STV Stereo Photogrammetry Technology Breakout
September 9, 2020

Meeting begins at 8:15 am PDT/ 11:15 am EDT

Q&A Polls : https://arc.cnf.io/sessions/qkrg/#!/dashboard

Ground Rules

- Please place yourself on **mute** and **turn video off** unless speaking

  - [The pandemic version of please silence your cell phone]
  - Please feel free to interject with a question for clarification
- 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
    - In either abstracts or presentations
- **Q&A:** https://arc.cnf.io/sessions/qkrg/#!/dashboard

AGENDA

Time	Presenter	Affiliation	Title	Duration (minutes)
11:15am EDT 8:15am PDT 3:15pm UCT	Jon Ranson	NASA GSFC	Welcome and logistics	5
11:20am EDT	Andrea Donnellon	NASA JPL	Study Overview and Measurement Needs	20
11:40am EDT	David Harding	NASA GSFC	Introduction of Technology Scope	20
12:00pm EDT	Jon Ranson	NASA GSFC	STV Stereophotogrammetry and Decadal Survey Science	20
12:20pm EDT	All		Poll Questions #1	15
12:35pm EDT	John Mootz	USDA, Farm Production and Conservation Business Center	National Agriculture Imagery Program (NAIP) Elevation Data Options	10 + 5
12:50pm EDT	Andrea Donnellon	NASA JPL	QUAKES-I Stereo Photogrammetric Imager	10 + 5
1:05pm EDT	Laurent Lebègue	CNES	The CO3D demonstrator, a worldwide one-meter accuracy DEM	10 + 5
1:20pm EDT		Break		25
1:45pm EDT	Fabio Pacifici	MAXAR	Introducing WorldViewLegion	10 + 5
2:00pm EDT	Chris Neigh	NASA GSFC	VHR DSMs provide robust estimates of boreal canopy height for estimating carbon stock	10+5
2:15pm EDT	All		Poll Questions #2 and Discussion	45
3:00pm EDT	End			

Surface Topography and Vegetation
Incubation Study

Study Overview and Measurement Needs

Andrea Donnellan, STV Study Lead

NASA, Jet Propulsion Laboratory, California Institute of Technology

Technology Breakouts

Surface Topography and Vegetation (STV) Incubation Study

Introduction of Technology Scope

David Harding, STV Technology Lead
NASA Goddard Space Flight Center

STV Stereo Photogrammetry Technology Breakout

STV Stereo Photogrammetry and Decadal Survey Science

Jon Ranson
NASA GSFC
Biospheric Sciences Lab.
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Connections to the Decadal Survey

Overview of the state-of-the-art

Spaceflight technology and missions

Question and Answer Polls

Gaps we perceive?

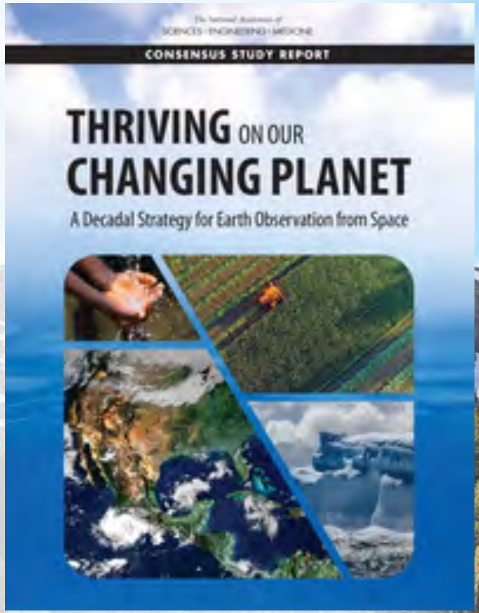
Are we missing any current capabilities we should know about?

Brought to you by the 2017 Decadal Survey

From TABLE 3.5 Observing System Priorities—Observations (Targeted Observables)

Targeted Observable	Science/Applications Summary	Candidate Measurement Approach	Designated	Explorer	Incubation
Surface Deformation and Change	Earth surface dynamics from earthquakes and landslides to ice sheets and permafrost	Interferometric Synthetic Aperture Radar (InSAR) with ionospheric correction	X		
Ice Elevation	Global ice characterization including elevation change of land ice to assess sea level contributions and freeboard height of sea ice to assess sea ice/ocean/atmosphere interaction	Lidar**		X	
Terrestrial Ecosystem Structure	3D structure of terrestrial ecosystem including forest canopy and above ground biomass and changes in above ground carbon	Lidar**		X	
Planetary Boundary Layer	Diurnal 3D PBL thermodynamic properties and 2D PBL structure to understand the impact of PBL processes on weather and AQ through high vertical and temporal profiling of PBL temperature, moisture and heights	Microwave, hyperspectral IR sounder(s) (e.g., in geo or small sat constellation), GPS radio occultation for diurnal PBL temperature and humidity and heights; water vapor profiling DIAL lidar, and lidar** for PBL height			X
Surface Topography and Vegetation	High-resolution global topography including bare surface land topography ice topography, vegetation structure, and shallow water bathymetry	Radar; or lidar**			X

** Could potentially be addressed by a multi-function lidar designed to address two or more of the Targeted Observables



STV Targeted Observable and Derived Parameters

ECOSYSTEMS

3-D vegetation structure and change
- Vegetation height (Canopy height model, CHM)
- Vegetation vertical distribution
- Canopy Cover Fraction (CCF)
- Vector shape of crowns
- Leaf area index (LAI) profiles
- Above ground biomass (ABG)

CRYOSPHERE

Sea level change (mass balance)
- Ice elevation and change(Digital Terrain Model)
- Change in Surface Topography
  - glaciers (fast, slow)
  - Ice shelves

Polar Amplification
- Sea ice freeboard and change

COASTAL PROCESSES

Bottom topography (DEM)
Seafloor rugosity
Vegetation (mangroves and submerged veg.) height
Land Topography
Time series shallow bathymetry, seafloor structure and rugosity

HYDROLOGY

Surface Topography and change
- Watershed topography
- Bathymetry
- Water surface height
- Bottom friction and resistance to flow
- Sea level

Vegetation Structure
- Resistance to flow

SOLID EARTH

Surface topography and change
- Bare Earth and Water Bottom and Change
- Pre-, syn- and post volcanic eruption deformation
- Inter-, pre-, co- and post seismic measurements and forecasts
- Landslides, tsunamis, surface deformation
- Abrupt change
- Coastal land surface change

The Reference Elevation Model of Antarctica

Ian M. Howat[1,2] , Claire Porter[3] , Benjamin E. Smith[4] , Myoung-Jong Noh[1] , and Paul Morin[3] [1]Byrd Polar and Climate Research Center, Ohio State University, Columbus, OH, USA [2]School of Earth Sciences, Ohio State University, Columbus, OH, USA [3]Polar Geospatial Center, University of Minnesota, St. Paul, MN, USA [4]Polar Science Center, Applied Physics Laboratory, University of Washington, Seattle, WA, USA

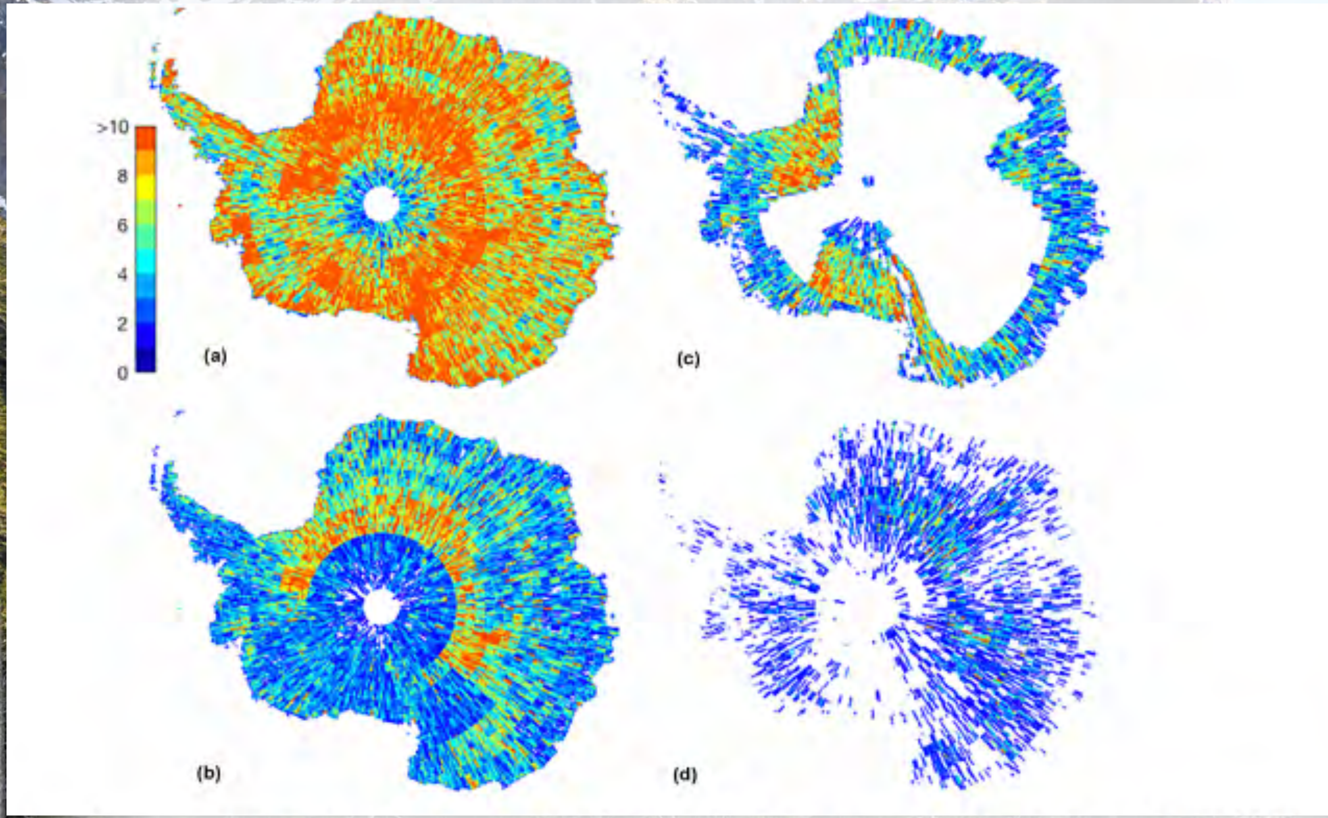


Figure 1. Maps of coverage of individual digital elevation models (DEMs) produced from stereoscopic submeter imagery for the REMA project, with color indicating the number of repeats, for (a) all data, (b) DEMs that passed visual quality inspection (note regional decrease in repeat coverage due to change in procedure), and quality-controlled DEMs with registrations within acceptable criteria from (c) CryoSat-2 and (d) the ICESat GLAS 2-D campaign.

Table 1. Specifications of satellites and imagery used in REMA.

Satellite name	Launch date	Panchromatic band ground sample distance at nadir (cm)	Swath width at nadir (km)
GeoEye-1	6 Sep 2008	41	15.2
WorldView-1	18 Sep 2007	46	17.6
WorldView-2	8 Oct 2009	46	16.4
WorldView-3	13 Aug 2014	31	13.1

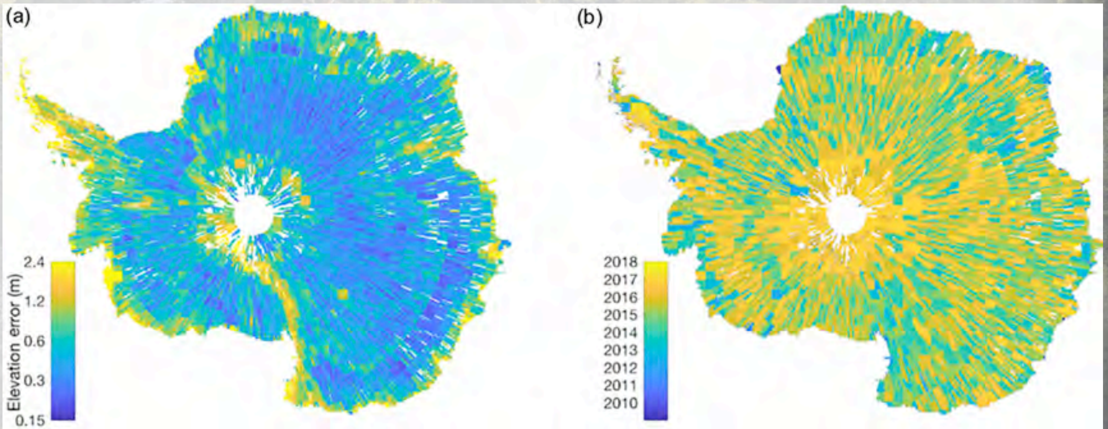


Figure 4. Maps of REMA (a) elevation error, obtained from the root mean square of the differences in elevation between the DEM and altimetry data following registration, or the differences among co-registered DEMs in the case of alignment (note the logarithmic color scale), and (b) date stamp obtained from the date of image acquisition.

Howat, I.M., Porter, C., Smith, B.E., Noh, M.J. and Morin, P., 2019. The Reference Elevation Model of Antarctica. Cryosphere, 13(2).

Deriving High Spatial-Resolution Coastal Topography From Sub-meter Satellite Stereo Imagery

Luís Pedro Almeida, Rafael Almar, Erwin W. J. Bergsma, Etienne Berthier, Paulo Baptista, Erwan Garel, Olusegun A. Dada and Bruna Alves

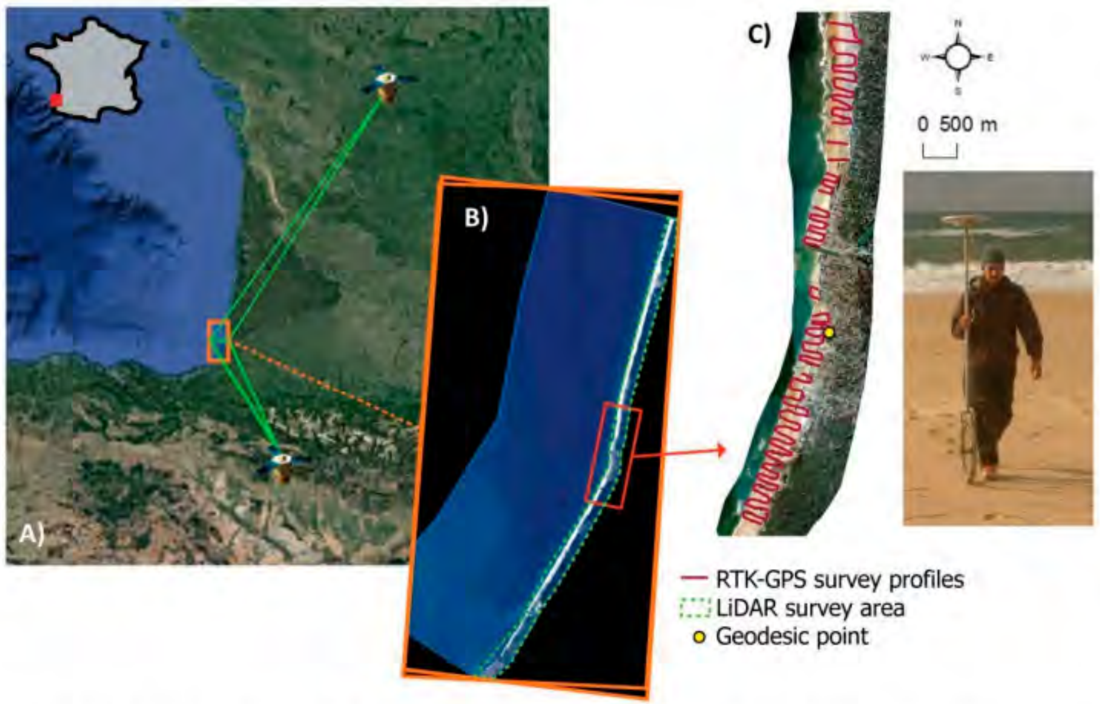


Figure 1. Satellite image of the West of France (source: Google Earth Pro 2018) showing the location where Pleiades stereo-pair was obtained (orange rectangle located in the Southwest of France) on the 14th of November 2017 (**A**). Zoom in of the Pleiades mosaic showing the area where the airborne-LiDAR topographic survey was performed (polygon with dashed green outline) and the region where RTK-GPS topographic measurements were undertaken (**B**). Panel (**C**) shows the RTK-GPS survey lines (red) and photograph of the surveyor with the GPS rover unit.

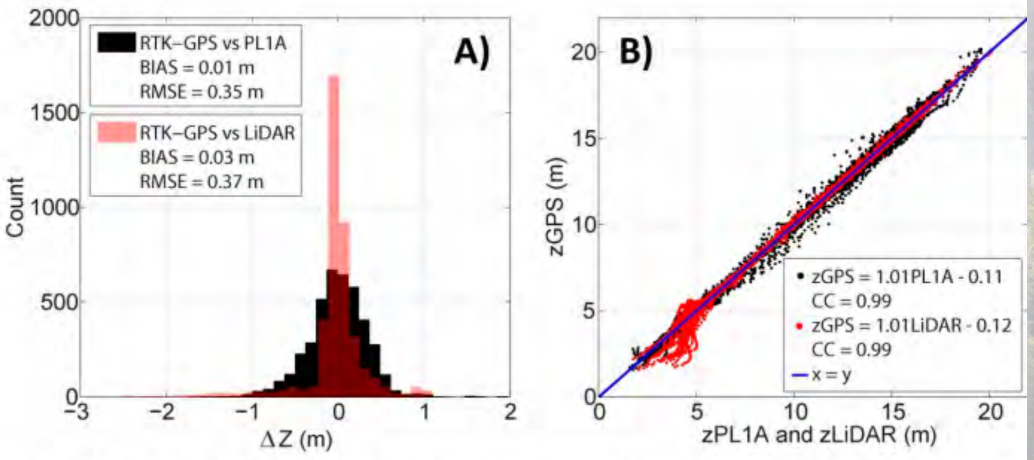


Figure 2. Pleiades (PL1A) and LiDAR survey accuracy assessed by comparison to concurrent on-ground RTK-GPS survey; histogram of the differences between elevations measured by RTK-GPS and remote sensing methods; (**A**); scatter plot of RTK-GPS elevations vs remotely sensed elevations (**B**).

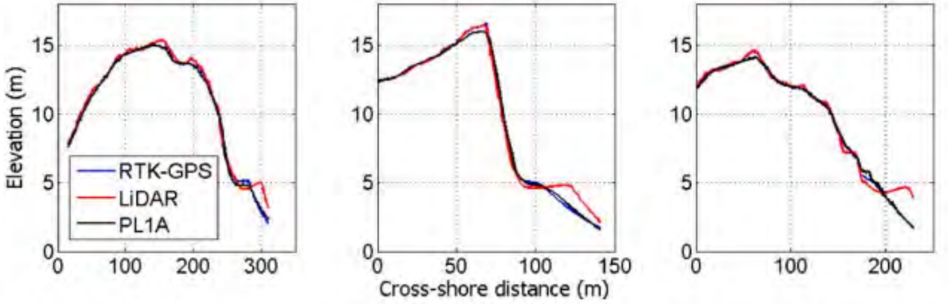
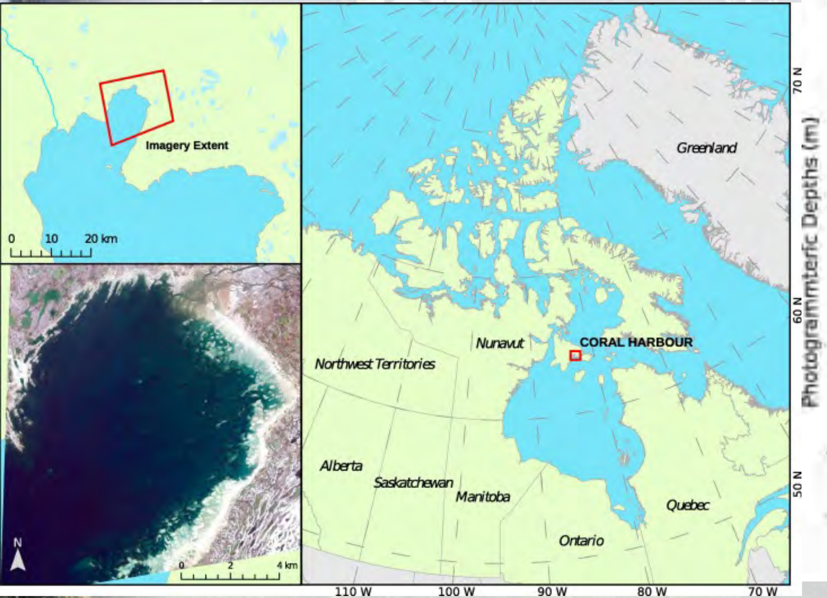
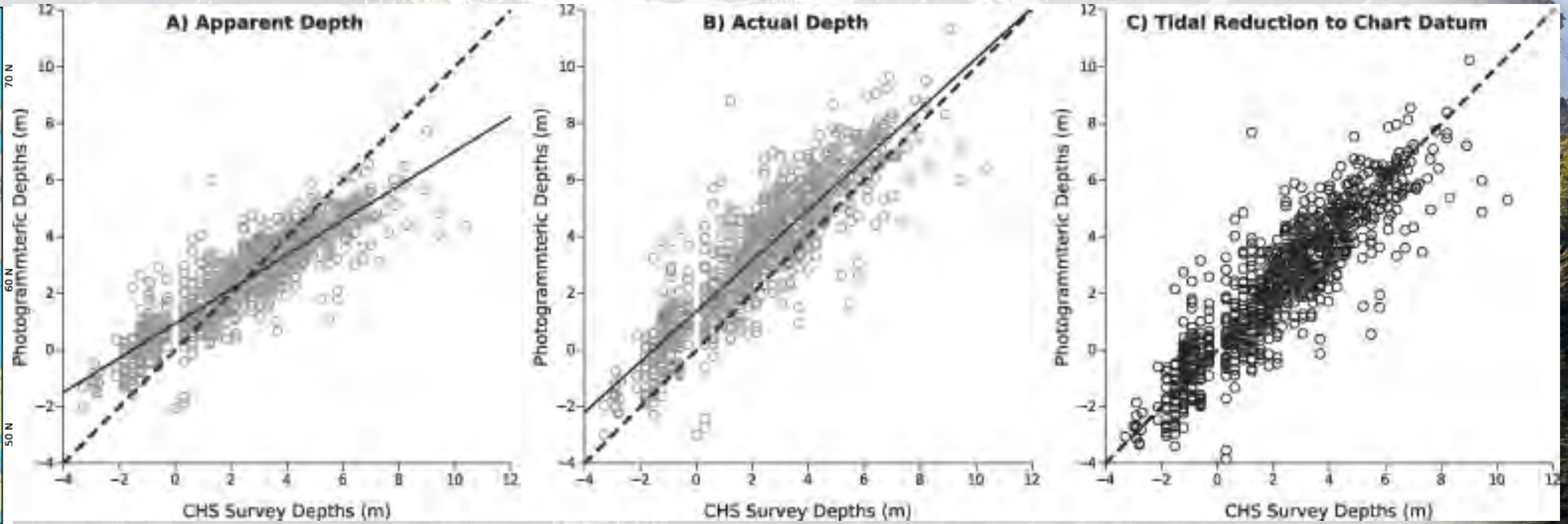


Figure 3. Three beach profiles showing the comparison between RTK-GPS, Pleiades (PL1A) and LiDAR, showing the berm erosion that occurred between the LiDAR survey and RTK-GPS and Pleiades.

Almeida, L.P., Almar, R., Bergsma, E.W., Berthier, E., Baptista, P., Garel, E., Dada, O.A. and Alves, B., 2019. Deriving high spatial-resolution coastal topography from sub-meter satellite stereo imagery. Remote Sensing, 11(5), p.590.

