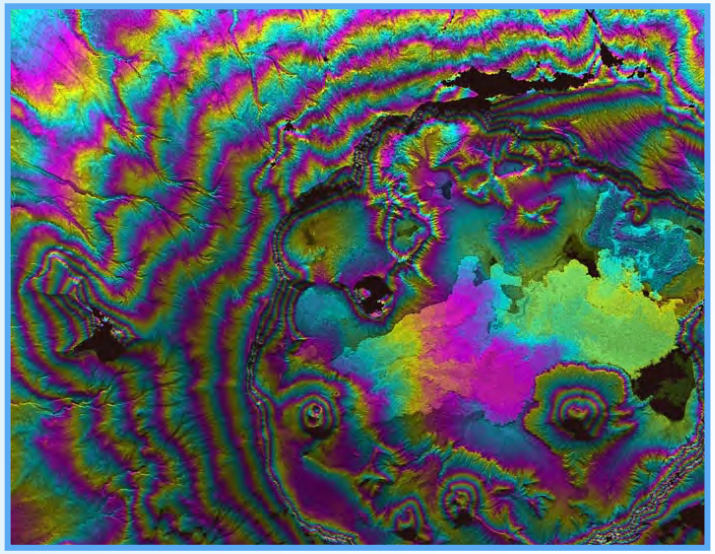
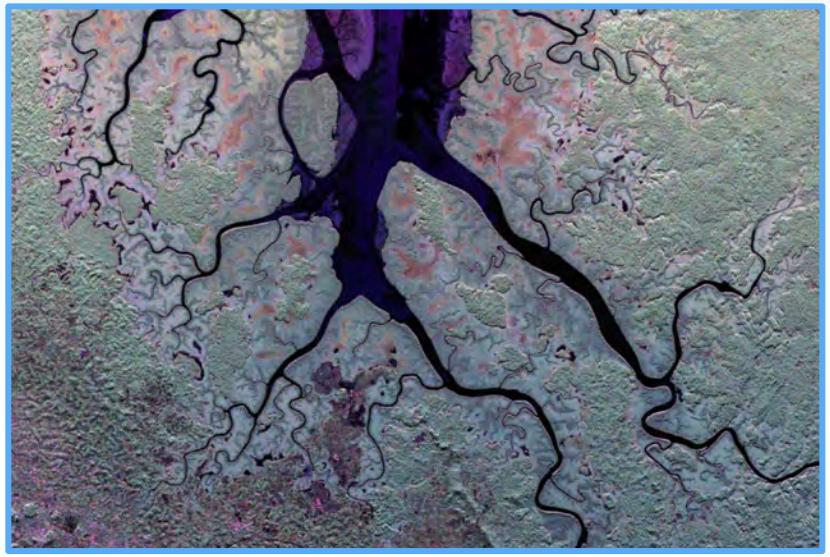
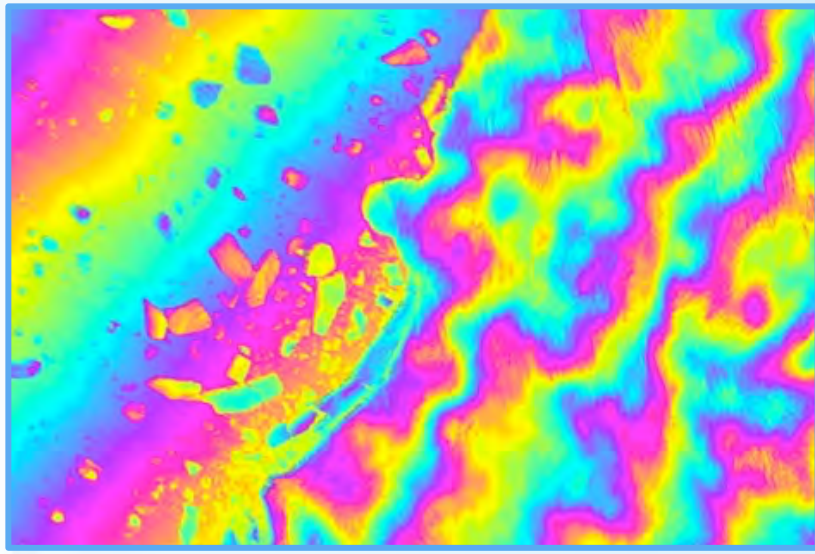




