3.1 Introduction

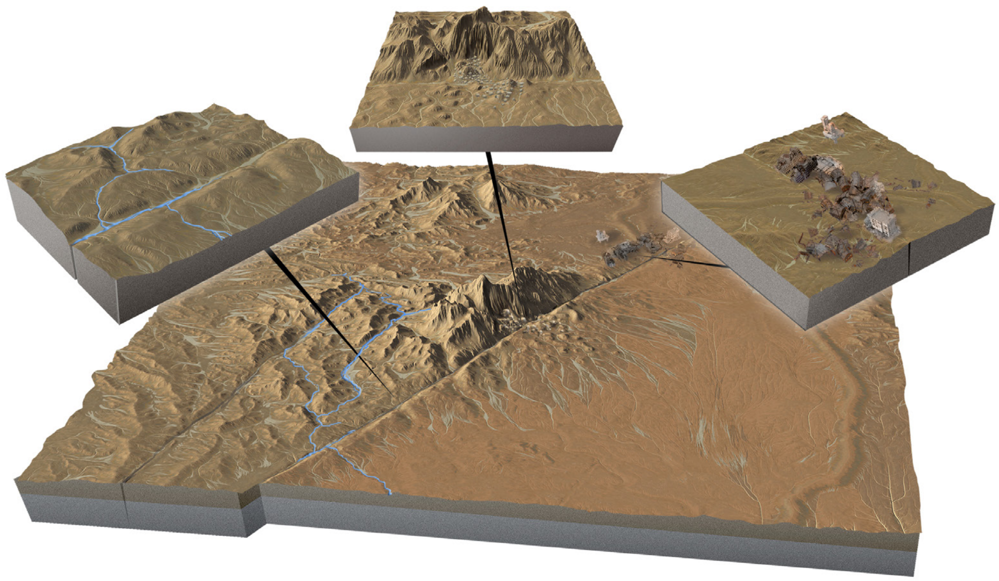
STV measurements can serve a broad range of science and applications goals and objectives, integrating variety of observables associated with surface topography, vegetation structure, and shallow water bathymetry. Measuring these observables over time will improve models through a better understanding of the driving processes and associated change, benefitting science and providing actionable information for decision making to agencies and organizations with operational mandates. The following sections describe the goals, objectives and product needs for the disciplines defined by the STV team. The SATM is organized by the five STV disciplines and applications. Where possible the disciplines in the SATM incorporate all science and applications objectives, because the measurements serve objectives which have both science and applications aspects without a distinct separation between them. We devote a section to the unique driving needs for some applications that are more stringent than what is typically required for a scientific investigation. Those needs are primarily related to latency (product delivery time), repeat frequency, and resolution.

STV goals, objectives and product needs were compiled in a preliminary SATM containing both aspirational and threshold value measurement needs (Appendix A). When referencing material directly from the DS we call it out as "(DS:)." When we have updated the DS needs based on our expert knowledge, and community input we call it out as "(New:)." We developed the SATM by synthesizing information obtained through five means (Figure 1-2):

1. Review of the sections in the 2017 DS related to STV
2. Review of the DS Requests for Information White Papers submitted for use in developing those sections
3. Six community-outreach online workshops, distributed over several weeks, consisting of a plenary session and five discipline sessions on solid Earth, vegetation structure, cryosphere, hydrology and coastal processes (Appendix C)
4. An online questionnaire seeking community input on objectives and product needs to meet those objectives (Appendix D)
5. The expertise of the members of the STV Study team

The need for high accuracy, repeat measurements to measure change was common to all disciplines and apparent for all means used to develop the SATM.

FIGURE 3-1. Actively deforming plate boundary zones contain active faulting and landslides. High-resolution topography is needed to measure past activity and in response to present-day activity.



3.2 Solid Earth

Solid Earth (SE) processes relevant to high-resolution topography and topographic change include earthquakes and fault movement (Figure 3-1); volcanic unrest and eruptions; landslides; landscape change through tectonic-climate interactions, hydrology, and resource extraction; and vertical land motion contributing to relative sea-level (RSL) change. Bare earth surface topography and its continuation below shallow water, especially in near coastal zones, is the main observation of interest to solid Earth. Measurements that penetrate vegetation to resolve the bare Earth surface are thus essential to solid Earth science and applications.

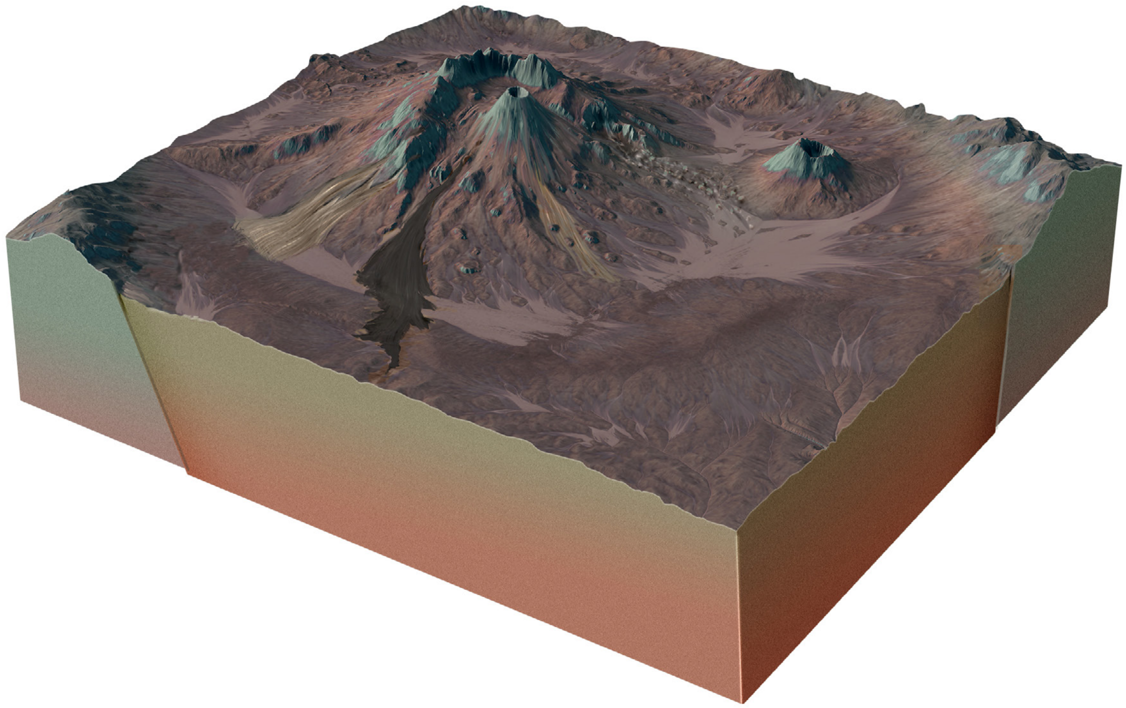
3.2.1 Solid Earth Goals/Questions

The overarching questions from the DS relevant to STV and Solid Earth are as follows. "DS: S-n" in parentheses indicates DS: S=Solid Earth and the number index of the question; the words within square brackets indicate relative importance [Most Important, Very Important, or Important].

1. How can geological hazards (**earthquakes, volcanoes, landslides**) be accurately **forecasted** and eventually predicted in a socially relevant timeframe? (DS: S-1) [Most Important]
2. How do **geological disasters** directly **impact** the Earth system and society following an event? (DS: S-2) [Most Important]
3. How will **local sea level** change along coastlines around the world in the next decade to century? (DS: S-3) [Most Important]
4. What processes and interactions determine the rates of **landscape change**? (DS: S-4) [Most Important]
5. What are the impacts of deep underground water on geologic processes and water supplies? (DS: S-6) [Very Important
6. Improve discovery of energy, mineral, and soil resources (DS: S-7) [Important]

Of these, products related to (5) are covered under Hydrology. (6) has the least mention in the DS but has less stringent product needs than (1) and (2).

FIGURE 3-2. Volcanoes are capable of large changes in topography, from edifice-scale caldera formation to active lava flows, dome extrusion, and pyroclastic flows and secondary landslides.



3.2.2 Solid Earth Objectives

The overarching questions for Solid Earth are addressed through a number of specific objectives, where the letter-number letter combination is related to the primary question (e.g., S-1b would be the second objective of question S-1). The objectives relevant to STV are described below:

> *Measure the pre-, syn-, and post* ***eruption*** *surface deformation and* ***products*** *of Earth's entire active land volcano inventory with a time scale of days to weeks (DS: S-1a).*

Volcano topography is needed at high resolution to define the present state of volcanic systems, including mapping of structures and for mapping lava flow and debris/lahar flow erosion and deposition and for constraining lava flow and debris paths, such as lahars, for hazard forecasting during and following volcanic eruptions (Figure 3-2). An additional need is repeat topography observations to track lava flows and deposits and to constrain dynamic volcano eruption models through changes in effusive volume and/or caldera collapse or other significant changes in edifice morphology.

> *Measure and forecast inter-, pre-, co-, and post-****seismic*** *activity over tectonically active areas on time scales ranging from hours to decades (DS: s-1b).*

Topography covering fault systems is used to detect and measure paleo-displacements of active faults, and, when combined with age dating methods, fault slip rates can be estimated. When an earthquake occurs, repeat topography measurements shortly following the event are used to measure fault displacements and geomorphological changes used to understand shallow fault mechanics and ground disruption relevant to human infrastructure. During the postseismic period large aftershocks and other induced processes such as landslides are likely to continue to change the landscape, generating new hazards that affect society. Therefore, repeated topography measurements are needed for the duration of this process until reaching a new baseline topography.

*Forecast and monitor **landslides**, especially those near population centers (DS: S-1c).*

Landslides generate significant time-varying topography. Given sufficiently fine spatial resolution, topography time series are used to measure surface motion and detect changes from nearby background rates. Following catastrophic landslides, differential topography can be used to infer large-scale displacements and landslide volumes, which can then be used to constrain physical models. Given their significant geographic spread both within the U.S. and globally, landslide monitoring and forecasting for science and applications requires frequent global coverage over areas with significant topographic slope.

*Rapidly capture the **transient** processes following disasters for improved predictive modeling, as well as response and mitigation through optimal retasking and analysis of space data. (DS: S-2a).*

Relevant quantities are defined by the disaster but can include high-resolution optical and SAR data to provide information on the magnitude and extent of damage. In addition, *"High-resolution topography enables quantified assessments of landscape change due to erosion, deposition, and vegetation disturbance. An important objective for all of these data is the rapid dissemination of higher-level products to local emergency responders and the global scientific community."* Though not specifically defined in the DS, frequent data repeat or rapid and directed tasking and low latency are implicit.

*Assess surface deformation, extent of surface change…of **volcanic products** following a volcanic eruption (hourly to daily temporal sampling). (DS: S-2b)*

This is the volcano disaster response, and builds on S-2a. Relevant topography data would include short repeat interval topography at low latency to measure loss and depositional changes to the landscape that would affect the severity and distribution of co- and post-eruption hazards such as lava flows, pyroclastic flows, and lahars.

*Assess co- and post-seismic ground deformation and **damage to infrastructure** following an earthquake. (DS: S-2c)*

This is the earthquake response, and builds on S-2a. Relevant topography data would include short repeat interval topography at low latency to measure large topographic disturbance due to fault motion as well as associated secondary effects such as induced landslides. In addition, very high-resolution (≤1 m) topography could be used to quantitatively assess building and infrastructure damage, which would be a more direct measurement than, for example, methods based on InSAR coherence change that can only identify the extent of the damaged area.

*Determine **vertical motion** of land along coastlines. (DS: S-3b)*

Vertical land motion (VLM) in near coastal regions is the on-land component of relative sea-level (RSLR) rise, and locally can be as much as two orders of magnitude greater than regional or global sea level rise. High accuracy, high precision topography forms the basis for predicting future inundation due to RSL and storm surges. Time series of such bare earth topography maps could allow resolution of VLM rates in areas where conventional observations from GNSS or InSAR are incomplete. The spatial heterogeneity of subsidence in coastal areas prevent local GNSS measurement from capturing the complexity of VLM with sufficient resolution to identify driving processes, and InSAR is not able to measure VLM in many areas because of temporal decorrelation due to changes in vegetation, soil moisture and periodic inundation due to tides and river discharge.

*Quantify global, decadal **landscape change** produced by abrupt events and by continuous reshaping of Earth's surface due to surface processes, tectonics, and societal activity. (DS: S-4a)*

Science and applications analyses include the combination of tectonic activity, erosion through climate-driven variations in precipitation and vegetation, and human activity. High-resolution bare-earth topography is needed to analyze the current state of the landscape and relate its properties (e.g., curvature, gradients, stream and river catchments) to tectonic, hydrological, and climate processes. In addition, rapid changes to the landscape due to floods or sinkholes require repeated observations to update the landscape topography, understand different processes, and inform resiliency and response.

> *Map topography, surface mineralogic composition and distribution, thermal properties, soil properties/water content, and solar irradiance for improved development and management of energy, mineral, agricultural, and natural resources. (DS: S-7a)*

Extraction of resources whether from the surface or from the subsurface can produce surface topography disturbance or surface deformation. Moderate resolution topography is needed to track surface disturbance and serve as the base map for InSAR deformation measurements.

3.2.3 Solid Earth Product Needs

Based on the DS science and application goals and objectives, SE needs the following products:

- Bare-earth topography for baseline topography and topographic change.
- Shallow water bathymetry for continuation of SE processes below water.

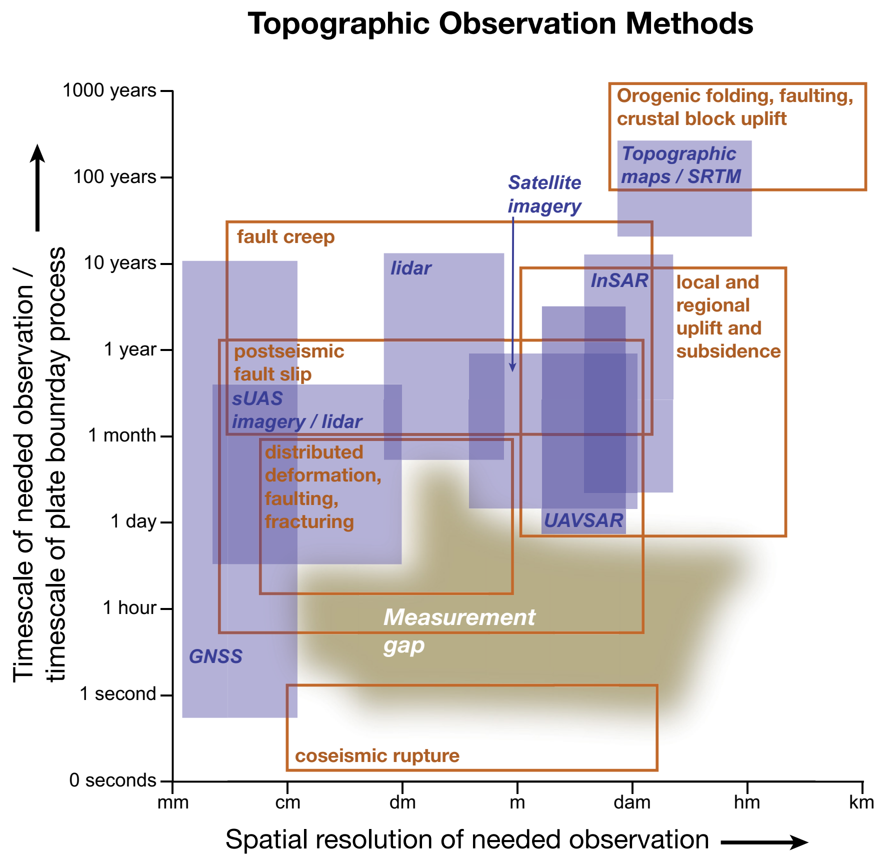
These are recommended as continuous gridded products with horizontal and vertical resolutions as given in the SATM. In addition, specific temporal needs were identified in order to meet the science and application goals identified in the DS and through this study.

3.2.4 Solid Earth Unique Challenges

The SE science and application needs are particularly stringent. The DS and our subsequent study and community inputs identified global, gridded, high-resolution bare earth topography, and its extension beneath water to the extent possible, at high temporal sampling to meet SE hazard crises and event response for both science and applications. In the DS high resolution was considered 1-5 m posting with 0.1 m vertical resolution (see SATM for final array of measurement product needs). These needs and measurement gaps (Figure 3-3) put significant pressure on the sensor and architectures in order to meet these product needs and are investigated in detail in Section 4.

Meeting the SE hazard science and application needs, particularly at the temporal sampling frequency (e.g., subdaily to a few days), post-event delay, and event duration (months) will possibly require a hybrid approach combining airborne observations with less frequent satellite topography acquisitions, with the airborne assets providing frequent, high-resolution observations of a targeted area. However, this presents challenges to global reach due to airborne platform range and availability and airspace access, as pointed out in the DS.

FIGURE 3-3. Summary of current estimates of the spatial resolution and the timescale of needed observations. Relevant timescale of the solid earth process of interest. Measurement gap emphasizes need for high-frequency observations over a range of spatial scales and resolutions.



The VLM needs for mapping localized changes in the surface topography can be achieved if global, high-resolution, high vertical accuracy, repeat topography at sufficient temporal sampling are acquired that allow generation of topography time series.

FIGURE 3-4. Schematic image of tropical, intact forest (left), natural or anthropogenically disturbed forest (middle-right), and regrowing forest (right), with birds showing habitat preference for taller forests

3.3 Vegetation Structure

Vegetation structure is the vertical configuration of aboveground vegetation and its horizontal landscape variations (Brokaw and Lent, 1999). In most habitats, vegetation provides the main structure of the environment. There is a strong relationship between the geometrical form and architecture of the habitat as a biological system and its function (Shugart et al., 2010). The three-dimensional form of plants, influences their function and their function in turn influences their form. Plants, via their diverse growth forms and distributions across the landscape provide the three-dimensional structure necessary for light conditions and nutrients cycling that promote growth and habitat niches utilized by a variety of organisms. Measures of structure define the state of the habitat in terms of its vertical and horizontal heterogeneity, biological diversity, ecological functions, and ecosystem services (Figure 3-4). Structure has profound effects on how ecosystems support delivering services such as recycling carbon from photosynthesis and biomass production, recycling water through evapotranspiration and delaying precipitation run-off via canopy interception, and energy recycling through heat exchange and evaporative cooling. Distinguishing horizontal from vertical variations of structure across different spatial and temporal scales is important for quantifying changes of habitat that impact some taxa (e.g., birds and mammals preferring canopy and open areas for nesting and foraging) (Rose et al., 2015; Bergen et al., 2009) and ecological functions (e.g., biomass dynamics from disturbance and recovery processes) (Frolking et al., 2009).

3.3.1 Vegetation Structure Goals

The overarching science goals and questions relevant to vegetation structure are:

(Goals taken directly from DS = DS, new goals from current study = New)

- What are the structure, function, and biodiversity of Earth's ecosystems, and how and why are they changing in time and space? (DS: E-1)
- What are the fluxes (of carbon, water, nutrients, and energy) within ecosystems, and how and why are they changing? (DS: E-3)
- What are the carbon storage and dynamics of ecosystems, and how are the carbon sinks in global vegetation changing in time? (New: E-4, E-5)
- How do natural and anthropogenic disturbances (deforestation, degradation, fire, droughts, etc.) impact ecosystem productivity and function and their resilience in a changing climate? (New: E-6, E-7, E-8)
- How does vegetation structure influence the water exchange (evapotranspiration) and hydrological processes across gradients of dry to wet ecosystems and from inland to coastal regions? (New: H-3c, E-11).

3.3.2 Vegetation Structure Objectives

The overarching goals for Vegetation Structure are addressed through a number of specific objectives, where the letter-number-letter combination is related to the primary question (e.g., E-3b would be the second objective of Goal E-3). During the study, a large number of detailed objectives were considered and then combined into a manageable number of objectives to inform the rest of the SATM process. The DS listed "E-1b. Quantify the global three-dimensional (3D) structure of terrestrial vegetation" (Most Important) as a science objective under Goal E-1. However, the STV study team believed this was a stated solution rather than a science objective and therefore developed more specific objectives under E-1.

The questions relevant to vegetation structure of STV are:

1. How is ecosystem structure changing due to climate change and human activities? (New: E-1b2)
2. To what extent does 3D vegetation structure explain variations in composition and biological diversity (flora and fauna) of ecosystems at various scales? (New: E-1f1)
3. How will ecosystem ecological functions (e.g., carbon, water cycling) and services (e.g., sustaining food and fiber, air and water, societal benefits) change with increased pressure from humans and climate? (New: E-1b2)
4. What is the impact of anthropogenic disturbances (e.g., deforestation, degradation, fragmentation, and increasing CO_2) on vegetation biomass and growth rate? (New: E-4b)
5. How are climate change and anthropogenic disturbances impacting the structure and biomass accumulation in temperature limited (e.g., boreal) and water limited (e.g., savanna and dry woodlands) ecosystems? (New: E-1b4, E-1f12)
6. To what extent is the 3D habitat structure altered by changes in species composition (e.g., foundation species, invasive species, indicator species etc.)? (E-1e)
7. What is the rate of forest fire fuel loading change, as well as spatial and temporal vegetation variability in built and natural landscapes and for different ecosystem types, and how does this affect fire risk, severity, and behavior? (New: E-8b).

A number of vegetation structure-related objectives that are more specifically aimed at decision making with high socio-economic value are listed within the Applications Section (3.7).

3.3.3 Vegetation Structure Product Needs

Given the diversity of vegetation structure related science and application objectives and the wide range of product needs identified through the questionnaire, the above objectives were arranged into three groups with similar product needs: (i) Global Carbon Cycle, (ii) Ecology and Biodiversity, and (iii) Applications (preliminary SATM Appendix A).

The primary STV products identified to meet the objectives listed in Sec. 3.3.2 are:

- Vegetation canopy height and changes
- Vegetation canopy vertical profile and changes
- Digital Terrain Model (DTM)

The secondary products derived from the primary STV products are:

- Aboveground biomass (AGB) and change
- Leaf area index (LAI), or plant area index (PAI) and change
- Vertical and horizontal vegetation structural diversity and change
- Canopy gap frequency/size and change

Based on input from the ecosystem science community (59 completed questionnaires were received), the STV study team converged on the product specifications for the preliminary SATM. Note that these specifications are associated to final science products and typically require lower-level products to be acquired at finer spatial and temporal sampling.

3.3.3.1 Global Carbon Cycle Product Needs

Vegetation 3D structure, and in particular vegetation canopy height and its rate of change, is directly linked to AGB and AGB change via stand-level, forest type-specific allometric equations (Chave et al., 2005). The decadal survey specified requirements for AGB as global, daily sampling at 30 m / 300 m horizontal resolution (10–25 m Lidar footprint size within 1 ha cells), global sampling every 5 years. The present study found that in order to quantify the magnitude and geographic location of carbon stock and change, we must quantify AGB globally over the range of AGB stocks 0–1000 Mg/ha with ±10% or 10 Mg/ha absolute accuracy, whichever is greater, at 50–100 m (0.25–1 ha) horizontal resolution (aspirational to threshold) and with seasonal to annual (90–365 days) repeat interval, over a period of 3–9 years. AGB change must be estimated with accuracy ranging from ±10% or 10 Mg/ha/y, whichever is greater at the scale of disturbance (< 1ha), to the aspirational goal of ±10% or 1 Mg/ha/y, whichever is larger at landscape scales (100–10000 ha). The desired accuracy is based on the fact that, in the worst-case scenario for tropical forests, AGB changes range from less than 1 Mg/ha/y for mature intact forests (Phillips et al., 2014; Meyer et al., 2013; Treuhaft et al., 2017) to 5–10 Mg/ha/y for secondary forests of different ages (Poorter et al., 2016) (e.g., Neef and dos Santos, 2005). Future STV products must also be able to monitor subtle biomass changes (e.g., including regrowth, forest degradation, shrub encroachment) in low-biomass-density areas (<50 Mg/ha) such as savannas and boreal regions across the globe as these ecosystems cover large areas and contribute substantially to the global carbon cycle (McNicol et al., 2018; de Miranda et al., 2014).

3.3.3.2 Ecology and Biodiversity Product Needs

In order to answer the science questions related to ecology and biodiversity, we must quantify vegetation structure globally across 50–90% of all landscapes covered by vegetation contiguously (aspirational) or in a systematic sampling approach (threshold) at the spatial resolution of 5–25 m (aspirational vs. threshold), vertical resolution of 1–2 m, with vertical accuracy of 1–1.5 m, and the repeat cycle of 90–365 days to detect seasonal to annual dynamics and changes (Krieger et al., 2009; Quegan et al., 2019; Kugler et al., 2014). Note that these are more stringent product needs compared to those of the carbon cycle products outlined in Sec. 3.3.3.1. Related products, e.g., gap frequency and size, which are essential to biodiversity studies, can be derived from the 3D structure product. It should be noted that some community participants believed that there was insufficient scientific evidence to inform the product needs for biodiversity-related objectives, especially since literature suggests that the relationship between fauna and vegetation structure varies for different scales and taxa (Eitel et al., 2016; Cooper et al., 2020), and therefore, this is considered a knowledge gap.

3.3.4 Vegetation Structure Operational and Commercial Applications

Agriculture, Wildfire, Commercial Forestry, and Deforestation Monitoring require vegetation height and 3D structure products with the most stringent and diverse needs with horizontal resolutions of 1–100 m and vertical resolution of 0.25–2 m (aspirational to threshold). Products must be produced routinely every 3–90 days for specific areas of interest and made available with latency of 3–90 days (aspirational to threshold). Systems for continuous deforestation monitoring and near real-time alerting require wide coverage, very frequent revisit cycles (3–10 days) and short latencies (1 day). The actual magnitude of biomass change will be estimated less frequently for aggregated periods (e.g., 90 to 365 days). Fire applications and deforestation alerting drove the highest repeat and latency specifications (1–3 days), while commercial forestry drove the highest horizontal (1–20 m) and vertical resolution (0.5–1 m) specifications. For fire applications, subcanopy structure to quantify fuel load and more specifically, ladder fuels, required accurate understory estimation with 1–2 m vertical resolution.

3.3.5 Vegetation Structure Unique Challenges

The STV incubation study has focused on remote-sensing techniques capable of mapping vegetation canopy profiles and derived products with the desired spatial and temporal sampling, accuracies, and coverage (Sec. 3.3.3). These techniques hinge on lidar or radar technologies, which have different and unique challenges. Vegetation structure is accurately measured with airborne lidar (ALS) (Blair & Hofton, 1999; R. Dubayah et al., 2020; Lefsky, Cohen, Parker, et al., 2002; Popescu et al., 2018); however, ALS has very limited coverage, which precludes regional to global studies. While ALS measurements can be scaled up to larger area by means of empirical models and SAR imagery with very wide coverage, the uncertainty of the estimated vegetation structure products is larger than most science and application requirements. Errors in estimating vegetation structure are propagated when extrapolating to large scales by other remote sensing data, detecting changes, and estimating biomass using local or regional models. These errors are accumulated, making the large-scale science products less reliable for carbon accounting and programs that incentivize the conservation forest habitats for ecosystem services.

One challenge for lidar-based techniques is to drastically increase coverage while maintaining a high accuracy to allow monitoring of various forms of vegetation structure change and to allow detection of changes of biomass and stocking volume from subtle degradation (e.g., timber extraction) and recovery (e.g., regeneration) (Asner & Mascaro, 2014; Dubayah et al., 2010; Naesset, 2007; Neigh et al., 2013; Saatchi et al., 2011; Schimil et al., 2015). The space-based GEDI and ICESat-2 missions are currently providing lidar data that sample vegetation structure across the globe. The scientific and user communities are only starting to use their derived vegetation metrics to address science questions, and it will take some time to determine if this stand-alone lidar data and their gridded products meet community needs. GEDI and IceSat-2 lidar data are limited in their coverage and sensitivity to dense forests, respectively, and are not specifically designed to monitor changes of vegetation structure in time.

Synthetic aperture radar (SAR) measurements using polarimetric (i.e., PolSAR) and interferometric (i.e., InSAR, polarimetric InSAR [PolInSAR], tomographic SAR [TomoSAR]) techniques at different wavelengths have been used extensively to provide forest height (Lavalle and Khun, 2013; Lavalle and Hensley, 2012; Hajnsek et al., 2009; Praks et al., 2007; Treuhaft et al., 2017), forest vertical profile (Ho Tong Minh et al., 2016; Tebaldini et al., 2019; Tebaldini and Rocca, 2012; Treuhaft et al., 2010; Wasik et al., 2018b) and forest volume and AGB (Askne et al., 2017; Treuhaft et al., 2015; Neumann et al., 2012; S. Saatchi et al., 2011). These techniques have been mostly developed using SAR observations from airborne platforms and have been critical in the design of spaceborne SAR systems (ALOS, NISAR, BIOMASS) and applications for global forest structure and carbon monitoring (Askne et al., 2018; Santoro et al., 2018; Yu and Saatchi, 2006; Yang et al., 2021; Rizzoli et al., 2018). Spaceborne SAR has also been used in the development of biomass modeling (Kasischke et al., 1994; Kasischke et al., 1995; Harrell et al., 1995; Harrell et al., 1997).

SAR systems have the ability to provide vegetation 3D structure contiguously over larger areas from air and spaceborne platforms and are designed for repeated measurements that quantify changes of vegetation structure and biomass. NASA's NISAR is designed to provide estimates of forest biomass globally over low biomass density regions (<100 Mg/ha) and ESA's BIOMASS mission will provide forest 3D vertical structure and biomass for high biomass densities (>100 Mg/ha), particularly across tropical regions with coarse spatial resolution. However, the Tomo SAR technique, requiring multiple observations from varying look angles to map accurately 3D structure across all ranges of biomass, is challenging to implement on spaceborne platforms. Synergistic observations from both lidar and SAR techniques are shown to overcome the challenges of each for spaceborne observations (Qi et al., 2019; Marshak et al., 2020). The STV incubation study has identified challenges for existing technologies and gaps in approaches that are recommended to be addressed during the next decade.

Regardless of the technology employed, one additional challenge in mapping the forest AGB is the spatial uncertainty, particularly in areas of high biomass density (Mitchard et al., 2013; Saatchi et al., 2015; Rodriguez-

Veiga et al., 2017). These uncertainties are associated with 1) the limited high-quality, in-situ biomass data to allow developing reliable empirical models between biomass and remote sensing observations globally and across different forest types, 2) sensitivity and sampling density of existing remote sensing observations to capture the variability of global vegetation biomass, and 3) heterogeneity and variations of forest structure, species composition, and wood density introducing large errors in extrapolating or predicting biomass over large areas. There have been concerted efforts to address these sources of uncertainty by developing protocols for calibration and validation of remote sensing observations (Duncanson et al., 2019, Chave et al., 2019, Rejou-Mechain et al., 2019). SAR-derived biomass is confounded everywhere by surface and canopy moisture/water status. A large contingent of researchers use active and passive microwave for soil and vegetation water (e.g., Bourgeau-Chavez et al., 2013, Kasischke et al., 2011). The use of other active and passive capabilities and multi-modal SAR systems to separate biomass, structure, and moisture in the SAR signal is a clear need.

A representative set of in-situ measurements are currently compiled in different databases for biomass and forest structure calibration and validation. These include, the GEDI Forest Structure and Biomass Database (FSBD) of more than more than 100 supersites globally that includes thousands of individual ground plots accompanied by airborne lidar data required to scale-up the biomass estimates (https://gedi.umd.edu/science/calibration-validation/; Dubayah et al., 2020), and the NISAR and Biomass mission supersites distributed across the global biomes (http://forest-observation-system.net/). The challenge is that these field measurements are biased towards northern hemisphere and developed countries. In addition, the measurements are not updated frequently and will be likely out of date by the time future STV-related missions are launched. Therefore, any STV concept for vegetation structure measurements from space must support concurrent in-situ and airborne observations to allow calibration and validation of algorithms to derive vegetation biomass and other ecological characteristics.

3.4 Cryosphere

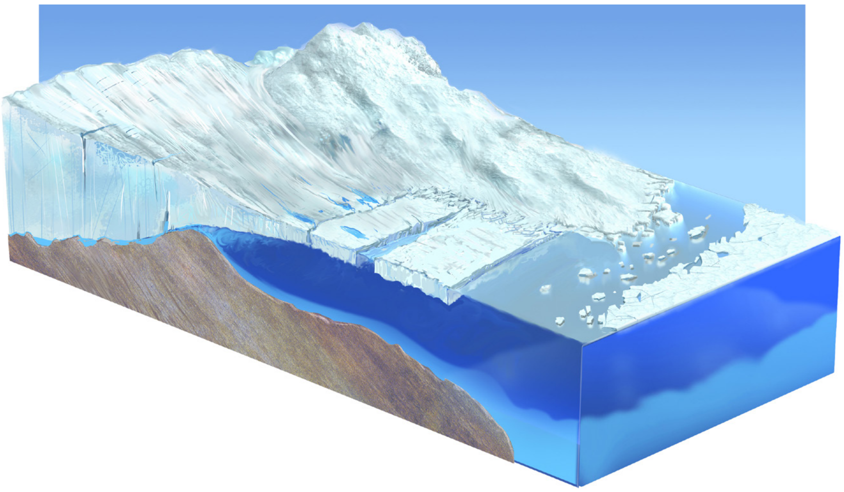
The cryosphere (glaciers, ice sheets and sea ice) plays a critical role in the Earth's climate system and has significant societal impact: Changes in glacier and ice sheet mass dictate decadal to millennial changes in sea levels. Ice discharge and meltwater runoff can impact local ocean circulation (DS: C-8) and ocean biology. Runoff from glaciers can be a critical source of water for drinking and irrigation during warm and dry seasons. Sea ice modulates the amount of shortwave radiation absorbed by the Earth's surface and regulates ocean-atmosphere mass and energy fluxes in polar oceans. Much of Earth's ice exists in environments that are near the melting point, making them particularly vulnerable to changes in ocean and atmosphere temperatures. Moreover, both sea ice and ice sheets are susceptible to feedback, sometimes irreversible, in processes that can result in large and sustained changes to ice mass, sea level and sea ice cover (Figure 3-5).

3.4.1 Cryosphere Science and Societal Goals/Questions

For this reason, the DS has identified improving understanding of glacier and ice sheet change and its consequences for sea level change as ***Most Important*** and identifying the role of sea ice change in contributing to Arctic amplification as *Very Important*. Specifically:

- How much will sea level rise, globally and regionally, over the next decade and beyond, and what will be the role of ice sheets and ocean heat storage? (DS: C-1)
- How will local sea level change along coastlines around the world in the next decade to century? (DS: S-3)
- What will be the consequences of amplified climate change already observed in the Arctic and projected for Antarctica on global trends of sea level rise, atmospheric circulation, extreme weather events, global ocean circulation, and carbon fluxes? (DS: C-8)

FIGURE 3-5. Illustration of an ice sheet outlet glacier and its interactions with the atmosphere and ocean that can lead to changes in rates of ice loss and sea level change. The processes illustrated here, and their importance for future sea level, are detailed in the Special Report on the Ocean and Cryosphere in a Changing Climate (Oppenheimer et al., 2020).



All of the above priority science and societal questions from the DS are targeted toward improving our ability to project the future state of land ice and sea ice in a warming world. This requires improved understanding of key physical processes (e.g., Figure 3-5) that greatly influence projections and that are responsible for existing large uncertainties. Those processes deemed most important for advancing cryosphere science over the coming decades, and relevant to STV observations, as follows:

1. [*Glacier and ice sheet*] *Surface mass balance processes* including precipitation, surface melt, firn processes, supraglacial water volume and transport, and proglacial lake formation.
2. [*Glacier and ice sheet*] Tidewater and grounding zone (transition zone from grounded to floating ice) mechanics, including the influence of subglacial freshwater across the grounding zone, control rates of ice discharge into the ocean and are responsible for the initiation of large, sometimes irreversible, feedbacks that can drive ice sheet collapse.
3. [*Ice shelves and glaciers*] Flexure, fracture, and calving influence the geometry and strength of the ice and its ability to resist oceanward flow of inland ice and affects mass balance.
4. [*Ice shelves and glaciers*] Ocean melting at tidal to multi-annual time scales, including basal melting and front melting, and its influence on thinning rates of ice shelves, which can reduce buttressing and drive grounding zone retreat.
5. [*Sea ice*] Thermodynamic and dynamic forcing of the *ice thickness distribution* and its role in modulating atmosphere-ocean energy exchange.
6. [*Sea ice*] Variability in *momentum transfer* associated with wind/ocean stress at the surface from changes in sea ice roughness (i.e., aerodynamic and form drag).
7. [*Sea ice*] Snow depth and its time-varying redistribution, responsible for controlling the surface energy balance, winter ice growth and mechanical loading at the ice surface.
8. [*Sea ice*] Coverage and evolution of *melt ponds* during summer along with their impact on end of summer ice volume and positive albedo feedbacks.

Advancing our understanding of these processes is critically dependent on the observation of key geophysical properties, including surface topography.

3.4.2 Cryosphere Objectives

The DS has identified the measurement of surface topography as one of the priority observables needed to address questions C-1, S-3, and C-8. The measurement of ice elevation is identified as both an Explorer and Incubator (STV) observing system priority (DS Table 3.6, DS Table S.2, DS Table 6.2). The measurement of sea ice topography (i.e., freeboard) was not identified as an STV target. Given the importance that the DS placed on understanding the role of sea ice in Arctic amplification, and the importance of sea ice thickness measurements in advancing this understanding, we consider the omission of sea ice from STV as an oversight by the DS and therefore include it here.

3.4.3 Cryosphere Product Needs

Following from the identified needs for improved process understanding required to address the high priority questions posed by the DS, STV has identified 6 key STV measurements:

- Glacier and ice sheet surface elevation
- Glacier and ice sheet surface elevation change
- Glacier and ice sheet snow depth distribution
- Proglacial and supraglacial water depth
- Sea ice thickness distribution and change
- Sea ice roughness distribution
- Sea ice snow depth distribution

Specifically, the STV team, with community consultation and guidance from the DS, identified seven surface targets (see Appendix A) having unique measurement needs. Overall, the needs identified by STV align well with those originally suggested by the DS.

The use of satellite derived elevation, elevation change, and sea ice thickness are relatively mature but more research is needed to better identify methods for snow depth estimation over both land ice and sea ice that present unique challenges not encountered over stable terrain. There is a general consensus that future satellite cryosphere elevation products should follow those currently provided by NASA's ICESat-2 mission.

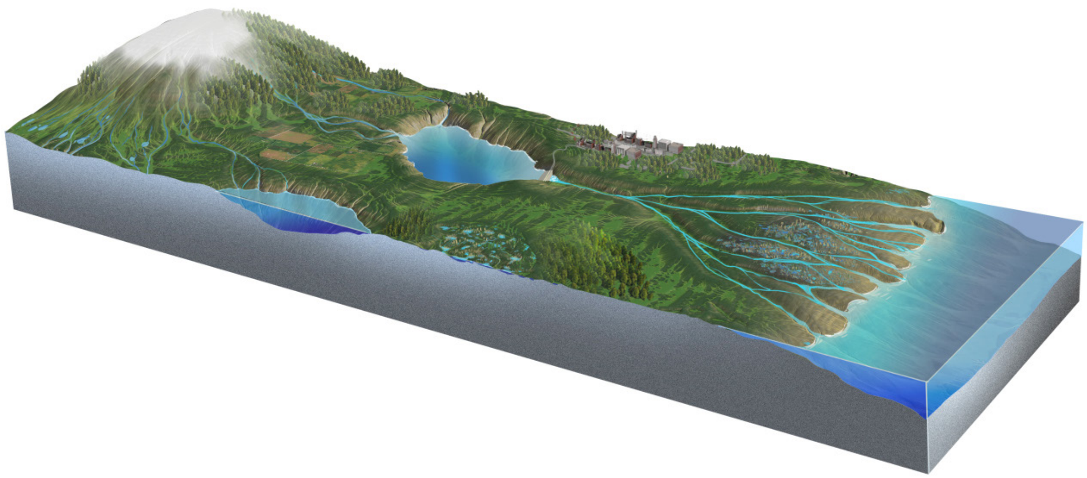
3.4.4 Cryosphere Unique Challenges

Through the process of the incubator study several key technology and measurement gaps were identified and need to be highlighted here:

1. **Spatial sampling vs target size:** Different cryosphere applications have different data requirements that may be difficult to satisfy with a single measurement strategy. For example, understanding surface-mass-balance processes of ice sheets requires dense temporal sampling and broad-scale spatial coverage to high latitudes, while understanding outlet-glacier processes requires concentrated observation at high spatiotemporal resolution of small areas. Developing a mission to satisfy both requirements with a single satellite platform will require studies of how each type of observation could be scheduled to achieve mission goals that have potentially conflicting design constraints. Combining measurements from multiple satellite platforms may provide more satisfactory solutions but increases the number of mission parameters to be studied, and may not be a good fit in the DS strategic framework.

2. **Temporal sampling and data latency:** Many cryospheric targets are subject to changes on a variety of timescales from daily to decadal. Repeat periods for data collection should be at least seasonally (every 3 months), which restricts the use of optical photogrammetry in isolation because of polar night when the polar regions are without sunlight for several months on end. Thus, some combination of technologies is likely necessary (as further discussed in 4.). Some important events such as iceberg calving and surface melt and runoff require shorter data latency.
3. **Refine prioritization:** Making measurements that satisfy the identified needs will be challenging with current technologies. Any future mission will likely need to leverage new technologies that offer increased coverage and resolution compared to past missions. With technology improvements, and advances in our understanding of glaciers, ice sheets, and ice shelves, the measurement needs will need to be revisited closer to formulation to obtain a consistent prioritization of surface targets, resolution, and repeat frequency. This refined prioritization should be supported by OSSEs which we broadly define as any study that uses data and/or models to refine measurement needs. Such efforts could include in-depth analysis of high-spatial-and-temporal-resolution data to determine resolution gaps for any of the processes identified in 3.4.1. Efforts could also include purchase or acquisition of new datasets needed for such analysis.
4. **Surface properties:** The measurement precision required over the inland portions of Antarctica and Greenland restricts the range of technologies that might prove acceptable. The changing dielectric properties of snow, firn, and ice (in space and time) make the interpretation of surface height measurements from satellite radar altimeter observations challenging. Many efforts have been made to account for such changes, both empirically and using radiative transfer models, with varying degrees of success. However, interpretation of elevation changes derived from satellite radar altimetry at the accuracy needed for measurement of seasonal-to-annual changes in land ice elevation remains challenging. At the same time, the precision of state-of-the-art optical photogrammetry is not sufficient to meet the requirements without calibration data from a precision altimetry system. For these reasons, at present, it appears that a mission design including some component of lidar measurements is necessary to meet glacier and ice sheet research needs.
5. **Snow depth:** Snow depth over sea ice and land ice are needed to resolve ice-atmosphere-ocean heat and mass exchange, and is essential for the estimation of sea ice thickness from elevation measurements. Such measurements are not routinely made from satellite data and require significant study to determine the feasibility of their retrieval from space. Such studies should be specific to snow over sea ice and snow over land ice, which present unique observational challenges relative to snow depth retrieval over land.
6. **Lead detection:** Identifying gaps (leads) between sea ice floes is critical to resolving the sea ice height above ocean (freeboard), sea ice thickness, floe size distribution, and the sea surface height of the polar ocean. Such measurements will likely require a radiometer to be paired with an altimeter. It is our recommendation that NASA study the feasibility of such a system.
7. **Coincident non-STV observations:** Across all identified cryosphere science gaps there is a critical need to acquire multiple coincident non-STV observations (surface motion, reflectance, emitted radiance, surface temperature, salinity, and wind stress). Such observations will require substantial efforts to coordinate agency, national and international Earth Science observations that are desperately needed to accelerate science outcomes. The whole is greater than the sum of its parts.

FIGURE 3-6. The STV Hydrology observables include elevation of land surface water from mountains to sea, in its snow and liquid state. Water depths is a critical measurement to quantify the water volumes and flows in rivers, lakes, reservoirs and wetlands, and seasonal snow depth over land is needed to determine water availability as it melts. Measurement of depth requires a DTM and a DSM. Lateral fluxes between elements of the landscape are interconnected and their evaluation is necessary to primarily close the water budget, but also to improve estimates of carbon, sediment, nutrient and pollutant exchanges across the landscape and between the land and the ocean.



3.5 Hydrology

The coupled hydrological and biogeochemical cycles and the energy cycle can no longer be considered to be changing solely due to natural variability. Anthropogenic influences on these cycles occur across a range of spatial and temporal scales that require sufficient accuracy to close the budgets. The water cycle includes processes over land and within the atmosphere that occur in all water phases. Water drives vegetation structure and productivity, lateral fluxes of carbon and sediment, transforming landscapes through erosion and deposition (Figure 3-6).

3.5.1 Hydrology Goals and Objectives

The following objectives identified in the DS can be partially addressed by the four Target Observables (shallow bathymetry, surface and ice topography, vegetation structure) of the STV mission or other Target Observables of vertical dimension (TO-16= Snow Depth and Snow Water Equivalent (SDSWE); TO-19 Surface deformation and change (SDC); TO-21=Surface Water Height (SWH); TO-22 = Terrestrial Ecosystem Structure (TES))

1. Develop and evaluate an integrated Earth system analysis with sufficient observational input to accurately quantify the components of the water and energy cycles and their interactions, and to close the water balance from <u>headwater catchments to continental-scale river basins</u>. (DS: H-1a, interaction of Water and Energy Cycles) [TO = SDSWE]
2. Quantify rates of <u>snow accumulation, snowmelt, ice melt, and sublimation from snow and ice worldwide</u> at scales driven by topographic variability. (DS: H-1c, snow cover) [SDC/SDSWE/SWH/STV]
3. Quantify how <u>changes in land use, land cover</u>, and water use related to agricultural activities, food production, and forest management affect water quality and especially groundwater recharge, <u>threatening sustainability of future water supplies</u>. (DS: H-2c, Land Use and Water) [STV/SDC]

4. Quantify the magnitude of anthropogenic processes that cause changes in radiative forcing, temperature, snowmelt, and ice melt, as they alter downstream water quantity and quality. (DS: H-2b) [STV, SDSWE]
5. Determine structure, productivity, and health of plants to constrain estimates of evapotranspiration. (DS: H-3c) [STV, TES]
6. Quantify key meteorological, glaciological, and solid Earth dynamical and state variables and processes controlling flash floods and rapid hazard chains to improve detection, prediction, and preparedness. (DS: H-4b; This is a critical socioeconomic priority that depends on success of addressing H-1c and H-4a.) [STV]
7. Understand linkages between anthropogenic modification of the land, including fire suppression, land use, and urbanization on frequency of, and response to, hazards (VI). (DS: H-4d) [STV]
8. Quantify weather events, surface hydrology, and changes in ice/water content of near-surface materials that produce landscape change (DS: S4-b) [STV/SDC]
9. Measure all significant fluxes in and out of the groundwater system across the recharge area (DS: S6-b) [STV/SDC]
10. Flows Sustaining Ecosystem Life Cycles. Quantify the flows of energy, carbon, water, nutrients, and so on, sustaining the life cycle of terrestrial and marine ecosystems and partitioning into functional types. (DS: E-3a) [TES/STV/SDC]

In addition to the above objectives of the DS, we considered additional questions identified by the 230 scientists of the international hydrology community (Blöschl et al., 2019) and those discussed during the STV Hydrology Breakout session (Community Workshop) that can partially be addressed by the STV observables:

1. How will cold region runoff and groundwater change in a warmer climate (e.g., with glacier melt and permafrost thaw)?
2. What are the impacts of land cover change and soil disturbances on water and energy fluxes at the land surface, and on the resulting groundwater recharge?
3. What causes spatial heterogeneity and homogeneity in runoff, evaporation, subsurface water and material fluxes (carbon and other nutrients, sediments), and in their sensitivity to their controls (e.g., snow fall regime, aridity, reaction coefficients)?
4. Why, how and when do rain-on-snow events produce exceptional runoff?
5. How can hydrological models be adapted to be able to extrapolate to changing conditions, including changing vegetation dynamics (e.g., in wetlands)?
6. How can we use water elevation measurements to improve our quantification of lake/reservoir water balances, and their responses to climate extremes and human activities?
7. How are wetland elevation and function changing relative to changes in water levels induced by climate, land cover change, and diversion projects?
8. How do variations in surface water extent, depth, and quantity affect biogeochemical processes such as the carbon and nitrogen cycles?
9. How are surface water bodies responding to climate change and permafrost thaw?
10. How will water storage and balance in lakes and reservoirs respond to climate extreme and human activity?

3.5.2 Hydrology Product Needs

The STV Hydrology community identified the product needs that are similar to those of the DS with an overall median spatial resolution of 5 m and vertical accuracy of 0.1 m. Detailed spatial requirements are found in Appendix A. Point-scale measurements of river discharge, sediment flux, and carbon content are sparse and in global decline. Moreover, *in situ* gauges are of limited utility in complex two-dimensional flow environments such as wetlands, floodplains, and estuaries. To achieve our objectives, spatially-distributed measurements of terrestrial water stores and fluxes are needed. Remote sensing technologies, combined with *in situ* measurements and models, offer the best alternative to improve understanding of large-scale hydrological and biogeophysical processes. While optical imaging sensors may provide information relevant to water quality (e.g., carbon and sediment concentrations), this information may not be sufficient to support modeling of transport, thus requiring different remote sensing technologies. The STV observables are surface topography, water surface height, shallow bathymetry, snow depth and vegetation structure. All are important measurement for science and applications in hydrology.

3.5.3 Hydrology Unique Challenges

Through the process of this study, the hydrology community has identified several knowledge gaps that hinder the development of an optimum STV. The interdisciplinary nature and diversity of components of the hydrological cycle that is reflected in the Hydrology goals and objectives offers significant scientific and technical challenges. In particular, while an STV product may serve to address several components of hydrology (e.g., snow depth and river flows), the desired product qualities associated with each objective may differ greatly. These qualities (e.g., spatial resolution, vertical accuracy, repeat frequency, geographical coverage) are often derived from expert knowledge or current airborne capabilities. A quantitative analysis of model sensitivity to STV parameters (i.e., bathymetry, surface elevation, vegetation structure) is required to understand the science benefits of the STV observables and reach a compromise. These analyses are needed to support the definition of the STV mission.

The development of these models will also be used to propagate uncertainty from needed model output uncertainty to remote-sensing product and to instrumental precision, and vice versa. This is achieved through OSSEs, which require these models as input to evaluate the different technologies toward achieving the Hydrology objectives.

In addition, the variety of ecological, hydrological and geomorphological conditions characterizing Earth landscape offer an additional challenge. While there exist several datasets sufficient to characterize some landscapes, others are needed to sample the diversity of landscapes, with various vegetation covers, complexity of river networks and man-made structures. These existing and new datasets should provide realistic representations of landscapes to sensitivity models and OSSEs, with the needed range of eco- and hydro- and geo-morphological conditions.

3.6 Coastal Processes

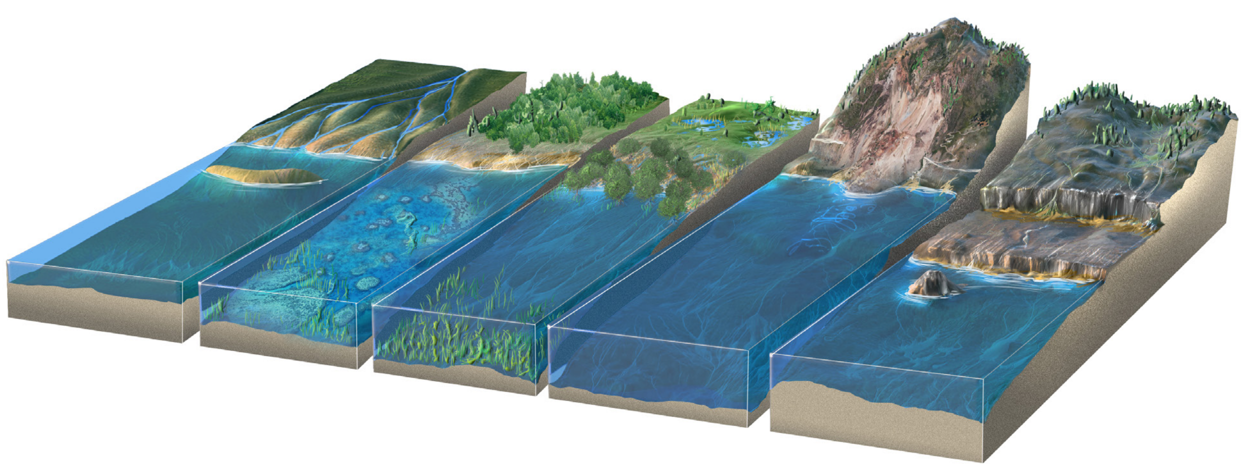
Coastal areas are among the Earth's most economically and ecologically important regions, and also among the most densely populated (Martínez et al., 2007). It has been estimated that 39% of the U.S. population lives in coastal shoreline counties and 52% in coastal watershed counties (Crossett et al., 2013), while approximately half of the world's population lives within 100 km of the coast. Coastal areas provide critical ecosystem services, including food (e.g., fishing, aquaculture), carbon sequestration, flood protection, tourism and recreation (Barbier et al., 2011; Liquete et al., 2013). Additionally, coastal areas and the harbors and ports they encompass are critical to marine transportation, with $1.6 trillion of cargo imported and exported through U.S. ports in 2017 (NOAA, 2020). The Blue Economy is estimated to contribute to 3.3 million jobs and $304 billion to the U.S. gross domestic product annually (NOAA, 2020). However, coastal regions worldwide are experiencing increasing threats, including sea level rise, fishing pressure, erosion, wetlands loss, coral bleaching, and higher intensity and frequency storms (Harley et al., 2002; Ranasinghe, 2016; Sully et al., 2019). STV can contribute to the understanding of coastal processes and measurement of shallow water bathymetry (Figure 3-7).

A wide range of coastal science and application areas, which, for purposes of this study, are grouped under the broad term coastal processes (CP), are served by accurate, high-resolution topobathymetric elevation data. Science and application area priorities identified by the DS include (S-3): "How will local sea level change along coastlines around the world in the next decade to century?" The DS highlighted the interdisciplinary nature of studies of global sea level rise, with drivers including ice sheet melting, local subsidence (affecting relative sea-level change), and extreme weather. Heightened risks of inundation of coastal cities and towns necessitate improved coastal resilience planning. The DS also discussed remote sensing measurements for enhanced understanding of marine ecosystems, harmful algal blooms (HABs), coral reef health, marine biodiversity and fisheries.

Beyond those coastal science applications specifically mentioned in the DS, the STV incubation study identified additional coastal science and application areas that can be addressed by filling critical data gaps. Specific scientific disciplines supported by these data include coastal geomorphology, marine ecology, marine geology, marine archaeology, and wetlands ecology. Enhanced data of coastal regions can also support coastal management decisions, such as establishment of marine protected areas (MPAs), coastal building codes, and tsunami evacuation routes, to name just a few. The list of key coastal topics identified through this study and the STV Coastal Processes Breakout session held online on July 28, 2020 (see details in Appendix C: Community Engagement) includes:

- Storm surge and tsunami inundation hazards
- Relative sea level rise
- Shoreline erosion and sediment transport
- Benthic habitat and marine ecosystems
- Tidal interaction with mangroves and salt marshes
- Marine archaeology
- Marine navigation and hazards

FIGURE 3-7. Illustration of different coastal morphologies associated with a range of coastal processes and with varying needs for topographic and bathymetric information to support relevant science questions. From left to right: delta and barrier island; coral reef; salt marsh and mangroves; landslide; and tectonic uplift.



3.6.1 Coastal Processes Goals/Questions

The DS identified three broad science questions and goals that are of critical importance in the coastal zone and across the broad range of coastal science and application areas considered in this study. These are listed below, with the notation "(DS: S-n)," indicating section numbers from the DS:

1. How can large-scale geological hazards be accurately forecast in a socially relevant timeframe? (DS: S-1) (Note: this question is also addressed above under Solid Earth.)
2. What is the structure, function, and biodiversity of Earth's ecosystems, and how and why are they changing in time and space? (DS: E-1)
3. Quantify how increased fetch, sea level rise and permafrost thaw increase vulnerability of coastal communities to increased coastal inundation and erosion as winds and storms intensify. (DS: C-8i)

A fourth goal, which is to support safety of marine navigation in nearshore areas, is covered in the Applications section.

3.6.2 Coastal Processes Objectives

Based on the overarching goals and science questions listed above, the following specific CP objectives were identified:

1. Forecast, model, and measure tsunami generation, propagation, and run-up for major seafloor events. (DS: S-1d)
2. Predict threats to marine ecosystems and coastal/benthic habitats (e.g., coral reef, saltmarsh, mangroves, seagrass, oyster reefs, etc.) (New: 2a, b). This will include addressing the following questions:
    a) How will coasts change by rising seas, erosion, subsidence, accretion, and anthropogenic influences?
    b) What are the predicted impacts of coastal storms and surge on coasts?
3. Assess and model the processes that drive and the predicted impacts of sediment transport, erosion, and deposition.
4. Assess shoals, reefs and other hazards to marine navigation, and model their change with time.
5. Quantify the flows of energy, water, carbon, nutrients, etc., sustaining the life cycle and partitioning into functional types at the juncture of terrestrial and marine ecosystems.
6. Quantify the impact of land cover change, modification and soil disturbances on water, carbon, sediment and energy fluxes at the land-sea continuum.

3.6.3 Coastal Processes Measurement Needs

To meet the specific CP objectives listed above—and, in so doing, to satisfy the corresponding science goals and questions identified in the DS—the following measurements are needed:

1. Shallow bathymetry
2. Vegetation structure (mangroves and submerged aquatic vegetation)
3. Land topography
4. Water surface height

The most critical measurement need identified through the Coastal Processes Breakout session is the first item in the above list: high-resolution, shallow bathymetry. Through an online poll conducted during the session, participants were asked to specify the depth range of bathymetric measurements needed to support their work. The results indicate that bathymetric measurements up to 20 m water depth would serve the needs of nearly 75% of the respondents.

Participants from the fields of coastal and wetlands ecology also emphasized the importance of vegetation measurements for benthic habitat mapping and ecological assessments. Additionally, multiple Coastal Processes Breakout Session participants and questionnaire respondents listed the need for seamless topo-bathymetric elevation data across the land-water interface, leading to the inclusion of land topography (Item 3) in the list. An important criterion identified for topobathymetric models is that they be seamless across the land-water interface, meaning lacking in horizontal data gaps or vertical discontinuities.

While some science and application areas only require seafloor height relative to a specified vertical datum, others require measurement of water surface height. In particular, water surface height measurements can be used for sediment transport studies, hydrodynamic modeling, inundation modeling, discharge studies, and wetlands studies. Remote sensing measurements of water surface height made coincidentally with seafloor measurements can be used for applying refraction corrections (i.e., corrections for the change in direction and speed of light at the air-water interface) in the bathymetric mapping process. It is important to note that some instruments, such as bathymetric lidar, resolve both surfaces—water surface and seafloor/lakebed/riverbed—through the same (or simultaneous) measurement processes. Water surface height measurements made at sufficiently high temporal frequencies could support tide/water level modeling. As noted by one CP Breakout participant: “The ability to assess changes in water levels [through a future STV observational system] would be particularly useful, especially if this data could replace the need for tide gauges (at least to some extent).”

Another measurement need, which was discussed during the study but ultimately determined to be outside the scope of STV, is water turbidity, which is often characterized through the diffuse attenuation coefficient of downwelling irradiance, Kd. If estimates of turbidity can be obtained as a byproduct of the primary measurements listed above, they will serve to further benefit coastal and ocean science. For example, Kd data are currently used in water clarity monitoring, ecosystem modeling, and studies of ocean-atmospheric circulation.

3.6.4 Coastal Processes Product Needs

This study has identified critical needs for the following CP data products, derived from the measurements listed above:

1. 2D topo-bathymetric DTM
2. 2D grid of rugosity (seafloor roughness)
3. 2D water surface DSM
4. 2D vegetation height model
5. Time series of bathymetry DTMs (2D grid)
6. Time series of gridded seafloor rugosity

The need for parameters derived from bathymetry measurements, such as slope, rugosity (i.e., surface roughness), and geomorphic features, is based on their ability to support benthic habitat classification and ecological assessment (Wedding et al., 2008; Pittman et al., 2009). STV CP Breakout participants noted rugosity as being particularly important for study of community composition in coral reefs.

3.6.5 Coastal Processes Unique Challenges

Reliable estimates of uncertainty are required for each of the data products listed above. Because coastal elevation data are used in assessing vulnerability to flooding and coastal geohazards and in making associated policy decisions, it is important that topobathymetric DEMs be accompanied by uncertainty estimates in order to evaluate the uncertainty in the outputs of the models that make use of the data (e.g., Gesch, 2009; Gesch, 2018; Tulloch et al., 2013). Multiple CP Breakout participants stated that they could make use of elevation data of varying accuracy, provided that all data sets were provided with associated uncertainty estimates.

Another important consideration for coastal elevation data is the vertical datum to which the data are referenced. Ellipsoid heights, which do not provide information on the direction of water flow, are generally a very poor choice for coastal applications, such as modeling inundation. While orthometric heights (i.e., heights above the geoid) are generally a better choice, some coastal science applications, such as wetlands migration studies, require height data relative to a tidal datum, such as local mean sea level (MSL), mean high water (MHW), or mean higher high water (MHHW). Nautical charts, which support safe marine navigation, generally contain depths relative to a low water tidal datum (called chart datum): mean lower low water (MLLW) for U.S. nautical charts. Additionally, a consistent vertical datum is generally necessary to ensure the seamless of topobathymetric models at the land-water interface.

The time series needs are based on the fact that repeat mapping over long timescales is of fundamental importance for monitoring of changes over time. Input received from multiple participants included the observation that data collection on seasonal (or shorter) cycles is important for decoupling long-term geomorphic change and habitat change (e.g., seagrass habitat) from seasonal variation (e.g., seasonal erosion and accretion patterns, seasonal SAV growth cycles).

3.7 Additional Applications Needs

Earth surface elevation and vegetation structure are considered essential information to a broad range of end-users. Scientists use these data to initiate and constrain models in order to understand physical and ecological processes, whereas application end-users additionally use the same information for situational awareness and to inform management and policy decisions. Because of this commonality, the STV study team discussed both applications and science in all community breakout meetings and internal team discussions, and relevant finding where science and applications needs converge are included in Sections 3.2–3.6 above. There is a continuum from pure science objectives to operational applications, and the sections above exclude some goals associated with operational decision making of high socio-economic impact, be that for long-term planning or immediate decision making (Figure 3-8).

The scope of applications for STV is broad, so its data are of significant value to end-users even in the absence of very rapid or frequent acquisition and delivery. However, for many applications outlined here the value of products can significantly increase with timeliness that is determined by revisit frequency and latency. The well-known disaster management cycle covers the four phases of risk and disaster management activities: prevention, preparedness, response and recovery. Broadly speaking, operational agencies require data to inform activities that reduce risk, be that from resource availability, transportation and conveyance, or hazards and disasters. Where the needs of the science and applications communities most diverge is in timeliness of information because information about current conditions and current trends are most relevant to operational agencies, and in some cases the only relevant information, e.g., during disaster response or preparations for an imminent forewarned event. Even many "slow" processes, e.g., crop growth, require information at the scale of weeks not months to years. Furthermore, in the minority of cases is a single measurement sufficient, e.g., an agency might use a DEM to know the current land elevation, but in most cases, they need information about where the land is changing in order to assess risk, target more frequent *in situ* observations, and plan future land and resource use. For slow processes the frequency of repeat observations can be low, i.e., yearly or even longer, but the highest risk scenarios usually arise from rapidly evolving conditions.

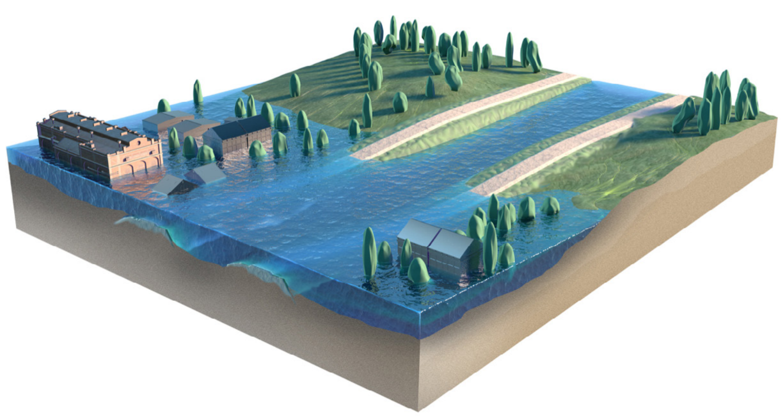
Applications goals and objectives address the needs of agencies with operational mandates for actionable information to support decision making beyond what is discussed in Sections 3.2–3.6 above. The SATM (Appendix A) provides an overview of all STV Applications topics.

3.7.1 Additional Applications Goals/Questions

The sections on Solid Earth, Vegetation Structure, Cryosphere, and Coastal Processes all contain applications that closely relate to the science and societal goals of the DS plus some of the additional high value topics identified in this study. The "Additional Applications" listed here focus on use cases that are clearly for operational decision making and management. In some cases, the applications are multidisciplinary and hence do not easily fit within the themes of the previous sections.

1. **Floods:** Provide information to forecast and respond to major flood events. (New: A-1)
2. **Wildfire:** Provide information to inform near- and long-term decisions to reduce the risk, occurrence, and societal impact of wildfires. (New: A-2)
3. **Geological & anthropogenic hazards:** Provide information to inform decisions related to geological hazards and industrial accidents. (New: A-3)
4. **Critical infrastructure monitoring:** How are critical infrastructure and their environs changing? (New: A-4)
5. **Agriculture:** How does crop health and productivity relate to vegetation structure and topography, and how can better estimates of current and forecasted yield and risk be made based on that information? (New: A-5)
6. **Commercial forestry:** What is the composition and status of natural and agroforest systems used for commercial forestry and how are they best monitored to effectively manage forest products and ecosystems services? (New: A-6)
7. **Deforestation:** Provide information for operational deforestation monitoring and alerting. (New: A-7)
8. **Maritime navigation, ice hazards:** Where and when is marine ice endangering maritime transportation routes? (New: A-8)
9. **Coastal resiliency:** What is the efficacy and consequences of RSLR mitigation activities that aim to improve coastal resiliency? (New: A-9)

FIGURE 3-8. An STV mission serves many applications because of the range of information it provides. For example, bare surface topography and topographic change measurements can identify low areas in the landscape and subsiding land and structures, in this case the location where the levee will be overtopped during high river discharge. Measurements of the water surface elevation can determine flood extent and when combined with bare surface topography provide floodwater depth.



3.7.2 Applications Unique Challenges

In the past, remote sensing technologies were often able to address science questions, but fell short of providing sufficient continuous, frequent and rapid data to meet operational needs. Now, space agencies worldwide are increasing their emphasis on applications with high societal impact to make full use of missions that advance scientific knowledge. The demand for operational Earth observation applications is expected to increase during the next decade and therefore the STV incubation study needs to address the more stringent product requirements of applications. The challenge of meeting the broad operational needs of agencies largely revolves around the timeliness of the information.