Satellite derived photogrammetric bathymetry

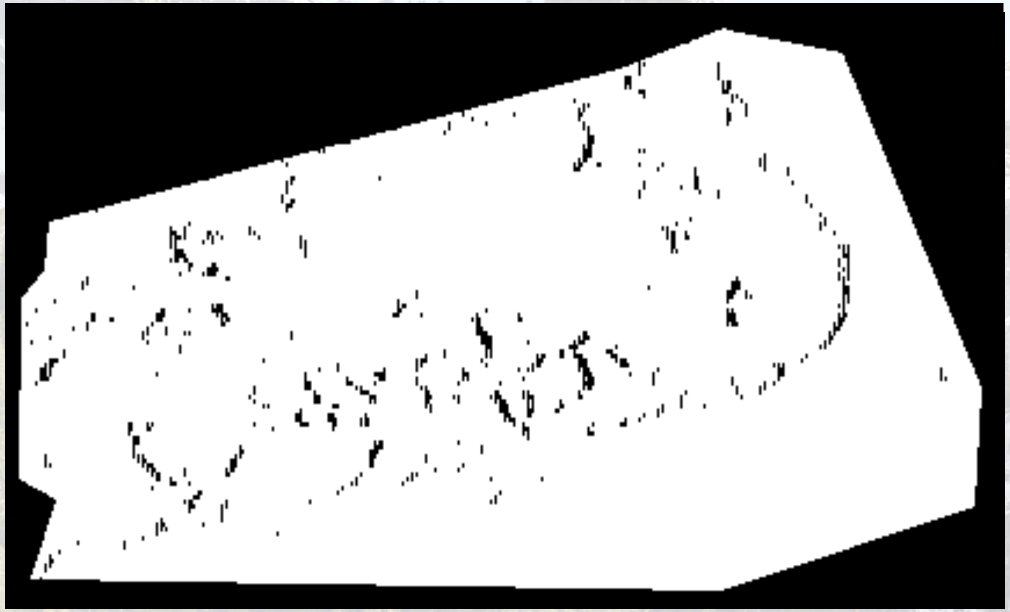




Worldview-2 depth estimates validation with Canadian Hydrographic Service survey data showing a mean error of 0.031 m and an RMSE of 1.178 m

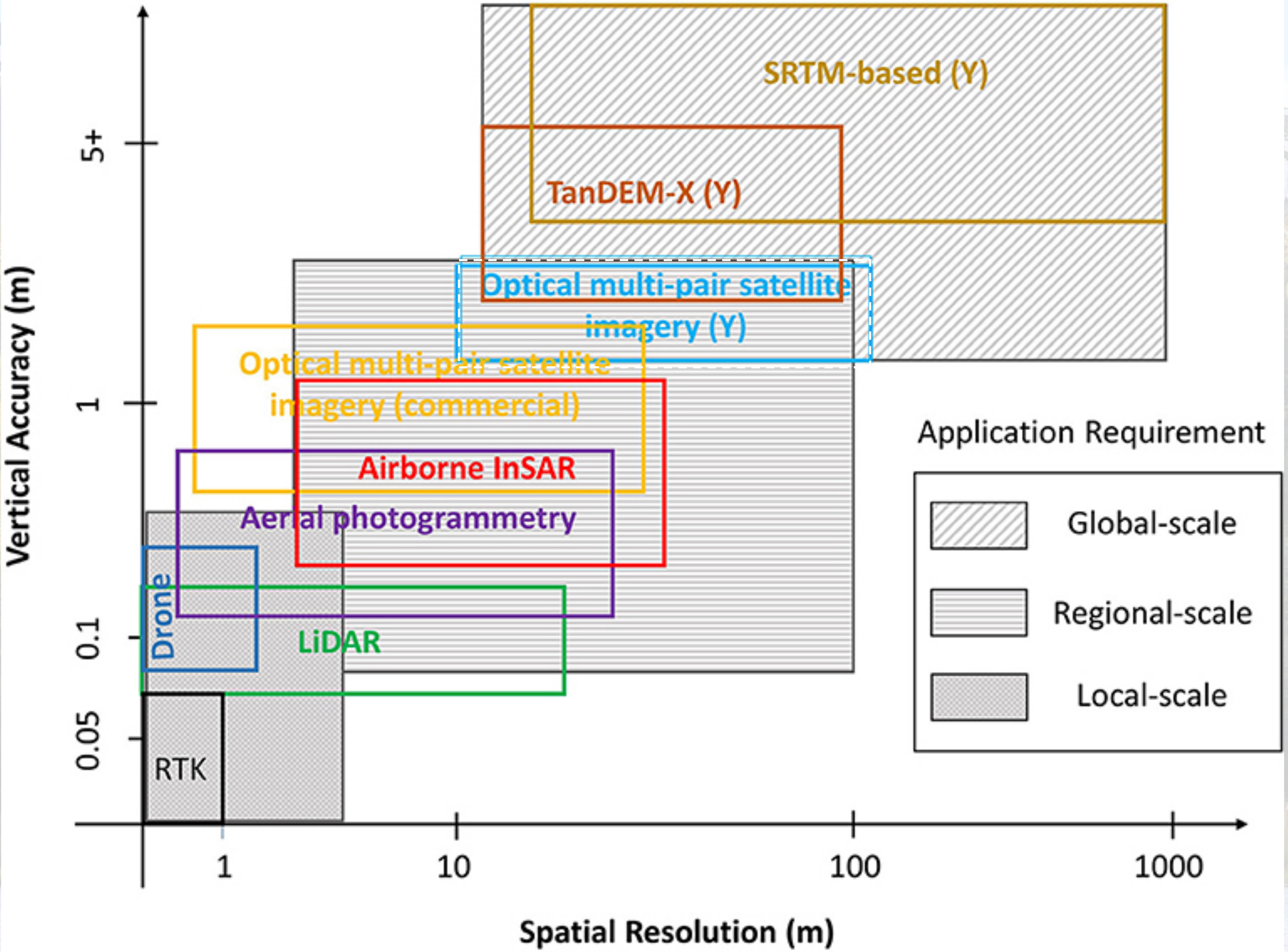
Hodúl, M., Bird, S., Knudby, A. and Chénier, R., 2018. Satellite derived photogrammetric bathymetry. *ISPRS Journal of Photogrammetry and Remote Sensing*, *142*, pp.268-277.

Proportion of sunlit pixels changes through day



Light environment as mediated through canopy structure varies throughout day

The Need for a High-Accuracy, Open-Access Global DEM



Schumann, G.J. and Bates, P.D., 2018. The need for a high-accuracy, open-access global DEM. *Frontiers in Earth Science*, *6*, p.225.

ALOS/PRISM (Japan) 2006-2011

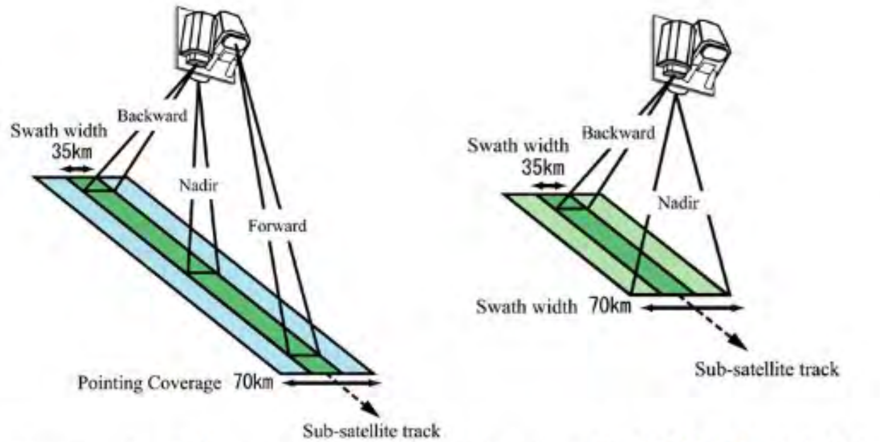
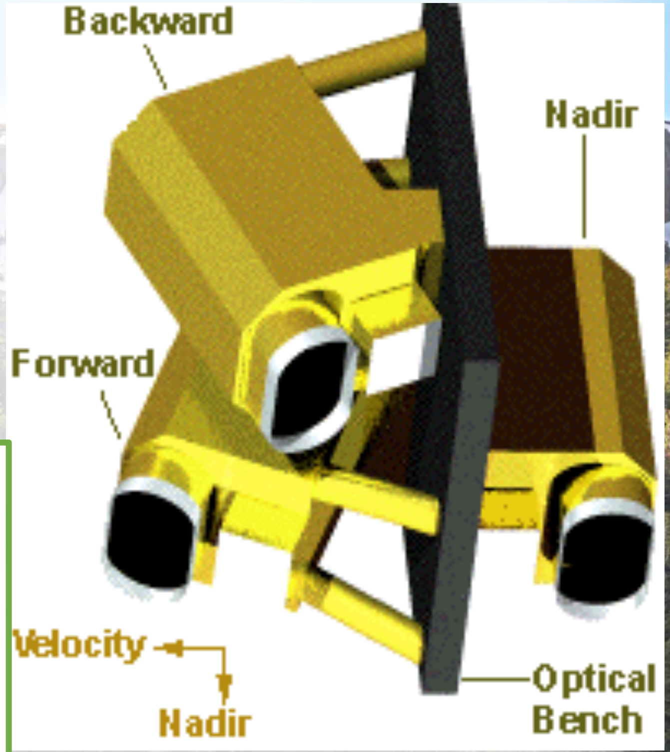


Figure 1. Observation geometries of PRISM triplet observing mode (OB1, left), and stereo (by nadir plus backward) observing mode (OB2, right).

PRISM characteristics.

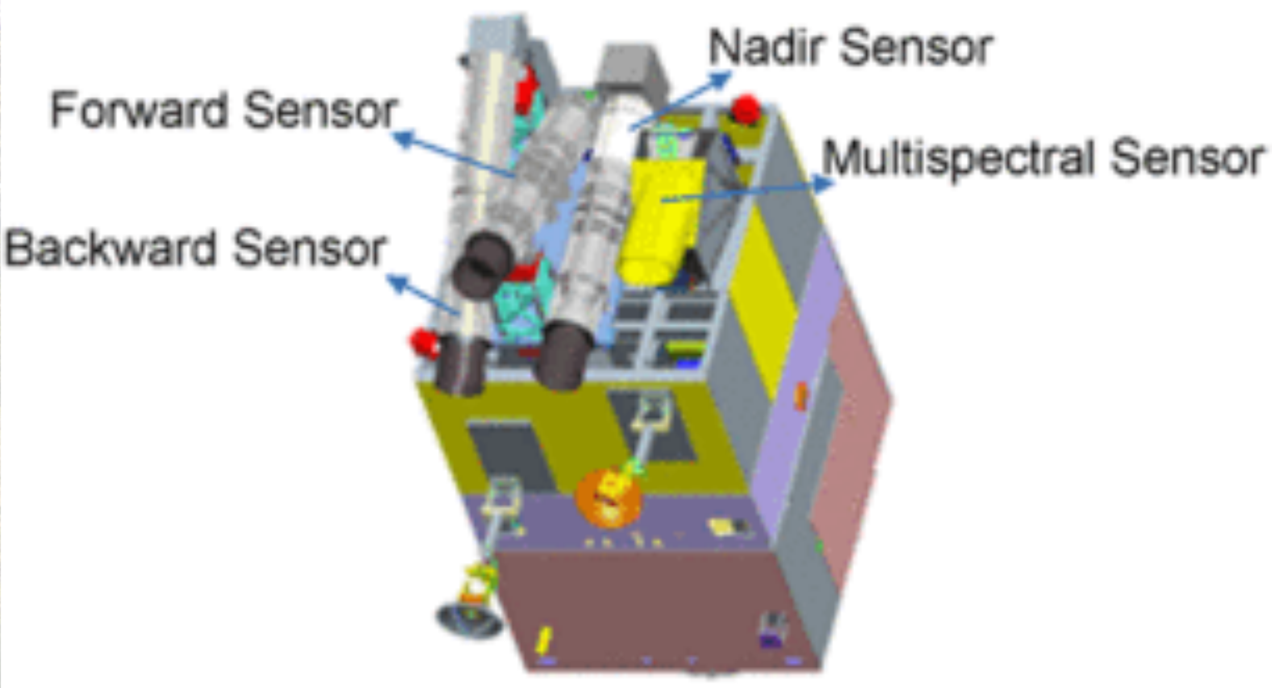
Item	Description
Number of bands	1 (Panchromatic)
Wavelength	0.52 - 0.77 micrometers
Number of optics	3 (NDR, FWD, and BWD)
Base to height ratio	1.0 (between FWD and BWD)
Spatial resolution	2.5 m (NDR)
Swath width	35 km (OB1) / 70 km (OB2)
Signal to noise ratio	> 70
MTF	> 0.2
Pointing angle	-1.2 / +1.2 degrees (OB1, NDR)
Bit length	8 bits/pixel
Data rate	960 Mbps (OB1, OB2)
Data compression	Lossy, JPEG extension (onboard)
Data downlink rate	240 Mbps (1/4.5 compression)



Tadono, T., Ishida, H., Oda, F., Naito, S., Minakawa, K. and Iwamoto, H., 2014. Precise global DEM generation by ALOS PRISM. *ISPRS Annals of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, *2*(4), p.71.

ZiYuan ZY-3 (China) 2012, 2016

Payload parameters	Triple scanner	Multispectral scanner
Wavelength	0.5–0.8 µm	Blue: 0.45–0.52 µm Green: 0.52–0.59 µm Red: 0.63–0.69 µm NIR: 0.77–0.89 µm
Spatial resolution	Nadir: 2.5 m Forward/Backward: 4 m	6.0 m
Focus	1700 mm	1750 mm
Width of pixel	Nadir: 7 um Forward/Backward: 10 um	20 µm
CCD array length	Nadir: 24576 pixels (8192 × 3) Forward/Backward: 16384 pixels (4096 × 4)	9216 pixels (3072 × 3)
Swath width	52 km	52 km
Bit length	10 bits/pixel	10 bits/pixel

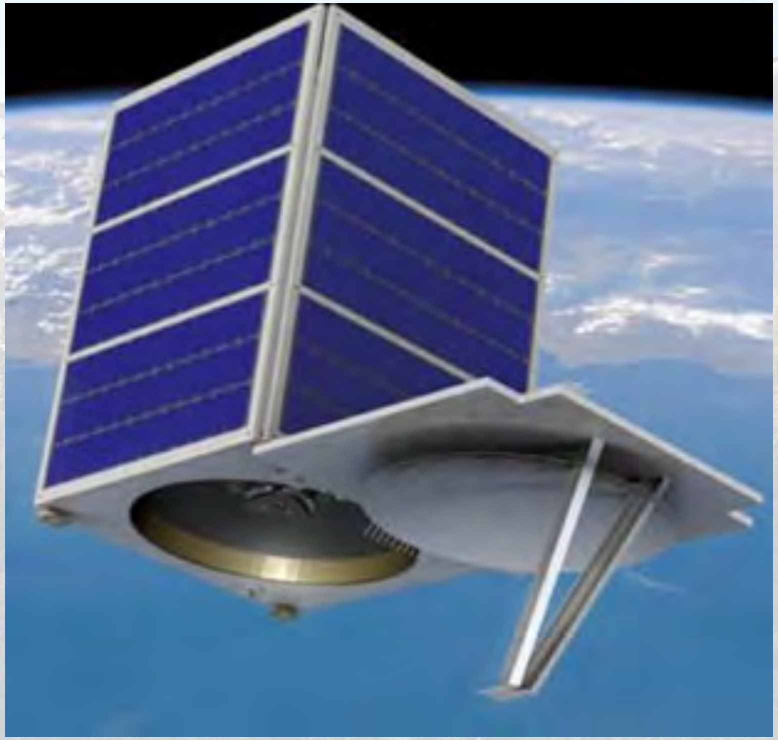


ZY-3 can obtain planimetric and vertical accuracy values of 15 m and 5 m respectively. 3 m and 2 m with " a few" ground control points (GCP)

Wang, T., Zhang, G., Li, D., Tang, X., Jiang, Y., Pan, H., Zhu, X. and Fang, C., 2013. Geometric accuracy validation for ZY-3 satellite imagery. *IEEE Geoscience and Remote Sensing Letters*, *11*(6), pp.1168-1171.

Planet SkySat

Spatial resolution	Pan (Panchromatic): 90 cm at nadir MS (multispectral): 2.0 m at nadir
Nominal swath width	8 km at nadir
Spectral bands	Pan: 450-900 nm MS: Blue = 450-515 nm MS : Green = 515-595 nm MS: Red = 605-695 nm MS: NIR = 740-900 nm
Video data	Pan, Duration up to 90 seconds Frame rate = 30/s GSD = 1.1 m at nadir FOV: No smaller than 2.0 km x 1.1 km



[SkySat-1, SkySat-2]
Panchromatic: 0.86m Multispectral: 1.0m
[SkySat-3 - SkySat-13]
Panchromatic: 0.72m Multispectral: 1.0m

MAXAR - formerly Digital Globe

Worldview, Pan

~13 Km swath

<1 m ,

1, 2007, 0.46m

2, 2009, 0.46m

3, 2014, 0.31m

Ground resolution = 31 cm nadir pan.

Ground swath 13.1km, 5 strips to make 66.5 km X 112 km image on single pass.

< 1 day revisit, $\leq$ 4.5 day. revisit for view angles $\leq$ 20 deg.

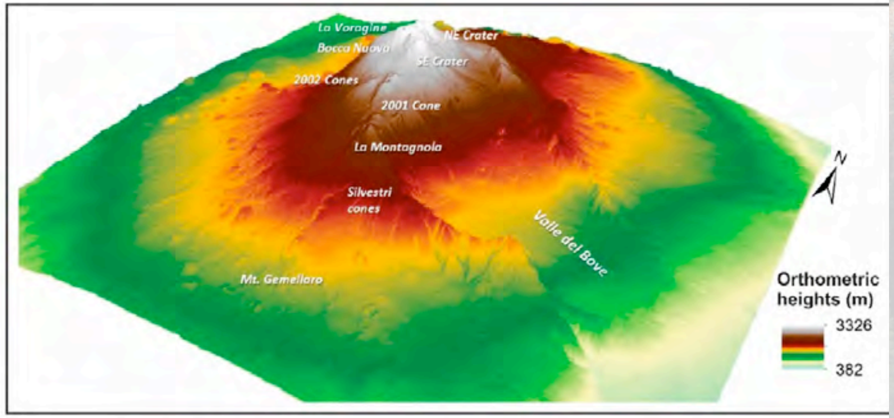
https://directory.eoportal.org/web/eoportal/home

Pleiades (2011,2012

Figure 13: Three pictures on the Mecca "tower clock" acquired by Pléiades 1B every 90 s in a single pass to see the minutes needle moving ! (image credit: CNES)

Figure 14: Three pictures on the Mecca "tower clock" acquired by Pléiades 1B every 90 s in a single pass to see the minutes needle moving ! (image credit: CNES)

Pleiades 1A and 1B (2 identical satellites in Spot 6 and 7 orbit plane). 0.5 m pan band resolution 1m multispectral VNIR resolution.



Pleiades DSM of Mt Etna in 2015 with submeter vertical RMSE error based on GCPs and lidar DSM.

Palaseanu-Lovejoy et a;. 2019. High-Resolution and Accurate Topography Reconstruction of Mount Etna from Pleiades Satellite Data. Remote Sens. 11, 2983; doi:10.3390/rs11242983

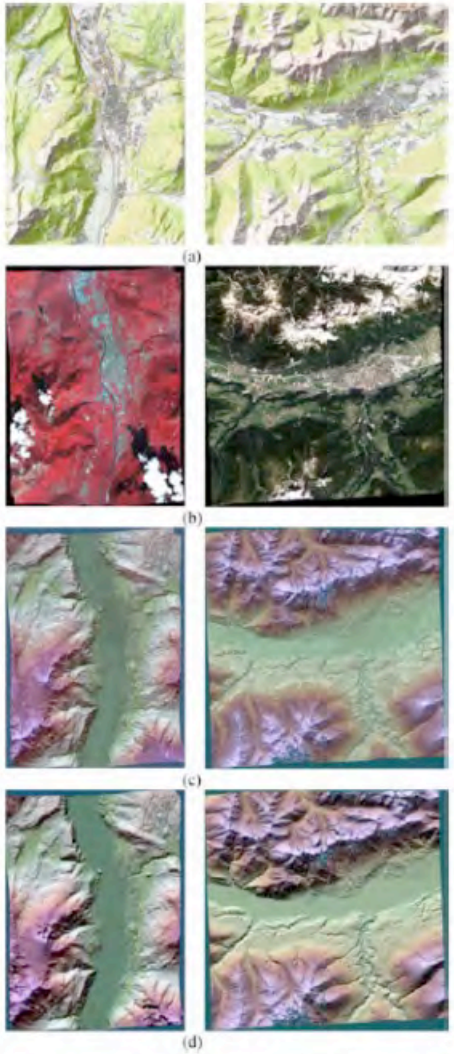
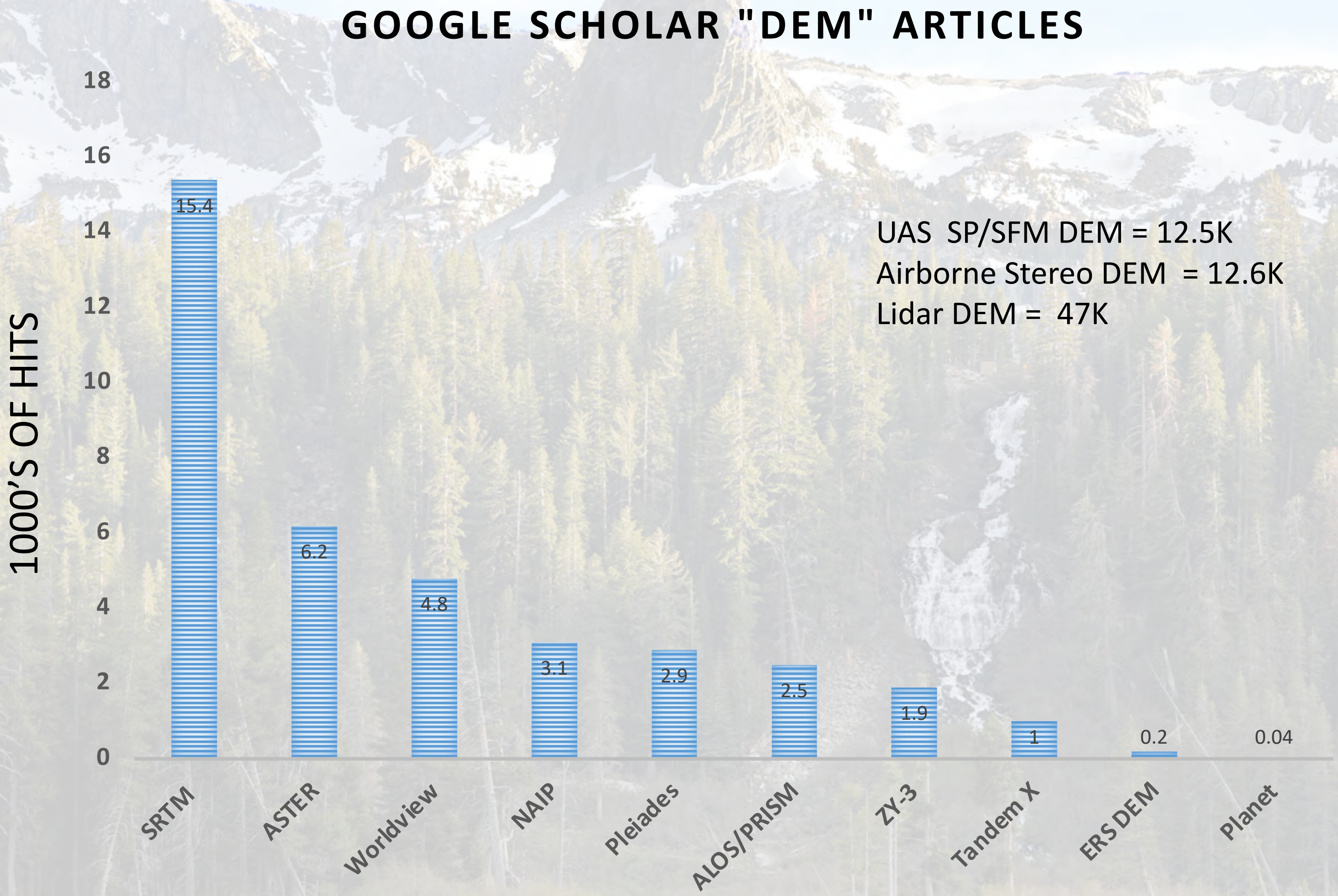


Figure 2. The two test sites (left: Trento; right: Innsbruck): (a) topographic map (opentopomap.org (CC-BY-SA)), (b) ortho-images (Trento CIR, Innsbruck RGB), (c) relief shaded DSMs, and (d) relief shaded DTMs. (b-d) were produced employing the proposed & implemented mapping workflow.

Perko, R., Raggam, H., Schardt, M. and Roth, P.M., 2018. Very high resolution mapping with the Pleiades satellite constellation. *Am. J. Remote Sens*, *6*(89), p.2019.

Impact


GOOGLE SCHOLAR "DEM" ARTICLES
1000'S OF HITS
18
16
14
12
10
8
6
4
2
0
15.4
6.2
4.8
3.1
2.9
2.5
1.9
1
0.2
0.04
SRTM
ASTER
Worldview
NAIP
Pleiades
ALOS/PRISM
ZY-3
Tandem X
ERS DEM
Planet
UAS SP/SFM DEM = 12.5K
Airborne Stereo DEM = 12.6K
Lidar DEM = 47K

Poll Questions #1

What science and applications disciplines are included in your work?

What instrumentation is used to acquire the height data you work with?

Are you involved in developing and/or testing new instrumentation?

What type of SP data have you worked with?

Do you need SP coverage that is Continuous- wall-to-wall mapping,

Transects/sampling, Spotlights- targeted areas, or Other?

What is the most important feature of a SP system to you (pick 1)?

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Poll Questions #2

What platforms are used to acquire the height data you work with?

Which of these platforms, that you currently do not use, would you use if available to you?

Are you involved in developing and/or testing new platforms?

Which of these technologies, that you currently do not use, would you use if available to you?

If you are a user of height data, what are the primary impediments in your work?

If you develop technologies, what are the primary impediments in your work?

What combination of co-located remote sensing data would provide the greatest benefit for improving height products?

Is there anything emerging or innovative as it relates to SP technology that the STV team needs to look in to not mentioned today?

Thank you!

Back Up

The Surface Topography and Vegetation (STV) incubation study is being conducted by an STV team at the request of NASA in response to recommendations made in the 2017-2027 Earth Science Decadal Survey. These technology breakouts are part of an ongoing series to collect community input.

The Decadal Survey recommended *high-resolution global topography, including bare surface land topography, ice topography, vegetation structure, and shallow water bathymetry* as a Targeted Observable (TO). Targeted observables address key priorities within and across disciplinary lines for a set of science objectives related to a common aspect of the Earth system. The survey identified STV as an Incubation Observable and called for assessment of next-generation measurement approaches that could be ready for spaceborne implementation in 10+ years. The survey recommends focused and sustained attention by NASA to the Incubation 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.

In late 2019 NASA established an STV Incubation Study Team. The objective of the incubation study team is to identify science and applications priorities, gaps in the specification of requirements and in technology capabilities needed to meet those priorities, and methods and activities to fill those gaps. The study team will develop a white paper for delivery to NASA outlining potential future methods and activity areas, such as modeling, Observing System Simulations Experiments (OSSEs), field campaigns, data analysis and evaluation of a range of potential observing system architectures utilizing emerging sensor, platform and information technologies, and activities to advance those technologies to the point where they could support future space-based STV observations. The team will produce a preliminary Science and Applications Traceability Matrix (SATM) that includes relevant societal or science questions, Earth science and application objectives, geophysical observables, product requirements and draft concepts of associated measurement approaches. The white paper and preliminary SATM will be used by NASA Headquarters to help inform future solicitations to advance STV.