Synthetic Aperture Radar for STV Overview

Yunling Lou (Jet Propulsion Laboratory, California Institute of Technology)

Contributors: Batu Osmanoglu (GSFC)

Surface Topography and Vegetation Structure Incubation Study

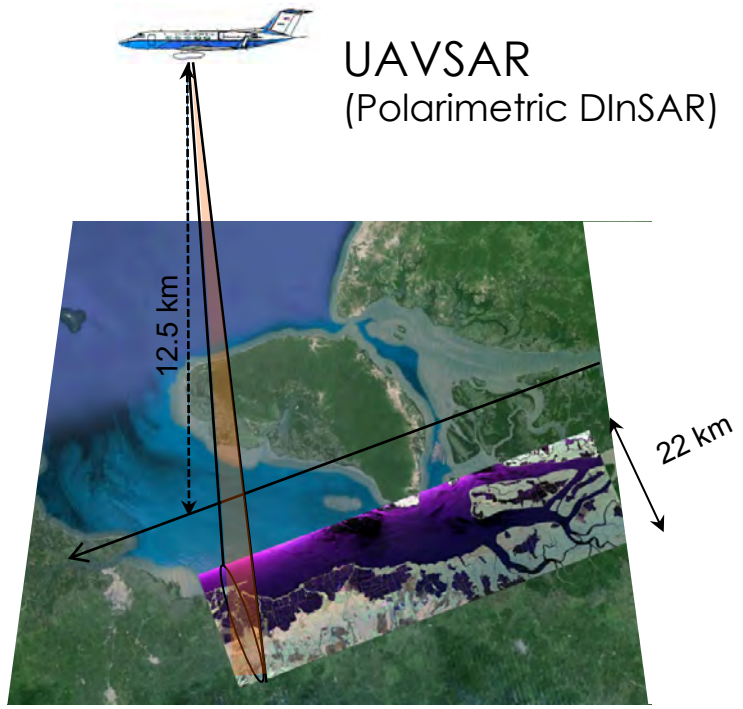
Radar Breakout Virtual Workshop • 10 September, 2020

Agenda

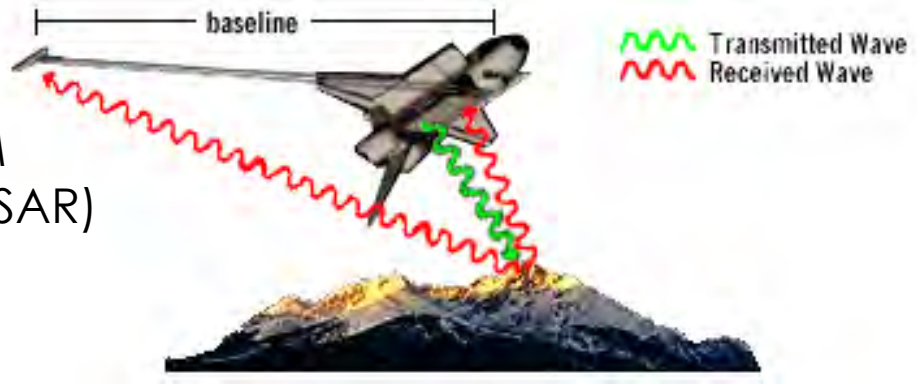
- SAR Introduction
- Airborne technologies
- Spaceflight technologies and missions
- Perceived gaps
- Discussion

Synthetic Aperture Radar Overview

- Radar's advantages: day/night imaging, ability to see through smoke and clouds, and wide coverage
- SAR is side-looking; it uses platform motion to synthesize a large antenna to improve along track resolution; along track resolution is independent of range!
- Single-pass interferometry (TopSAR) uses two antennas with appropriate cross-track separation to map topography
- Repeat-pass interferometry (DInSAR) uses repeat passes to detect line-of-sight ground motion between passes
- Polarimetry is used to study the geometrical structure and orientation of the scatterer