- Timeliness is important because agencies are interested in current conditions. This requires having low latency between when data are acquired and products are delivered, particularly for topography and to a lesser extent, vegetation structure.
- Having repeated measurements at the timescale of developing events is very important, and the driving timescale is the most critical condition of concern, i.e., change in crop status during the growth season, progression of levee slope failure, etc. The more frequently STV measurements are repeated, the more applications that they will address. Yearly-updated maps are of use, but bi-weekly to monthly updates much more so. Addressing disaster response phase applications is the hardest, for which data are stale after less than a week and in most cases at that point only useful for post-event modeling or mitigation.
- Measurement duration is very important, possibly the most important, to many agencies, with the exception of establishing a baseline high-resolution topographic map. An agency looking at trends is unlikely to adopt usage of a product that is not going to be available or replaced by an equivalent product over a long period of time, i.e., 3+ years and preferably many decades.

A final challenge for applications is the need to have topographic change information in areas with changing vegetation, soil moisture, and even water coverage, i.e., those areas where radar interferometry (InSAR) is not able to provide spatially extensive elevation change information. Lidar or photogrammetry DTM data are particularly important over earthen structures (dams, levees) and in low elevation coastal areas for which SAR decorrelates. This challenge applies to global measurement of vertical land motion along coastlines, a critical component of RSLR (DS: S-3b).

3.8 Summary

STV observables map to the six science and applications disciplines considered in this study (Table 3-1). The need for repeated measurements to measure change and improve understanding of processes for each discipline emerged as a key finding of this study (Figure 3-9). A compilation of the needs from the five disciplines and applications shows that a common set of measurements would meet at least the threshold if not aspirational levels (Table 3-2). The team obtained feedback from the community via a questionnaire and through the plenary and breakout workshops and combined that with their expertise to identify product and coverage needs for each discipline.

The STV identified a set of product needs for all science and applications that could be met by an STV mission. Baseline measurement of topography with targeted repeat measurements collected systematically are needed to understand science processes or change. Targeted suborbital measurements would complement orbital observations and add higher-resolution where needed.

TABLE 3-1. Mapping between STV observables and disciplines showing strength of relationships with comments. Green cells indicate a direct relationship, yellow an indirect relationship, red little relationship, and white no relationship.

OBSERVABLES

DISCIPLINES	Surface Topography	Vegetation Structure	Shallow Water Bathymetry	Snow Depth
Solid Earth	Needed to measure Earth surface and interior processes	Needs to be removed for most SE needs; information layer for landslides and landscape change	Faults, landslides, and volcanoes extend offshore	
Vegetation	Needed for impact on landslides and geomorphic processes	Needed to quantify vegetation carbon emissions and uptakes (source/sink), terrestrial carbon dynamics.	Important for wetlands studies	Needed to estimate snow under vegetation, Snow on vegetation impact
Cryosphere	Needed to study and model cryosphere processes	No vegetation over target of interest	Study of supraglacial lakes and proglacial lakes	Needed to improve estimates of mass flux
Hydrology	DTM is needed for flood mapping, and DSM is needed as water surface height to model river discharge and wetland hydroperiod, and estimate water storage in lakes and reservoirs	Needed to as input to hydrodynamic model (resistance to flow) and calculating evapotranspiration	Need to model hydrodynamic and vegetation feedbacks	Needed for snow pack and seasonal fresh water availability
Coastal Processes	Needed to model inundation from storm surge, tsunamis, etc., and to monitor coastal erosion.	Nearshore terrestrial vegetation; submerged aquatic vegetation (SAV); mangroves.	Needed to model coastal inundation, map/monitor benthic habitats, conduct benthic ecological assessment, study sediment transport, and monitor wetlands.	Needed to model coastal inundation and estimate/ forecast discharge during spring melt in northern and arctic deltas and estuaries.
Other Applica-tions	Needed for nearly all applications. Overall, this is the most impactful STV observable for applications, particularly given that it is used for land, water, and ice elevation.	Needed for all VS-related applications and many other applications (wildfire; critical infrastructure/ landslide/land change monitoring, coastal VLM and resiliency)	Needed for many applications including marine navigation, coastal resiliency, geologic & tsunami hazards.	Needed for water resource management and flood forecasting

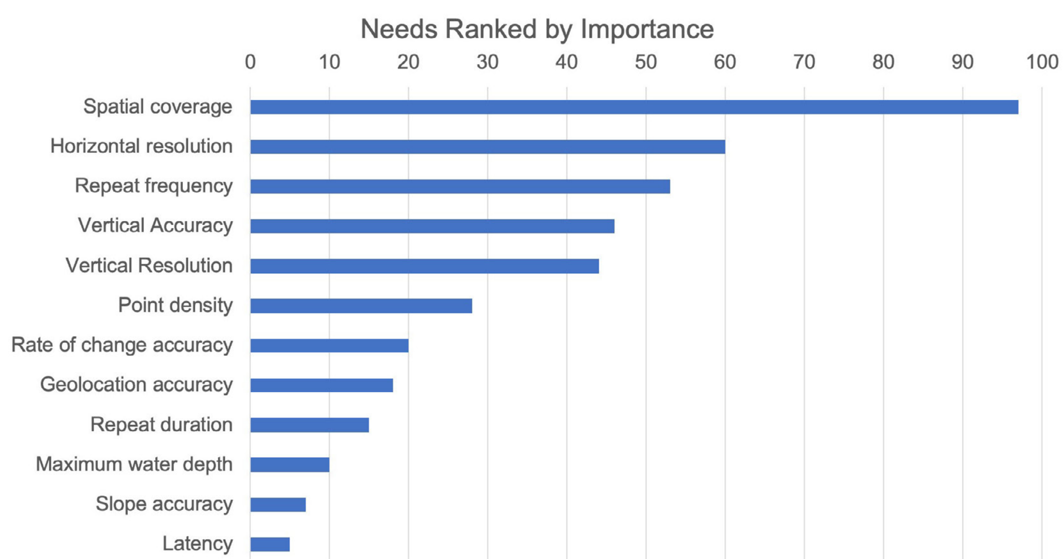
TABLE 3-2. Summary of preliminary measurement needs to accomplish STV science and applications objectives.

PARAMETER		ASPIRATIONAL			THRESHOLD		
		Median Need (rounded)	Most Stringent Need	Most Stringent Discipline	Median Need (rounded)	Most Stringent Need	Most Stringent Discipline
Coverage Area of Interest	%	90	95	C, H	55	90	C
Latency	Days	5	0.5	SE	60	1	SE
Duration	Years	9	10	SE, C, A	3	3	SE, V, C, CP
Repeat Frequency	Months	0.1	0.03	SE, A	3	0.2	SE
Horizontal Resolution	m	1	1	SE, C, H, A	20	3	SE
Vertical Accuracy	m	0.2	0.03	SE, C, H	0.5	0.1	C
Vegetation Vertical Resolution	m	1	0.5	H, A	2	0.2	CP
Bathymetry Max Depth	m	25	30	C, CP	10	10	SE, C, CP
Geolocation Accuracy	m	1	1.0	SE, V, H, A	5	3	SE, V
Rate of Change Accuracy	cm/y	5	1	SE, C, A	35	1	SE

3.8.1 Global Coverage and Repeat are Key Product Needs

Global coverage, horizontal resolution, repeat frequency, and vertical resolution emerged as the highest priorities for the STV team and from community input (Figure 3-9). Rate of change and geolocation accuracy are also related to repeat measurements. Measuring topographic and vegetation structure change enables better understanding of processes and drivers of change, for example, denudation due to wildfires and subsequent rains, tectonic motion, sea level rise, or climate change.

FIGURE 3-9. Most important needs ranked as expressed by community input. The need for change detection is a high priority requiring repeated measurements.



3.8.2 Product Quality Needs that an Orbital Mission Could Address

A set of products from a single orbital mission could address many needs of the science and applications communities for the various STV disciplines (Table 3-2). Global coverage is needed for each discipline. All of the disciplines require global baseline surface topography observations (Figure 2-5). Several years of repeated measurements will enable understanding of change and a variety of processes across all of the disciplines. Seasonal or better measurements will enable removal of seasonal signals to obtain long-term trends. Longer time series will enable measurement of slower or more subtle change or allow for observation of more episodic events. Some disciplines and most applications need higher resolution products or rapid and repeated response, which might be satisfied by targeted suborbital observations that would complement systematic orbital observations or constellations of spaceborne instruments.

Horizontal resolution and rate of change accuracy are among the most variable across all disciplines. However, the median product need could satisfy parts of each discipline. In general, though, a horizontal resolution of better than a few meters with submeter vertical accuracy would meet many needs of the community. Decimeter/year rate of change products would be useful for measuring large solid Earth, cryosphere, hydrological, and coastal events and processes, and meets the threshold requirement for the most stringent application, critical infrastructure monitoring.

It is difficult to satisfy the diversity of needs within disciplines. However, significant advances could be made by an orbital platform that meets the majority of either aspirational or threshold needs across the disciplines (Table 3-2). Consideration in later studies should be made as to whether to strive for a longer class A mission or perhaps a shorter duration, potentially riskier and shorter mission. Alternatively, more stringent needs within science disciplines and for the applications community could be met with suborbital components that complement an orbiting STV platform. Smart tasking could improve the usefulness of an orbital mission for lower latency or more frequent imaging of discrete events (e.g., disaster, volcanic unrest).

3.8.3 Meeting Needs through Suborbital Measurements

A combination of orbital and suborbital platforms could meet most of the needs of all disciplines and applications. OSSEs would identify what scales of processes would be addressed for a given capability. An orbiting platform would provide global baseline measurements and systematic repeating, long-term measurements. The advantage of suborbital platforms is the ability to target response, to specific events and locations and achieve higher resolution with smaller instruments. Suborbital platforms can achieve frequent visits. Suborbital platforms could host different technologies best suited for particular observational needs on a single platform or on several platforms. Suborbital measurements could also serve to provide experimental proof-of-concept for spaceborne measurements and technologies.

CHAPTER 4

SENSORS, PLATFORMS, AND INFORMATION SYSTEMS

4.1 Introduction

We evaluated current sensor, platform, and information systems to assess which needs stemming from the goals and objectives can be met with current capabilities. We considered lidar (L), radar (R), stereophotogrammetry (SP), and information systems (IS). Our assessment of current and emerging capabilities was informed by input solicited from technologists in the form of quad charts (Appendix E) describing technologies which have the potential to contribute to capabilities needed for STV. Part II describes the current and emerging sensors, platforms, and information systems. Here we describe each technique and then summarize the current maturity of all techniques.

4.2 Lidar

Light detection and ranging, or lidar, is an active laser-based remote sensing system concept used in a wide range of applications. Lidar as a general technology is platform agnostic, and has been integrated into many platforms including on tripods (Keightley, K. E., & Bawden, 2010); backpacks (Glennie et al., 2013); kinematic platforms such as automobiles (Rasshofer and Gresser, 2005), trains (Gézero, and Antunes, 2019); helicopters (Omasa et al., 2000), UAS (Jozkow et al., 2016), and aerostats/balloons (Brooks et al., 2013). The two primary platforms for the purpose of this report are aircraft (Nilsson, 1996), and satellite (Zwally et al., 2002).

Lidar has become an attractive technology for STV applications due to its high-resolution, high accuracy, high precision, bathymetric ability, and foliage penetration. Not only can lidar systems penetrate vegetation canopies to resolve bare earth surfaces underneath vegetation, they can also image the complete three-dimensional structure of the vegetation canopy. Figure 4-1 summarizes the current measurement approaches used in airborne and spaceflight systems.

Knowing the orientation of the laser and the detector are critical for precise positioning. An inertial navigation system (INS), the main component of which is an inertial measurement unit (IMU) comprising orthogonal triads of gyroscopes and accelerometers, is used in calculating the angular orientation of the transmitted laser pulse. There are many different types of INS devices used, each with different levels of precision. For airborne scanning systems used to measure swaths the INS information is augmented by an angle encoder on the scanning system. For satellite platforms the INS information is integrated with star tracking cameras where very high-precision pointing knowledge is required. Knowing the location of the sensor in 3D space is also critical for precise positioning, as this translates to the geolocation accuracy of the resultant pulses and laser returns. GPS/GNSS systems are typically used for lidar systems on commercial aircraft and satellite platforms. Table 4-1 provides examples of the data, geophysical information, and products acquired by three types of lidar sensor and platform configurations.

FIGURE 4-1. Lidar measurement approaches are divided into methods using single, high-energy laser pulses and those using high-repetition, low-energy micropulses.

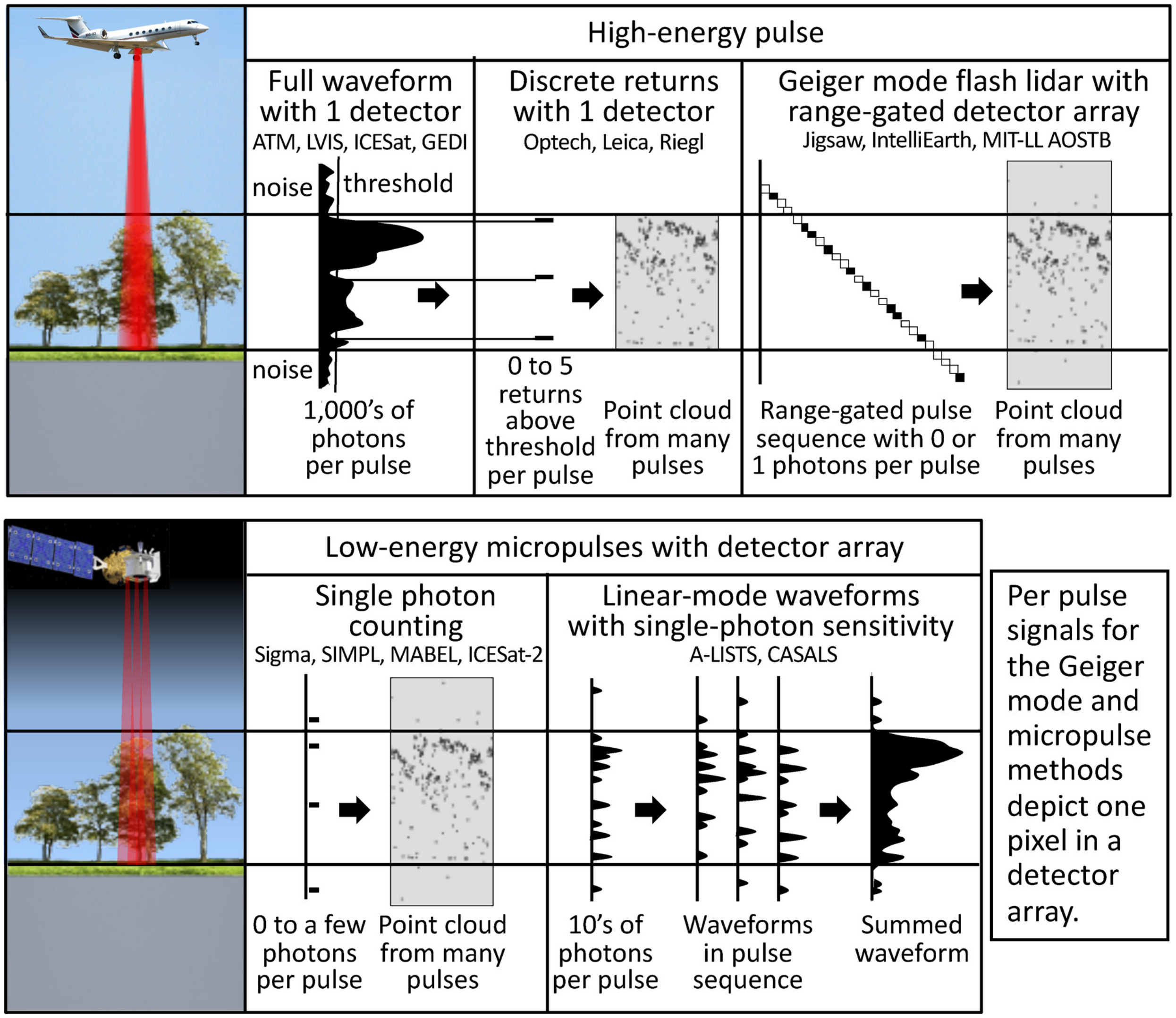


TABLE 4-1. Data, geophysical information, and products acquired by three lidar sensor and platform configurations.

Method	Sensor and Platform	Geolocated Calibrated Data	Geophysical Information	Height, Vegetation, and Depth Products
Lidar	GEDI on International Space Station	Single footprint return-energy waveform	Ground and canopy vertical distributions of reflected energy	Profiles of topography, canopy height, 1D vegetation vertical structure and derived cover fraction, leaf area index and aboveground biomass
	ATLAS on ICESat-2	2D photon point cloud along profiles	2D classified point cloud	Profiles of ice elevation, sea ice freeboard, topography, water height, shallow water depth, canopy height and 2D vegetation structure
	Commercial scanning lidar on airplane	3D discrete return point cloud with energies in swath	3D classified point cloud	Digital terrain model, digital surface model, 3D vegetation structure, meshes of buildings and infrastructure and shallow water depth (if green laser)

4.2.1 Emerging Lidar Technologies

Activities are on-going to advance capabilities of airborne and spaceborne systems. None are specifically directed toward accomplishing the global mapping STV objectives, but several are raising the technical readiness levels of applicable technologies that can serve as a pathfinder to meeting STV needs.

4.2.1.1 Airborne Lidar Systems

Activities to advance airborne lidar systems in the commercial sector are limited, with the focus on increasing small-footprint sampling density from low- to-moderate altitude aircraft to serve the commercial mapping market. A secondary focus within the commercial sector has been miniaturization for use of scanning lidars on small UAV platforms. L3Harris is evaluating the applicability of their efficient, high-resolution Geiger mode commercial capability for deployment on high altitude and low Earth orbit platforms which could serve STV objectives. The airborne focus within NASA has primarily been on improving and utilizing the ATM, LVIS and G-LiHT instruments in campaigns for science and applications objectives, often in coordination with other organizations' sensors and platforms. An advance that is directly applicable to STV utilizes G-LiHT in a modeling capability for conducting stereophotogrammetry trade studies. The capability is enabling sensitivity analyses and architecture design simulations to optimize spaceflight stereo imaging for measurements of topography and forest canopy structure. The approach combines G-LiHT's lidar and stereo imaging instruments along with the DART forest radiative transfer model.

4.2.1.2 Spaceborne Lidar Systems

NASA's recent spaceflight lidar investments primarily focus on advancing near-range lidars for very high-resolution imaging. Purposes for this capability include (i) satellite rendezvous and docking, (ii) detailed mapping while closely orbiting small bodies (asteroids and comets), and (iii) lander descent to characterize surface roughness in real-time for hazard avoidance. These near-range lidars use technologies not easily adapted to lidar mapping of the Earth and planets from higher-altitude orbits. Several organizations have been funded by NASA's Earth Science Technology Office to advance technologies for adaptive lidar mapping from Earth orbit. Goddard Space Flight Center is developing the Concurrent Artificially-intelligent Spectrometry and Adaptive Lidar System (CASALS). The lidar approach is highly efficient, using micro-pulse transmission and linear-mode, waveform detection, to enable swath mapping from a SmallSat platform. Lidar targeting by scanning a single laser beam, using a novel wavelength-tuning method, would be guided by real-time, machine-learning-aided analysis of the hyperspectral imaging. The scanning would make possible rapid, adaptive reconfiguration of profile distributions across a wide swath (~7 km) and 3D mapping in a narrow swath (~1 km). This would enable cloud avoidance and targeting high-priority objectives such as areas of active topographic and vegetation cover change. The CASALS development is focused on serving DS ice elevation, ecosystem structure and snow depth Explorer observables in the later part of this decade. Further advancement of these technologies could lead to wider 3D swath mapping needed for STV objectives. A second concept in formulation at Goddard, the Canopy Height and Glacier Elevation (CHANGE) mission is also directed towards DS Explorer Observables. It would be based on established spaceflight instruments, integrating a multi-beam lidar and stereo imaging to map an ~10 km wide swath. The goal is to provide continuity with ICESat-2 and GEDI while also expanding elevation mapping coverage.

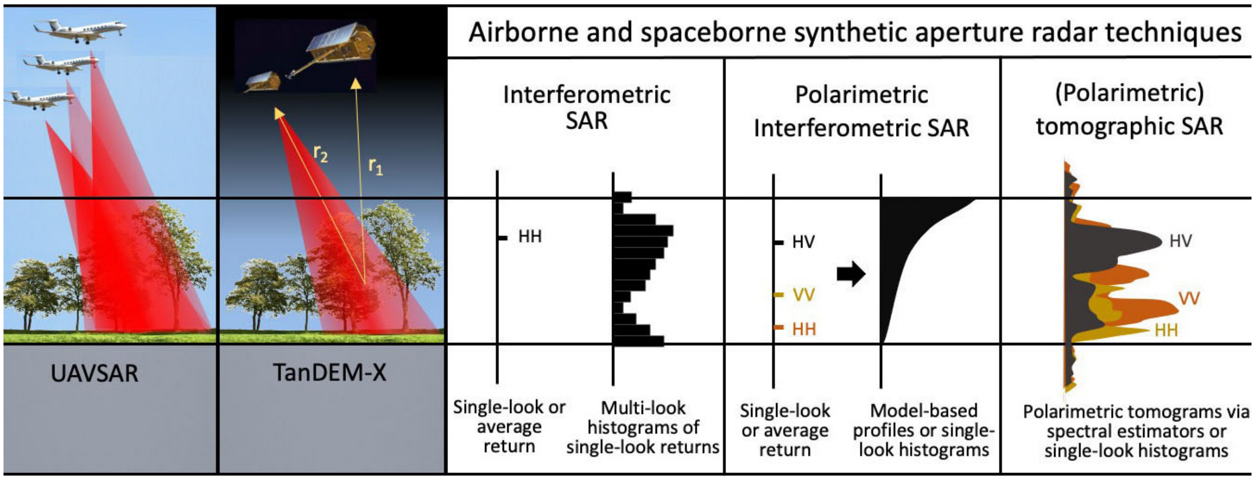
4.3 Radar

Radio detection and ranging, or radar, is an active remote sensing technology that operates in the microwave portion of the electromagnetic spectrum to infer properties of the Earth's surface. Synthetic aperture radar, or SAR, is a side-looking imaging system that produces a two-dimensional image by transmitting radar pulses for ranging in the cross-track direction and utilizing the Doppler frequency shift due to platform motion to synthesize a large antenna, thereby improving along track resolution (Curlander and McDonough, 1991). SAR can operate from various platforms, including ground-based towers, aircraft and spacecraft; along track resolution of SAR is independent of range (or platform altitude). Typical radar bands for operational instruments most directly relevant to STV are X (3.2 cm wavelength), C (5.5 cm), S (10 cm), L (wavelength 24 cm), and P (70 cm). Typically, P- and L-band are most effective for measuring vegetation structure and topography of dense vegetation canopies, S- and C-band are used for studying crops, and X-band is better suited for high-resolution measurements in areas with canopy gaps. In addition, the shorter wavelength Ku (1.7-2.5 cm) to Ka (0.75-1.11 cm) band instruments are used for snow measurements and Ka-band is used for studying ice.

SAR has been used for a variety of disciplines ranging from ecosystem science to cryosphere and solid Earth. Several SAR techniques have been developed over the past two decades aiming to extend the capabilities of single-channel SARs. There are three SAR techniques that are relevant to STV, cross-track single-pass interferometry (InSAR), which uses two instruments imaging the surface at the same time to determine surface topography, PolInSAR, which uses multiple coherent polarimetric channels coupled with interferometric signals to gain sensitivity of the different vegetation vertical components, and multibaseline InSAR, also known as tomographic SAR (TomoSAR), which has been demonstrated to be able to provide a full image of the 3D vegetation structure from which surface topography and other vegetation characteristics can be extracted (Shiroma, 2020).

Figure 4-2 shows examples of current interferometric airborne and spaceborne systems for STV mapping with associated InSAR, PolInSAR and TomoSAR measurement approaches. PolInSAR is capable of measuring various 3-D metrics (Cloude, 2003; Treuhaft, 2000) including total height (Kugler, 2015; Papathanassiou, 2001; Lavalle, 2013), mean height, and rates of change of heights (Askne, 2018, Treuhaft 2017). The PolInSAR sensitivity to vegetation height is schematically shown in Figure 4-2, with the only existing spaceborne platform that can do single-pass radar interferometry for vegetation structure, TanDEM-X (Krieger, 2007). The PolInSAR phase is proportional to the differential distance, r_1-r_2, which in turn is proportional to vegetation height.

FIGURE 4-2. Examples of current airborne and spaceborne systems for STV mapping with associated InSAR, PolInSAR and TomoSAR measurements approaches.



TomoSAR is an extension of InSAR that combines coherently multiple interferometric signals received under different look angles (Reigber, 2000; Tebaldini and Rocca, 2012; Khati, 2019). TomoSAR can be implemented by either a distributed formation of SAR platforms (single-pass TomoSAR) or by drifting the orbit of one or two platforms at each pass (repeat-pass TomoSAR). TomoSAR provides vertical backscatter profiles of vegetation and underlying ground surface, enabling the generation of high-resolution maps of terrain elevation, surface elevation, tree height and several other structural indicators.

Radar has the advantage of imaging large ground swaths day and night through clouds and smoke. In the following section, we will summarize the emerging radar technologies.

4.3.1 Emerging Radar Technologies

Key radar imaging techniques have emerged to address challenges in monitoring vegetation structure and cryosphere elevation changes. Two such techniques, PolInSAR and TomoSAR, are enabled by distributed formations of two or more synthetic aperture radar spacecraft, which can map vegetation height and structure, and their spatiotemporal changes, with the desired coverage, resolution and accuracy requirements. Formations with two polarimetric radars enable single-pass, single-baseline PolInSAR for height detection, with a wide range of published accuracies from 2 m (Papathanassiou 2001) to 5 m (Kugler 2015). Gap-filling activities can quantify accuracies and multi-frequency sensitivity relative to vegetation type and density. Two-spacecraft formations can also enable pair-wise, repeat-pass TomoSAR by changing the distance between the two spacecraft at each pass. Formations with multiple radars, either polarimetric or non-polarimetric, enable single-pass TomoSAR technique with multiple baselines acquired simultaneously from which 3D vertical profiles can be directly generated. Simultaneous TomoSAR has the advantage of being robust against the disturbing effects of atmosphere and temporal decorrelation. Fewer satellites in the formation typically reduce the final product accuracy, although a systematic study of the impact of the formation geometry as a function of radar instrument parameters and vegetation characteristics has not been conducted yet and therefore is part of the gap-filling activities identified by this study Sec. 5.3.2. Repeat-pass PolInSAR and TomoSAR have been demonstrated from airborne platforms with short repeat-pass intervals and therefore with minimal impact of interferometric temporal decorrelation. Results of TomoSAR using the Uninhabited Aerial Vehicle Synthetic Aperture Radar (UAVSAR) are shown in Figure 4-2

(Lavalle et al., 2017; Shiroma, 2020). Because there is no spaceborne fixed-baseline PolInSAR at L-band (TanDEM-X is the only spaceborne interferometer) or distributed SAR formation that implements single-pass TomoSAR in space, gaps and gap-filling activities are proposed to evaluate modes of data acquisition and analysis (see Section 5.3.2).

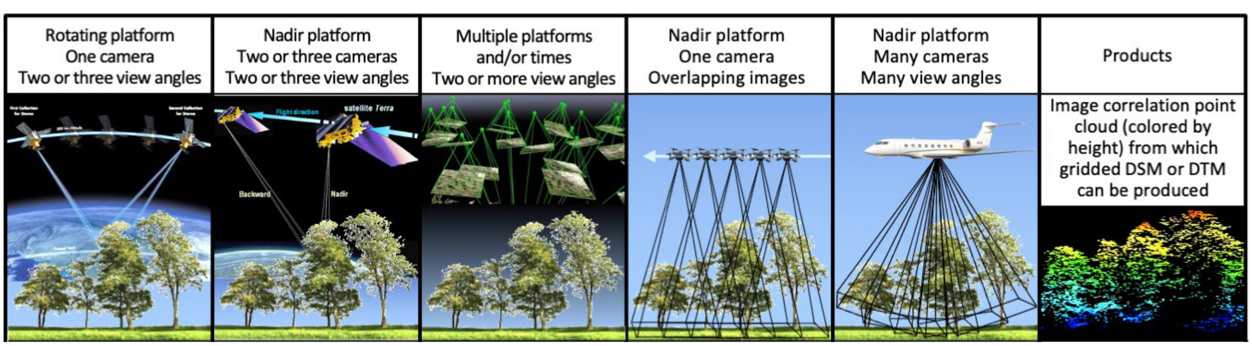
An accurate and efficient remote sensing methodology for monitoring snow accumulation has proven to be elusive for decades. Recent NASA-sponsored SnowEx campaign with UAVSAR have demonstrated the potential of L-band repeat-pass InSAR for measuring snow accumulation over Grand Mesa, Colorado. In a previous SnowEx campaign, the GLISTIN radar also showed the potential of Ka-band InSAR for measuring snow accumulation. Additional data with field and lidar validation are needed to determine the ideal frequency/methodology for monitoring snow accumulation over a variety of snow conditions and terrain types.

An emerging technique involves remote sensing of signals of opportunity (SoOps), with passive, bistatic reception of signals from spaceborne navigation and communication signals transmitters such as the Global Navigation Satellite System (GNSS), commercial transmitters such as Direct TV, or government communication signals like MUOS. The transmitted signals specular-reflect/scatter from the Earth's surface and have been applied to measurements such as wind speed, ocean surface height, snow-water equivalent, soil moisture, wetland characterization, and others. While the specular geometry limits resolution to the km level, global coverage is realized (with systems like GNSS) daily. Future modes of observation and analysis include using multiple frequencies to sense vegetation attenuation, flying two receivers in tandem for interferometric measurements, and using backscatter to improve resolution.

4.4 Stereophotogrammetry

The importance of analyzing planetary features as 3D surfaces has driven stereophotogrammetry (SP) technology forward for over a century. SP has been described as "the science and art that deals with the use of images to produce a 3D visual model with characteristics analogous to that of actual features viewed using true binocular vision" (La Prade et al., 1966) and has a long history of use for height measurements of a variety of Earth and planetary surfaces (Toutin et al., 2001). SP has evolved into an important tool for constructing digital elevation models (DEMs) for a large number of Earth and planetary surface investigations (Figure 4-3) beginning from hilltop observations, and proceeding through aircraft and satellite platforms. Currently, there are a large number of commercial providers of SP imagery of Earth surfaces that provide some level of SP using uncrewed aircraft (UASs), large aircraft and satellite-based sensor systems that meet some of the needs of STV.

FIGURE 4-3. The key to deriving surface height from stereophotogrammetry is image parallax and requires multiple images of a surface. There are different methods to acquire images suitable for stereogrammetric analysis as shown above. DEMs of bare and ice-covered surfaces, vegetation height and bathymetry depth can be measured at various scales using stereophotogrammetry.



The measurement of a surface height with stereophotogrammetry utilizes imagery and parallax. The process is based on imaging a point on the surface from two or more directions and measuring the apparent displacement of an observed object due to a change in the position of the observer (i.e., parallax). There are different methods now deployed or in development that tailor the principles of image parallax to height measurement for various applications as discussed below. Global DEMs are being produced using spaceborne data, but there are limitations of current systems for meeting STV science and applications objectives:

- STV SP data needs to be collected systematically rather than on a task order basis to properly characterize the data and in particular to measure change.
- Cloud obscures visible imagers from seeing the ground; particularly for equatorial latitudes SP observations should be supplemented by radar.
- When stereo imaging is acquired, the acquisition parameters vary widely (e.g., illumination conditions, view angles, season) making systematic use of the data for height models very challenging. However, these data sets have been used for regional and continental scale DEMs (e.g., Morin et al., 2016). Sun synchronous data mitigate some of the issues but is not always ideal for stereophotogrammetry. An existing need it to study the best acquisition strategy for SP.
- Existing satellite platforms that focus on ground topographic mapping use only two view angles with large angular separation. For urban and forest targets with significant variations in heights over short distances, this configuration is ill-suited for production of height models.

4.4.1 Emerging Stereophotogrammetry Technologies

Emerging technologies focus on fusing products from multiples sources, use several images to improve vertical accuracy through structure from motion, and employ framing cameras to improve the robustness of the stereo reconstructions, and focus on the development of new lightweight technologies. The majority of emerging space-based concepts employ multispectral pushbroom sensors that provide good global coverage, resolution, and repeated acquisitions. The focus of these spaceborne systems is generally on repeat nadir imaging of high priority areas. The observations are not well suited for serving STV science and applications objectives. For SP product generation, however, this mode of collection brings along some limitations that include Line-of-Sight (LOS) dynamics and SP from opportunistic collections. Pushbroom sensors render their 2-D image products using the orbital ground track to scan their cross-track arrays over the field of view. LOS dynamics during the collection break the rigid relationship between topography and a 2D image. A second image collect from the same or companion sensor will inject a different realization of LOS motion limiting the degree in which SP methods parse out the local topography. Unless constellations are dedicated to topography retrieval, the stereo observations made come opportunistically with variation in time separation and look-angle disparity within the pairs. Uncertainty quantification and its management within these SP products is critical for higher-order change detection and process estimation applications. These limitations are what drive developing framing imager concepts. An airborne SP imager under development, QUAKES-I uses framing cameras to prevent LOS disturbances that limit topographic products. This is further discussed in the section that addresses Gaps and Gap-Filling Activities.

Higher resolution from orbit requires larger telescopes. Rotating Synthetic Aperture (RSA) imaging offers a new path to low-cost, compact, high-resolution imaging systems. The technique combines directionally high-resolution imaging, rotational imaging conops and computation to incoherently synthesize larger circular aperture systems in post-processed products. This enables space-based 3D color stereo photogrammetric and change detection products for earthquake faults and ruptures, earthquake prone regions, volcanoes, landslides, wildfire scars, glaciers, vegetation, and ecosystems. From a 900km (high-LEO) perspective, system concepts have potential to resolve ≤20 cm features over 10+ km fields of view. Successful post-processing with large pointing errors and knowledge has been successfully demonstrated. Pointing control and momentum management for constantly rotating space-segment is an engineering challenge.

4.5 Information Systems

A future STV mission can be implemented using multiple spacecraft for which several layers of information systems can be leveraged.

- Single spacecraft information systems
- Multi-spacecraft coordination
- Multi-sensor data fusion

For any architecture, one way to lower the cost of the mission is to use a combination of lower-class spacecraft that can support a longer duration mission. For example, even though a single Class D spacecraft can be expected to last <2 years, with multiple spacecraft higher class missions can be realized. To that end, information systems technologies assisting the development of redundant systems with lower cost hardware can be an important aspect to realize a lower cost mission. Similarly, information technology to reduce the weight of the spacecraft would also ultimately lower the cost.

For a single spacecraft, technologies advancing the core Flight System (cFS), making it compatible with multiprocessing and containerized software, provide agility and fault tolerance (Cudmore and Hestnes, 2018; Marshall et al., 2020). Similarly, use of miniaturized, commercial-off-the-shelf radios capable of communicating with Tracking and Data Relay Satellites (TDRS) lowers the bar for continuous communication with the small spacecraft, which can be used to keep smart sensors connected (Perkins and Charles, 2020). Combined with technologies like scene understanding, and model predictive control architectures (Lieber; see Appendix E-6 for quad chart), continuous communication enables distributed space missions.

Architectures consisting of multiple spacecraft require unique mission design and assessment tools to optimize the scientific output of the entire architecture. These analyses can be done in the architecture design stage using OSSEs and technologies specifically designed for multispacecraft assessments (Grogan; Le Moigne; Forman; see Appendix E-6 for quad chart). After launch, scientific optimization can be achieved through a centralized assessment on the ground, or through distributed processing onboard multiple spacecraft (Nag; see Appendix E-6 for quad chart). Distributed space missions can further utilize autonomous navigation and guidance, to keep the constellation in optimal geometry and correcting for external impacts like atmospheric drag (Thompson and Marshak 2020).

Lidar, radar, and stereophotogrammetry provide ways to obtain the primary observable for STV. It is therefore important to establish information systems technologies to combine observations from multiple sensors. It is also important to note that even among the same family of observations (e.g., stereo imaging) observations using different platforms, and different geometries need to be reconciled. One way to combine different datasets is through the use of point-cloud-matching technologies (Scott et al., 2018). Once all data is collocated, technologies such as CEOS Data Cube (Killough, 2019) or JPL's Healpix (Gao et al., 2019) can provide the necessary structure to store and analyze multi-instrument, multi-resolution data.

A significant potential gap for future missions is adaptable imaging to target observations based upon information derived from acquisitions made on the single platform from one or more on-board sensors, from integration of information from multiple platforms, and from information acquired by ground-based sensors through commanding from a ground station. Adaptive imaging can enable rapid retasking for e.g., observation of dynamics within a localized area or redirecting of imaging for urgent response and reduce system cost and complexity through reduced data storage and downlink.

4.6 Summary

Each of the technologies considered in the study could provide the needed STV observables, but they are at different levels of maturity (Table 4-2).

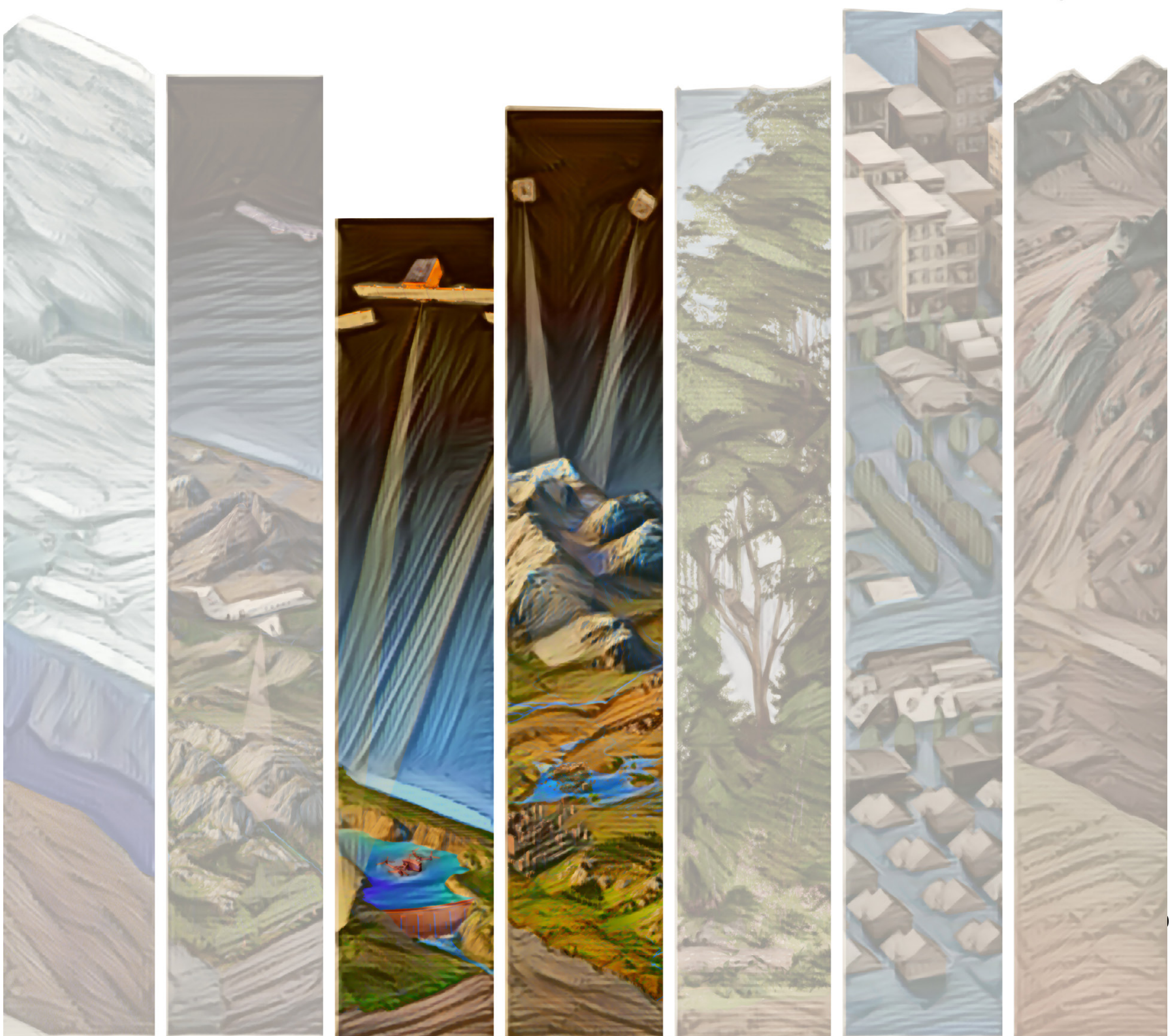
TABLE 4-2. Mapping between STV observables and technologies for orbital and suborbital products. Similar challenges are expected for both orbital and suborbital for information systems. Green cells indicate the technology is currently mature, yellow is being advanced, and orange is challenging. Text provides comments.

<table>
<tr><th></th><th></th><th>Lidar</th><th>Radar</th><th>Stereophotogram-
metry</th><th>Information Systems</th></tr>
<tr><td rowspan="3">Surface Topography</td><td>Orbital</td><td>Wide area coverage; resolution;
small footprint;
cryosphere surface;
sustained repeat frequency</td><td>Global coverage of DSM and DTM; High-resolution DTM/DSM in bare-surface and vegetated areas.
Change detection and elevation changes. Challenge meeting cryosphere gaps</td><td>Useful for bare surfaces. Vegetated surfaces may require fusion with other sensors</td><td rowspan="3">Change detection
Cloud avoidance
Landscape analysis
Multi-sensor data fusion
Onboard processing
Smart Tasking</td></tr>
<tr><td rowspan="2">Suborbital</td><td>Mature with narrow coverage and high resolution</td><td>Mature for local to regional</td><td rowspan="2">Wide area coverage; haze poses a problem</td></tr>
<tr><td>High altitude, long duration platforms</td><td>High altitude, long duration platforms</td></tr>
<tr><td rowspan="3">Vegetation Structure</td><td>Orbital</td><td>Wide area coverage; ground detection. Calibration of height and AGB with sampling.</td><td>Wide area coverage; Vegetation height/AGB with PolInSAR and TomoSAR. Change detection with repeated phase-height PolInSAR/TomoSAR observations</td><td>Vegetation height and outer canopy profile. Internal structure requires fusion</td><td rowspan="3">Algorithms for accuracy and error estimation
Algorithms and in-situ data for AGB estimation
Change detection
Cloud avoidance
Multi-sensor fusion
Onboard processing
Smart Tasking</td></tr>
<tr><td rowspan="2">Suborbital</td><td>Mature for local to regional with airborne lidar</td><td rowspan="2">Validation of spaceborne performance for structure and structure rate of change</td><td rowspan="2">CONUS High-resolution vegetation height and outer canopy profile.</td></tr>
<tr><td>High altitude, long duration platforms</td></tr>
</table>

		Lidar	Radar	Stereophotogram-metry	Information Systems
Water surface elevation	Orbital	Wide area coverage; sparse samples; small footprint; sustained repeat frequency	Global coverage of DSM; High-resolution DSM of open water surface. Surface elevation change and elevation slope. Challenge in calm waters and wetlands.	Delineation of flood and open water extent. But not elevation.	Algorithms for accuracy and error estimation Algorithms and in-situ data for discharge estimation Change detection Multi- sensor fusion Onboard processing Smart Tasking
	Suborbital	Mature with narrow coverage, fine resolution and high vertical accuracy.	Mature with narrow coverage, fine resolution and high vertical accuracy.	Mature with narrow coverage, fine resolution and high vertical accuracy.	Mature with narrow coverage, fine resolution and high vertical accuracy.
Shallow Water Bathymetry	Orbital	Wide area coverage; penetration depth, as a function of water clarity	Limited to mapping shallow channel patterns from radar backscatter or coarse, global ocean bathymetry estimates from radar altimetry sea surface topography measurement	Advancing from multiple on-orbit examples	Advance from local studies combining lidar and optical imagery Algorithms for accuracy and error estimation
	Suborbital	Penetration depth as a function of water clarity High altitude, long duration platforms		Advancing from local to regional use. Need robust refraction correction procedures/ algorithms integrated into photogrammetric software.	
Snow Depth	Orbital	Wide area coverage; snow identification	Wide area coverage; snow accumulation	Advancing from local area examples	Cloud avoidance Multi-sensor fusion Point cloud differencing Smart Tasking
	Suborbital	Repeat frequency High altitude, long duration platforms	Regional coverage; snow accumulation; potential SWE estimation.	Advancing from local area examples	

PART 2

ACTIVITIES TO ACHIEVE STV OBJECTIVES



CHAPTER 5

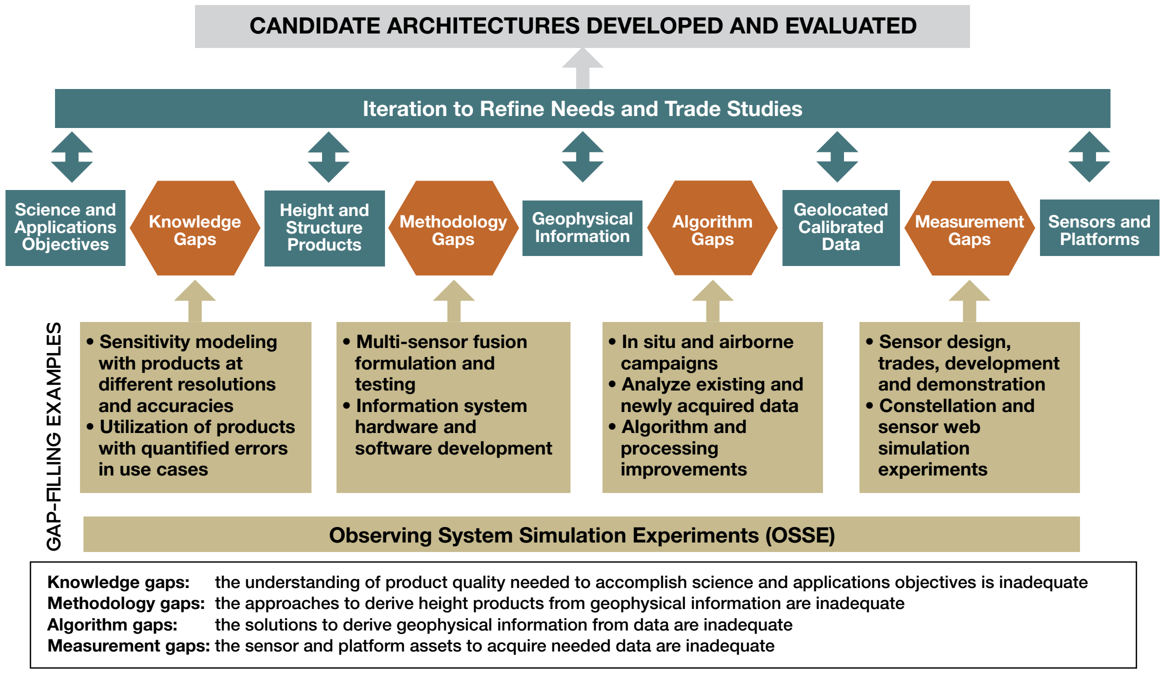
GAPS AND POTENTIAL GAP-FILLING ACTIVITIES

5.1 Introduction

We identified gaps in current capabilities after documenting the science applications and goals, objectives, product needs and current capabilities. In particular, gaps were identified that are road-blocks to the development and evaluation of observing system architectures that could meet the STV Observable challenge of high-resolution global mapping of topography, vegetation structure and shallow water bathymetry. Figure 5-1 is the framework in which gaps and gap-filling activities were identified. Gaps of four types were considered:

- Knowledge gaps: the understanding of product quality needed to accomplish science and applications objectives is inadequate (addressed in the science and applications discipline sections),
- Methodology gaps: the approaches to derive height products from geophysical information are inadequate,
- Algorithm gaps: the solutions to derive geophysical information from sensor data are inadequate,
- Measurement gaps: the sensor and platform assets to acquire needed data are inadequate.

FIGURE 5-1. Framework for identifying gaps and gap-filling activities, with components necessary to accomplish STV objectives indicated in blue, gaps between those components indicated in red and examples of potential gap-filling activities indicated in green. Gap-filling activities need to be accomplished in order to provide the necessary foundation for the development and evaluation of candidate architectures.



Examples of the sequence from sensors and platforms, geolocated calibrated data, geophysical information and products are presented in Table 4-1. Gaps in measurement performance, algorithm development and methodology capabilities limit the ability to provide the products needed to accomplish the goals and objectives, developed through the discipline breakouts, the product needs questionnaire and development of the preliminary SATM. As a group, these constitute the technology gaps referred to in this document. Identification of gaps in current technologies is based on the study team's expertise, presentations on current technologies given during the technology breakout sessions and quad charts solicited from technologists that describe current capabilities. Table 5-1 summarizes the key advantages and disadvantages of the three measurement approaches under consideration for STV. Less well established are methodology and algorithm gaps that present challenges in generating products of the required quality from sensor measurements. The evolution from "raw data" to geophysical information and products have to be advanced in many cases. For example, characterization of the three-dimensional organization of vegetation within forest canopies, and derived biomass, from space-based lidar and TomoSAR pose a significant challenge for current methods and algorithms. Furthermore, to date methods and algorithms have focused on input from a single sensor type, be that lidar, radar or stereophotogrammetry acquired from single platforms or baselines (in the case of interferometric SAR). The fusion of data from multi-sensor types and vantage points, from spaceborne, suborbital, and field components, is only in the earliest stages of development. Integration of sensor types can improve capabilities by leveraging the strengths of complimentary measurement approaches.

TABLE 5-1. Key advantages and disadvantages for lidar, radar and stereo technologies.

Sensor	Key Advantages	Key Disadvantages
Lidar	• High vertical accuracy • Detection of ground through vegetation • Vegetation structure • Day and night operation	• Coverage • Cloud cover • High power • Limited detection of ground through very dense vegetation
Radar	• Coverage • Day and night operation • Operates through clouds	• Complex to infer vegetation structure and underlying topography • Changing snow, firn and ice dielectric properties makes height measurements very challenging • High power
Stereophotogrammetry	• High spatial resolution • Low power • High maturity • High reliability	• Day only operation • Cloud cover • Limited detection of ground through dense vegetation

Knowledge gaps differ from technology gaps, which are limitations in the creation of products, and combine "methodology," "algorithm," and "measurement" gaps from Figure 5-1. Rather, they are uncertainties in knowing the quality of products needed. Although quantified needs are presented in the SATM, these are preliminary. In some cases, additional work will be required to achieve a fuller and more rigorous understanding of the quality of products needed to accomplish specific objectives. For example, in order to carry out observing system architecture design, we require greater accuracy about accuracy requirements. The SATM treats those at a high level. The distinction between absolute accuracy (with respect to a geodetic datum) and relative accuracy (the consistency within a data set) has not been made. Relative accuracy is critical for observations of change from repeated measurements whereas absolute accuracy is of primary concern when characterizing the shape and spatial organization of landscape features, such as slope magnitudes and orientations within a drainage basin or the depth, width and spacing of glacier crevasses. Similarly, product needs are described by mean values. In the traceability from product quality to sensor and mission requirements, the permissible deviation from those mean values (e.g., 1 sigma standard deviation or 95th percentile) must be quantified in order to quantify expected errors.

Following identification of knowledge and technology gaps, activities were identified that could potentially be used during the STV Incubation program to fill those gaps. Identification of potential gap-filling activities was based on the study team's expertise, presentations and discussions during the breakout sessions and input solicited from technologists in the form of quad charts describing emerging technologies which have the potential to contribute to capabilities needed for STV (Appendix E). Figure 5-1 provides, at a high level, examples of potential gap-filling activities. Some activities target specific gaps, whereas others, such as OSSEs, can span across all the gaps. The process of filling gaps during the STV Incubation program is envisioned as an iterative one, in which knowledge gained during the conduct of the activities propagates across the components indicated in blue. Through this iteration, the capabilities needed to accomplish the STV objectives, and trade studies to assess optimal approaches to fulfilling those needs, can be refined. A key component of that process is the trade space between cost and the science and applications benefits achieved. Quantifying the cost/benefit trade space is often a challenge during the development of mission observing systems. Investments to build tools to conduct quantifiable trade analyses of this type will be important during STV Incubation program activities. After the process of iterative gap-filling activities is conducted, a foundation will have been established whereby well-justified candidate STV architectures can be developed and evaluated.

5.2 Science and Applications Knowledge Gaps

The following sections compile knowledge gaps and gap-filling activities for each of the science and applications disciplines (Tables 5-2—5-7). The order in which these gaps and activities are listed is not intended to indicate a prioritization. The purpose is to provide a comprehensive compilation of gaps identified by the study team. In addition, in the study team's view not all activities must be conducted to fill a gap. A subset of activities can in some cases close a gap.

5.2.1 Solid Earth Knowledge Gaps

TABLE 5-2. Solid Earth knowledge gaps and potential gap-filling activities. Associated SATM product parameters are in parentheses. For associated SATM product parameters C = coverage, H = horizontal resolution, VS = vegetation 3D structure vertical resolution, VA = vertical accuracy, G = geolocation accuracy, B = bathymetry depth, S = slope accuracy, L = latency, RF = repeat frequency, RD = repeat duration, R = rate of change accuracy.

Solid Earth gap description	Potential gap-filling activities
Uncertainty in vertical accuracy of bare surface topography and its change as a function of horizontal resolution needed to study daily and seasonal inundation in low-lying coastal areas in the presence of variable, potentially dense vegetation. (C, H, VA, R)	• Combined airborne and field campaign or field campaign coordinated with commercial data buy. • Application of different methods for processing the data to obtain achievable accuracy as a function of horizontal resolution. • Development of a relationship between ground conditions and achievable accuracy. • Estimation of coverage vs. rate of change accuracy by region (e.g., for each major delta) based on known hydro-geomorphic features.
Uncertainty in vertical accuracy of bare surface topography and its change as a function of horizontal resolution needed for study of landslides of different types, materials, size, and vegetation cover. (C, H, VA, R)	• Combined in situ and airborne campaign, potentially in coordination with commercial data buy over exemplar sites. • Include landslide-prone areas where subject to wildfire to assess increased hazard associated with slope instability due to loss of vegetation cover.
Uncertainty in vertical accuracy of bare surface topography and its change as a function of horizontal resolution needed for study of lava flows of different types, depending on composition and temperature, size, and pre-eruption landscape topography and vegetation cover. (C, H, VA, R)	• Combined in situ and airborne campaign, potentially in coordination with commercial data buy over exemplar sites. • Ideally, data from active or recent flows over both previously bare and vegetation-covered would be used to 1) test sensitivity of volcano dynamic model needs to lava flow volume rate derived from repeat topography measurements; 2) test sensitivity of predicted lava-flow pathways to both the underlying bare-earth topography and to the measurement of lava-flow thickness and location as a function of resolution and accuracy; and 3) test sensitivity of lava-flow surface-thickness accuracy to lava-flow morphology (e.g., low fluid flows versus thick viscous flows and domes).

Solid Earth gap description	Potential gap-filling activities
Uncertainty in vertical accuracy of bare surface topography and its change as a function of horizontal resolution needed for study of past and new earthquakes at a range of magnitudes (from 6.5 to 7.5+) over a range of focal mechanisms (e.g., strike-slip, normal, thrust) and landscape vegetation. (C, H, VA, R)	• Combined in situ and airborne campaign, potentially in coordination with commercial data buy over exemplar sites. • Ideally, data from active or recent faults over both previously bare and vegetation-covered would be used to 1) test sensitivity deriving fault-slip-rate estimates for fault locations where in situ rate and offset information already exists (such as locations in California and elsewhere); and 2) test sensitivity of data quality towards measuring relevant co-seismic surface manifestations with data quality, (ideally locations in both desert and vegetated locations would be used in analysis).
Uncertainty in vertical accuracy of bare surface topography and its change as a function of horizontal resolution needed to understand the processes and interactions that determine the rates of landscape change. (C, H, VA, R)	• Combined in situ and airborne campaign, potentially in coordination with commercial data buy over exemplar sites where historical data is available to create long-term time series • Test sensitivity to deriving landscape properties related to river channel incision and sediment transport; hillslope mass wasting; tectonic uplift; climate change (on long time scales)

5.2.2 Vegetation Structure Knowledge Gaps

TABLE 5-3. Vegetation structure knowledge gaps and potential gap-filling activities. Associated SATM product parameters are in parentheses. For associated SATM product parameters C = coverage, H = horizontal resolution, VS = vegetation 3D structure vertical resolution, VA = vertical accuracy, G = geolocation accuracy, B = bathymetry depth, S = slope accuracy, L = latency, RF = repeat frequency, RD = repeat duration, R = rate of change accuracy.

Vegetation structure gap description	Potential gap-filling activities
Uncertainty in vertical accuracy of 3D vegetation structure products and their changes (VA, RF)	• Comparison with repeat airborne lidar data in areas experiencing known vegetation changes
Uncertainty in needed vertical accuracy of vegetation height estimates from stereo, lidar and InSAR sensors (VA, VS)	• Comparison of space-based or simulated space-based sensors with airborne lidar data • Strive to achieve 0.5–1m accuracy • Algorithm development
Low accuracy in biomass estimates derived from 3D vegetation structure and height across entire range of 0-1000 Mg/ha (VS, VA).	• Develop multisensor fusion (e.g., radar, stereo, lidar) methods • Algorithm development • Support the coordination of databases of globally distributed, updated field plot data on biomass • Support collection of field estimates of biomass in key site using terrestrial and drone-based lidar for rapid biomass estimation to facilitate calibration of models • Enable region-specific, user-specific biomass algorithm development, implementation and processing

Vegetation structure gap description	Potential gap-filling activities
Uncertainty in the relationship between biomass accuracy and canopy height and cover for sparser, lower vegetation (<10m) (H, VS, G, VA)	• Analysis of existing or newly acquired airborne swath mapping data in locations with in situ biomass data for lower, sparse vegetation to determine the relationship between the quality of vegetation structure information and biomass estimation accuracy, evaluated as a function of the associated parameters • Same as above using existing or newly acquired concurrent multi-sensor data, applying fusion methods to assess combinations of data from lidar, InSAR, TomoSAR radar altimetry, stereo and spectroscopic sensors
Uncertainty in the relationship between biodiversity and 3D vegetation structure across various scales (H, VS, G, VA)	• Analysis of existing or newly acquired airborne swath mapping data in locations with sufficient in situ biodiversity data to determine the relationship between the quality of vegetation structure information and biodiversity accuracy, evaluated as a function of the associated parameters • Analysis of multi-scale relationship between in-situ biodiversity and current space-based measures of vegetation 3D structure. • Same as above using existing or newly acquired concurrent multi-sensor data, applying fusion methods to assess combinations of data from lidar, InSAR, TomoSAR, radar altimetry, stereo and spectroscopic sensors
Uncertainty in the 3D understory structure that can be sensed at regional scale to characterize fuel loads and ladder fuels to predict fire danger. (H, VS, G, VA)	• Field campaign to characterize understory fuels • Airborne lidar and TomoSAR/PolInSAR campaign to simulate future space-based sensor to test accuracy of understory fuel estimates.

5.2.3 Cryosphere Gaps

TABLE 5-4. Cryosphere knowledge gaps and potential gap-filling activities. Associated SATM product parameters are in parentheses. Key for associated SATM product parameters C = coverage, H = horizontal resolution, VS = vegetation 3D structure vertical resolution, VA = vertical accuracy, G = geolocation accuracy, B = bathymetry depth, S = slope accuracy, L = latency, RF = repeat frequency, RD = repeat duration, R = rate of change accuracy.

Cryosphere Gap description	Potential gap-filling activities
Coordination of coincident, non-STV, measurements. Across all identified cryosphere science gaps there is a critical need to acquire multiple coincident non-STV observations (surface motion, reflectance, emitted radiance, surface temperature, salinity, and wind stress).	• Significant efforts are required to coordinate agency, national and international Earth Science observations to accelerate science outcomes.
Uncertainty of horizontal spatial resolution, repeat frequency and vertical accuracy needed to advance understanding of ice sheet and glacier surface mass balance and other surface processes and conditions, which are necessary for interpreting STV measurements (C, H, VA, G, RF, R, B)	• Comprehensive assessment of measurement technologies and algorithms for retrieving snow accumulation and firn compaction over glaciers and ice sheets from airborne and satellite platforms

Cryosphere Gap description	Potential gap-filling activities
Uncertainty of horizontal spatial resolution, repeat frequency and vertical accuracy needed to advance understanding of ice sheet and glacier surface mass balance and other surface processes and conditions, which are necessary for interpreting STV measurements (C, H, VA, G, RF, R, B)	• Assessment of the attainable accuracy of radar derived ice elevations and its dependence on radar frequency, including the role of spatiotemporally varying snow and firn properties and their vertical structure on surface retrievals • Assessment of the attainable accuracy of lidar derived ice elevations and its dependence on wavelength and seasonally-varying surface conditions • Temporally dense in situ measurements for selected field sites on ice sheets and glaciers spanning a range of climatic conditions targeted at the assessment of time-scales and rates of firn processes relevant to STV • Systematic experiments with existing altimetric datasets (airborne and spaceborne), surface-mass-balance, and firn models • Identification of potential improvements to surface mass balance and firn models, based on calibrated/validation experiments with in-situ data from field sites • Assessment of the necessary resolution and repeat frequency to retrieve the spatiotemporal evolution of surface meltwater features and their depths through experiments using existing satellite and airborne technologies.
Uncertainty of horizontal spatial resolution, repeat frequency, and vertical accuracy needed to recover ice stream and glacier force balance, and recover grounding zone evolution (C, H, VA, G, RF, R)	• Collection and analysis of velocity and surface-topography data for selected case studies to identify the scale, magnitude and rate of surface-topography changes associated with glacier force balance and grounding-line changes. • Experiments to test various spatial and temporal resolutions to obtain force balance and grounding-line changes (may include ice-sheet modeling)
Uncertainty of horizontal spatial resolution, repeat frequency and vertical accuracy needed to advance understanding of ice shelf basal melting (C, H, VA, RF, R)	• Collection and analysis of satellite and airborne data for selected case-study ice shelves to identify the spatial scale, magnitude, and temporal variability of surface-topography changes associated with basal-melt processes • These studies may include a modeling component
Uncertainty of horizontal spatial resolution, repeat frequency and vertical accuracy needed to advance understanding of ice shelf rift development and glacier-front calving (C, H, VA, G, RF, R)	• Targeted repeat surveys using high-resolution, frequent repeat satellite and airborne data for case studies of selected outlet glaciers and ice shelf rifts to identify temporal and spatial scales of calving and rifting rates • Analysis of imagery and high-resolution topographic data to identify the scale of surface features associated with calving and rift processes

Cryosphere Gap description	Potential gap-filling activities
Challenges associated with measuring melt pond coverage, volume and change over sea ice (H, VA, RD, R)	• Investigate algorithms and measurement techniques to improve identification of melt ponds over sea ice • Analysis of coincident high-resolution imagery to understand expected melt pond distribution
Uncertainty of horizontal spatial resolution, repeat frequency and vertical accuracy needed to advance understanding of snow depth and change over sea ice (H, VA, RD, R)	• Explore different technologies and algorithms for deriving snow depth on sea ice at the same resolution as the freeboard measurements needed to then derive sea ice thickness • Investigate new technologies and/or techniques to quantify melt pond influence on sea ice thickness retrievals
Uncertainty of horizontal spatial resolution and vertical accuracy needed to advance understanding of lead characteristics and floe size distribution	• Explore sampling and sensor biases when deriving lead properties (length/fraction) and chord length/ floe size from altimetry measurements, including the extremes (small/large) of the distribution • Analysis of coincident altimetry and imagery for exploring differences in floe discrimination.
Challenges associated with uncertain internal ice properties needed to convert freeboard to thickness.	• More targeted field campaigns to better understand spatiotemporal variability in snow-ice formation and snow/ice density evolution, especially in the Southern Ocean
Challenges associated with wave-ice interactions in the marginal ice zone.	• Investigate expected wave activity/attenuation within sea ice using numerical models and direct observations. • Investigate algorithms to automatically detect wave activity within the ice pack.
Uncertainty of horizontal spatial resolution and vertical accuracy needed to advance understanding of sea ice deformation/pressure ridging	• Investigate expected height distribution of pressure ridge/sail features at high-resolution to better inform altimetry retrievals over deformed ice regimes. • Numerical modelling and high-resolution observations to better understand the validity/errors introduced by the assumption of isostasy.

5.2.4 Hydrology Gaps

TABLE 5-5. Hydrology knowledge gaps and potential gap-filling activities. Associated SATM product parameters are in parentheses. For associated SATM product parameters C = coverage, H = horizontal resolution, VS = vegetation 3D structure vertical resolution, VA = vertical accuracy, G = geolocation accuracy, B = bathymetry depth, S = slope accuracy, L = latency, RF = repeat frequency, RD = repeat duration, R = rate of change accuracy.

Hydrology gap description	Potential gap-filling activities
[Land cover] Understanding and quantify how the landscape topographic features (e.g., bed roughness, mining, levees, roads) and vegetation structure (e.g., agriculture, wetlands, forests) impact various components of the water cycles such as river discharge, underground recharge and evapotranspiration. Can STV remote sensing provide adequate performance? (H, VS, VA, G, R)	• Perform a model sensitivity analysis to parameters representing catchment with a variety geo- hydro- and eco- morphological conditions. • Develop OSSEs, based on above models, to simulate remote sensing observations and assess STV retrieval algorithms for a variety of sensor configurations. • Use existing airborne and/or spaceborne remote sensing instruments to assess current remote sensing performance and achievable accuracy, and compare performance against above sensitivity analysis for representative geomorphological, hydrological, and vegetation conditions.
[Wetlands] Understanding the sensitivity of wetland health, structure and productivity to water surface height and hydroperiod? Can remote sensing provide adequate performance for various geo- hydro- and eco-morphological conditions? (H, VS, VA, G, R)	• Using hydrodynamic models, perform sensitivity analysis on various model parameters in representative wetlands with various geo- hydro- and eco- morphological conditions that includes interactions/connectivity with these components. • Develop OSSEs, based on above models, to simulate remote sensing observations and assess performance of STV retrieval algorithms. • Use airborne and/or spaceborne remote sensing instruments to assess current remote sensing performance and achievable accuracy, against above sensitivity analysis. • Assess different algorithms to processing remote sensing data to improve accuracy and potentially mitigate shortcoming of current or near-term remote sensing capabilities, over a variety of eco- and hydro- and geo-morphological conditions.