The team is soliciting input from the broader community through a series of virtual workshops and online questionnaires. Additional information about the study is available at:

https://science.nasa.gov/earth-science/decadal-stv

To complete the questionnaire, use this link.

https://docs.google.com/forms/d/e/1FAIpQLSelgd9hNfTobNh8ZvGEFObEvBOdLoD8T32U4fhn-TL9ODTQHg/viewform

The decadal survey can be found here:

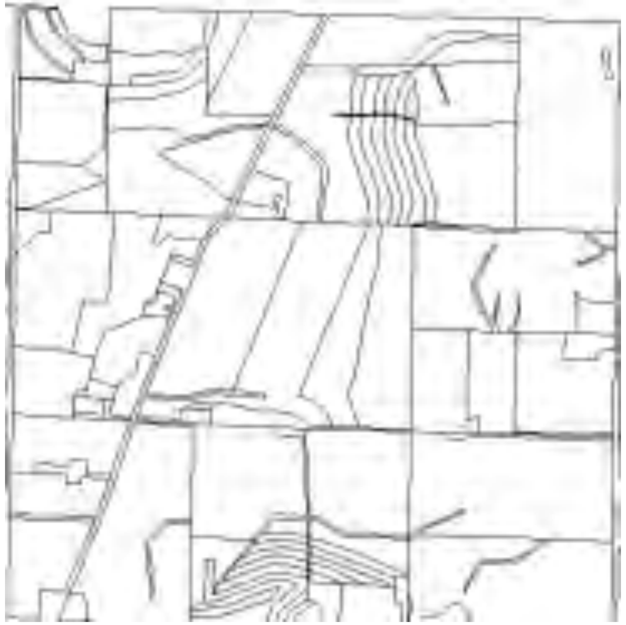
(https://www.nap.edu/catalog/24938/thriving-on-our-changing-planet-a-decadal-strategy-for-earth

National Agriculture Imagery Program (NAIP) Elevation Data Options

National Agriculture Imagery Program

- Started as a Farm Service Agency 2m ortho imagery program in 2003 to acquire only farm fields but quickly expended to full CONUS coverage with cost-share partners
  - Spatial Resolution – 1m (all states since 2008) & 60cm ground resolution (2018)
  - Spectral Resolution – Natural Color and False Color Infrared (all states since 2010)
  - Refresh – two-year CONUS collection cycle since 2008; changed to three-year in 2018
  - Acquisition Period – Leaf-on during peak agriculture growth
- Largest, longest running consistent airborne-based civilian program
- Public Domain dataset

FSA Imagery Needs



Common Land Unit (CLU)
+ Producer Crop Reporting

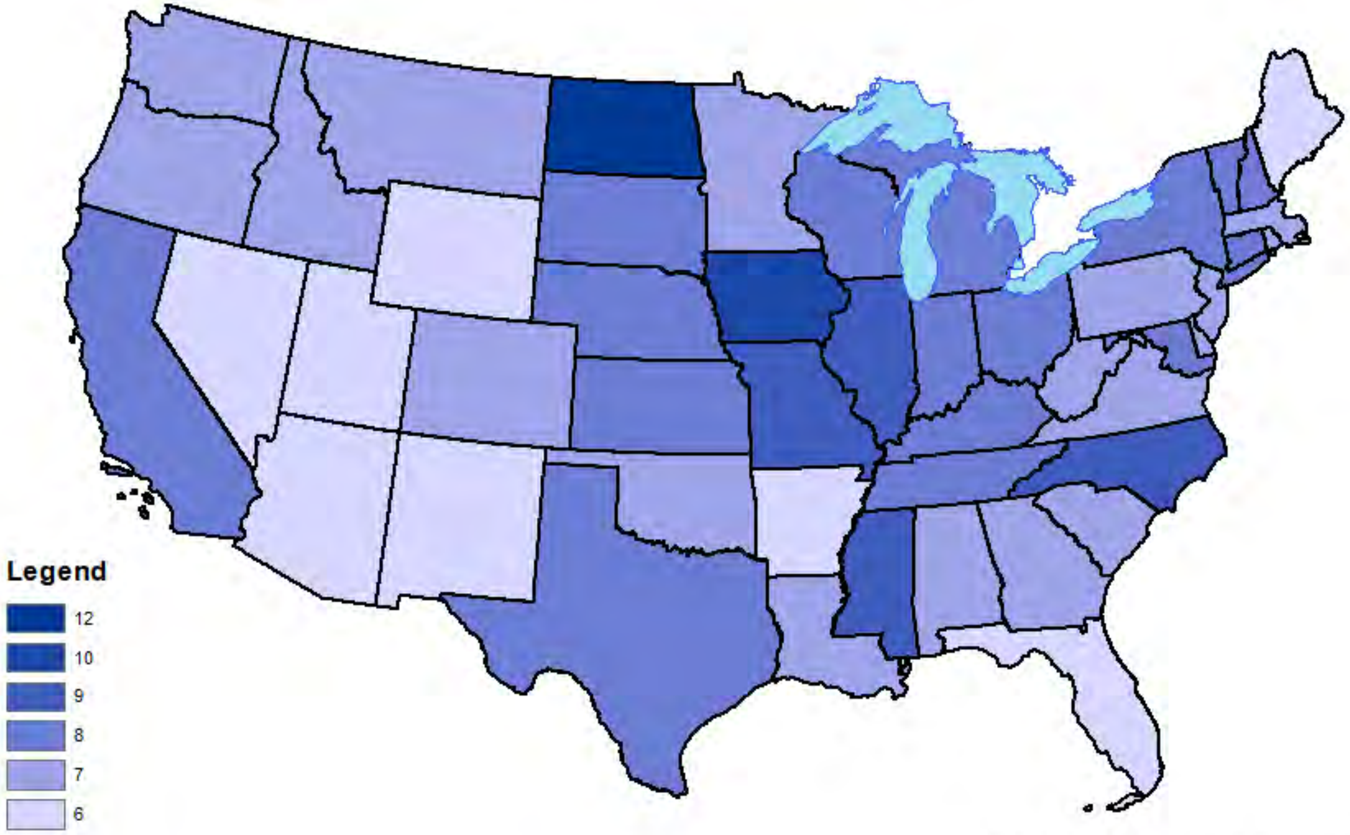
Current high-resolution imagery

Confirmation of area planted and crop types.

Within USDA; Farm, Conservation, Disaster, and Insurance Programs are administered at the CLU level.

National Agriculture Imagery Program

Number of 1m (or better) Collections



2003-2020 seasons

Current Buy-up Options under NAIP

- Stereo Imagery
  - Standard stereo-pairs and block file
- Digital Surface Model (photogrammetry derived from stereo)
  - Point clouds derived from the native resolution of the imagery, with nominal point spacing no greater than double the native imagery resolution
  - e.g. 80 cm spacing for 40 cm imagery
- “Pass thru” product
  - Customer is responsible for receiving, inspecting, and any GDA reporting/distribution
  - No admin fee charged
  - Signed Interagency Agreements required February timeframe (work around is to have request agency sole source but usually only valid until imagery collection starts)

Future Technology

- Simultaneous Elevation Data Collection
  - Industry is working on dual “imagery & Lidar” sensors which would potentially allow Level II Lidar data being collected on NAIP flights
- 2019 pilot funded by NRCS tested Hexagon’s CountryMapper
  - Findings recently published in Remote Sensing: https://www.mdpi.com/2072-4292/12/12/1974
- Future data collects will likely be managed thru FGDC’s 3DEP subcommittee

Point of Contact

John Mootz

Imagery Program Manager

Geospatial Enterprise Operation (GEO) Branch

Information Solutions Division (ISD)

FPAC Business Center

801-844-2916

john.mootz@usda.gov

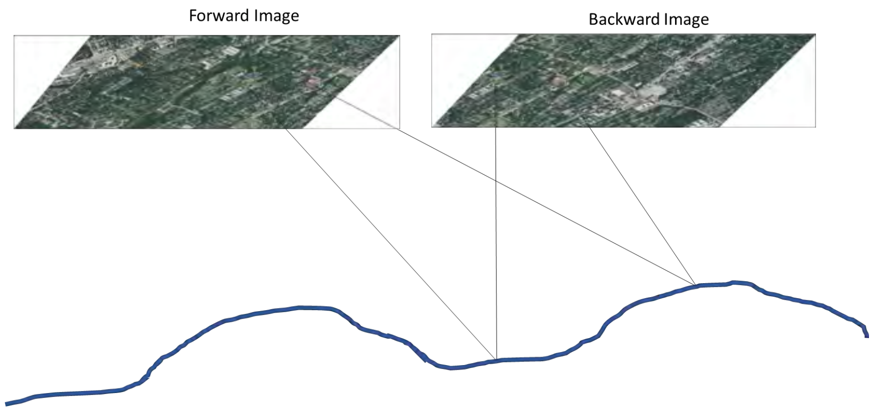
Current Technology Title

Principal Investigator and Organization

Summary

- Photogrammetry derived elevation model from stereo imagery collected from airborne sensor as part of the NAIP ortho imagery program

Graphics that convey the key aspects of the technology



Status

- TRL 9
- Well established, proven technology with decades worth of experience

Performance

- For instrumentation, what products are generated and what are their attributes?
  Autocorrelated elevation data, DSM, DEM
- For information systems, what are its capabilities?
  data ingest, throughput, delivery time
- For platforms, what are its capabilities?
  Hardware, software, data storage

Co-Is/Partners

Citations

Emerging Technology Title

Principal Investigator and Organization

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

- Industry is developing the technology for meeting their internal content programs (i.e., licensed data subscriptions-based services)

Technical Readiness Level

- TRL 7-8

  Pilot conducted in 2019

Citations

- https://www.mdpi.com/2072-4292/12/12/1974

Co-Is/Partners

Challenges

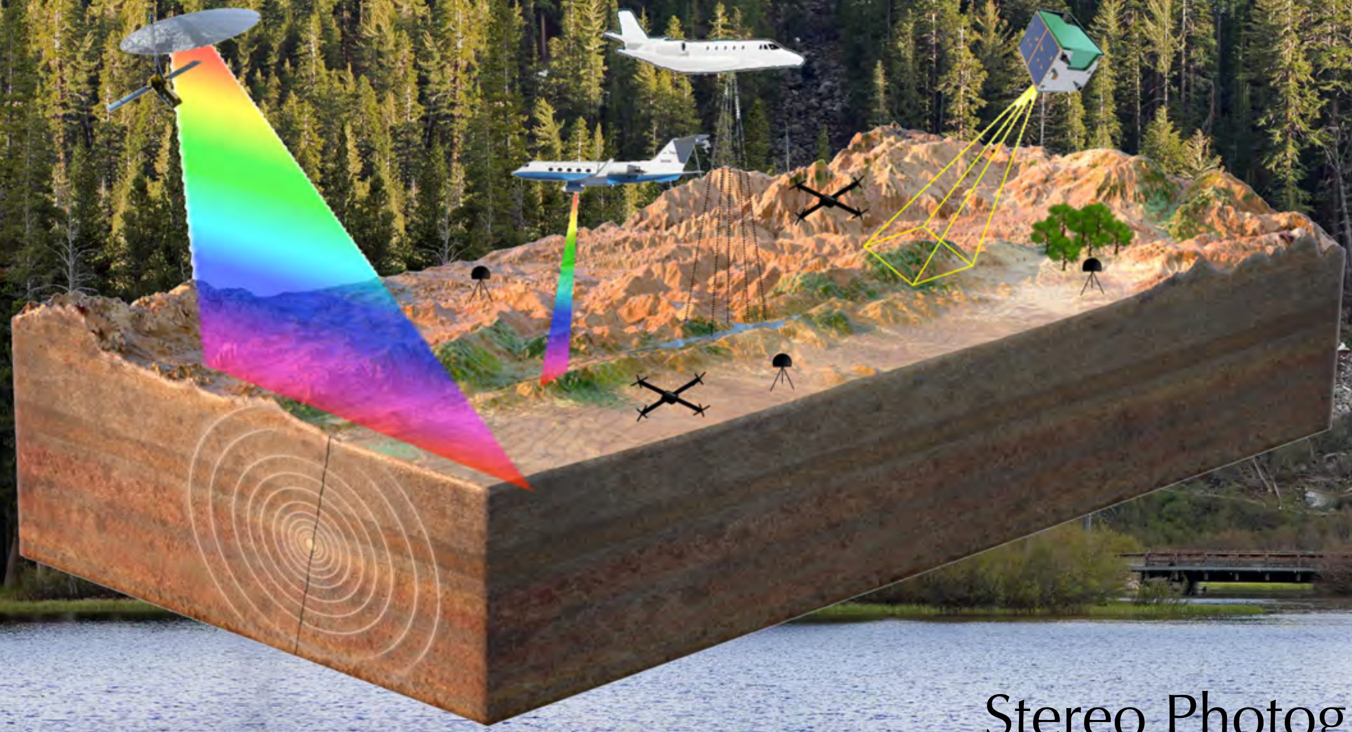
- The vendor system used for the 2019 pilot is changing imagery sensor and will likely require additional testing

Surface Topography and Vegetation
Incubation Study

QUAKES-I Stereo Photogrammetric Imager

Andrea Donnellan

NASA, Jet Propulsion Laboratory, California Institute of Technology



QUAKES-Imager

Quantifying Uncertainty and Kinematics of Earth Systems Imager (QUAKES-I)