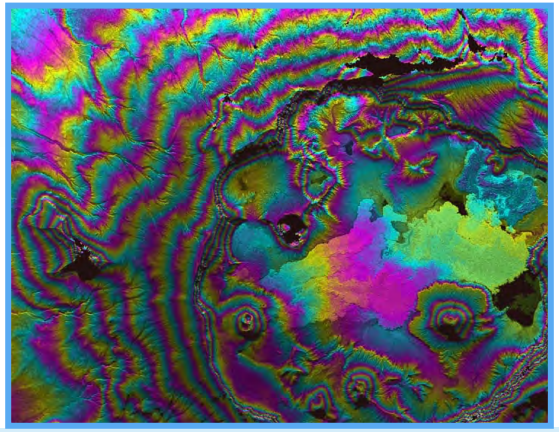


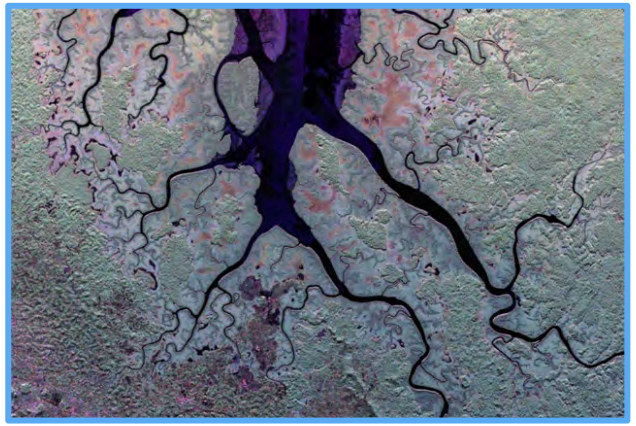
UAVSAR
(Polarimetric DInSAR)



SRTM
(TopSAR)

DEM of Okmok, Alaska



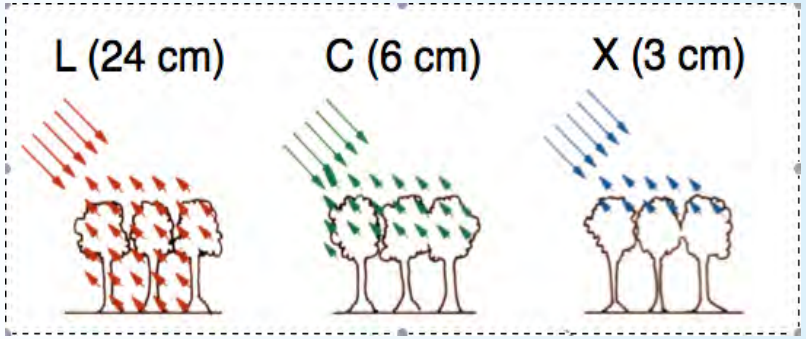


Pol. composite of Mondah Forest

SRTM used two antennas with cross-track baseline to map topography

Radar Bands of Interest

Band	P	L	S	X	Ka
Center Freq. (MHz)	430	1260	3200	9650	35750
Wavelength (cm)	70	24	9	3	0.8
Avail. Bandwidth (MHz)	6 (20 for airborne)	80	200	300	500
Nominal Resolution (m)	30 (10 for airborne)	3	1.2	0.8	0.5
Bare surface land topography	Yes	Yes	Yes	Yes	Yes
DTM under vegetation	Yes	Yes	No	No	No
Ice topography	No	No	No	Yes	Yes
Vegetation structure	Yes	Yes	Maybe	Maybe	No
Applications	Maybe*	Yes	Yes	Yes	Yes