Hydrology gap description	Potential gap-filling activities
[Snow] Understanding the spatial and temporal scales of geophysical and climatic processes acting on snow packs and the availability of fresh water availability. (H, VS, VA, G, R)	• Determine the level of quality of data product needed (e.g., spatial resolution, temporal sampling and vertical accuracy) to quantify the impact of climate change on snow packs and associated fresh water availability. • Use existing OSSE or develop new OSSEs that can be used to simulate remote sensing observations and retrieval of snow depth in various geomorphological conditions and characteristics of vegetation cover. • Use airborne and/or spaceborne remote sensing instruments to evaluate, in response to above data quality, current remote sensing performance and achievable accuracy given a variety of . • Assess different algorithms to processing remote sensing data to improve accuracy and potentially mitigate shortcoming of current or near-term remote sensing capabilities, over a variety of geo-morphological conditions and characteristics of vegetation cover.
[Permafrost] Understanding how the hydrology of permafrost regions evolves in response to climate change, and how it shapes the landscapes. (H, VS, VA, G, R)	• Using models, perform sensitivity analysis on various model parameters in representative permafrost regions with various geo- hydro- and eco- morphological conditions. How accurately should elevation parameters be measured? • Develop OSSEs, based on above models, to simulate remote sensing observations and assess performance of STV retrieval algorithms. • Use airborne and/or spaceborne remote sensing instruments to assess current remote sensing performance and achievable accuracy, against above sensitivity analysis. • Assess different algorithms to processing remote sensing data to improve accuracy and potentially mitigate shortcoming of current or near-term remote sensing capabilities, over a variety of eco- and hydro- and geo-morphological conditions.
[Water cycle] From watersheds to the ocean, what are the lateral fluxes of water between the different components of the landscape and water cycle? (H, VS, VA, G, R)	• Using hydrodynamic models, perform sensitivity analysis on various model parameters in representative river and/or river networks with various geo- hydro- and ecomorphological conditions. • Develop OSSEs, based on above models, to simulate remote sensing observations and assess performance of STV retrieval algorithms in those various conditions. • Use airborne and/or spaceborne remote sensing instruments to assess current remote sensing performance and achievable accuracy, against above sensitivity analysis. • Assess different algorithms to processing remote sensing data to improve accuracy and potentially mitigate shortcoming of current or near-term remote sensing capabilities, over a variety of eco- and hydro- and geo-morphological conditions.

Hydrology gap description	Potential gap-filling activities
[Lakes and reservoirs] What is the relative impact of lakes and reservoirs on local and regional hydrology? (H, VA, G, R)	• Determine the quality of data product needed (e.g., spatial resolution, temporal sampling and vertical accuracy) to model water balance in lakes and reservoirs. • Assess different algorithms to processing remote sensing data to improve accuracy and potentially mitigate shortcoming of current or near-term remote sensing capabilities, over a variety or seasonal and hydrological conditions.

5.2.5 Coastal Processes Gaps

TABLE 5-6. Coastal processes knowledge gaps and potential gap-filling activities. Associated SATM product parameters are in parentheses. For associated SATM product parameters C = coverage, H = horizontal resolution, VS = vegetation 3D structure vertical resolution, VA = vertical accuracy, G = geolocation accuracy, B = bathymetry depth, S = slope accuracy, L = latency, RF = repeat frequency, RD = repeat duration, R = rate of change accuracy

Coastal processes gap description	Potential gap-filling activities
Understanding the product quality needed to determine benthic habitat variability (e.g., submerged aquatic vegetation, shellfish beds, corals) (B, VS, R)	• Multi-temporal, variable-accuracy in situ, airborne and satellite data collection campaigns to assess sensitivity of habitat classification to product quality and temporal resolution
Understanding the vertical resolution needed to assess benthic community composition (B, VS, R)	• In situ, airborne and satellite data collection covering a range of vertical resolutions to assess relationships between vertical resolution and community composition
Understanding how bathymetric uncertainties propagate to uncertainties in benthic habitat maps/products and change estimates (B, R)	• In situ, airborne and satellite data collection covering a range of resolutions and accuracies • Total propagated uncertainty (TPU) analysis, coupled with empirical accuracy assessments
Understanding the topo-bathymetric data quality needed to forecast long-term morphological change (B, H, VA)	• Multi-temporal, variable-accuracy in situ, airborne and satellite data collection campaigns to assess impacts of product quality on model outputs

5.2.6 Other Applications Gaps

TABLE 5-7. Other applications knowledge gaps and potential gap-filling activities. Associated SATM product parameters are in parentheses. For associated SATM product parameters C = coverage, H = horizontal resolution, VS = vegetation 3D structure vertical resolution, VA = vertical accuracy, G = geolocation accuracy, B = bathymetry depth, S = slope accuracy, L = latency, RF = repeat frequency, RD = repeat duration, R = rate of change accuracy.

Other applications gap description	Potential gap-filling activities
It will be a challenge to deliver products with sufficient timeliness (combination of latency and repeat frequency) to be of value for disaster response and to a lesser extent other risk management activities. (RF, L)	• Evaluate the different architectures to determine STV's potential impact for different types of disasters.
It will be a challenge to deliver products with sufficiently timeliness (combination of latency and repeat frequency) to be of value for other risk management activities. (RF, L)	• Quantify anticipated timeliness and evaluate product usefulness for the non-response stages of the hazard/disaster management cycle.
The end-user community needs to be well-familiarized with the mission and products so that they are ready to generate information products and use them when STV is operational. (H, R, VS, VA, G, L, RF, C)	• Engage through Applications Workshops with the different user communities starting in the mission formulation stage and continuing through launch.
The required threshold coverage for sufficiently accurate flood forecasting is poorly defined and dependent upon ground conditions (snow vs. water, soil saturation, topography, soil type, etc.), which differ by watershed. (C)	• Model watersheds for which flooding is frequent and high impact to refine product needs as a function of time of year, location, weather conditions. This can be done with hind-casting.
The capability of STV to be used for monitoring critical infrastructure depends critically on the accuracy of topographic rate of change and the horizontal resolution. (R, H)	• Simulate or purchase or acquire data of equivalent quality for each candidate architecture (can use output of technology gap-filling activities). • Apply different methods for processing the data to obtain achievable rate of change accuracy as a function of horizontal resolution. • Evaluate STV's capability for monitoring critical infrastructure of different types, spatial scales, and typical desired measurement threshold given a particular type and size of structure.
Operational agencies require a reliable stream of information for many of their applications and some applications (coastal resiliency) require long term data sets to assess site conditions. (RD)	• Evaluate the different STV architectures for ability to meet data duration requirements accounting for the fact that long time series are not needed globally but in a limited number of areas and for specific applications.

5.3 Technology Gaps

The following sections compile technology gaps and potential gap-filling activities for each of the sensor technologies and information systems. The order in which these gaps and activities are listed is not intended to indicate a prioritization. The purpose is to provide a comprehensive compilation of gaps and activities identified by the study team. In addition, in the study team's view not all activities must be conducted to fill a gap and not all gaps must be closed to achieve the capabilities needed to accomplish the STV goals and objectives. A subset of activities can in some cases close a gap, and trade studies can identify alternate solutions in which not all gaps need to be closed. For example, increased downlink capacity can be traded against on-orbit processing to handle large data volumes acquired by sensors. In some cases, gaps are common to more than one sensor and can be addressed by the same activity or set of activities. Investments in these common gap-filling activities can provide high-impact results that close gaps spanning all the technologies. Examples of common activities are:

- OSSEs to perform trade analyses for the full path from data collection to product generation
- In situ and suborbital campaigns acquiring multi-sensor data specifically designed to develop data fusion algorithms, methods and information systems
- Advancement of on-orbit processing and compression resources and approaches to reduce data volume requiring downlink
- Investigation of new technologies for downlink of large data volumes
- Size, weight, and power (SWaP) reduction of all sensors for increased feasibility of suborbital UAS and SmallSat platforms

5.3.1 Lidar Gaps

Lidar technology gaps are primarily due to difficulties in achieving sufficient, continuous coverage and high spatial resolution from high suborbital altitudes and from orbit (Table 5-8). Specific gaps in current capabilities are:

- Insufficient coverage from a limited number of profiles, from current spacecraft sensors, or narrow swaths, from moderate- to high-altitude suborbital platforms.
- Insufficient coverage due to the inability to penetrate or avoid clouds.
- From high altitudes and in space the laser beam divergence results in large footprint sizes that cannot currently achieve the high spatial resolution called for in some of the science and applications objectives.
- Uncertainty about what type of feature the lidar return is from (e.g., vegetation type, open ground, open water, water under flooded vegetation, snow, firn, ice, buildings) limits the utility of the resultant data.
- Large data volumes for lidar swath mapping can exceed the on-board processing, storage and/or downlink capacity for satellites or long-duration, airborne platforms.
- Because of the high-power needs for active sensors, space-based lidars have typically been very large and expensive. Miniaturizing is needed to reduce SWaP enabling constellations of smaller, less expensive suborbital or satellite sensors.

TABLE 5-8. Lidar technology gaps and potential gap-filling activities. Associated SATM product parameters are in parentheses. For associated SATM product parameters C = coverage, H = horizontal resolution, VS = vegetation 3D structure vertical resolution, VA = vertical accuracy, G = geolocation accuracy, B = bathymetry depth, S = slope accuracy, L = latency, RF = repeat frequency, RD = repeat duration, R = rate of change accuracy.

Lidar gap description	Potential gap-filling activities
Limited number of profiles or narrow swath causing insufficient coverage (C, RF)	• Instrument investments to develop and demonstrate improved measurement efficiencies for methods, components, subsystems and systems that enable wide-swath mapping • Analysis of existing or newly acquired airborne swath mapping data to determine what sampling density and footprint size are required to meet STV requirements, evaluated as a function of land cover and topographic relief • Develop sensor capabilities to adaptively switch between different acquisition modes (e.g., pulse energy and footprint density) for (i) global coverage vs. (ii) higher resolution target areas. • Platform investments to improve available power (e.g., larger battery storage capacity for nighttime-operation, solar array efficiency) • Algorithm and model development using existing or newly acquired concurrent multi-sensor data to develop optimal fusion methods for wide-area height and bathymetry mapping, evaluated as a function of scaled spatial and vertical resolutions and assessing combinations of lidar, InSAR, radar altimetry, stereo and spectroscopic sensors • Simulations using realistic models of landscape heights and water depths to predict lidar-only and multi-sensor fusion accuracies for wide-area height and bathymetry mapping, as a function of modeled sensor performance • Simulation of constellation configurations consisting of multiple lidar platforms to increase coverage • Simulation and hardware investments for lidar constellations consisting of a laser transmitter platform and multiple time-synchronous receiver platforms, observing the laser illumination locations, for increased photon collection
Cloud cover causing insufficient coverage (C, RF)	• Instrument investments for autonomous, adaptive laser beam steering to point toward cloud-free areas • Platform investments for autonomous, rapid satellite pointing to point toward cloud-free area • Platform investments for UAS capability to autonomously travel to areas of less cloud cover • Analysis of existing satellite data from optical imaging and lidar to establish the frequency distribution of cloud and cloud-gap sizes, as a function of region, season, optical depth and lidar wavelength (cloud and gap sizes are important for beam steering, satellite pointing, UAS mobility and duty cycle requirements) • Sensor web and artificial intelligence investments to transmit cloud cover locations identified using other sensors (e.g., optical imagers), on the same platform or other platforms, to the lidar sensor

Lidar gap description	Potential gap-filling activities
Uncertainty about what type of feature the lidar return is from (e.g., vegetation type, open ground, open water, water under flooded vegetation, water bottom, snow, firn, ice, buildings, seafloor/ lakebed) (VA, R)	• Combined in situ, airborne and satellite data collection campaigns, designed specifically for STV needs, to acquire multi-sensor data sets for analysis and algorithm and model development. • Analysis of existing or newly acquired multi-wavelength and/ or polarimetric lidar data to establish what feature identification accuracies can be achieved using only lidar sensors, evaluated as a function of scaled spatial and vertical resolutions • Algorithm and model development using existing or newly acquired concurrent multi-sensor data to develop optimal fusion methods for identification of features, evaluated as a function of scaled spatial and vertical resolutions and assessing combinations of lidar, high-resolution images (panchromatic, multispectral and/or hyperspectral) and multi-frequency polarimetric SAR sensors
Large data volumes for lidar swath mapping which may exceed the on-board processing, storage and/or downlink capacity for satellites or long-duration, airborne platforms (C, RF)	• Conduct downlink simulations based on the capacities and costs of the emerging, high-capacity, commercial downlink networks (many-station ground networks and satellite-to-satellite, in-space communication networks) • Optical communication investments in low-cost, low-power satellite laser communication terminals and ground receiving stations • Algorithm, artificial intelligence and compressive sensing investments for on-platform data acquisition, processing and analysis to adaptively compress sensor data (e.g., as a function of data attributes and objectives) and/or convert data to reduced-dimensionality geophysical parameter • Sensor web and artificial intelligence investments to identify time-varying targets (e.g., vegetation leaf emergence, active natural hazards, ice sheet melt) in order to optimize the lidar data collection focusing on high-priority objectives, thereby reducing the sensor duty cycle
Large laser footprint size causing insufficient horizontal resolution for some objectives (H, S)	• Hardware investments for imaging laser footprints onto a detector array so that detector pixels define the spatial resolution rather than footprint size • Algorithm investments for resolution improvement employing super-resolution sharpening of returns from overlapping, large footprints • System design investments for reduction in micro-pulse laser beam divergence to produce smaller footprints while preserving eye-safe operation

Lidar gap description	Potential gap-filling activities
Miniaturized laser transmitters, optics and electronics to reduce size, weight and power (SWaP) and cost (C, RF)	• Deployable telescope and free-form optics investments to increase receiver aperture, for increased photon collection, with reduced size and weight • Photonics integrated circuit (PIC) laser and fiber amplifier investments for more efficient laser transmitters • Space qualified processor, digitizer and data storage device investments for higher speed, lower power and reduced-volume • LiDAR SWAP improvements to allow it to be hosted on HALE platforms or other UASs.
Conflicting needs for high horizontal and vertical resolution of 3D vegetation structure while maximizing coverage and revisit frequency. (H, VR, RF, C)	• Conduct trade studies of alternative sensor and platform concepts to establish optimal approach to meet product needs.
Vertical accuracy and resolution of vegetation height and 3D structure by space-based lidar sensor with maximized coverage, geolocation and revisit frequency. (VA, RF, C)	• Investigate alternative sensor and platform concepts that that would meet the product needs. • Investigate improvements to geolocation of lidar footprints from space-based platforms.
Conflicting needs for data with very high horizontal and vertical resolution for specific locations and objectives but need for global coverage for other objectives that can be met by data of lower resolution. (H, VR, RF, C)	• Investigate options for having a dual mode lidar system with (i) high-resolution mode for targeted priority areas with global reach, and (ii) coverage mode that provides lower resolution data that systematically acquires data across the entire globe.

5.3.2 Radar Gaps

InSAR technologies to determine surface deformation (the displacement of ground surfaces) are mature and have been employed on a number of suborbital and satellite platforms. However, in their typical implementation, i.e., with single-radar (repeat-track) and nominally-zero spatial baselines, InSAR systems to measure deformation do not measure the absolute heights of ground surfaces nor the 3D organization of vegetation canopies and several gaps exist (Table 5-9). A key gap is specifying the optimal configuration of multiple, nonzero, simultaneous baselines along with radar instrument parameters (e.g., wavelength) for PolInSAR or TomoSAR vegetation structure measurement of surface properties (e.g., vegetation profiles, snow and ice elevations). PolInSAR and TomoSAR techniques enabled by distributed radar formations offer a viable solution for STV mapping, but the algorithms to generate the relevant products are under development.

Specific radar gaps are:

Vegetation Structure Methodology and Algorithm Gaps

- Optimal radar frequency for observing forest structure, AGB and change via PolInSAR and TomoSAR over a few-year period is not known.
- Algorithms and models needed to map STV structure from TomoSAR/PolInSAR observations are not mature and are only partially assessed
- Optimal spacecraft formation configuration for TomoSAR and PolInSAR for STV mapping is not sufficiently studied.

- Effects of short-term and long-term temporal decorrelation, including seasonal changes, in repeat-pass TomoSAR and pair-wise, single-pass TomoSAR are not quantified.
- Uncertainties in TomoSAR and PolInSAR-derived products are not fully quantified and properly linked to observations, instrument, retrieval algorithm and vegetation parameters
- Optimal features of the TomoSAR profiles to be used in biophysical descriptor estimation are not well identified
- PolInSAR methods using raw radar coherence and/or phase for estimating vegetation structure and its change are currently immature and only tested for a limited number of vegetation structures.
- Opportunities for fusing lidar and TomoSAR/PolInSAR profiles are underexplored.

Cryosphere Methodology Gaps

- Optimal radar frequency and imaging method(s) for observing change in snow accumulation with sufficient accuracy over varying snow conditions and terrain types.
- Optimal radar frequency and imaging method(s) in measuring seasonal and annual changes in land ice height with sufficient accuracy.

Measurement Gaps

- Advancements are needed for miniaturized radar antennas and electronics to reduce size, weight and power (SWaP) and cost
- Intersatellite communication links need to be designed and/or optimized for radar distributed formations
- As with lidar mapping, large data volumes for high-resolution imaging SAR mapping can exceed the on-board processing, storage and/or downlink capacity for satellites or long-duration, airborne platforms.

Table 5-9. Radar gaps and potential gap-filling activities. Associated SATM product parameters are in parentheses. For associated SATM product parameters C = coverage, H = horizontal resolution, VS = vegetation 3D structure vertical resolution, VA = vertical accuracy, G = geolocation accuracy, B = bathymetry depth, S = slope accuracy, L = latency, RF = repeat frequency, RD = repeat duration, R = rate of change accuracy.

Radar Gap description	Potential gap-filling activities
Optimal radar frequency for observing forest structure and change via PolInSAR and TomoSAR over a few-year period is not known. (VA, R)	• Conduct permanent-plot (tag trees) field, lidar and TomoSAR/PolInSAR airborne experiments in fixed-baseline and repeat-track modes, as above, with PolInSAR simultaneously at multiple radar frequencies; repeat 10 times per year for 3 years
Optimal spacecraft formation configuration for TomoSAR and PolInSAR for STV mapping is not sufficiently studied. (C, RF, VA, R)	• Develop orbital space simulators that include TomoSAR and PolInSAR scattering processes • Conduct experiments with airborne/UAS with variable constellation configurations

Radar Gap description	Potential gap-filling activities
Algorithms and models needed to map surface topography and vegetation structure from TomoSAR/PolInSAR observations are not mature and are only partially assessed (C, RF, VA, R)	• Develop and assess retrieval algorithms to generate L3 STV products from TomoSAR and PolInSAR profiles • Conduct field, lidar and mutli-baseline TomoSAR/PolInSAR airborne/UAS experiments in fixed-baseline and repeat-track modes; repeat 10 times per year • Find the lidar and TomoSAR profile features (height, H75, Fourier transform…) which are most sensitive to biophysical features such as AGB, leaf area density, habitat, species richness, abundance, and diversity • Evaluate performance on principal forest types (tropical, temperate, boreal) • Study effects of short- and long-term temporal decorrelation in repeat-pass and pair-wise, single-pass TomoSAR • Fuse lidar and TomoSAR profiles and PolInSAR observations to improve coverage and overall accuracy.
End-to-end TomoSAR and PolInSAR analysis and performance modeling and evaluation (C, RF, VA, R)	• Develop simulators for lidar and TomoSAR/PolInSAR measurements with comprehensive list of inputs and representative STV products as output • Collaborate with international institutes and universities (e.g., ESA, European groups) that have developed previous performance tool for TomoSAR/PolInSAR in preparation for BIOMASS and TanDEM-L missions • Conduct simulations and performance evaluations informed by field, lidar and TomoSAR/PolInSAR airborne/UAS experiments
Best radar frequencies and imaging method(s) for observing snow accumulation over varying snow conditions and terrain types. (VA, R)	• Host L-band and Ka-band InSAR on same aircraft for comparison of snow accumulation sensitivity • Add a depth sensor to radar platform: e.g., camera system for structure from motion • Wide frequency range radar such as an ultrabroadband frequency-modulated continuous-wave (FMCW) SAR to observe frequency dependence on snow backscatter • Conduct airborne experiments over a wide range of snow conditions (dry to wet snow) and terrains with field validation (e.g., SnowEx) to study radar sensitivities and variabilities of different methodologies.
Miniaturized radar antennas and electronics to reduce size, weight and power (SWaP) and cost (C, RF)	• Deployable antenna with sufficient aperture flatness with respect to radar wavelength, and reduced size and weight • L-band and X-band T/R module investments to improve efficiency, reduce size and weight • High voltage power supply investments to address corona issue (for Ka-band or Ku-band SAR) • Distributed architecture investments in synchronizing multiple receivers on SmallSats • Space-qualified processor, digitizer, and data-storage device investments for higher speed, lower power, and reduced volume • Onboard processor development to reduce downlink data volume

Radar Gap description	Potential gap-filling activities
Improved observation duty cycle of small satellite SARs (C, RF)	• Develop more effective thermal management methodology suitable for small satellite SARs • Develop lower power electronics to reduce power needs and thermal dissipation
Large data volumes for radar swath mapping which may exceed the on-board processing, storage and/or downlink capacity for satellites or long-duration, airborne platforms (C, RF)	• Conduct downlink simulations based on the capacities and costs of the emerging, high-capacity, commercial downlink networks (many-station ground networks and satellite-to-satellite, in-space communication networks) • Optical communication investments in low-cost, low-power satellite laser communication terminals and ground receiving stations • Algorithm, artificial intelligence and compressive sensing investments for on-platform data acquisition, processing and analysis to adaptively compress sensor data (e.g., as a function of data attributes and objectives) and/or convert data to reduced-dimensionality geophysical parameters
Large data volumes for radar swath mapping which may exceed the on-board processing, storage and/or downlink capacity for satellites or long-duration, airborne platforms (C, RF)	• Sensor web and artificial intelligence investments to identify time-varying targets (e.g., vegetation leaf emergence, active natural hazards, ice sheet melt) in order to optimize the radar data collection focusing on high-priority objectives, thereby reducing the sensor duty cycle
Improved InSAR signal processing algorithms to reduce errors (VA, R)	• Improve fidelity of tropospheric correction technique for repeat-pass InSAR data • Improve efficiency and effectiveness of InSAR phase unwrapping technique
Improved DEM generation algorithms (C, VA)	• Improve DEM void filling efficiency and effectiveness • Develop efficient and effective approach to merge remote sensing data from multiple platforms and measurement methodologies
Observing system architecture to support high-spatial-resolution sampling at 0.1 m height accuracy at selected locations, and to provide hourly revisit observation of specific events (C, RF)	• Identify areas with high-spatial-resolution sampling and height accuracy needs, and frequent revisit observation needs • Develop different observing system architectures to accomplish multiple accuracy and coverage needs • Conduct optimization study to identify the most efficient observing system architecture

5.3.3 Stereophotogrammetry Gaps

Because of the maturity, low-power and high spatial resolution of stereophotogrammetry methods, fewer technology gaps have been identified (Table 5-10) compared to lidar and radar instrumentation. None-the-less, current capabilities cannot fully address the needs for STV primarily because of operational considerations. Specific gaps are:

- Commercial providers of high-resolution imaging have business models that are not well suited for serving STV science and applications objectives. In particular, their focus is on repeat nadir imaging of high priority areas for commercial and military customers.
- Because of this business model, stereo imagery is only acquired on a task-order basis, not systematically, so global coverage is incomplete.
- Coverage is further limited by cloud cover, especially at equatorial latitudes.
- When stereo imaging is acquired, the acquisition parameters vary widely (e.g., illumination conditions, view angles, season) making systematic use of the data for height models very challenging. However, these data sets have been used for regional and continental scale DEMs (e.g., Morin et al., 2016)
- For both airborne and satellite platforms the primary commercial focus is on ground topographic mapping, using only two view angles with large angular separation. For urban and forest targets with significant variations in heights over short distances, this configuration is ill-suited for production of height models.
- As with the other sensors, large data volumes for high-resolution swath mapping can exceed the on-board processing, storage and/or downlink capacity for satellites or long-duration, airborne platforms
- The primary stereo processing systems used by NASA on high-performance computing platforms, the Ames Stereo Pipeline (ASP), was designed to work well on bare surfaces like the Moon and Mars and is not optimized for urban or vegetated areas.
- Unlike lidar and radar processing methods, ASP and other processing systems (Surface Extraction from Tin-Based Search Minimization [SETSM] and Chaîne Automatique de Restitution Stéréoscopique [CARS]) do not return an uncertainty metric per pixel, so product accuracy is difficult to quantify.

TABLE 5-10. Stereophotogrammetry gaps and potential gap-filling activities. Associated SATM product parameters are in parentheses. For associated SATM product parameters C = coverage, H = horizontal resolution, VS = vegetation 3D structure vertical resolution, VA = vertical accuracy, G = geolocation accuracy, B = bathymetry depth, S = slope accuracy, L = latency, RF = repeat frequency, RD = repeat duration, R = rate of change accuracy.

Stereophotogrammetry gap description	Potential gap-filling activities
Stereo imagery is acquired on a task-order basis, not systematically, so global coverage is incomplete. (C, R)	• Develop strategy to cover under-represented areas on the Earth's land and coastal areas. • Expanded coverage with existing or new assets • Utilize large coverage airborne assets to fill in missing CONUS coverage (the National Agriculture Imagery Program [NAIP] is an example program). • Develop SmallSat high-resolution stereo imagers to fill in CONUS and global data gaps.
Systematic repeat high-resolution topography measurements to meet science and applications community needs. (C, R)	• Develop SmallSat high-resolution stereo imagers to add repeat capability • Explore platforms such as ISS for augmenting other sources.

Stereophotogrammetry gap description	Potential gap-filling activities
Current SP measures outer forest canopy surfaces. (VS)	• Explore new data processing techniques to infer canopy vertical profile. • Develop new models to simulate vertical profiles using multiple SP metrics.
Multiple samples of terrain collected near-concurrently to reduce noise and improve 3D recovery do not exist. (VS, VA)	• Explore strengths and weaknesses of framing versus pushbroom imagery • Develop concepts to increase the number of images collected over targets during a pass • Develop new algorithms to efficiently process multiple images of a target
Large data volumes for high-resolution swath mapping can exceed the on-board processing, storage and/or downlink capacity for satellites or long-duration, airborne platforms. (C)	• Explore onboard processing to reduce the amount of downloaded data • Develop new processing algorithms that utilize multiple samples to estimate and reduce error • Develop electronics for high capacity SmallSat missions to efficiently acquire, process, store and transmit massive volumes of data that 3D imaging requires. • Consider lidar-comm for downlink.
High-resolution framing imagers are large and heavy and thus expensive to launch. (C, VA)	• Develop new technologies such as Rotating Synthetic Aperture (RSA) Imaging for low-cost, compact, high-resolution imaging systems
Coverage is limited by cloud cover, especially at equatorial latitudes. (C)	• Acquire multiple wavelengths to reduce measurement uncertainty and penetrate smoke and haze. • Develop smart tasking using sensor webs to identify cloud free areas for targeting. • Develop methods such as constellation of SmallSat stereo imagers to access cloudy areas more frequently
Stereo imaging is challenging with widely varying acquisition parameters (e.g., illumination conditions, view angles, season) making systematic use of the data for height models very challenging. (C, VA)	• Develop data processing strategies to exploit information in variable measurements • Develop sampling strategies to obtain systematic measurements
Topographic mapping typically uses only two view angles with large angular separation for airborne and satellite platforms, resulting in lower accuracy height models. (C, VA)	• Identify appropriate image acquisition parameters and observations to suit measurement needs. • Develop and launch multiple view angle sensor packages with programmable view angle selection. • Develop multiple imager framing systems to increase number of images acquired per target
The primary stereo processing systems used by NASA on high-performance computing platforms, the Ames Stereo Pipeline (ASP), was designed to work well on bare surfaces like the Moon and Mars and is not optimized for urban or vegetated areas. (C, VA)	• Develop new processing capabilities employing machine learning to optimize for different type of Earth surfaces.

Stereophotogrammetry gap description	Potential gap-filling activities
Uncertainty metric per pixel are not typically computed so product accuracy is difficult to quantify. (VA)	• Develop processing software to calculate and output appropriate accuracy and error statistics. • Develop algorithms to return an uncertainty metric per pixel to quantify product accuracy
Stereophotogrammetry software is generally designed for terrestrial mapping only, and does not account for the refraction of light at the air-water interface in determining the height of subaqueous terrain. (B)	• Develop automated software for a) segmenting subaerial and subaqueous regions; and b) rigorously accounting for refraction in generating submerged topography (aka bathymetry).
Improve the vegetation height estimate accuracy, coverage and revisit frequency to make SP a feasible monitoring option. (VA, RF, C)	• Investigate feasibility of high-resolution stereo imaging SmallSat constellation to provide accuracy, coverage, and revisit frequency required to monitor vegetation height and change.
Sensors used for stereophotogrammetry are not optimized for imaging the water body bottom topography. (B)	• Develop sensors optimized for bathymetry imaging, focusing on polarization, optimal band selection for different Jerlov water types, and exposure optimization.

5.3.4 Information System Gaps

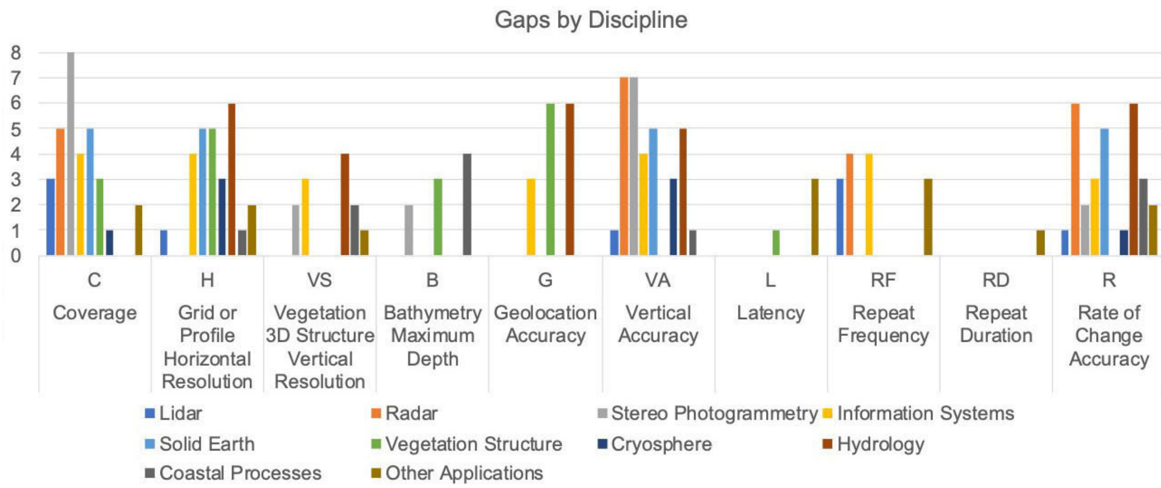
Information systems, to analyze options for and operate observing systems, have often focused on a relatively limited set of objectives within one science discipline and without emphasis on application needs. This applies both to the collection of data and the generation of products. Therefore, the applicability of these capabilities to the diverse STV objectives is not fully mature (Table 5-11). Key gaps are

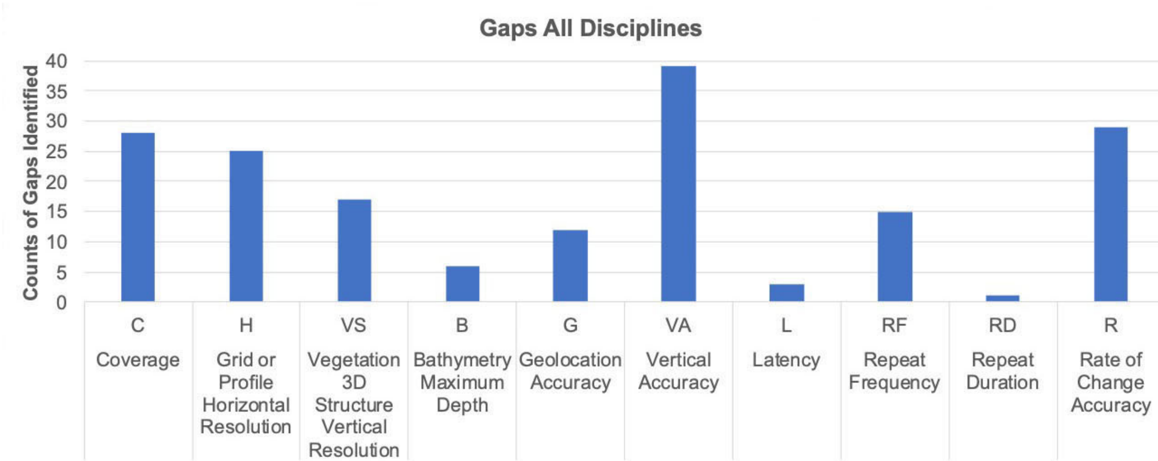
- Insufficient capabilities for multi-sensor data fusion methods and algorithms, accounting for differences in
    - measurement physics (e.g., radar vs. lidar)
    - imaging geometries (nadir vs. side-looking)
    - horizontal resolution
    - vertical resolution
    - acquisition times (sun angle)
- Inability to define the best performing combination of sensors for STV
- Low community acceptance for targeted observations using sensor webs and distributed architectures, as opposed to wall-to-wall coverage from a single sensor and platform
- Gaps in formation-flying technologies, which can benefit distributed sensor apertures, SAR tomography, and super-resolution imagery systems using multiple low-resolution imagers

TABLE 5-11. Information Systems gaps and potential gap-filling activities. Associated SATM product parameters are in parentheses. For associated SATM product parameters C = coverage, H = horizontal resolution, VS = vegetation 3D structure vertical resolution, VA = vertical accuracy, G = geolocation accuracy, B = bathymetry depth, S = slope accuracy, L = latency, RF = repeat frequency, RD = repeat duration, R = rate of change accuracy.

Information Systems Gap description	Potential gap-filling activities
Insufficient capabilities for multi-sensor data fusion methods and algorithms, accounting for differences in - measurement physics (e.g., radar vs. lidar) - imaging geometries (nadir vs. side looking) - horizontal resolution - vertical resolution - acquisition times (sun angle) (C, RF, VA, G, H, VS, R)	• Combined in situ, airborne and satellite data collection campaigns, designed for height mapping purposes, to acquire multi-sensor data sets for analysis and algorithm and model development. • Algorithm and model development using existing or newly acquired concurrent multi-sensor data to develop optimal fusion methods for identification of features, evaluated as a function of scaled spatial and vertical resolutions and assessing combinations of lidar, high-resolution images (panchromatic, multispectral and/or hyperspectral) and multi-frequency polarimetric SAR sensors
Inability to define the best performing combination of sensors for STV (C, RF, VA, G, H, VS, R)	• Leverage tools such as Trade Analysis Tool for Constellations and New Observing Strategies Testbed to develop an Observing System Simulation Experiment (OSSE) • Identify the optimal combination of sensors
Targeted observations using sensor webs and distributed architectures, as opposed to wall-to-wall coverage from a single sensor and platform (C)	• Conduct quantitative analysis of scientific objectives and their fulfillment using targeted observation strategy. • Test sampling strategies to establish minimum observation requirements to achieve science goals.
On-board processing or ground-directed retargeting is needed to capture short timescale dynamics for science and applications. (C, L, RF)	• Develop on-board analysis systems capable of generating and evaluating products for rapid change features. • Develop communication and ground-based methods for rapidly retasking imaged area on-orbit.
Gaps in formation flying technologies, which can benefit distributed sensor apertures, SAR tomography, and super-resolution imagery systems using multiple low-resolution imagers (C, RF, VA, G, H, VS)	• Improve on-board decision-making systems for platform navigation, potentially leveraging AI/ML. • Conduct testing of these algorithms through simulations or physical systems
Robust change and feature detection algorithms. (VA, G, H, RF, R)	• Improve on-board decision-making systems for platform navigation, potentially leveraging AI/ML. • Conduct testing of these algorithms through simulations or physical systems

FIGURE 5-2. Top) Number of times products identified by the study team that are associated with knowledge and technology gaps, by science, applications, and technology discipline. Coverage, vertical accuracy, horizontal resolution, rate of change accuracy, repeat frequency, bathymetry maximum depth, and vegetation 3D structure are the most frequent gaps that need to be closed. Bottom) Total number of times products are identified as associated with a gap for all disciplines.





5.4 Emerging Gap-Filling Activities Summary

During the identification of the gaps by the study team, each science, applications, and technology discipline designated which products related to the identified gaps. A summary shows the key gaps that need to be filled in order to mature STV into a global observing mission (Figure 5-2). Vertical accuracy is the largest gap that needs to be filled, followed by rate-of-change accuracy, coverage, horizontal resolution, vegetation-structure vertical resolution, repeat frequency, geolocation accuracy, bathymetry maximum depth, and latency.

The detailed lists of gap-filling activities in Section 5.3 are summarized in Figures 5-3 through 5-7, which present them in terms of the challenge to accomplish an activity versus the potential benefit that would result. Rigorous cost-benefit analysis was not applied. Instead, the following charts are based on the technology expertise of the study team members. They are intended as a high-level synopsis, to provide a framework for future investments to advance capabilities needed for STV. The charts have been developed so that the activities are categorized in terms of level of challenge and benefit so that they are all plotted on the same qualitative scale across the technologies. In some cases, the same activity appears on some or all of the charts with equivalent challenge but differing benefits. The benefit is dependent on how significant that limitation is for a specific technology. For each technology, the two activities considered by the team to be of most importance are highlighted as bold.

In addition to sensor and information system technologies, the trade space for STV architecture designs should consider utilization of sensors on multiple platforms, potentially including constellations in space augmented by suborbital platforms. Because these areas are being advanced broadly for many NASA mission needs, comprehensive identification of platform gaps and activities was not done in this study. However, a general consideration of activity challenges and benefits was done and is summarized in Figures 5-3 through 5-7.

Closing key gaps would enable the implementation of an STV mission concept. Each technology has challenges to be overcome. The STV team identified key maturation activities and plotted them against benefit (Figures 5-3 through 5-7). The two highest ranked maturation activities for each technology are noted by bold font and the team roughly normalized the activities across all of the plots.

FIGURE 5-3. Candidate lidar maturation activities showing the challenge in accomplishing the activity versus expected benefit. The two activities judged to be of greatest importance by the study team are highlighted in bold.

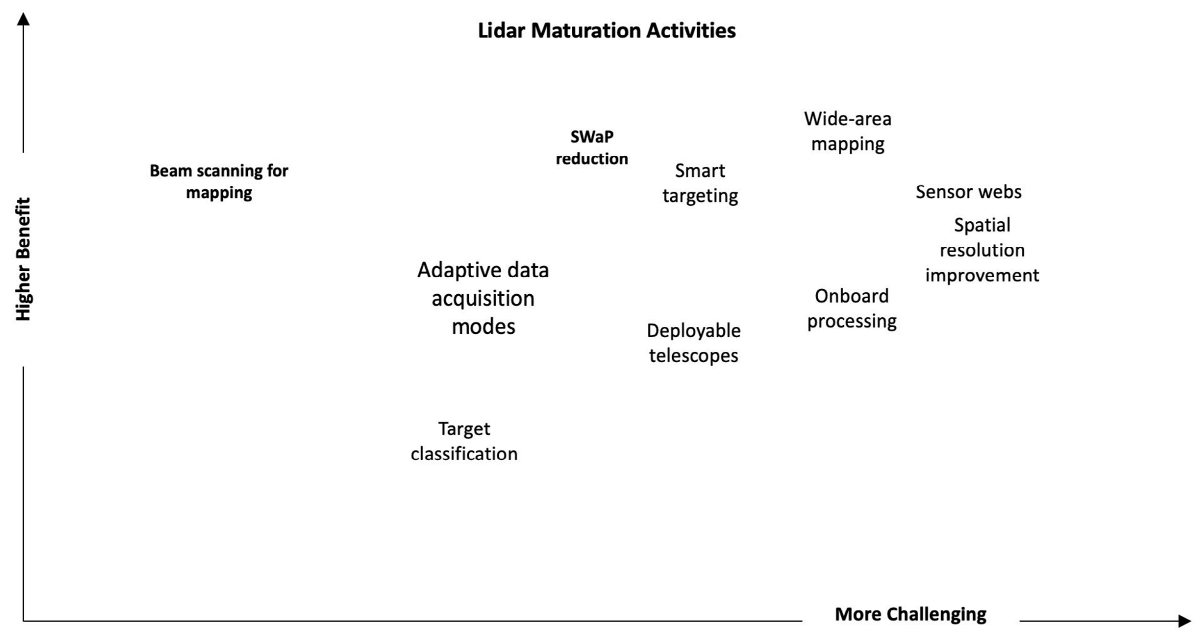


FIGURE 5-4. Candidate radar maturation activities showing the challenge in accomplishing the activity versus expected benefit. The two activities judged to be of greatest importance by the study team are highlighted in bold.

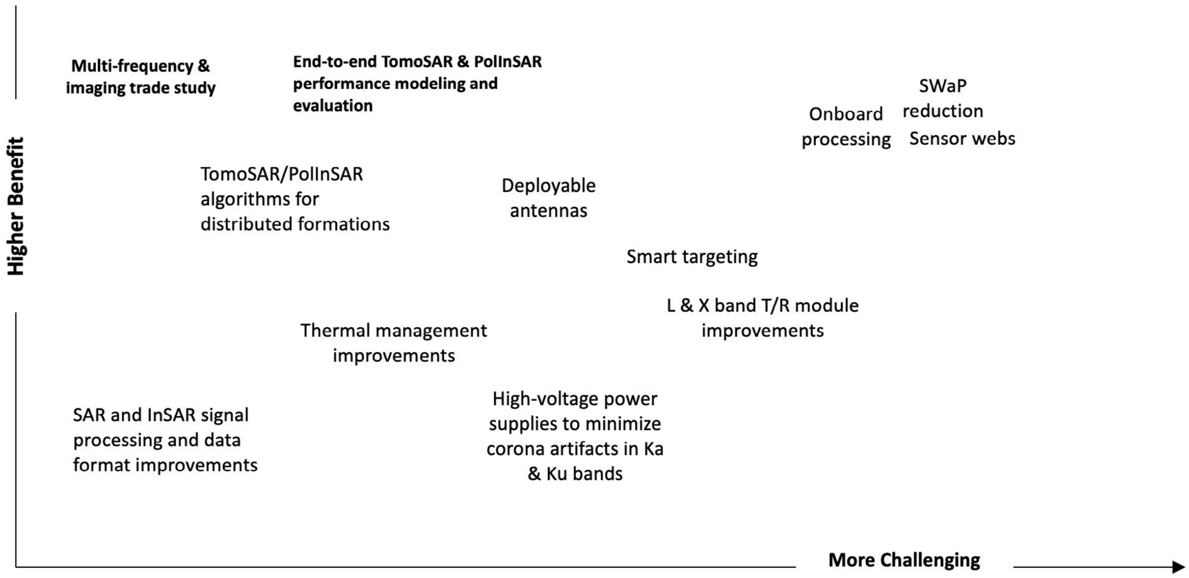


FIGURE 5-5. Candidate stereophotogrammetry maturation activities showing the challenge in accomplishing the activity versus expected benefit. The two activities judged to be of greatest importance by the study team are highlighted in bold.

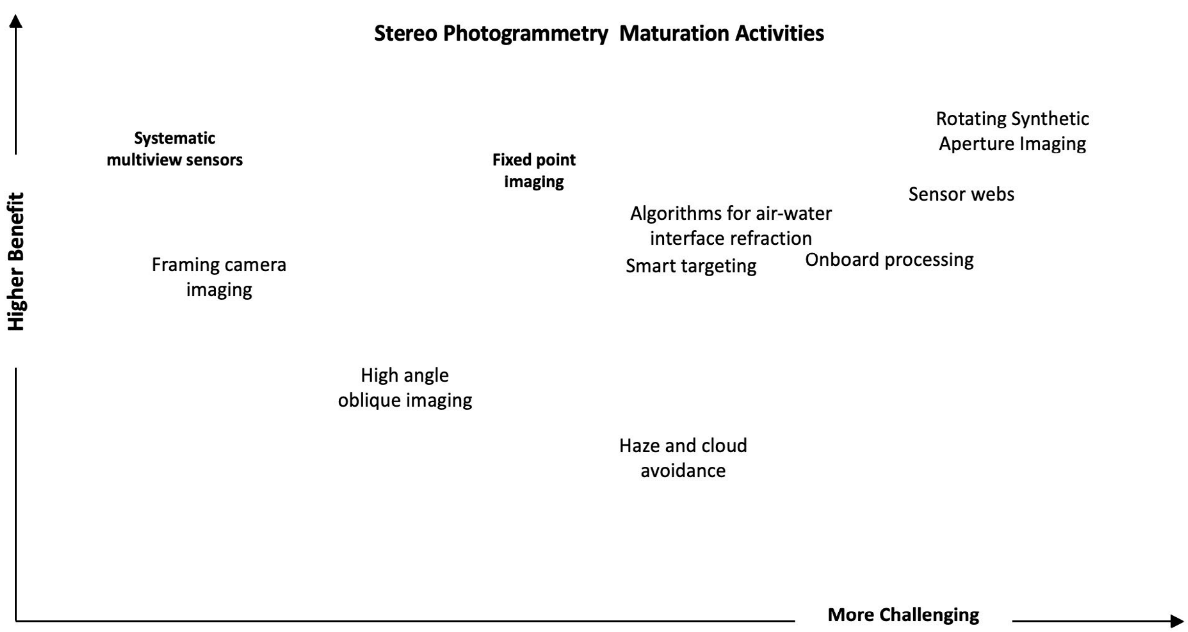


FIGURE 5-6. Candidate information system maturation activities showing the challenge in accomplishing the activity versus expected benefit. The two activities judged to be of greatest importance by the study team are highlighted in bold.

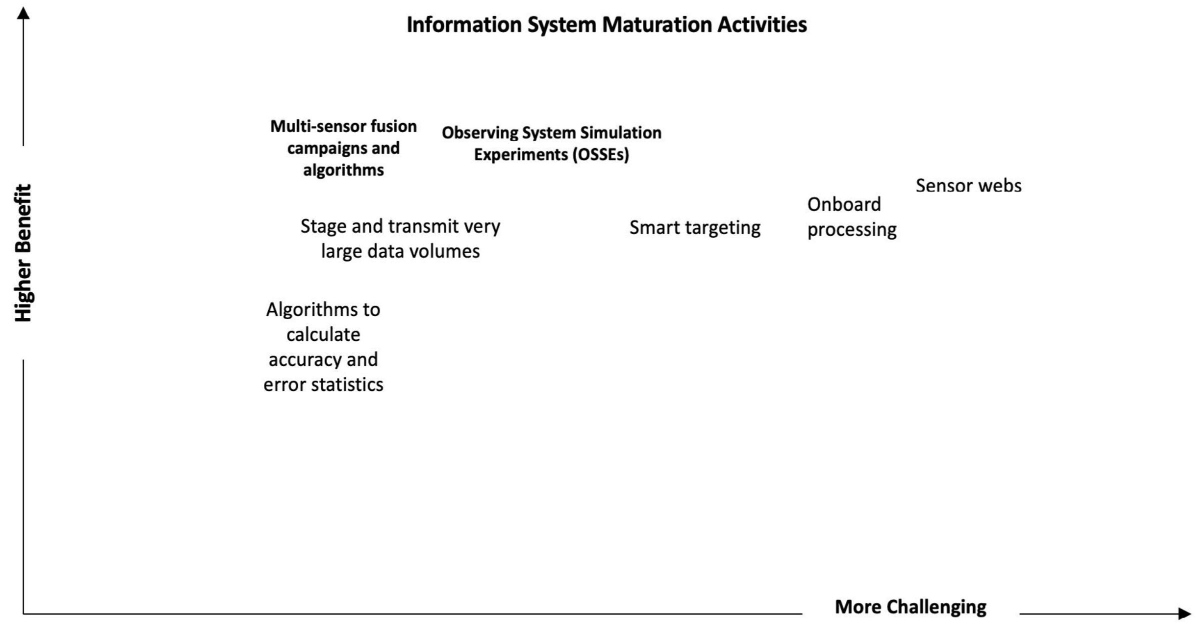
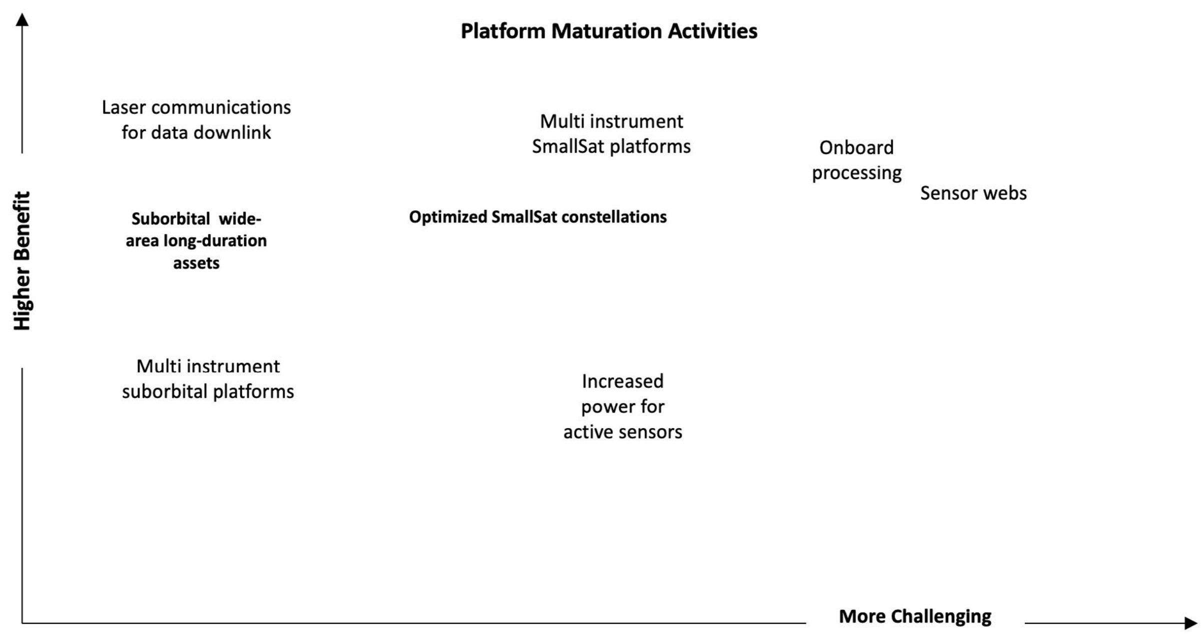
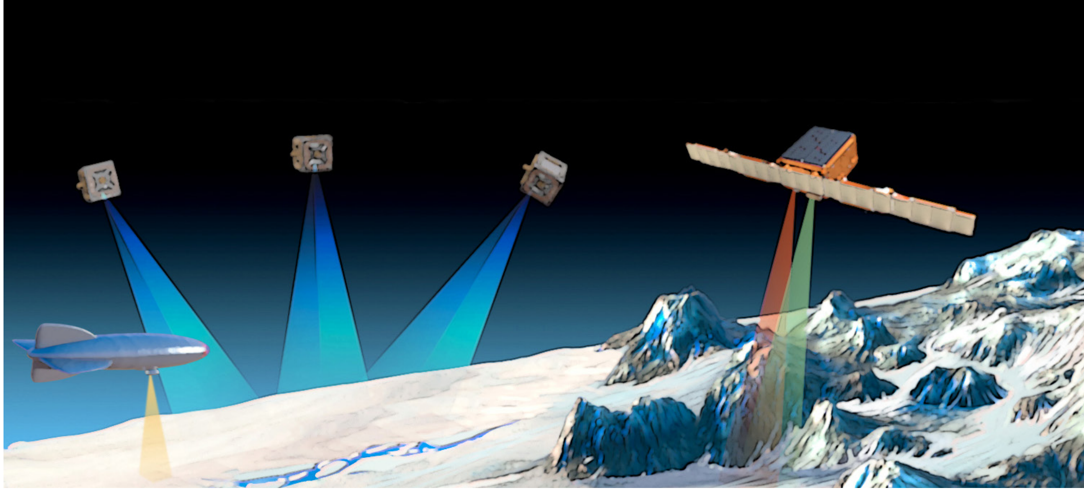


FIGURE 5-7. Candidate platform maturation activities showing the challenge in accomplishing the activity versus expected benefit. The two activities judged to be of greatest importance by the study team are highlighted in bold.





CHAPTER 6

ARCHITECTING AN STV OBSERVING SYSTEM

Developing and evaluating candidate observing system architectures that can meet the STV goals and objectives is an end-goal of a process underpinned by OSSEs (Figure 5-1). The architecture that ultimately becomes the solution for STV will follow from the types of activities identified in this study to fill gaps in technical capabilities and in knowledge of how to best acquire and analyze remote-sensing observations that meet the STV product needs. A number of activities performed separately as pieces of an OSSE and eventually integrated into a comprehensive one will enable the optimal design of the ultimate STV architecture.

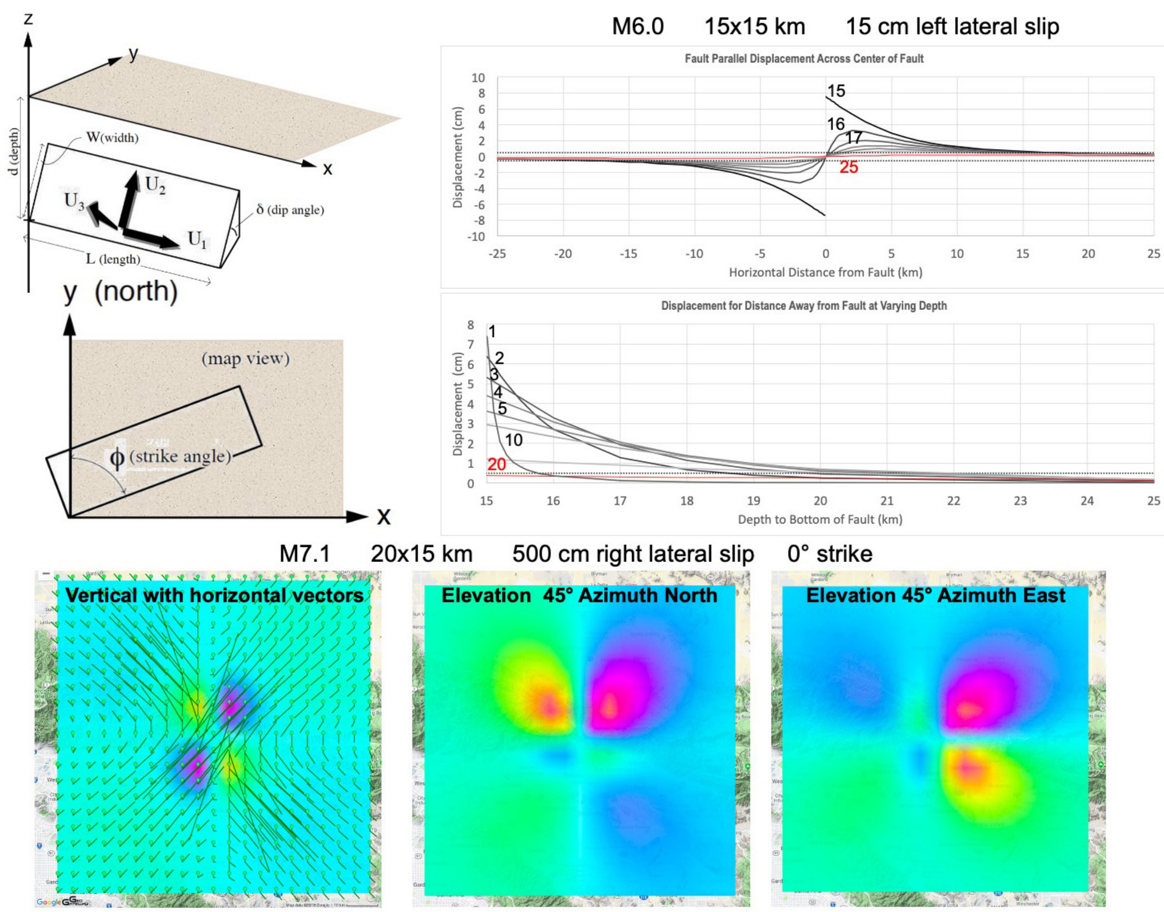
Trade space options that need to be considered for observing system solutions are extensive. The solution may consist of one or more sensor types, using lidar, radar, stereo photogrammetric and/or spectrometry methods, that are hosted in space or potentially suborbitally. The satellite component might consist of a single platform or multiple platforms, possibly in a constellation, using CubeSat, SmallSat and/or LargeSat spacecraft. The spacecraft could be dedicated to STV and/or be spacecraft that provide hosted-payload opportunities for STV sensors. Suborbital platforms might consist of fixed-wing or lighter-than-air UASs, including platforms capable of deployments of days to months, or crewed aircraft. If multiple platforms and/or sensors are used they could operate independently in a distributed architecture, with downlinked data integrated on the ground, or operate as a sensor web with nodes that are interconnected by a communications fabric and that function as a single, highly coordinated, virtual instrument. Some data processing could be conducted on-platform, either in real-time or applied to stored data, or raw sensor data could be downlinked for later processing. The architecture solution may be implemented solely by NASA or in collaboration with other U.S. government agencies, international space agencies, and/or commercial entities.

Meeting STV objectives fits within NASA New Observing Strategies (NOS) type architectures coupled with Analytic Collaborative Frameworks (ACFs). The goal of both NOS and ACF is to create flexible and evolving constellations of orbital and suborbital systems. This type of architecture is ideal for STV, where a variety of technologies and platforms could contribute best to meet the product needs of the science and applications communities. This is particularly important for measuring change, responding to events, and creating long observational time series. Better understanding the performance and capabilities of instruments and platforms to meet STV goals and objectives requires investment in science modeling, data analysis, technology performance characterization, and an integration of these components into OSSEs.

6.1 Science

Understanding needed STV capability requires modeling the physical processes to be observed. Output from process models and simulations would demonstrate the needed measurement thresholds to observe, characterize, and understand a process. A single comprehensive model is not initially needed to make progress with understanding the observational needs. Given the wide array of science disciplines such a model is also not desirable. Even simple parameterizations can bound the needed capabilities for an STV observing system. For example, an earthquake of the same magnitude can produce different amounts of surface displacement based on the area, orientation, and depth of a rupture (Figure 6-1). As a fault is progressively buried deeper the amount of surface displacement decreases. Typically, the amount of damage to the built environment also decreases in the absence of liquification or some other amplification of seismic waves such as from the presence of a basin. Models and simulations can bound the sensitivity needed to observe current earthquake or past fault activity of a given size and geometry. Similar simple parameterizations can bound observational needs to measure given processes.

FIGURE 6-1. Example sensitivity models for dislocations in an elastic half space. Model parameters are noted in the top left diagram. Top right shows model output for a M6.0 earthquake. The top model shows displacements perpendicular to a vertical strike slip fault. Dotted horizontal line marks an example 0.5 cm displacement threshold. Deformation would not be detectible for a depth of 25 km for the bottom of the fault. Plotting depth of fault versus displacement profiles for various distances away from the fault shows how the deformation spreads out for deeper faults and is not detectible more than 20 km away from the fault. The bottom panels show simulated images for different line of sight components. Observed deformation is sensitive to the orientation of the fault and the line-of-sight direction for an InSAR instrument.



Potential science studies to refine STV needs into requirements and to established needed instrument performance include, but would not necessarily be limited to:

- Modeling and simulation of a single process of a more complex system.
- Integrated modeling and simulation of multiple processes to form a more comprehensive model.
- Parameterization of observed process, model output, and measurement capability.
- Modeling and quantification of error sources and impact on observational system.

6.2 Observing System Simulation Experiments (OSSEs)

Architecting an STV mission requires OSSEs to better quantify the observational needs of STV and evaluate the relative importance of the various technologies and measurement approaches involved in the mission design. Essential components of an OSSE for STV are the instrument performance models, the measurement and target models, the orbit models, and the science metrics generation and validation. The complexity and fidelity of the models required by an OSSE depends on the type of analysis or science metric of interest. The components of an OSSE are typically built up over time and can come from detailed observations, parameterizations, and models often tailored to a specific science discipline. Analysis of spaceborne, airborne, and field data can inform the forward and inverse models as well as be integrated in the validation component of an OSSE.

For STV, OSSEs are required to produce or simulate STV products from different measurement approaches that incorporate various error sources, for which model development is needed. Coupled science/technology tools are needed to find intersections and gaps between science needs and capabilities. Trade spaces need to be explored to understand instrument performance and platform architectures. The science and applications community should be engaged to define needs and develop OSSEs. Small process studies, analysis of existing data, and collecting new data should all be part of explorations to better define parameter space, understand instrument capability and performance, and quantify uncertainties. The STV community has experience with OSSE development, but current implementations are based on simple models, lack necessary capabilities, or focus on a single sensor type or one science discipline. These provide building blocks that are a useful first step but ultimately a more integrated, comprehensive capability will be needed for multi-sensor OSSEs serving multiple science and applications objectives. Some relevant emerging efforts (Appendix E-8) include:

- Distributed Aperture Radar Tomographic Sensors (DARTS) (E.4 Radar Emerging Technologies)
- Polarimetric Interferometric (PolInSAR) Estimates of Forest Height (E.4 Radar Emerging Technologies)
- Towards the Next Generation of Land Surface Remote Sensing: A Comparative Analysis (E.8 Information Systems Emerging Technologies)
- Trade-space Analysis Tool for Constellations (TAT-C) (E.8 Information Systems Emerging Technologies)
- G-LiHT Airborne Data and DART Modeling to Explore Lidar-Optical Synergies (E.1 Lidar Current Technologies)
- Automated Mission Analysis (E.3 Radar Current Technologies)

DARTS is conducting OSSEs that combine high-fidelity interferometric/tomographic SAR (TomoSAR) simulations informed by 3D electromagnetic models and state-of-the-art algorithms and technologies with demonstrated performance. The focus of the DARTS OSSEs is on the following aspects that are relevant to STV mapping with a distributed formation of SAR satellites: 1) an absolute timing reference which is invariant to positioning of the platforms, 2) relative positioning and attitude knowledge in three dimensions for platforms, 3) intercommunication and assimilation of each radar's data for coherent data processing, 4) miniaturized, lightweight radar components conducive to affordable launch of multi-satellite formations; 5) lightweight, deployable antenna, 6) optimal orbital and radar mode configuration, 7) conversion of tomograms into L3 science product, and 8) validation of system performance with prototype hardware.

For vegetation structure a joint JPL and Caltech collaboration has initiated the development of an OSSE that uses a 3-D electromagnetic model to simulate multi-frequency (X-, C-, L-, and P-band) SAR observations including polarimetry, PolInSAR and TomoSAR techniques of forest structure and other biophysical parameters and an ecosystem Data Assimilation Model (CARDAMOM) to include with the following components: 1) Nature Runs based on a 3-D electromagnetic model of forest structure on complex terrain to provide synthetic observations used as the "truth." A version of a radiative transfer model for simulating lidar observations of STV can be included to allow multi-sensor Nature Runs, 2) SAR and lidar error models that provide realistic and suitable uncertainty to the synthetic observations, 3) CARDAMOM with internal Bayesian spatial estimation scheme to allow for multiple sensitivity analysis using forest structure and biomass across the globe and to validate the observations or measurements for different STV mission requirements, and 4) instrument simulators and observing system configuration for evaluation of mission performance. This approach will allow the OSSE to follow the SATM from goals and objectives to measurement requirements, observables, and to instrument configurations and performance.

The Next Generation of Land Surface Remote Sensing effort had begun foundational steps to develop a multi-sensor OSSE framework, with a focus on hydrologic and ecosystem sciences, by integrating the Land Information System (LIS), the Trade-space Analysis Tool for Constellations (TAT-C) and sensor models for passive optical, passive and active radar and lidar systems. LIS is a land surface modeling and data assimilation software framework. TAT-C is a framework to perform pre-Phase A mission analysis of Distributed Spacecraft Missions (DSM). The hydrology community, using multi-sensor data acquired through the SnowEx field campaign, is applying this capability to assess mission architectures for the DS Snow Depth and Snow Water Equivalent Explorer Observable. This is an example of an emerging capability that could be expanded to address the broader range of STV objectives.

Construction of OSSEs for the use of remote sensing observations that integrate models addressing a science question or hypothesis with electromagnetic models that simulate the observations will allow for end-to-end trade studies and performance analysis. Components can be developed initially with inputs and outputs well-defined to be compatible with ultimately creating an end-to-end system. Developing components that provide useful information for maturing STV should result in a more useful and robust end-to-end OSSE ultimately. This will allow the community to develop scalable OSSEs that include standardized and testable metrics to evaluate the results and the performance of observations and geophysical or biophysical parameters through a traceable mechanism between the science question and instrument/platform performance.

6.3 Data

Analyzing existing data, collecting new datasets, and sampling those new data sets in the way an STV sensor will observe provides a means of defining the needs for a new observational system. Sensitivity studies leveraging the science modeling will define what needs to be measured to understand the science or application physical process being addressed. Surrogate datasets, whether collected or simulated, will help drive technology and development and validate expected future observations for various system designs.

Activities related to data analysis would include but not be limited to:

- Assessment and acquisition of existing data for analysis from commercial and government sources
- In situ data collection of higher resolution representative observations or data required for validation
- Suborbital flight demonstrations to create high-resolution observations for surrogate and validation data
- Simulated data for comparison with observed data
- Characterize error sources and uncertainties

6.4 Technology

Chapter 5 outlines in detail technology maturation gaps and activities needed to fill those gaps. Key technology development activities would mature STV in the next five years (Table 6-1). A TRL assessment of existing technologies and those under development should be carried out. TRLs of current and emerging technologies are noted in the technology quad charts in Appendix E that were submitted by the community.

6.5 Architecting STV Conclusions

Throughout the maturation of STV, components of the system from science through instrument and platform should be developed or matured in a coordinated fashion with a goal of creating an end-to-end simulation system and ultimately STV observing system. Activities need to include 1) science modeling, 2) instrument characterization and performance analysis, 3) creation of new data and identification and analysis of existing data, and 4) technology development. STV will serve five science disciplines with additional applications. This STV incubation study demonstrates that an STV observing platform with a single set of measurement performance could address aspects of each discipline. Suborbital observations or the inclusion of observations from other instruments can complement STV measurements and achieve additional needs for each discipline. It is important to maintain a coordinated set of activities to achieve STV goals.

TABLE 6-1. Aspirational maturation activities for STV to attain by 2026.