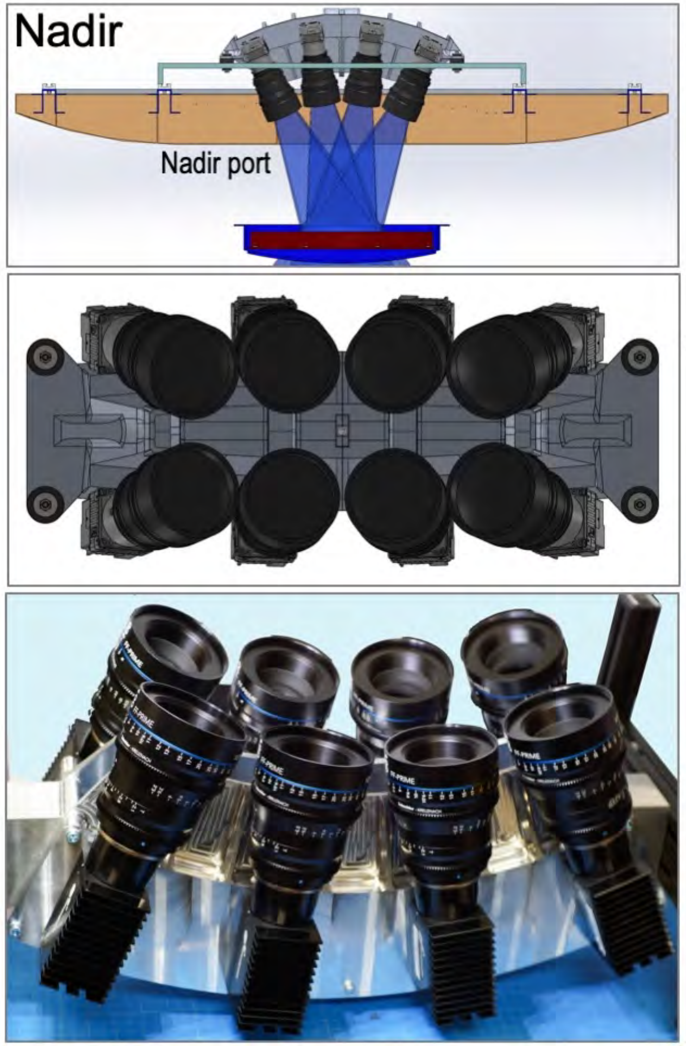
<u>UAVSAR</u>

- Airborne InSAR
- Flown on a Gulfstream III

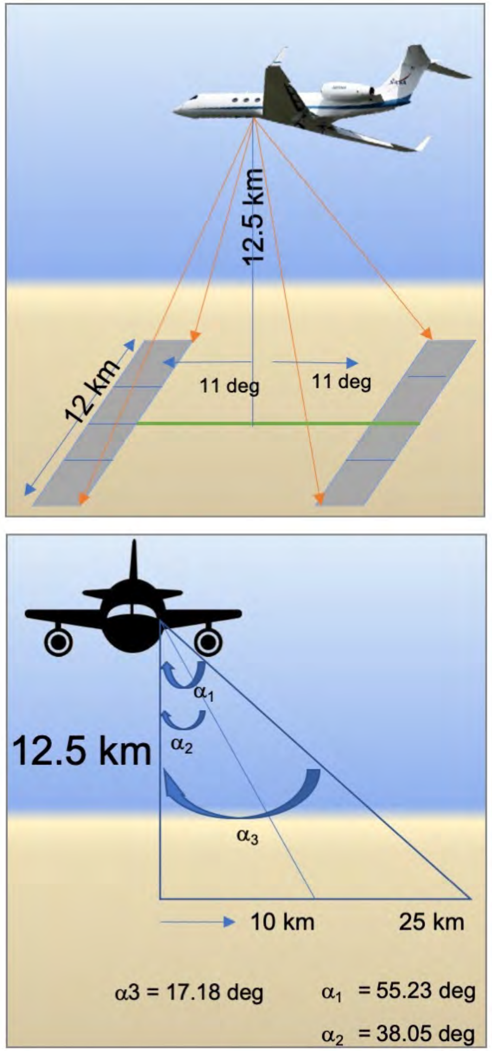
SAR-Fusion Prototype

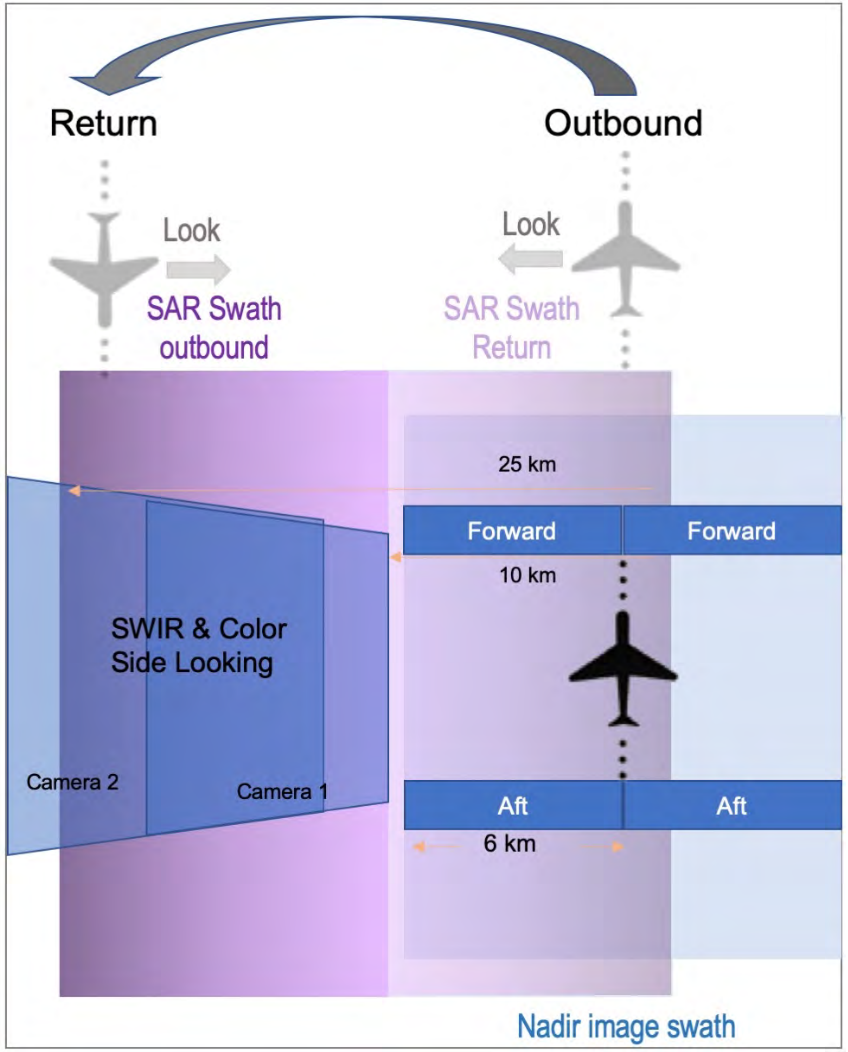
Cameras and Coverage

QUAKES-I

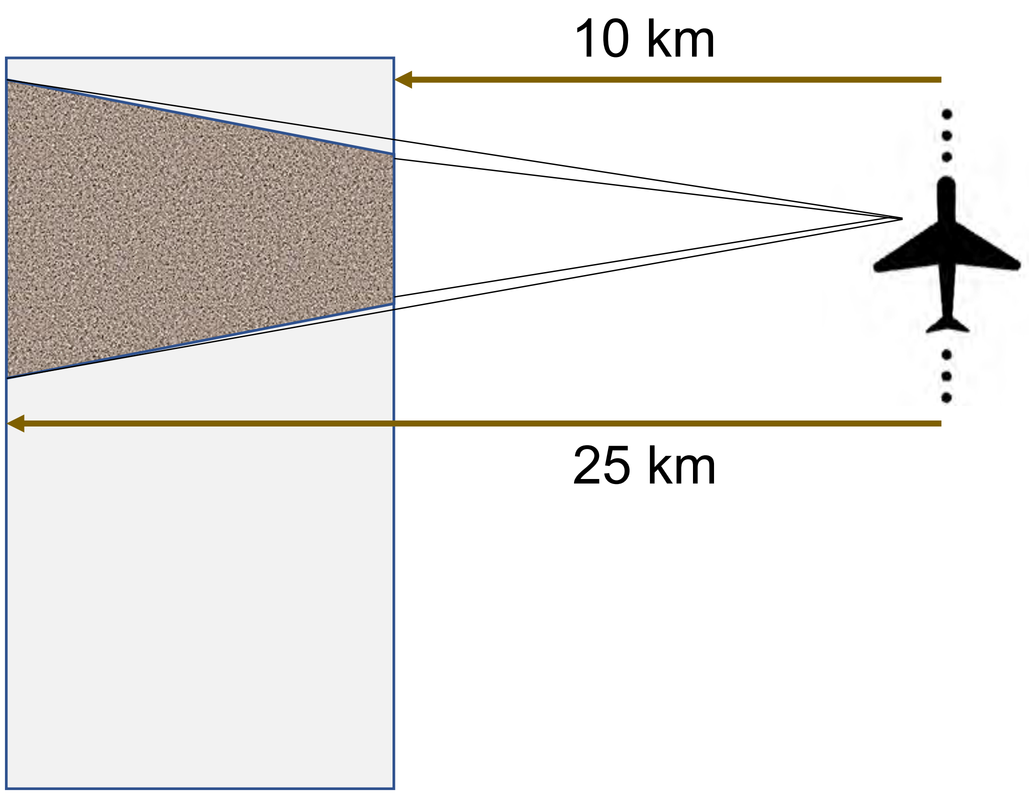


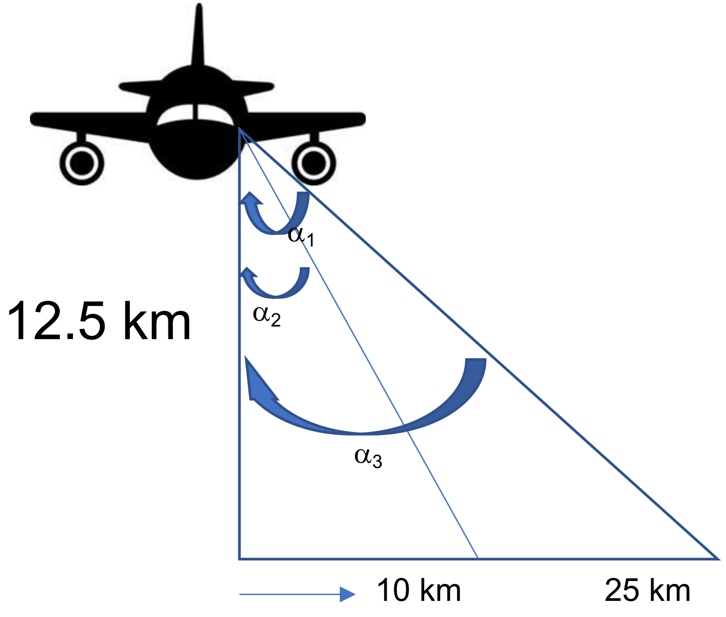
SAR-Fusion





QUAKES-I Sensor Array, Side Looking





$\alpha 3$ = 17.18 deg

α_1 = 55.23 deg

α_2 = 38.05 deg

QUAKES-I SA-SL-Visible

Two CMOS, 35 mm sensor, 100 mm lens

5120 x 3840 pixel (20 MP) with Global Shutter

Bayer with 8 & 10 bit options

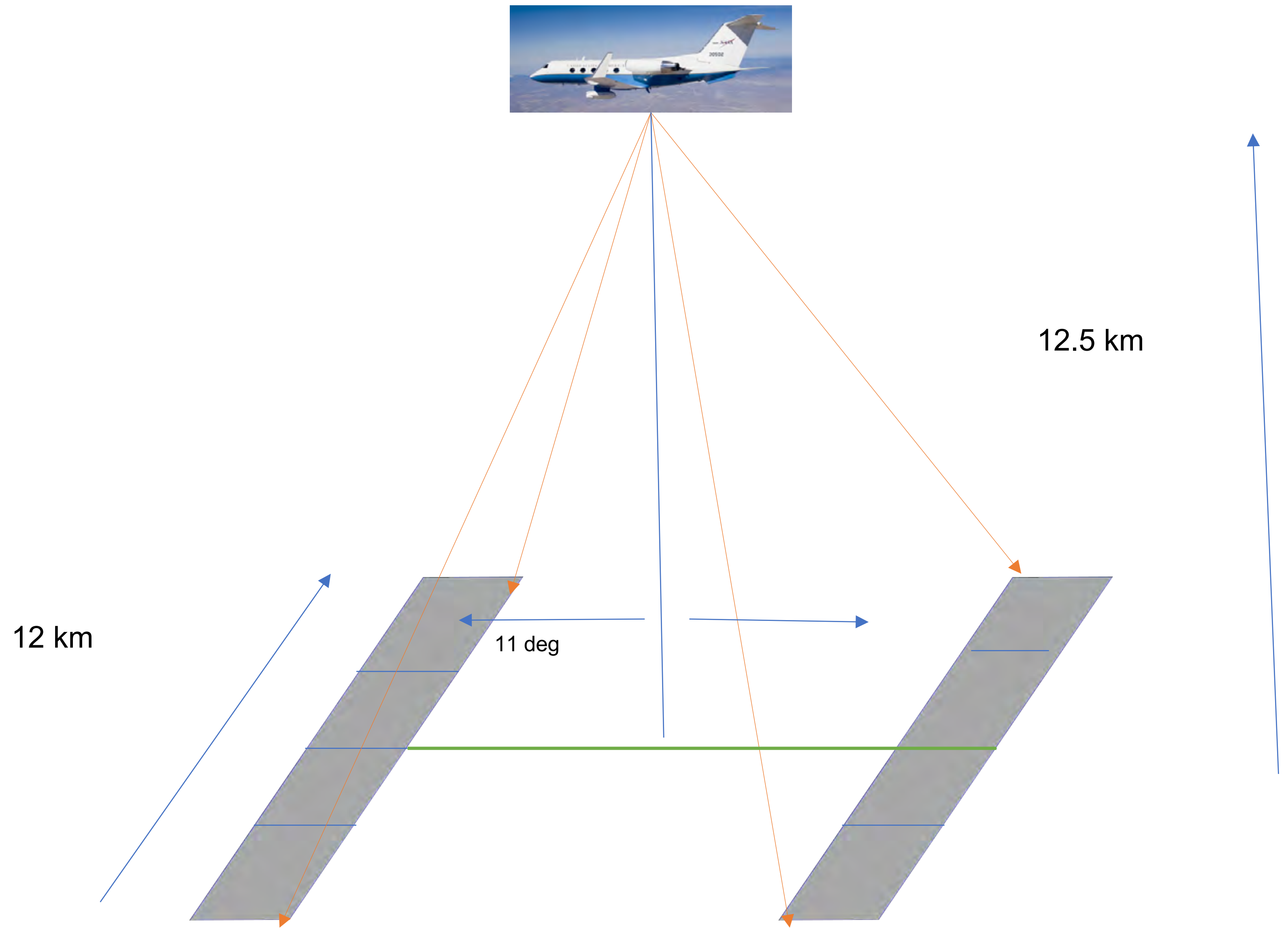
QUAKES-I SA-SL-SWIR

Two InGaAs, 9.6 x 7.68 mm focal plane, 35 mm lens

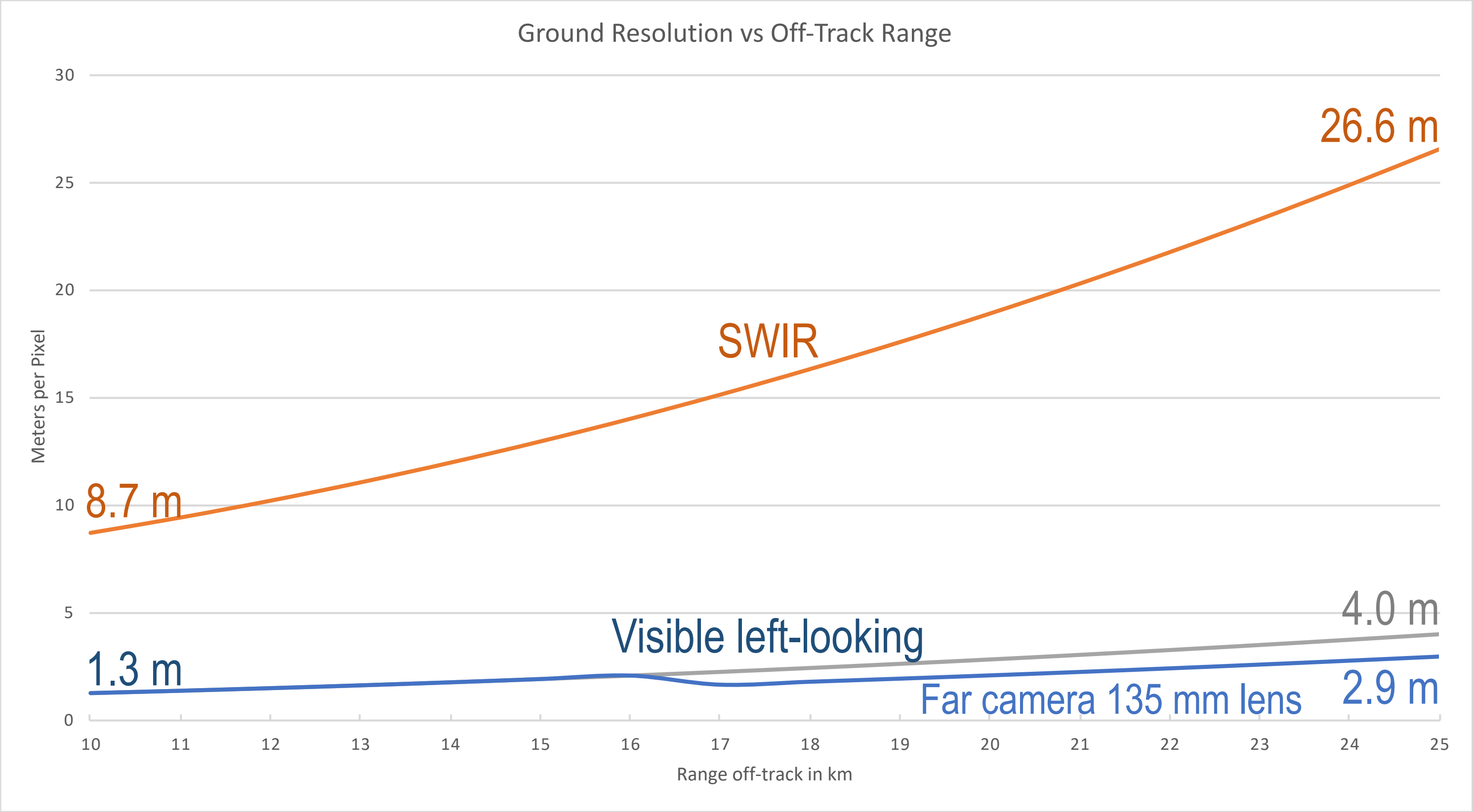
640 x 512 pixel (0.3 MP) with Spectral Range 0.9-1.7 μm

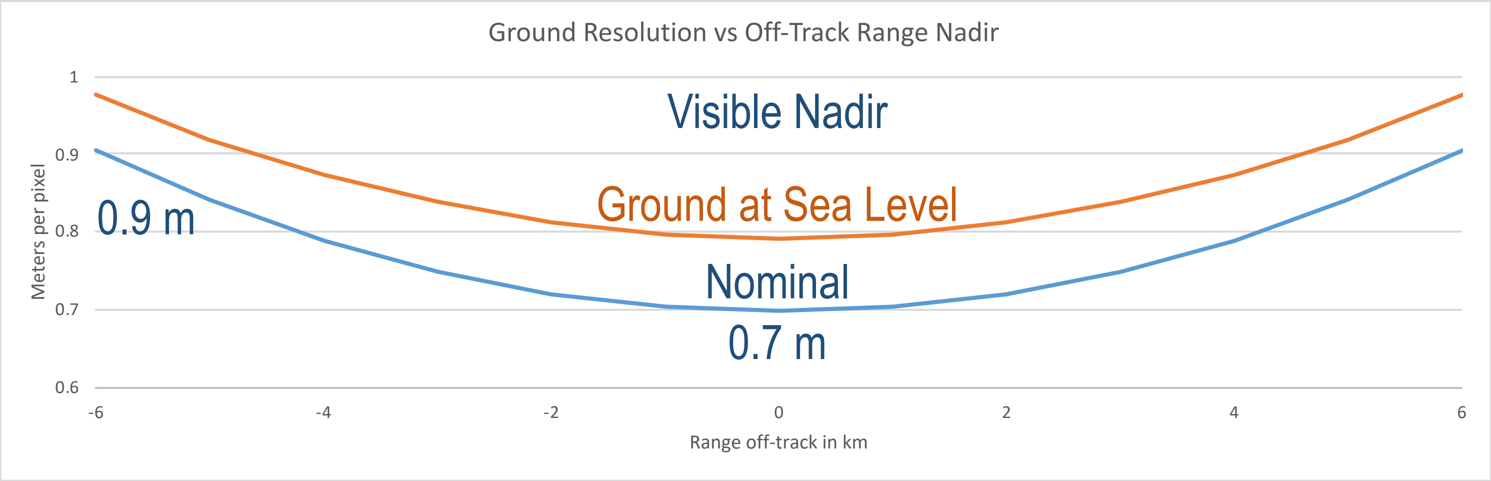
FLIR Tau SWIR

Structure From Motion Sensor Array Down Looking



Ground Resolution

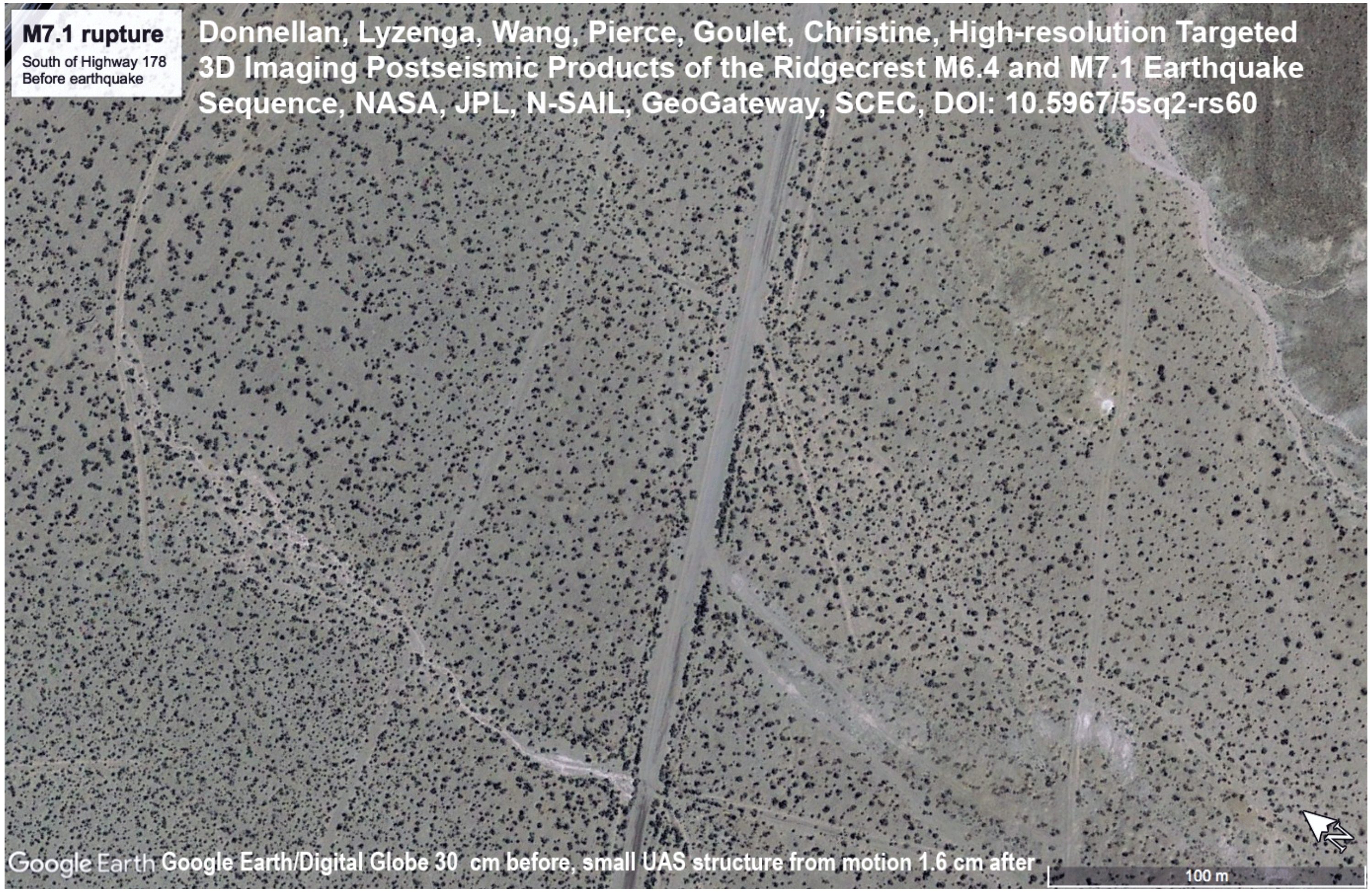




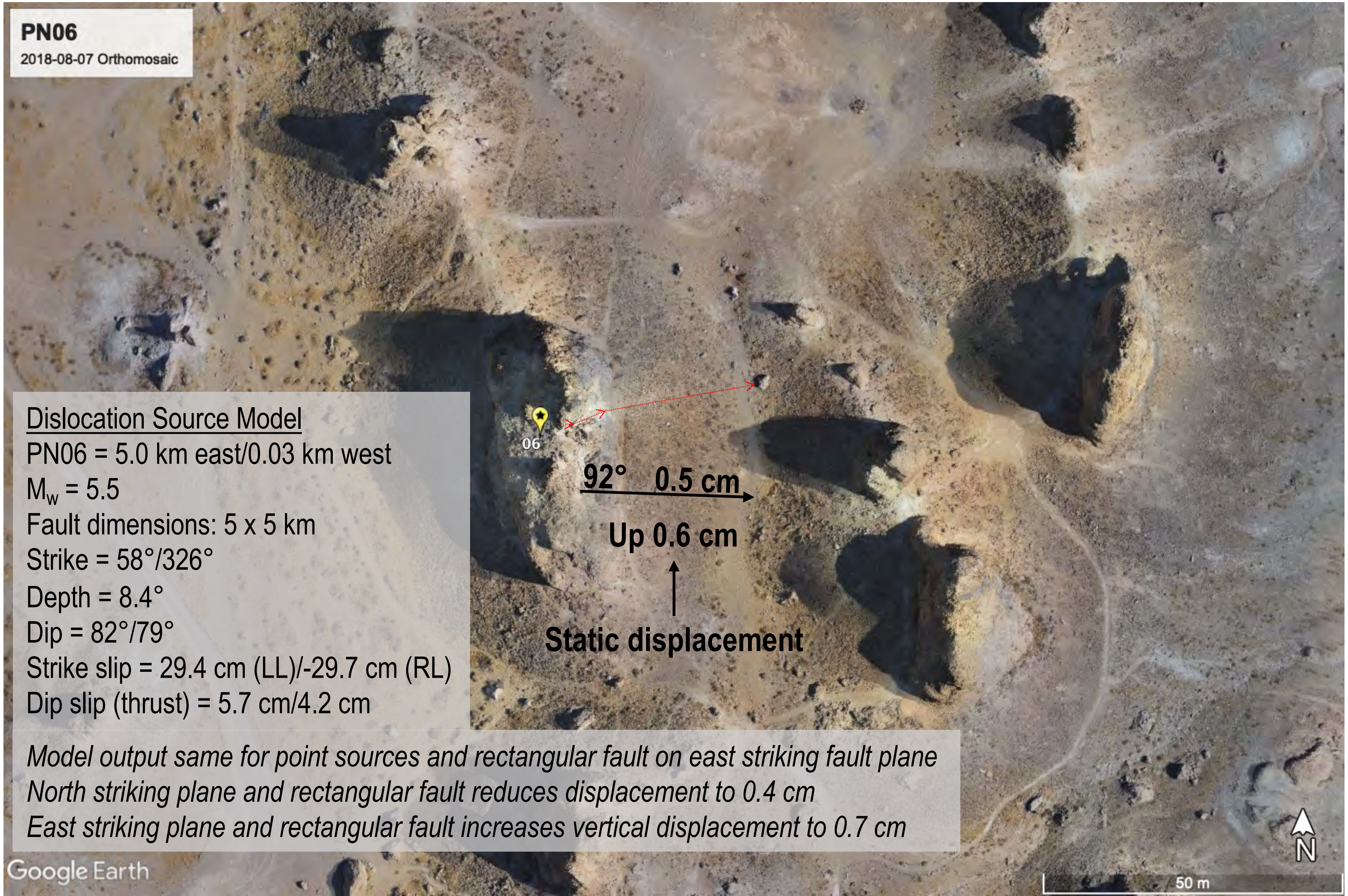
Nominal GSD for Side Looking Sensor Arrays for differing off track ranges (ground at sea level)

Displacements – Ridgecrest Earthquake

- ≤40 cm topographic change where accessible

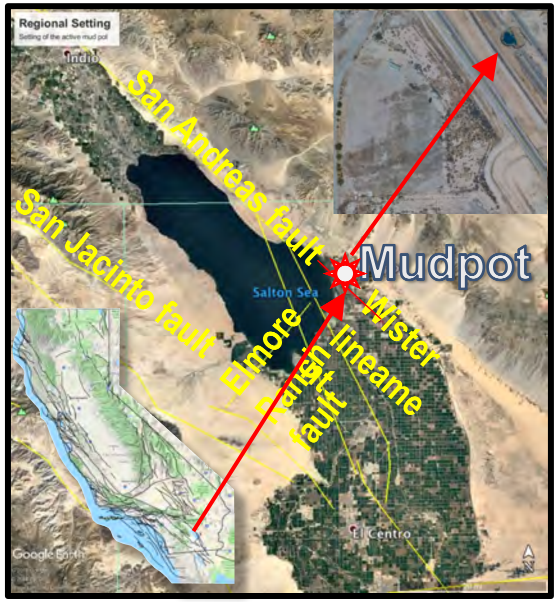


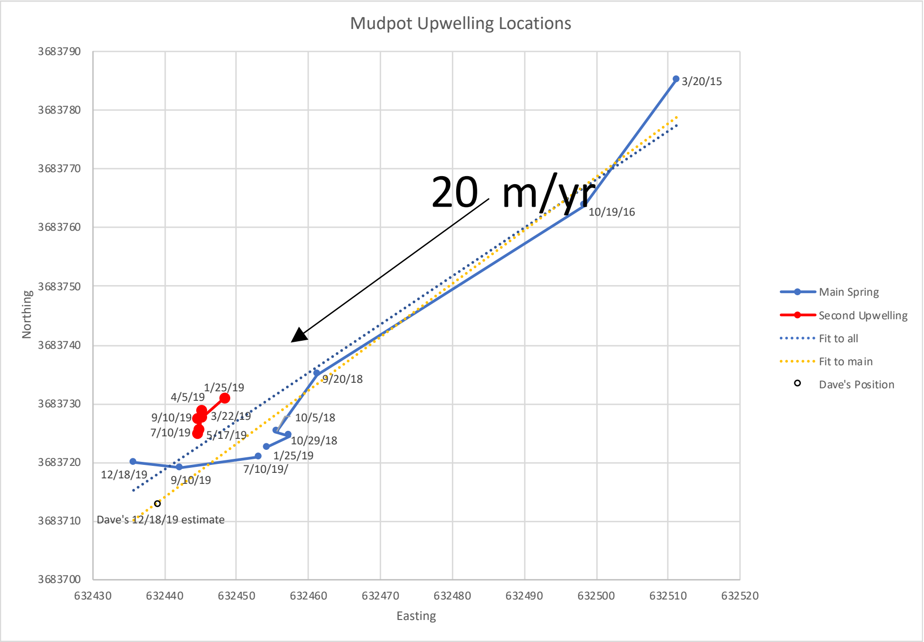
Fragile Features – Trona Pinnacles



Moving Features – Mundo Mudpot

➢Landslides are similar scale

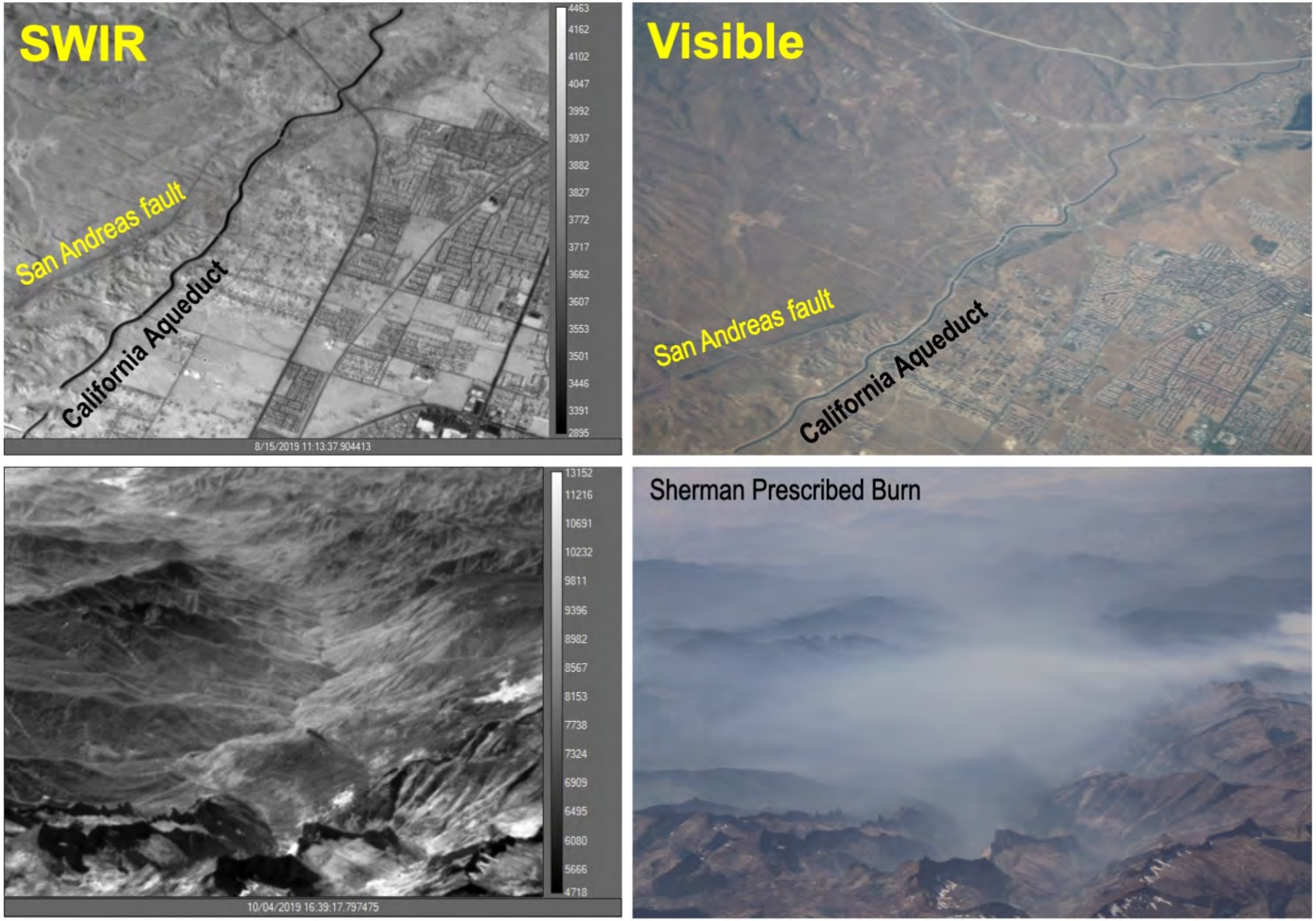




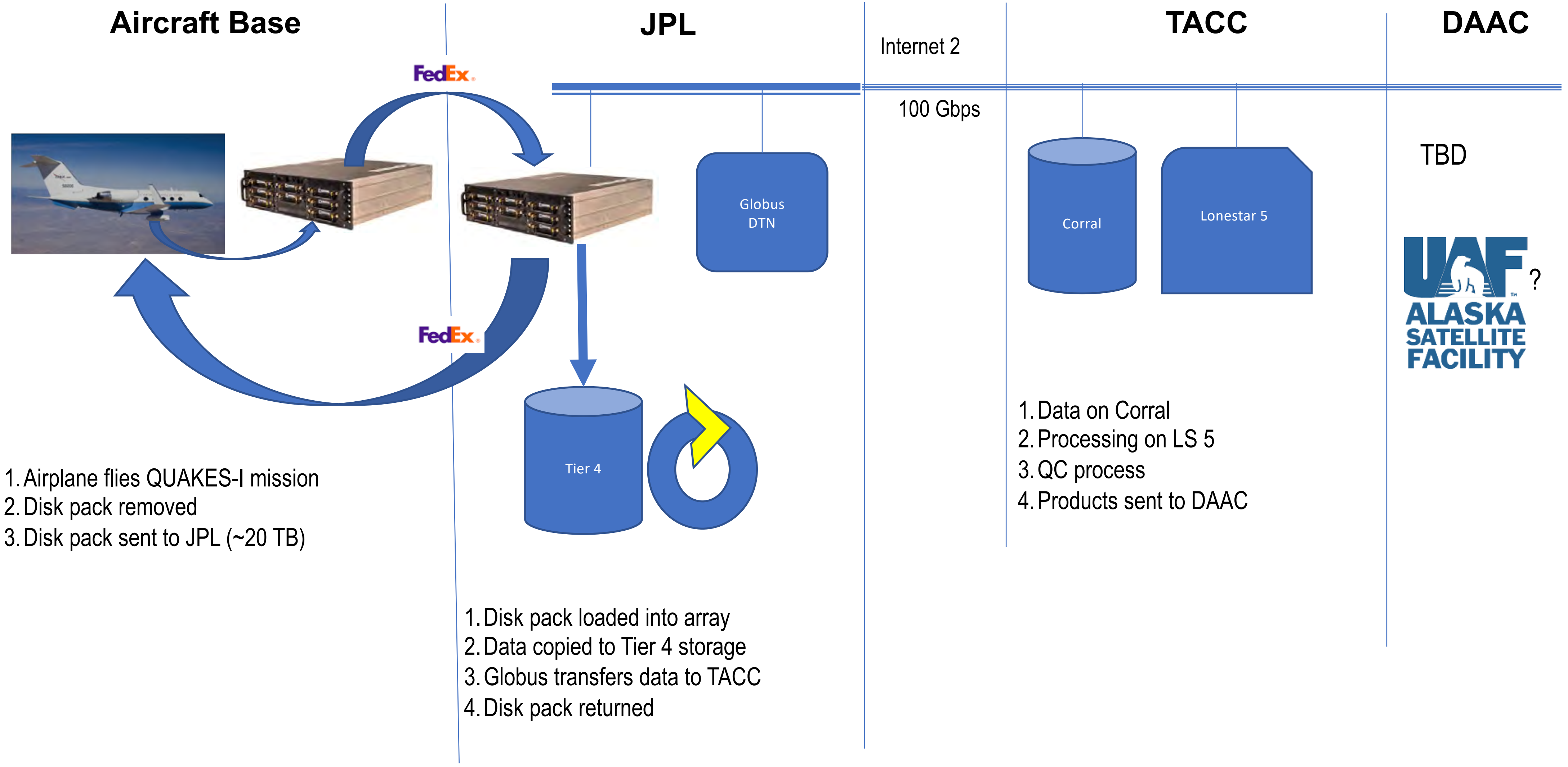
Sample 3D Reconstruction

- **Visible image and topographic resolution**
  - –Single camera, 23 images, 3m average ground sample distance (GSD)

SWIR and Visible Products



Data Architecture and Flow



Quantifying Uncertainty and Kinematics of Earth Systems Imager (QUAKES-I)

PI: Andrea Donnellan

Objective

Provide color orthorectified topographic images:

- 60 cm resolution topographic images at nadir along a 12 km wide swath
- 9 m resolution SWIR images along 15 km wide UAVSAR image swath
- 2 m resolution visible images along 15 km wide UAVSAR image swath

Enable studies **of** full 3D surface morphology and change over time.

Targets: Earthquake prone regions, volcanoes, landslides, wildfire scars, glaciers, vegetation, and ecosystems.

Approach:

Carry out engineering-focused activities to test, calibrate, and deploy the QUAKES-I imaging suite:

- 8 camera full-frame, nadir port multi-angle imager
- 2 camera side imager compatible with UAVSAR swath
- 2 SWIR cameras for nadir port and side window compatible with UAVSAR swath

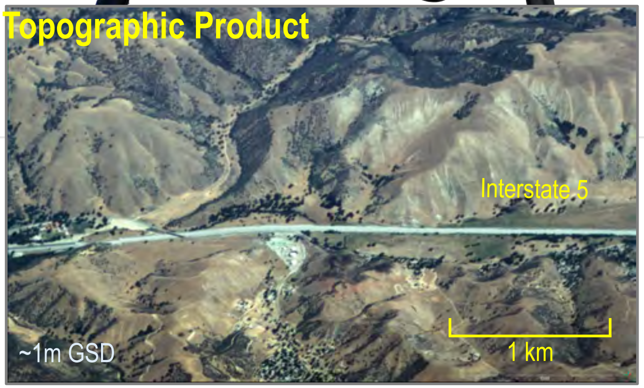
Integrate with IMU and precise GNSS

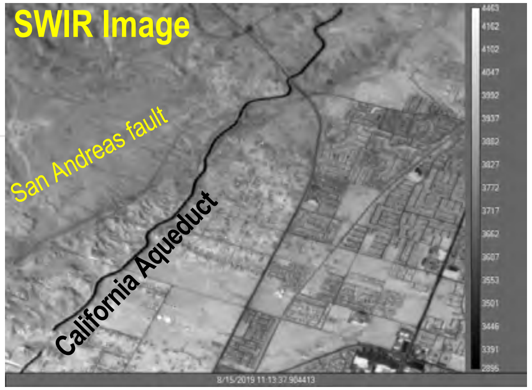
Mature processing pipeline

Nadir Arch with Cameras

8 camera nadir visible system produces color 3D products.

SWIR cameras image through haze and smoke.

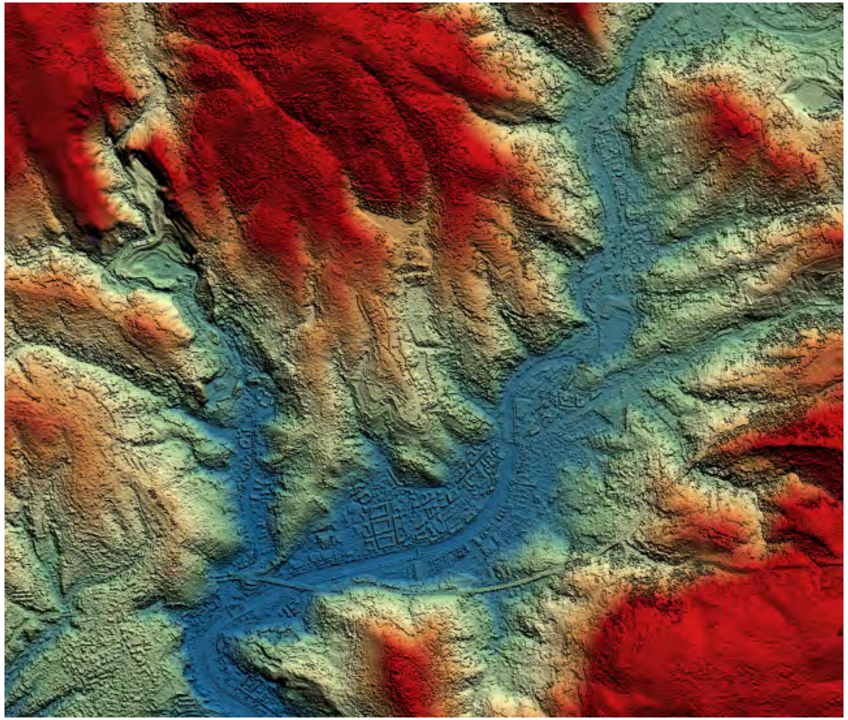




CoIs: Curtis Padgett (JPL), Jay Parker (JPL), Yunling Lou (JPL), Joseph Green (JPL), Bruce Chapman (JPL), Mihailo Derek Rutovic (JSC), Stephen DeLong (USGS)

$TRL_{in} = 5$

The CO3D demonstrator,
a worldwide one-meter accuracy DEM

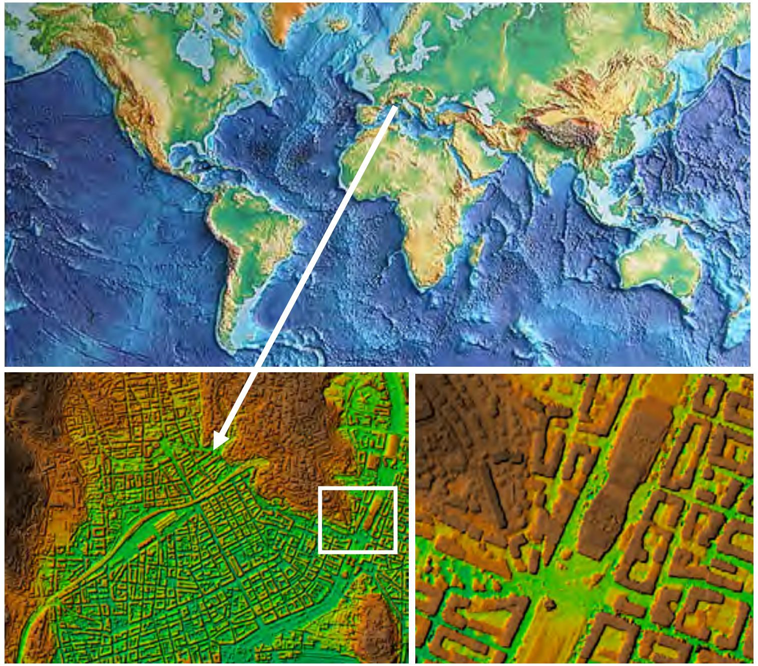


Laurent Lebègue (CNES)

NASA Surface Topography and Vegetation
Technology Breakouts, Stereo Photogrammetry
2020, September 9

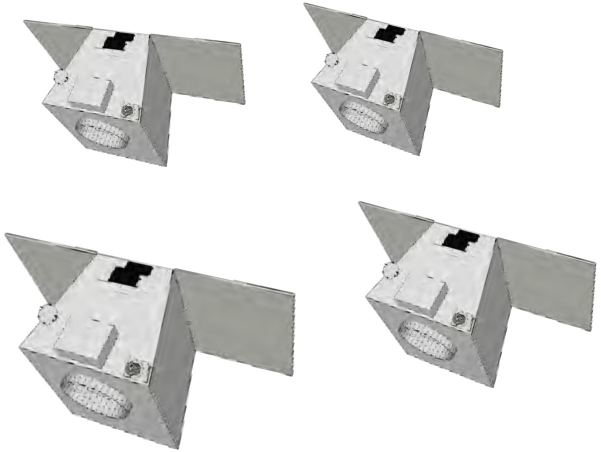
CO3D Main Challenges

Worldwide DEM



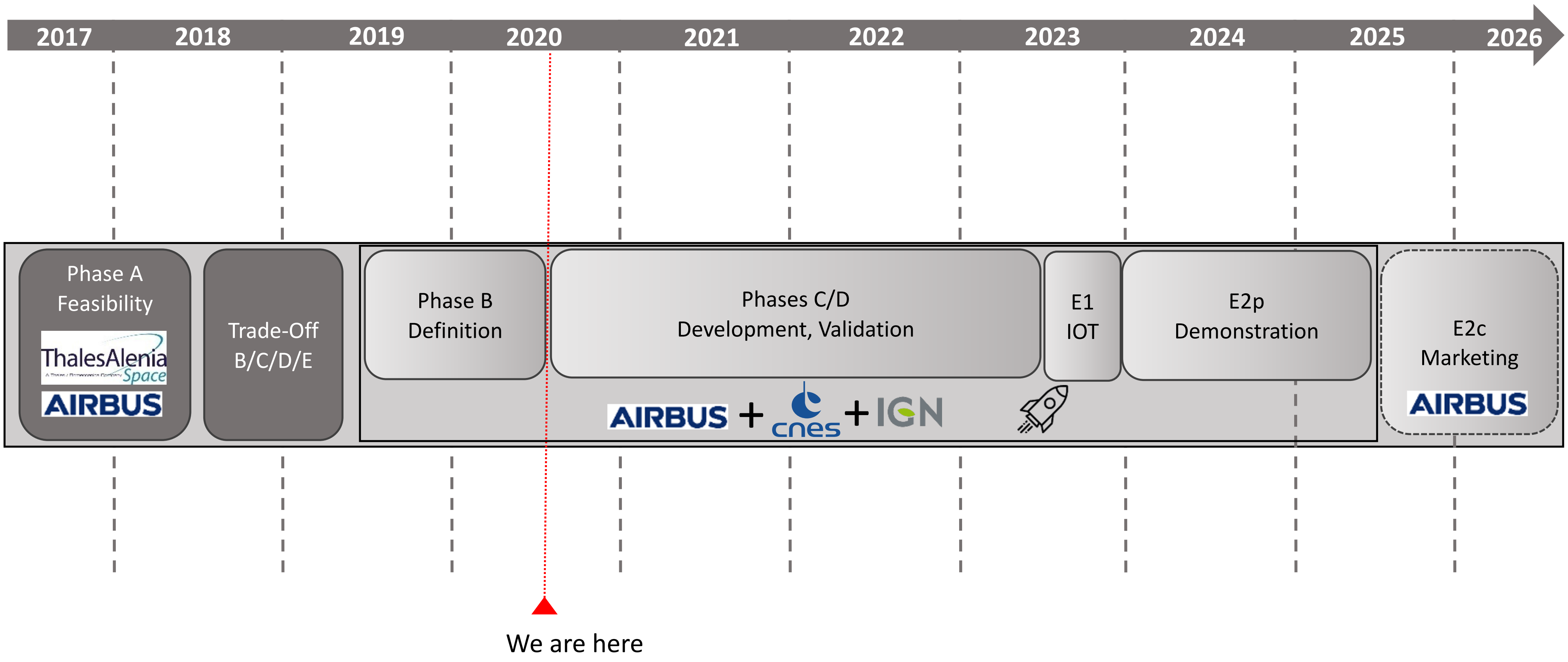
Altimetric accuracy
Goal 1m (relative)

Low-cost
full-automatic
cloud-processing



Low-cost EO satellite
constellation
50 cm imagery

Program Schedule



Demonstration Phase

< 18-months, <= 2025

Metropolitan FRANCE
~500 000 km2
50% DEM production

Relative **and absolute** altimetric accuracy

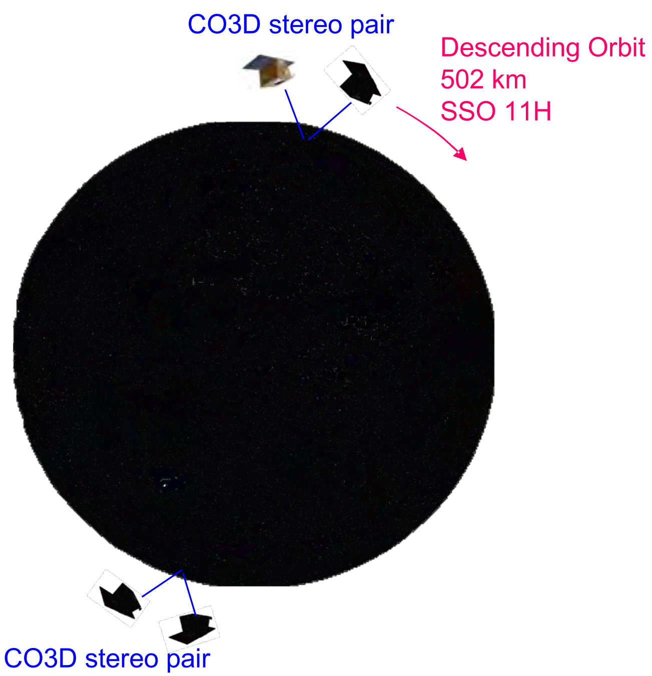
Defense Arc Of Interest
~27 Mkm2
70% DEM production

Relative altimetric accuracy

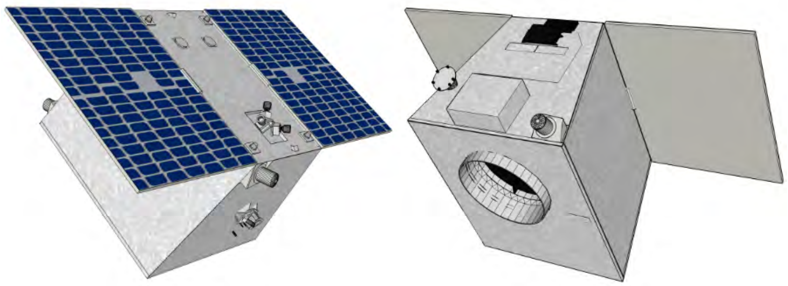
World landmasses (+/- 70° latitude)
~123 Mkm2
50% DEM production
(Goal 90% in 3 years)

Large cities quadruplets
~ 200 x (400 km²)

CO3D Spatial Segment

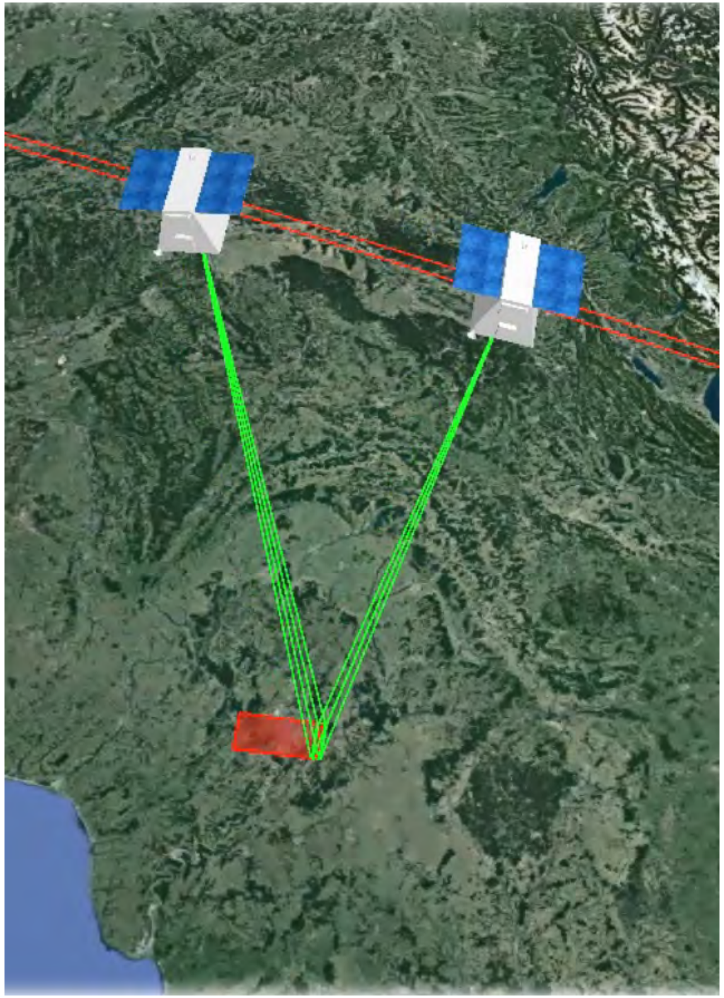


4 CO3D satellites occupying ½ of a Vega-C rocket

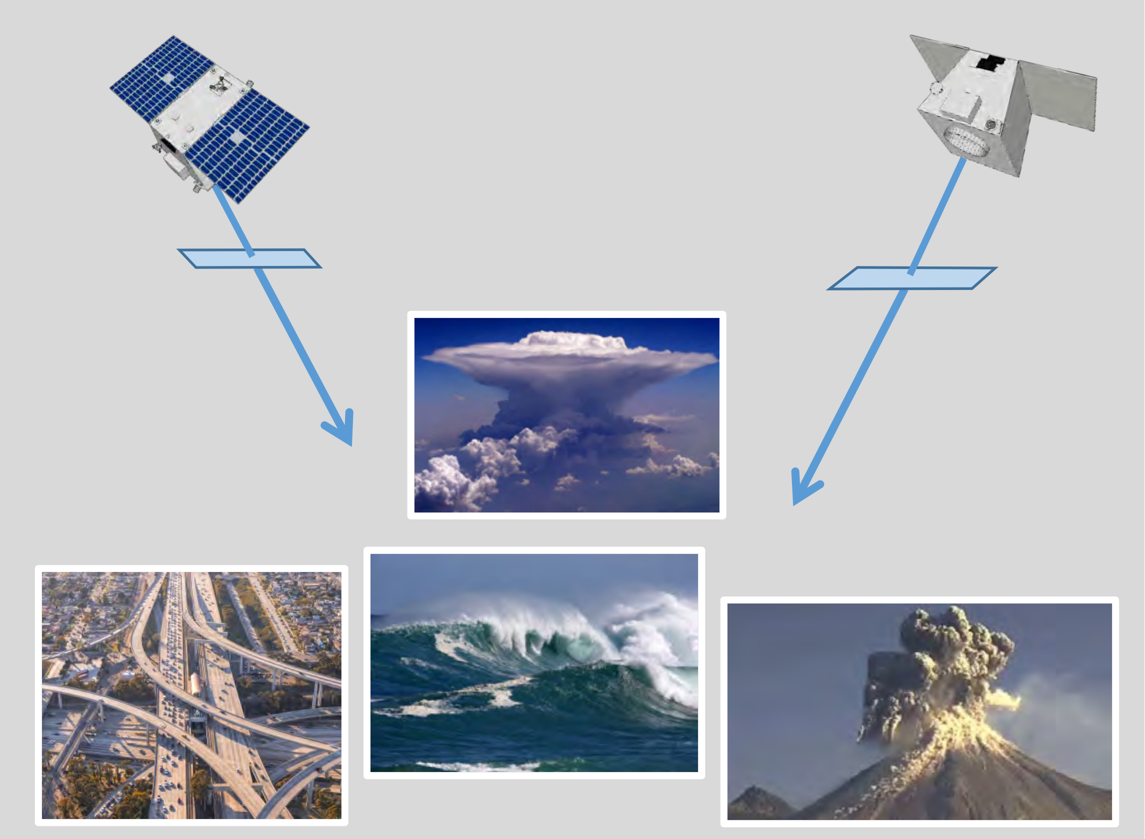


CO3D satellites

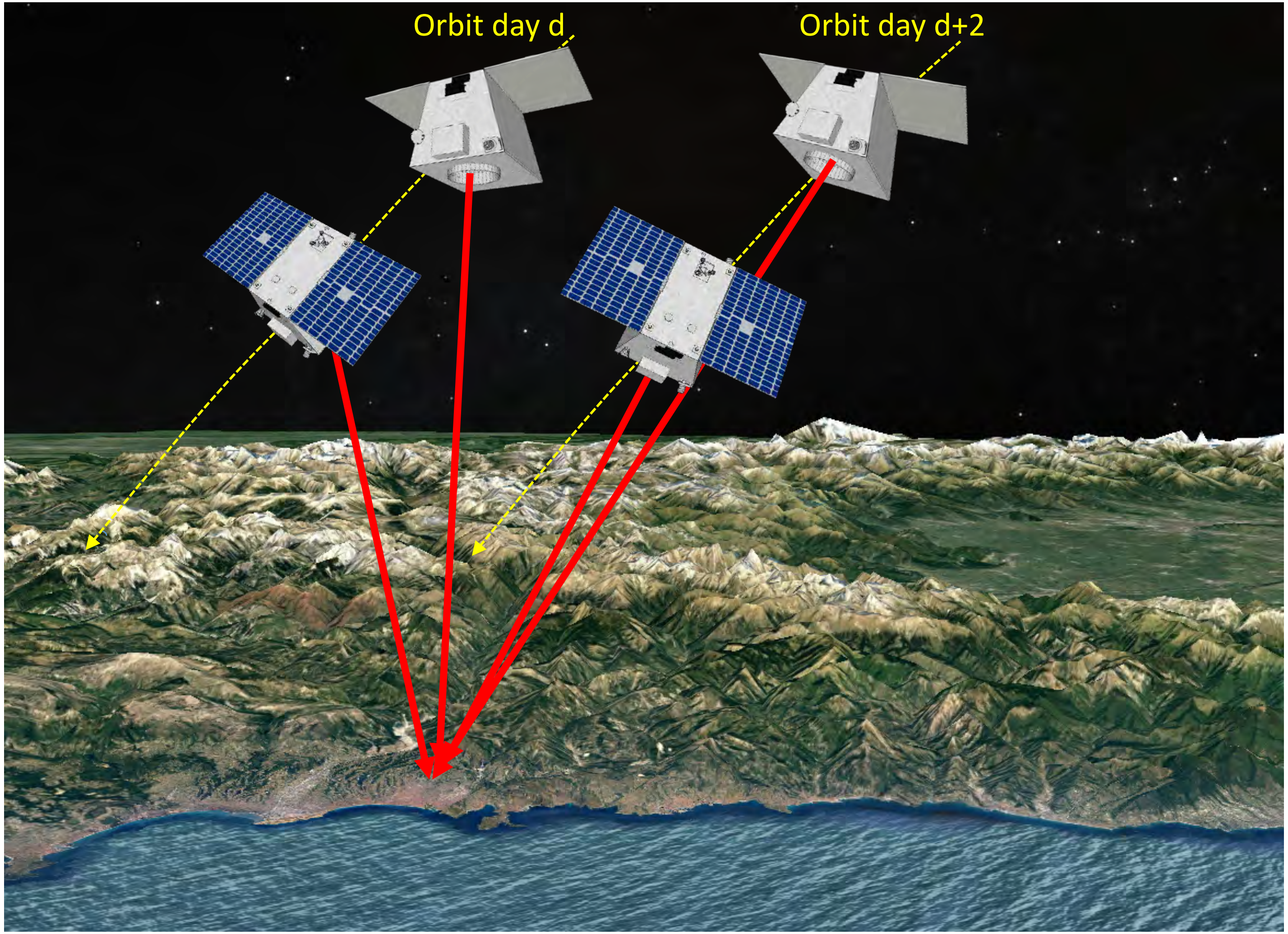
Synchronous stereo acquisitions capacity



A few miliseconds satellites pair synchronicity to freeze in tree dimensions most of moving objects



Benefits of quadruplet vs stereo



Quadruplet in « Diamond Geometry » reduces noise and occlusions thanks to azimut viewing angle variety.