Technology	Maturation Activity
Lidar	Beam scanning for mapping Size, weight, and power reduction
Radar	Multi-frequency and imaging trade study End-to-end TomoSAR and PolInSAR performance modeling and evaluation
Stereophotogrammetry	Systematic Multiview sensors Fixed point imaging
Information Systems	Multi-sensor fusion campaigns and algorithms Observing System Simulation Experiments
Platforms	Suborbital wide-area long-duration assets Optimized SmallSat constellations

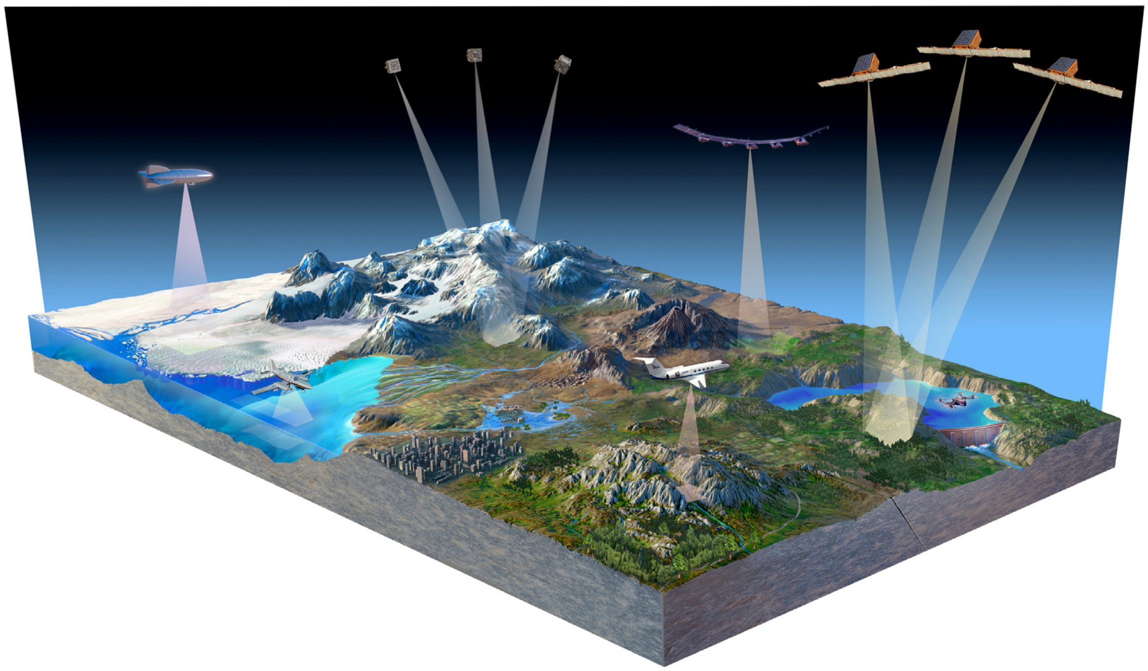
CHAPTER 7

KEY FINDINGS AND PRELIMINARY ROADMAP

The STV study team focused on the science and applications disciplines of solid Earth, vegetation structure, cryosphere, hydrology and coastal processes. It considered the efficacy of observations of surface topography, vegetation structure, shallow water bathymetry, and snow depth in addressing the above disciplines. Sensors studied were lidar, interferometric SAR, and stereophotogrammetry. Information systems and platforms were also considered as part of the technology brought to bear on discipline needs. Key themes and findings emerged across the disciplines and technologies:

- The need for repeated observations of the heights of the Earth's surface is a common theme across all science and applications disciplines. One-time mapping is insufficient to achieve a large majority of the goals and objectives documented in this study. The communities that will be served by STV observables have advanced beyond characterization and inventory of static features. Instead, understanding the dynamics of the Earth's vertical structure and the processes by which change is occurring is paramount. Observations of change are required for this purpose and drives product needs related to the ability to quantify changes, including vertical accuracy, geolocation accuracy, rate of change accuracy and the duration over which observations are repeated.
- Rapidly-changing dynamic events, often associated with localized hazards, impose additional drivers in order to support timely mitigation and response decision-making. In particular, products with high-resolution, high-repeat frequency and low-latency are often needed.
- A single orbital platform with wide-area coverage using one sensor could meet a subset of STV science and applications needs, partially serving the goals and objective of the five STV disciplines. In particular, those requiring large coverage and relatively infrequent repeats to monitor slowly changing phenomenon could be well served. However, this approach has significant limitations. Sufficiently large wide-area coverage is unlikely to be achieved by lidar technologies in the time-frame necessary for STV, even with emerging advances that could be matured in this decade. No emerging capabilities have been identified to overcome the challenge for stereophotogrammetry in measuring topography beneath dense vegetation cover. While radar approaches for characterization of 3D vegetation structure are emerging, there are gaps in how best to accomplish this and what retrieval accuracies could be achieved. Furthermore, the changing properties of snow, firn and ice pose challenges in achieving sufficient vertical accuracies to monitor changes in land ice elevations, sea ice thickness and snow depth.
- Given the challenges that face a single-platform and single-sensor solution, an architecture of multiple platforms and sensors, including some combination of lidar, radar, and stereophotogrammetry methods, on orbital and suborbital assets would address STV needs more thoroughly (Figure 7-1).

FIGURE 7-1. Examples of candidate elements for an STV observing system, incorporating lidar, radar and stereophotogrammetry sensors on orbital and suborbital platforms. STV objectives may be best met by new observing strategies that employ flexible multi-source measurements from a variety of orbital and suborbital assets. This flexible approach, coupled with modeling, simulation, and sensitivity studies would also aid the design of a future STV observational system.



Substantial work is required to lay the foundation necessary to conduct architecture trade and optimization studies that can identify cost-effective platform and sensor combinations. Key gap-filling activities include collection and analysis of multi-sensor airborne and in situ data sets to establish fusion algorithms, the conduct of OSSE simulations to assess viable platform/sensor combinations and advancement of information system capabilities that enable optimized design of smart sensor webs.

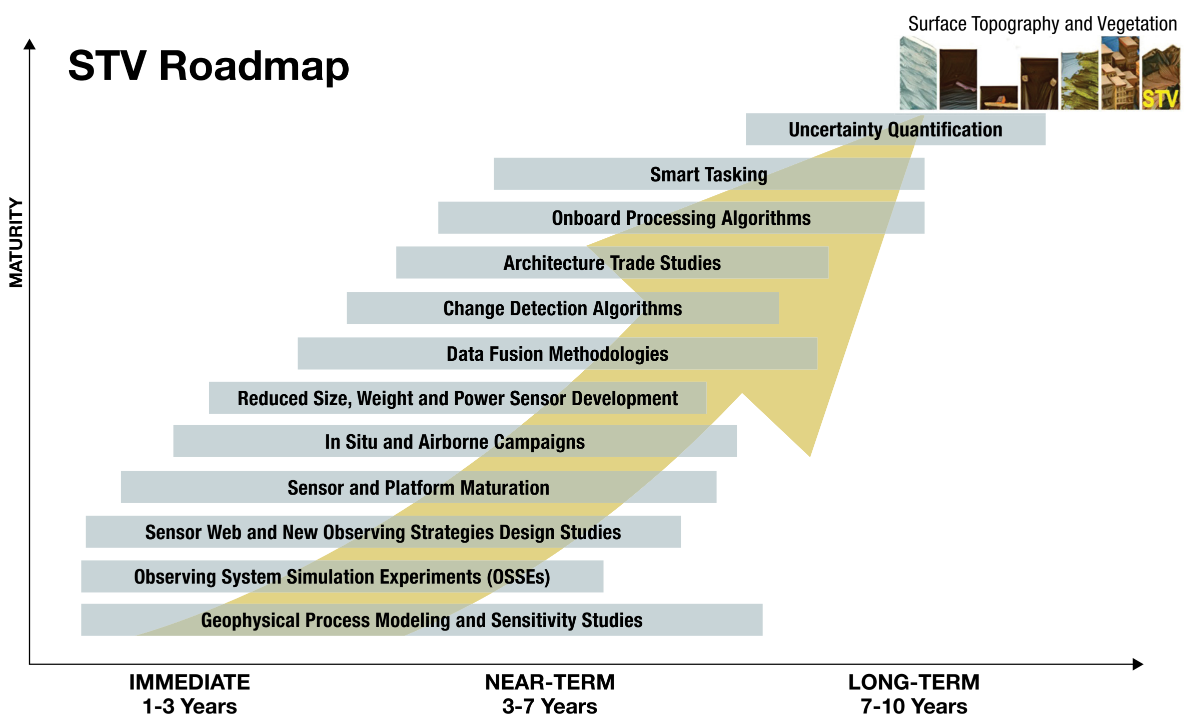
- There are key knowledge gaps common to the science disciplines (Section 5.2) that involve understanding the dependence of geophysical information quality on measurement performance and algorithm maturity. Gap-filling activities included simulations (OSSEs) or sensitivity analyses.
- Technology gaps common to sensors and information systems (Section 5.3) include uncertainty in how to achieve or assess required measurement performance that is necessary to yield products of the needed quality. Gap-filling activities included airborne campaigns, with simultaneous, multi-sensor data acquisitions (with e.g., lidar, interferometric SAR, and stereophotogrammetry). These campaigns are envisioned to be supported by in situ observations.

Meeting STV science and applications product needs drives the need for maturation of instrument and software technologies to close existing gaps in product availability and technology capability. A flexible and responsive STV system follows the description of NASA's New Observing Strategies (NOS) and Analytic Collaborative Frameworks (ACF). Following a system of systems approach should lead to a more robust STV observational framework that can provide baseline and targeted observations while providing opportunity to extend the observational record by augmenting the constellation or by swapping in new instrument platforms. SmallSats could host lidar, radar, or stereophotogrammetry instruments on single or combined platforms. Suborbital components could be used to target regions of interest and add increased temporal sampling; these could include high-altitude long duration vehicles, aircraft, and small uncrewed aircraft systems (SUASs). Onboard processing and smart targeting would improve data quality, reduce data volume, and provide enhanced event response.

Next steps for STV should include constructing an SATM based on the preliminary SATM presented here. Justification of the SATM based on simulations and OSSEs would substantiate identified measurement needs. Detailed substantiated justification was outside the scope of this study, but is a necessary next step for STV. Instrument requirements should be explicitly stated and flowed down from the measurement requirements, derived from the needs presented in this study team report. Sensitivity studies and performance models will enable the requirements flow down. Working as a team, the authors of this study team report were able to converge on a set of measurements that could meet various needs of each discipline. Continued development of the STV mission or observing system concept would benefit if STV maturation activities are carried out within the framework of an STV incubation team that works together to achieve STV objectives.

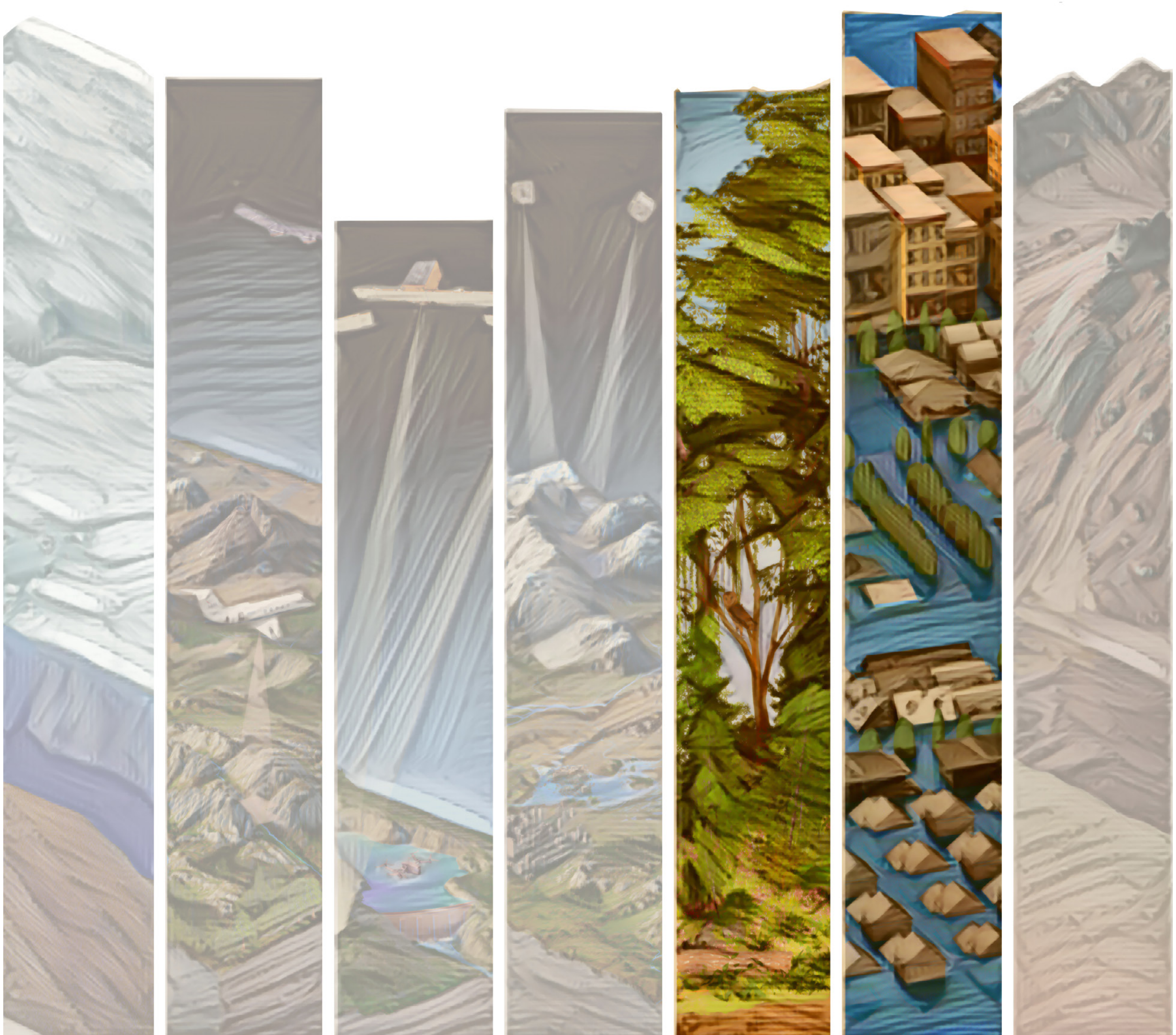
A framework for developing an STV architecture within the next decade includes integrated modeling, simulations, technology development, and trade studies. Geophysical process modeling and sensitivity studies and OSSEs will help define an architecture that will meet science and applications objectives and product needs. A preliminary roadmap identifies classes of technology and gap-filling activities needed to develop a surface topography and observational system (Figure 7-2). The incubation study team is confident that the STV roadmap of critical activities will mature technology sufficiently to make STV a feasible DO by 2028. The study clearly demonstrated that a well-architected STV will make complementary, vertical measurements of cryospheric, aquatic and terrestrial systems that will significantly improve our understanding of processes and allow applications with high socio-economic benefit. Architecting this observational system to provide both global and targeted repeat high-resolution STV measurements should be achievable in the next decade.

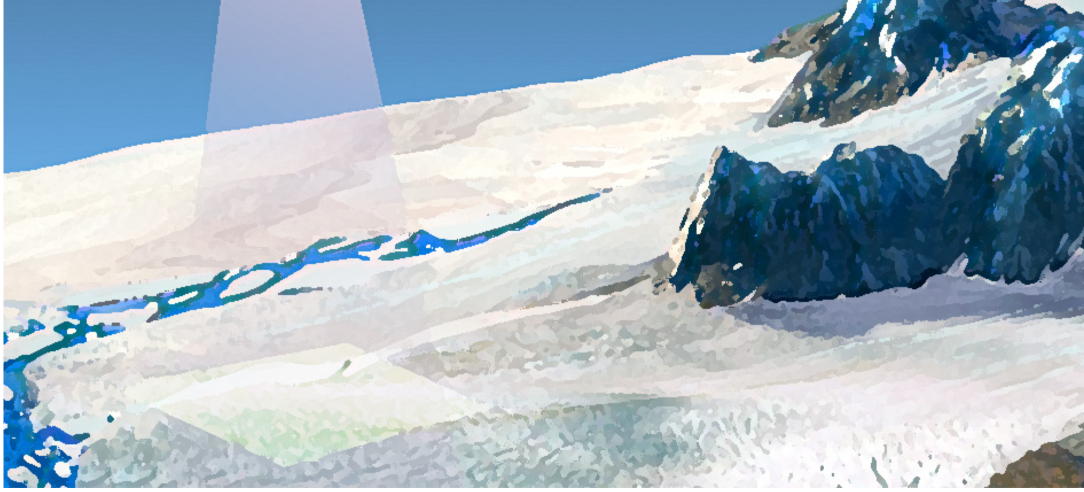
FIGURE 7-2. Preliminary roadmap to mature STV technologies to enable an STV observational system within the next decade.



PART 3

STV EXPANDED DETAIL





CHAPTER 8

SCIENCE DETAIL

8.1 Solid Earth

The DS identified four *most important* solid Earth science and application questions that covered 1) forecasting geological hazards; 2) quantifying geological disasters' impacts on Earth systems and society; 3) determining vertical motion along coastlines; and 4) understanding landscape change processes (Table 8-1). The first two include earthquakes, volcanoes, and landslides and specific topography needs, with topography often presented as providing the basis for observations of change following earthquakes, volcanic eruptions, or landslides. Topography also provides an enabling data set for other techniques, such as InSAR deformation imaging. The desired observation spatial and vertical resolutions vary depending on the specific process. For many processes within Solid Earth, the recommended topography from the DS is 1 m posting with 0.1 m vertical accuracy provided as a gridded product over the processes of interest, globally (DS Table B.2, pp. B-20—B-26). Through further analysis and synthesis of community input the SE subgroup of this STV team reached similar conclusions and recommends 1 m horizontal resolution and 0.2 m vertical accuracy.

One area that is not specifically addressed by the DS for solid Earth processes is repeat topography, although it is often implied. For example, quantifying volcanic hazards following a large eruption implies measuring large changes in topography and pre- and post-event mapping would be essential. Therefore, we have explicitly included time-varying topography in this study team report. Topics with explicit topography time series needs include large volcanic eruptions (Kubanek et al., 2017, 2021), such as the 2018 Kilauea caldera collapse and large lava flows and new land formation (Neal et al., 2019; Lundgren et al., 2019; Anderson et al., 2019; Patrick et al., 2019; Dietterich et al., 2021) whereby topography-derived volume changes are used to constrain dynamic volcano models (Anderson and Poland, 2016; Roman and Lundgren, 2021). In the case of lava flows, the resolution of new flows is exemplified by data at various resolutions from before and after the start of the 2018 Kilauea eruption as shown in Figure 8-1. Landslides exhibit changes in their topography that can vary in rate due to surges (Alberti et al., 2020) that can be related to precipitation (Booth et al., 2020) or changing glacial environments (Bessette-Kirton et al., 2018), which may become catastrophic (Warrick et al., 2019). Large earthquakes disrupt the Earth's surface either through direct surface offsets (Donnellan et al., 2017; Hamling et al., 2017), or secondary processes such as liquefaction and landslides (Kargel et al., 2016), which in turn can cause widespread infrastructure damage. Furthermore, attaining high accuracy vertical land elevation change along coastlines (Wöppelmann and Marcos, 2016), near the 1 mm/y over 10 years given in the DS, will require repeated measurements if each has 0.1-0.2 m vertical accuracy.

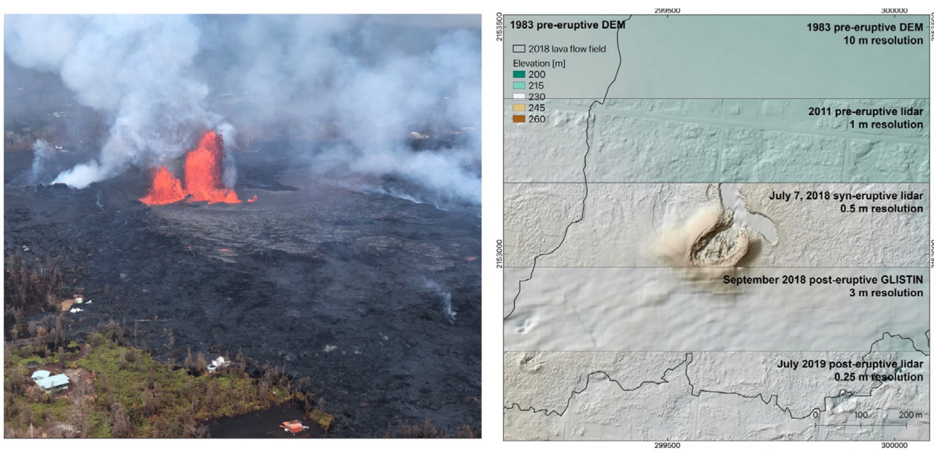
TABLE 8-1. DS objectives related to STV.

DS	Process	Importance	STV observation
S-1 Geological hazards forecasting	Volcano pre-, syn-, and post-eruption surface topography change and products	Lava flow, edifice change for volcano mass balance; eruption deposition products	Surface topography change
	Earthquake pre-, co-, and post-seismic topography and topography change	Fault surface offsets	Surface topography and topo change
	Landslide forecasting and monitoring	Landslide motion	Surface topography change
S-2 Geological disasters	Rapid capture of transient processes following disasters	Sudden Landscape Change	Surface topography change
	Assess extent of change and erupted products following a volcanic eruption	Volcano flows and deposits; erupted volume with time	Surface topography change
	Assess co- and post-seismic ground movement and damage to infrastructure	Location and amount of earthquake-induced ground movement and damage	Surface topography change
S-3 Local sea level change	Determine vertical motion along coastlines	Predict local inundation and storm surge hazards; inform models of sea level rise impact	Surface topography change
S-4 Landscape change	Determine global landscape change due to natural and anthropogenic processes	Tectonic-climate geomorphology, mining and oil/gas extraction ground movement and subsidence	Surface topography change

8.2 Vegetation Structure

The 2017–2027 DS has identified observations of three-dimensional structure of land-based vegetation to provide critical information on ecosystem gross and net primary production, ecological functioning, and carbon storage and changes due to land use and environmental factors. In addition to the obvious linkages between vegetation structure and ecological functions, the changes of structure over time have direct connections to climate through the carbon cycle from loss and gain of vegetation biomass (Houghton et al., 2009), to water cycle from impacts on the evapotranspiration (Longo et al., 2020), and to energy cycles by influencing the surface energy balance (Bastiaanssen et al., 1998). Within the DS, Target Observable (TO-22) Terrestrial Ecosystem Structure is linked to overlapping Goals and Objectives listed below (E-1b, E-3a). Therefore, this study in effect also addressed TO-22 of DS. The DS specifies the requirement for 3D vegetation structure as 1ha cells, with 10-25m footprint size, every 5 years, global coverage (DS Table B-1). The STV study built on these specifications with the objective of capturing forward-looking product needs for vegetation structure that would **significantly improve the understanding of ecosystems,** including carbon stocks and fluxes, and relationships between biodiversity and habitat structure. It should be acknowledged the Vegetation Structure has the most diverse range of science and application objectives; hence the product needs are equally diverse and therefore the SATM for vegetation structure was split into three groups, (i) Global Carbon Cycle, (ii) Ecology and Biodiversity, and (ii) Applications (e.g., agriculture, wildfires, commercial forestry and deforestation monitoring).

FIGURE 8-1. Examples of digital elevation models before and after the start of the 2018 eruption in Kilauea volcano's lower East Rift Zone. (Right) aerial photograph of lava fountaining from Fissure 8, viewed from the SE, photo courtesy the USGS). (Left) slices of topography centered on Fissure 8 (courtesy H. Dietterich, USGS). At this scale (scene is approximately 1 km wide) 1 m or better spatial resolution is required to resolve features, including streets in pre-eruptive bare-earth lidar. The impacts of different resolution levels on volcano models, lava flow prediction, and other hazards will require model-based sensitivity tests.



Courtesy Hannah Dietterich, USGS

Among the most important science and application goals of vegetation 3D structure is its use in evaluating the carbon stock and changes in forests. Globally, forests store about 85% of terrestrial vegetation carbon stocks and their primary production is a major sink of atmospheric carbon. Deforestation and forest degradation account for 12-29% of annual greenhouse gas (GHG) emissions that can be reduced significantly to mitigate climate change by safeguarding and managing forest ecosystems globally. Therefore, accurately estimating forest aboveground biomass (AGB) and its changes through time is key to carbon accounting and developing mitigation policies through global initiatives, such as UN-REDD+, aimed at reducing emissions. Existing regional or global spatial estimates of biomass using remote-sensing observations are based on static sampling of vegetation structure from air and space (Xu et al., 2017; Asner et al., 2013) and do not provide changes of biomass needed for reducing global carbon cycle uncertainties. The science community is urgently in need of remote-sensing techniques that move beyond deforestation mapping and inventory towards accurately monitoring more subtle changes of forest structure and biomass attributed to forest degradation (logging, timber harvesting, environmental disturbance; e.g., Lei et al., 2018) and post-disturbance regrowth. Currently estimates of biomass at the scale of land use activities and disturbance have large uncertainty (Houghton et al., 2009; Saatchi et al., 2011; Mitchard et al., 2013) that introduce significantly larger errors in estimates of carbon emissions (Le Quéré et al., 2018). The uncertainties undermine global initiatives to incentivize the conservation and restoration of forests for climate change mitigation. Current and planned observations from NASA's GEDI and NISAR, and ESA's BIOMASS missions will significantly improve estimates of carbon stocks and changes at large spatial scales (100–10000 ha). However, reducing uncertainties associated with forest biomass changes at the scale of disturbance (0.1-10 ha) remains a challenging problem. Studies are beginning to emerge with ~1 m/y accuracy at ha scales (Askne 2018, Solberg 2014, Treuhaft 2017). STV observations should be designed to address this problem by significantly improving the horizontal and vertical accuracy of vegetation 3D structure and providing the temporal resolution for detecting changes associated with fast processes of large carbon emissions (forest disturbance) and slow processes of small carbon uptakes (forest growth) (Schimel et al., 2015).

STV incubation activities aim to evaluate how existing and future remote sensing technologies can meet the observational needs and address the data gaps of the vegetation 3D structure while significantly reducing uncertainties. The goals and objectives of the science and application communities can be addressed by a set of Vegetation structure products (Table 8-2).

TABLE 8-2. DS goals and objectives linked to vegetation structure and required STV observation.

DS	Process	Importance	STV observation (and derived products)
E-1,1e,3a Ecosystem Structure and Biodiversity	Habitat intactness and fragmentation processes	Biodiversity, animal habitat, shifts in composition, wildfire management,	3D vegetation structure, understory, tree height, changes (habitat diversity across landscape)
	Biogeochemistry (water, carbon, energy) and ecological functions	Ecosystem services, land-atmosphere processes,	3D vegetation structure and changes
	Community demography and dynamics	Ecosystem modeling, allometry, Forestry	3D vegetation structure
E-2,3,4,5 Terrestrial Carbon Cycle and Dynamics	Biomass carbon stocks	GHG inventory carbon accounting, forestry	3D vegetation structure (aboveground biomass [AGB])
	Fast fluxes: emissions from natural and anthropogenic disturbances of biomass	Global carbon cycle, REDD+, climate mitigation	3D vegetation structure and tree-height changes (AGB)
	Slow processes: forest carbon sink dynamics, secondary regeneration,	Global carbon dynamics, climate mitigation, ecosystem restoration	3D Vegetation structure changes, (AGB)
E-1b2, E-1f1, E6, E7, E Forestry and Fire Applications	Forestry, timber harvesting, logging	Predict local sea-level inundation and storm surge hazards	3D forest structure and tree-height changes
	Fire fuel loads accumulation and combustion efficiency	Fire-risk models, early-warning systems, fire-spread models	Tree height, 3D vegetation structure, understory, surface topography
	Water stress, drought, and pathogen tree mortality	Forest management, forest thinning, riparian conservation. Intersection of pests and fire: Water stress, disease, etc. are a part of the fire-risk calculation in many ecosystems.	3D forest structure changes

8.3 Cryosphere

Observations collected as part of any future STV mission will play a critical role in advancing key cryosphere related science questions that have been identified by the DS as being ***Most Important*** and *Very Important* for NASA to make progress on over the next decade and beyond. Specifically, these questions are:

- How much will sea level rise, globally and regionally, over the next decade and beyond, and what will be the role of ice sheets and ocean heat storage? (DS: C-1)
- How will local sea level change along coastlines around the world in the next decade to century? (DS: S-3)
- What will be the consequences of amplified climate change—already observed in the Arctic and projected for Antarctica on global trends of sea level rise, atmospheric circulation, extreme weather events, global ocean circulation, and carbon fluxes? (DS: C-8)

TABLE 8-3. Cryosphere processes and required STV observation

DS	Process	Importance	STV observation
C-1 & S-3	Surface mass balance	Ice sheet mass balance	Ice sheet and glacier elevation change
	Tidewater-glacier mechanics	Controls ice discharge into ocean	Elevation change of outlet glaciers
	Ice shelf and glacier calving	Controls ice discharge into ocean	Ice front geometry and elevation change
	Ice shelf melting by ocean (floating extensions of ice sheets)	Controls ice discharge into ocean	Ice shelf elevation change
	Grounding zone mechanics (where glacier transitions from grounded to floating)	Controls ice discharge into ocean	Elevation changes of grounding zone
	Ice flexure & fracture	Controls ice discharge into ocean	Ice shelf topography and elevation change
C-8	Sea ice thickness	Controls ocean-atmosphere energy exchange	Sea ice freeboard
	Sea ice roughness	Controls sea ice motion	Sea ice topography
	Snow on sea ice	Controls sea ice temperature and albedo & needed to retrieve thickness	Snow thickness

In their most basic form, these questions deal with issues of improving predictability of ice sheet and glacier mass change, and changes in sea ice area. Such improvements will only be achievable through enhanced understanding of atmosphere-ice, and ocean-ice energy exchanges, and of critical internal rate limiting processes. To stay true to the intent of the DS, we emphasized those STV measurement needs that are most relevant to advancing understanding these three areas. These can be can be summarized as topography measurements that help to quantify surface processes related to atmosphere-ice interactions (accumulation, ablation, snow depth, meltwater routing, sea ice thickness and momentum transfer), influence of the ocean on ice mass (sea ice thickness, changes in ice shelf thickness, and grounding zone migration) and ice mechanics (fracture, calving, flexure, grounding zone migration, and basal friction).These processes, along with their importance and required STV observation, are listed in Table 8-3.

8.4 Hydrology

Hydrology (H) is an important topic in the DS with implications for other topics such as Solid Earth, Marine and Terrestrial Ecosystems and Natural Resource Panel. However, the Global Hydrological Cycles and Water Resource panel identified high-resolution precipitation measurements as highest priority, requiring measurements of rainfall, snowfall, and accumulated snow, in order to constrain the key inputs of that analysis. Other water-related variables that are central to the most important hydrological science challenges and to water resource applications include soil moisture, stream flow, lake and reservoir levels, snow cover, glaciers and ice mass, evaporation and transpiration, groundwater, water quality, and water use. It is clear that the STV elevation measurements of water accumulation in lakes, reservoirs and snow packs, and flows through rivers and across wetlands can support the development of an integrated system. Below, we briefly discuss the breadth of these systems to help identify the knowledge gaps and scope of research needed to address those gaps.

Over land, fluxes of water control lateral fluxes of carbon, sediment and pollutants, and therefore require accurate estimates of flows to avoid error propagation into other variables. Three percent (~4.5M km^2) of land surface has been under water between 1984 and 2015 with 2.8M km^2 considered permanently covered with water (Pekel et al., 2016). The total fluxes of water, along with carbon export, from the land surface into the global ocean is not well constrained and if better known would help to close the hydrological and carbon cycle. In addition, high-frequency temporal variations are rarely known, and only measured *in situ* in a few large rivers. As such, constraining spatial and temporal variations in water fluxes across the landscape and to the ocean is needed to close the water cycle. An integrated hydrology system requires knowledge of land and water surface topography to account for lateral fluxes of water across the land surface and the associated fluxes of carbon and sediment. These fluxes vary greatly in both space and time. It should be noted that while the SWOT mission addresses some components of surface hydrology, it does not meet all requirements discussed in this document, and also does not address components such as snow, wetlands and permafrost hydrology.

Snow plays a critical role in hydrology and the water cycle by modulating the delivery of freshwater to streams and reservoirs, providing fresh drinking water to 17% of the global population (Barnett et al., 2005) among other services. Snow area is mainly monitored by satellites (Dietz et al., 2012). Snow cover in the Northern hemisphere occupies 63% of the land surface compared to less than 5% in the Southern hemisphere. Between the arctic and Antarctic, snow covers 36% of land with most (98%) in the Northern Hemisphere (Hammond et al., 2018). The mean maximum snow cover extent is 47.4 km^2 in the northern hemisphere (Estilow et al., 2015). The duration of snow cover increases by about 10 weeks for every 10° latitude northward (Estilow et al., 2015). While the DS identifies snow measurement of snow depth and SWE as priorities, an STV mission could only provide snow depth.

According to the USFWS' National Wetlands Inventory, "wetlands are lands transitional between terrestrial and aquatic systems where the water table is usually at or near the surface or the land is covered by shallow water." For purposes of this classification, wetlands must have one or more of the following three attributes: 1) at least periodically, the land supports predominantly hydrophytes; 2) the substrate is predominantly undrained hydric soil; and 3) the substrate is non-soil and is saturated with water or covered by shallow water at some time during the growing season of each year." A recent inventory estimates wetland cover globally ~12.1M km^2 (Davidson et al., 2017) and other studies summarized by Shengjie et al. (2017) find global extent varies between 0.5 to 29.8M km^2. The discrepancies stem from different wetland definition, spectral mixing of vegetation and water, and seasonal variability. According to latest estimates (Davidson et al., 2017), continental and coastal wetland area account for 92.8% and 7.2% respectively.

The STV mission could significantly benefit permafrost hydrology research to better understand and quantify interconnections between frozen ground and hydrological processes. Permafrost covers ~24% of exposed land surface of the Northern hemisphere (Brown et al., 2002) and exerts a primary control on water fluxes, flow paths and distribution. The subsurface heterogeneity of permafrost landscapes, with varying thaw patterns and rates are difficult to associate to hydrologic change. The active layer (i.e., the lesser of seasonal frost depth and maximum seasonal thaw depth) exerts control on surface and near-surface water storage, drainage, and routing. Thus, permafrost degradation will likely produce large changes in surface and subsurface hydrology, and impact ecosystem dynamics (Walvoord & Kurylyk, 2016). Process assemblage specific to permafrost hydrology include (1) unconfined groundwater surface dynamics related to the active layer development; (2) water migration in the soil matrix, driven by phase transitions in the freezing active layer; and (3) transient water storage in both surface and subsurface compartments, redistributing runoff on various time scales (Tananaev et al., 2020).

The DS panel concluded that (1) couplings between water and energy are central to understanding water and energy balances on river basin scales; (2) evapotranspiration (ET) is a net result of coupled processes; (3) precipitation and surface water information is needed on increasingly finer spatial and temporal scales; and (4) the consequences of changes in the hydrologic cycle will have significant impact on the Earth population and environment. These conclusions led the panel to identify four priority societal and scientific goals associated with the hydrologic cycle: Coupling the Water and Energy Cycles; Prediction of Changes; Availability of Freshwater and Coupling with Biogeochemical Cycles; and Hazards, Extremes, and Sea-Level Rise. Of the 13 science and applications questions identified by the Global Hydrological and Water Resources panel, 4 objectives were deemed "Most important," and 5 were associated with the STV observable.

Specific hydrology goals are deemed "most important," in particular for questions related to 1) water cycle acceleration and 2) impact of land use changes on water and energy cycles. Other Ecosystems Panel priorities highlight observing key underlying carbon cycle dynamics, including the factors governing primary production by plants and phytoplankton and the connection of carbon fluxes to water, energy, and nutrient cycles. It is also a topic with societal relevance, addressing issues related to Food Security, Human Health, Markets for ecosystem services, Environmental protection and conservation, Extreme events and hazard prediction and response, Urbanization and other demographic change, and Improved weather prediction (Table 4.1 of DS).

The STV mission can provide versatile measurements that could greatly benefit several components of hydrology. To appreciate its potential, the STV-hydrology subgroup produced a set of objectives summarizing science and application goals and questions from the hydrologic science community, expressed in the DS, international community workshops (Bloschl et al., 2019) and the STV-hydrology workshop.

The DS identified four scientific and societal goals associated with the hydrologic cycle:

1. **Coupling the water and energy cycles:** How is the water cycle changing? Are changes in evapotranspiration and precipitation accelerating, with greater rates of evapotranspiration and thereby precipitation, and how are these changes expressed in the space-time distribution of rainfall, snowfall, evapotranspiration, and the frequency and magnitude of extremes such as droughts and floods?
2. **Prediction of changes:** How do anthropogenic changes in climate, land use, water use, and water storage interact and modify the water and energy cycles locally, regionally and globally and what are the short- and long-term consequences?
3. **Availability of freshwater and coupling with biogeochemical cycles:** How do changes in the water cycle impact local and regional freshwater availability, alter the biotic life of streams, and affect ecosystems and the services these provide?
4. **Hazards, Extremes, and Sea Level Rise:** How does the water cycle interact with other Earth System processes to change the predictability and impacts of hazardous events and hazard-chains (e.g., floods, wildfires, landslides, coastal loss, subsidence, droughts, human health, and ecosystem health), and how do we improve preparedness and mitigation of water-related extreme events?

The DS emphasizes that both natural variability and anthropogenic influences control hydrological, biogeochemical cycles, and the energy cycle.

Considering the DS and broader hydrological science community, we elaborated the goals and objectives in Table 8-4 and the needed products in Table 8-5. These are represented in the SATM. Applications' goals, objectives, and needed products related to the Hydrology goals are listed in Table 8-6.

TABLE 8-4. Goals and objectives serving the interests of the hydrological science community.

Goal	Objectives	STV Observable
How is the water cycle and fresh water availability changing with climate change, land cover change and water diversion structures?	Develop and evaluate an integrated Earth system analysis with sufficient observational input to accurately quantify the components of the water and energy cycles and their interactions, and to close the water balance from headwater catchments to continental-scale river basins.	Surface topo Bathymetry Veg. structure Snow depth
	Quantify the impact of land cover change, modification and soil disturbances on water, carbon, sediment, and energy fluxes at/below/above the land surface.	Surface topo Bathymetry
	Quantify rates of snow accumulation, snowmelt, ice melt, and sublimation from snow and ice worldwide.	Surface topo Bathymetry Snow depth
	Quantify lake and reservoir water balances, and their responses to climate extremes and human activities?	Surface topo Bathymetry
How do changes in the water cycle impact local and regional freshwater availability affect biogeochemical processes, ecosystems, and the services these provide?	Quantify lake and reservoir water balances, and their responses to climate extremes and human activities?	Surface topo Bathymetry
	Quantify the flows of energy, water, carbon, nutrients, etc., sustaining the life cycle of terrestrial and marine ecosystems (e.g., wetlands) and partitioning into functional types.	Surface topo Bathymetry Veg. structure
	Quantify how changes in land use, land cover, and water use related to agricultural activities, food production, and forest management affect water quantity and quality of above and below groundwater.	Surface topo Bathymetry Veg. structure
	Quantify rates of snow accumulation, snowmelt, ice melt, from snow and ice within catchments.	Surface topo Snow depth
How does the water cycle interact with other Earth System processes to change the predictability and impacts of hazardous events and hazard-chains?	Develop and evaluate an integrated Earth system analysis with sufficient observational input to accurately quantify the components of the water and energy cycles and their interactions, and to close the water balance from headwater catchments to continental-scale river basins.	Surface topo Bathymetry Veg. structure Snow depth
How will cold region runoff, surface water bodies and groundwater respond to climate change and permafrost thaw?	Develop and evaluate an integrated Earth system analysis with sufficient observational input to accurately quantify the components (e.g., temperature, snow, surface water, vegetation structure, hydrologic connectivity), of the water and energy cycles and their interactions.	Surface topo Bathymetry Veg. structure Snow depth

TABLE 8-5. Needed STV Hydrology Products.

Geophysical Measurements	STV Products	Resolution (m)	Vertical Accuracy (m)	Repeat/Duration
River flows	Shallow bathymetry DTM	1	0.1	1 y/5 y
	Water surface height DSM	1	0.1	1 d/4 y
	Bank height continuous	1	0.1	1 y/5 y
Water volume in lakes and reservoirs	Water surface height DSM	1	0.1	1 m/5 y
	Shallow bathymetry DTM	1	0.1	1 y/5 y
Measure changes in hydrological framework of Permafrost	Veg Structure Height	30	1	1 y/5 y
	Topography DTM and change	10	0.1	10 d/4 y
	Shallow bathymetry DTM	10	0.1	1 y/5 y
	Snow depth (DSM-DTM)	10	0.1	1 y/5 y
	Water surface elevation DSM	1	0.2	10 d/4 y
Flow and hydroperiod in Wetlands	Water surface height DSM	10	0.1	7 d/5 y
	Shallow bathymetry DSM	5	0.1	1 y/5 y
	Vegetation structure Height + profile	10	0.5	1 m/5 y
Snow packs	Snow depth DSM-DTM	100	1	1 y/5 y
Watershed/basin flows	Topography DTM	3	1	1 y/5 y
Flood Plain Topography	Topography DTM	5	0.25	1 y/5 y

TABLE 8-6. **Applications in Hydrology**

HYDROLOGY APPLICATIONS		
Goals	Objectives	Targeted Observable(s)
Flood Disaster Response	Map floodwater extent	Surface topo and bathy
	Map the change in water level in forested and urban areas	Surface topo (& change)
Flood forecast	Forecast the flood pathway and extent from surface water runoff	Surface topo Veg Structure
	Measure the change in snow water and forecast the future snow melt	Surface topo change
Hydrological connectivity	Map runoff pathways	Surface topo
	Map channel networks	Surface topo
Water resource management	Measure changes in aquifer (below ground) and lake/reservoir (above ground) storage, and recharge, both natural and anthropogenic	Surface topo change
	Measure water stored in snow (snow extent and SWE)	Surface topo
Permafrost	Map permafrost location and extent.	Surface topo
	Map permafrost active layer thickness	Surface topo change

The DS elucidated several very important geophysical factors of the hydrological cycle: surface topography, underground water and lateral flows of water. While surface topography was not identified as a required geophysical parameter to support hydrology, ground topography remains a critical measurement to determine direction of flows, overflows, and spatial and temporal inundation patterns to quantify ecological and biochemical processes. Underground water resources as well as permafrost hydrology, on the other hand, are discussed in terms of the use of radar interferometry (TO-19 Surface deformation and change), rather than scientific value. Similarly, the flow of water in rivers, lakes and reservoirs, measured as water surface elevation, are associated with the program of record from the Surface Water and Ocean Topography (SWOT) mission or to the unallocated TO-21 (Surface Water Height). A part of the Target Observables identified by the DS Committee (DS Table 3.3) were not specifically allocated to a flight program. The SWOT mission, currently under development by NASA and CNES, with an expected launch of 2022, is expected to provide the first simultaneous, two dimensional measurements of water surface elevation and inundation extent in rivers, lakes, many wetlands, and oceans around the world (Biancamaria et al., 2016). Unlike legacy nadir altimeters such as the Jason series, it is designed to measure the submesoscale vertical and horizontal surface ocean structures required to understand the movement of water in coastal ocean environments. However, SWOT will measure variations in water surface elevations only in large rivers (>100 m) and in lakes and reservoirs larger than 250m by 250m. Moreover, SWOT is a 3-year mission operating between 2022 and 2025 with no planned follow-on mission. We believe that in addition to addressing more hydrological components, the STV may alleviate the loss of water surface elevation measurements or at least complement a follow-on SWOT mission and nadir altimeters with the accuracy required to achieve our objectives (Table 8-4.). Therefore, we explicitly include SWH in the STV observables.

The DS states that characterizing surface topography with contiguous measurements at 5 m spatial resolution and 0.1 m vertical resolution will allow for detailed understanding of geologic structure and geomorphological processes, which in turn can provide new insights into surface water flow, the implications of sea-level rise and storm surge in coastal areas, the depth of off-shore water in near coastal areas, and more. The solid Earth community expressed the goal of reaching 1 m spacing at 0.1 m vertical precision (the common standard in airborne lidar surveys) from space.

8.5 Coastal Processes

A future STV mission has the capability to simultaneously address several key science questions related to coastal processes (CP), including those highlighted by the DS (Table 8-7). Shallow-water bathymetry is the primary STV observation that is needed to address the identified CP science questions. However, since studies of inundation, coastal erosion and coastal vulnerability require continuous data across the land-water interface, bathymetric data alone are insufficient: adjacent land topography is needed to generate contiguous, gap-free topobathymetric models spanning the coastal zone. In addition, addressing many of the science questions will also require measurement of vegetation (e.g., mangroves and submerged aquatic vegetation). It is also important to note that single-epoch measurements of the targeted observables (shallow bathymetry, vegetation, and coastal topography) are generally inadequate to address the identified science needs: time series are needed to assess and model change over time and to make predictions of inundation due to storm surge and sea level rise, benthic habitat change, and coastal erosion.

Although there are a number of science applications that require bathymetric data for entire continental margins (e.g., study of submarine landslides on continental slopes), nearly all of the coastal processes data needs identified by this study can be satisfied by bathymetric data covering the region from the shoreline to the 20-m depth contour. Fortunately, this coincides fairly well with the region for which satellite-based bathymetric measurements are feasible in clear waters. Bathymetric measurement from spaceborne sensors, whether active or passive, is generally limited to ~1-1.5 Secchi depths (Gao, 2009; Jégat et al., 2016; Parrish et al., 2019), where 1 Secchi depth is the depth at which a 30-cm diameter white disk, lowered into the water column, ceases to be visible from the surface (Seafarers et al., 2017). However, for turbid to moderately-clear waters, there continues to exist a gap between the maximum observable depths and the 20-m depth contour. To address this, further studies (e.g., OSSEs and field campaigns) are needed to investigate the ability to satisfy the 0–20 m bathymetric requirement in more turbid regions. Of particular interest will be studies of fusion of active and passive sensor data to improve coverage and accuracy of bathymetry over this depth range, as well as integration of spaceborne, airborne, and in situ measurements.

An additional finding from the STV incubation study was the need for robust total propagated uncertainty (TPU) estimates to accompany all bathymetric measurements. Because of the complete lack of nearshore bathymetry in many regions around the world, scientists are often willing to accept data with a range of quality levels (e.g., spatial accuracies and resolutions). However, to meaningfully compare and/or merge bathymetric data from a range of sources and with a range of quality levels, we must have accompanying uncertainty data for each bathymetric data set. Additionally, we need uncertainties to evaluate the suitability of various bathymetric data sets for a range of science and application needs. Because empirical accuracy assessments (comparisons against independent reference data of higher accuracy) are generally infeasible for submerged regions, we need statistical methods to compute propagated uncertainty, based on uncertainties in the raw measurements and models used to generate the bathymetry.

Table 8-7. Coastal processes objectives related to STV.

DS	Goals	Objectives	STV Observation
S-1 Geological hazards forecasting	(S-1) How can large-scale geological hazards be accurately forecast in a socially relevant timeframe?	(S-1d) Forecast, model, and measure tsunami generation, propagation, and run-up for major seafloor events. Map the change in water level in forested and urban areas	Shallow bathymetry Vegetation (mangroves & submerged aquatic veg) Land topography
E-1 Ecosystem Change	What are the structure, function, and biodiversity of Earth's ecosystems, and how and why are they changing in time and space?	(STV) What are current and predicted threats to marine ecosystems and coastal/benthic habitats (e.g., coral reef, saltmarsh, mangroves, seagrass, oyster reefs, etc.)?	Shallow bathymetry Vegetation (mangroves & submerged aquatic veg) Land topography
C-8i Consequence of amplified polar climate change on Earth system	Quantify how increased fetch, sea level rise and permafrost thaw increase vulnerability of coastal communities to increased coastal inundation and erosion as winds and storms intensify.	A) How will coasts change by rising seas, erosion, subsidence, accretion, and anthropogenic influences? B) What are the predicted impacts of coastal storms and surge on coasts? C) What are the processes that drive and the predicted impacts of sediment transport, erosion, and deposition?	Shallow bathymetry Vegetation (mangroves & submerged aquatic veg) Land topography
N/A	Support safety of marine navigation in nearshore areas	Where are shoals, reefs and other hazards to marine navigation, and how are they changing with time?	Shallow bathymetry

8.6 Additional Applications

STV can serve a number of applications beyond those described in the disciplines above.

8.6.1 Additional Applications Objectives

Here we describe the objectives for additional applications beyond those described in the previous sections.

8.6.1.1 Floods

A-1. Floods: Provide information to forecast and respond to major flood events.

A-1.a. What are the current flood conditions and how are they expected to change in the near term?

Objectives are to provide timely information for flood response.

A-1.b. What is the flood forecast for the upcoming flood season?

Objectives are to provide information needed to forecast river discharge and water surface elevation on the timescale of days to months. Factors relevant to STV are surface water level in rivers and streams; snow conditions, specifically snow depth and change in snow depth; permafrost melt; ice topography and melt (e.g., flooding from ice jams, glacial outbursts), and surface water flow paths.

8.6.1.2 Subsidence and Coastal Processes

A-1.c. How is subsidence and coastal processes (sediment deposition, erosion, loss of wetlands) impacting flood risk, egress routes, and other factors of societal importance?

Objectives are to provide information needed to prepare for evaluation during flood events and to account and mitigate impact through policy, e.g., zoning, building codes, location of hospitals and schools, flood insurance, etc.

8.6.1.3 Wildfires

A-2. Wildfire: Provide information to inform near- and long-term decisions to reduce the risk, occurrence, and societal impact of wildfires.

A-2.a. What is the current fire risk, where is the fire perimeter, and in what direction is the fire likely to spread?

Objectives are to provide timely information for wildfire risk to enable preparedness and response. STV information of topography, biomass, and vegetation structure all contribute to calculating fire risk, along with other parameters, e.g., weather conditions and fuel moisture content. Subcanopy 3D vegetation structure information is essential to estimate debris, ladder fuels (Kramer et al., 2016), fuel loads and types, which all determine risk of ignition and initial rate of spread [Add reference]. During pre- and post-fire periods, information about fire risk and fire perimeter are used to plan activities that reduce risk, e.g., placing fire breaks.

A-2.b What is the burn severity and where are the areas at risk of post-fire debris flow?

As for 2.a, STV information is not sufficient to determine burn severity and debris flow risk, but topography, biomass, and vegetation structure products all contribute to identifying areas to target for additional measurements. Before-to-after-wildfire topographic change can help determine debris depth and run-out pathways.

A-2.c. How does vegetation structure relate to fire risk?

The objectives are to understand the relationship between forest type and fire risk by determining how subcanopy structure (<10m) as a function of fuel type and condition relates to fire risk and spread.

A-2.d. How does fire and fire regime impact regeneration and biomass in different biomes?

The objectives are to determine 1) the long-term impact of fire regime on forest biomass and vertical structure, and 2) whether the fire regime is changing at the regional scale and if so, how.

8.6.1.4 Cascading hazards

A-3. Provide information to inform decisions related to geological hazards and industrial accidents. (Note: some specific hazards related to DS goals are in the Solid Earth SATM and included in Section 3.2.)

A-3.a. Where and to what extent has the event caused damage with significant societal impact?

All phases of the disaster management cycle require information pertaining to geological and related hazards presented in the Solid Earth section, e.g., earthquakes, volcanic eruption, landslides, sinkholes, mine collapse, etc.

A-3.b. What are the interrelationships between geological, hydrological and coastal processes that lead to cascading hazards and where are they at most risk of occurring?

Information is needed on the processes and probability of cascading hazards, e.g., earthquake-triggered landslides or subsidence and sea level rise contributing to more frequent catastrophic sinkhole collapse. The objectives are 1) to use STV information and models to understand the interactions between natural hazards with different driving processes, and 2) based on the models identify locations at risk of triggered events.

8.6.1.5 Critical Infrastructure

A-4. Critical infrastructure monitoring: How are critical infrastructure and their environs changing?

Objectives are to monitor surface conditions of the structures and their environs relevant to hazard assessment. Critical infrastructure, defined broadly, encompass structures supporting many sectors (e.g., energy, transportation, natural resources, etc.) located on land or at sea. Situational awareness data are needed to assess current conditions and forecast future conditions based upon how the structures and environs are changing. The area over which data is needed depends upon the relevant hazard and the scale of the structure. For example., non-local sea ice and iceberg location and drift is needed for rigs in the Arctic to give time to move the structure; flood extent informs operations at a nuclear power plant or planned evacuation routes; proximity to trees informs maintenance near power lines; and surface elevation informs repair of levees that can fail or be overtopped.

8.6.1.6 Agriculture and Commercial Forestry

A-5. Agriculture: How does crop health and productivity relate to vegetation structure and topography, and how can better estimates of current and forecasted yield and risk be made based on that information?

Objectives pertain to both field level information and regional information. At the field level, time series information needed is 1) crop yield/biomass and 2) growth stage during the crop season. At the regional level, the same information is needed to 1) assess and forecast risk of crop loss, e.g., from disease or drought, 2) assess changes in crop yield, and 3) determine where cultivation is taking place and more generally how crop productivity is related to topographic position.

A-6. Commercial forestry: What is the composition and status of natural and agroforest systems used for commercial forestry and how are they best monitored to effectively manage forest products and ecosystems services?

Commercial forestry is a diverse industry with forest stocks managed for harvest and conversion to other uses, plantations that are harvested and replanted and private owned woodlands that are subject to a variety of management practices. In general, foresters, scientists and policy makers need information to track forest area and change to answer the following questions.

1. What are the growth and removal rates of forests?
2. What is the areal coverage and change of commercial forests?
3. How does forest health and productivity relate to vegetation structure and topography, and how can better estimates of GPP be made based on that information?
4. Which areas are logged and when were they logged?
5. Where is conversion of primary forests to silvicultural production areas occurring (e.g., palm oil)?
6. How are agroforestry systems distinguished from natural forest systems?

A-7. Deforestation: Provide information for operational deforestation monitoring and alerting.

In many parts of the world, monitoring deforestation is not only about carbon accounting and reducing carbon emissions, but involves law enforcement to curb illegal logging and “land grabs.” Systems for continuous deforestation monitoring and near real-time alerting must rapidly identify areal extent of forest height changes in tropical environments with near-constant cloud cover. Deforestation information for other uses, e.g., REDD+ and emissions estimation from land cover change, have the less stringent latency requirements, but need accurate aboveground biomass change information that can also quantify regrowth and forest degradation.

A-8. Maritime navigation, ice hazards: Where and when is marine ice endangering maritime transportation routes?

The objectives are to provide situational awareness data for current conditions and to initiate models predicting where ice is located or forming, its size/thickness, and the drift path.

A-9. Coastal resiliency: What is the efficacy and consequences of RSLR mitigation activities that aim to improve coastal resiliency?

Many communities are planning and undertaking activities to mitigate the impact of climate change. Projects range from engineered solutions, e.g., sea walls, leveeing, and sediment redistribution, to green or blue infrastructure that uses the natural environment to retain or build land or decrease flooding. The objective for STV is to determine through measurement how the restoration or remediation activity is both performing the intended function (e.g., reducing flooding) and altering the environment through inter-related processes (e.g., leveeing causes reduced salinity, which leads to changes in vegetation type and health, which in turn alters sediment retention and organic deposition, potentially leading to land loss). Studies need to monitor surface elevation, both on land and below water, vegetation status, hydrological connectivity, and continuous and intermittent (e.g., tidal) surface water level starting before remediation measures are initiated and continuing for years to decades thereafter.

8.6.2 Applications Measurement Needs

Measurements needed for applications encompass all STV observables of topography, vegetation structure, bathymetry, and snow depth. Table 8-7 summarizes the products by Additional Application goal/objective and specifies spatial and temporal measurement needs not met by those provided for SE, C, H, and CP. The paragraphs below summarize need measurements and derived products and the general reasoning behind the specified driving needs.

8.6.2.1 A-1. Floods

A-1.a. What are the current flood conditions and how are they expected to change in the near term?

Products of use are surface water height, topography (DTM and DSM) maps, and bathymetry. Timeliness, ideally on the scale of hours but potentially useful with several day delay, is the primary driving requirement. Surface topography with sufficient horizontal resolution to map the height of flood protection infrastructure (1-10 m) is needed.

A-1.b. What is the flood forecast for the upcoming flood season?

Products of use are topography (land and ice) and snow depth. Driving requirements are measurement repeat frequency (TBD) and latency (TBD) to update the forecast models.

A-1.c. How is subsidence and coastal processes (sediment deposition, erosion, loss of wetlands) impacting flood risk, egress routes, and other factors of societal importance?

Relevant products are time series of land topography and, in some areas, bathymetry and vegetation structure (e.g., wetland conditions).

8.6.2.2 A-2. Wildfire

A-2.a. What is the current fire risk, where is the fire perimeter, and in what direction is the fire likely to spread?

Measurements needed are topography and vegetation structure, and derived subcanopy 3D vegetation structure and biomass. Timeliness of information, i.e., daily updates, drive requirements only during periods of high fire risk and fire response.

A-2.b What is the burn severity and where are the areas at risk of post-fire debris flow?

Measurements needed are topography and vegetation structure, derived subcanopy 3D vegetation structure and biomass, and change in structure and biomass. Low latency information is not needed unless a major storm closely follows the fire. However, delivery of information within 1-2 weeks of the fire is desired to direct ground crews.

A-2.c. How does vegetation structure relate to fire risk? and how does fire and fire regime impact regeneration and biomass in different ecosystems?

The measurement needed is vegetation structure. Spatial and temporal needs are consistent with those specified for Ecological and Biodiversity Habitat.

A-2.d. How does fire and fire regime impact regeneration and biomass in different biomes?

The measurement needed is vegetation structure. Spatial and temporal needs are consistent with those specified for Ecological and Biodiversity Habitat.

8.6.2.3 A-3. Geological hazards and industrial accidents

A-3.a. Where and to what extent has the event caused damage with significant societal impact?

The Solid Earth products provide information suitable for end-users except in the case of emergency response when timeliness is key. For disasters in which people are trapped in rubble or cavities, which is often the case for geological and industrial disasters, information is needed ideally within hours of the event and always within 3 days to reduce loss of life.

A-3.b. What are the interrelationships between geological, hydrological and coastal processes that lead to cascading hazards and where are they at most risk of occurring?

Measurements needed are topography, but for specific triggers may include bathymetry and vegetation structure.

8.6.2.4 A-4. Critical infrastructure monitoring

Products needed are topography, including the DSM to monitor the structure, and in some cases surface water extent and surrounding vegetation structure. The spatial scale of the structures drives measurement horizontal resolution needs. Large scale structures (dams, bridges, major roads, seawalls, industrial facilities, major power infrastructure, large levees and aqueducts) fall into one category and are most important to monitor, but many smaller scale structures (buildings, pipelines, smaller roads and levees) monitored by agencies can be added given better horizontal resolution. Other needs are driven by the DSM, with vertical change accuracy of 0.1 m/y (th) / 0.01 m/y (asp) and rate of change accuracy of 0.01 cm/y (0.1) being the driving requirements. In general, very low latency information is not required for situational awareness, but information must be available over an extended period to measure trends: latency 60 d (th) / 14 d (asp); repeat frequency 90 d (th) / 15 d (asp); and repeat duration as long as reasonably possible because operational agencies require a reliable data source. For rapidly developing hazards, which are not considered here, timeliness of information becomes more critical (see A-1,2,3 and SE S-2 objectives).

8.6.2.5 A-5. Agriculture

Products needed are bare earth topography and vegetation structure. Time series are needed for the vegetation structure. The driving requirement is information timeliness during the growing season, with weekly updates desired.

A-6. Commercial forestry: What is the composition and status of natural and agroforest systems used for commercial forestry and how are they best monitored to effectively manage forest products and ecosystems services?

Products: Forest structure related needs that could be filled by STV include

1. Forest change—areal extent, forest vertical profile, DSM or CHM over time
2. Forest height—3D vertical profile, DTM, CHM
3. Forest productivity—change in height and coverage over specified time intervals, site index information

8.6.2.6 A-7. Deforestation

Product needed is vegetation structure change. It does not require highly accurate height or biomass estimates or high resolution to allow rapid monitoring of disturbance, such as illegal logging in conservation areas. Systems for continuous deforestation monitoring and near real-time alerting require wide coverage, very frequent revisit cycles (3–10 days) and short latencies (<1 day). The actual magnitude of biomass change will be estimated less frequently for aggregated periods (e.g., 90 to 365 days).

8.6.2.7 A-8. Maritime navigation, ice hazards

Measurement needed is topography, specifically of sea ice, and water surface elevation, but only during specific times and locations (ice likely to enter trade routes).

8.6.2.8 A-9. Coastal resiliency

Measurements needed are time series of topography, including water surface level, bathymetry and vegetation structure. Although some indicators of activities to improve resiliency will be apparent within a year, the long-term impact and cascading effects are not evident for years. The driving requirement is repeat duration to resolve causal trends from natural variability, so studies ideally would be ongoing for a decade or more.

8.7 Measurement needs to accomplish STV objectives

In Part I we summarize the measurement needs to accomplish STV science and applications objectives. Here we further break them down by discipline and general observing platform needs (Figure 8-2) and needs related to the instrument (Figure 8-3).

TABLE 8-7. **Additional Application STV goal/objective and associated STV measurements. If the measurement needs are not commensurate with needs of the science disciplines (Sections 3.2—3.6) then the application-specific driving requirement(s) are given in the third column. If two numbers are given, the value in parentheses is the threshold.**

Goal/Objective	STV Measurements	Driving Requirements
Flood, disaster response (A-1.a)	Topography (T), bathymetry (B)	T: repeat frequency of 1 (3) day during event, latency of 1 (3) day
Flood, near-to-mid-term forecast (A-1.b)	Topography, snow depth (S)	T, S: Repeat frequency of 7 (14) days, latency of 3 (14) day
Flood risk, long-term forecast (A-1.c)	Topography, bathymetry, vegetation structure	
Wildfire, disaster response (A-2.a)	Topography, vegetation structure (V)	V: Repeat frequency of 1 (3) day during fire, latency of 1 (3) day
Wildfire, post-fire (A-2b)	Topography, vegetation structure	V: Repeat frequency of 7 (30) days, latency of 7 (14) days
Wildfire, long-term preparedness (A-2c,d)	Vegetation structure	
Other disaster/hazards, response (A-3a)	Topography	T: repeat frequency of 1 (7) day during response, latency of 1 (3) day
Cascading hazards (A-3b)	Topography, bathymetry, vegetation structure	
Critical infrastructure monitoring (A-4)	Topography, bathymetry, vegetation structure	T: vertical accuracy 0.05 (0.2 m), vertical velocity accuracy 0.01 (0.1) m/y
Agriculture (A-5)	Topography, vegetation structure	V: repeat frequency 5 (14) days, latency of 7 (14) days
Commercial forestry (A-6)	Vegetation structure	
Deforestation (A-7)	Vegetation structure	V: repeat frequency 3 (10) day, latency 3 (5) days
Maritime navigation (A-8)	Topography	T: repeat frequency 1 (7) day, latency 1 (3) day
Coastal resiliency efforts (A-9)	Topography, bathymetry, vegetation structure	All: repeat duration 10+ (3) years

FIGURE 8-2. Observing platform needs based on synthesis of community input and STV team study activity. Blue bars show aspirational need and red bars threshold needs. Median value for each is noted.

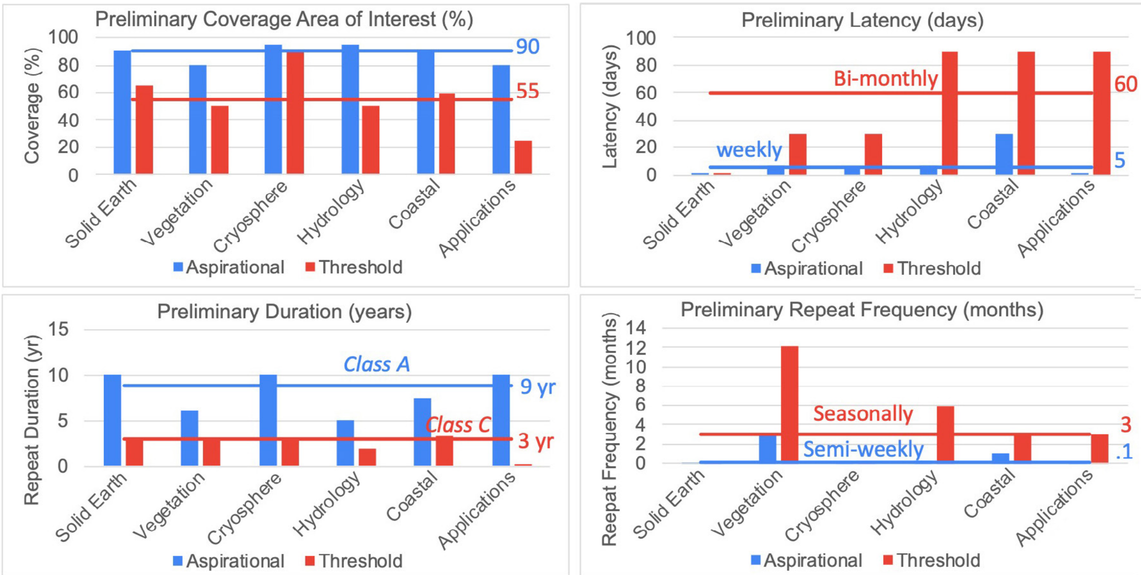
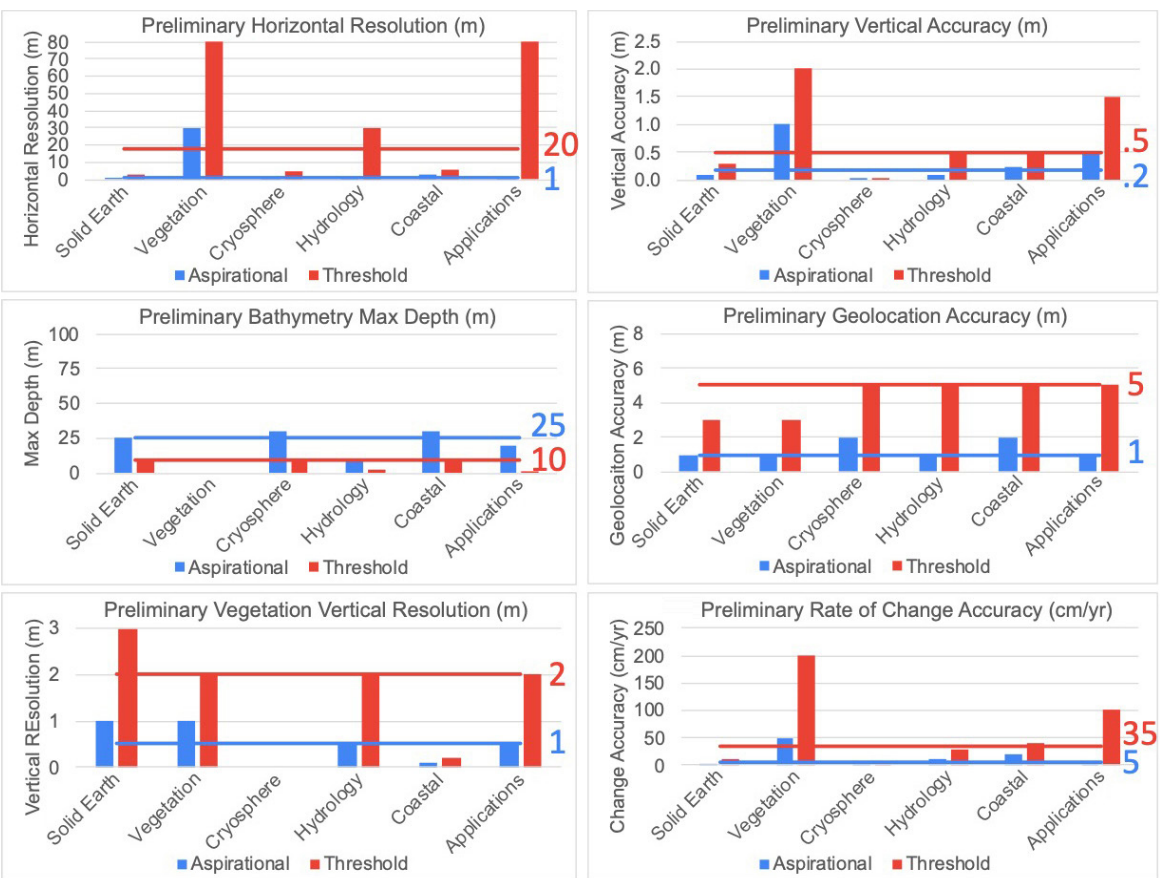


FIGURE 8-3. Instrument needs. For the resolution blue bars show aspirational needs and red threshold. Bars show median values across the disciplines with values noted.



CHAPTER 9

CURRENT AND EMERGING SENSORS

9.1 Introduction

Here we provide background information on the sensor measurement approaches and current and capabilities for lidar, radar, and stereophotogrammetry.

9.2 Current Lidar Sensors, Platforms and Existing Data

Lidar technology is a system of components that work together to provide three-dimensional information about the targets the laser interacts with. These components include:

- Laser
- Detector
- INS/IMU (orientation)
- GPS/GNSS/Other (position)
- Scanning mirror/beam splitter (for swath-based systems)

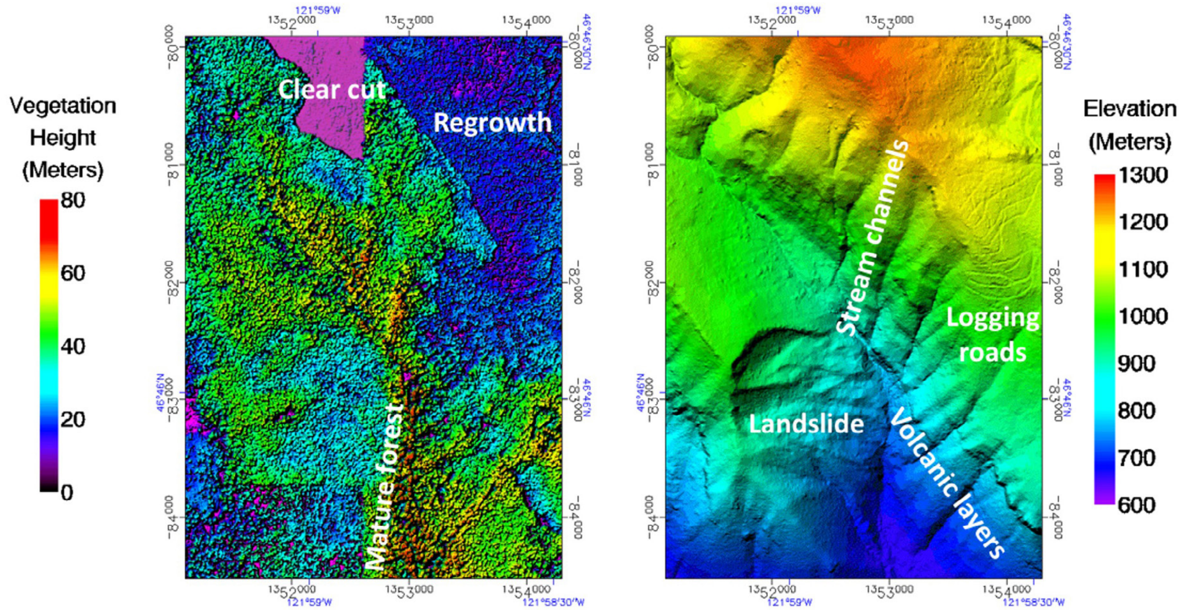
Laser wavelengths used can vary, but most lasers for airborne systems are at 532, 1064, or 1550 nm wavelengths, and spaceflight systems have been at 532 or 1064nm. 532nm systems have the ability to penetrate water and measure water depths, typically up to 40–70 m depth through very clear water but decreasing in maximum detectable depth as water column turbidity increases.

Detectors are typically avalanche photodiodes (APDs), or photomultiplier tubes (PMTs). Detectors can be single detector systems, or arrays of detectors. Detectors can digitize the complete waveform of energy returned, trigger recordings after a certain threshold had been reached (discrete return), be single-photon sensitive where a recording is triggered after a single photon hits the detector, or counting photons above a certain threshold per pulse that sums to build a waveform.

9.2.1 Airborne Lidar Systems

Airborne lidar instrumentation that acquires altimetry measurements of land, snow and ice elevations, vegetation height and structure, and shallow water bathymetry consist of commercial systems and research and development systems. Over the last 20 years a robust commercial lidar mapping industry has developed, leveraging technologies originally demonstrated by NASA. Most commercial lidar instruments are deployed via aircraft flying between 1,000 and 6,000 m above ground level (AGL). Because of the low to moderate flight altitudes the swath widths of

FIGURE 9-1. Hill-shaded images of a canopy-top digital surface model, colored by vegetation height, and the underlying ground digital terrain model, colored by elevation, in a 600 m wide swath with 1.8 m pixels



commercial sensors are relatively narrow, typically with widths of 700–2,800 m. Figure 9-1 is an example of products derived from a discrete return point cloud acquired by a commercial sensor. To achieve greater coverage, airborne systems are flown in a sequence of parallel swaths.

Miniaturized lidar sensors are now being developed commercially for very low-altitude operation on small UAV platforms. However, because of their very limited coverage capabilities, with limited applicability to STV objectives, they are not covered in this report. Terrestrial laser scanners, which operate on the ground in fixed locations or mounted on moving vehicles, are also not covered.

There are three main commercial instrument manufacturers of lidar systems for operation on aircraft:

- Teledyne Optech (https://www.teledyneoptech.com/en/products/airborne-survey/);
- Hexagon/Leica Geosystems (https://leica-geosystems.com/en-us/products/airborne-systems);
- Riegl GmbH (http://www.riegl.com/nc/products/airborne-scanning/). .

Table 9-1 compiles details on these instrument capabilities. These commercial sensors are primarily discrete-return lidar systems but several include full waveform recording options. Waveform recording systems typically also do some form of conversion of the waveforms into discrete returns for ease of use. Small laser footprints, typically less than 1m in diameter, are used to achieve high spatial resolution mapping. Current generation systems can acquire many tens of laser pulses per square meter, achieving very high-resolutions. The LAS file format from American Society of Photogrammetry and Remote Sensing (ASPRS) is the defacto standard data exchange format for these manufacturers and software providers. The LAS file format stores many attributes including source IDs, X, Y, Z, Intensity, Return Number, GPS time, scan angle, classification, and other user data. (http://www.asprs.org/wp-content/uploads/2019/03/LAS_1_4_r14.pdf).

Improvements over time in the commercial sector have primarily focused on increasing pulse repetition rates, enabling more dense data at the same aircraft speed, the same density of data at higher altitudes, or both. Other changes include developing lidar systems to acquire bathymetric elevation information using 532 nm lasers and multiple channels of detectors. A multiwavelength lidar (Optech's Titan) operating at 532, 1064, and 1550 nm, was developed to provide enhanced intensity information for target discrimination (Teo and Wu, 2017; Fernandez-Diaz et al., 2016); however, the potential of this system was not fully explored before it was discontinued due to lack of commercial interest. Instead, lidar systems are now often flown with color or multispectral cameras to aid in the identification of the features mapped by lidar and produce realistic 3D renderings.

While most commercial sensors are built to be operated on small aircraft at lower altitudes, two sensors have been built to operate at moderate altitudes: L3 Harris's IntelliEarth, and Hexagon/Leica's SPL-100. The IntelliEarth sensor uses a Geiger-mode lidar detector, and builds probabilities of detections based on aggregating multiple looks to create point clouds (Stoker et al., 2016). The SPL-100 uses a very sensitive detector with a lower signal-to-noise ratio to generate point clouds from higher altitudes. While the detector initially produces noisy point clouds, we can use noise-filtering algorithms in post-processing to identify noise points.

Commercial airborne lidar instruments have been used beginning in about 1990 with expanding areas of coverage and improved data quality as the technology has advanced. Regional to nation-wide mapping programs are now conducted. Currently the USGS manages the 3D Elevation Program (3DEP), with numerous federal agency and state partners. The program began in 2015 and has completed mapping 70% of the conterminous United States, with a goal of 100% coverage by 2023. Because the primary objective is topography the 3DEP data is usually collected during leaf-off conditions, where vegetation cover is deciduous, and when snow is absent. This limits the value of these data for characterization of vegetation structure of the sort applicable to ecosystem science and applications and for snow depth measurements. Also, the coverage has been acquired using a diverse array of instruments operated by a large number of service providers. While the 3DEP has instituted an acquisition specification attempting to ensure interoperability between projects, varying acquisition parameters and data quality introduces a lack of uniformity between regions.

TABLE 9-1. Instrument characteristics for the current generation of commercial airborne lidar systems.

Supplier	System	Subsystem	Operational Envelope (m AGL)	Laser Wave-length	PRF	Returns/ pulse	Beam Div-er-gence (mrad 1/ e^2)	Intensity Capture	Scan Angle FOV
Teledyne Optech	Airborne Laser Terrain Mapper (ALTM) Galaxy	Galaxy CM2000	150-2000	1064 nm	50–2000 kHz	up to 8	0.23	Up to 8 intensity measurements, including last (12-bit)	20-60°
	ALTM Galaxy	Galaxy Prime	150-6000	1064 nm	50–1000 kHz	Up to 8 range measurements, including last	0.25	Up to 8 range measurements, including last	10-60°
	ALTM Galaxy	Galaxy T2000	150-6500	1064 nm	50–2000 kHz	Up to 8 range measurements, including last	0.23	Up to 8 intensity measurements, including last (12-bit)	10-60°
	Eclipse		50-1000	1550 nm	450 kHz (effective 300 kHz)	Maximum 7 range measurements per pulse		Intensity measurements for all corresponding range measurements (maximum 7 per pulse)	60°

Supplier	System	Subsystem	Operational Envelope (m AGL)	Laser Wavelength	PRF	Returns/ pulse	Beam Div-er-gence (mrad 1/e^2)	Intensity Capture	Scan Angle FOV
	Orion	C	50-1100	1541 nm	100–300 kHz	Up to 4 range measurements, including 1st, 2nd, 3rd, and last returns	0.21	Up to 4 intensity returns for each pulse, including last (12 bit)	10-50°
	Orion	H	150-4000	1064 nm	35–300 kHz	Up to 4 range measurements, including 1st, 2nd, 3rd, and last returns	0.21	Up to 4 intensity returns for each pulse, including last (12 bit)	0-50°
	Orion	M	100 - 2500	1064 nm	50–300 kHz	Up to 4 range measurements, including 1st, 2nd, 3rd, and last returns	0.21	Up to 4 intensity returns for each pulse, including last (12 bit)	0-50°
	Pegasus	HA-500	150-5000	1064 nm	100–500 kHz	Up to 4 range measurements, including 1st, 2nd, 3rd, and last returns	0.21	Up to 4 intensity returns for each pulse, including last (12 bit)	0-75°
	Titan		300-2000	1550 nm, 1064 nm, and 532 nm	50–300 kHz (per channel); 900 kHz total	Up to 4 range measurements for each pulse, including last	Channel 1 & 2: ≈0.59 Channel 3: ≈0.7	Up to 4 range measurements for each pulse, including last 12-bit dynamic measurement and data range	0-60°
	CZMIL NOVA		400- 1000	532 nm	70 kHz shallow; 10 kHz deep, 80 kHz topo	Full waveform + intensity	7	Full waveform	20°
Leica Geosystems	SPL100		2,000 - 4500	532 nm	60 kHz (6.0 mHz effective pulse rate)	Up to 10 returns per channel per laser shot including intensity	0.08	Yes	20°, 30°, 40° or 60° fixed
	Terrain Mapper and City Mapper		300 - 5500	1,064 nm	Up to 2 mHz (height dependent)	• Programmable up to 15 returns • Full waveform recording option at downsampled rates • Multiple-Pulses-in-the-Air (MPiA): Up to 35	0.25	Yes, 14 bits	20 - 40°
	ALS80	CM	100-1600	1,064 nm	1 mHz	Unlimited	0.20-0.26	3 (first, second, third)	0 - 72°
	ALS80	HP	100-3500	1,064 nm	1 mHz	Unlimited	0.20-0.26	3 (first, second, third)	0 - 72°
	ALS80	HA	100-5000	1,064 nm	1 mHz	Unlimited	0.20-0.26	3 (first, second, third)	0 - 75°
	Chiroptera 4X		400-600	532 nm	140 kHz (bathymetry)	Waveform	4.75	Yes	20°
Riegl Gmbh	LMS-Q680i		800-1600	1,064 nm	400 kHz	Digitized Waveform	≤0.5	16 bit	0 - 60°
	VQ-780i		350-5600	1064 nm	up to 1 mHz	5-15	<+ 0.25	Provided for each echo signal	0 - 60°

Supplier	System	Subsys-tem	Oper-ational Envelope (m AGL)	Laser Wave-length	PRF	Returns/ pulse	Beam Div-er-gence (mrad 1/ e²)	Intensity Capture	Scan Angle FOV
	VUX-1LR		55-1050	1064 nm	550 kHz	4 - 15	0.5	16 bit	330°
	VQ-1560i		450-3700	1064 nm	2 × 2 mHz	waveform, 4-14	<+ 0.25	Provided for each echo signal	60°
	VQ-1560i DW		450-3700	1064 nm and 532 nm	2 × 2 mHz	Waveform, 4-14	<+ 0.25	Provided for each echo signal	60° per chan-nel
	VQ-880-GH		100-1000	1064 nm and 532 nm	Up to 900 kHz		0.3 (NIR), 0.7–2 (green)	Yes	20°-40°
L3 Harris	IntelliEarth		4000-10000	1064 nm	50 kHz	1	35 urads	No	30°

Commercial lidars have also been incorporated into research-oriented aircraft sensor suites, often combined with commercial hyperspectral imaging systems to combine the lidar height information with composition and ecosystem function information from the spectrometry. Examples of these are the G-LiHT and NEON multi-sensor systems, with a focus on ecosystem science and applications, ASO, with a focus on snow depth and snow water equivalent, and NCALM which acquires data for NSF-sponsored investigations.

NASA, Ball Aerospace, L3Harris, and Sigma Space Corp. (now a part of Hexagon) have led the development of advanced technology airborne lidar instruments. These instruments have been used to demonstrate new measurement capabilities, serve as technology pathfinders for spaceflight missions, conduct science and applications investigations and support national and foreign security objectives. Systems developed at NASA's Goddard Space Flight Center are identified in Figure 9-2. The Airborne Topographic Mapper (ATM) began operation in the 1990s, integrating for the first time lidar, GPS and INS subsystems and demonstrating low-altitude, small-footprint waveform and discrete return detection. ATM has evolved through several iterations to enhance its capabilities, focusing on coastline topographic mapping and producing a long time series of Greenland and Antarctic ice sheet elevation change, culminating in the IceBridge program from 2009 to 2019. The Scanning Lidar Imager of Canopies by Echo Recovery (SLICER) was the first system to demonstrate large-footprint (10m) full-waveform measurements, acquiring data in a narrow swath (50m) from moderate altitude. This led to the development of the Land, Vegetation, and Ice Sensor (LVIS), a wide-swath, higher-altitude, full-waveform system with 20m footprints. A next-generation LVIS acquires higher density data with 10m footprints. The LVIS instruments have participated in a large number of campaigns, acquiring data over diverse forest ecosystems throughout North America and West Africa and participating in the IceBridge program. Three Goddard systems advanced micro-pulse, photon-counting technologies, leading to the use of this measurement approach for ICESat-2. The Multi-KiloHertz Micro-Laser Altimeter (MMLA) was the first airborne system using this measurement approach, employing a helical scanner for narrow swath mapping. The MMLA capability was expanded by Sigma Space Corp. in a series of swath-mapping photon-counting systems which provide extremely high-density photon-counting point clouds utilizing a dense grid of laser beamlets and a detector array. The Slope Imaging Multi-Polarization Photon-counting Lidar (SIMPL) is a multi-beam system focused on advancing measurement capabilities directed toward spaceflight use, in particular by demonstrating multi-channel altimetry for target characterization using dual-wavelength (532 and 1064 nm), polarimetry measurements of laser and solar reflectance. The Multiple Altimeter Beam Experimental Lidar (MABEL) implemented 532 and 1064nm beams for operation at high altitudes to measure through most of the atmosphere column in order to emulate data to be collected by ICESat-2 in preparation for that mission. The Airborne LIST Simulator (A-LISTS) was the first system to implement linear-mode, photon-sensitive waveform acquisition, to achieve swath-mapping with a highly efficient measurement approach as a pathfinder for the Lidar Surface Topography (LIST) mission recommended in the 2007 Earth Science DS.

Ball Aerospace developed an adaptive scanning, flash-lidar airborne system which used a forward-looking imager for cloud avoidance and machine-learning for targeting. The system has been used to measure forest canopy height, tree crown sizes, topography and cloud top structure.

DoD airborne 3-D lidar deployments have been focused on Geiger-mode lidar systems and have included Jigsaw (DARPA); ALIRT (NGA); HALOE (DARPA/Air Force); BuckEye and JAUDIT (TACOP) (US Army); Machete (US Navy) and have proven lidar surveillance and targeting capabilities in Iraq, Afghanistan, AFRICOM, and US SOUTHCOM regions.

The Jigsaw Program started under DARPA to demonstrate the feasibility to perform human-based target identification of ground vehicles under foliage and camouflage obscurants with data collected from an airborne platform (a manned UH-1 helicopter) operating at speeds and altitudes similar to those expected for future operational UAS systems (Marino and Davis Jr., 2005). Descendant systems include MACHETE and JAUDIT (Jungle Advanced Under Dense Vegetation Imaging Technology), which was renamed to TACOP (Tactical Operational Lidar).

MIT Lincoln Laboratory's Airborne Lidar Imaging Research Testbed (ALIRT) uses short laser pulses and a focal plane array of Geiger-mode avalanche photodiode (GM APD) detectors having independent digital time-of-flight counting circuits at each pixel. Principal applications of ALIRT were demonstrated in January 2010, during post-earthquake operations in Haiti. Over a period of 30 days, 49 flights collected ALIRT data to produce 30 cm digital surface models over the majority of the earthquake-impacted city of Port-au-Prince.

The HALOE project has involved arrays of Geiger-mode avalanche photodiode (GmAPD) detectors able to detect just one photon. The extreme sensitivity of GmAPD detectors enables operation of lidar sensors at unprecedented altitudes and area collection rates in excess of 1,000 square kilometers per hour (or about 620 square miles).

BuckEye began with a helicopter-mounted digital color camera that produced high-resolution imagery for intelligence, surveillance and reconnaissance (ISR) and change detection missions. In November 2007, a fixed-wing aircraft with both a color camera and lidar sensor began operations at Bagram Airfield. Multiple fixed-wing aircraft were deployed to Afghanistan in 2010 and 2011 to increase support throughout the country. Buckeye uses a commercial Optech Airborne Laser Terrain Mapper lidar sensor system, ALTM 3100.

9.2.2 Spaceborne Lidar Systems

NASA is the only agency that has operated lidar missions in Earth orbit used for measurements of land, snow and ice elevations, vegetation structure and bathymetry. Commercial entities have supported the development of NASA lidar instruments, but none have conducted orbital lidar operations for commercials purposes and none have indicated any plans to do so. Figure 9-2 illustrates the time-line of the NASA Earth-orbiting spaceborne missions. The timeline of NASA airborne lidars used to advance the measurement capabilities and technical readiness for these missions is also shown. Figure 9-3 shows the sampling pattern of these and planetary missions. All of these systems have been profiling instruments, composed of one profile or several profiles. Other than ICESat-2, all of these systems have used near-infrared (1064 nm) laser transmitters operating at relatively low pulse rates of 10 to a few hundred pulses per second. These have used waveform detection, with the Earth orbiting systems downlinking full waveforms and the planetary systems downlinking parameterized representations of the waveforms due to low bandwidth. ICESat-2 is the only spaceflight system that has employed the micro-pulse, photon counting measurement approach using a green (532 nm) laser transmitter operating at 10,000 pulses per second. With this approach it acquires continuous measurements from overlapping footprint along six profiles. By operating in the green, ICESat-2 is the only spaceflight lidar capable of measuring shallow water bathymetry. The other systems have discrete footprints separated along the profiles. Figure 9-3 shows the decrease in footprint size and increasing profile density over time in order to achieve higher resolution measurements and greater coverage. GEDI, operating aboard the International Space Station (ISS), achieves the greatest number of profiles by splitting the output from three laser transmitters. Despite the advance in coverage achieved by beam splitting, the progression toward higher resolutions has not advanced to the point where swath mapping lidars comparable to an airborne system are capable of operating in Earth orbit. The Japan space agency, JAXA, will deploy the MOLI lidar on the ISS, with a target launch in 2022. MOLI will make waveform measurements similar to GEDI with two closely space profiles separated by ~40 m measuring local slope in order to better distinguish ground and vegetation components in the waveforms. The lidar will fly with a three-band imager to improve discrimination of the targets observed by the waveforms.

FIGURE 9-2. Timeline of NASA spaceborne lidar missions and airborne technology maturation systems.

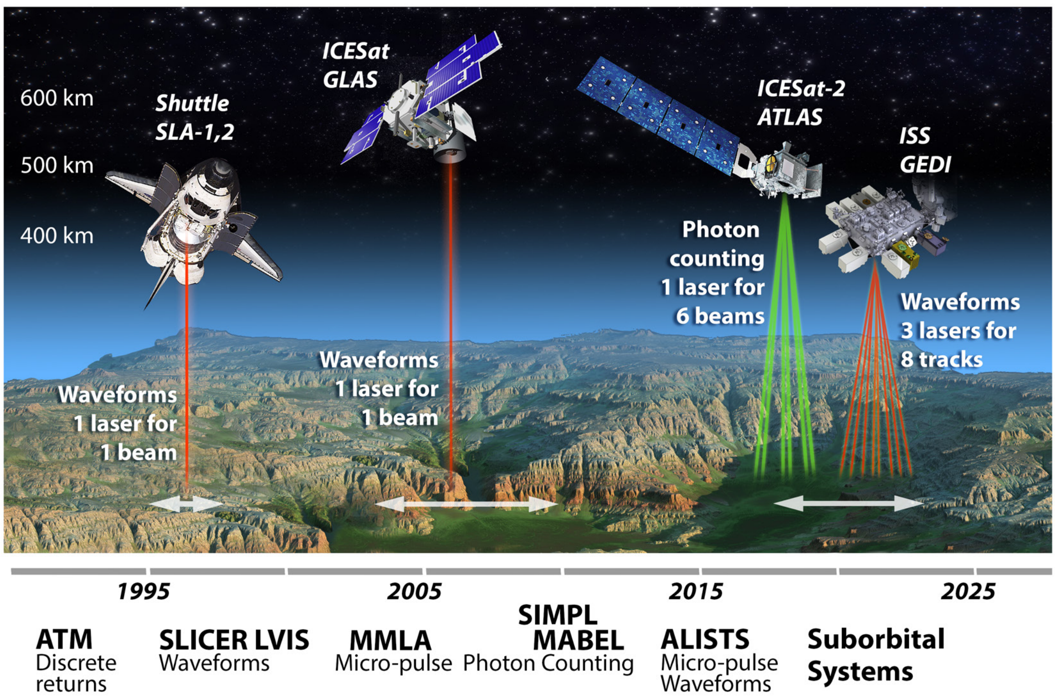
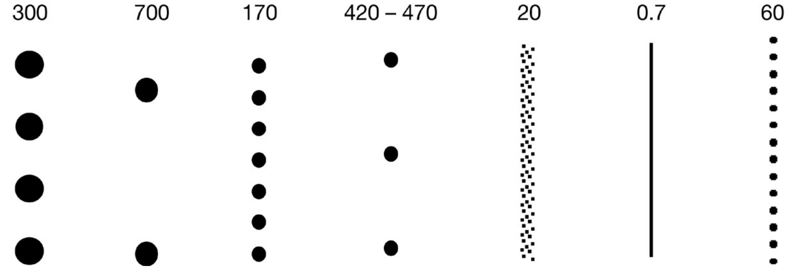


FIGURE 9-3. Profile sampling patterns for NASA Earth and planetary lidars. ICESat-2's six profiles are composed of profile pairs separated by 90 m to determine local slopes, with the pairs separated by 2 km. GEDI's eight profiles are separated by 600 m to sample terrestrial ecosystems uniformly. The starting dates of operations for these missions progress from left to right.

	Mars MOLA	Earth SLA	Earth ICESat	Mercury MLA	Moon LOLA	Earth ICESat-2	Earth GEDI
Profiles	1	1	1	1	1	6	8
Footprint Size (m)	120	100	50 – 90	20 – 100	5	12	25
Footprint Spacing (m)	300	700	170	420 – 470	20	0.7	60



9.3 Current Radar Sensors, Platforms and Existing Data

Near-global DEMs have been generated from spaceborne InSAR-based measurements since the early 2000s. Airborne InSAR instruments have also been commissioned by government entities to generate higher-resolution DTMs and DSMs for more than two decades, but most of these data sets are proprietary. These large-scale DEM productions typically take 3-5 years to complete and are not well suited for monitoring short-term elevation changes. Table 9-2 gives examples of the data, geophysical information, and products acquired by five radar sensor and platform configurations.

TABLE 9-2. Data, geophysical information and products acquired by five radar sensor and platform configurations. Current airborne sensors are discussed in detail in Section 9.3.1.2.

Method	Sensor and Platform	Geolocated Calibrated Data	Geophysical Information	Height and Structure Products
Radar	DLR/TanDEM-X (InSAR mode)	X-band single-pass interferograms	Elevation, (ground and forest canopy vertical distributions, and change)	Profiles of topography, (canopy structure and derived cover fraction)
	DLR/TanDEM-X (PolInSAR mode)	X-band single-pass dual-polarimetric interferograms	Structure-dependent elevation, and change	Profiles of topography, canopy height
	DLR/TanDEM-X (TomoSAR mode)	X-band pairwise single-pass tomograms	Elevation, ground and canopy vertical distributions and change	Profiles of topography, canopy height, 2D canopy structure and derived cover fraction, leaf area index and AGB
	ESA/BIOMASS (Pol-InSAR and TomoSAR modes, launch: 2023)	P-band repeat-pass full-polarimetric interferograms and tomograms	Elevation, ground and canopy vertical distributions	Profiles of topography, canopy height, 2D canopy structure and derived cover fraction, leaf area index and AGB
Radar	Airborne SAR, e.g., NASA-JPL/UAVSAR (InSAR, PolInSAR and TomoSAR modes)	L-band short-repeat-pass full-polarimetric interferograms and tomograms	Elevation, ground and canopy vertical distributions	Profiles of topography, canopy height, 2D canopy structure and derived cover fraction, leaf area index and AGB

9.3.1 Spaceborne Radar Systems

Spaceborne interferometric radar systems are relevant to STV. The NASA Shuttle Radar Topography Mission (SRTM) in 2000 was a C-band interferometric SAR that imaged the Earth's land mass in 10 days and has been the primary source of free and redistributable elevation data on an almost global scale between 56º S and 60º N latitude and at 30-m (Farr, 2007). In 2018 NASA released a new version of 30-m posting DEM, named NASADEM, that combines SRTM processing improvements, elevation control, void-filling and merging with data unavailable at the time of the original SRTM production, such as ICESat GLAS lidar data, ASTER GDEM2 and GDEM3, and the ALOS PRISM AW3D30 DEM (Crippen, 2016; Buckley, 2016).

The German TanDEM-X mission is a public-private partnership between DLR and AirBus (Astrium GmbH). The two X-band satellites (TerraSAR-X and TanDEM-X) were launched in 2007 and 2010 respectively and began flying in close formation, between 200 to 600 meters apart, in late 2010 to image the earth's surface simultaneously from slightly different angles. The images were combined to form accurate elevation maps. The TanDEM-X mission completed two cycles of global imaging between 2011 and 2013 with two different baselines to facilitate dual-baseline interferometric phase unwrapping for elevation generation (Lachaise, 2014). Three DEM products of different spatial resolutions were released around 2016 and the performance of these products are listed in Table 9-3. Imaging of the DEM change layer will be completed in 2020, and a new science phase over forest, permafrost, and ice sheets will start in 2021 (Hajnsek, 2019). There are currently no plans for a follow-on TanDEM-X mission. The TanDEM-X mission's X-band payload weighs just under 400 kg and utilizes a 4.8 m x 0.7 m active phased array antenna with 384 transmit/receive modules transmitting 2.26 kW peak power (Krieger, 2007). For DEM generation, the X-band radar operates in strip-map mode with a 30 km range swath and 3 m resolution. The global mapping effort took 60,000 acquisitions to accomplish (Rizzoli, 2017).

TABLE 9-3. TanDEM-X DEM product types and respective accuracies.

DEM Product	Spatial Resolution Absolute	Horizontal Accuracy CE90	Absolute Vertical Accuracy LE90	Relative Vertical Accuracy
TanDEM-X DEM (standard product 0.4 arcsec)	12 m (0.4 arcsec @ equator)	<10 m	<10 m	<2 m (slope @ 20%) <4 m (slope > 20%) 90% linear point-to-point error within an area 1deg x 1deg
TanDEM-X DEM (1 arcsec)	30 m (1 arcsec @ equator)	<10 m	<10 m	Not specified
TanDEM-X DEM (3 arcsec)	90 m (3 arcsec @ equator)	<10 m	<10 m	Not specified

Harmony is a proposed ESA mission to measure surface motion and deformation due to air-sea interactions (winds, waves, surface currents), and deformation (velocity gradients) that include tectonic strain and cryosphere (glacier flows and surface heights). It is composed of two lightweight satellite companions to the Sentinel-1 mission spacecraft. Depending on formation configuration, different observations are possible from the spacecraft's passive, receive-only radars. One such configuration will allow single-pass topography measurements, as stated in the Harmony proposal's Executive Summary:

> *The fractionated architecture of Harmony enables the unique capability to reconfigure its flight formation so that instead of being optimised for the measurement of motion vectors, it is optimised for the measurement of time-series of surface topography. This will, among other outcomes, result in a globally consistent and highly resolved view of multi-annual glacier volume changes between well-defined epochs, needed to better quantify the climatic response of glaciers. At the same time, Harmony will allow studying the seasonal and subseasonal processes from space that play a role in such responses, for instance by measuring variations in lateral ice flow and associated elevation changes simultaneously over large areas for the first time.*

Specific objectives and associated topographic observations include the following:

Cryosphere:

- Quantify multi-year average elevation change for most glaciers and ice sheet outlets, with a high spatial resolution of at least 100m, and submeter accuracy.
- Providing (i) elevation change, at high spatial resolution of at least 100 m, at subseasonal timescale, and with vertical accuracy of 5 m or better, together with (ii) simultaneously acquired SAR data from which horizontal displacements can be derived.

Permafrost:

- Quantify the extent, magnitude, and rates of rapid thaw subsidence and erosion of permafrost, at multi-annual time scale, at high spatial resolution of at least 100 m, and with submeter vertical accuracy.

Volcanoes:

- Provide measurements of topographic change at actively erupting volcanoes with a spatial resolution of 20 x 20 m^2.

9.3.2 Airborne Radar Systems

The Intermap multifrequency airborne X-band IFSAR and P-band polarimetric SAR system has been in operation since 2002 to provide high-resolution imagery and DEMs and subcanopy information for international government agencies, telecommunication, airline, and insurance industries. Standard data products include a 25-cm orthorectified range image (OSI) and a 1-m posted DSM, accurate up to 1 m horizontally and 0.5 m vertically for open and non-vegetated unobstructed areas with slopes less than 10 degrees.

The Intermap airborne mapping system provides data collection, elevation data generation, and advanced data processing algorithms to deliver hydro-enforced DSM and DTM. The system has deployed in over 40 countries including Alaska, Indonesia, Philippines, and Malaysia, producing proprietary elevation products. Intermap and GeoSAR systems combined to complete the USGS Alaska 3DEP IFSAR program, delivering 5 m posting DEMs to the public. Intermap's NEXTMap One project to produce worldwide 1 m DSM and DTM is underway. These data are available for purchase.

The GeoSAR InSAR airborne mapping system uses P-band and X-band SARs to generate elevation models and orthorectified radar reflectance maps near the tops of trees as well as beneath foliage. This very capable system has conducted large scale elevation mapping campaigns for DoD and US and international governments for many years, but has recently been mothballed.

The NASA/JPL UAVSAR instrument suite is an airborne radar that has three different versions of front-end electronics, each supporting a different radar band, P-, L-, and Ka-band. Each radar band occupies a 3-m long pod that is attached to the belly of a NASA Gulfstream-III aircraft equipped with a real-time differential GPS unit to guide the aircraft's precision autopilot to repeat flight tracks to within a 5 m tube. The L-band quad-polarimetric SAR was developed for repeat-pass interferometry (InSAR), equipped with an electronically scanned antenna array to compensate for aircraft yaw. The 3.1 kW radar features high-resolution, low noise floor, programmable transmit waveform, and multi-squint angle imaging. This radar has been conducting scientific observations since 2009, acquiring data to study solid earth surface deformation to centimeter accuracy, soil moisture, forest biomass, and disaster response applications such as oil spill, flooding, landslide, and wildfire. More recently, scientists have utilized UAVSAR to develop vegetation structure study techniques such as TomoSAR and PolInSAR. In addition, recent SnowEx campaign data have shown the L-band InSAR technique's sensitivity to snow water equivalent, which is directly proportional to the measured snow accumulation.

The P-band configuration (AirMOSS) is also a quad-polarimetric SAR suitable for repeat-pass interferometry. It was developed for the AirMOSS mission and has mainly been used to study subcanopy and subsurface root-zone soil moisture. More recently the P-band radar has been used to study permafrost and boreal forest in Alaska and Canada, as well as vegetation structure with PolInSAR techniques.

The GLISTIN Ka-band InSAR configuration was developed for ice surface topography mapping. This radar was used by the Oceans Melting Greenland mission to map Greenland's coastal glacier topography change from 2016-2019. Scientists have also been using GLISTIN to image alpine glaciers, snow accumulation in the Rockies, and lava volume in Hawaii after the 2018 Kilauea volcano eruption. This radar currently generates 3-m posting DEMs with 0.3—3 m precision depending on the terrain complexity. There are plans to upgrade the radar to improve range resolution by a factor of 2, which will improve the DEM performance as well.

F-SAR is the airborne radar built and operated by DLR. It provides SAR image data in five different frequency bands (X, C, S, L and P)—up to four of these bands can be used simultaneously. At the same time, F-SAR offers fully polarimetric measurement modes in all bands, as well as single-pass interferometric imaging for higher frequencies.

9.3.3 Emerging Spaceborne Radar Systems

Several government agencies are planning SAR missions in the coming decade that span P, L, S, C, and X-band. Table 9-4 is a list of the upcoming satellite missions. Some missions were not included in the table due to perceived lifetime and lack of data access issues. All these missions consist of 1 to 4 of the traditional large SAR payloads weighing several hundred kilograms and generally have lifespan of more than 10 years. The missions that could potentially support STV measurements are ROSE-L, TanDEM-L, and Biomass. ROSE-L is currently designed to support InSAR observations, but may be augmented to support height measurements. TanDEM-L is an InSAR mission designed specifically for elevation measurements and has the ability to penetrate through tree canopies to study canopy density distribution. The European Space Agency's BIOMASS mission is scheduled to launch in 2023 and will be the first P-band radar in space. BIOMASS will also be the first repeat-pass TomoSAR instrument in space designed specifically for vegetation structure mapping, though coverage will be limited due to the transmit restrictions of the P-band wavelength and the poor sensitivity to low biomass vegetation. BIOMASS will generate products highly relevant to STV, including bare earth topography, tree height and vegetation structure. Products will be delivered with relatively coarse spatial resolution due to the 6 MHz bandwidth and with a 7+ months tomographic cycle.

TABLE 9-4. Government Agency SAR satellite missions planned for now through 2027. ROSE-L is an InSAR mission whereas TanDEM-L is a single-pass interferometer mission.

Agency**	Mission	Band	First Launch	Swath (km)	# Sat. (Now/2027)
ESA/Copernicus	Sentinel-1	C	2014	250	2/4
CSA	RCM	C	2019	125	3/3
NASA-ISRO	NISAR	L & S	2022	240	1
ESA	ROSE-L*	L	2027	250	2
DLR	TanDEM-L**	L	202X	350	2
JAXA	ALOS-4	L	2021	200	1
ASI	CSG	X	2019	40	2
INTA	PAZ	X	2018	30	1
ESA	Biomass	P	2022	160	1

Table 9-5 is a list of the upcoming commercial SAR satellite missions planned for now through 2027. Most of these missions are lower cost small satellites in contrast to the government-sponsored large satellites. As a result, most of the commercial SARs operate in X-band with very narrow swath and low duty cycle in order to be small and lightweight, typically weighing just under 100 kg. These missions are designed to provide very high-resolution maps for surveillance and change-detection applications such as monitoring infrastructure change and post-disaster damage assessment. Although commercial SAR satellite orbits are currently not designed for DEM generation, they may be useful for providing deformation change products for solid earth applications. However, X-band signals do not penetrate vegetation canopies nearly as much as longer wavelength signals such as L-band and P-band, and therefore are not well-suited for vegetation structure studies to measure stock. X-band PolInSAR phase does seem to be a good way to monitor change of tree canopy-covered surfaces (Askne 2018). Data from commercial SAR missions are available for purchase and users may also pay to task the observations, but purchased products are in general not redistributable. Finally, some of the small satellite technologies may be directly applicable to future STV missions. Examples include small and lightweight deployable reflector antennas, compact electronics assemblies, and observation planning coordination of a constellation of satellites.

TABLE 9-5. Commercial SAR satellite missions planned for now through 2027.

Company*	Mission	Band	First Launch	Swath (km)	Inclination	# Sat. (Now/2027)
ICEYE, Finland	ICEYE	X	2018	30	97.68°	3/18
Surrey Sat. Tech., UK	NovaSAR	S	2018	20	97.5°	1/? (1)
NEC, Japan	Asnaro-2	X	2018	12	97.4°	1/ (1)
Capella Space, CA	Sequoia	X	2020	40	~90°	1/36
UrthecastSAR, Canada	OptiSAR	L & X	2022	10	45°	8
iQPS, Japan	QPS1/2	X	2019	? (30)	37°	1/36
XpressSAR, VA	XpressSAR	X	2022	? (30)	48°	4
Synspective, Japan	StriX-α	X	2020	30	? (SSO)	25
Umbra Lab, CA	Umbra	X	2022	? (30)	? (SSO)	12
Trident Space, VA	Trident Space	X	2021	? (30)	? (SSO)	7 + 12N = 43
EOS, CA	EOS SAR	S & X	2022	20/25	? (SSO)	6

Two commercial companies, ICEYE of Finland and Capella Space of California, are at the forefront in deploying a constellation of X-band small SAR satellites to provide very frequent global revisit times. ICEYE has three satellites in orbit to date. Each satellite weighs 85 kg and operates in X-band with VV polarization. Resolution varies from 0.25 to 3 m depending on imaging mode. The advertised geolocation accuracy is better than 10 m and the predicted orbit precision is 500 m, which may not be sufficient for reliable baseline control for routine elevation mapping.

Capella Space just launched and successfully commissioned its first operational X-band SAR in fall 2020. The company plans to deploy a 36-satellite constellation to provide hourly coverage of any location on earth. The X-band SAR boasts high sensitivity and submeter resolution. First images released by the company in October 2020 indeed show impressive SNR and resolution.

Antenna technology continues to drive the size and cost of a SAR satellite. A few companies have been actively developing deployable reflector antenna and feed elements with low mass density. Some of the latest developments have shown promise in lowering the antenna mass density (including feed) to less than 5 kg/m^2. EOS SAR, of Silicon Valley, California announced that it has an unfurl-able mesh antenna technology that can support 3 to 20-m diameter antennas from L-band to Ka-band. This company is targeting dual-frequency SAR payloads for small satellite platforms weighing 200-500 kg. The company also plans to reach TRL 6 by first quarter of 2021.

9.3.4 Emerging Airborne Radar Systems

A commercial airborne SAR development that is worth investigating is the HALE InSAR development that can trace its roots to the CIRES CubeSat S-band SAR development funded by NASA's Instrument Incubator Program (IIP). Aloft Research Corporation is developing small radar payload and solar-powered airship technology to reliably and continuously observe topographic changes from dynamic events like earthquakes, volcanoes, landslides, and flooding. The target payloads will be constrained to < 10 kg and < 150 W. Current TRL is < 2 and the company plans to reach TRL 9 in 5 years if resources are available.

A recently awarded NASA IIP is developing snow radar/radiometer with meta-surface Ku-band antenna and compact electronics with high dynamic range in excess of 60 dB. The antenna technology and compact, power efficient electronics may be applicable to HALE InSAR.

9.4 Stereophotogrammetry Sensors, Platforms and Existing Data

Table 9-6 provides examples of the data, geophysical information and products acquired by three types of stereophotogrammetry sensor and platform configurations.

TABLE 9-6. Data, geophysical information and products acquired by two stereophotogrammetry sensor and platform configurations.

Method	Sensor and Platform	Geolocated Calibrated Data	Geophysical Information	Height, Vegetation and Depth Products
Stereo	Imager on Maxar or Planet satellites	Images at two view angles	3D classified cloud of correlation points	Digital terrain model (where vegetation is absent or sparse), digital surface model and shallow water depth
	Camera(s) on aircraft or sUAS	Images at many view angles	3D classified cloud of correlation points	Digital terrain model (where vegetation is absent or sparse), digital surface model, meshes of buildings and infrastructure and shallow water depth

9.4.1 Airborne Stereophotogrammetry Systems

The United States Department of Agriculture's National Agriculture Imagery Program (NAIP) acquires aerial imagery during the agricultural growing seasons in the continental U.S. (see Appendix E-5 for quad chart) A primary goal is to make digital ortho photography available to governmental agencies and the public within a year of acquisition. NAIP is used by many non-FSA public and private sector customers for a wide variety of projects. The aerial survey overlap requirement makes the images suitable for generating DEMs using SP.

Present acquisition is entirely with digital sensors, that must meet rigid calibration specifications. Two-year CONUS Refresh collection cycle since 2008; changed to three-year in 2018. NAIP Products include autocorrelated elevation data, DSM, DEM at 1m spatial resolution (all states since 2008) & 60cm ground resolution since 2018. Photogrammetry derived elevation model from stereo imagery collected from airborne sensor is available as a priced option for cost-share partners.

There are rapidly growing capabilities with uncrewed aerial vehicles (UAVs) to acquire stereo photography and produce high-resolution DEMS. Either conventional SP procedures or Structure from Motion (SfM) can be used to produce the DEMS. Though the aerial coverage is limited the DEMS can be used to check the accuracy of results acquired by other methods.

9.4.2 Spaceborne Stereophotogrammetry Systems

Early attempts to use satellite-based photogrammetry from Landsat, Skylab, and Space Shuttle cameras were not suitable for detailed studies of the Earth's surface with large ground resolution elements and terrain relief errors on the order of 15-120m (e.g., Toutin et al., 2001). In the last decade the Japanese ALOS PRISM and the Chinese Zi Yuan (ZY-) series were launched explicitly to acquire surface DEM quality data with three-camera systems and errors of around 3-5 m (Ni et al., 2015) and ~3-7 m for PRISM (Tadono, 2013), respectively. Wang et al., 2013 reported that ZY-3 can obtain planimetric and vertical accuracy values of 15 m and 5 m respectively and 3 m and 2 m with "a few" ground control points (GCP).

Maxar (formerly DigitalGlobe) with its Worldview series of hi-resolution (<30/50cm) satellite observations has proven the concept of space-based DEMS. Example of this include the collating of multiyear of images to produce continent scale 2 m DEMs such as the University of Minnesota's Polar Geospatial Center's ArcticDEM (Morin et al., 2018, ArcticDEM., available online: https://www.pgc.umn.edu/data/arcticdem). Several scientific disciplines have benefited from this DEM including Arctic hydrology (e.g., Lu et al., 2020), forestry (e.g., Meddins et al., 2018) and volcanology (Dai et al., 2017). ArcticDEM is reported to have 0.2 m internal accuracy, but with systematic vertical and horizontal bias of 3-5 m (can be improved by use of GCP) (Noh et al., 2015). Previously acquired WorldView imagery is available to NASA investigators through an agreement with National Geospatial Agency and Maxar i.e., Neigh et al., 2013) DEMs from these data compare favorably with airborne lidar DEMS (e.g., Neigh et al., 2014)

Planet, another spaceborne imaging company, features two constellations with DEM capabilities: PlanetScope and SkySat. PlanetScope consist of a constellation of three-unit (3U) CubeSats provide observations of points on the Earth's surface multiple times per day at 3–4 m resolution. The current operational mode of nadir acquisitions and the small swath width results in small base to height ratios (BL/H) (1:10). However, Ghuffar (2018) reported that DEMs prepared from Planet scope and compared to 5m lidar DEM and 3m ALOS Prism produced DEM elevation differences of about 4 m. The SkySat constellation will be composed of 21 SmallSats with panchromatic sensor resolution and multispectral resolution of about 0.8 m and 1.0 m, respectively. The constellation will have up to twice daily revisit capabilities. There were few published articles using these data for DEM generation.

In 2014, CNES launched the Pleiades 1A and 1B constellation with spatial resolution of 0.5 m pan and pan-sharpened multispectral with f 20 km X 280km swaths. Pleiades DEM errors of less than 1 m have been reported when compared to a lidar DEM (e.g., Almeida et al., 2019, Bernard et al., 2012)

This group of commercial satellite DEM providers have demonstrated that it is feasible to acquire significant coverage of DEMs at accuracies relevant to the STV requirements. However, Planet and Maxar do not routinely provide DEMs so data availability may be limited to custom acquisitions or finding suitable image pairs in existing imagery. As mentioned above, PGC was successful in acquiring enough suitable image pairs over a multiple year time period to construct the ArcticDEM. A study by the French IGN (National Institute of Geographic and Forest Information), which provide coverage of the entirety of France and other areas every 3 years, demonstrated the feasibility of substituting Pleiades stereo imagery for aircraft products (Michel et al., 2013).

Table 9-7 provides a summary of a few examples of existing and planned orbital higher resolution stereo-capable missions. All are commercial endeavors or partnerships between space agencies and commercial entities.

TABLE 9-7. Example providers of on-orbit 3D capable high-resolution imagery.

Organization	Mission	No. of Satellites	Pixel res. (m)	Swath (km)	Height accuracy (m)	Start Date
Maxar	Worldview-2	1	1	16.4	0.5-2	2009
CNES/Airbus	Pleiades	2	1	20	0.5-2	2011
SPOT Image	SPOT 6,7	2	8	60	0.5-2	2012
Planet	SkySat	21	0.72-0.86	5.5-8.0	TBD	2016
Maxar	Worldview Legion	6	0.29	9	1	2021
CNES/Airbus	CO3D	4	0.50	20	1	2023

9.4.3 Emerging Stereophotogrammetry Technologies

The continuing success of NAIP has led to increasing demand for high-resolution imaging and topographic products. A new airborne sensor is being developed that acquires imagery and Lidar data simultaneously (Kim et al., 2020; See Appendix E6 for quad chart)

Another airborne imaging system example, QUAKES-I (Donnellan et al., 2019) (see Appendix E-6 for quad chart), employs 8 hi-res framing cameras to provide multispectral and 3D data for measuring land surface morphology, land surface change. QUAKES-I is designed to produce submeter resolution topographic images at nadir and 3 m resolution visible orthorectified topographic products along a 12 km–wide swath. There are also SWIR cameras producing 9 m resolution images along with visible products.

CNES and Airbus have teamed up to build, launch and fly a four satellite constellation called Constellation Optique 3D (CO3D) to produce a worldwide one-meter accuracy DEM (see Appendix E6 for quad chart). The constellation will produce multiresolution DSM: 1 m, 4 m, 12 m, 15 m, 30 m within local area ($< 0.5° \times 0.5°$) and $0.25° \times 0.25°$ tile world coverage within the constraints of their data policy. For example, the 15 m and 30 m DEMS will be designated open data. In addition, ortho-imagery products will also be produced with 50 cm resolution, temporal and geometrical coherency (Lebeque et al., 2020).

Maxar is developing a six satellite constellation called Worldview Legion. With a launch planned for 2021, the mission is directed at commercial imagery sales, monitoring for national security, acquiring a global point cloud with updates for DOD, monitoring natural disasters, and humanitarian studies. The constellation will consist of 2+4 satellites with instruments capable of 29cm Pan, and 1.16 m, 8-band VNIR imagery from a 450 km mid-inclination orbit swath will be 9 km with geodetic accuracy of <5 m CE90. Constellation satellites will be flown in a range of sun-synchronous and mid-inclination providing 15-17 observations per day. It will be possible to derive DEMS from multiple images. It may also be possible to use an existing contract for federal/civilian entities to acquire no cost data access.

9.5 Platforms

NASA missions traditionally fly on satellites and aircraft of various sizes. CYGNSS (Cyclone Global Navigation Satellite System, ~29 kg each) is an example of an Earth observation mission on a smaller satellite, and the TERRA satellite (~ 4864 kg) is an example on the heavier end. NASA maintains a well distributed portfolio of Earth observation satellites in terms of their mass (Figure 9-4).

The main drivers for choosing a platform are derived from the instrument and its needs in terms of size, power and attitude control. For example, smaller satellites tend to have lower available power due to the linear relationship between solar panel size and output power under a constant areal power density assumption, which can vary from ~100 to 250 W/m^2 (Reddy 2003). Similarly, smaller satellites have less space for batteries, resulting in limited energy storage capacity (Chin et al., 2018). Some attitude control and propulsion technologies are also not available on smaller platforms (Krejci and Lozano 2018). Despite these limitations, many observation capabilities have been implemented on smaller satellites (Poghosyan and Golkar 2017).

It is also important to note that SmallSats and CubeSats are utilized a lot more in multi-satellite observation strategies, which can allow for graceful degradation (or increase) of capability as well as generational improvement of observation capabilities over time (Sandau et al., 2010). The smaller size, reduced weight, and lower cost of small satellites also result in faster development times (Figure 9-5).

FIGURE 9-4. Government based active earth observation satellites for US (left) and the whole world (right) by their weight. Blue: Less than 500 kg, Orange: Between 500 and 1000kg, Green: More than 1000kg (World Meteorological Institution 2020, Grimwood 2020).

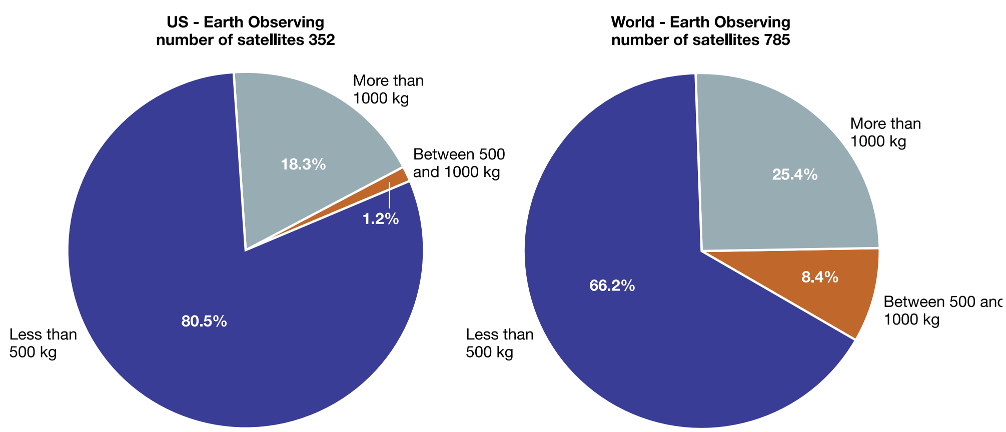
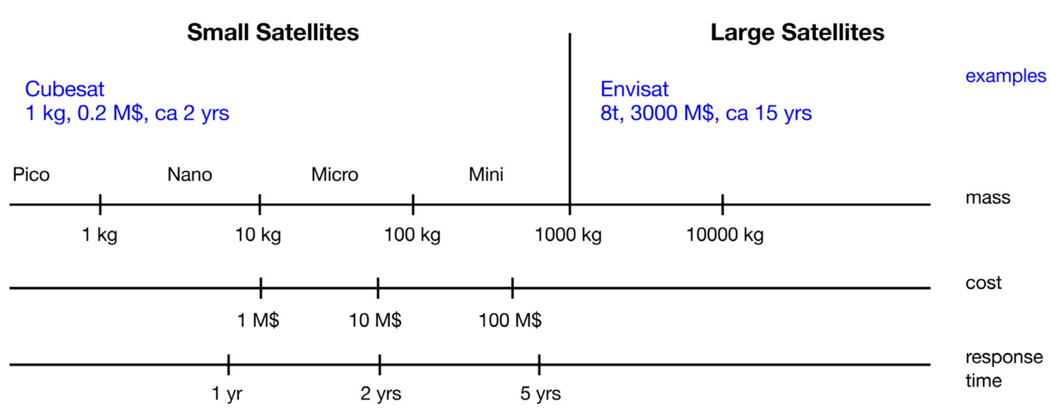


FIGURE 9-5. Mass, cost and response (development) time of various size satellites (Sandau et al 2010). The cost information contained in this document is of a budgetary and planning nature and is intended for informational purposes only. It does not constitute a commitment on the part of JPL and/or Caltech.



Suborbital platforms can also be useful for STV by optimizing the coverage and repeat observation needs of various science disciplines. A major advantage of suborbital platforms is the ability to rapidly deploy over a specific area and achieve higher temporal or spatial sampling of the target area. All instruments of interest for STV have suborbital examples and are shown in Table 9-7.

High Altitude Long-Endurance (HALE) systems have been in development for many decades (Simons and Valk 1993) and NASA has demonstrated several generations (DelFrate 2006). These aircrafts fly above the commercial aircraft traffic (i.e., > 14 km MSL) and have longer endurance allowing them to act as High Altitude Pseudo Satellites (HAPS). Recent advances in batteries have reached the power density and recharge cycles necessary for HAPS propulsion. New battery chemistries including Li-Sulphur are also making the aircraft safer. Strong, light-weight materials required to sustain wind gusts and low SWAP avionics have recently become available, enabling science from high altitude (18-21 km) and with long duration flights (24-36 hours). For example, Swift Engineering recently demonstrated its HALE UAS first flight at SpacePort America in New Mexico in cooperation with NASA Ames (Figure 9-6). Swift is partnering with USFS and USGS to demonstrate a long endurance remote sensing mission in summer 2021 following additional envelope expansion flights later this year.

TABLE 9-7. STV relevant NASA airborne sensors and the platforms they fly on.

	Example Sensor	Platform
Optical	Quakes-Imager	G-III
Lidar	SIMPL	Learjet 25, P-3 Orion, Twin Otter
	LVIS	B-200, C-130H, Cessna 402B, Cessna Citation, DC-8, P-3 Orion
	ATM	C-130H, DC-8, P-3 Orion, Twin Otter, HU-25A Guardian, G-V
SAR	UAVSAR-Ka	G-III
	EcoSAR	P3 Orion

FIGURE 9-6. Swift HALE UAS first flight at Spaceport America in New Mexico on July 7, 2020.

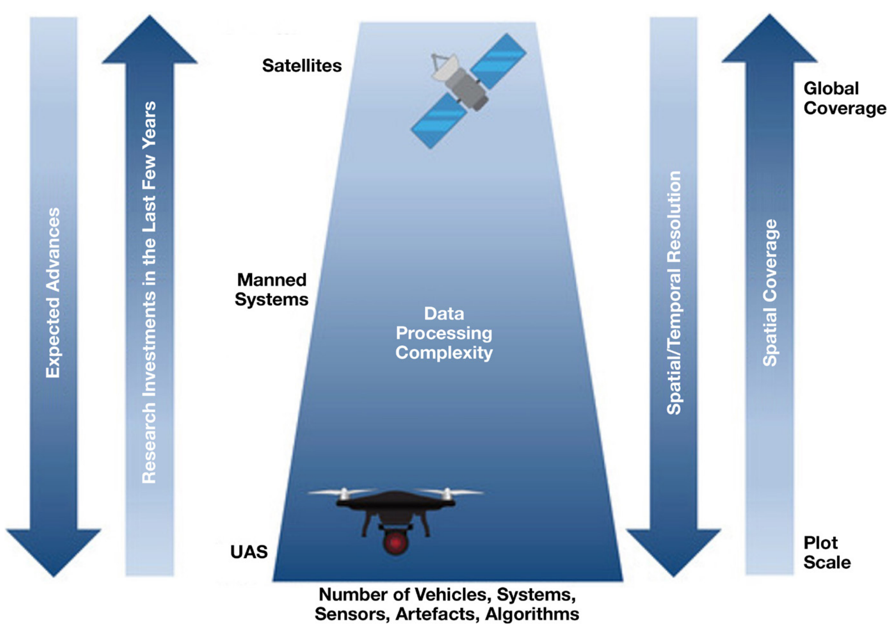
Aerovironment's HAPSMobile Sunglider (a joint venture with Softbank) recently completed low altitude test flights (Figure 9-7). This 260-ft wingspan HALE has a 6-month endurance and payload capacity of about 100 lb, and is designed to carry telecommunications equipment to provide better communications to under-served areas, including rural communities.

FIGURE 9-7. HAPSMobile Sunglider in flight at Spaceport America in New Mexico on July 23, 2020.

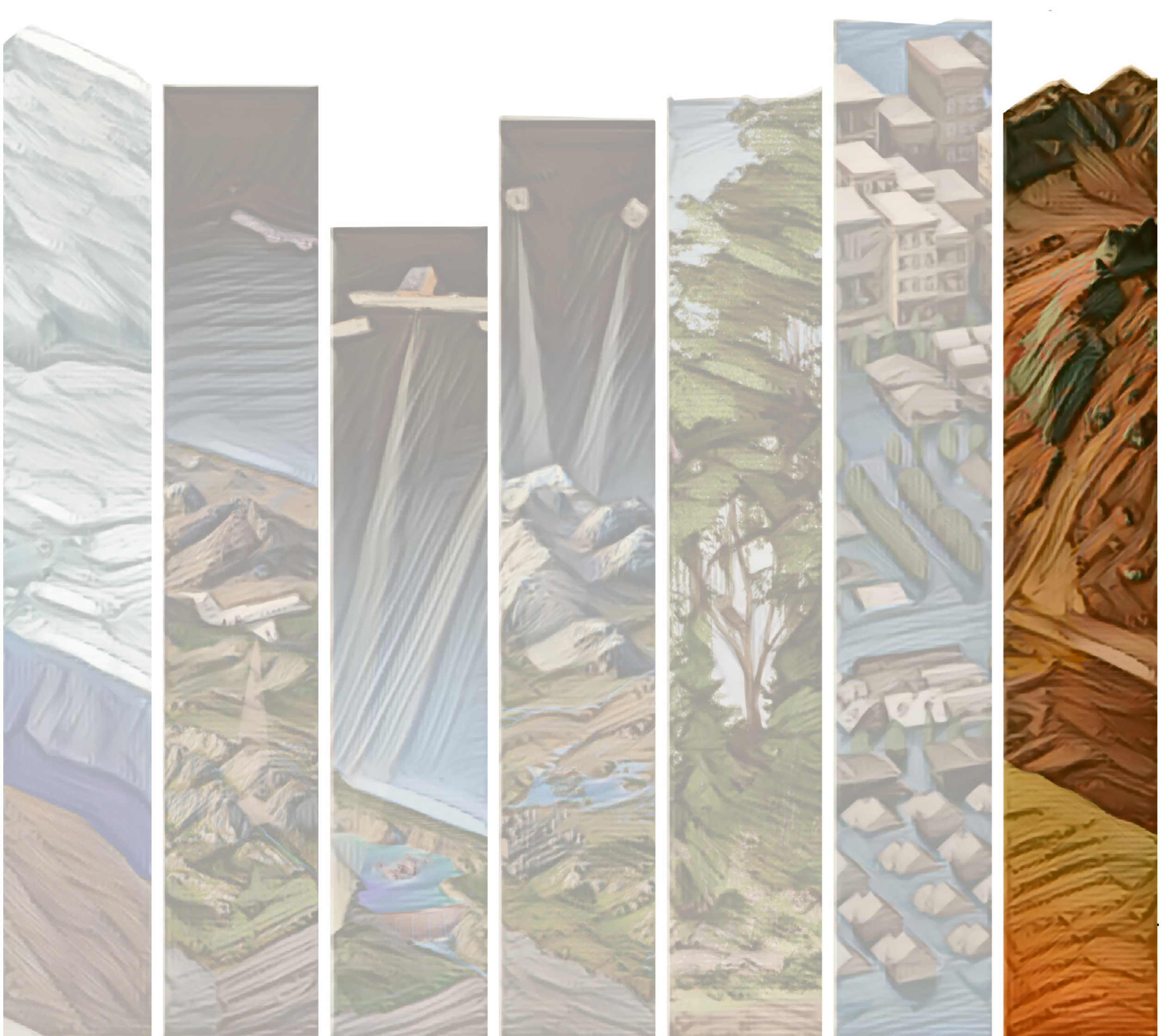
In addition to aircraft-like designs where large wings provide lift, balloons (airships) can also be used. These are sometimes referred to as heavier-than-air (HTA) and lighter-than-air (LTA) platforms respectively (Nickol et al., 2007). One of the main benefits of the LTA platforms is that they can carry much heavier payloads to altitude, and can provide large amounts of power to instruments. For solar powered systems, operating in high latitudes in winter is a drawback (Colozza and Dolce 2005).

At lower altitudes, UASs provide a cost-effective platform for scientific observations. NASA has several UASs that operate below 5 km altitude (e.g., DragonEye, SIERRA, Viking), which can carry payloads of up to 45 kg (Fladeland et al., 2011; Albertson et al., 2015). Aside from these fixed-wing aircraft, there are also rotary-wing platforms. These aircraft tend to be easier to operate but also provide lower endurance and payload as more energy is needed to generate lift with the propellers (Harrington and Kroninger 2014). In summary the UAS provide rapid testing and development cycles and require lower investments compared to larger platforms. They are also able to provide higher temporal and spatial sampling due to their closer proximity to the target area, but have difficulty in covering very large areas (Figure 9-8).

FIGURE 9-8. Comparison of various size platforms on development timeframe, life-span, resolution and coverage (Manfreda et al 2018).



APPENDICES



APPENDIX A PRELIMINARY SATM

This appendix contains the complete preliminary Science and Applications Traceability Matrices for each discipline and for additional applications. In all cases, cells without values are not applicable to the goal. T denotes threshold values and A aspirational values.

Solid Earth

Solid Earth																						
Science or Application		Product	Spatial Requirements												Temporal Requirements							
Goal	Objective		Coverage for Area of Interest (%) (global, region or feature)		Grid or Profile Horizontal Resolution (m)		Vegetation 3D Structure Vertical Resolution (m)		Bathymetry Maximum Depth (m)		Geolocation Accuracy (m)		Vertical Accuracy (m)		Latency (days)		Repeat Frequency (days)		Duration for Repeating (months)		Rate of Change Accuracy (m per year)	
			A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T
Accurately forecast large-scale geological hazards in a socially relevant timeframe	Measure the pre-, co-, and post-eruption surface deformation and products of the Earth's entire active land volcano inventory at a time scale of days-weeks.	Surface Topography DTM Shallow Water Bathymetry	90	65	1	3			25	10	1	3	0.1	0.3	0.5	2	1	7	6	2		
	Measure and forecast interseismic, preseismic, coseismic, and postseismic activity over tectonically active areas on time scales ranging from hours to decades.		90	65	0.5	2			25	10	1	3	0.1	0.3	1	2	7	14	12	4		
	Forecast and monitor landslides, especially those near population centers.		90	65	0.5	2			25	10	1	3	0.1	0.3	1	2	1	14	72	36	0.10	0.5
	Forecast, model, and measure tsunami generation, propagation, and run-up for major seafloor events.		90	65	1	5			50	20	1	3	0.1	0.3	1	15	0	0	0	0		
Assess the impacts geological disasters have on the Earth system and society following an event	Rapidly capture the transient processes following disasters for improved predictive modeling, as well as response and mitigation through optimal retasking and analysis of space data.	Surface Topography DTM Shallow Water Bathymetry	90	65	0.5	2			25	10	1	3	0.1	0.3	0.5	1	1	3	4	1		
	Assess surface deformation, extent of surface change of volcanic products following a volcanic eruption (hourly to daily temporal sampling).		90	65	1	3			25	10	1	3	0.1	0.3	0.5	1	1	3	4	2		
	Assess co- and post-seismic ground deformation and damage to infrastructure following an earthquake.		90	65	0.5	2	w		25	10	1	3	0.1	0.3	0.5	2	1	3	4	1		

Solid Earth

Science or Application		Product	Spatial Requirements												Temporal Requirements							
Goal	Objective		Coverage for Area of Interest (%) (global, region or feature)		Grid or Profile Horizontal Resolution (m)		Vegetation 3D Structure Vertical Resolution (m)		Bathymetry Maximum Depth (m)		Geolocation Accuracy (m)		Vertical Accuracy (m)		Latency (days)		Repeat Frequency (days)		Duration for Repeating (months)		Rate of Change Accuracy (m per year)	
			A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T
Forecast local sea level change along coastlines around the world in the next decade to century	Determine vertical motion of land along coastlines at uncertainty <1 mm y-1.	Surface Topography DTM Shallow Water Bathymetry	90	65	10	100			25	5	1	3	0.05	0.2	15	30	15	30	72	36	0.01	0.1
Understand the processes and interactions that determine the rates of landscape change	Quantify global, decadal landscape change produced by abrupt events and by continuous reshaping of Earth's surface due to surface processes, tectonics, and societal activity.	Surface Topography DTM Vegetation Height	90	65	1	5	1	3			1	3	0.1	0.3	15	30	90	180	72	36	0.10	0.3
Improve discovery of energy, mineral, and soil resources	Map topography, surface mineralogic composition and distribution, thermal properties, soil properties/ water content, and solar irradiance for improved development and management of energy, mineral, agricultural, and natural resources.	Surface Topography DTM	75	50	5	20					1	3	0.1	1.0	15	30	90	180	72	36	0.30	1.0
Applications: Volcanoes	Response: 1. Monitor volcanic lava-dome growth/collapse 2. Map the extent of eruptive products (lava, lahars, landslides, and pyroclastic flows and ash deposits) from topography change during an eruption. 3. Measure the amount of eruption material and erupted volume as a function of time during an eruption.	Surface Topography DTM Shallow Water Bathymetry	90	65	1	3			25	10	1	3	0.1	0.3	0.5	1	1	3	4	2		
	Hazards: 1. Monitor surface topography at active & quiescent active volcanoes. 2. Map localized topography change associated with volcanic flows to understand physical property of volcanic flows.		90	65	1	3			25	10	1	3	0.1	0.3	7	14	7	14	72	36		

Solid Earth

Science or Application		Product	Spatial Requirements												Temporal Requirements							
Goal	Objective		Coverage for Area of Interest (%) (global, region or feature)		Grid or Profile Horizontal Resolution (m)		Vegetation 3D Structure Vertical Resolution (m)		Bathymetry Maximum Depth (m)		Geolocation Accuracy (m)		Vertical Accuracy (m)		Latency (days)		Repeat Frequency (days)		Duration for Repeating (months)		Rate of Change Accuracy (m per year)	
			A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T
Applications: Earthquakes	Response: Where has fault rupture occurred? How much ground movement occurred? Provide model predictions for aftershock location and magnitude.	Surface Topography DTM Shallow Water Bathymetry	90	65	0.5	2			25	10	1	3	0.1	0.3	0.5	2	1	3	4	1		
	Hazards: Where is aseismic creep resulting in ground movement occurring and at what rate? Predict earthquakes and assess earthquake risk based on interseismic strain accumulation. Where are faults located, how are faults interconnected, and what is the predicted maximum magnitude and frequency of earthquakes on the fault?		90	65	0.5	2			25	10	1	3	0.1	0.3	7	14	7	14	72	36	0.10	0.5
Applications: Landslides	Background ground displacement monitoring to identify and track active landslides	Surface Topography DTM Shallow Water Bathymetry	90	65	0.5	2			25	10	1	3	0.1	0.3	1	2	1	14	72	36	0.10	0.5
Applications: Coastal subsidence	What is the current land surface elevation at the local scale? What are the current rates of subsidence at the local-to-regional scale? What are the main drivers of subsidence at the local-to-regional scale? How much is subsidence contributing to relative sea level rise? Where should remediation activities be undertaken to have the highest impact on coastal sustainability? What is the sustainability at the decade-to-century timescale? How is flood risk changing due to RSLR?	Surface Topography DTM Shallow Water Bathymetry	90	65	10	100			25	5	1	3	0.05	0.2	15	30	15	30	72	36	0.01	0.1

Solid Earth																						
Science or Application		Product	Spatial Requirements												Temporal Requirements							
Goal	Objective		Coverage for Area of Interest (%) (global, region or feature)		Grid or Profile Horizontal Resolution (m)		Vegetation 3D Structure Vertical Resolution (m)		Bathymetry Maximum Depth (m)		Geolocation Accuracy (m)		Vertical Accuracy (m)		Latency (days)		Repeat Frequency (days)		Duration for Repeating (months)		Rate of Change Accuracy (m per year)	
			A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T
Applications: Subsidence	Water/Oil/Gas extraction: Where and at what rate is vertical land elevation change from resource extraction or related injection activities occurring and what is the cause?	Surface Topography DTM	75	50	5	20					1	3	0.1	1.0	15	30	90	180	72	36	0.30	1.0
	Subsidence related to permafrost thaw: Where and at what rate is land elevation changing in permafrost regions?		75	50	10	100					1	3	0.1	1.0	15	30	90	180	72	36	0.30	1.0
Applications: Ground movement related to mining activities	What is the rate of ground movement at mining facilities?	Surface Topography DTM	75	50	3	5					1	3	0.1	1.0	15	30	15	30	72	36	0.10	0.5
Applications: Sinkhole and Cavern collapse	Sinkhole detection: Identify topography change related to sinkhole precursors & progression: Where are sinkholes located (active or inactive)? Where are sinkholes actively changing the ground surface elevation? Is the rate of ground movement associated with a sinkhole constant or accelerating? What is the underlying cause (human activity vs. natural), i.e., related to rainfall, groundwater extraction, mining, etc.?	Surface Topography DTM	90	65	1	5					1	3	0.1	0.3	7	14	7	14	72	36	0.10	0.5
Applications: Space Archaeology	Identify and map archaeological heritage sites in remote locations	Surface Topography DTM	90	65	1	5					1	3	0.1	0.3	15	30						

Vegetation Structure

Vegetation Structure																						
Science or Application		Product	Spatial Requirements												Temporal Requirements							
Goal	Objective		Coverage for Area of Interest (%) (global, region or feature)		Grid or Profile Horizontal Resolution (m)		Vegetation 3D Structure Vertical Resolution (m)		Bathymetry Maximum Depth (m)		Geolocation Accuracy (m)		Vertical Accuracy (m)		Latency (days)		Repeat Frequency (days)		Duration for Repeating (months)		Rate of Change Accuracy (m per year)	
			A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T
What are the carbon storage and dynamics of ecosystems and how the carbon sinks in global vegetation are changing in time? (New: E-4, E-5) What are the fluxes (of carbon, water, nutrients, and energy) within ecosystems, and how and why are they changing? [E-3]	What is the impact of anthropogenic disturbances (e.g., deforestation, degradation, fragmentation, and increasing CO2) on vegetation biomass and growth rate?	Vegetation Height Vegetation 3D Structure	80	50	50	100	1	2			1	3	1.00	2.0	5	30	90	180	72	36	1.0	2
	How is climate change and anthropogenic disturbances impacting the structure and biomass accumulation in temperature limited (e.g., boreal) and water limited (e.g., savanna and dry woodlands) ecosystems?																					
	What is the impact of anthropogenic disturbances (e.g., deforestation, degradation, fragmentation, and increasing CO2) on vegetation biomass and growth rate?																					