Particularly interesting over urban areas…

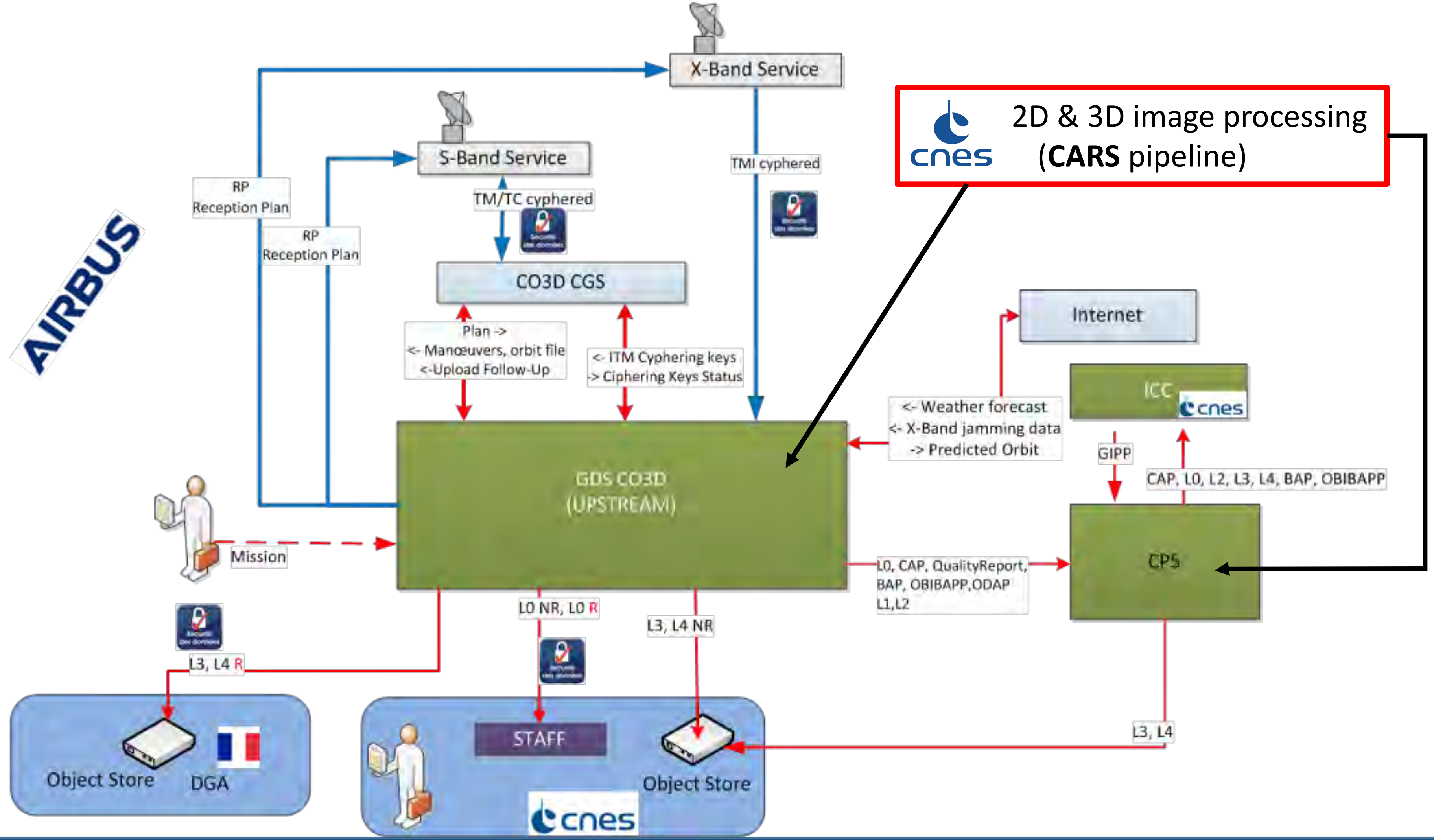
DSM examples with Pleiades satellites (stereo and quadruplet)

Full automatic 1 m resolution DSM - Nice downtown (France). Stereo (left), Quadruplet (right)

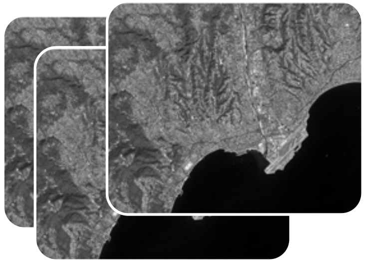
CO3D Image Quality

CO3D image simulation 50 cm R,G,B (left) and NIR (right) – Lyon (France)

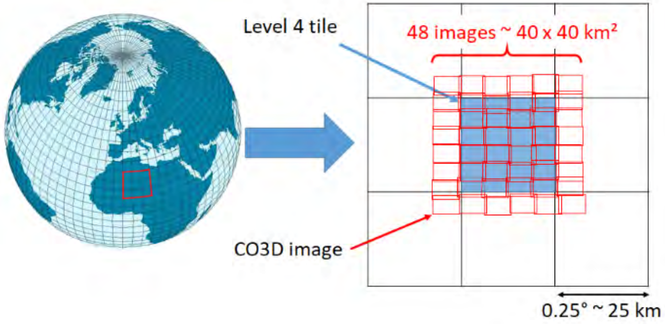
CO3D Ground Segment

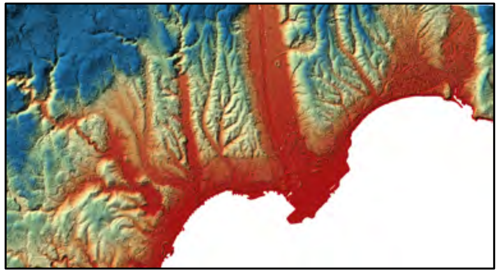


CO3D System Products



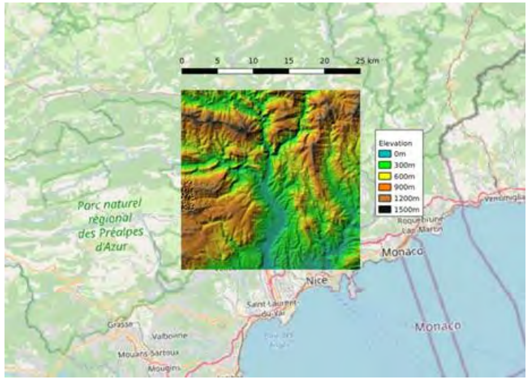
Perfect Sensor geometry





3D products

- Multi-resolution DSM : 1m, 4m, 12m, 15m, 30m *(respecting DGED format)* ***opendata***
- Level 3 : Local area (< 0.5°x 0.5°) **dated** DSM
- Level 4 : 0.25° x 0.25° tile world coverage
- Many quality and data masks



Ortho-images

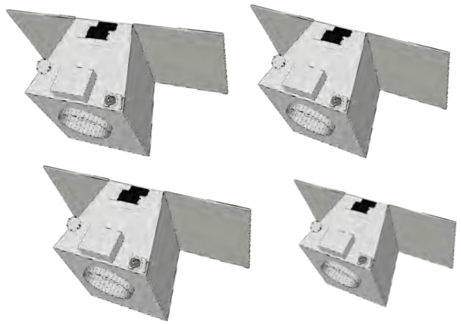
- 50 cm resolution
- Temporal and geometrical coherency with 3D data

Synthesis

Worldwide DEM (goal 2025)

1 m relative altimetric accuracy

Low-cost
full-automatic
3D products



A new generation of low-cost EO satellite

Thank you for your attention !

Contact:
Laurent Lebègue – CNES Toulouse
E-mail : laurent.lebegue@cnes.fr

Introducing WorldView Legion

Unprecedented visibility into our changing planet

Fabio Pacifici

Fellow Scientist
Research and Development

MAXAR

WorldView Legion is the cornerstone of our future constellation

IKONOS	QuickBird	WorldView-4	WorldView-1	GeoEye-1	WorldView-2	WorldView-3	WorldView Legion
82 cm resolution	65 cm resolution	31 cm resolution	50 cm resolution	41 cm resolution	46 cm resolution	31 cm resolution	29-34 cm resolution
9.0 m CE90	23 m CE90	5.0 m CE90	5.0 m CE90	5.0 m CE90	5.0 m CE90	5.0 m CE90	< 5 m CE90
6.0 m RMSE	10.6 m RMSE	3.7 m RMSE	3.0 m RMSE	2.7 m RMSE	3.0 m RMSE	2.5 m RMSE	Launching 2021

Available in archive (IKONOS, QuickBird, WorldView-4)

Currently imaging in orbit (WorldView-1, GeoEye-1, WorldView-2, WorldView-3)

6x constellation (WorldView Legion)

MAXAR

Our next-generation satellites

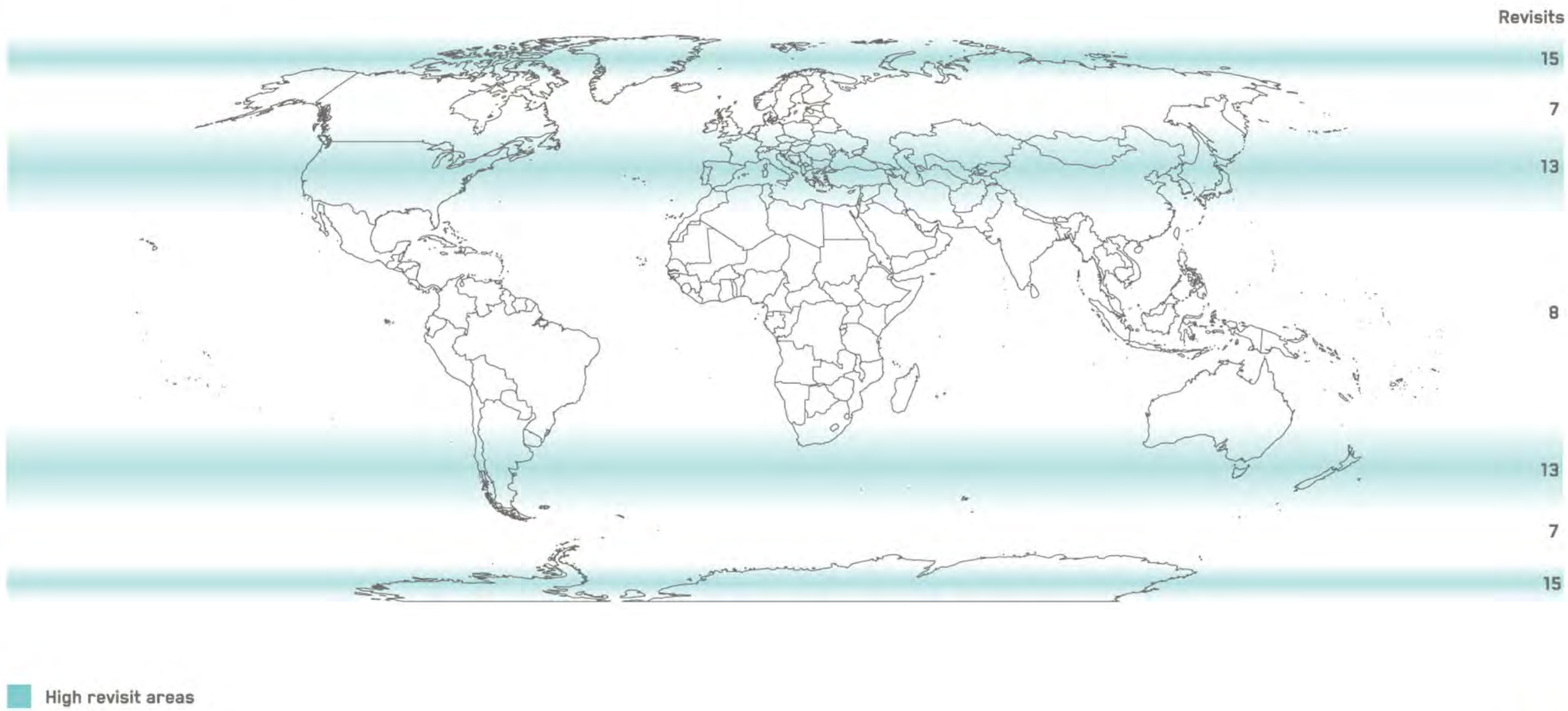
WorldView Legion is a fleet of six high-performing satellites that expands our ability to revisit the most rapidly changing areas on Earth to better inform critical, time-sensitive decisions.

- Launches in 2021
- Will enable up to 15 revisits per day
- Triples Maxar capacity to collect 30 cm imagery
- Triples our overall capacity over high-demand areas
- Highest image quality and geometric accuracy available
- Simultaneous tasking, image and downlink with customer ground stations

Satellite design and specifications

	Launch 1	Launch 2
Number satellites	2	4
Orbit	SSO	MIO
Resolution **Panchromatic** **8-band multispectral** **NIIRS rating**	 29 cm 1.16 m 5.9	 34 cm 1.36 m 5.7
launch window	Q1 2021	Q3 2021
Life	Expected service life: 10 years	
Spacecraft size and mass	Size: 3 m tall x 2 m x 2 m (not including width of solar array) Wet mass: < 750 kg	
Sensor bands	Panchromatic: 450-800 nm 8 multispectral Coastal: Blue: 400-450 nm Blue: 400-510 nm Green: 510-580 nm Yellow: 585-612 nm Red: 630-690 nm Red Edge 1: 695-715 nm Red Edge 2: 730-750 nm Near-IR: 770-895 nm	
Swath width	At nadir: 9 km	
Geolocation accuracy (CE90)	< 5 m CE90 without ground control points	

Enabling up to 15 revisits per day



MAXAR

High revisit over densest populations on Earth

7.1 billion people in MIO range | 93% of the world's population

Extent of MIO coverage

Legion provides within the MIO band*

10% more capacity

70% more color capacity

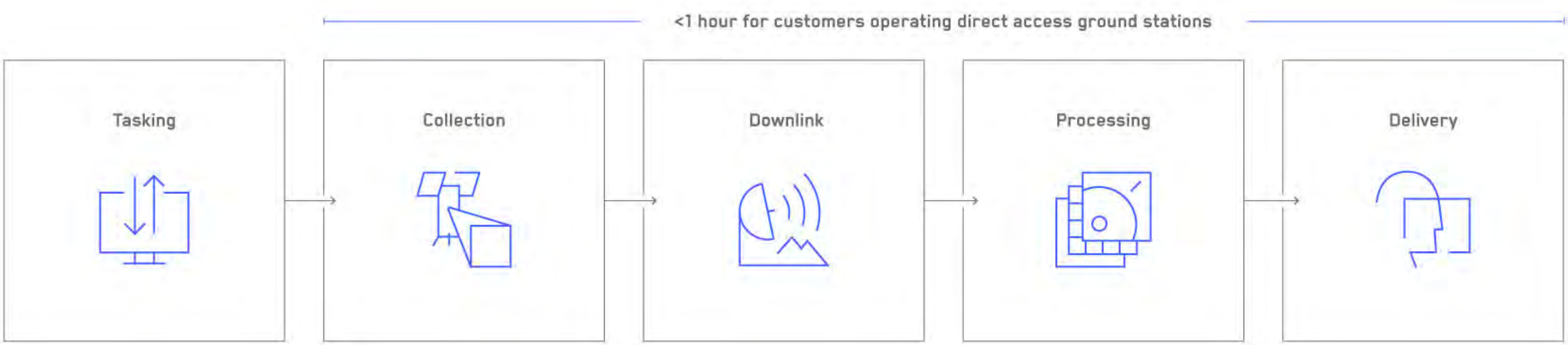
450% more 30 cm capacity

75% more point collection capability

*As compared to the GeoEye-1, WorldView-1, WorldView-2 and WorldView-3 Constellation

Low latency matters for an intelligence advantage

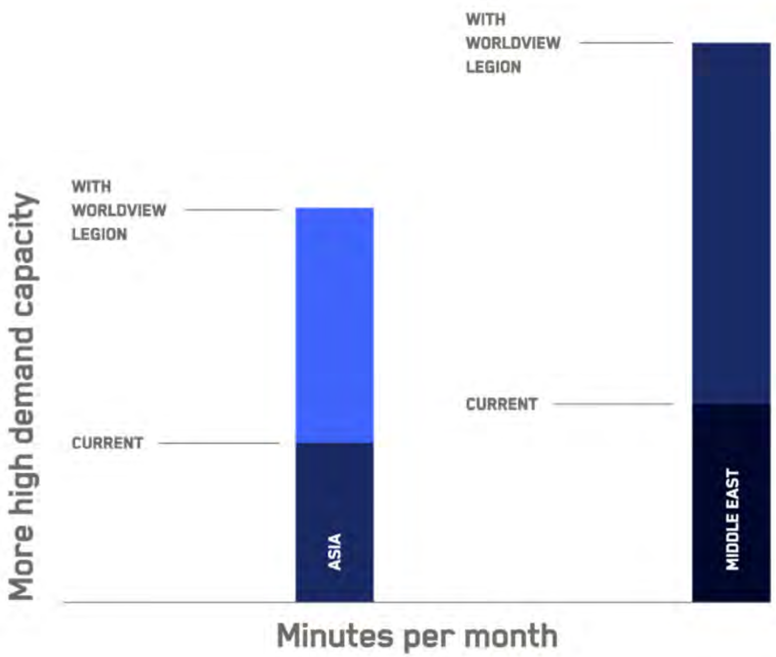
Reducing the time between collection and delivery makes intelligence more actionable.

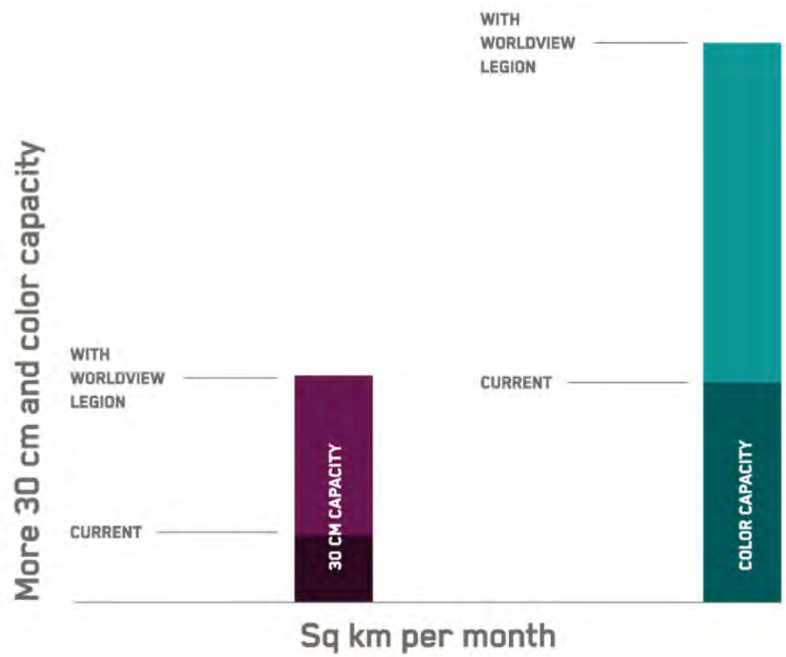


Capacity availability pre/post launch

ENTIRE CONSTELLATION CAPACITY PER DAY WITH WORLDVIEW LEGION
3.7 Million sq km/day → 5.9 Million sq km/day

30 CM CAPACITY PER DAY WITH WORLDVIEW LEGION
680K sq km/day → 2.8 Million sq km/day





Why Quality Matters

Native resolution matters for detailed insight

Legion class

1.5 m GSD
NIIRS 3.4

1.0 m GSD
NIIRS 4.0

0.5 m GSD
NIIRS 5.0

0.3 m GSD
NIIRS 5.7

Spectral richness matters for seeing hidden details

Monitoring throughout the day

Increased collection opportunities over areas of high interest, unlocking monitoring and change-detection capabilities.

Geolocation accuracy matters for precision mapping

- 5 M ACCURACY
- 20 M ACCURACY
- 100 M ACCURACY

MAXAR

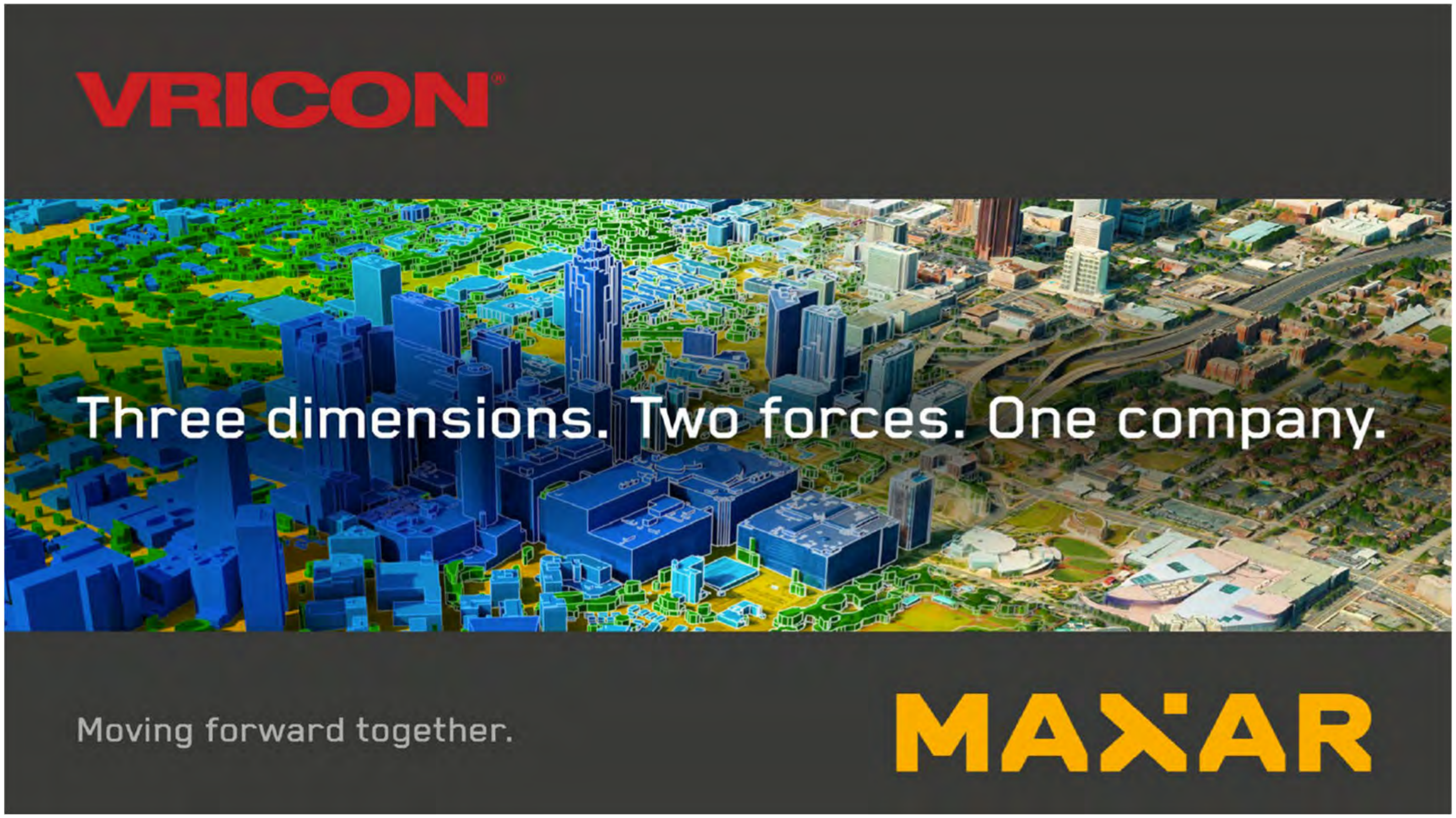
High agility matters for challenging collections

WorldView Legion will dramatically slew to collect the maximum number of images and at the most extreme angles.

The Earth in 3D

The Earth in 3D

WorldView Legion's agility and stereo capabilities will substantially increase our ability to model the Earth in 3D.



The Earth in 3D

WorldView Legion's agility and stereo capabilities will substantially increase our ability to model the Earth in 3D.

https://www.youtube.com/c/Vricon/videos

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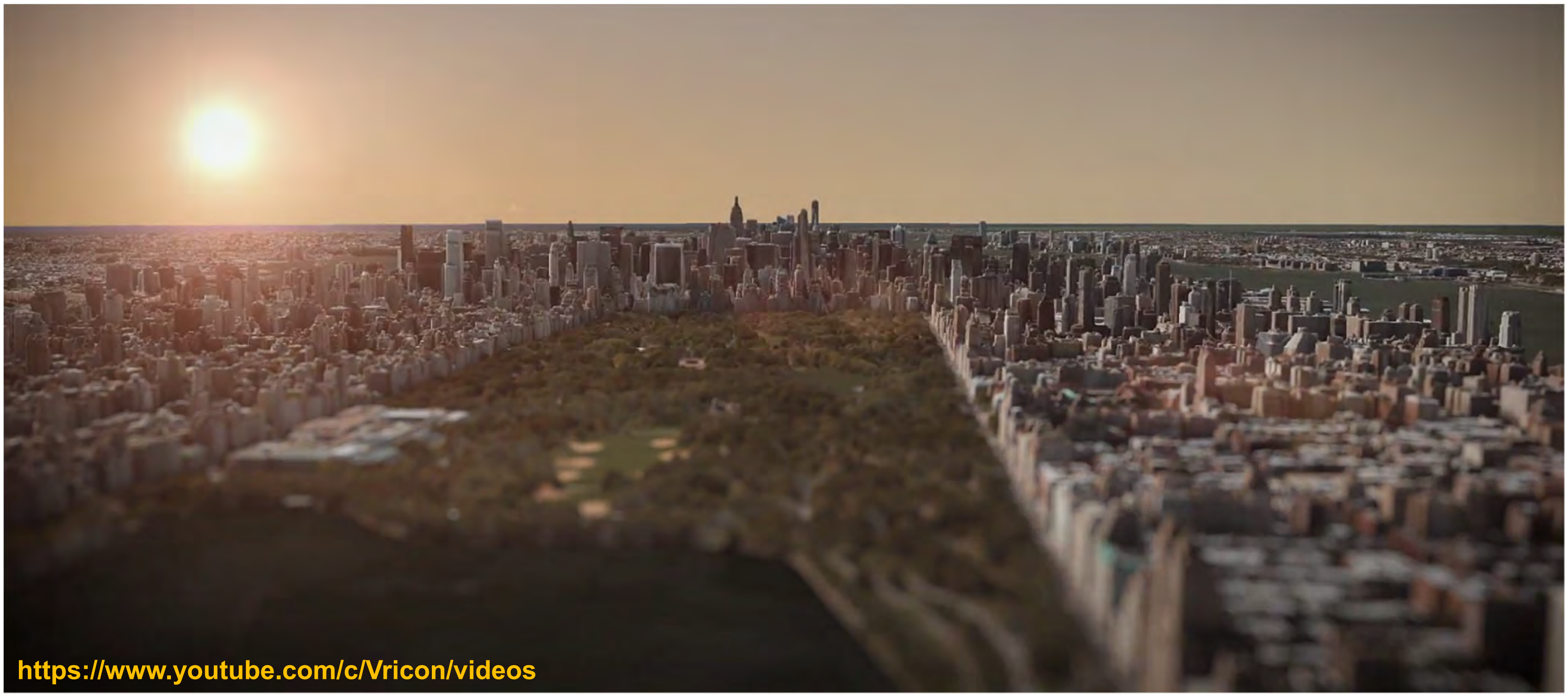


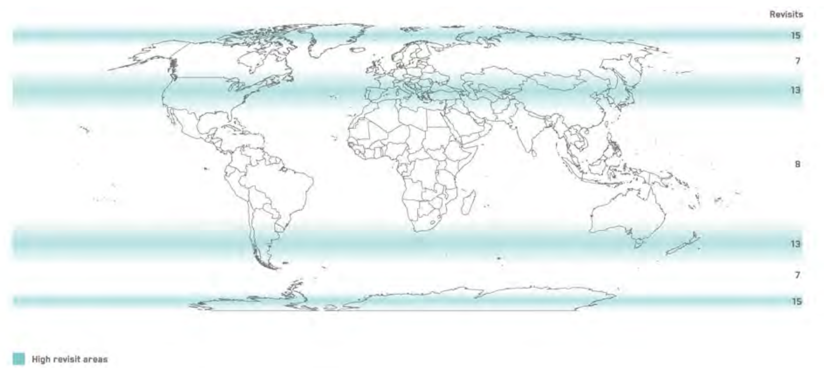
WorldView Legion Satellites

Maxar

Objectives

- In 2021, Maxar will launch WorldView Legion, providing up to 15 revisits per day:
  - 6 satellites
  - 29-34 cm resolution
  - <5 m CE90 accuracy
  - 8 spectral bands
  - 2 million sq km per day capacity
- WorldView Legion's agility and stereo capabilities will substantially increase our ability to model the Earth in 3D.
- https://www.maxar.com/splash/worldview-legion

Graphics that convey the key aspects of the technology development



Approach

- WorldView Legion offers more frequent monitoring for enhanced support of emergency response, maritime surveillance, infrastructure and other remote monitoring needs.
- The revisit rate of WorldView Legion enables more real-time, actionable analysis to deliver insights into rapid change faster.
- With increased capacity and revisit, Maxar will be able to more quickly and accurately generate a 3D skin of the Earth and regenerate that skin at the speed of change.

Technical Readiness Level

- WorldView Legion satellites
  - TRL8
  - Launch in 2021
- The Earth in 3D
  - TRL 9
  - Software fully operational

Thank you!