Vegetation Structure																						
Science or Application		Product	Spatial Requirements												Temporal Requirements							
Goal	Objective		Coverage for Area of Interest (%) (global, region or feature)		Grid or Profile Horizontal Resolution (m)		Vegetation 3D Structure Vertical Resolution (m)		Bathymetry Maximum Depth (m)		Geolocation Accuracy (m)		Vertical Accuracy (m)		Latency (days)		Repeat Frequency (days)		Duration for Repeating (months)		Rate of Change Accuracy (m per year)	
			A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T
What are the structure, function, and biodiversity of Earth's ecosystems, and how and why are they changing in time and space? (DS: E-1) How natural and anthropogenic disturbances (deforestation, degradation, fire, droughts, etc.) impact ecosystem productivity and function and their resilience in changing climate? [New: E-6, E-7, E-8]	How is ecosystem structure changing due to climate change and human activities? (new: E-1b2)	Surface Topography DTM Vegetation Height Vegetation 3D Structure	80	50	30	50	1	2			1	2	1.00	1.5	5	30	90	180	72	36	0.5	1
	To what extent does 3D vegetation structure explain variations in composition and biological diversity (flora and fauna) of ecosystems at various scales? (new: E-1f1]																					
	How will ecosystem ecological functions (e.g., carbon, water cycling) and services (e.g., sustaining food and fiber, air and water, societal benefits) with increased pressure from humans and climate																					
	To what extent the 3D habitat structure is altered by changes in species composition (e.g., foundation species, invasive species, indicator species etc.).																					

Cryosphere Processes

Cryosphere Processes																						
Science or Application		Product	Spatial Requirements												Temporal Requirements							
Goal	Objective		Coverage for Area of Interest (%) (global, region or feature)		Grid or Profile Horizontal Resolution (m)		Vegetation 3D Structure Vertical Resolution (m)		Bathymetry Maximum Depth (m)		Geolocation Accuracy (m)		Vertical Accuracy (m)		Latency (days)		Repeat Frequency (days)		Duration for Repeating (months)		Rate of Change Accuracy (m per year)	
			A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T
How will sea level change, globally and regionally, over the next decade and beyond? [DS: S-3, C-1] [Most Important]	Monitor surface mass balance processes (precipitation, compaction, runoff)	Gridded land ice height change	95	80	10	50					2	5			30	90	1	5	120	36	0.05	0.10
	Monitor fast moving (>50 m/y) glacier processes [outlet glaciers]	Gridded land ice height change	95	80	10	50					2	5			30	90	5	10	120	36	0.05	0.10
	Monitor slow moving (<50 m/y) glacier processes [interior ice]	Gridded land ice height change	80	50	200	500					2	5			30	90	30	90	120	36	0.01	0.01
	Monitor Antarctic and Greenland Ice Shelve processes	Gridded land ice height change	95	75	10	50					2	5			30	90	5	10	120	36	0.01	0.01
	Monitor mountain glacier (larger than 10 km^2) processes	Gridded land ice height change	95	50	10	25					2	5			30	90	5	10	120	36	0.05	0.10
	High-resolution DEM for ice sheet model initialization	Gridded land ice height DSM	95	90	1	5					2	5	0.50	1.00	30	90						
What will be the consequences of amplified climate change in the Arctic and Antarctic? [DS: C-8] [Very Important]	Quantify time-varying sea ice thickness distribution	Sea ice thickness	95	90	10	25					3	6	0.30	0.40	5	30	5	30	120	36		
	Quantify snow depth on sea ice (needed for freeboard to thickness conversion)	Snow depth on sea ice	95	90	10	25					3	6	0.03	0.05	5	30	5	30	120	36		

Hydrology

Hydrology																						
Science or Application		Product	Spatial Requirements												Temporal Requirements							
Goal	Objective		Coverage for Area of Interest (%) (global, region or feature)		Grid or Profile Horizontal Resolution (m)		Vegetation 3D Structure Vertical Resolution (m)		Bathymetry Maximum Depth (m)		Geolocation Accuracy (m)		Vertical Accuracy (m)		Latency (days)		Repeat Frequency (days)		Duration for Repeating (months)		Rate of Change Accuracy (m per year)	
			A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T
How is the water cycle and fresh water availability changing with climate change, land cover change and water diversion structures?	Develop and evaluate an integrated Earth system analysis with sufficient observational input to accurately quantify the components of the water and energy cycles and their interactions, and to close the water balance.	Surface topography DTM, DSM	95	75	3	5					2	3	1	2			365	1825	60	24	0.1	0.5
		Vegetation 3D structure	95	75	10	30	0.5	2			5	7	1	2			30	365	60	24		
		Shallow water bathymetry DTM	95	75	1	10			5	1	1	5	0.1	0.25			365	1825	60	24		
		Snow depth DSM-DTM	95	75	100	10					50	5	1	2			365	1825	60	24		
	Quantify the impact of land cover change, modification and soil disturbances on water, carbon, sediment and energy fluxes at/below/above the land surface.	Shallow water bathymetry DTM	95	75	1	10			5	2	1	5	0.1	0.25			365	1825	60	24		
		Surface topography DTM	95	75	3	5					2	3	1	2			365	1825	60	24		
	Quantify rates of snow accumulation, snowmelt, ice melt, and sublimation from snow and ice worldwide.	Surface topography DSM	95	75	3	5					2	2	1	2			365	1825	60	24		
		Bathymetry	95	75	5	10			5	2	3	5	0.1	0.25			365	1825	60	24		
		Snow depth DSM-DTM	95	75	100	1000					50	500	1	2			365	1825	60	24		
	Quantify lake and reservoir water balances, and their responses to climate extremes and human activities?	Water surface height DSM	95	75	1	10					1	5	0.05	0.2			30	365	60	24	0.1	0.5
		Shallow water bathymetry DTM	95	75	1	30			25	?	1	15	0.1	0.25			365	1825	60	24		

Hydrology																										
Science or Application		Product	Spatial Requirements												Temporal Requirements							
Goal	Objective		Coverage for Area of Interest (%) (global, region or feature)		Grid or Profile Horizontal Resolution (m)		Vegetation 3D Structure Vertical Resolution (m)		Bathymetry Maximum Depth (m)		Geolocation Accuracy (m)		Vertical Accuracy (m)		Latency (days)		Repeat Frequency (days)		Duration for Repeating (months)		Rate of Change Accuracy (m per year)	
			A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T
How do changes in the water cycle impact local and regional freshwater availability affect biogeochemical processes, ecosystems, and the services these provide?	Quantify lake and reservoir water balances, and their responses to climate extremes and human activities?	Water surface height DSM	95	75	1	30					1	15	0.05	0.2			30	365	60	24	0.1	0.5
		Shallow water bathymetry DTM	95	75	1	10			25	?	1	5	0.1	0.25			365	1825	60	24		
	Quantify the flows of energy, water, carbon, nutrients, etc., sustaining the life cycle of terrestrial and marine ecosystems (e.g., wetlands) and partitioning into functional types.	Water surface height DSM	95	50	10	30					5	15	0.05	0.2			7	14	60	24	0.1	0.5
		Shallow water bathymetry DTM	95	50	5	10			5	2	3	5	0.1	0.25			365	1825	60	24		
		Vegetation height and 3D structure	95	50	10	100	0.5	1			5	50					30	365	60	24		
	Quantify how changes in land use, land cover, and water use related to agricultural activities, food production, and forest management affect water quantity and quality of above and below groundwater.	Surface topography DTM, DSM	95	50	3	5					2	3	1	2			365	1825	60	24		
		Shallow water bathymetry DTM	95	50	5	10			5	2	3	5	0.1	0.25			365	1825	60	24		
		Vegetation 3D structure	95	50	10	30	0.5	2			5	15					30	365	60	24		
	Quantify rates of snow accumulation, snowmelt, ice melt, from snow and ice within catchments.	Surface topography DTM, DSM	95	50	3	5					2	3	1	2			365	1825	60	24		
		Snow depth DSM-DTM	95	50	100	1000					50	500	1	2			365	1825	60	24		

Hydrology																						
Science or Application		Product	Spatial Requirements												Temporal Requirements							
Goal	Objective		Coverage for Area of Interest (%) (global, region or feature)		Grid or Profile Horizontal Resolution (m)		Vegetation 3D Structure Vertical Resolution (m)		Bathymetry Maximum Depth (m)		Geolocation Accuracy (m)		Vertical Accuracy (m)		Latency (days)		Repeat Frequency (days)		Duration for Repeating (months)		Rate of Change Accuracy (m per year)	
			A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T
How does the water cycle interact with other Earth System processes to change the predictability and impacts of hazardous events and hazard-chains?	Develop and evaluate an integrated Earth system analysis with sufficient observational input to accurately quantify the components of the water and energy cycles and their interactions, and to close the water balance.	Surface topography DTM, DSM	95	50	3	5					2	3	1	2			365	1825	60	24		
		Shallow water bathymetry DTM	95	50	5	10			5	2	3	5	0.1	0.25			365	1825	60	24		
		Vegetation 3D structure	95	50	10	30	0.5	2			5	15					30	365	60	24		
		Snow depth DSM-DTM	95	50	100	1000					50	500	1	2			365	1825	60	24		
How will cold region runoff, surface water bodies and groundwater respond to climate change and permafrost thaw?	Develop and evaluate an integrated Earth system analysis with sufficient observational input to accurately quantify the components (e.g., temperature, snow, surface water, vegetation structure, hydrologic connectivity), of the water and energy cycles and their interactions.	Vegetation height	95	50	30	100	1	2			15	50	1	2			365	1825	60	24		
		Surface Topography DTM	95	50	10	30					5	15	0.1	0.2			10	365	48	24	0.1	0.5
		Shallow water bathymetry DTM	95	50	10	10			5	2	5	5	0.1	0.25			365	1825	60	24		
		Snow depth DSM-DTM	95	50	100	1000					50	100	1	2			365	1825	60	24		
		Water surface height DSM	95	50	1	30					1	15	0.2	0.25			10	365	48	24	0.1	0.5

Coastal Processes

Coastal Processes																						
Science or Application		Product	Spatial Requirements												Temporal Requirements							
Goal	Objective		Coverage for Area of Interest (%) (global, region or feature)		Grid or Profile Horizontal Resolution (m)		Vegetation 3D Structure Vertical Resolution (m)		Bathymetry Maximum Depth (m)		Geolocation Accuracy (m)		Vertical Accuracy (m)		Latency (days)		Repeat Frequency (days)		Duration for Repeating (months)		Rate of Change Accuracy (m per year)	
			A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T
How can large-scale geological hazards be accurately forecast in a socially relevant timeframe? (DS: S-1)	Quantify the impact of land cover change, modification and soil disturbances on water, carbon, sediment and energy fluxes at the land-sea continuum.	Topobathymetric DTM	80	60	5	15	0.2	0.3	25	10	2	5	0.25	0.50	30	30	45	365	90	40	0.20	0.40
What are the structure, function, and biodiversity of Earth's ecosystems, and how and why are they changing in time and space? (DS: E-1)	Predict threats to marine ecosystems and coastal/ benthic habitats (e.g., coral reef, saltmarsh, mangroves, seagrass, oyster reefs, etc.) (New: 2a,b). This will include addressing the following questions: a) How will coasts change by rising seas, erosion, subsidence, accretion, and anthropogenic influences? b) What are the predicted impacts of coastal storms and surge on coasts?	Topobathymetric DTM Water Surface DSM Vegetation Height	75	50	3	5	0.1	0.2	25	10	1	3	0.10	0.20	30	30	30	150	90	40	0.20	0.40
	Quantify the flows of energy, water, carbon, nutrients, etc., sustaining the life cycle and partitioning into functional types at the juncture of terrestrial and marine ecosystems.																					

Coastal Processes																						
Science or Application		Product	Spatial Requirements												Temporal Requirements							
Goal	Objective		Coverage for Area of Interest (%) (global, region or feature)		Grid or Profile Horizontal Resolution (m)		Vegetation 3D Structure Vertical Resolution (m)		Bathymetry Maximum Depth (m)		Geolocation Accuracy (m)		Vertical Accuracy (m)		Latency (days)		Repeat Frequency (days)		Duration for Repeating (months)		Rate of Change Accuracy (m per year)	
			A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T
Quantify how increased fetch, sea level rise and permafrost thaw increase vulnerability of coastal communities to increased coastal inundation and erosion as winds and storms intensify. (DS: C-8i)	Forecast, model, and measure tsunami generation, propagation, and run-up for major seafloor events. (DS: S-1d)	Topobathymetric DTM Water Surface DSM	95	80	1	5			15	10	2	5	0.20	0.50	30	30	30	150	90	40	0.20	0.40
	Assess and model the processes that drive and the predicted impacts of sediment transport, erosion, and deposition.																					
Support safety of marine navigation in nearshore areas	Assess shoals, reefs and other hazards to marine navigation, and model their change with time.	Topobathymetric DTM	95	80	2	5	0.3	0.5	20	10	2	5	0.25	0.50	30	30	30	150	90	40	0.20	0.40

Cross-cutting Applications

Cross-cutting Applications																										
Science or Application		Product	Spatial Requirements																Temporal Requirements							
Goal	Objective		Coverage for Area of Interest (%) (global, region or feature)		Grid or Profile Horizontal Resolution (m)		Point Cloud or Mesh Density (points per m^2)		Vegetation 3D Structure Vertical Resolution (m)		Bathymetry Maximum Depth (m)		Geolocation Accuracy (m)		Vertical Accuracy (m)		Slope Accuracy (rise over run)		Latency (days)		Repeat Frequency (days)		Duration for Repeating (months)		Rate of Change Accuracy (m per year)	
			A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T
Floods: Provide information to forecast and respond to major flood events. (New: A.1)	What are the current flood conditions and how are they expected to change in the near term? (New: A.1.a)	Surface Topography DTM Water Surface Height Vegetation Height Vegetation 3D Structure	90	75	5	30							1	3	0.1	0.5			1	3	1	3	2	1		
	What is the flood forecast for the upcoming flood season? (New: A.1.b)		80	50	10	30							1	3	0.1	0.5			3	14	7	14	12	6		
	How is subsidence and coastal processes (sediment deposition, erosion, loss of wetlands) impacting flood risk, egress routes, and other factors of societal importance? (New: A.1.c)		80	25	10	50	20	10	1	2			1	3	0.1	0.5			30	90	15	30	72	36		

Cross-cutting Applications																										
Science or Application		Product	Spatial Requirements																Temporal Requirements							
Goal	Objective		Coverage for Area of Interest (%) (global, region or feature)		Grid or Profile Horizontal Resolution (m)		Point Cloud or Mesh Density (points per m^2)		Vegetation 3D Structure Vertical Resolution (m)		Bathymetry Maximum Depth (m)		Geolocation Accuracy (m)		Vertical Accuracy (m)		Slope Accuracy (rise over run)		Latency (days)		Repeat Frequency (days)		Duration for Repeating (months)		Rate of Change Accuracy (m per year)	
			A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T
Wildfire: Provide information to inform near- and long-term decisions to reduce the risk, occurrence, and societal impact of wildfires. (New: A.2)	What is the current fire risk, where is the fire perimeter, and in what direction is the fire likely to spread? (New: A.2.a)	Surface Topography DTM Vegetation Height Vegetation 3D Structure	80	50	10	100	20	10	1	2			1	2	0.5	1.5			1	3	1	3	6	1		
	What is the burn severity and where are the areas at risk of post-fire debris flow? (New: A.2.b)		80	50	10	100	20	10	1	2			2	3	1.0	1.5			7	14	7	30	6	1		
	How does vegetation structure relate to fire risk? (New: A.2.c)		80	50	30	100	20	10	1	2			1	2	1.0	1.5			7	30	90	365	72	36	0.5	1.0
	How does fire and fire regime impact regeneration and biomass in different biomes? (New: A.2.d)		80	50	30	100	20	10	1	2			1	2	1.0	1.5			7	30	90	365	72	36	0.5	1.0

Cross-cutting Applications																										
Science or Application		Product	Spatial Requirements																Temporal Requirements							
Goal	Objective		Coverage for Area of Interest (%) (global, region or feature)		Grid or Profile Horizontal Resolution (m)		Point Cloud or Mesh Density (points per m²)		Vegetation 3D Structure Vertical Resolution (m)		Bathymetry Maximum Depth (m)		Geolocation Accuracy (m)		Vertical Accuracy (m)		Slope Accuracy (rise over run)		Latency (days)		Repeat Frequency (days)		Duration for Repeating (months)		Rate of Change Accuracy (m per year)	
			A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T
Geological, Cascading, and Industrial Hazards: Provide information to inform decisions related to geological hazards and industrial accidents. (New: A.3) (Note: some specific hazards related to DS goals are in the Solid Earth SATM)	Where and to what extent has the event caused damage with significant societal impact? (New: A.3.a)	Surface Topography DTM Surface Topography DSM Built Environment Water Surface Height	80	25	3	20							1	5	0.05	0.5			1	3	1	7	2	1	0.1	0.5
	What are the interrelationships between geological, hydrological and coastal processes that lead to cascading hazards and where are they at most risk of occurring? (New: A.3.b)		80	25	3	20							1	5	0.10	0.5			14	60	15	90	72	36	0.1	0.5
Critical Infrastructure monitoring: How are critical infrastructure and their environs changing? (New: A.4)	Monitor surface conditions of the structures and their environs relevant to hazard assessment.	Surface Topography DTM Surface Topography DSM Vegetation Height Built Environment Water Surface Height	80	25	3	20	20	10	1	2	20	5	1	5	0.05	0.2			14	60	15	90	72	36	0.01	0.10

Cross-cutting Applications																												
Science or Application		Product	Spatial Requirements																Temporal Requirements							
Goal	Objective		Coverage for Area of Interest (%) (global, region or feature)		Grid or Profile Horizontal Resolution (m)		Point Cloud or Mesh Density (points per m^2)		Vegetation 3D Structure Vertical Resolution (m)		Bathymetry Maximum Depth (m)		Geolocation Accuracy (m)		Vertical Accuracy (m)		Slope Accuracy (rise over run)		Latency (days)		Repeat Frequency (days)		Duration for Repeating (months)		Rate of Change Accuracy (m per year)	
			A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T
Agriculture: How does crop health and productivity relate to vegetation structure and topography, and how can better estimates of current and forecasted yield and risk be made based on that information? (New: A.5)	Provide relevant information at the field and regional scale.	Surface Topography DTM Vegetation Height Vegetation 3D Structure	80	25	10	30	20	10	0.5	1			1	2	0.25	1.0			7	7	5	14	72	36		
Commercial forestry: What is the composition and status of natural and agroforest systems used for commercial forestry and how are they best monitored to effectively manage forest products and ecosystems services? (New: A.6)	What are the growth and removal rates of forests? What is the areal coverage and change of commercial forests? How does forest health and productivity relate to vegetation structure and topography, and how can better estimates of GPP be made based on that information? Which areas are logged and when were they logged? Where is conversion of primary forests to silvicultural production areas occurring (e.g., palm oil)? How are agroforestry systems distinguished from natural forest systems?	Vegetation Height Vegetation 3D Structure	80	25	1	20	20	10	0.5	1			1	2	0.25	0.5			7	10	30	90	72	36	0.25	1.0

Cross-cutting Applications																										
Science or Application		Product	Spatial Requirements																Temporal Requirements							
Goal	Objective		Coverage for Area of Interest (%) (global, region or feature)		Grid or Profile Horizontal Resolution (m)		Point Cloud or Mesh Density (points per m^2)		Vegetation 3D Structure Vertical Resolution (m)		Bathymetry Maximum Depth (m)		Geolocation Accuracy (m)		Vertical Accuracy (m)		Slope Accuracy (rise over run)		Latency (days)		Repeat Frequency (days)		Duration for Repeating (months)		Rate of Change Accuracy (m per year)	
			A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T	A	T
Deforestation: Provide information for operational deforestation monitoring and alerting. (New: A.7)	Provide information for near-real-time alerting of illegal logging.	Vegetation Height Vegetation 3D Structure	80	50	10	30	20	10	1	2			1	2	1.0	1.5			3	5	3	10	72	36		
	Provide information for REDD+ and emissions estimation from land cover change.		80	50	30	50	20	10	1	2			1	2	1.0	1.5			7	30	90	365	72	36		
Maritime navigation, ice hazards: Where and when is marine ice endangering maritime transportation routes? (New: A.8)		Surface Topography DSM Water Surface Height	80	50	10	50							10	50	0.50	3.0			1	3	1	7	8	4		
Coastal resiliency: What is the efficacy and consequences of RSLR mitigation activities that aim to improve coastal resiliency? (New: A.9)	Determine through measurement how the restoration or remediation activity is both performing the intended function and altering the environment through inter-related processes.	Surface Topography DTM Surface Topography DSM Vegetation Height Vegetation 3D Structure Built Environment Shallow Water Bathymetry Water Surface Height	80	20	5	20	20	10	1	2	10	5	1	3	0.05	0.5			30	90	15	30	120	36	0.1	0.5

APPENDIX B TEAM MEMBER CONTRIBUTIONS

Background

The National Aeronautics and Space Administration (NASA) solicited Decadal Survey Incubation Study Team proposals for the purpose of assembling a study team to advance Surface Topography and Vegetation (STV) incubation Targeted Observables (TO) program goals as outlined in the 2018 Decadal Survey. The Decadal Survey incubation program intends to accelerate the readiness of high-priority observables not yet feasible for cost-effective flight implementation. STV science goals call for exploring next-generation measurement approaches that could be ready for spaceborne implementation in 10+ years. The objective of the selected STV incubation study team is to identify methods and activities for improving the understanding of and advancing the maturity of the technologies applicable to STV and its associated science and applications priorities. The main deliverable produced by the study team is this study team report outlining potential future methods and activity areas, such as modeling and OSSEs; field campaigns; and a range of potential observing system architectures utilizing emerging sensor and information technologies.

NASA received a total of 62 proposals in response to this NRA for STV and Planetary Boundary Layer (PBL) and selected 11 STV proposals for funding. NASA added an additional three team members to round out the expertise for the study. This appendix summarizes the investigator contributions.

Andrea Donnellan

Jet Propulsion Laboratory, California Institute of Technology—STV Lead

Study Team Lead: Surface Topography and Vegetation

Andrea Donnellan is lead of NASA's Decadal Survey Surface Topography and Vegetation Incubation Study Team. The team will identify needed investments to help accelerate the readiness to implement high-priority and cost-effective flight observables in the next decade. Donnellan builds on her near decade of experience in exploring and maturing measurement capabilities and implementation concepts for measuring surface structure, from which land and ice surface topography and vegetation structure can be determined. These are necessary for understanding a wide range of land surface processes. Donnellan builds on her experience developing the community and implementation plan for ground based GNSS networks, such as SCIGN and PBO, and on her pre-formulation experience working as pre-project scientist and as a member of the project team for what is now the NISAR mission. Donnellan works with the study team to develop a preliminary SATM that identifies goals and objectives that are relevant to NASA and flow from the 2018 Decadal Survey. The team will identify existing measurement gaps and characterize physical parameters and observables as the scientific measurement requirements needed to meet the goals and objectives. From these flow the observing system requirements, projected performance and mission requirements. The team will need to identify modeling and OSSEs to characterize system concepts and needed field campaigns to provide proof of concept or validate measurements. The team will be divided into subteams to address various scientific or technical aspects of the study. The final product will be a range of potential observing system architectures utilizing emerging sensor and information technologies. In addition to the team developing requirements flow down, needed activities, and system architectures, the study team will develop a strategy to build a broad stakeholder community.

Donnellan builds on previous experience to meet the objectives of the STV study. Her work as pre-project scientist of the Deformation, Ecosystems Structure and Dynamics of Ice (DESDynI) mission (now superseded by GEDI and NISAR) required her to work with the solid Earth, crysosphere, and ecosystems/vegetation communities. It also required her to understand both lidar and radar measurements. More recently she has been working with optical, multispectral, and infrared imaging products to produce topographic products and characterize the land surface.

Donnellan has worked on mission concept formulation and understanding of the technologies, but her lead role is in achieving science goals and developing new scientific understanding. She brings this range of experience to leading the incubator study team, developing and synthesizing their expertise and contributions into a final product that is responsive to the Decadal Survey and NASA program goals.

David Harding

Goddard Space Flight Center—Technology Lead

Observing Strategies for Measurement of Surface Topography and Vegetation Structure

Observations of surface topography and vegetation structure, and their change, are critical foundation data necessary for a broad range of science objectives and applications needs, spanning solid Earth, biosphere, hydrosphere and cryosphere disciplines. Several technologies, deployed on UAV, aircraft and spacecraft, are being used to acquire this information. Those include LIght Detection and Ranging (lidar), Interferometric Synthetic Aperture Radar (InSAR), and stereo-photogrammetry. The optimal combination of platforms and technologies differs depending on the purpose for the data collection and is a function of surface characteristics and atmosphere conditions as well as spatial extent, horizontal and vertical resolution and accuracy, and temporal frequency and latency requirements. For example, airborne lidar, in the absence of clouds, is uniquely well suited for measurements of the vertical structure of dense vegetation and the elevation of the underlying ground, at local to regional scales, with very high resolution and accuracy. Spaceflight InSAR is well suited for global mapping of topography, in the absence of vegetation, at moderate resolution and accuracy day-or-night through any atmospheric conditions. Spaceflight stereo-photogrammetry, during daylight, cloud-free conditions, is well suited to make frequent, high-resolution, repeated measurements anywhere across the globe, of changing ground and vegetation top elevations. To meet the National Academy of Sciences recommendations, in the 2017 Earth Science Decadal Survey, for global observations of surface topography (including land, ice and snow) and vegetation structure (height and 3-D organization), an observing strategy that integrates NASA, international partner and commercial measurements from multiple platforms and instruments will likely be required. This requires rigorous knowledge of the science and applications objectives and measurement requirements, the current platform and instrumentation states-of-the-art, emerging capabilities and technical readiness of advanced technologies. With this information in-hand, trade studies can be conducted to design a well-conceived, cost-effective strategy that provides the roadmap for the next-generation of comprehensive, global topography and vegetation structure observations. As Technology Co-Lead for the Surface Topography and Vegetation Study Team, I will provide leadership for compiling the necessary information, conducting trade studies, identifying key technologies requiring advancement and publishing the findings of the study. For this activity, I bring considerable expertise in the design, development and utilization of state-of-the-art airborne and spaceflight lidar instruments. My Co-Investigators and Collaborators are leaders in instrument development and mission design study teams, and bring expertise in the acquisition, utilization and comparison of lidar, InSAR and stereo-photogrammetric data.

Alex Gardner

Jet Propulsion Laboratory, California Institute of Technology

Topography Measurements Required to Advance Ice Sheet, Ice Shelf and Glacier Science Over the Coming Decades

This proposal seeks membership to the Surface Topography and Vegetation (STV) study team. More specifically, I would like to represent the science needs of the ice sheet, ice shelf and glacier research communities and to inform the team on the strengths and limitations of various sensor technologies and sampling strategies when applied to measure surface topography over land ice. Accurate measurement of subtle changes in snow/firn/ice topography present unique challenges to laser and radar altimeters and to stereo reconstruction from optical imagery. Selecting the next STV mission that satisfies the measurement needs of the ice sheet, ice shelf and glacier communities, as outlined in the Decadal Survey Report, will require a careful exploration of measurement technologies and their performance capabilities over snow, firn and ice surfaces.

I feel I am qualified to assist with this task: I have published extensively on measuring ice sheet and glacier changes from space, I am a contributing author to the "Observations: Cryosphere" and "Sea Level" chapters of the IPCC's 5th Assessment Report on Climate Change, I am the PI of a large NASA MEaSUREs award to provide a continuous record of ice sheet elevation for the satellite era by synthesizing observations from 4 radar and 2 laser altimetry missions, I am funded to reconstruct past glacier topography from declassified analog stereo imagery, I have been the PI and a Co-I on numerous Earth Venture (Mission, Instrument, and Suborbital) concepts to measure changes in surface topography over ice, and I have been, for the past 5 years, one of three land ice scientists on the ICESat-2 science team.

By participating in the STV team I will work with the other land ice scientists to help NASA to further refine surface topography observational needs that are necessary to advance land ice research over the coming decades, as outlined in the Decadal Survey and supported by the land ice community through outreach activities. Once the needs are refined, I will work with the rest of the STV disciplines to provide guidance on the suitability of different surface topography measurement techniques (stereophotogrammetry, lidar, and radar altimetry) and sampling strategies (e.g., spatial and temporal coverage and vertical and horizontal resolution) to satisfy the identified measurement needs. I will work closely with the other STV scientists and technologists to examine an extensive set of technology options and to provide guidance on what additional work (e.g., community engagement, field campaigns, technology development, modelling, and OSSEs) should be recommended. I will help to summarize all of these findings in a study team report that will be presented by the team lead to NASA HQ. The outcome of this effort will ensure that NASA is well positioned to satisfy the Decadal Survey recommendations for observations of surface topography within the next decade and beyond.

Cathleen Jones

Jet Propulsion Laboratory, California Institute of Technology—Applications Lead

Surface Topography and Vegetation Incubation Study Support for Applications and Radar Technology

I applied for membership on the STV Incubation Targeted Observables (TO) Study Team to provide cross-cutting expertise between science/applications and technology. I proposed to lead the development of the "Applications" component of the SATM and, secondarily, to provide expertise on the capabilities and feasibilities of different radar technologies for contributing to STV TOs, both independently and in combination with other technologies, and for onboard processing and smart tasking to help handle the data-volume-related limitations of high-resolution space-based measurement of the STV TO.

As my primary role in the study, I lead the development of the Applications component of the STV TO SATM and identification of gaps and driving needs for the study team report, working with other team members who have experience and interest in applications. Building on experience with NISAR, I identify applications of relevance to a STV mission; prioritize the applications according to their impact to the end user community in terms of 1) uniqueness in filling an existing information gap and 2) the societal impact in terms of human, environmental and economic damage; and harmonize the Applications components to be commensurate with the Science components so that the same mission can achieve both Science and Applications goals and objectives. In performing this function, I will use literature search, input from the reports on NISAR's Applications Workshops that engage with the end user community in omnibus (2014, 2015) and topic-focused (2016—2019) workshops [See https://nisar.jpl.nasa.gov/applications/ for workshop reports], and contact with specific agencies, as relevant, in addition to the STV TO study team's community engagement.

As secondary roles, I support evaluation of the different technologies under consideration, in particular radars. I support activities to identify and evaluate on-board processing and smart tasking that reduce data storage and downlink requirements.

Yunling Lou

Jet Propulsion Laboratory, California Institute of Technology

Radar Trades and Technology Roadmap Development for Surface Topography and Vegetation Targeted Observables

I propose to participate in the Surface Topography and Vegetation (STV) incubation study team to develop a roadmap for maturing observing system architectures and identifying associated technology needs. If selected, I plan to represent the radar system and technology community to examine how radar interferometry may complement lidar observations in providing all weather land and ice topography measurements and vegetation structure, and identify activities such as data analysis and field campaigns to help mature observing system architectures and identify associated technology gaps.

There have been C-band and X-band spaceborne interferometric radars for land topography as well as Ka-band airborne interferometric radar for ice topography. More recently, researchers have demonstrated the use of PolInSAR and TomoSAR techniques with airborne P-band and L-band radars for vegetation structure studies. There has also been reports of using C-band SAR intensity to infer shallow water bathymetry. I propose that we examine existing spaceborne and airborne radar data, combined with modeling if necessary, to determine the best radar frequency for generating land and ice topography in complex terrain as well as the most suitable radar imaging technique for vegetation structure in wet ecosystems that will complement lidar observations. I propose we strategize the most effective and efficient architectures to combine lidar and radar techniques and perhaps stereo optical sensors that will meet all the objectives of the STV observing system. I will identify technology feasibility in assisting with the observing system architecture trade study.

Paul Lundgren

Jet Propulsion Laboratory, California Institute of Technology

STV: Earth Surface and Interior Science Topography and Topography Change

Surface topography and topography change are fundamental to a number of areas within Earth Surface and Interior science. High-resolution topography is important to a number of disparate subdisciplines, including near coastal bare-earth topography relevant to sea level rise; high-resolution in areas prone to landslides; near-fault topography for earthquake science and hazard; high-resolution topography and topography change relevant to volcano science and hazard. Examples exist of the benefits of high-resolution, often bare-earth, topography in each area, yet future science and applications in each area will require global datasets that meet the needs of each subdiscipline.

I propose to represent Earth Surface and Interior science and applications topography and topography change as a member of the Surface Topography Vegetation (STV) science team. In particular I will bring my experience with volcano science and applications needs to the science team. For volcano hazards topography has long been recognized as important. During eruptions hazards include pyroclastic flows, lava dome collapse and lava flows. Accurate, high-resolution topography is needed to better predict flow directions and run-outs, while growing domes and expanding lava flows require high-resolution repeat topography to measure their growth. Post-eruption, volcano topography is needed for hazards such as lahars (debris flows along river channels). Topography change is also important for constraining physical volcano models in which lava domes and flows measure one component necessary to constrain dynamical models governed by mass balance and momentum conservation. While still a research topic, such models have the potential to forecast system behavior on timescales relevant to volcano unrest and eruption forecasting when topography change observations are combined with surface deformation and possibly other constraints.

As an example, we recently used the NASA GLISTIN-A instrument to map topography changes due to lava flows and caldera collapse associated with the 2018 eruption of Kilauea volcano, Hawaii (Lundgren et al., submitted). Here we found that for the caldera collapse (over 500 m of topography change), pre- and syn-eruption digital elevation models (DEMs) from GLISTIN-A's single-pass radar could be differenced to produce reliable maps of topography change and track the caldera volume loss with time. Instead, detailed volume estimates from the Lower East Rift Zone lava flows required use of a lidar bare-earth DEM to remove the effects of vegetation, which, otherwise, would prohibit accurate effusion volume estimations.

Most of my experience lies in the use of surface deformation to problems in volcano and earthquake/fault processes, combined with numerical forward and inverse modeling of volcano/earthquake/fault mechanical source studies. My current research is focused on constraining dynamical physics-based models constrained by deformation, thermal, and mass balance (caldera/lava effusion) observations as available. Such time variable models are important for developing volcano OSSEs that would include the effects of topography change data on constraining these model parameters, including forecasts of eruption duration and volume. My experience in the analysis of fault slip and the effects of groundwater volume changes to fault stress changes are relevant to high-resolution, high accuracy topography and topography change data. As part of the science team I would contribute to the anticipated reporting and writing.

My background in volcano and fault processes and their demands for high-resolution, high accuracy topography and topography change measurements will allow me to bring an important solid Earth perspective to the STV team, with recommendations for the observations required to achieve the underlying measurements that will advance Earth Surface and Interior science and applications.

Sassan Saatchi

Jet Propulsion Laboratory, California Institute of Technology

Multi-Sensor/Platform SAR and Lidar Techniques for Surface Topography and Vegetation Structure Incubation Study

Bare surface topography (ST) under vegetation is referred to as the digital terrain model (DTM) and is considered a critical characteristic of the land surface structure controlling a variety of ecological and hydrological processes of the Earth system (Franklin, 1995; Ambroise, Beven and Freer, 1996; Price, 2011). Furthermore, the horizontal and vertical variations of vegetation structure (VS) above the earth surface define the terrestrial ecosystem health, diversity, and function such as carbon, water, and energy cycling from local to global scales. Together ST and VS play a critical role in defining the dynamics of Earth's critical zone and the climate system. In recent year, two techniques have been developed to provide the surface topography and vegetation structure (STV) measurements from airborne and spaceborne platforms. Synthetic Aperture Radar (SAR) interferometry and Tomography (TomoSAR) measurements at very low frequencies (P-band and L-band) with penetration into the forest canopy have demonstrated the potential of providing estimates of DTM and vegetation vertical structure simultaneously but with medium spatial resolution and variable DTM precision. As an alternative, Lidar sensors, have been able to provide precise forest structure and DTM under dense vegetation and shallow water, but with limited coverage and variable technology readiness for long-term observations.

STV incubation study provides a great opportunity to examine the potential of both imaging SAR and Lidar techniques in terms of technology readiness for space applications, measurement performance, and data fusions approaches. I propose to participate in the STV study team and to nominate myself as the science lead to address and achieve the following objectives during the incubation study period:

1. To develop science and measurement requirements following the decadal survey guidance using existing and emerging science and technology
2. To review existing and emerging STV technology, mission architectures, small satellite, information technologies, and identify data and technology gaps, and recommend studies, experiments and airborne and field campaigns.
3. To develop OSSEs to address mission design and performance during the incubation period.
4. To develop the SATM for the space implementation by linking the science goals and objectives of STV to observables and instrument and mission functional requirements
5. To follow the study guidelines by focusing on studies associated with required deliverables, including the final study team report.

Marc Simard

Jet Propulsion Laboratory, California Institute of Technology

The Path to Remote Sensing of 3D Landscapes

I participate in the Surface Topography and Vegetation (STV) Team to provide interdisciplinary expertise in: 1) global mapping of forest canopy height with lidar and Synthetic Aperture Radar (SAR) interferometry (InSAR); 2) generating digital elevation model NASADEM and 3) integrating remote sensing with hydrological and ecological models.

The Surface Topography and Vegetation (STV) Targert Observable (TO-20) addresses 23 science objectives of which 8 are classified as Most Important. While the Decadal Survey (DS) identifies STV as a high priority TO, it is deemed to "lack sufficient technical maturity to be considered ready for low-risk implementation." I strongly believe it can quickly be brought to maturity for consideration for a mission opportunity. Already, significant advances can be achieved using the existing plethora of radar, lidar and optical remote sensing data from airborne and spaceborne platforms. These data can be used to develop, improve and evaluate algorithms to accurately measure surface topography, retrieve vegetation 3D structure, and observed hydrologic processes in rivers, lakes, reservoirs and wetlands.

The DS introduces a preliminary SATM. The SATM is an effective tool to develop missions responding to science needs as it connects the science requirements to instrument and mission requirements. As such, the proposed study aims at developing the SATM, refining requirements, studying measurement alternatives, and identifying activities to advance the STV mission.

As a member of the STV Science Team, I will work with the Science Lead, the Technology Co-lead, and other members of the STV Team to organize team meetings, foster integration of scientific needs, and actively participate drafting and finalizing the study study team report. I plan to address the following themes with supporting tasks, emphasizing the Most Important Objectives:

1. Science and measurement requirements:
    a) identify and justify the required accuracy on estimation of geophysical parameters required to enable a science leap or at least a significant advance—i.e., baseline and threshold requirements. (e.g., canopy height within 1-meter, ground elevation within 2-meters)
    b) Identify (e.g., Where, when and how often are measurements needed) and justify (i.e., why?) functional requirements (i.e., timing, spatial and temporal sampling) to enable a science leap or at least a significant advance. The functional requirements, with remote sensing observables, define the mission configuration (e.g., orbit cycle and instrument's field of view).
2. Remote-sensing methods:
    a) Inventory current data and algorithms, and evaluate their ability to respond to estimation of geophysical parameters within accuracy requirements.
    b) Identify and assess the impact of technological limitations of spaceborne lidar, InSAR, PolinSAR, TomoSAR and photogrammetric instruments in achieving needed measurements within functional requirements. In addition to supporting the development of the SATM, these themes—and supporting tasks—will help identify the research and development activities necessary to provide commensurate technological alternatives for an STV Mission.

Jason Stoker

US Geological Survey Reston

Assessing Surface Topography and Vegetation Missions in Relation to the 3D Elevation Program

As the civilian mapping agency responsible for terrestrial elevation data for the United States, USGS has been collecting topographic data since its inception, and we continue that tradition via collecting and providing high-resolution elevation data useful for a wide variety of applications via the 3D Elevation Program (3DEP). We have been working on formulation and implementation of a similar National-specific strategy for many years and have been executing it via the 3DEP. We created a requirements and cost/benefit study in 2012- the National Enhanced Elevation Assessment (NEEA)- that gave USGS the information needed to design a National airborne lidar campaign.

At the time spaceborne technology could not support the level of detail that the study requirements outlined for 3D data. I personally believe that there are now potential technological solutions available that could meet a large part of our national stakeholders' requirements via a capability NASA could design and implement.

We are working toward future development of a 3D National Terrain Model that expands the scope of what the 3D Elevation Program is involved in to include mapping elevation values inland- above and below water surfaces. As a result, our interests have expanded to understanding technologies that can image both above and below the water surface. We plan to better understand what potential technologies may help us achieve our National 3DEP related requirements. Another part of my personal vision as it relates to 3DEP and this study is that there is not likely a "one size fits all solution" to meet all our known stakeholders' requirements. 3DEP was originally designed to use a single technology to maximize the return on investment of users' needs. I have been advocating a multi-modal approach for the next generation of 3DEP, one where a spaceborne solution developed from this effort in addition to other technologies could be an extremely valuable component of the future of 3DEP. This approach has also been advocated by our current USGS Director. Multi-modal may include non lidar-based technologies as well. Integration across platforms will be key.

In addition to being involved in the National Enhanced Elevation Assessment mentioned above, which allowed us to develop a National 3DEP implementation plan, I have also been extremely active in the new "3D Nation Requirements and Benefits study." This study, in partnership with NOAA, is a comprehensive study of requirements and benefits for improved elevation data that covers the geographic scope as defined by the 3D Nation vision will help Federal mapping agencies to develop and refine future program alternatives for enhanced 3D elevation data to meet many Federal, State, and other national business needs. (https://communities.geoplatform.gov/ngda-elevation/3d-nation-study/) I believe that the information we extract from this comprehensive study will be extremely valuable to this NASA STV Study Team. This study is focused on specific requirements for the United States but is expanding to include bathymetric information- including inland and coastal/ocean regions.

Robert Treuhaft

Jet Propulsion Laboratory, California Institute of Technology

Vegetation Structure, Biomass, and Dynamics: Measurement Strategies for Carbon Accounting

This proposal is about next-generation measurement approaches to the Surface Topography and Vegetation targeted observable (TO). It is specifically aimed at vegetation structure and aboveground biomass (AGB), and their changes.

The science question to which the TO in the Decadal Survey (DS) responds, is in E-1 of DS Table S.1: "What are the structure, function, and biodiversity of Earth's ecosystems, and how and why are they changing in time and space?" The objective which will answer this question is in DS Table 3.2: "quantify the global 3-dimensional structure of terrestrial vegetation...spatially and over time." The PI's personal science vision for this DS objective is that the incubation-science-team (ST) report include science-driven numbers for resolutions and performance specifications by the end of the incubation period. As a starting point, the ST should recommend structure and AGB data products with ~subhectare (ha) spatial resolution and ~1-month temporal resolution, consistent with time scales of human and natural disturbance. Current large errors in global atmospheric carbon-flux due to land use change of ~50% should be reduced, consistent with the FA, by global, contiguous repeat structure and AGB measurements.

The PI's personal technical vision of this proposal is to prompt the ST to consider the concept of an observation vector, as a way to generate incubator descriptions of mission architecture. The observation vector contains measurements from all instruments/platforms relevant to measuring vegetation structure and AGB. A transfer function is applied to the observation vector which converts remote sensing observations into forest structure and

AGB estimates. Demonstrations of the feasibility and accuracy of the products of the observation-vector/transfer-function formalism, perhaps by simulations or results in the literature, will shed light on the efficacy of mission components determining mission architectures. The vision includes constructing a sensitivity table or matrix, the i,j element of which is the derivative of observation i with respect to structural parameter j. This matrix will inform the formulation of observation vectors and transfer functions.

The approach to work accomplished in this proposal on the ST for 1 year is:

1. Refine the scientific objectives of this TO in the DS by suggesting science-driven resolutions and accuracies of the structure and AGB parameters to be estimated. This will rely on searching the literature to understand the large errors in land-use-dynamics estimates (50%).
2. Determine what activities are needed to formulate the sensitivity matrix, described above. By exploring literature and by simulation, the PI and other members of the ST will start the evaluation of both mechanistic, model-based methods and empirical (regression) approaches, to be recommended in the ST report. The recommended activities for the incubation period could include, for example, field measurements along with hyperspectral and interferometric airborne passes, both existing and new, over diverse forest types.
3. Specify what activities are needed during incubation to define the transfer functions between the most promising remote sensing observations and structural parameters (e.g., height), as well as the transfer functions from structural parameters to AGB. Derive candidate mission architectures based on observation vectors and transfer functions. The PI and other members of the ST will search the literature for analyses pertinent to estimating structural and AGB parameters from remote sensing data, and begin the assessment as to the most promising approaches, to be elaborated in the study team report.
4. Determine activities for multiple-epoch, structure and AGB dynamics studies. These could include permanent-plot fieldwork, or analysis of new or in-hand airborne or spaceborne sensor data taken at multiple epochs, and simulations including common-mode errors.

Konrad Wessels

George Mason University

Vegetation structure

Dr. Wessels has extensive experience in the remotely sensed characterization of the vegetation structure TO with lidar, SAR, and MISR. As Chief Scientist with the Council for Scientific and Industrial Research (CSIR, South Africa) he played a leading role in a collaborative research program with Carnegie Airborne Observatory (CAO, an integrated lidar and hyperspectral system, led by Dr. Greg Asner) on the relative impacts of fire, humans, and elephants on woody savanna structure in and around Kruger National Park (South Africa). He furthermore directed (i) the implementation of a remote-sensing and modelling system to perform South Africa's National Terrestrial Carbon Sink Assessment, and (ii) a national system to map woody biomass with SAR data using airborne lidar training data and machine learning (South Africa and Namibia). He and his colleagues at CSIR specialized in estimating aboveground biomass change and 3D structure in low-biomass savanna environments, publishing widely on the topic. With a strong background in ecology and operational monitoring, reporting, and verification (MRV), he understands the user requirements of the community and challenges they face due to current high levels of error in remotely sensed products. He has led multidisciplinary remote-sensing research projects in the following application areas: fire (active, burned area, fuel condition and fire danger modelling), modelling carbon stocks and fluxes at country level, AGB estimation, quantifying ecosystem services, savanna ecology, communal resource management, land degradation, land use and land cover change. He has gained crucial experience in SATM development as a member of the Application Working

Group of the Surface Biology, Geology (SBG) mission, specifically in applications related to terrestrial ecosystems, carbon, and conservation. He has worked closely with JPL staff for the past 7 months to formulate numerous applications and their required observations (spatial, temporal resolutions, latency, etc.) under specific Designated Observables science questions. He was the first author of a poster at the SBG Community Workshop (Washington, DC, June 2019) titled "SBG Applications: Terrestrial Ecosystems—Carbon and Conservation." He was previously involved in mission preformulation in the EOSAT1 Mission Advisory Committee (appointed by the South African National Space Agency). The proposal suggests how TO20, vegetation structure, and TO22, 3D canopy structure and biomass, as well as changes in aboveground carbon stocks will be addressed simultaneously. The incubation study team is suggested to follow a process similar to that of the SBG working groups, which recently completed the STM for TO-18. Three working groups are proposed: Science Questions and Measurements (SQM), Sensor Technologies and Architectures (STA), and Modelling and Algorithms (MA). Following a brief review of measurement requirements and current sensor technologies, observation gaps will be identified. The STA working group, broader community, as well as specific experts and private industry will be invited to consider alternative sensor technologies aligned with the required measurements and their technology readiness. The most promising technologies will be identified for incubation over the next 10 years.

Christopher Parrish

Oregon State University

Shallow Water Bathymetry—STV Incubation Program Study Team

There is a pressing need for shallow bathymetry in coastal and inland waters throughout the world. Challenges to mapping shallow bathymetry include: 1) hazards associated with operating small boats in uncharted nearshore water, particularly in the presence of breaking waves, coral reefs, rocks, and other submerged dangers to navigation; 2) high-energy nearshore environments; 3) nearshore processes and rapid morphological change; and 4) the remoteness of many coastal and inland waters. As a result, shallow bathymetric data are either obsolete—in some cases, derived from surveys conducted in the 1800s—or entirely nonexistent for many areas. This data gap inhibits storm vulnerability assessments, benthic habitat mapping and monitoring (e.g., coral reef and seagrass habitat), tsunami inundation modeling, wetlands studies, coastal zone management, sea level rise studies, and a range of hydrologic applications. As a member of the STV incubation study team, Christopher Parrish will contribute expertise on shallow bathymetric mapping using a wide-range of remote sensing platforms, sensors, and algorithms in order to achieve the following objectives:

1. Document the current state-of-the-art in shallow water bathymetric mapping.
2. Interface with stakeholders across a broad range of coastal-hydrologic subdisciplines, including coastal zone management, nautical charting, benthic habitat mapping and regional sediment management to quantitatively document unmet shallow bathymetry requirements (e.g., spatial and temporal accuracies and resolutions) and related geophysical observables.
3. Prototype bathymetry retrieval algorithms using existing sensor data, including ICESat-2 ATLAS, Landsat 8 OLI, and Sentinel-2, among others.
4. Develop recommendations for dedicated future spaceborne shallow bathymetry sensor suite.
5. Deliver conference/workshop presentations on STV ST efforts (e.g., at JALBTCX Coastal Mapping and Charting Workshop, ASPRS, Coastal GeoTools) and solicit feedback from participants.
6. Contribute to STV study team report (the final deliverable from the STV Study Team), as well as the interim report.

Marco Lavalle

Jet Propulsion Laboratory, California Institute of Technology

Surface Topography and Vegetation Study Team: From Scientific Objectives to TomoSAR Measurements

The recent report from the 2017 US National Academies of Sciences, Engineering, and Medicine Decadal Survey recommended the fine-scale, global mapping of three-dimensional vegetation structure, bare-Earth topography, ice topography and shallow water bathymetry as high-priority incubator observables to undertake in the next decade. These observables are critical to improve understanding of geologic structure, tectonic and volcanic activity, geomorphic processes, sea-level rise and storm surge in coastal areas, ice mass balance, carbon cycle and carbon storage, land-use change, and linkage between biodiversity and habitat. Despite their extremely high relevance, an affordable space mission for measuring surface topography and vegetation (STV) with the desired spatial and temporal sampling has not been proposed to date due to the technological limitations.

Recent advances in radar technology and remote sensing have shown that multiple InSAR observations taken from different look angles, i.e., TomoSAR observations, can provide high-resolution, gap-free maps of 3D vegetation structure and underlying topography, and can be implemented via simplified and lightweight distributed radar architectures. Supported by these advances and preliminary studies conducted at NASA/JPL, my long-term vision is to work towards the best satellite architecture for measuring STV through a rigorous end-to-end trade study that encompasses state-of-the-art radar and lidar technologies and recent retrieval algorithms, and generates measurable metrics to be evaluated under varying scene parameters, orbital configurations, and satellite and instrument characteristics.

In this context, my role as a Study Team member is to represent the TomoSAR measurement by providing expertise ranging from scientific objectives definition to technology requirements evaluation. During the one-year study, (1) I will help refine the scientific objectives starting from the Decadal Survey's recommendations and by leveraging my experience with leading the Decadal Survey's RFI #2 "3D Vegetation Structure and Dynamics." My inputs will contribute to define the left-hand side of the SATM for all STV objectives that are expected to be addressed by radar technology. (2) I will assess the recent Histogram Tomography approach over AfriSAR and ABoVE campaign sites, and compare the performance between L and P bands, lidar and previous TomoSAR algorithms to generate a report with the observed TomoSAR performance for the STV Study Team meetings. (3) Using existing tools at JPL, and informed by the TomoSAR data analysis, I will generate a preliminary TomoSAR SATM for inclusion in the study team report to be delivered at the end of the 1-year study.

As a background, I have over 10 years of experience in algorithm development, model formulation, and mission concept design for STV mapping, with emphasis on tomographic SAR technique. I led the Decadal Survey RFI-2 study team report "3D Vegetation Structure and Dynamics." I have been PI and Co-I of NASA and ESA-funded proposals working closely with science and technology radar and lidar experts. I led the innovations of the SRTM processor for the generation of the recent NASADEM. I am member of the MAG of the future ESA ROSE-L mission and member of the JPL NISAR Project and UAVSAR Project Science Teams. I have published several peer-reviewed papers utilizing radar and optical data. I am the radar Project Scientist for the Multi-Mission Algorithm and Analysis Platform. I have been peer-reviewing tens of papers on radar techniques for ecosystem science. I have been part of the scientific committee of the PolInSAR workshop, IGARSS, and the Multi-static SAR ESA workshop. I have been organizing invited sessions on vegetation structure at international conferences and have been invited to give talks at international conferences and universities.

APPENDIX C COMMUNITY ENGAGEMENT

Introduction

In developing the STV SATM, input from the science and applications communities was solicited through six online workshops, distributed over several weeks in July and August, consisting of the first plenary workshop and five discipline breakouts on solid Earth, vegetation structure, cryosphere, hydrology and coastal processes. The plenary introduced the STV Observable, explained the purposes of the STV study, introduced the community to the SATM and product needs questionnaire, and provided overviews of the five discipline areas. In the discipline breakouts, organized by the study team leads for each discipline, the study purposes and SATM were reviewed, the leads gave an overview of the scope of that discipline in the context of STV and discipline experts gave presentations on key science and applications activities. That was followed by a discussion period for questions, answers and comments, accompanied for some of the breakouts by interactive poll questions. The number of participants in each discipline breakout is shown in Figure C-1 and the number of participants during the course of the four-hour breakouts are in Figure C-2, showing very strong retention throughout the breakouts.

FIGURE C-1. Number of participants in the science and application breakouts, by discipline.

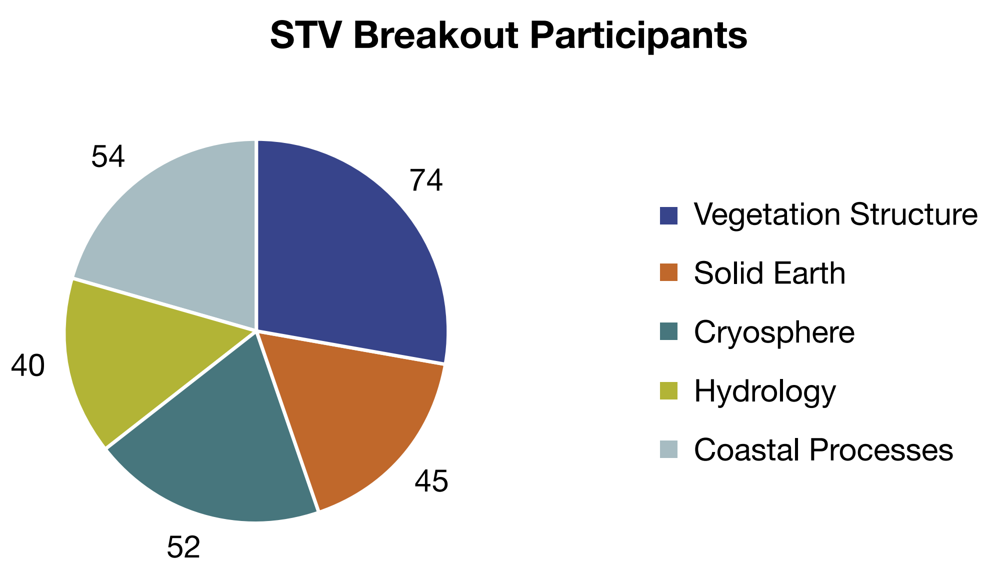
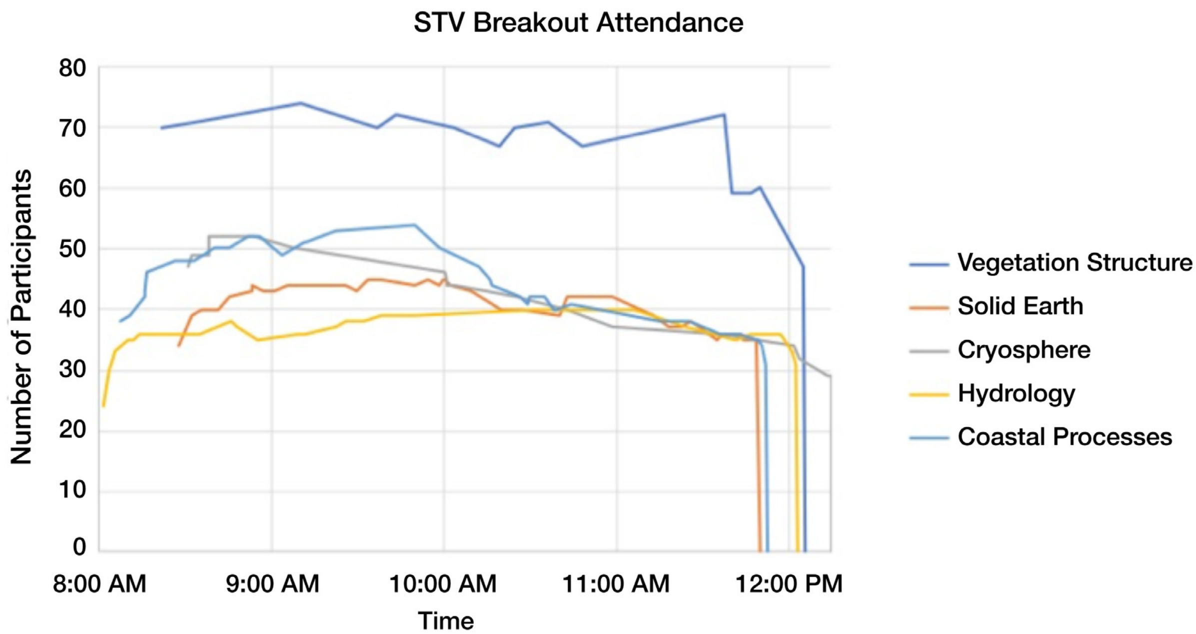


FIGURE C-2. Number of participants during the course of the breakouts, by discipline.



Over several weeks in September, four technology breakouts were held, for lidar, radar, stereophotogrammetry and information systems. The breakouts were organized by the study team leads for each of the technologies. In each breakout preliminary questionnaire results on product needs were presented and the technology scope for STV was described. Following that, the leads gave overview presentations about current capabilities and technology experts gave presentations on emerging technologies pertinent to STV. Interactive poll questionnaires were used to gather input from the workshop participants. A discussion period for questions, answers and comments concluded these breakouts. Each technology breakout maintained a consistent number of participants during the course of the four-hour breakouts showing strong retention throughout the breakouts.

APPENDIX D PRODUCT NEEDS QUESTIONNAIRE

Community input for the STV SATM was solicited on science and application objectives, and product needs to meet those objectives, using an on-line questionnaire. The questionnaire was made available following the discipline breakout sessions. Requests to provide responses were distributed to experts in the STV science and applications disciplines identified by Study Team members as well as through NASA HQ program manager mailing lists. The total number of responses was 149. The breakdown of number of responses per discipline is shown in Figure D-1. The high number of responses in the vegetation structure and cryosphere disciplines likely reflects the substantial expertise in those communities using satellite-based are airborne height measurements that are widely available and well suited for their objectives.

The questionnaire requested product requirement inputs for science or applications objectives specified by the responders. The focus was on height and bathymetry products, independent of the technologies used to acquire the data. Responders we able to provide requirements for up to five products, selected from:

- Digital Terrain Model (gridded ground surface)
- Digital Surface Model (gridded highest surface)
- Vegetation height (gridded maximum height above the ground; terrestrial or benthic)
- Vegetation 3D structure (gridded organization of vegetation components and gaps; terrestrial or benthic)
- Built environment (gridded footprints and heights of buildings and infrastructure)
- Shallow water bathymetry (gridded depth)
- Water surface (gridded elevation)
- Profile
- Point cloud
- Mesh (Triangulated Irregular Network—TIN)

For the selected product, responders were asked to provide information for:

- **Products you currently use**
- **ASPIRATIONAL** and **THRESHOLD** requirements: What would enable an advance in your objective beyond what can be accomplished with regional to global products that are currently available or are expected to be available in this decade.
- **ASPIRATIONAL QUALITY**: What would enable a **DRAMATIC ADVANCE** at regional to global scales
- **THRESHOLD QUALITY**: What would enable an **IMPORTANT ADVANCE** at regional to global scales

They were asked to consider these factors while providing their responses:

- The requirements you provide need to be well justified. We ask you to identify if published literature and/or your professional experience provides the foundation for your responses. If there are questions for which you do not have a basis for requirements, please do not provide a response.
- Consider if aspirational and threshold qualities that are sufficient for regional to global objectives can be lower quality than what you currently use for local studies.
- Objectives which focus on a limited number of areas for which data can be acquired by local aircraft or drone flights are outside the scope of STV. Do not provide requirements for those kinds of objectives.
- Do not limit your threshold and aspirational requirements by what you think technology can accomplish, now or in the future. Focus on what product quality you need to advance your science or application.

The information requested consisted of spatial and temporal parameters. Because only well-justified requirements were to be included in the SATM, for each parameter responders were asked to indicate whether the requirements they specified were based on published literature or on their professional experience. To establish traceability, citations to the pertinent literature and a description of the responder's professional experience were requested.

The parameters consisted of:

Spatial

- Coverage: the percentage of their area of interested included in the product, identifying their area of interest by specifying geographic extent and/or specific features
- Horizontal resolution for gridded or profile products
- Density (points per square meter) for point cloud or mesh products
- Vertical resolution for vegetation structure
- Maximum water depth for bathymetry
- Geolocation accuracy
- Vertical accuracy
- Slope accuracy

Temporal

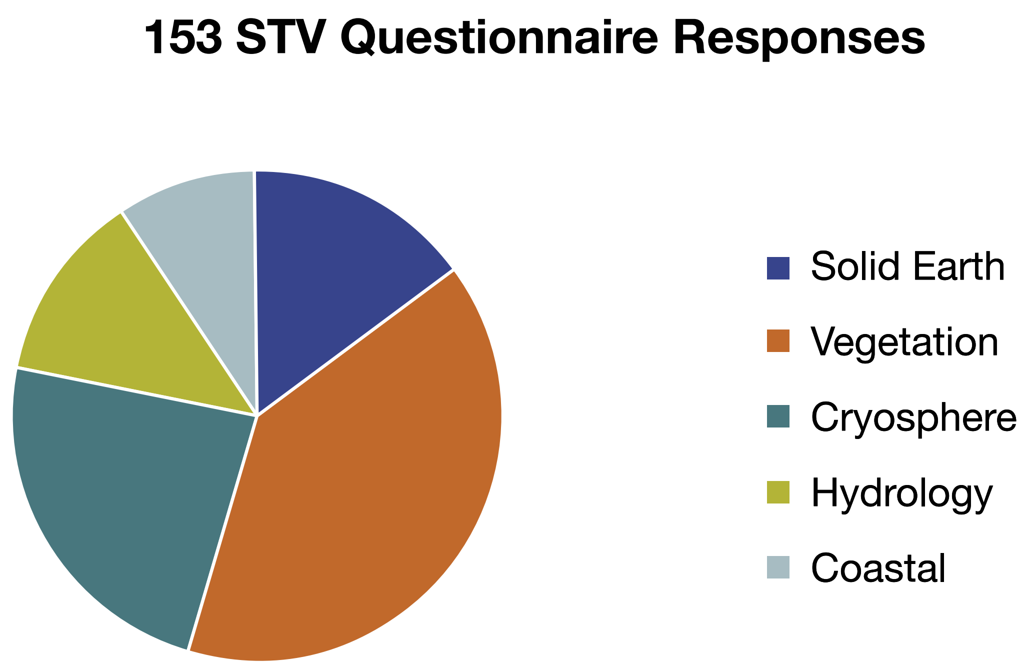
- Latency: time from acquisition of the data to delivery of the product
- Repeat frequency
- Duration: for how long are the measurements repeated
- Rate of change accuracy

For the product being described, responders were also asked to identify which of these parameters were most important to be improved in order to better accomplish their objective, selecting up to three.

The following figures plot mean values for these parameters, combining all product types, for the five science and applications disciplines. Prior to computing the means, the team lead for each discipline reviewed their communities' responses. Based on their professional expertise and understanding of the purpose of the STV SATM, and in consultation with other team members with expertise in that discipline, they selected minimum and maximum values to exclude outliers.

- Minimum value to exclude responses that are unrealistically too stringent, and are not necessary for regional to global objectives. These could, for example, be based on very high-resolution data the responder is using for limited, local studies.
- Maximum value to exclude outliers that were judged to be inadequate for the specified objective. In some of those instances, it was apparent that a responder did not understand the meaning of a parameter.

FIGURE D-1. Community input questionnaire discipline response breakdown.



APPENDIX E TECHNOLOGY QUAD CHARTS

Input from technologists were solicited in the form of quad charts patterned after the NASA Earth Science Technology Office (ESTO) format, seeking information on technologies relevant for STV. Information on the following technologies was requested:

- Instrumentation (hardware or processing and analysis methods)
- Information systems (hardware or software for assessment or operation of observing systems, sensor webs, or multi-source data fusion and analysis)
- Platforms (UAV, aircraft or satellites and systems for on-platform data processing and transmission).

Requests for inputs on current and emerging technologies were sent to technology leaders identified by Study Team members and those on the ESTO email distribution list, and were also requested during the technology breakout meetings. Follow-up requests were made to investigators identified in the searchable ESTO Portfolio database. Technologists included those working in the federal government, academia and the commercial sector. To distinguish current and emerging technologies, definitions of technical readiness level (TRL) established by ESTO were provided in the requests (Tables E-1, E-2). Responders were asked to use the current technologies template (Figure E-1) for activities they judged to be at TRL levels 7 through 9 and the emerging technologies template (Figure E-2) for activities at TRL levels 1 through 6.

Quad charts were not requested for one current lidar technology approach. A large number of commercial airborne scanning sensors, acquiring discrete-return lidar mapping data, are in operation. These were not included because information on them is readily available. The focus here is on technologies that expand capabilities beyond those standard systems.

Responders were directed to only provide material suitable for full and open distribution. They were informed that submittals shall be considered approved by the providing organization to be suitable for full and open distribution. No proprietary, export controlled, classified, or sensitive material should be provided.

Sections follow that compile the current and emerging quad charts received for lidar, radar, stereophotogrammetry and information system technologies.

TABLE E-1. NASA ESTO Technical Readiness Level definitions for current technologies.

TRL	Definition	Hardware Description	Software Description	Exit Criteria
7	System prototype demonstration in an operational environment.	A high fidelity engineering unit that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate performance in the actual operational environment and platform (ground, airborne, or space).	Prototype software exists having all key functionality available for demonstration and test. Well integrated with operational hardware/software systems demonstrating operational feasibility. Most software bugs removed. Limited documentation available.	Documented test performance demonstrating agreement with analytical predictions.
8	Actual system completed and "flight qualified" through test and demonstration.	The final product in its final configuration is successfully demonstrated through test and analysis for its intended operational environment and platform (ground, airborne, or space).	All software has been thoroughly debugged and fully integrated with all operational hardware and software systems. All user documentation, training documentation, and maintenance documentation completed. All functionality successfully demonstrated in simulated operational scenarios. Verification and Validation (V&V) completed.	Documented test performance verifying analytical predictions.
9	Actual system flight proven through successful mission operations.	The final product is successfully operated in an actual mission.	All software has been thoroughly debugged and fully integrated with all operational hardware/software systems. All documentation has been completed. Sustaining software engineering support is in place. System has been successfully operated in the operational environment.	Documented mission operational results.

TABLE E-2. NASA ESTO Technical Readiness Level definitions for emerging technologies.

TRL	Definition	Hardware Description	Software Description	Exit Criteria
1	Basic principles observed and reported.	Scientific knowledge generated underpinning hardware technology concepts/applications.	Scientific knowledge generated underpinning basic properties of software architecture and mathematical formulation.	Peer reviewed publication of research underlying the proposed concept/application.
2	Technology concept and/or application formulated.	Invention begins, practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture.	Practical application is identified but is speculative, no experimental proof or detailed analysis is available to support the conjecture. Basic properties of algorithms, representations and concepts defined. Basic principles coded. Experiments performed with synthetic data.	Documented description of the application/concept that addresses feasibility and benefit.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Analytical studies place the technology in an appropriate context and laboratory demonstrations, modeling and simulation validate analytical prediction.	Development of limited functionality to validate critical properties and predictions using non-integrated software components.	Documented analytical/experi-mental results validating predictions of key parameters.
4	Component and/or breadboard validation in laboratory environment.	A low fidelity system/component breadboard is built and operated to demonstrate basic functionality and critical test environments, and associated performance predictions are defined relative to the final operating environment.	Key, functionally critical, software components are integrated, and functionally validated, to establish interoperability and begin architecture development. Relevant Environments defined and performance in this environment predicted.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of relevant environment.
5	Component and/or breadboard validation in relevant environment.	A medium fidelity system/component brassboard is built and operated to demonstrate overall performance in a simulated operational environment with realistic support elements that demonstrates overall performance in critical areas. Performance predictions are made for subsequent development phases.	End-to-end software elements implemented and interfaced with existing systems/simulations conforming to target environment. End-to-end software system, tested in relevant environment, meeting predicted performance. Operational environment performance predicted. Prototype implementations developed.	Documented test performance demonstrating agreement with analytical predictions. Documented definition of scaling requirements.
6	System/sub-system model or prototype demonstration in an operational environment.	A high fidelity system/component prototype that adequately addresses all critical scaling issues is built and operated in a relevant environment to demonstrate operations under critical environmental conditions.	Prototype implementations of the software demonstrated on full-scale realistic problems. Partially integrate with existing hardware/software systems. Limited documentation available. Engineering feasibility fully demonstrated.	Documented test performance demonstrating agreement with analytical predictions.

FIGURE E-1. Current technologies quad chart template.

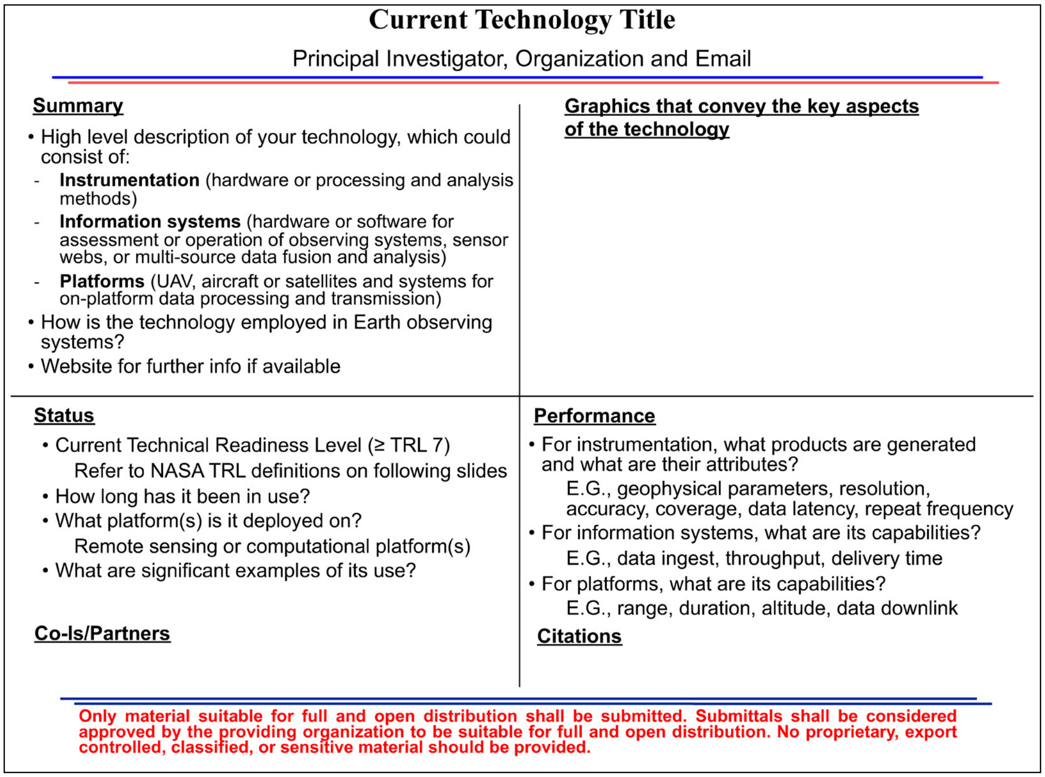
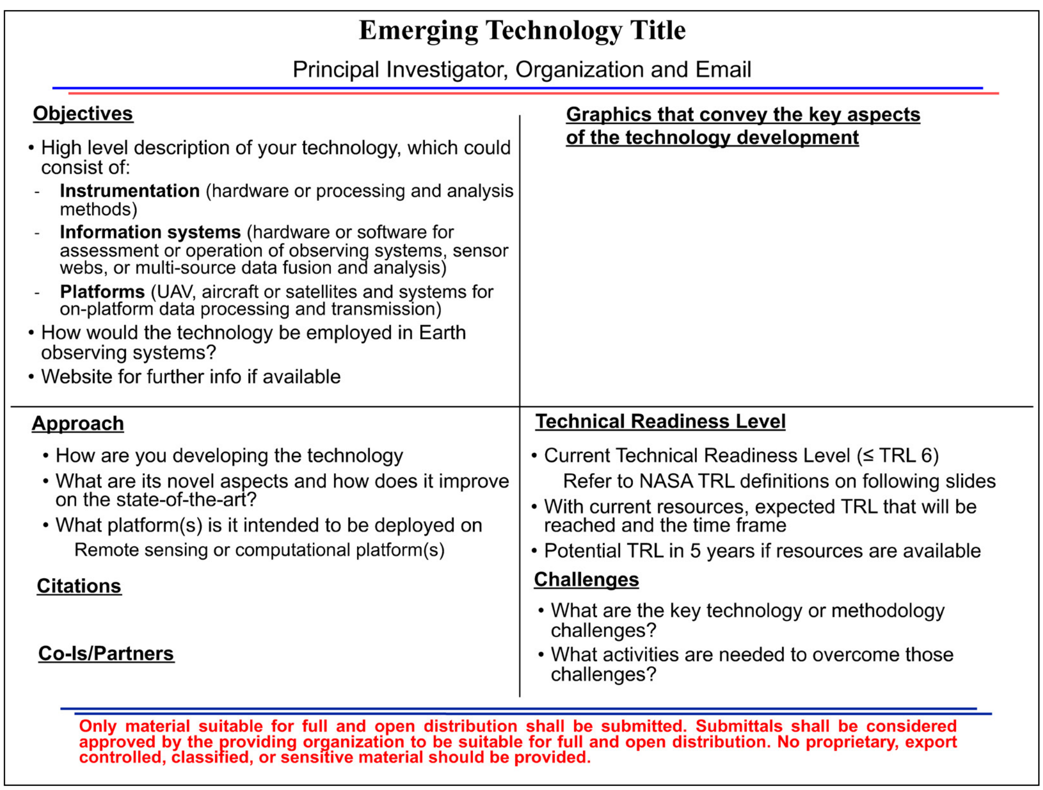


Figure E-2. Emerging technologies quad chart template.



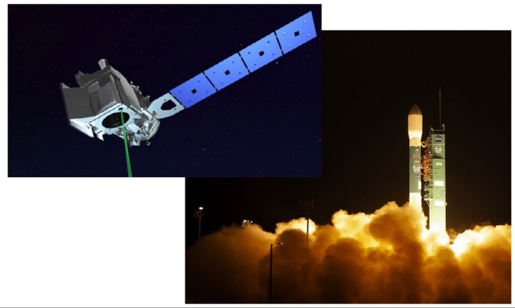
E.1 Lidar Current Technologies

The Ice, Cloud, and land Elevation Satellite - 2

Neumann, Project Scientist; Kurtz, Deputy Project Scientist (NASA GSFC)

Summary

- ICESat-2 carries the Advanced Topographic Laser Altimeter System (ATLAS):
  - **Six- beam lidar**: photon counting instrument using 532nm light. 10 kHz laser rep rate.
  - **Repeating orbit:** 1387 ground tracks repeat every 91 days supporting elevation change measurements in the polar regions. Over mid-latitudes, a sequence of off-pointing increases track density
  - **Platforms** (UAV, aircraft or satellites and systems for on-platform data processing and transmission)
- Collects data between 88 degrees N and S latitudes
- https://icesat-2.gsfc.nasa.gov/



Status

- Current Technical Readiness Level (TRL 9)
- How long has it been in use? 23 Months
- What platform(s) is it deployed on?
  Currently on-orbit.
- What are significant examples of its use?

https://icesat-2.gsfc.nasa.gov/publications

~30 publications to date with on-orbit data.

Co-Is/Partners

https://icesat-2.gsfc.nasa.gov/science_definition_team.

Northrop-Grumman Innovation Systems, Fibertek, SigmaSpace / Hexagon

Performance

- Data products available at NSIDC:
  - https://nsidc.org/data/icesat-2
  - 12 products including geolocated photons, ice sheet height, sea ice elevation and freeboard, vegetation and canopy height, ocean height, inland water body elevation.
  - Release 003 available now, Rel 004 in early 2021
- Data latency ~45 days
  ~ 300 TB of data / year
- Spacecraft and ATLAS instrument remain nominal.

Citations

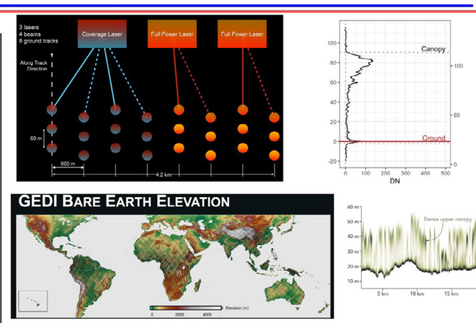
Neumann, T. Martino, T. Markus, et al. **The Ice, Cloud and Land Elevation Satellite-2 Mission: A Global Geolocated Photon Product.** *Rem. Sens. Env.* 2019, 233. https://doi.org/10.1016/j.rse.2019.111325.

Global Ecosystem Dynamics Investigation (GEDI)

Ralph Dubayah, University of Maryland & Bryan Blair, NASA GSFC

Summary

- GEDI is a multibeam laser altimeter that is used to provide observations of forest canopy height and structure, topography, and other altimetric observations of the Earth's surface such as water levels, and snow and ice.
- GEDI consists of 3 near-infrared (1064 nm) Nd:YAG lasers, each firing at 242 Hz. One laser is split into two beams, and all beams are dithered to provide a total of 8 tracks of data spaced 600 m apart across-track. Each beam footprint is 25 m and along-track spacing is 60 m.
- GEDI is a full waveform lidar i.e. both the transmitted and received pulses/waveforms are recorded
- GEDI has been deployed on ISS/JEM-EF since Dec 2018.



Status

- GEDI is currently operating and acquiring data from the ISS (TRL 9). It was commissioned by April 2019 and has been collecting data continuously. Its prime mission is scheduled to end April 2021 and is under consideration for a mission extension through 2023.
- GEDI has already provided the best existing maps of bare earth topography and canopy height yet. And its data have been used to estimate continental scale biomass, for biodiversity studies, for carbon modeling, and forest fire modeling and prediction.

Co-Is/Partners

US Forest Service, Brown University, NAU, DLR

Performance

- GEDI generates 25 m footprint level products and 1 km gridded products of canopy height, canopy height metrics, plant area index, plant area vertical profile, canopy cover, and biomass.
- GEDI's data sets cover from 51.6 N & S Latitude and uses an active pointing system for even coverage.
- GEDI has acquired over 7 billion quality observations with minimal detected laser degradation

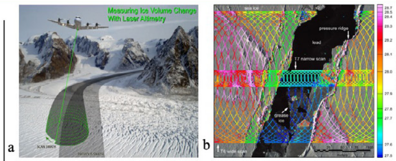
Citation: The Global Ecosystem Dynamics Investigation, Dubayah et al, 2020, *Science of Remote Sensing*

NASA Airborne Topographic Mapper (ATM)

Dr Michael Studinger NASA GSFC Code 615 (michael.studinger@nasa.gov)

Summary

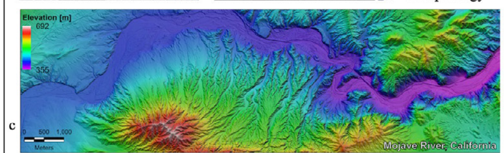
- The Airborne Topographic Mapper (ATM) is an airborne scanning lidar mapping sensor that measures geodetic-quality topography of features such as: river channel morphology, volcanoes, impact craters, glaciers, and polar land/sea ice.
- Incorporates laser with multi-trigger waveform recording, GNSS, attitude sensor, and aircraft steering subsystems.
- ATM instrument suite includes nadir visible and thermal cameras, and hyperspectral scanner.
- Instrument descriptions and evaluations of measurements published in >500 papers.
- https://atm.wff.nasa.gov/



a. ATM mapping concept (left)

b. Sea ice lead data example (right)

c. Mojave River morphology



Status

- ATM's Current Technical Readiness Level- TRL 9
- ATM has conducted precise topographic mapping for over 26 years.
- ATM has flown on a wide variety of aircraft (P-3, DC-8, C-130, Twin Otter and Gulfstream V) from NASA, NOAA, NCAR, and commercial suppliers.
- ATM was a principal instrument for NASA's Operation IceBridge (2009-2019) and earlier programs for monitoring polar land and sea ice elevation changes, coastal change mapping, ocean wave studies, and geomorphology research.

Co-Is/Partners: NOAA, USGS, CRREL, NRL

Performance

- ATM produces HDF5 format georeferenced point elevations with multi-trigger waveform digitization from ~75 cm diameter laser footprint at 10KHz. Elevation accuracy <5 cm. Single pass coverage dependent on platform attitude and speed on the order of 0.5 to 2 elevations/m2 (overlapping passes increase density).
- ATM can provide quick data processing in 1 hour, high-precision processing in 1 month.
- ATM's extremely long GPS baseline techniques and flexible aircraft capabilities provide global mapping coverage with accuracy of <10 cm even at the poles.

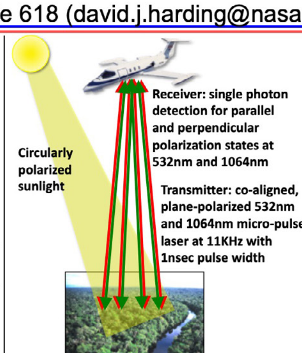
Citations: https://atm.wff.nasa.gov/publications/

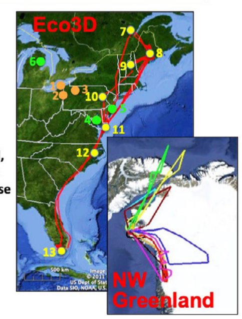
Slope Imaging Multi-polarization Photon-counting Lidar (SIMPL)

David Harding NASA GSFC Code 618 (david.j.harding@nasa.gov)

Summary

- The Slope Imaging Multi-polarization Photon-counting Lidar is a multi-beam airborne lidar sensor that was developed to advance and demonstrate innovative capabilities for space-flight use.
- SIMPL measures surface heights and properties by transmitting co-aligned 532nm and 1064nm beams and detecting laser and solar reflected photons in perpendicular and parallel polarization states.
- The polarimetry characterizes targets based on dual-wavelength photon scattering properties, enabling definitive identification of liquid water, measurements of multi-scale roughness and extinction profiling through water, snow, ice and vegetation.
- https://icesat-2.gsfc.nasa.gov/data





Status

- Current Technical Readiness Level - TRL 7.
- Began operations in 2009.
- Has flown on several aircraft operated by NASA (Learjet 25, P-3B Orion and King Air UC-12B).
- Significant deployments include
  - Eco3D in 2011, targeting ecosystem study sites from Ontario to Florida, flown with SAR and scanning radiometry instrumentation
  - Northwest Greenland in 2015, targeting summer ice sheet and sea ice melt conditions, flown with hyperspectral instrumentation.

Co-Is/Partners: Philip Dabney, Anthony Yu and Susan Valett, NASA GSFC and Sigma Space Corp.

Performance

- 0.25m laser footprints along 4 profiles with 5m cross-track spacing from 2km nominal flight altitude.
- 100 psec photon event timing for up to 16 million photons/sec from atmosphere column and the surface.
- 1nsec pulse widths achieving 8cm single photon range precision.
- Typically 5 to 10 surface photons/m for each channel on each beam, achieving sub-cm range precision for flat surfaces at 10m length scales.

Citations:

Harding, D. J., P. W. Dabney, and S. Valett. 2011. Proc. SPIE 8286: [10.1117/12.913960]

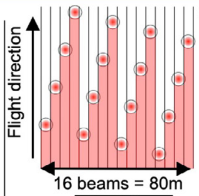
Yu, A. W., D. J. Harding, and P. Dabney. 2016. Proc. SPIE 9726: [10.1117/12.2213005]

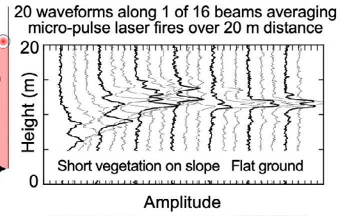
Airborne Lidar Surface Topography Simulator (A-LISTS)

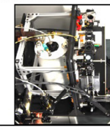
Anthony Yu, NASA GSFC Code 554, (anthony.w.yu@nasa.gov)

Summary

- The Airborne Lidar Surface Topography Simulator is a multi-beam airborne lidar sensor that was developed to advance and demonstrate innovative swath mapping capabilities for space-flight use.
- A-LISTS implemented a highly efficient measurement approach utilizing a near-infrared, 10kHz micropulse, master-oscillator-power-amplifier (MOPA) laser transmitter divided into a rotated 4 x 4 push-broom beam array, forming an 80m swath with 5m footprints
- The receiver used four 4-element hybrid PMT detector arrays with output digitized at 1nsec sampling and consecutive, overlapping laser fires were averaged to form a 3-D waveform cube.







Status

- Current Technical Readiness Level - TRL 6-7.
- Began operations in 2011
- No longer in operation.
- Flew on NASA Learjet 25.
- Significant deployments include
  - Forest and agricultural land cover in the mid-Atlantic region of the U.S. east coast

Co-Is/Partners

David Harding, Xioali Sun, John Cavanaugh and Susan Valett, NASA GSFC; Raytheon (Laser) and Intevac (Detector).

Performance

Parameters	On Lear Jet 25
Altitude	10 km
Detector FOV	7 m (0.7 mrad)
Laser Spot	5 m (0.5 mrad)
Spot Spacing	20 m (2 mrad)
Swath Width	80 m (16 x 5 m)

- At 11% wall plug efficiency (WPE), the microchip laser is least 3X more efficient than traditional space flight laser transmitters (typical 3%).
- Measurements demonstrated and validated over a variety of surface types, including those of vegetation canopy and underlying topography.
- Advanced technical readiness of a scalable instrument architecture for Lidar Surface Topography mission recommended in the 2007 Earth Science Decadal Survey.

Citations:

Yu, A. W., M. A. Krainak, D. J. Harding, et al. 2012. "Multi-beam Laser Altimeter System Simulator for the Lidar Surface Topography (LIST) Mission." 2012 CLEO [10.1364/CLEO_AT.2012.ATu2G.6]

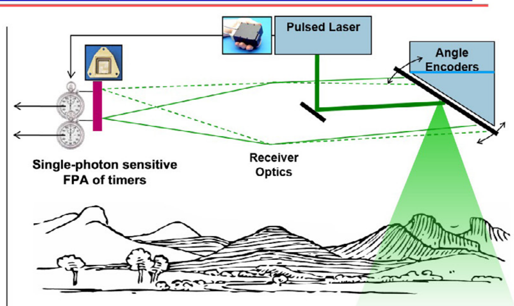
Yu, A. W., M. A. Krainak, D. J. Harding, et al. 2013. "A 16-beam non-scanning swath mapping laser altimeter instrument." Solid State Lasers XXII: Technology and Devices, Proc. SPIE 8599: [10.1117/12.2005651]

3D Imaging Using Photon Counting Lidar

Luke Skelly / MIT Lincoln Laboratory

Summary

- Airborne Geiger-mode ladar imaging and processing systems:
  - Demonstrated and operational on multiple aircraft
    - >450,000 sq. km @ 1m and >27,000 sq. km @ 30cm
  - Building lander-traceable demonstration prototype
- Single photon sensitivity enables high altitude and high area coverage rates
- https://www.ll.mit.edu/news/technology-confronts-disasters
- https://www.ll.mit.edu/news/lidar-scans-over-carolinas-accelerate-hurricane-recovery



Status

- Current Technical Readiness Level 9
- First airborne demonstration: 2002 (Jigsaw)
- First deployment: 2010 (ALIRT)
- Currently operational on MACHETE
- Disaster relief, foliage penetration, wide-area mapping

- Advanced photon counting detectors transitioned to industry (PLI, Boeing Spectra Labs)
- Spin-off startup on commercializing Gm-APD ladar (3DEO)

Performance

- Altitude: >25kft
- Range resolution: 20cm
- IFOV: 20 urad
- Area coverage rate: >2000 sq km / hr

Citations

- Marino, R. and Davis, W.R.. “Jigsaw: A Foliage-Penetrating 3D Imaging Laser Radar System.” (2004).

This material is based upon work supported under Air Force Contract No. FA8721-05-C-0002 and/or FA8702-15-D-0001. Any opinions, findings, conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the U.S. Air Force.

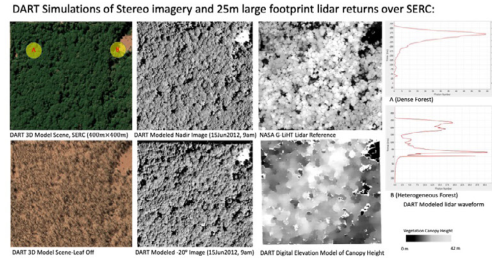
G-LiHT Airborne Data and DART Modeling to Explore Lidar-Optical Synergies

B. Cook, D. Morton, L. Corp, Yin, P. Montesano, C. Neigh, T. Neumann (NASA GSFC)

Summary

- Synergies between lidar and stereo optical data are being explored through the acquisition of airborne data and 3D radiative transfer modeling.
  - **Instrumentation**: NASA's G-LiHT multi-sensor airborne imager equipped with scanning lidars and a fine-resolution (3 cm) stereo RGB-NIR camera system.
  - **Lidar-Optical Simulations:** DART radiative transfer model to understand optimal overpass times and sensor configurations based on model simulations with varying sun-sensor geometry and environmental conditions (e.g., topography, vegetation structure, etc.)
  - **Data Integration:** Workflows that optimize digital elevation models and change measurements from a combination of lidar-optical data.

DART Simulations of Stereo imagery and 25m large footprint lidar returns over SERC:



Status

- G-LiHT has operated since 2011; TRL 9 w/RBG camera
- COTS NIR camera will be integrated during 2020
- Leaf-on/off flight will occur during 2021 on King Air A90
- DART was developed in 1992, and NASA scientists have been using it to simulate different types of lidars and optical sensors on space and aircraft platforms.
- G-LiHT lidar data can be used to create realistic 3D scenes for DART simulations, which can be validated with G-LiHT stereo optical data.

Co-Is/Partners

USDA Forest Service, Smithsonian Environmental Research Center, American University

Performance

- Simulated stereo data will allow us to construct an error matrix and explore STV uncertainty covering a broad range of instrument configurations and environmental conditions, including:
  - Vegetation structure, topography, surface reflectance
  - Latitude, seasonality, time of day
  - View angle, optical wavelength, lidar footprint and spacing

Citations

Gastellu-Etchegorry, J.-P, *et al.* 2015. Discrete Anisotropic Radiative Transfer (DART 5) for Modeling Airborne and Satellite Spectroradiometer and LIDAR Acquisitions of Natural and Urban Landscapes. *Remote Sensing*, 7:1667-1701.

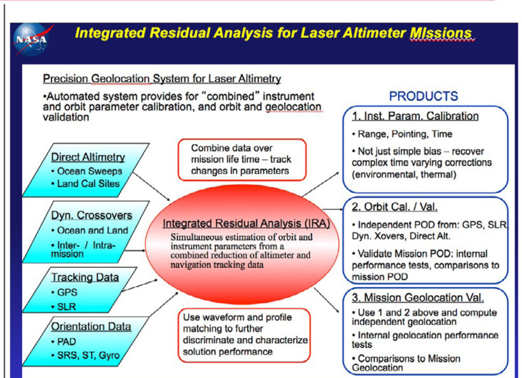
Neigh, C. *et al.* 2014. Deciphering the precision of stereo IKONOS canopy height models for U.S. forests with G-LiHT airborne LiDAR. Remote Sensing 6:1762-1782; doi:10.3390/rs6031762.

GEODYN Orbit Determination and Geodetic Parameter Estimation

David Rowlands, NASA GSFC Code 61A (david.d.rowlands@nasa.gov)

Summary

- GEODYN is a software system for precise orbit determination and geodetic parameter estimation.
  - For Earth orbiting and planetary satellites
- Applies integrated residual analysis to:
  - Range and Doppler navigation tracking between Earth based stations and satellites, and between satellites
  - Radar and laser ranging to calibration targets
  - Altimetry cross-overs
  - Instrument orientation data
  - Camera images taken from satellites
- Employs precise Earth geophysical models for geolocation, including Earth orientation and tides
- https://earth.gsfc.nasa.gov/geo/data/geodyn-documentation



Status

- Current Technical Readiness Level - TRL 9.
- In use and under development for almost 50 years at Goddard Space Flight Center.
- System is installed on GSFC and NASA collaborator computing platforms.
- Currently being used for OSIRIS-Rex asteroid navigation and GEDI and ICESat-2 laser altimetry geolocation.
- Gravity fields developed for Earth, Mars, Moon and various asteroids.

Performance

- Establishes time-varying biases for altimeter range, pointing and timing
- Determines high precision orbits
- Biases and orbits used for altimetry and image geolocation

Citations:

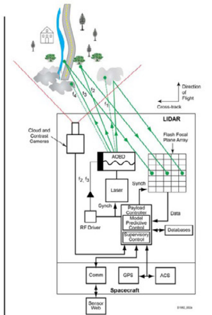
Luthcke, S.B. et al. "Calibration and reduction of ICESat geolocation errors and the impact on ice sheet elevation change detection," *Geophys. Res. Lett.,* VOL. 32, L21S05, doi:10.1029/2005GL023689, 2005.

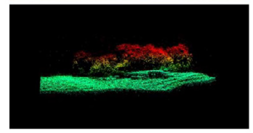
Adaptive Lidar for Earth Science

Carl Weimer, Ball Aerospace cweimer@ball.com, and Yong Hu, NASA LaRC

Summary

- Mission Level approach to developing an observation system that uses forward looking imagers to inform an adaptive lidar where to make vertically resolved measurements, and the lidar adapts its beam number to optimize SNR; includes an advanced control system based on Model Predictive Control with Deep Learning
- Previously demonstrated - can map forest canopy height, crown size, surface topography, map water edges, can measure cloud tops, or operate in cloud avoidance to improve surface measurements
- See ES Flash Lidar video at this site: https://www.ball.com/aerospace/markets-capabilities/capabilities/instruments-sensors/laser-lidar-imaging





TRL and Status

- Current TRL 5+; but improvements in focal planes would increase TRL, could be full waveform or photon counting (PC) (we have GmAPD PC arrays)
- Developed in 2008-2009 under IIP, additional flight testing under AITT– demonstrations and advanced developments of hardware through 2016, Advanced Control System developed under AIST and has ongoing development
- Flown on Twin Otters, goal is space mission
- Full system concept that includes mission optimization, hardware, onboard control systems
- Flown over many different ecological types and cross-compared against traditional scanning vegetation lidars

Past Co-Is/Partners: Michael Lefsky (CSU), Jason Stoker (USGS); Ingrid Burke (Yale)

Performance

A space implementation could have up to 40 beams, 25 m spot size, Vertical resolution < 1 m, minimum of 256 by 1 array, with the number of spots used optimized for the scene

Citations

- Lefsky, M. A., et al. *Remote Sensing of Environment* 115.6 (2011): 1361-1368.
- Duong, Hieu V., et al. *IEEE transactions on geoscience and remote sensing* 50.11 (2012): 4809-4820.
- Weimer, Carl, et al. *IEEE International Geoscience and Remote Sensing Symposium (IGARSS)*. IEEE, 2017.

ASTRALiTe EDGE™: Shallow Water Topo-Bathy LiDAR System

Gerald Thompson, ASTRALiTe Inc.

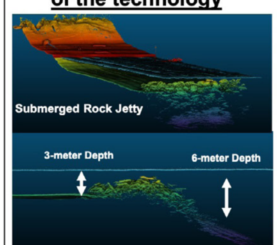
Summary

ASTRALiTe EDGE™ is the first scanning topographic & bathymetric LiDAR system to be flown from a UAV

- **Flexibility & quick access** to previously unsurveyable locations using a UAV
- **2-in-1 Topo-Bathy system** – reducing the need for two sensors
- **Near real-time data visualization** of the point cloud (vs. lengthy post-processing of large data sets)
- **"High Definition" (HD) / high density point cloud** "*painting the scene*": 100x higher point density than traditional airborne bathy systems, at 10x lower price.

https://www.astralite.net/

Graphics that convey the key aspects of the technology



Status

- **TRL:** 8/9
- The EDGE has been available commercially since January 2019, and have sold and deployed systems internationally.
- **Platform:** The sensor is platform agnostic. It has been deployed on UAVs, boats and other autonomous platforms
- **Applications:** Coastal Mapping, River Engineering, Infrastructure Engineering / Inspection, Natural Disaster Assessment & Recovery, Military Logistics

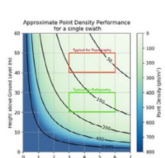
Co-Is/Partners

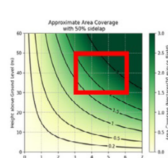
Dr. Jeffrey Thayer, Andy Gisler

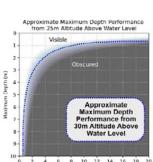
Performance

"Emerging Trends in Bathymetric LiDAR Technology." Hydro International. August 2019.

LiDAR Performance	
Weight	5 kg
Accuracy	5-10 cm
Laser Wavelength	532 nm
Flight Altitude	30m – 50m
Depth Penetration	1.5-2 Secchi Depth
Pulse Repetition Rate	20-40 kHz (design option)
Laser Beam Footprint	3 cm at 10 m (design option)







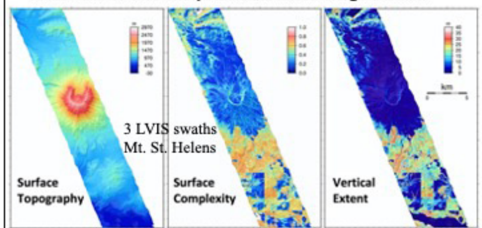
NASA's Land, Vegetation, and Ice Sensor (LVIS) Facility Lidar

J. Bryan Blair (Bryan.blair@nasa.gov) NASA/GSFC & Dr. Michelle Hofton (University of Maryland)

Summary

- NASA's Land, Vegetation and Ice Sensor (LVIS) Facility is an wide-swath, imaging LIDAR and camera sensor suite for precise and accurate large-area 3-D surface mapping and characterization of vegetation vertical structure.
- Primary products are surface elevation, vegetation height and structure metrics, and 3-D profile of vegetation.
- Data are used in numerous science applications requiring accurate surface topography and/or vegetation height and structure data, including in dense tropical forests.
- Comprehensive geodetic-class lidar infrastructure (GPS, IMUs, Data system, precise scanning system) can serve as a testbed for algorithm and hardware design supporting space-based sensor and mission development.

Wide swath and return waveforms provide multi-dimensional products over large areas



Status

- Currently operational as a subsidized Facility.
- Has deployed on numerous airborne platforms (ex. NASA/NSF G-V's, B-200's, DC-8, P-3, C-130, & Global Hawk. Most recent deployment consisted of 2 LVIS lidars and cameras co-mounted on NASA's G-V aircraft.
- LVIS is the airborne emulator for NASA GEDI: provided pre-flight data sets for engineering, science, & mission design studies and now flying for post-launch cal/val.
- Flown numerous missions (100's of hours) for NASA Operation Ice Bridge (Arctic and Antarctica) and ABoVE.
- 100,000's of km^2 of LVIS Data (including waveforms) available from NSIDC, Earthdata, and the LVIS website

Performance

- LVIS generates footprint-level products as well as the precisely geolocated laser return waveform
- Surface elevation with ~2 cm range precision and < 10 cm absolute accuracy with 1-2 m horizontal accuracy
- Dense canopy penetration (> 99% canopy cover)
- LVIS nominally operates from altitudes of 10-12 km with a 2 – 2.5 km-wide swath. Raster scan with 100% coverage.
- Unique scanning system with wide range of sampling configurations possible, with 5 - 25m diameter footprints. Modifications underway to increase spatial resolution.

Citation: Blair, J. B., D. L. Rabine, and M. A. Hofton, The Laser Vegetation Imaging Sensor (LVIS): A medium-altitude, digitization-only, airborne laser altimeter for mapping vegetation and topography, ISPRS Journal of Photogrammetry and Remote Sensing, 54, 115-122, 1999.

Only material suitable for full and open distribution shall be submitted. Submittals shall be considered approved by the providing organization to be suitable for full and open distribution. No proprietary, export controlled, classified, or sensitive material should be provided.

E.2 Lidar Emerging Technologies

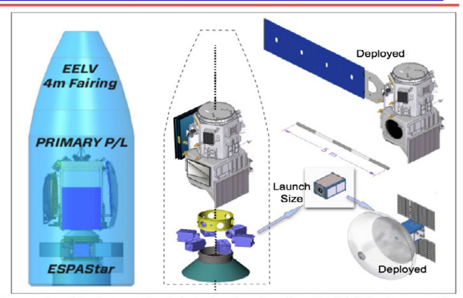
Breakthrough Technologies Enabling ESPA-Class SmallSat Implementation of Earth Science Lidar Missions

Mark Stephen / 550, NASA-GSFC (mark.a.stephen@nasa.gov)

Objectives

We are developing key technologies to enable smaller, lighter and less expensive implementation of space-based lidar while maintaining performance.

- This development program uses CO_2 requirements to verify the technology efficacy, but results can benefit seven of the 2017 Decadal Survey Targeted Observables addressable with Lidar!
  - EXPLORER - Greenhouse gases, Ice elevation, Snow Depth and Snow Water Equivalent, Terrestrial Ecosystem Structure, Atmospheric Winds;
  - INCUBATION - Atmospheric Winds, Planetary Boundary Layer, Surface Topography and Vegetation



Example of instrument miniaturization leading to ESPA-class payload

Approach

We are developing 3 critical miniaturization technologies to enable lidar implementation as a secondary payload, resulting in significant cost-savings to meet Decadal survey recommendations:

- Miniaturized and efficient wavelength-tunable **seed lasers and wavelength references** using photonic integrated circuits;
- Compact, efficient, high peak power **optical amplifiers** using highly-doped, large-mode-area fiber laser technology;
- Lightweight deployable, membrane **receiver telescopes** coupled with custom free-form optical aberration correction.

Co-Is/Partners: UCSB; NeXolve; BYU-CMR

Technical Readiness Level

- Current Technical Readiness Level: TRL-2
- TRL should reach 3 in one year with current resources,
- Potential to reach TRL-6 in 5 years if resources are available

Challenges

- Key technology or methodology challenges
  - Achieving sufficient optical performance from deployable structure
  - Achieving large aperture optics
- Activities needed to overcome challenges
  - Developing repeatable deployment mechanisms
  - Using passive and active optical correction techniques

Only material suitable for full and open distribution shall be submitted. Submittals shall be considered approved by the providing organization to be suitable for full and open distribution. No proprietary, export controlled, classified, or sensitive material should be provided.

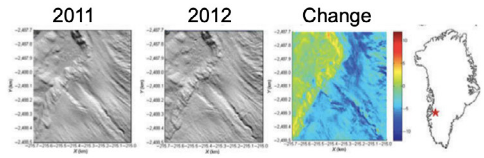
Canopy Height and Glacier Elevation (CHANGE) Mission Concept

Morton, Neumann, Cook (NASA GSFC)

Objectives

Understand processes that drive ice and vegetation change on seasonal time scales. Early detection of change processes is a critical component of characterizing and responding to climate-driven changes in the Earth system. Our fusion of lidar and stereo optical imaging enables science that will:

- identify mechanisms that alter biogeochemical cycling in forests, woodlands, and savanna ecosystems
- quantify ice sheet mass loss and mass loss change
- provide continuity with current and planned measurements of ice sheet elevation, sea ice thickness changes (e.g., ICESat-2), and vegetation structure measurements (e.g., GEDI)
- advance data fusion science and applications for change detection and surface characterization



Surface elevation change with DEMs from stereo pairs plus lidar from Noh and Howat (2015) for a site in southwest Greenland. Panels (a) and (b) show orthorectified images from 5 June 2011 and 21 July 2012 by WorldView-1. The height difference between the DEMs is shown in (c). Location is shown in (d).

Approach

- Aiming to leverage space-qualified COTS as much as possible
- Will generate ~10km wide swaths (in regions with sufficient structure) rather than tracks limited to lidar beam diameter.
- Aiming for Earth Systems Explorers AO

Co-Is/Partners

Univ of Washington, Polar Geospatial Center / Univ. of Minnesota, Ohio State Univ., JPL

Technical Readiness Level

- Current Technical Readiness Level (5)
  Refer to NASA TRL definitions on following slides
- With current resources, expected TRL that will be reached and the time frame
- Potential TRL in 5 years if resources are available: 6

Challenges

- Rapidly evolving optical imagery in commercial sector.
- Cost limitations of ESE outlined in 2017 DS

MOLI (Multi-footprint Observation Lidar and Imager)

PI: Tadashi IMAI, JAXA(Japan) imai.tadashi@jaxa.jp

Objectives

- Design, build and demonstrate a first earth observation lidar to validate space qualified laser technology, detector, error reduction of biomass estimation on the tropical forests.
  - **Instrumentation:** Space qualified laser technology
  - **Platforms** International Space Station
- MOLI employs a laser altimeter and imager to achieve precise forest canopy measurement over the slant ground for dense forest such as tropical forests.

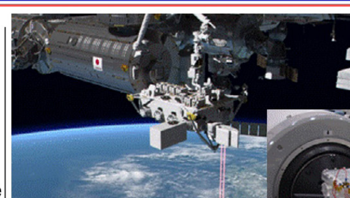
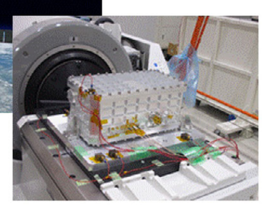


Image of MOLI System on ISS



Pressurized laser vibrational test model

Approach

- Complemental measurement of lidar and imager
- Conduct a space qualified laser architecture study.
- Investigate pressurized laser transmitter for next future earth observation lidar systems (Doppler wind lidar, multi-channel laser scanner) on the LEO or super low altitude satellite.

Citations

- D. Sakaizawa et. al. : IGARSS 2019 - 2019 IEEEIGARSS, Yokohama, Japan, 2019, pp. 4849-4850, doi: 10.1109/IGARSS.2019.8899196.

Co-Is/Partners: Daisuke Sakaizawa (JAXA)
Sakaizawa.daisuke@jaxa.jp

Key Milestones

- Pressurized laser lifetime test 2015.12 ~ 2017.7
- Vibrational tolerance test 2019.3 / 2020.3
- Project start JFY2022 (TBD)
- Launch Date JFY2024 (TBD)

TRL=~4

Challenges

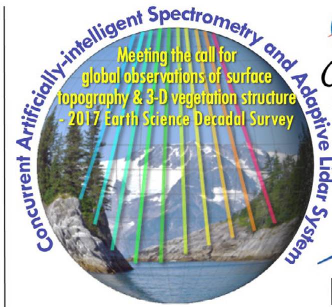
- The first pressurized laser transmitter in Japan EO
- Error reduction of canopy height measurement on slant ground by using complemental measurement of dual beam configuration lidar and imager.

Concurrent Artificially-intelligent Spectrometry and Adaptive Lidar System

Guangning Yang NASA GSFC Code 554 (guangning.yang-1@nasa.gov)

Objectives

- The Concurrent Artificially-intelligent Spectrometry and Adaptive Lidar System (CASALS) is a SmallSat observing system to acquire structure, composition and function observations of the Earth's surface.
- Merges and improves the ICESat-2 and GEDI lidar profiling capabilities and, for the first time from Earth orbit, conducts 3-D lidar swath mapping.
- Incorporates hyperspectral imaging to expand science and operational capabilities.
- Contributes to five of the 2017 Decadal Survey Explorer and Incubation observables: ice elevation, ecosystem structure, snow depth, surface topography and vegetation and the planetary boundary layer.



Approach

- Ground-based demonstration of the system with components and efficiencies required for space.
- Novel technologies:
  - Integration of high-speed, 1030nm wavelength-tuning photon-integrated-circuit seed-laser, a compact fiber power amplifier and transmissive grating for passive wavelength-to-angle beam scanning
  - High-efficiency lidar receiver with grating for wide-band solar background rejection and a 90% QE, photon-sensitive, analog HgCdTe detector array
  - Freeform mirrors and grating for dramatic mass and volume reduction of the receiver telescope and VNIR-SWIR spectrometer
  - Machine-learning trained real-time data analysis for autonomous, on-orbit decision making
- Intended platform: polar, low Earth orbiting SmallSat.

Technical Readiness Level

- Current TRL: 2 at system level
- Expected TRL with current funding: 5 in 2023
- Potential TRL in 5 years: 6

Challenges

- Adapting mature 1550nm laser telecom technologies to 1030nm needed to meet spaceflight requirements
  - Working with partners to modify their existing wavelength-tuning and amplification technologies
- Reducing power for high-speed waveform digitizing
  - Developing time-domain multiplexing to reduce number of required digitizers by 10x

Co-Is/Partners David Harding, Jeffrey Chen, Mark Stephen, Xioali Sun, James Mackinnon and Jon Ranson, NASA GSFC, Freedom Photonics, UC Santa Barbara, AdValue Technology and Leonardo DRS

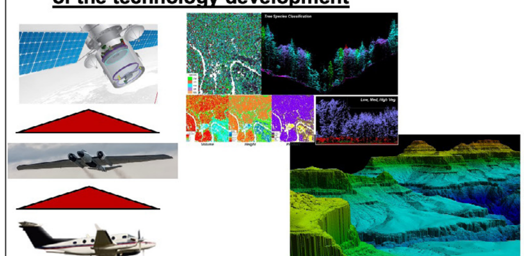
Geiger-Mode LIDAR for STV

Steven G. Blask, Ph.D., L3Harris Technologies

Objectives

- As a systems integrator and state-of-the-art technology developer, L3Harris provides end-to-end 3D imaging solutions using our Geiger-mode LIDAR capabilities, including:
  - **Instrumentation** – Gm LIDAR sensors & data collection hardware, scalable onboard and ground processing hardware and software workflows and analysis methods
  - **Information systems** – ground element hardware & software for assessment or operation of observing systems, sensor webs, or multi-source data fusion and analysis
  - **Platforms** – UAV & manned aircraft mapping and ISR advanced sensor systems with RT/NRT/low latency on-platform data processing and transmission, scalable from airborne to satellites
- How would the technology be employed in Earth observing systems? Scale from medium altitude to high altitude or LEO
- https://www.l3harrisgeospatial.com/Data-Imagery/Geiger-mode-LiDAR

Graphics that convey the key aspects of the technology development



Approach

- *How are you developing the technology?* Leveraging COTS GmAPD cameras and DPSS or fiber lasers within a standardized transceiver architecture with innovative pointing & scanning optics designed to meet mission-specific requirements; laser & optics must scale for increased range to target. Transitioning ground element processing flows designed for high accuracy, large area 3D mapping from pure CPU to GPU-enabled implementations for lower-latency onboard processing and analytics.
- *What are its novel aspects and does it improve on the state-of-the-art?* Improved photon efficiency increases range-to-target, ACR, or resolution, and reduces SWaP.
- *What platform(s) is it intended to be deployed on?* Current sensor for manned or unmanned medium altitude aircraft (10-30kft); future platforms to include high altitude and LEO. Current processing hosted within enterprise-class ground element with significant cores; porting L1 & L2 processing, analytics to GPU.

Citations – see speed talk for tech & application references

Technical Readiness Level

- Current Technical Readiness Level:
  Med. altitude sensor HW TRL6-9,
  RT/NRT OBP SW TRL4-6, Ground PED TRL9.
  High altitude to space-based sensor & OBP HW TRL2.
- With current resources, expected TRL that will be reached and the time frame: TBD (resources in flux)
- Potential TRL in 5 years if resources are available: TRL7.

Challenges

- What are the key technology or methodology challenges? Higher power, high PRF, narrow pulse width lasers; space-qual'ed GmAPD cameras
- What activities are needed to overcome those challenges? Sensor HW design & dev., SW porting

Quantum Parametric Mode Sorting Lidar for Earth Science

Carl Weimer, Ball Aerospace cweimer@ball.com

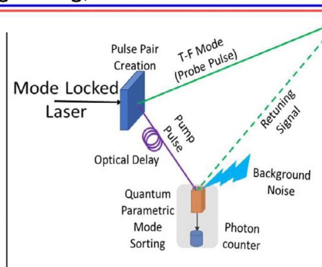
Co-Is Yong Hu, NASA LaRC; Yuping Huang, Knut Stamnes Stevens Institute

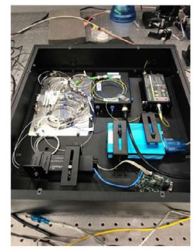
Objectives

Our team is leveraging recent developments in Quantum Information Science instrumentation and applying them to improve the performance of lidars/altimeters for Earth Science

- Probe is bright and fast optical pulses in single temporal-frequency modes carrying signature phase coherence
- Receiver admits the true signal with the signature phase coherence and very efficiently rejects noise without, even if they are temporally, spectrally, and spatially overlap, achieving a significant advantage over ideal matched filters
- Receiver has sub-photon sensitivity, operable in daytime with mm range resolution
- Eliminates multiple scattering induced errors

We are exploring Earth Science applications via radiative transfer modeling of different types of scenes





Approach

- Advancing techniques via laboratory testing with different targets and attenuation levels; first long range test out of the laboratory off of hard targets this year
- Radiative transfer modeling of this type of beam is underway
- Approach is not sensitivity to background light and can detect ballistic photons through 10 Optical depths for dense canopy and turbid water, with mm timing precision, and sub photon sensitivity
- Ultimate goal is to implement this in space

Citations

1. *Optics express* 26.12 (2018): 15914-15923.
2. Nature Communictions:(2020) 11:921

TRL and Status

- Current TRL = 3; first rounds of laboratory testing complete, applying to snow depth under ESTO funds
- TRL 4; with current funding; supporting some applications by summer 2021
- TRL 6; in 5 years with adequate funding

Challenges

- Details of the scattering of these modes is still being worked out, end-to-end efficiency evaluated, technical challenges with use of high rep rate lasers
- Radiative modeling & system modelling need to be completed, new approach to spectral encoding in work, eventually needs to be flown for different Earth scenes

Deep-learning for Automated ICESat-2 Bathymetry Extraction

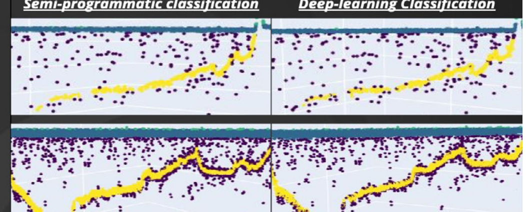
Ross Smith, TCarta Marine LLC

Objectives

- Engineer machine-learning/deep learning algorithm for automatic delineation and extraction of seafloor, sea surface and water column depth data from ICESat-2's ALT03 Geolocated Photon Data product
- Incorporate the automated extraction algorithm with TCarta's Space-Based Laser Bathymetry Extraction Tool for civilian/government/GEOINT end-users
- Deploy the automated extraction algorithm at scale for global extraction of ICESat-2-derived bathymetry
- Integrate global ICESat-2 bathymetry data with space-based multispectral imagery and TCarta automated satellite-derived bathymetry algorithms to produce continuously updated global littoral depth modelling at scale.

Current performance of ATL03 classification for automated ICESat-2 depth retrieval

Semi-programmatic classification | *Deep-learning Classification*



Approach

- Utilize TCarta's semi-programmatic ICESat-2 bathymetry extraction software to generate labeled training data
  - Training database currently houses (DOI 23Sep20):
    - 54.2 million labeled training data points generated from ICESat-2 ATL03 transects
      - 9.8 million bathymetry points
- Engineer deep-learning model which learns relations between points in local neighborhood spaces, and introduces permutation invariance over irregular raw point cloud data to detect local geometrical features
- Stack additional unsupervised machine-learning techniques for noise reduction and outlier mitigation

Co-Is/Partners

- Kyle Goodrich, TCarta
- Felicia Nurindrawati, TCarta

Technical Readiness Level

- Current TRL: 3
- With current resources: TRL 7 will be reached in 2-3 years
- If additional resources available: TRL 7 will be reached in 6 months - 1 year
- TRL after 5 years, If additional resources available: TRL 9

Challenges

- Access to ATL03 data via NSIDC is a significant limiting factor for training data collection and global bathymetry extraction- speed and data volume is severely insufficient.
- On-hand hardware (GPU) resources are insufficient- this limits model testing and ultimately will slow throughput of global bathymetry extraction
- Limited machine-learning engineers on staff- limits development throughput and capability

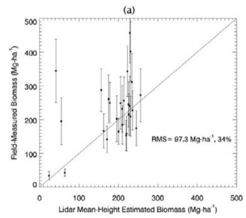
Estimating Aboveground Biomass from Fourier-Transformed Profiles

Robert Treuhaft JPL/Caltech

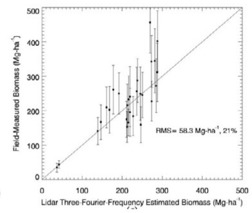
Objectives

- Aboveground biomass (AGB) is estimated as a function of lidar or photogrammetric (PG) profile, frequently mean height.
- We propose to estimate AGB as a function of Fourier amplitudes and phases from lidar waveforms or PG equivalent at optimal Fourier frequencies
- To be used on airborne or spaceborne lidar/PG platforms to attain higher AGB accuracy
- On Earth-observing systems, actual waveforms or synthetic waveforms (from point clouds) or PG profiles will be Fourier transformed

Fourier-Transform Estimation Potentially Higher Performance



AGB = f(mean-height)



AGB = f(Fourier transform)

Approach

- Developing the technology: Fourier transform profiles from existing sensors; regress to AGB
- Novel aspects: Mean height uses a very small part of the profile: two Fourier frequencies near zero.
- We will use multiple Fourier frequencies as needed
- Demonstrate on all existing lidar (GEDI, LVIS) and PG

Citations Treuhaft et al. Biomass estimation in a tropical…,GRSL, 2010.

Almeida et al. Estimation of biomass using digital aerial PG and the Fourier transform, in review

Co-Is/Partners Fabio Gonçalves, Canopy Rem Sens solutions, Brazil; Andre Almeida, U. Sergripe, Brazil; Yang Lei, Caltech

Technical Readiness Level

- Current Technical Readiness Level: 2
- With current resources, expected TRL that will be reached in the time frame 4 in 10 years
- Potential TRL in 5 years if resources are available: 8

Challenges

- What are the key technology or methodology challenges? Lack of studies with Fourier transform for AGB estimation.
- What activities are needed to overcome those challenges? Analysis of existing profiles, airborne and GEDI. Run process models for Fourier mechanistic characterization.

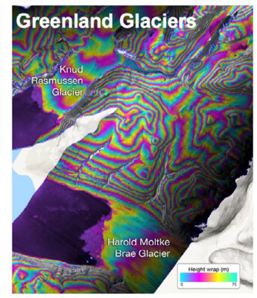
E.3 Radar Current Technologies

NASA Glacier and Ice Topography Interferometer (GLISTIN)

Yunling Lou, NASA JPL/Caltech (yunling.lou@jpl.nasa.gov)

Summary

- GLISTIN is an airborne Ka-band single-pass interferometer that leverages UAVSAR's radar backend for ice surface topography mapping.
  - The left-looking synthetic aperture radar employs two vertically-separated antennas to image the ground simultaneously and derives the topography from the differential phase between the received signals of the two antennas.
  - The Ka-band radar front-end consists of solid state amplifiers and two slotted waveguide antennas.
  - SAR technique enables high resolution large ground swath topographic imaging.
- https://uavsar.jpl.nasa.gov/technology/ka-band.html



Status

- Current Technical Readiness Level: TRL 9
- GLISTIN flies on NASA G-IIIs that are outfitted to carry the UAVSAR radar pod.
- GLISTIN has been flying since 2016, imaging alpine glaciers, snow accumulation in the Rockies, floodplains, and lava fields in Hawaii.
- GLISTIN monitored Greenland's coastal glacier topography change for the EVS-2 Oceans Melting Greenland mission and Kilauea volcano's lava volume after the 2018 eruption.

Performance

- GLISTIN produces georeferenced height, height precision, correlation, intensity images in 3 m posting
- Nominal cross track swath: 10 km
- Height precision at 3x3 m posting: 0.3 - 3 m
- Data delivery latency: 2 weeks to 2 months
- Onboard processor: quicklook interferogram for radar health check and imaging coverage verification
- Nominal altitude: 10-12 km
- Endurance/Range: 6 hours / 2600 nmi

Co-Is/Partners Delwyn Moller of Remote Sensing Solutions (PI during the instrument development)

Citations

https://uavsar.jpl.nasa.gov/cgi-bin/publications.pl?band=Ka-band

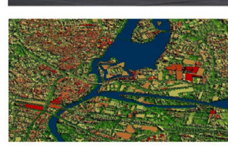
Only material suitable for full and open distribution shall be submitted. Submittals shall be considered approved by the providing organization to be suitable for full and open distribution. No proprietary, export controlled, classified, or sensitive material should be provided.

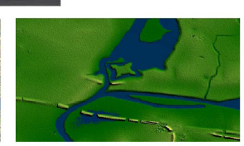
Intermap Multifrequency Airborne X/P IFSAR System

Michael Wollersheim, Executive VP of Gov't Solutions, Intermap (mwollersheim@intermap.com)

Summary

- Intermap's multifrequency airborne mapping system consists of X-band single-pass InSAR (IFSAR) and P-band polarimetric SAR to provide high resolution imagery and DEMs and sub-canopy information.
  - Dual-side looking radar aboard the FAA-certified Learjet-36 that flies at 38kft and can map ~12,500 sq. miles per flight
  - Standard data product includes a 25-cm orthorectified range image (OSI) and a 1-m posted DSM, accurate up to 1-m horizontally and 0.5-m vertically for open, unobstructed areas with slopes less than 10 degrees
  - Can also accommodate optical and LiDAR sensors by mounting these in the rear fairing, the avionics bay, and/or underwing pods
- https://www.intermap.com





Intermap's DSM (left) showing buildings and other surface features. DTM (right) showing the bare-earth surface.

Status

- Current Technical Readiness Level: TRL 9
- Intermap provides data collection, elevation data generation, and advanced data processing algorithms
- Deployed in over 40 countries and mapped more than 15 million sq. km of high-resolution 3D data and ortho image products, including collection and processing campaigns in 2019/2020 in Alaska and Malaysia, delivering hydro-enforced DSM and DEM
- Data products have supported analytics for underwriting flood risk around the world and provided certified, global aviation terrain database

Co-Is/Partners

Carolyn Johnston, Chief Scientist of Intermap

Performance

	X-Band	P-Band
Frequency	9.65 GHz center	340 MHz center
Bandwidth	270 – 1080 MHz	220 – 800 MHz
Operational Altitude	28,000 ft typical	28,000 ft typical
Operational Speed	200 m/s	200 m/s
Resolution	25 cm imagery, 1m posted DEM	83 – 30 cm
Products	Orthorectified image, digital surface model (DSM), digital terrain model (DTM), application-dependent derivatives	Co-polarized orthorectified images, cross-polarized orthorectified images, application-dependent derivatives

Citations

Goering, K., 2010. NEXTMap USA: A GPS Coordinate for Everything in the United States. GeoInformatics, 13(4), p.26.

Only material suitable for full and open distribution shall be submitted. Submittals shall be considered approved by the providing organization to be suitable for full and open distribution. No proprietary, export controlled, classified, or sensitive material should be provided.

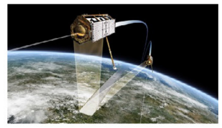
TanDEM-X - High Resolution Interferometric SAR Mission

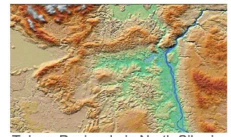
Prof. Dr.-Ing. Alberto Moreira, German Aerospace Center (DLR)

Summary

- Two X-band Synthetic Aperture Radar (TerraSAR-X) flying in close formation 200-600 meters apart, imaging the terrain below simultaneously from slightly different angles. The images are combined to form accurate elevation maps.
  - **Spacecraft:** 1230 kg (payload=394 kg), 5 m (height) x 2.4 m (diameter), X-band data downlink: 300 Mbps
  - **Instrument:** 5 m x 0.8 m active phased array antenna with 384 T/R modules, 1.8 kW peak (800 W average), quad-pol, 150/300 MHz bandwidth
- Generate global digital elevation model (DEM) with 12-m posting; study forest, ice sheets, and permafrost regions with X-band InSAR techniques.
- https://tandemx-science.dlr.de/

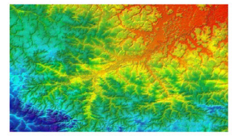
TerraSAR-X Spacecraft





Tajmyr Peninsula in North Siberia

Formation Flying



Bolivian Rain Forest

Status

- Current Technical Readiness Level (TRL 9)
- TerraSAR-X (TSX) was launched in 2010 and a second satellite (TDX) was launched in 2013
- Global DEM mapping: 2013-2016; mapping for global DEM change will complete in 2020; new science phase over forest, permafrost, and ice sheets to start in 2021
- Scientists have used TDX DEM to study ice dynamics and glacier topography due to climate change, derive global forest/non-forest maps, study geohazards such as volcano eruptions and landslides using differential InSAR

Co-Is/Partners

- Astrium GmbH (AirBus)

Performance

DEM Product	Spatial Resolution Absolute	Horizontal Accuracy CE90	Absolute Vertical Accuracy LE90	Relative Vertical Accuracy
TanDEM-X DEM (standard product 0.4 arcsec)	~12 m (0.4 arcsec @ equator)	<10 m	<10 m	< 2 m (slope @ 20%) < 4 m (slope > 20%) 90% linear point-to-point error within an area of 1°x1°
TanDEM-X DEM (1 arcsec)	~30 m (1 arcsec @ equator)	<10 m	<10 m	Not specified
TanDEM-X DEM (3 arcsec)	~90 m (3 arcsec @ equator)	<10 m	<10 m	Not specified

Citations

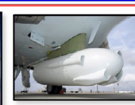
M. Zink et al., "TanDEM-X: The New Global DEM Takes Shape," in IEEE Geoscience and Remote Sensing Magazine, vol. 2, no. 2, pp. 8-23, June 2014, doi: 10.1109/MGRS.2014.2318895.

NASA Uninhabited Airborne Vehicle Synthetic Aperture Radar (UAVSAR)

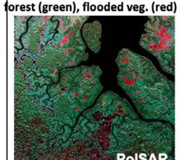
Yunling Lou, NASA JPL/Caltech (yunling.lou@jpl.nasa.gov)

Summary

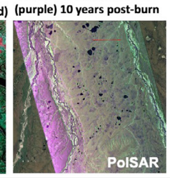
- UAVSAR is an airborne L-band quad-polarimetric synthetic aperture radar developed for repeat-pass interferometry.
  - UAVSAR has an electronically scanned antenna array to compensate for aircraft yaw and a real-time differential GPS unit to guide the aircraft's precision autopilot to repeat flight tracks to within a 5 m tube.
  - The 3.1 kW radar features high resolution, low noise floor, programmable TX waveform, and multi-squint angle imaging.
  - Instrument in the non-pressurized pod is compact, modular, and adaptable to support frequency upgrades (P, Ka-band).
  - Applications include solid earth surface deformation, soil moisture, vegetation structure, snow and glacier studies.
- https://uavsar.jpl.nasa.gov



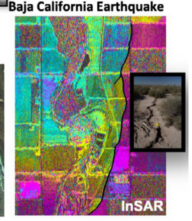
Gabon's Akanda Nat'l Park forest (green), flooded veg. (red)



Anaktuvuk River fire scar (purple) 10 years post-burn



Apr 4, 2010 M 7.2 Baja California Earthquake



Status

- Current Technical Readiness Level: TRL 9
- UAVSAR has been flying aboard NASA G-IIIs since 2009, and had 2 demonstration flights aboard a Global Hawk.
  - G-III altitude: 12.5 km (nom.), range: 2600 nmi (~6 hours)
- UAVSAR supports ~500 flight hours of science flights/year
- Notable campaigns: San Andreas fault and Sacramento Delta levee monitoring since 2010, Arctic-Boreal Vulnerability Experiment (ABoVE), SMAPVEX, NISAR cal/val, SnowEx, Hawaii volcanoes, Miss. River Delta studies, tropical forest studies (Gabon, Costa Rica, Peru), disaster response for oil spill, flooding, and wildfire

Co-Is/Partners

Scott Hensley, UAVSAR Chief Scientist, NASA JPL/Caltech

Performance

Frequency (MHz) / Polarization	1217.5-1297.5 / Quad-pol
Noise Equivalent Sigma0 (dB)	< -45
Radiometric Accuracy (dB)	< 1 absolute
One-look Res., slant rg./az. (m)	1.8 / 0.8
Georeferenced Spatial Posting (m)	6
Data Latency	1 - 4 weeks
Standard Processing	PolSAR, InSAR pair, InSAR stack
Experimental Processing	PolInSAR, TomoSAR
Experimental Mode	Multi-squint angle, Mono-pulse

Citations

https://uavsar.jpl.nasa.gov/cgi-bin/publications.pl

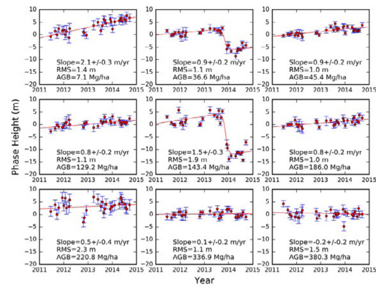
E.4 Radar Emerging Technologies

Structure and AGB Dynamics from InSAR Phase-Height Changes

Robert Treuhaft JPL/Caltech

Objectives

- InSAR phase-height is close to the radar-power-weighted average height. As such, it contains info about the height and structure of the vegetation. Since, over the course of a few years' growth, the structure may not change much, our objectives are 1) to use changes in phase-height as equivalent to changes in mean height. 2) To find a transformation from rate-of-change of phase-height to rate-of-change of AGB.
- From the above, we plan to observe rates of regrowth (e.g. panel 1 of Figure) and deforestation (e.g. panels 2 and 5 of Figure), as well as the biomass change associated with each. The biomass change is a measure of CO2 flux between the forest and the atmosphere, and so bears on atmospheric carbon and warming.