WorldView stereo data provide robust DSMs for estimating boreal forest structure and AGB

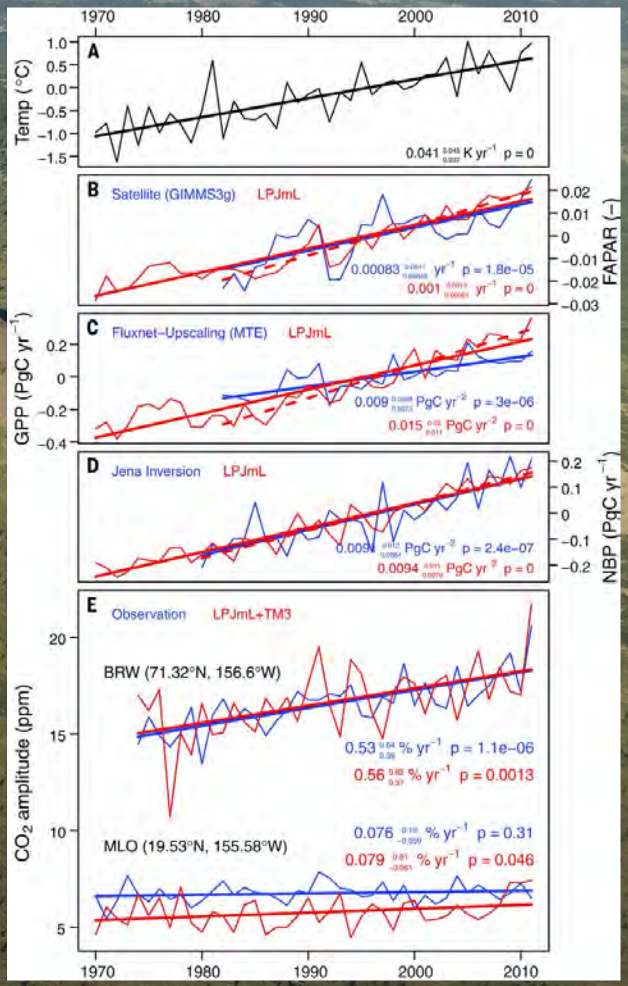
Christopher S.R. Neigh NASA GSFC Biospheric Sciences Laboratory

Co-I's/Collaborators: Montesano P., Wooten M., Wagner W., Poulter B., Calle L., Carvalhais N., Sexton J., Wang P., Feng M., Forkel M., Channan S. + many others

NASA ROSES Projects: PI CCS 2016, PI AIST 2017, PI cad4nasa.gsfc.nasa.gov (CSDAP)

STV Stereo Breakout 9/9/20

Matthias Forkel et al. Science 2016;351:696-699



A brief review of our vegetation studies using commercial stereo data with general questions:

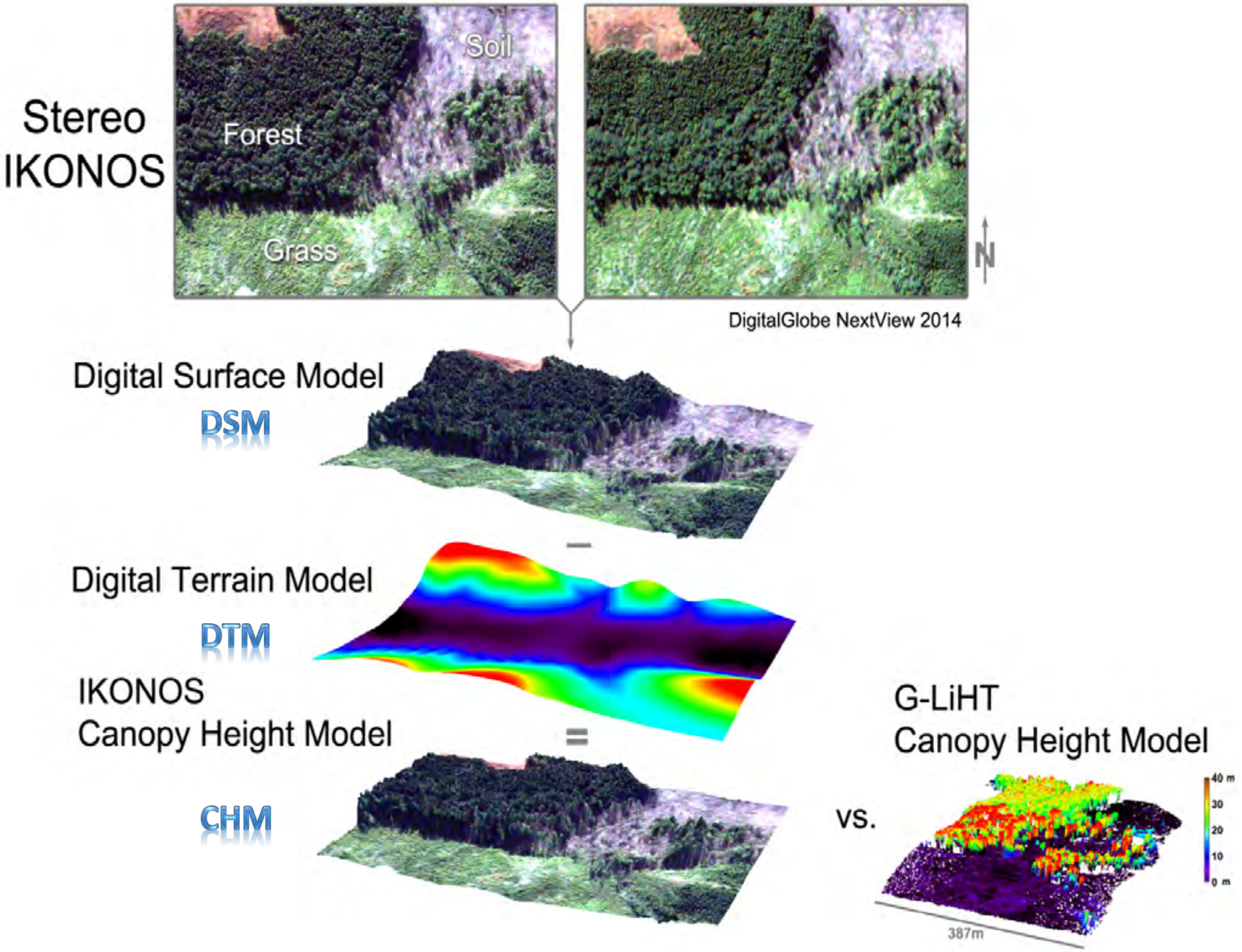
- How good are stereo WV canopy height estimates for boreal forests?
- What amount of structural detail does stereo VHR provide under different acquisition parameters, canopy cover, density, etc.?
- What is the variance of height-growth rate between disturbed forest patches?
- What is driving the relationship of Northern Hemisphere CO_2/GPP amplification?

Disturbance – Forest Age Composition – Site Index

Photo by C.S.R. Neigh
Kotuy River Expedition, Krasnoyarsk Russia 7/2016

Prior work: CONUS Forest Canopy Heights, Stereo IKONOS vs. G-LiHT

Neigh *et al.* 2014 *remote sensing*
Neigh et al. 2016 *Remote Sensing of Environment*



Early comparison work found ~2 m RMSE in CONUS using manual processing (ENVI DEM extraction module).

Technology and Data Policy Advances

1 — ~2008

Open US Gov. access to DG sub-m data
Neigh et al. 2013 . EOS trans.

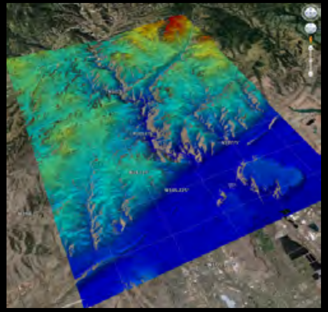
USGS opens Landsat archive

2011 - NASA GSFC begins acquiring data
http://cad4nasa.gsfc.nasa.gov

2 — ~2012

AMES stereo pipeline
Originally developed for
1997 Mars Pathfinder mission
used for intelligent robotics navigation

Open-source released for DG data
http://irg.arc.nasa.gov/ngt
Shean *et al.* 2016 *ISPRS J. Photogrammetry and Remote Sensing*



3 — ~2014

GSFC ADAPT Cluster
Originally developed for
Discover supercomputer for
climate simulation.

No cost access granted to
NASA funded scientists
http://nccs.nasa.gov


Advanced Data Analytics Platform (ADAPT)

WorldView Stereo DSMs across the boreal domain

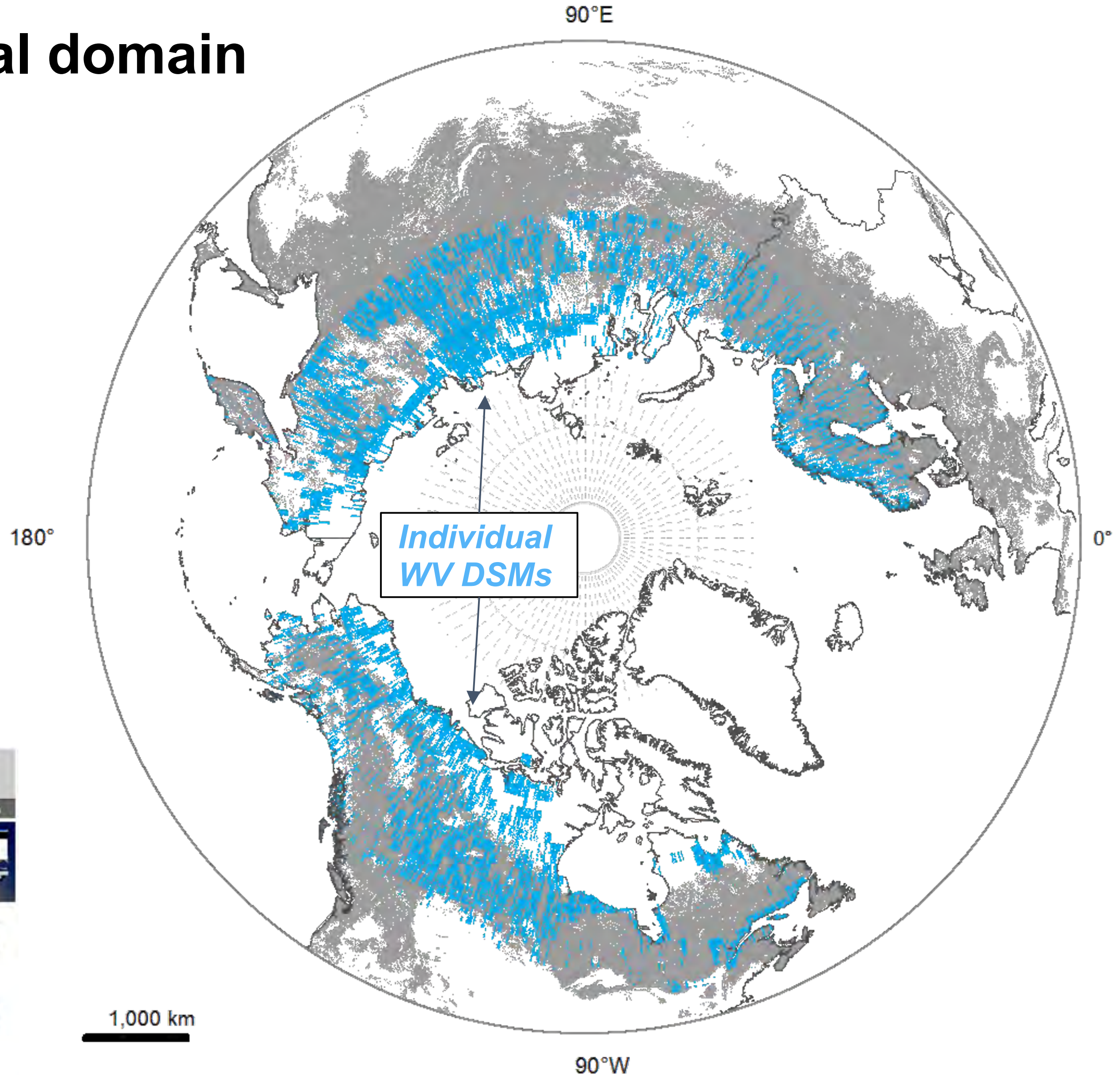
Forest height is approximated by estimating forest vertical structure signals in HRSI DSMs

- Maxar; primarily Worldview-1,2,3
- Each DSM covers ~2000 km^2 with 1m spatial resolution.
- Dense archive of WV stereo >60° N

Using HPC clusters:

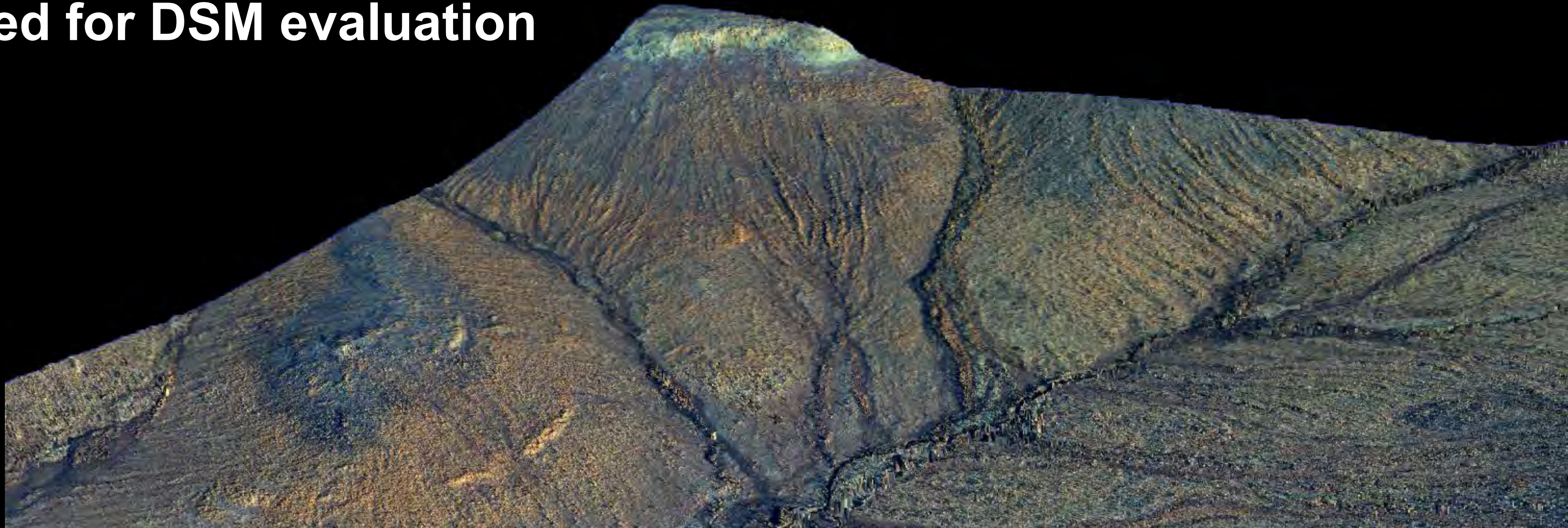
- Thousands of individual DSMs have been processed in the boreal.
- Billions of individual pixels.


Discover HPC + ASP ¼ petabyte of DSMs

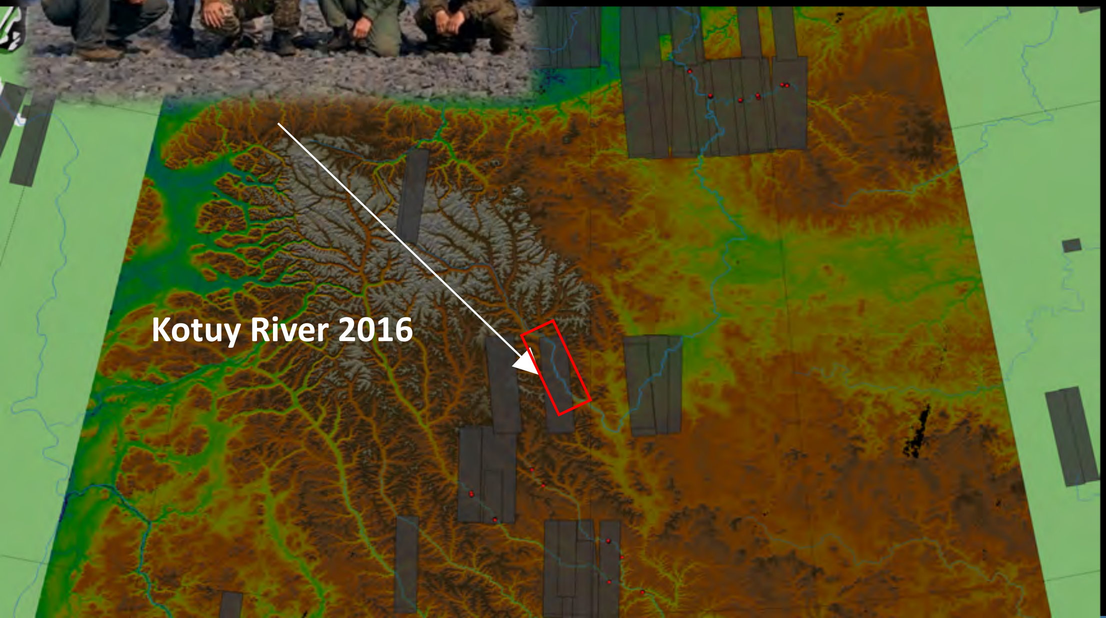


Katoy River Expedition Siberia 7/2016

Siberia field data used for DSM evaluation



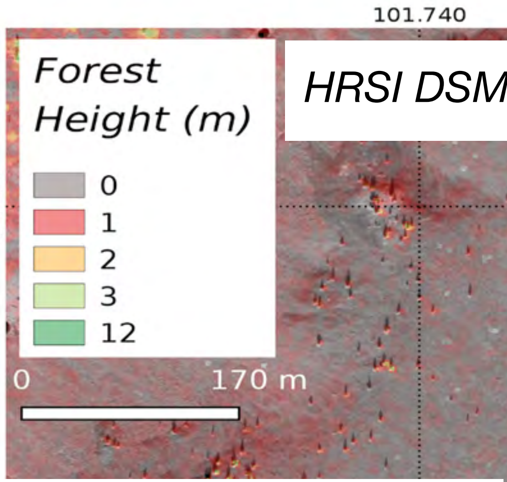
WorldView-1 DTM and WorldView-2 pan sharpened 0.5 m in true color Sept 9 2011, shown in 3D near the Kotuy River Siberia © Maxar NextView 2011

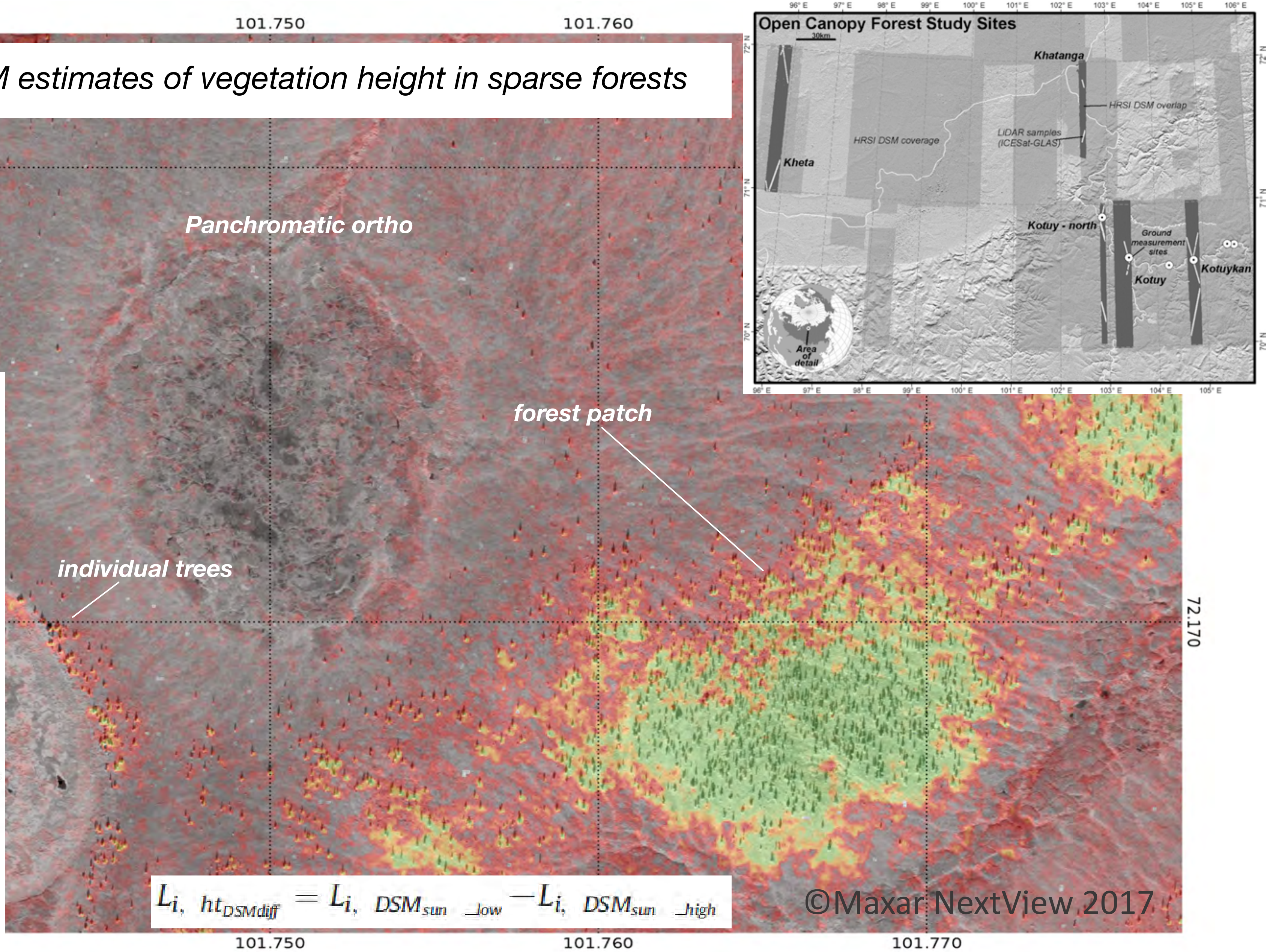


2016 Field Data – 68 Plots
30 m radius plots @ GLAS pulse centroid
DBH – All trees > 3 cm
Health – Healthy/Intermediate/Dying/Dead
Canopy Height – Lasers 30+ dominant trees, top & first live branch
Canopy – Size m
Dendro – Cores of 5 dominant trees, burn history
Permafrost depth – cm 5+ samples
GPS Photo – 360° Panoramic

Overlapping WV DSM estimates of vegetation height – Open Canopy – low vs. high sun angles

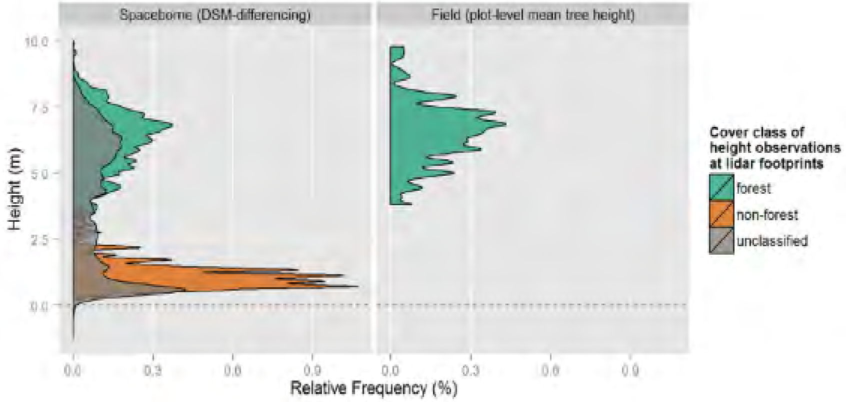
2017 Montesano, P., Neigh, C.S.R., Sun, G., Duncanson, L.I., Van Den Hoek, J., & Ranson, J. The use of sun elevation angle for stereogrammetric boreal forest height in open canopies. *Remote Sensing of Environment, 196*, 76-88. 10.1016/j.rse.2017.04.024





$$L_{i,\ ht_{DSMdiff}} = L_{i,\ DSM_{sun\_low}} - L_{i,\ DSM_{sun\_high}}$$

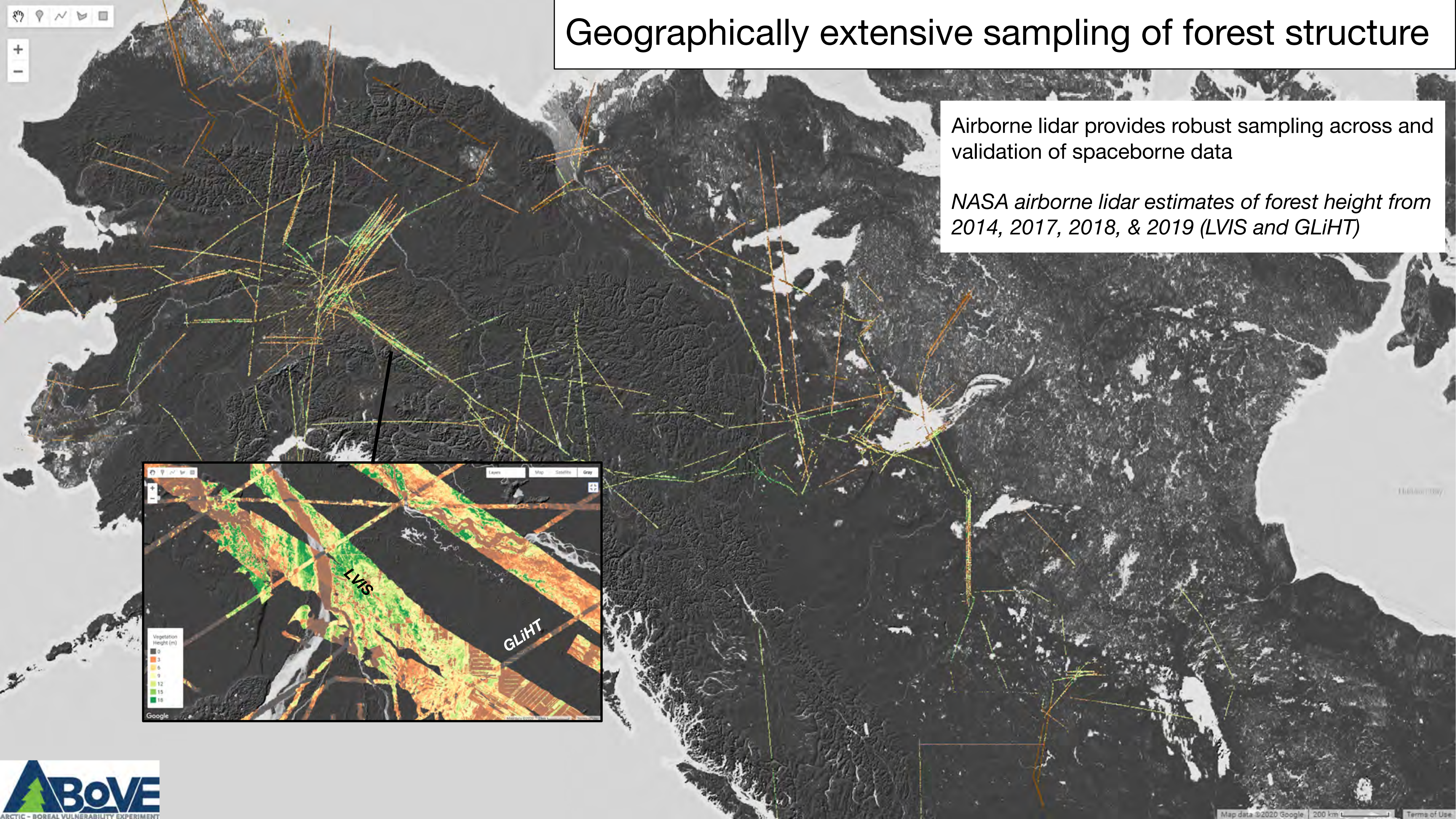
- Snow free conditions Siberian *Larix* forests with slopes < 10°
- High-sun more closely associated to ground from ICESat-1 GLAS (RMSEs < 0.68 m)
- Low-sun DSMs (μ = 6.0m, σ = 1.4m) more closely associated to open canopy mean height field plots (μ = 6.5m, σ = 1.2m)