InSAR phase-height versus time from TanDEM-X in the Amazon; Treuhaft et. al.

Approach

- After removing instrumental and topographic slopes, use TanDEM-X phase-height measured over 3-8 years, linear slopes, height rates are estimated
- The rapidity and severity of deforestation events are also observed
- For nearly direct measurement of change, the accompanying figure, converted to AGB rate, will be the state of the art

Citations Treuhaft et al., 2017. Tropical-Forest Structure and Biomass Dynamics from TanDEM-X Radar Interferometry, Forests; Y. Lei et al. 2018. "Quantification of selective logging in tropical forest with spaceborne interferometry," Rem Sens of Env

Co-Is/Partners

- Yang Lei, Caltech; Fabio Gonçalves, Canopy Remote Sensing Solutions, Brazil, Michael Keller, JPL; Andre Almeida, U. Sergripe, Brazil

Technical Readiness Level

- Current Technical Readiness Level: 2
- Current resources, are not expended for phase-height rate studies, so the TRL will remain 2
- Potential TRL in 5 years if resources are available: 8

Challenges

- Optimal InSAR frequency is unknown
- Airborne InSAR demos over time at L, C, and X band are needed to determine optimal frequencies
- The transform to AGB rate may depend on location and type of forest. Airborne experiments needed.

Only material suitable for full and open distribution shall be submitted. Submittals shall be considered approved by the providing organization to be suitable for full and open distribution. No proprietary, export controlled, classified, or sensitive material should be provided.

Distributed Aperture Radar Tomographic Sensors (DARTS)

PI: Marco Lavalle, JPL/Caltech

Objectives

Goal:

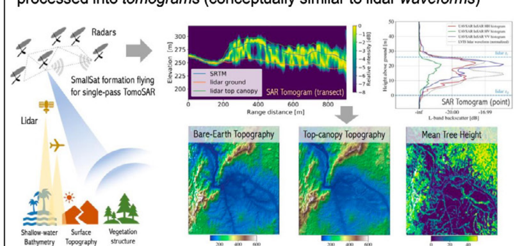
Mature and demonstrate a set of technologies that, when coupled with recent developments in miniaturized spaceborne radars, will enable formations of satellites to perform global vegetation structure and surface topography measurements via simultaneous SAR tomography technique.

Specific objectives:

1. Design, build and test a distributed system to synchronize timing, clock, relative position and sensor data for all of the distributed elements.
2. Miniaturize the distributed phase-coherent radar system
3. Design the instrument architecture and orbital configuration for 3D vegetation structure and surface topography.
4. Test SmallSat compatible L-band deployable antenna

Website: NASA ESTO IIP-19 funded tasks

One or more satellite(s) transmit a radar signal and multiple spacecrafts in close formation receive the scattered echoes, which are coherently processed into *tomograms* (conceptually similar to lidar *waveforms*)



Approach

- Develop and assess synchronization and relative localization algorithms via field/bench tests
- Generate radar tomograms from synchronized signals acquired by small unmanned aircraft systems (sUASs) for changing geometry/site
- Conduct integrated trade-study analysis with orbital, scene, radar, and platform parameters via simulations informed by synchronization/localization algorithm assessment
- Build and test light-weight, deployable, antenna with mechanical support for Transmit/Receive and Receive-only SmallSats

Co-Is/Partners

Team is a synergy between the JPL Radar Section (334) and other JPL Sections (e.g., 335) in collaboration with Caltech (Prof. S. Chung).

Technical Readiness Level

- Current Technical Readiness Level = 2/3
- With current funded IIP resources, expected TRL = 5
- TRL in 5 years if resources are available = 7

Additional Challenges

- Conversion of radar tomograms into L3 products
- Further radar miniaturization (e.g. leveraging RF photonics)
- Integrated TomoSAR performances leveraging existing missions (SAR or GNSS)
- Data volume, on-board processing and downlink
- Multi-frequency TomoSAR data collection with airborne SAR

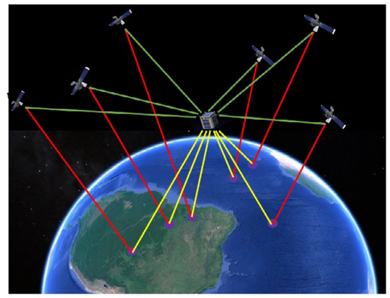
Only material suitable for full and open distribution shall be submitted. Submittals shall be considered approved by the providing organization to be suitable for full and open distribution. No proprietary, export controlled, classified, or sensitive material should be provided.

Multi-frequency Signals of Opportunity

Rashmi Shah, JPL

Objectives

- To apply multi-frequency measurement approach for Signals of Opportunity (SoOp) bistatic radar technique for remote sensing on vegetation with potential for high temporal coverage at low-cost.
  - **Instrumentation:** Multi-frequency reflectometry receivers looking at reflections from the ground with wide-beam electronically steerable antennas.
  - **Information systems:** Onboard tunable receivers processing data from multiple frequency with data analysis on ground.
  - **Platforms**: Adaptable to multiple platforms (UAVs, aircraft, spacecraft)
- The data can be used for other observations as well.



Approach

- Building upon SoOp/GNSS-R receivers capability based on wideband System-on-a-Chip (SoC)
- Utilize multi-frequency simulation capability in OSSE to develop requirements for different frequencies for measuring vegetation

Citations

V. Meyer, A. A. Bloom, M. S. Burgin, J. T. Reager, R. Shah and A. Konings, "Reduced Uncertainties from Multifrequency Constraints on Terrestrial Carbon and Water Processes," IGARSS 2019.

Co-Is/Partners

Anthony Bloom, JT Reager, Garth Franklin, Robert Treuhaft

Technical Readiness Level

- Current TRL = 2
- No resources currently available for this concept
- Potential TRL in 5 years = 6

Benefit

- With a variety of attenuations, multi-frequency data can provide information at different depths of vegetation

Challenges

- Development of measurement capabilities and how it ties to the science needs
- Receiver and antenna development

Baseline Interferometry with GNSS-Reflection

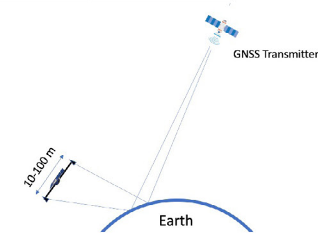
George Hajj, JPL, (Radar Science and Engineering Section, 334)

Objectives

Apply interferometric principles to Global Navigation Satellite System-Reflection (GNSS-R) for remote sensing of surface topography and vegetation providing low-cost, global, and rapid coverage.

- **Instrumentation:** Advanced GNSS receivers tracking multiple GNSS signals reflected off the Earth's surface. Multibeam electronically steerable GNSS antenna array with 16 db gain or higher.
- **Information systems** onboard processing system for forming interferogram images. Ground processing system for data analysis
- **Platforms:** two satellites separated by 10s of meters

Graphics that convey the key aspects of the technology development



Approach

- Utilize/modify the radar simulation and processing capabilities in section 334 for bistatic reflections
- Utilize advanced GNSS-R receiver built in sections 334 and 335
- Perform simulation studies for feasibility, optimization, and system requirement analyses
- Perform antenna design analysis
- A potential factor of 10-100 improvement in vertical and horizonal resolution over tradition GNSS-R with a rapid global daily coverage.

Co-Is/Partners

Stephen Lowe (335), Rashmi Shah (335), Bryan Stiles (334)

Technical Readiness Level

- Current TRL = 5
- With current resources, expected TRL that will be reached and the time frame: no resources are currently available for this concept
- Potential TRL in 5 years = 8

Challenges

- Low bandwidth and SNR which can be overcome with:

1- Use other satellites of opportunity with wider bandwidth

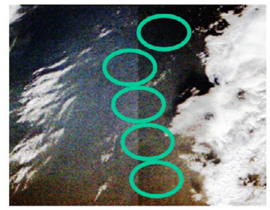
2- Advanced antenna designs

Dynamic Targeting

Steve Chien, Jet Propulsion Laboratory steve.a.chien@jpl.nasa.gov

Objectives

- Use lookahead sensing to target or avoid targets of interest/non interest.
  - **Use Case:** OCO or VSWIR target around clouds
  - **Use Case:** Smart Radar targets deep convective storms
- Analysis of MODIS cloud data indicates that dynamic targeting could double non cloudy data and avoid cloud
- Website for further info if available



"Take non-cloudy data"

Approach

- Detection algorithms suitable for flight. (Often use machine learning technologies)
- Pointing planning algorithms account for slewing, off-nadir effects, to maximize utility of observations
- Concept applies to single spacecraft with lookahead sensor or to "smart train" where spotter spacecraft communicates detections to trailing spacecraft

Co-Is/Partners

- Northrop Grumman Corporation (SMICES)

Technical Readiness Level

- Current TRL 5-6
- With development could be TRL 8 in few years.

Challenges

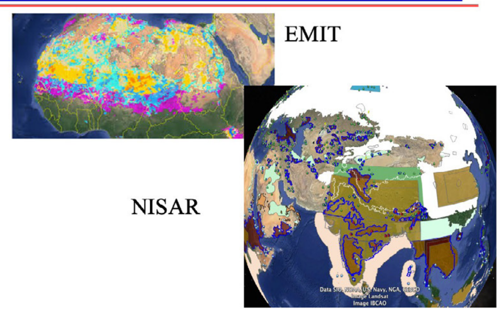
- Accurate detection of features of interest/rejection
- Dynamic targeting algorithms in embedded online planning environment
- Further maturation and concept refinement

Automated Mission Analysis

Steve Chien, Jet Propulsion Laboratory steve.a.chien@jpl.nasa.gov

Objectives

- Use operations planning tools to assess mission design, configuration, and operations concepts at early mission conceptualization stages.
  - **Use Case:** Evaluation of observations strategies (ECOSTRESS, EMIT)
  - **Use Case:** Detailed curation and evaluation of science mission plans (NISAR)
- Enable principled analysis of design trades earlier in mission development
- Enable improvement and optimization of mission design, spacecraft design, and operations concept



Approach

- Model operations of missions including stochastic factors (such as cloud obscuration); generate range of mission plans based on said model
- Quantitatively evaluate science return, cost, risk
- Iterate to update model with mission formulation team (partially to fully automated)

Citations

- https://ai.jpl.nasa.gov/public/projects/clasp/
- https://ai.jpl.nasa.gov/public/projects/relic/

Technical Readiness Level

- Current TRL 7-9
- Additional development enables greater automated search of mission options
  - Can increase mission return
  - Can enable evaluation with reduced effort

Challenges

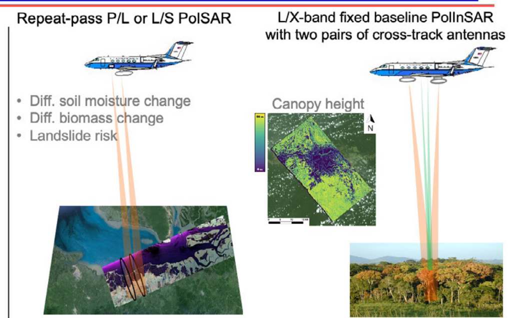
- Facilitating iterative process with science team
- Quantification of science goals

NextGen UAVSAR

Yunling Lou, NASA JPL/Caltech (yunling.lou@jpl.nasa.gov)

Objectives

- Modernize UAVSAR capabilities to push the envelope of future technologies and enable new measurements to mature future decadal survey concepts:
  - **Radar configurations:** simultaneous P/L/S-band repeat-pass PolInSAR; L/X-band fixed baseline PolInSAR; Ka-band InSAR; coincident stereo optical imager; bistatic observation
  - **Information systems:** TomoSAR products for vegetation structure; high resolution DSM and DTM; radar and optical data fusion; onboard processing for rapid response
  - **Platforms:** G-III and G-V; HALE (?)
- Contribute instrument and processing technology to support multi-frequency and multi-static observations for Surface Deformation and Change, Terrestrial Ecosystem Structure, Snow Depth, and Ice Elevation



Approach

- Leverage UAVSAR hardware framework to add new radar bands and bistatic observation
- Add antennas to G-III fuselage to enable simultaneous multi-frequency operation
- Demonstrate PolInSAR imaging for vegetation height over a variety of biomes and topography
- Mature PolInSAR and TomoSAR algorithms for generating vegetation structure and snow accumulation products
- Demonstrate DSM and DTM generation with L/X-band InSAR and stereo optical imager

Co-Is/Partners

- Airborne SAR science community, SDC and STV study team members; Andrea Donnellan, JPL (optical imager)

Technical Readiness Level

- Current Technical Readiness Level: 4
  - **Repeat-Pass PolInSAR** and **TomoSAR** have been demonstrated with UAVSAR and qualitatively compared to lidar profiles for veg. structure
  - Prelim. results from L-band DInSAR show sensitivity to snow water equivalent
- Anticipated current resources will enable multi-freq. & bistatic observations, and veg. structure retrieval in 3 yrs; SnowEx campaigns will develop/assess L-DInSAR for SWE retrieval over complex terrain and different snow conditions
- Potential TRL in 5 years if resources are available to implement L/X-band fixed baseline PolInSAR: 6

Challenges

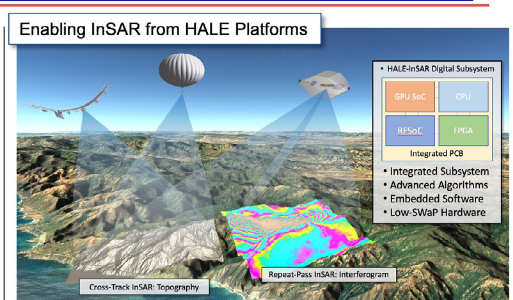
- Secure funding to build fixed baseline L/X-band PolInSAR
- Conduct multi-institutional PolInSAR/TomoSAR observations along with lidar and field observations to assess veg. height retrieval algorithm robustness and accuracy

High-Altitude Long-Endurance Interferometric Synthetic Aperture Radar

Patrick Rennich, Aloft Research Corporation, patrick.rennich@aloftresearch.com

Objectives

- Stratospheric HALE-based InSAR provides a new type of affordable and persistent radar sensing
  - **Instrumentation:** Multi-channel coherent radar payload leverages ultra-low-SWaP digital hardware
  - **Algorithms:** Embedded HALE-optimized algorithms for low-latency high-resolution imagery and mm-level precision deformation measurements
  - **Platforms:** Solar-powered airships, high-altitude UAVs, stratospheric balloons; compatibility with aircraft and small satellites supports distributed mesh operations
- Reliably and continuously observe topographic changes from dynamic events like earthquakes, volcanoes, landslides, and flooding.



Approach

- High-bandwidth, SoC-based hardware combined with SAR backprojection and track estimation algorithms solve key HALE operational challenges
  - Payloads are SWaP constrained (< 10 kg, <150 W)
  - InSAR collection complicated by slow HALE velocities and non-linear repeat-track trajectories

Citations

- P. Rennich, et al., "Analyzing new data from CIRES: CubeSat Imaging Radar for Earth Science," *NASA ESTF*, June 2020.
- P. Rennich, et al., "Synthetic Aperture Radar from a Stratospheric Balloon," *65th Tri-Service Radar Symposium*, June 2019.

Co-Is/Partners

L. Wye (Aloft), J. Carswell (RSS), J. Stock (USGS), S-H Yun (JPL)

Technical Readiness Level

- Current Technical Readiness Level (≤ TRL 2)
- TRL 4-5 within 2 years with anticipated resources
- TRL 9 in 5 years if resources are available

Challenges

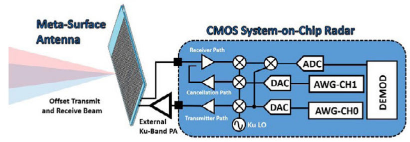
- Key challenges are applying InSAR algorithms to HALE collection geometries and efficiently embedding processing within on-board digital resources
- Challenges to be overcome with representative test flights and simulation-based development

CMOS Enhanced Meta-Surface Array for Active/Passive Snow Sensing

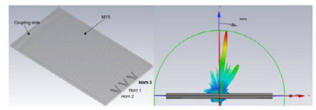
PI: Hans-Peter Marshall, Boise State University

Objective

- Develop an advanced spaceborne Ku-band (15 GHz) active and passive (radar/radiometer) instrument to measure snow in dry and wet conditions
  - Provides key parameters for snow water equivalence (SWE) estimation by retrieving snow density, depth, and liquid water content, with a Ku-band radar system that can double as a radiometer.
- Use the CMOS system-on-a-chip (SoC) electronics technology originating from the mobile phone industry combined with an advanced meta-surface (MTS) antenna to achieve high radar isolation and broad dynamic range required for accurate snow measurement.



Block diagram of the CMOS SoC radar chip with the meta-surface antenna.



Beam steering MTS antenna

Approach

- Develop the key circuitry required to enhance the transmitter-to-receiver isolation achievable with an MTS antenna
- Integrate that circuitry into a CMOS radar chip with all radar functions and fabricate that chip for testing
- Develop a 30cm MTS antenna for airborne testing and design a 100cm spaceborne MTS antenna with isolation suitable for sensing snow at Ku-band,
- Combine the 30cm antenna with the radar chip and validate instrument performance for dry and wet snow conditions through ground observatories and from a UAV aircraft

Co-Is/Partners:

Adrian Tang, Nacer Chahat, Goutam Chattopadhyay, JPL; Thomas Painter, Frank Mau-Chung Chang, UCLA

Technology Readiness Level

- Current Overall TRL: 3
- Expected TRL: 5 (at completion of NASA IIP, January 2023)
- Potential TRL: 6 (by 2025 with additional resources)

Challenges

- Large payload drone in development and testing with capacity to support CMOS radar experiments
- Additional C-band system has been added for testing Sentinel snow depth retrievals

04/20 IIP-19-0005

ESTO Earth Science Technology Office

CAPELLA SAR SATELLITE

Capella Space Corp.

Objectives

- Synthetic Aperture Radar (SAR) - 0.5 m resolution high quality imaging (spotlight, stripmap)
- Small satellite platform under 100 kg mass
- Sequoia is the first Capella's Satellite and the first American commercial SAR satellite
- Automated processing and data product distribution system in Cloud Optimized Geotiff format
- Satellite tasking system accessible via API using STAC metadata
- Derived product such as change detection from SAR data stack (in the roadmap)
- Constellation composed by multiple satellites (in the roadmap)

https://www.capellaspace.com

Graphics that convey the key aspects of the technology development

Approach

- Capella Space builds Satellites, Payload, Processing Pipeline and Data Analytics
- X-band SAR satellite system allowing to collect 0.5-meter resolution SAR imagery multilooked and ground projected
- Intuitive self-serve online platform with simple catalog exploration, ordering and on-demand tasking

Citations

C. Stringham, G. Farquharson, D. Castelletti, E. Quist, L. Riggi, D. Eddy, S. Soenen, "The Capella X-band SAR Constellation for Rapid Imaging," IGARSS 2019 - 2019 IEEE International Geoscience and Remote Sensing Symposium, Yokohama, Japan, 2019, pp. 9248-9251.

D. Castelletti, G. Farquharson, C. Stringham, D. Eddy, "Operational Readiness of the Capella Space SAR System," IGARSS 2020 IEEE International Geoscience and Remote Sensing Symposium.

Technical Readiness Level

Current Technical Readiness Level is TRL 9

Sequoia, Capella's first SAR satellite, has been launched and is currently operative

Sequoia is currently under commissioning phase

High quality SAR image acquisition and processing has been demonstrated and is currently operative

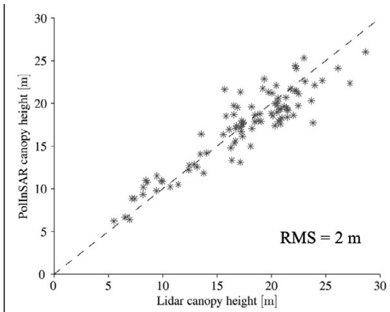
Tasking system and other operational features are operative and currently under testing

Polarimetric Interferometric (PolInSAR) Estimates of Forest Height

Robert Treuhaft JPL/Caltech

Objectives

- PolInSAR forest-height measurements allow for the determination of contiguous, high-resolution, vegetation-structure-metrics, with global coverage. Interferometric SAR (InSAR)observations (amplitude and phase) are sensitive to forest height, and properties of forest vegetation profiles. InSAR observations at different polarizations (PolInSAR) are, in addition, sensitive to the polarimetric characteristics of the ground. Models of the PolInSAR sensitivity to vertical characteristics have been used to estimate forest height with a range of accuracies, from 2 to 5 m. Our objectives are 1) to perform near-simultaneous airborne PolInSAR observations at P-, L-, C-, and X-band, each with a fixed-baseline (*not* repeat pass,*no* temporal decorrelation) over boreal, temperate and tropical forests; and 2) to develop algorithms for estimating forest height using PolInSAR at multiple frequencies, and 3) to assess accuracy by comparing to lidar and field observations.



Forest height from L-band 3-baseline PolInSAR airborne radar, DLR, E-SAR over Sweeden; versus lidar height, Lavalle and Kuhn 2014

Approach

- Plan and execute acquisition of multi-fixed-baseline, multi-temporal, multi-frequency airborne PolInSAR observations over diverse forest types
- Plan and execute simultaneous lidar and field obs
- Start with variants of existing models to develop a multi-baseline/frequency, PolInSAR algorithm for forest height.

Citations Lavalle and Khun 2014. Three-Baseline InSAR Estimation of Forest Height, *IEEE Geoscience and Remote Sensing Letters;*

Treuhaft /Siqueira 2000. The vertical structure of vegetated land surfaces from interferometric and polarimetric radar, Rad Sci.

Co-Is/Partners

Marco Lavalle, JPL; Yunling Lou, JPL;
Scott Hensley, JPL; Sassan Saatchi, JPL.

Technical Readiness Level

- Current Technical Readiness Level: 4
- Current resources, are not expended for phase-height rate studies, so the TRL will remain 4
- Potential TRL in 5 years if resources are available: 8

Challenges

- Fixed-baseline interferometric radar at L-band must be built (see airborne NextGen UAVSASR quad-chart)
- Multi-institutional PolInSAR observations must be planned along with lidar and field observations
- Algorithms for estimating forest height must account for soil/canopy moisture, phenology, and topography

Only material suitable for full and open distribution shall be submitted. Submittals shall be considered approved by the providing organization to be suitable for full and open distribution. No proprietary, export controlled, classified, or sensitive material should be provided.

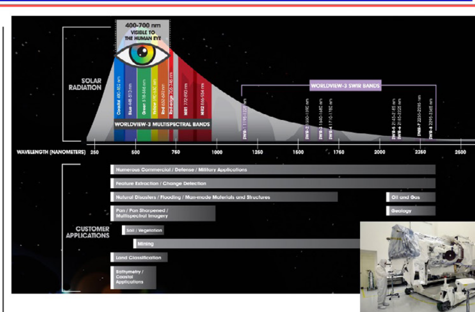
E.5 Stereophotogrammetry Current Technologies

WorldView-1,2,3,4

© Maxar technologies maxar.com formerly DigitalGlobe

Objectives

- Commercial imagery sales, national security imagery supplement, DOD requirements 2007 - present:
  - **Instrumentation** 4 satellites, 31-52cm Pan, 1.16-1.82 m 8-band VNIR (WV2,3), 4 m 8-band SWIR (WV3), 30 m 12-band CAVIS (WV3), 496-770km polar orbiting, Mass >kg 3x2x2 m, 13-17km swath, GEO acc. < 5m CE90, pushbroom
  - **Information systems** Lev. 1B (sens-oriented radiometrically cal.), Lev. 2A/2B map projected, Lev. 3 ortho prod.
  - **Platforms** Satellites flown sun-syn polar orbiting 10-11 AM overpass
- NGA/NRO contract fed/civ no cost data access



Approach

- Monetizing gigapixels, 11-bit
- Spacecraft cost >$800m each
- 680,000 – 1.2 m km^2 per day per satellite
- Large optics, high SNR, pushbroom
- Multiple collection scenarios, large area single pass 30° off nadir collect 138x112km mono, 63x112km stereo, long strip 16.4x360km

Citations

https://www.digitalglobe.com/company/about-us

Co-Is/Partners

Vricon/3D pc, Radiant Sol/AI, MDA/downlink

Technical Readiness Level

- Current Technical Readiness Level >TRL 9, Operational class B

Challenges

- High demand capacity over densely populated regions
- Onboard data volume storage and downlink "blackouts"
- High SNR needed for <15° sun angle
- Pointing accuracy, slewing speed and jitter
- Aperture size tradespace, sat size/cost – SNR/image size/res
- WV3 SWIR and CAVIS comprise ~10% of collects
- Point and shoot tasking, no systematic collect
- Largest archive of in-track stereo but global coverage still does not exist from 2007 WV-1 launch
- Limited capacity for fed/civ stereo tasking

Only material suitable for full and open distribution shall be submitted. Submittals shall be considered approved by the providing organization to be suitable for full and open distribution. No proprietary, export controlled, classified, or sensitive material should be provided.

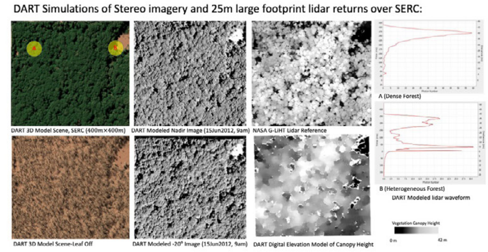
G-LiHT Airborne Data and DART Modeling to Explore Lidar-Optical Synergies

B. Cook, D. Morton, L. Corp, Yin, P. Montesano, C. Neigh, T. Neumann (NASA GSFC)

Summary

- Synergies between lidar and stereo optical data are being explored through the acquisition of airborne data and 3D radiative transfer modeling.
  - **Instrumentation**: NASA's G-LiHT multi-sensor airborne imager equipped with scanning lidars and a fine-resolution (3 cm) stereo RGB-NIR camera system.
  - **Lidar-Optical Simulations:** DART radiative transfer model to understand optimal overpass times and sensor configurations based on model simulations with varying sun-sensor geometry and environmental conditions (e.g., topography, vegetation structure, etc.)
  - **Data Integration:** Workflows that optimize digital elevation models and change measurements from a combination of lidar-optical data.

DART Simulations of Stereo imagery and 25m large footprint lidar returns over SERC:



Status

- G-LiHT has operated since 2011; TRL 9 w/RBG camera
- COTS NIR camera will be integrated during 2020
- Leaf-on/off flight will occur during 2021 on King Air A90
- DART was developed in 1992, and NASA scientists have been using it to simulate different types of lidars and optical sensors on space and aircraft platforms.
- G-LiHT lidar data can be used to create realistic 3D scenes for DART simulations, which can be validated with G-LiHT stereo optical data.

Co-Is/Partners

USDA Forest Service, Smithsonian Environmental Research Center, American University

Performance

- Simulated stereo data will allow us to construct an error matrix and explore STV uncertainty covering a broad range of instrument configurations and environmental conditions, including:
  - Vegetation structure, topography, surface reflectance
  - Latitude, seasonality, time of day
  - View angle, optical wavelength, lidar footprint and spacing

Citations

Gastellu-Etchegorry, J.-P, *et al.* 2015. Discrete Anisotropic Radiative Transfer (DART 5) for Modeling Airborne and Satellite Spectroradiometer and LIDAR Acquisitions of Natural and Urban Landscapes. *Remote Sensing*, 7:1667-1701.

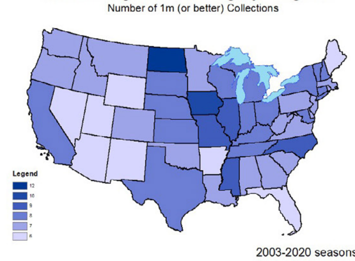
Neigh, C. *et al.* 2014. Deciphering the precision of stereo IKONOS canopy height models for U.S. forests with G-LiHT airborne LiDAR. Remote Sensing 6:1762-1782; doi:10.3390/rs6031762.

National Agriculture Imagery Program (NAIP) Elevation Data Options

John Mootz, USDA/FPAC, john.mootz@usda.gov

Summary

- Largest, longest running consistent airborne-based civilian program
- Public Domain dataset
- 60cm ortho imagery program acquires full CONUS coverage with cost-share partners
- Acquisition Period – Leaf-on during peak agriculture growth
- Photogrammetry derived elevation model from stereo imagery collected from airborne sensor is available as a priced option for cost-share partners



Status

- Well established, proven technology with decades of experience
- Present acquisition is entirely with digital sensors.
- Must meet rigid calibration specifications
- Refresh – two-year CONUS collection cycle since 2008; changed to three-year in 2018
- TRL 9

Co-Is/Partners

- Contracted aerial survey companies.

Performance

- Autocorrelated elevation data, DSM, DEM
- Spatial Resolution – 1m (all states since 2008) & 60cm ground resolution (2018)
- Spectral Resolution – Natural Color and False Color Infrared (all states since 2010)
- Platforms are contracted aircraft.

Citations

E.6 Stereophotogrammetry Emerging Technologies

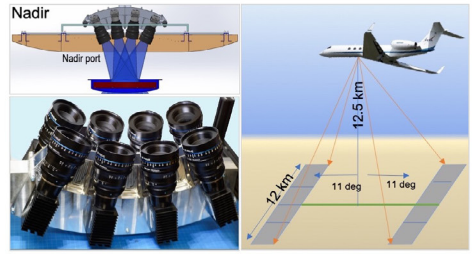
QUAKES-I Airborne Stereo Photogrammetry Imager

Andrea Donnellan, NASA/JPL/Caltech

Objectives

- Provide topographic products for measuring land surface morphology, land surface change, and provide radiometric terrain correction for UAVSAR
- Develop an airborne imager to provide color and 3D stereo photogrammetric products
  - Targets: earthquake faults and ruptures, earthquake prone regions, volcanoes, landslides, wildfire scars, glaciers, vegetation, and ecosystems
- Produce sub-meter resolution topographic images at nadir along a 12 km wide swath
- Provide imagery concurrent with the UAVSAR image swath
  - 3 m resolution visible orthorectified topographic products
  - 9 m resolution SWIR imagery
- Airborne instrument flown at 12.5 km altitude

Camera array for the nadir port and ground coverage



Approach

- Test, calibrate, and deploy the full 8 camera full-frame, multi-angle imager and the 2 SWIR cameras for both side window and nadir ports on the JSC Gulfstream III and V respectively
- Conduct test flights over multiple targets with ground validation
- Establish processing pipeline for a supercomputing resource

Citation

Donnellan, et al, 2019. Improving UAVSAR Results with GPS, Radiometry, and QUAKES Topographic Imager, IEEE Aerospace Conference, Big Sky, Montana, 2019.

Co-Is/Partners C. Padgett, J. Green, A. Ansar, Y. Lou, J. Parker(JPL), S. DeLong (USGS)

Technical Readiness Level

- Current Technical Readiness Level (TRL) = 5
- With current resources, expect TRL 7 reached by end of fiscal year 2021
- Potential TRL 9 in 5 years if resources are available

Challenges

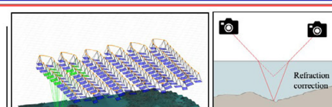
- Improving accuracy with over sampling techniques
- Data product turn around in flight or with low latency for support of wild fire and natural disasters
- Understanding how calibration errors impact overall performance

Bathymetric Mapping from Imagery: Combined Geometric-Radiometric Approach

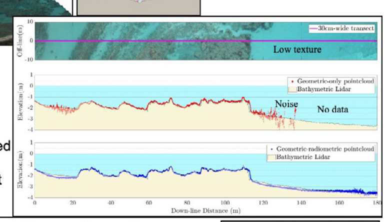
Richard Slocum and Christopher Parrish, Oregon State University

Objectives

- Goal: fill nearshore data gap
  - Many coastal areas around world lack nearshore bathymetry
  - Challenging, inefficient and potentially dangerous to collect data in shallow areas (e.g., coral reefs)
  - Nearshore data void hinders coastal science, coastal resilience efforts, and marine navigation
- Motivation: geometric (stereo photogrammetry) and radiometric (spectrally-derived bathymetry) approaches to bathymetric mapping are highly complementary
  - Geometric works well with high texture; radiometric works well with uniform bottom types and water clarity
  - Combined approach → improve accuracy & reduce gaps



Refraction-corrected SfM photogrammetry + spectrally-derived bathymetry



- Top: transect location
- Middle: geometric-only point cloud
- Bottom: combined geometric-radiometric point cloud

Approach

- Input = overlapping RGB imagery
- Process with SfM/MVS photogrammetric software
- Results used to train machine learning (ML) model for bathymetry retrieval from spectral info
- Combine for all images

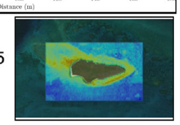
Citations

Slocum, R.K., C.E. Parrish, and C.H. Simpson, 2020. Combined Geometric-Radiometric and Neural Network Approach to Shallow Bathymetric Mapping with UAS Imagery. *ISPRS Journal of Photogrammetry and Remote Sensing* (in press).

Co-Is/Partners

- NOAA NCCOS

Technical Readiness Level



- Current Technical Readiness Level: TRL 5
- With current resources, expected TRL that will be reached and the time frame: TRL 6 (5 years)
- Potential TRL in 5 years if resources are available: TRL 8

Challenges

- Only works in optically-clear waters
  - Non-negligible contribution from seafloor to at-sensor radiance
- Need to test in a across a wider range of environmental conditions (substrate and cover types, water clarity)
- Extend to stereo satellite imagery (to date, only tested with low-altitude UAS imagery)

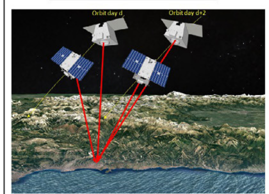
CO3D Demonstrator

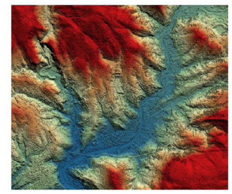
CNES (French Space Agency)

Summary

- Constellation of low-cost 50 cm resolution optic Earth Observation satellites flying by pair to acquire the world landmasses in stereo.
- Digital Surface Model (DSM) massively and automatically generated thanks to cloud computing
- Synchronicity capacity between stereo acquisitions to freeze moving objects in three dimensions
- Constellation multi-view tasking to enhance 3D reconstruction on dedicated sites
- A 18 month demonstration phase is defined after the constellation launch to verify the system performance over France and a defense Arc of Interest area.

Graphics that convey the key aspects of the technology





Status

- System definition phase is ending
- Launch scheduled for mid 2023
- Demonstration phase is to end before 2025
- Market phase following demonstration phase

Performance

- 90 % of the world landmasses DSM produced within 3 years
- 50 cm resolution images in Red, Green, Blue and Near Infra-red channels
- One meter relative altimetry accuracy DSM
- 3D data : Multi-resolution DSM (best one is one meter)
- 2D data : ortho-images temporally and geometrically consistent with 3D data

Co-Is/Partners

- Co-engineering with industrial partner AIRBUS

Citations

Only material suitable for full and open distribution shall be submitted. Submittals shall be considered approved by the providing organization to be suitable for full and open distribution. No proprietary, export controlled, classified, or sensitive material should be provided.

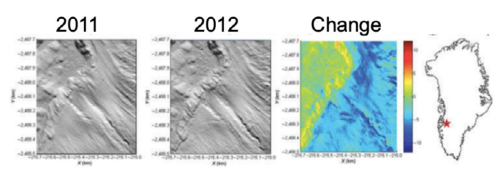
Canopy Height and Glacier Elevation (CHANGE) Mission Concept

Doug Morton, Tom Neumann, Bruce Cook (NASA GSFC)

Objectives

Understand processes that drive ice and vegetation change on seasonal time scales. Early detection of change processes is a critical component of characterizing and responding to climate-driven changes in the Earth system. Our fusion of lidar and stereo optical imaging enables science that will:

- identify mechanisms that alter biogeochemical cycling in forests, woodlands, and savanna ecosystems
- quantify ice sheet mass loss and mass loss change
- provide continuity with current and planned measurements of ice sheet elevation, sea ice thickness changes (e.g., ICESat-2), and vegetation structure measurements (e.g., GEDI)
- advance data fusion science and applications for change detection and surface characterization



Surface elevation change with DEMs from stereo pairs plus lidar from Noh and Howat (2015) for a site in southwest Greenland. Panels (a) and (b) show orthorectified images from 5 June 2011 and 21 July 2012 by WorldView-1. The height difference between the DEMs is shown in (c). Location is shown in (d).

Approach

- Aiming to leverage space-qualified COTS as much as possible
- Will generate ~10km wide swaths (in regions with sufficient structure) rather than tracks limited to lidar beam diameter.
- Aiming for Earth Systems Explorers AO

Technical Readiness Level

- Current Technical Readiness Level (5)
  Refer to NASA TRL definitions on following slides
- With current resources, expected TRL that will be reached and the time frame
- Potential TRL in 5 years if resources are available: 6

Co-Is/Partners

Univ of Washington, Polar Geospatial Center / Univ. of Minnesota, Ohio State Univ., JPL

Challenges

- Rapidly evolving optical imagery in commercial sector.
- Cost limitations of ESE outlined in 2017 DS

Only material suitable for full and open distribution shall be submitted. Submittals shall be considered approved by the providing organization to be suitable for full and open distribution. No proprietary, export controlled, classified, or sensitive material should be provided.

NAIP Potential Future Technology

John Mootz, USDA/FPAC, john.mootz@usda.gov

Objectives

- Single airborne sensor system that collects both imagery & Lidar data simultaneously
- When paired with an existing national imagery programs such as NAIP, a "single flight" could provide lower cost options for state based QL 2 data collections

Graphics that convey the key aspects of the technology development

Approach

- CountryMapper is a Leica hybrid system with imaging and lidar with elliptical scan pattern
- Operational altitude =.6 km, speed of 180 knots
- Pulse repetition frequency (PRF) = 750 KHz
- Scan rate of 112 Hz
- Provides imagery product of 20 cm and a pulse density 2.9 points per square meter

Citation

- https://www.mdpi.com/2072-4292/12/12/1974

Co-Is/Partners

Leica Geosystems

Technical Readiness Level

- TRL 7-8
  Pilot conducted in 2019

Challenges

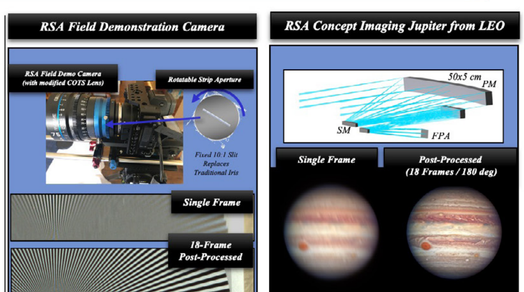
- The vendor system used for the 2019 pilot is changing the imagery sensor and will likely require additional testing

Rotating Synthetic Aperture Imaging for High Resolution Earth Observation

Joseph J. Green, JPL

Objectives

- Rotating Synthetic Aperture (RSA) Imaging offers a new path to low-cost, compact, high-resolution imaging systems
  - Combines directionally high resolution imaging, rotational imaging conops and computation to incoherently synthesize larger circular aperture systems in post-processed products
- Enables space-based 3D color stereo photogrammetric and change detection products for
  - Earthquake faults and ruptures, earthquake prone regions, volcanoes, landslides, wildfire scars, glaciers, vegetation, and ecosystems
- From a 900km (high-LEO) perspective, system concepts have potential to resolve sub-20cm features over 10+ km fields of view



Approach

- Developed exo-planet spectroscopic RSA concepts in 2018
- Co-I on MIT-lead APRA study on Rotating Pointing Control concepts for future small-sat RSA demo
- In Y2 of Topical R&TD demonstrating RSA imaging performance

Citations

- J. J. Green, et al, "Architecture for space-based exoplanet spectroscopy in the mid-infrared," Proc. SPIE, (Austin 2018).
- J. J. Green et al, "Super-Resolution in a Synthetic Aperture Imaging System," IEEE ICIP, 1997.

Co-Is/Partners

JPL: A. Donnellan, C. Padgett, B. Dube, E. Sidick
MIT: Rebecca Masterson **U Rochester:** James Fienup

Technical Readiness Level

- The FY20 R&TD Demonstration brought RSA to TRL-4 for the imaging concept, and software
- Completion of APRA Study with MIT will bring pointing concept to TRL-4 by end of CY22
- If we could get the funding, we hope to execute a demonstration mission within a 5-year timeframe bringing the concept to TRL-9
  - TRL-8 if sub-scale demo

Challenges

- Pointing control and momentum management for constantly rotating space-segment is an engineering challenge
- Successful post-processing with large pointing errors and knowledge has now been ***successfully demonstrated*** in the 2020 R&TD demonstration

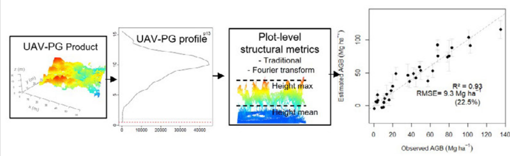
Estimating AGB using Fourier-Transforms of vertical profiles derived from photogrammetry

André Quintão de Almeida UFS/Brazil

Objectives

- Aboveground biomass (AGB) is estimated as a function of LiDAR profile, frequently traditional canopy height metrics, i.e. height mean, maximum and percentiles.
- The cost of obtaining LiDAR data is high and the traditional canopy height metrics explore only a small part of the structural information contained in the 3D data.
- We propose to produce point clouds of photogrammetric (PG) data and estimate AGB from metrics extracted from Fourier amplitude.
- On Earth-observing systems, waveforms PG profiles will be Fourier transformed.

Graphics that convey the key aspects of the technology development



Approach

- Developing the technology: Produce point clouds/profiles from Unmanned Aerial Vehicle (UAV) PG; regress to AGB.
- Novel aspects: In addition to traditional metrics, we will use multiple Fourier amplitudes from UAV-PG waveforms for estimate AGB.
- Demonstrate on vertical profiles derived from UAV-PG waveforms.

Citations

Almeida et al. Estimating structure and biomass of a secondary Atlantic Forest in Brazil using Fourier transforms of vertical profiles derived from UAV photogrammetry point clouds, in review.

Co-Is/Partners Robert Treuhaft JPL/Caltech; Yang Lei, Caltech; Fabio Gonçalves, Canopy Rem Sens solutions.

Technical Readiness Level

- Current Technical Readiness Level: 3.
- In 3 years, with current resources, potential TRL = 7.

Challenges

- What are the key technology or methodology challenges? Further experiments are needed to quantify the performance of UAV-PG.
- What is needed to overcome those challenges? Development of studies in different types of forest to validate the PG cloud production technique and estimate AGB from Fourier amplitudes.

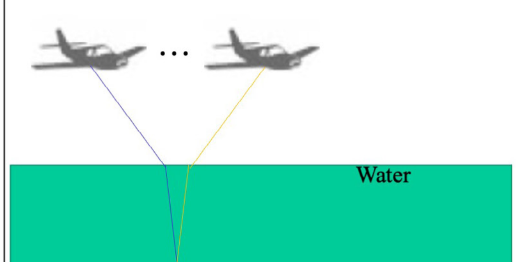
Bathymetry using Aerial Stereo Photogrammetry

Curtis Padgett, NASA/JPL/Caltech

Objectives

- Provide topographic solutions for measuring shallow water bathymetry from an aerial, stereo photogrammetry sensor (QUAKES)
- Develop software that works on visible imagery with temporally coherent and consistent viewing geometries
  - Targets: coastal regions
  - Change detection in areas of global changes
- Produces reliable sub-meter resolution of submerged topographic features

Aerial Coastal Imagery for Bathymetric Evaluation



Approach

- Apply machine learning techniques to depth estimation using SFM
- Conduct test flights over coastal targets with known topography
- Incorporate over sampling of locations to improve depth estimate

Citation

Agrafiotis, P.; Karantzalos, K.; Georgopoulos, A.; Skarlatos, D. Correcting Image Refraction: Towards Accurate Aerial Image-Based Bathymetry Mapping in Shallow Waters. Remote Sens. 2020, 12, 322..

Co-Is/Partners A. Donnellan, J. Green, A. Ansar, Y. Lou, J. Parker(JPL), S. DeLong (USGS)

Technical Readiness Level

- Current Technical Readiness Level (TRL) = 3
- Expected TRL level with modest (I FTE) level of funding in one year (TRL 5)
- Potential TRL 9 in 5 years if resources are available

Challenges

- Improving accuracy with over sampling techniques
- Resolving refraction issues
- Develop and measure estimation errors

E.7 Information Systems Current Technologies

NASA Ames Stereo Pipeline

Ross Beyer – ross.a.beyer@nasa.gov
Oleg Alexandrov – oleg.alexandrov@nasa.gov, Scott McMichael – scott.t.mcmichael@nasa.gov

Summary

- The NASA Ames Stereo Pipeline (ASP) is a suite of open source geodesy and stereogrammetry tools designed to process stereo images, primarily from satellites and aerial platforms.
- Well suited for large scale automated processing. No manual editing is needed.
- Originally designed for use with moons and planets but it also works well on icy and rocky terrain.
- ASP has been successfully used to study glaciers and polar ice, including in historical images from the 70's.
- Source code, binaries, and documentation are available at https://github.com/NeoGeographyToolkit/StereoPipeline

Status

- ASP has been in use for more than a decade.
- Linux and macOS computers are supported. Installation is very simple with precompiled binaries.
- Significant usage examples:
  - Ice elevation level measuring with HEXAGON historical satellite images.
  - DEM creation from NASA Operation IceBridge aerial camera.
  - Bulk processing of Apollo Metric and LRONAC lunar images.
  - Supporting VIPER landing sites for a 2023 Moon landing.

Performance

- Used for large scale processing jobs including the Moon, West Antarctica, and high-mountain Asia.
- Processing time, output resolution, etc are dependent on the type of input data and the processing options selected.
- Compatible with WorldView, Pleiades, SkySat, and other satellites that provide RPC metadata.
- Supports most non-terrestrial images and some aerial images.
- Tools for map projection, bundle adjustment, shape-from-shading, point cloud alignment, DEM blending, and more.

Citations

https://stereopipeline.readthedocs.io/en/latest/zzreferences.html

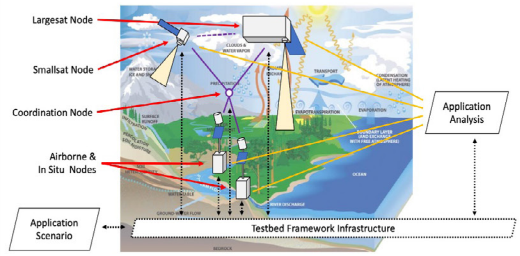
E.8 Information Systems Emerging Technologies

New Observing Strategies (NOS) and Testbed (NOS-T)

Jacqueline Le Moigne, Earth Science Technology Office

Objectives

- New Observing Strategies (NOS) will optimize measurement acquisition using diverse observing capabilities, collaborating across multiple dimensions and creating a unified architecture.
- The Testbed Main Goals are to:
  1. Validate new NOS technologies, independently and as a system
  2. Demonstrate novel distributed operations concepts
  3. Enable meaningful comparisons of competing technologies
  4. Socialize new NOS technologies and concepts to the science community by significantly retiring the risk of integrating these new technologies.



NOS Testbed Concept

Approach

- Develop use cases corresponding to various science domains and 3 types of NOS scenarios – tactical, operational and strategic
- Design NOS-T framework architecture and interfaces
- Identify, develop and validate key NOS capabilities
- Conduct regular demonstrations

Citations

J. Le Moigne and al, "New Observing Strategy (NOS) for Future Earth Science Missions," *IGARSS'19,* Yokohama, Japan, July 2019.

Co-Is/Partners: P. Grogan, J. Sellers/SERC; I. Brosnan, D. Cellucci, C. Frost, N. Oza/ARC; S. Kumar/GSFC; S. Chien, D. Crichton, C. David, B. Smith/JPL; L. Rogers/LaRC; M. Cole, J. Ellis/KBR

Technical Readiness Level

- Current Technical Readiness Level TRL 2
- With current resources, expected TRL of 4 will be reached in FY21
- Potential TRL of 8 in 5 years if resources are available

Challenges

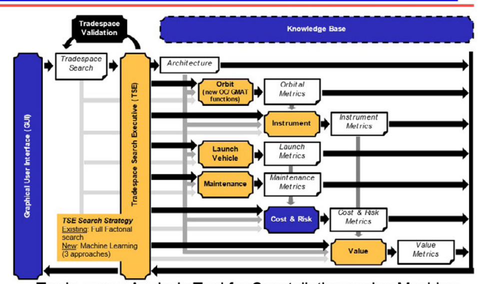
- Identify all NOS required technologies
- Define and validate appropriate use cases
- Define appropriate, flexible and scalable standards and interfaces
- Gather wide community input and feedback

Trade-space Analysis Tool for Constellations (TAT-C)

Paul Grogan, Stevens Institute of Technology

Objectives

- Provide a framework to perform pre-Phase A mission analysis of Distributed Spacecraft Missions (DSM)
  - Handle multiple spacecraft sharing mission objectives, including sets of SmallSats up through flagships
  - Explore trade-space of variables (trajectories, orbital planes, instruments, launches, etc.) for pre-defined science, cost and risk goals, and metrics (e.g., spatial coverage, revisit frequency, etc.)
  - Optimize cost, risk and performance
- Optimize the trade-space exploration by utilizing Machine Learning and a fully functional Knowledge Base (KB)
- Create an open access toolset which optimizes specific science objectives by investigating various constellation architectures with improved efficiency, e.g., through parallelization
- Government Release: https://software.nasa.gov/software/GSC-18399-1



Trade-space Analysis Tool for Constellations using Machine Learning (TAT-C ML): Modular Architecture

Approach

- Knowledge Base from historical constellation missions
- Novel mission architectures valuation
- Machine Learning (ML) knowledge-driven evolutionary strategies for fast traversal of large trade-spaces
- Instrument-level performance metrics for scanning optical imagers and SAR sensors
- Docker Container for Unix and non-Unix deployment

Citations

- J. Le Moigne et al, "Trade-space Analysis Tool for Designing Constellations (TAT-C)," *IGARSS'17,* TX. Others, more recent, upon request.

Co-Is/Partners: J. Le Moigne/ESTO, J. Verville, P. Dabney, S. Hughes/GSFC; S. Nag/BAERI; O. DeWeck, A. Siddiqi/MIT; D. Selva/Texas A&M – Current: J. Johnson/OSU; M. French/USC-ISI

Technical Readiness Level

- Current Technical Readiness Level: TRL 5
- Currently being extended to include onboard computing as well as operations trades.
- Expected TRL of 6 in July 2021.
- Potential TRL of 8/9 in 5 years if resources available

Challenges

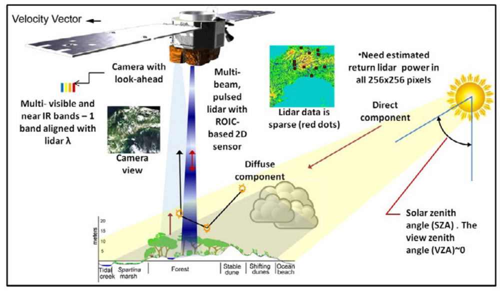
- Enumeration of large number of potential architectures; extract essential constellation variables and trades
- Integrate in-situ and airborne trade considerations
- Beta testing and feedback from science community

Deep Learning Enabled MPC Architecture for Adaptive Data Collection

Michael Lieber, Ball Aerospace mlieber@ball.com

Objectives

- Combine Deep Learning (DL) algorithms with Model Predictive Control (MPC) to
  - Enable a new suite of active instruments for STV
  - Develop on-board hierarchical and adaptive MPC architecture capability, significantly increasing data collection efficiency
  - Insert deep learning algorithms for high speed processing of optimization and classification.
- Application examples:
  - Multi-beam lidar systems and distributed formations of hetergeneous satellite platforms
  - Lidar systems for canopy interrogation and revisit
  - Lidar systems for cloud avoidance to maximize topography observations



Approach

- Mature current technology using available remote sensing data and existing hardware/ software testbeds; develop extensive models and OSSE's in parallel to guide algorithms and assess DL training
- MPC architecture leverages developing autonomous car technology with DL improving computational metrics for true on-board autonomous operation for remote sensing

Citations

https://esto.nasa.gov/forums/estf2017/presentations/Lieber_B1P1_ESTF2017.pdf M. Lieber, et al, "Characterization of planetary resources with deep learning enabled model predictive control: applied to lunar ice mapping, 43rd Annual AAS GN&C, Breckinridge, Co, Feb 2020.

Co-Is/Partners LaRC, GSFC, USGS

Technical Readiness Level

- Current TRL= 4
- Proposed TRL Advancement
  - TRL= 6; 3 years development and aircraft validation
  - TRL = 8; 5 years, with additional resources and leveraging ground developments

Challenges

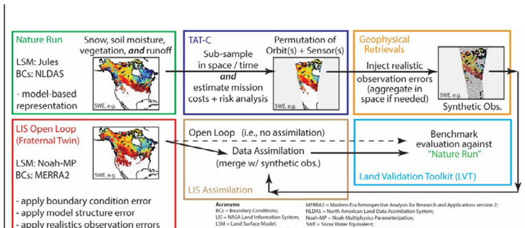
- Requires large on-board computational capability and memory resources to obtain RT capability
- To support this development, machine learning, advanced and efficient algorithms and large-scale modeling to provide system level program direction

Towards the Next Generation of Land Surface Remote Sensing: A Comparative Analysis of Passive Optical, Passive Microwave, Active Microwave, and LiDAR Retrievals

PI: Associate Professor Barton A. Forman, University of Maryland (baforman@umd.edu)

Objective

- Create a mission planning tool to help inform experimental design with relevance to global snow, soil moisture, and vegetation in the terrestrial environment
- Use the extensive sensor simulation, orbital configuration, data assimilation, optimization, uncertainty estimation, cost estimation, and risk assessment tools in LIS and TAT-C to harness the information content of Earth science mission data
- Technologies include passive and active microwave remote sensing, optical remote sensing, LiDAR, hydrologic modeling, orbital emulators, adaptive sensor viewing, and data assimilation



Approach

- Develop a coupled snow-soil moisture-vegetation observing system simulation experiment (OSSE) extending the capabilities of LIS and TAT-C
- Conduct end-to-end OSSEs to investigate the impact of new and future mission concepts on LIS model efficacy, including the impact of adaptive versus fixed viewing of space-borne sensors
- Conduct end-to-end OSSEs to characterize tradeoffs in spatiotemporal resolutions and orbital configurations (constellations), including mission cost estimates and risk assessments

Technical Readiness Level

- Current TRL=3
- Anticipated TRL=6 by January 2022
- Potential TRL≥7 in 5 year if resources are available

Key Challenges Include

- Software development for multivariate assimilation
- Computational expense and data storage for a near-infinite number of possible scenarios
- Characterization of unknown observation errors for hypothetical, space-borne sensors

Co-Is/Partners: Sujay Kumar, GSFC; Paul Grogan, Stevens Inst.; Rhae Sung Kim, GSFC; Yonghwan Kwon, GSFC; Yeosang Yoon, GSFC;

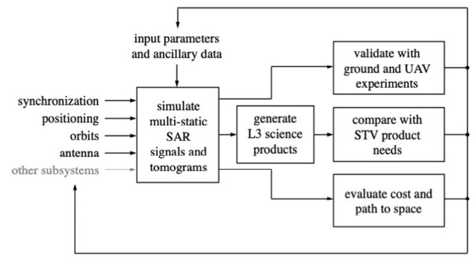
OSSE of Distributed SmallSat Radar Formations for STV

Marco Lavalle JPL/Caltech

Objectives

- Design optimal tomographic SmallSat SARs constellation for STV based on quantitative science metrics
- Explore the trade space of distributed SmallSat formations that includes jointly instrument and orbital parameters
- Simulate tomographic observations and extract STV science parameters (e.g., biomass, surface topography)
- Run trade studies informed by NASA STV study to compare formation options and multi-static SAR modes
- Evaluate the need and characteristics for additional subsystems (e.g., sync links) in distributed formations
- Guide the development of tomographic and polarimetric interferometric radar scattering models and retrieval algorithms for STV

High-level diagram showing the OSSE under development as part of the NASA-funded project DARTS (Lavalle et al., 2021) [1]



Approach

- Develop models and algorithms of individual sub-systems (e.g. radar operation, orbits, sync link, science metric extraction) then integrate the sub-systems into OSSE
- Run trade studies to evaluate and compare the performance of given input architectures; optimize the system architecture given input science metrics

Citations [1] Lavalle, M. et al. "Distributed Aperture Radar Tomographic Sensors (darts) to map surface topography and vegetation structure", submitted to IEEE IGARSS 2021.

[2] Seker I., and Lavalle M. "Tomographic Performance of Multi-Static Radar Formations: Theory and Simulations." Remote Sensing, 13, no. 4: 737, 2021.

Co-Is/Partners: R. Ahmed, I. Seker, E. Loria, B. Hawkins, R. Treuhaft, JPL

Technical Readiness Level

- Current Technical Readiness Level: 3/4
- Expected TRL by 2022: 5/6
- Potential TRL by 2025 if resources are available: 8

Challenges

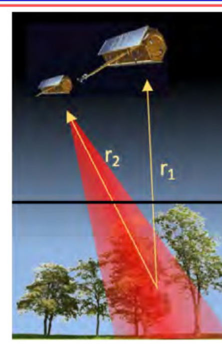
- Retrieval algorithms to convert polarimetric radar tomograms into STV science parameters are not mature
- Integrating sub-systems into an end-to-end OSSE will require deeper understanding of the inter-connections between subsystems

OSSEs for Polarimetric Interferometric SAR (PolInSAR) Forest 3-D Structure

Robert Treuhaft JPL/Caltech

Objectives

- PolInSAR measurements of 3-D forest structure, including top height, average height, and profile model parameters (e.g. Gaussian standard deviation), can be done with various baseline, polarization, and frequency configurations of Interferometric SAR (InSAR) [Lavalle 2014], [Treuhaft 2000]. Observing System Simulations Experiments (OSSE) will be required to simulate different hardware configurations and determine vertical-structure performance. Our objectives will be:
- Determine typical InSAR observation phase and amplitude noise as a function of sensor and platform characteristics.
- Build simulated-forest models which accept as input phase and amplitude accuracy from previous objective.
- Evaluate the accuracy of forest structural metrics (e.g. height) on the basis of simulated data from various baselines, polarizations, and frequencies.



PolInSAR involves 2 or more satellites with specified polarization. Different baselines, polarizations, and radar frequencies, along with diverse scatterer characteristics will be simulated in OSSEs.

Approach

- Evaluate realistic PolInSAR phase and amplitude noise from bare-surface interferometric data and link budgets
- Simulate the forest with a discrete-scattering model with an underlying polarimetric plane for the ground surface.
- Run simulator for structural-metric accuracies depending on # of baselines, polarizations, and frequencies.

Citations Lavalle and Khun 2014. Three-Baseline InSAR Estimation of Forest Height, *IEEE Geoscience and Remote Sensing Letters;*

Treuhaft /Siqueira 2000. The vertical structure of vegetated land surfaces from interferometric and polarimetric radar, Rad Sci.

Co-Is/Partners

Marco Lavalle, JPL; Yunling Lou, JPL;
Scott Hensley, JPL; Sassan Saatchi, JPL.

Technical Readiness Level

- Current Technical Readiness Level: 4
- Current resources are not expended specifically for development of PolInSAR OSSEs: TRL will remain 4
- Potential TRL in 5 years if resources are available: 8

Challenges

- Current discrete-scattering models may require refinements to stochastic variables (such as leaf orientation) to enhance simulation realism
- Interferometric models may require slope, ground-roughness, or soil moisture detection/correction.

ACRONYMS

2D	Two-dimensional
3D	Three-dimensional
3DEP	3D Elevation Program
A	Applications
A-LISTS	Airborne Lidar Surface Topography Simulator
AFRICOM	United States Africa Command
AGB	Aboveground Biomass
AirMOSS	Airborne Microwave Observatory of Subcanopy and Subsurface
ALIRT	Airborne Lidar Imaging Research Testbed
ALISTS	Airborne Lidar Surface Topography Simulator
ALOS	Advanced Land Observing Satellite
ALTM	Airborne Laser Terrain Mapper
AOSTB	Airborne Optical Systems Testbed
ASI	Agenzia Spaziale Italiana (Italian Space Agency)
ASO	Airborne Snow Observatory
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
ATLAS	Advanced Topographic Laser Altimeter System
ATM	Airborne Topographic Mapper
AW3D30	ALOS World 3D—30 m
C	Cryosphere
CALIPSO	Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation
CARS	Chaîne Automatique de Restitution Stéréoscopique
CASALS	Concurrent Artificially Intelligent Spectrometry and Adaptive Lidar System
cFS	core Flight System
CHANGE	Canopy Height and Glacier Elevation
CHM	Canopy Height Model
CIRES	Cooperative Institute for Research in Environmental Sciences
CNES	Centre National d'Études Spatiales (National Center for Space Studies)
conops	Concept of Operations
CONUS	Continental United States
COSMO	Constellation of Small Satellites for Mediterranean Basin Observation
CP	Coastal Processes
CSA	Canadian Space Agency
CSG	COSMO-SkyMed Second Generation
DARPA	Defense Advanced Research Projects Agency
DART	Discrete Anisotropic Radiative Transfer
DEM	Digital Elevation Model
DLR	Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center)
DO	Designated Observable
DoD	Department of Defense
DS	Decadal Survey
DSM	Digital Surface Model
DTM	Digital Terrain Model
ESA	European Space Agency
FMCW	Frequency-Modulated Continuous-Wave
FSA	Farm Service Agency
FSBD	Forest Structure and Biomass Database
G-LiHT	Goddard's LiDAR, Hyperspectral and Thermal (imager)
GDEM	Global Digital Elevation Map
GEDI	Global Ecosystem Dynamics Investigation
GLAS	Geoscience Laser Altimeter System

GLISTIN	Glacier and Ice Surface Topography Interferometer
GM APD	Geiger-mode Avalanche Photodiode
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
H	Hydrology
HALE	High Altitude, Long Endurance
HALOE	High Altitude Lidar Operations Experiment
HQ	Headquarters
ICESat	Ice, Cloud, and Land Elevation Satellite
IFSAR	Interferometric Synthetic Aperture Radar
IIP	Instrument Incubator Program
INS	Inertial Navigation System
InSAR	Interferometric Synthetic Aperture Radar
INTA	Instituto Nacional de Técnica Aeroespacial (National Institute for Aerospace Technology)
INU	Inertial Measurement Unit
IS	Information Systems
ISRO	Indian Space Research Organization
ISS	International Space Station
JAUDIT	Jungle Advanced under Dense Vegetation Imaging Technology
JAXA	Japan Aerospace Exploration Agency
JEM	Japanese Experiment Module
JEM-EF	Japanese Experiment Module Exposed Facility
JPL	Jet Propulsion Laboratory
L	Lidar
LAI	Leaf Area Index
LEO	Low Earth Orbit
Lidar	Light Detection and Ranging
LIST	Lidar Surface Topography
LOLA	Lunar Orbiter Laser Altimeter
LOS	Line of Sight
LVIS	Land, Vegetation, and Ice Sensor
M	Magnitude
MABEL	Multiple Altimeter Beam Experimental Lidar
MACHETE	Multi-look Airborne Collector for Human Encampment and Terrain Extraction
MHW	Mean High Water
MIT-LL	Massachusetts Institute of Technology Lincoln Laboratory
MLA	Mercury Laser Altimeter
MLLW	Mean Lower Low Water
MMLA	Multi-kilohertz Microlaser Altimeter
MOLA	Mars Orbiter Laser Altimeter
MOLI	Multi-footprint Observation Lidar and Imager
MSL	Mean Sea Level
MUOS	Mobile User Objective System
NAIP	National Agriculture Imagery Program
NASA	National Aeronautics and Space Administration
NASADEM	NASA Digital Elevation Model
NASEM	National Academies of Sciences, Engineering, and Medicine
NCALM	National Center for Airborne Laser Mapping
NEON	National Ecological Observatory Network
NGA	National Geospatial-Intelligence Agency
NGS	National Geodetic Survey
NISAR	NASA-ISRO Synthetic Aperture Radar
NSF	National Science Foundation
OSSE	Observing System Simulation Experiment
PAI	Plant Area Index
PolInSAR	Polarimetric InSAR
PolSAR	Polarimetric Synthetic Aperture Radar
POR	Program of Record

PRISM	Pico-Satellite for Remote-Sensing and Innovative Space Missions
QUAKES-I	Quantifying Uncertainty and Kinematics of Earth Systems Imager
R	Radar
Radar	Radio Detection and Ranging
RCM	RADARSAT Constellation Mission
RMSE	Root-Mean Square Error
ROSE-L	Radar Observing System for Europe—L-band
RSA	Rotating Synthetic Aperture
RSL	Relative Sea Level
RSLR	Relative Sea-Level Rise
S	Solid Earth
SAR	Synthetic Aperture Radar
SATM	Science and Applications Traceability Matrix
SAV	Submerged Aquatic Vegetation
SD	Snow Depth
SDC	Surface Deformation and Change
SDSWE	Snow Depth and Snow Water Equivalent
SE	Solid Earth
SfM	Structure from Motion
SIMPL	Slope Imaging Multi-polarization Photon-counting Lidar
SLA	Shuttle Laser Altimeter
SLICER	Scanning Lidar Imager of Canopies by Echo Recovery
SNR	Signal-to-Noise Ratio
SoOp	Signals of Opportunity
SOUTHCOM	U.S. Southern Command
SP	Stereophotogrammetry
SPOT	Satellite pour l'Observation de la Terre (Satellite for Earth Observation)
SRTM	Shuttle Radar Topography Mission
ST	Surface Topography
STV	Surface Topography and Vegetation
sUAS	Small Uncrewed Aerial System
SWaP	Size, Weight, and Power
SWB	Shallow-Water Bathymetry
SWH	Surface Water Height
SWOT	Surface Water and Ocean Topography
TACOP	Tactical Operations Lidar
TanDEM-X	TerraSAR-X Add-on for Digital Elevation Measurement
TDRS	Tracking and Data Relay Satellite
TES	Terrestrial Ecosystem Structure
TO	Targeted Observable
TomoSAR	Tomographic Synthetic Aperture Radar
TPU	Total Propagated Uncertainty
UAS	Uncrewed Aircraft System
UAV	Uncrewed Aerial Vehicle
UAVSAR	Uninhabited Aerial Vehicle Synthetic Aperture Radar
US	United States
USGS	United States Geological Survey
V	Vegetation
VLM	Vertical Land Motion
VS	Vegetation Structure

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