Geographically extensive sampling of forest structure

Airborne lidar provides robust sampling across and validation of spaceborne data

NASA airborne lidar estimates of forest height from 2014, 2017, 2018, & 2019 (LVIS and GLiHT)



ABoVE
ARCTIC - BOREAL VULNERABILITY EXPERIMENT

Which WV stereo data are most effective at estimating boreal forest height? – Closed Canopy –

P.M. Montesano, C.S.R. Neigh, W. Wagner, M. Wooten, & B.D. Cook (Feb 2019) Boreal canopy surfaces from spaceborne stereogrammetry, *RSE*, 225, 148-159. [10.1016/j.rse.2019.02.012](https://doi.org/10.1016/j.rse.2019.02.012)

In the Tanana Valley AK:

1) DSMs grouped by sun elevation angle (low <30° vs. high >30°)
2) Varying canopy closure (20% bins of Landsat Tree Canopy Cover)
3) Snow presence/absence
4) Stereo Algorithm (ASP and SETSM)

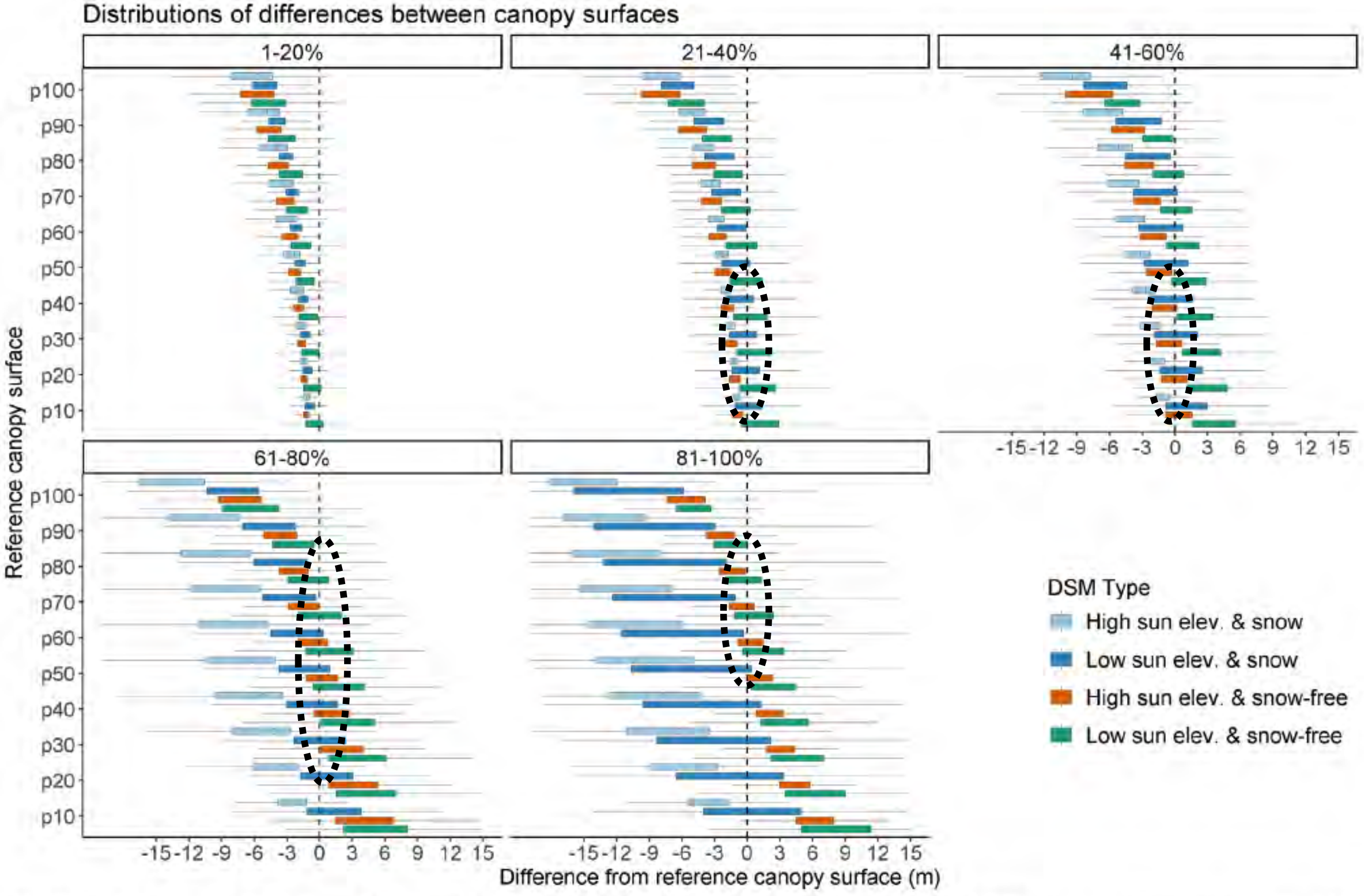
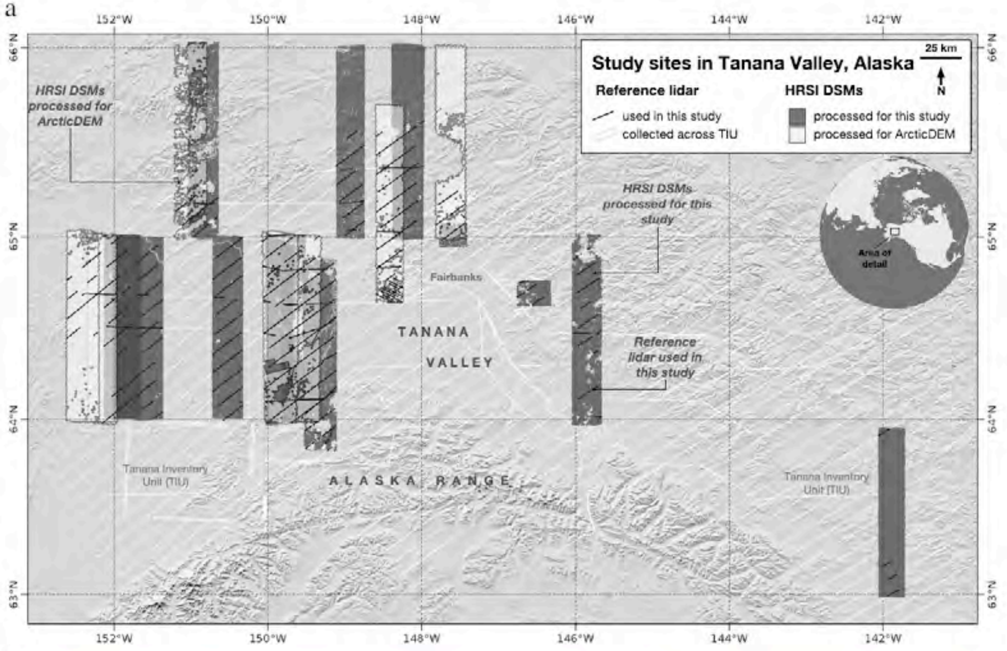


Fig. 3. Boxplots show the distributions of differences between HRSI DSMs and reference canopy surfaces for each DSM type across 5 canopy cover intervals.

a



b

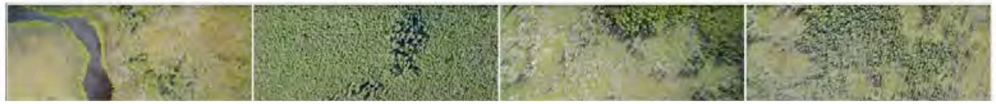


Table 1
List of HRSI DSMs from which observations of canopy surfaces were compared with those from reference lidar in the TIU. The number of observations are summarized by canopy cover interval, and the total is tallied for each DSM.

DSM type	Sensor	Acquisition date (m/d/yyyy)	# of DSM observations per reference canopy cover interval (%)					Total # of observations per DSM
			1–20	21–40	41–60	61–80	81–100	
High sun elev. & snow	WV-1	4/10/2013	959	98	809	156	1010	3032
	WV-1	4/16/2013	71,314	3744	2444	3490	12,604	93,596
	WV-2	4/6/2016	17,468	5136	924	2902	3438	29,868
High sun elev. & snow-free	WV-2	7/21/2015	27,020	4542	2910	3878	6662	45,012
	WV-1	8/15/2012	31,180	1974	1313	1205	2717	38,389
	WV-1	8/8/2014	22,189	1364	441	492	12,535	37,021
	WV-1	6/17/2016	24,065	1885	554	634	4846	31,984
	WV-2	5/22/2015	3317	197	103	112	639	4368
	WV-2	6/23/2016	13,116	1709	909	1206	2781	19,721
	WV-3	6/18/2016	7978	217	115	59	38	8407
Low sun elev. & snow	WV-1	3/31/2015	29,453	1909	181	137	1673	33,353
	WV-1	4/15/2016	12,558	2325	592	329	857	16,661
	WV-2	1/28/2013	28,736	3502	1456	1076	6150	40,920
	WV-2	2/27/2014	13,999	688	129	46	1606	16,468
	WV-3	2/13/2015	17,578	858	125	273	5267	24,101
Low sun elev. & snow-free	WV-1	6/13/2013	58,886	6368	2422	2306	17,432	87,414
	WV-1	6/17/2013	4226	2775	451	181	650	8283
	WV-2	6/9/2015	10,695	2131	1224	1512	6070	21,632
	WV-2	7/11/2015	2206	308	597	352	800	4263
	WV-2	6/30/2016	926	200	40	30	232	1428

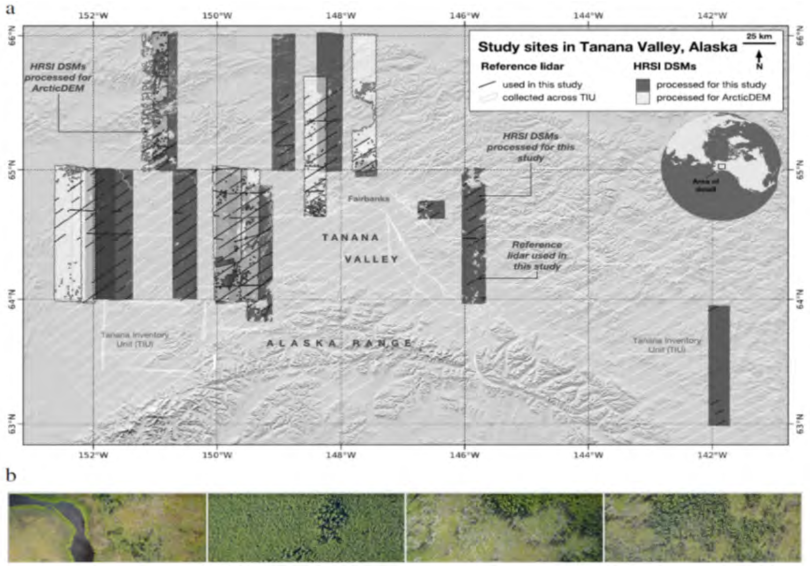
DSMs derived from WV stereo provide robust estimates of boreal canopy height

PI Neigh C.S.R. NASA - GSFC

Objectives

Science Question –

Can commercial stereo data be used for estimating boreal forest canopy height in different forest cover densities, seasons and view angles?



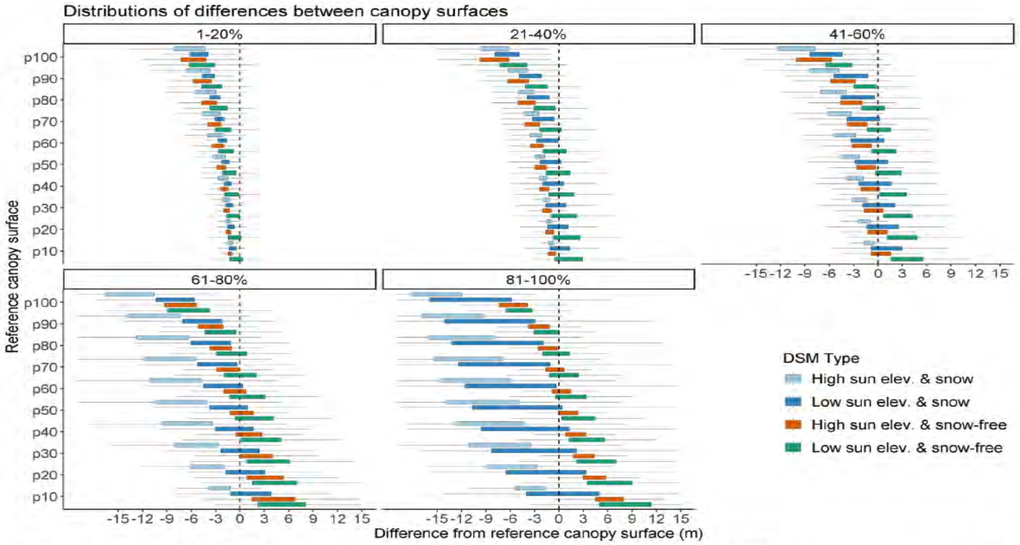


Fig. 3. Boxplots show the distributions of differences between HRSI DSMs and reference canopy surfaces for each DSM type across 5 canopy cover intervals.

Approach

- NASA's Ames Stereo pipeline was used to process stereo WV-1,2,3 (0.3 – 0.5 m) in Alaska where 1 m small footprint LiDAR (GLiHT) data were available.
- 13x13m surfaces from GLiHT and 20 WV1,2,3 stereo strips are compared with varying canopy cover, sun angle, and seasonality.

Citations

P.M. Montesano, C.S.R. Neigh, W. Wagner, M. Wooten, & B.D. Cook (Feb 2019) Boreal canopy surfaces from spaceborne stereogrammetry, *RSE*, 225, 148-159. [10.1016/j.rse.2019.02.012](https://doi.org/10.1016/j.rse.2019.02.012)

Co-Is/Partners

Neigh C.S.R., Montesano P., Wagner W., Wooten M., Cook B.

Results

- Low sun elev. And snow free conditions provide the most representative 70 – 80th percentile heights in dense forest cover > 60%, with a median difference of 0.24 m

Challenges

- Limited number of stereo obs. H/L sun angle & snow free at high latitudes
- Limited capacity for fed/civ stereo tasking
- Maxar has the largest archive of in-track stereo but global coverage still does not exist from 2007 WV-1 launch
- Other forest cover types need to be evaluated with 1 m LiDAR.

RF model to estimate above ground biomass for Norway >60°N

S. Puliti, M. Hauglin, J. Breidenbach, P. Montesano, C.S.R. Neigh, J. Rahlf, S. Solberg, F. Klingenberg, & R. Astrup (Jan 2020) Modeling above ground biomass stock over Norway using national forest inventory data with ArcticDEM and Sentinel-2 data, *RSE,* 236, 1-11. [10.1016/j.rse.2019.111501](10.1016/j.rse.2019.111501)

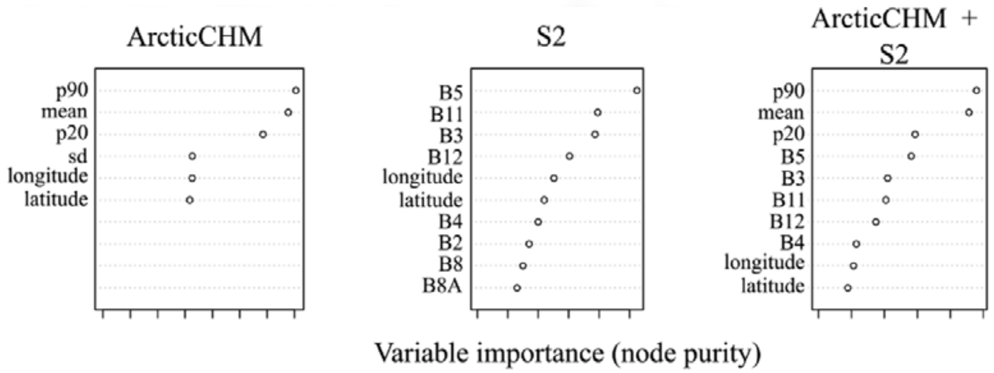
Detailed maps of predicted above ground biomass using different predictive models, column represents areas where the ArcticCHM is either:

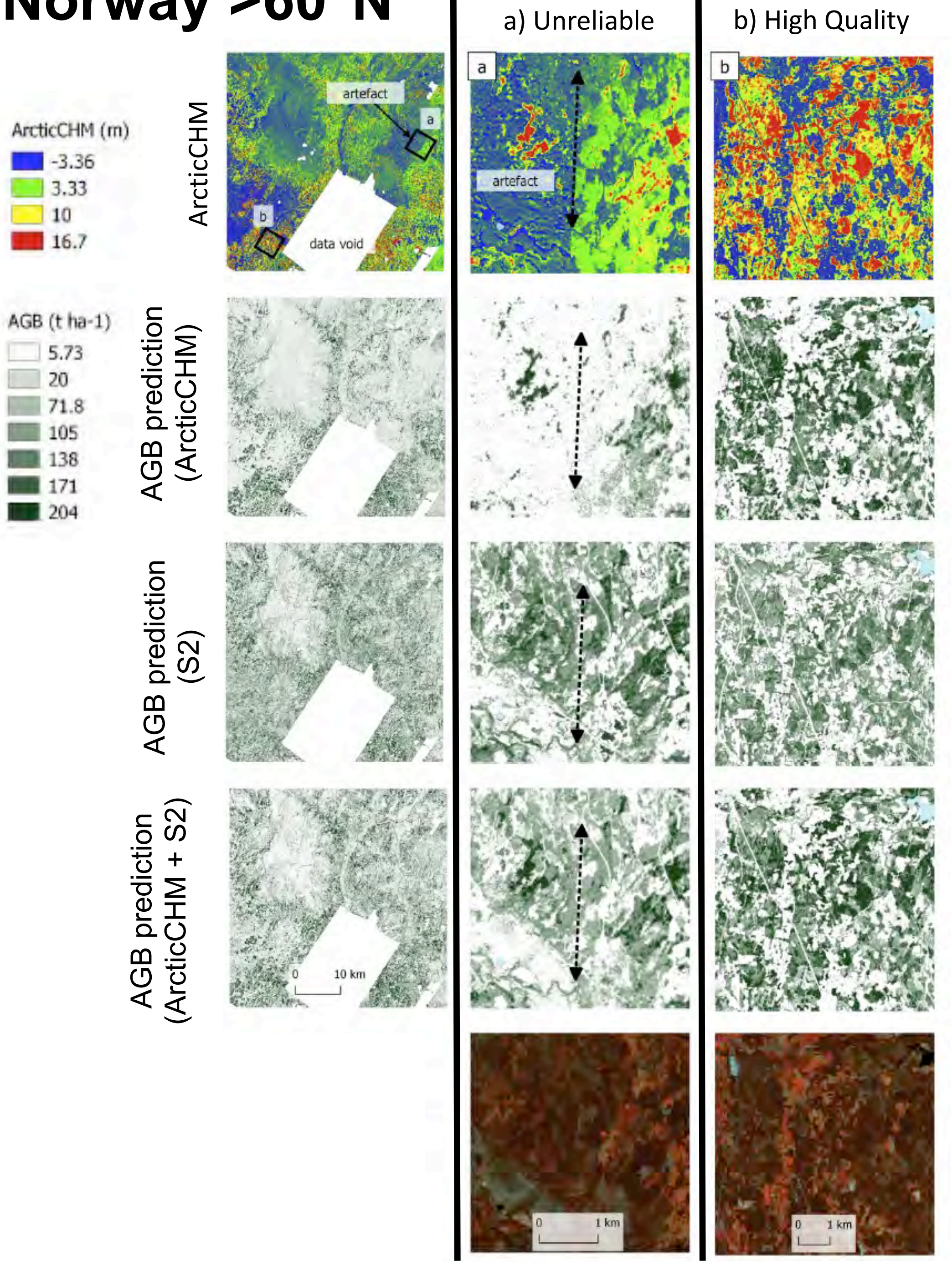
a) unreliable or

b) high quality with reference false color composites (lower images).

Summary diagnostics for the AGB models including the percentage of the variance explained (% var) by the model, root mean square error (RMSE), mean difference (MD), and their values as the percentage of the mean.

	% var	RMSE (t ha^{-1})	RMSE (%)	MD (t ha^{-1})	MD (%)
ArcticCHM	43	47.7	84.0	−0.9	−1.6
S2	47	45.8	80.7	−1.6	−2.8
ArcticCHM + S2	57	41.4	72.8	−1.4	−2.5





Very-high resolution stereo data provide robust estimates of boreal forest carbon stock

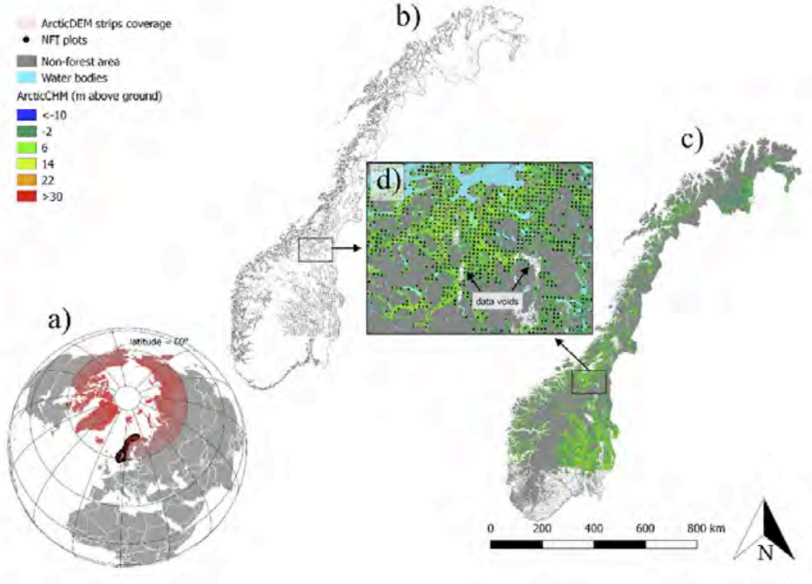
PI Neigh C.S.R. NASA - GSFC

Objectives

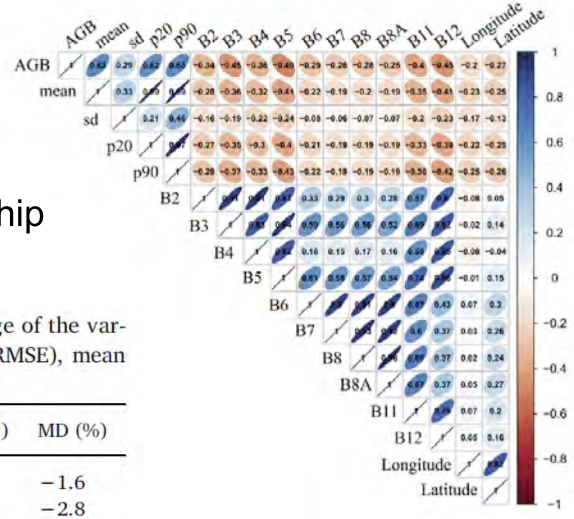
Science Question –

Is commercial stereo data a viable tool for estimating boreal forest carbon stock?

Can the ArctDEM be used to predict above ground biomass for all of Norway?



Correlation matrix for the studied response AGB and predictor variables. The ellipse direction indicates whether there is a positive or negative relationship and the color indicates p-value.



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ArcticCHM	43	47.7	84.0	−0.9	−1.6
S2	47	45.8	80.7	−1.6	−2.8
ArcticCHM + S2	57	41.4	72.8	−1.4	−2.5

Approach

- Arctic DEM was used in a machine learning approach with a LiDAR DTM, Sentinel-2 and forest inventory data to estimate boreal above ground forest carbon stock in Norway.

Citations

S. Puliti, M. Hauglin, J. Breidenbach, P. Montesano, C.S.R. Neigh, J. Rahlf, S. Solberg, F. Klingenberg, & R. Astrup (Jan 2020) Modeling above ground biomass stock over Norway using national forest inventory data with ArcticDEM and Sentinel-2 data, *RSE,* 236, 1-11. 10.1016/j.rse.2019.111501

Co-Is/Partners

Neigh C.S.R., Montesano P., Puliti S.

Results

- Combining these data in a machine learning model is a viable solution for mapping forest carbon stock across the boreal forest.
- First demonstrated use of combining fine-scale stereo data to estimate country scale AGB

Challenges

- Voids/Artifacts in ArcticDEM reduce model performance
- A wall-to-wall LiDAR DTM was available for Norway, many countries do not have this data available to produce a CHM from stereo DSMs.
- Other forest cover types need to be evaluated with this approach

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Photo by C.S.R. Neigh
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