Rosen, 2009

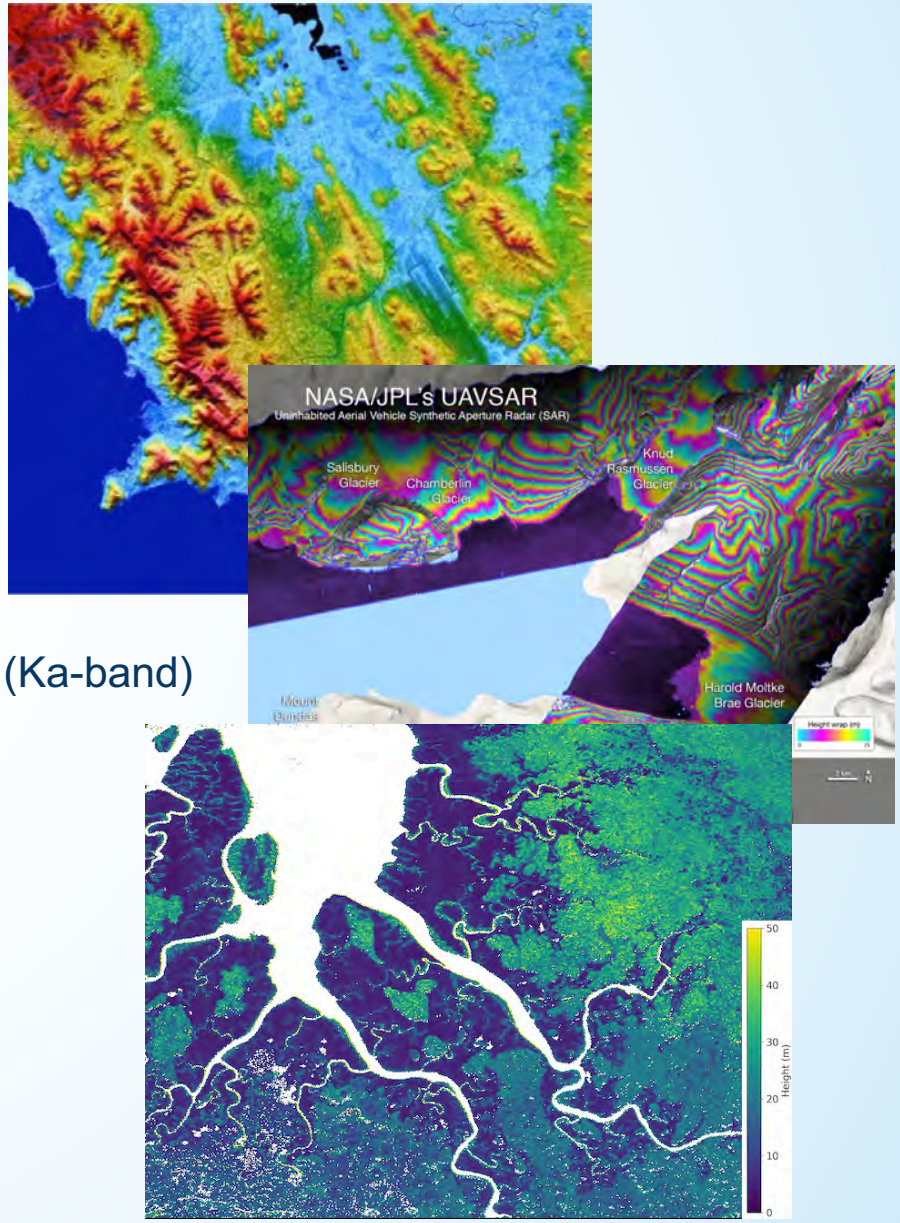
Microwave interacts most strongly with objects the size of the wavelength

Leaves reflect X-band wavelength but not L-band

* P-band's bandwidth limitation results in lower resolution imagery, which may reduce the utility of data for change detection applications

STV Research Areas: *Radar's Contribution*

- ✓ Bare-surface land topography
  - ➢ Low frequency InSAR and TomoSAR (L-band or lower?)
  - ➢ Spaceborne example: none
  - ➢ Airborne example: GeoSAR (P-band)
- ✓ Ice topography
  - ➢ High frequency InSAR (X-band or higher?)
  - ➢ Spaceborne example: TanDEM-X
  - ➢ Airborne examples: F-SAR and GeoSAR (X-band), GLISTIN-A (Ka-band)
- ✓ Vegetation structure
  - ➢ Low frequency TomoSAR (L-band or lower?)
  - ➢ Spaceborne examples: none
  - ➢ Airborne examples: F-SAR, SETHI, UAVSAR



Operational Airborne SAR Systems for STV

	Current		Future	
Instrument	Configurations	Capabilities	Configurations	Capabilities
UAVSAR (NASA)	P- & L-band polarimetric DInSAR, Ka-band HH TopSAR	Surface deformation change detection, vegetation structure, volcano topography, ice/snow topography	P/L/S-band polarimetric DInSAR, L/X-band pol. TopSAR, Ka-band HH TopSAR	Surface deformation change detection, vegetation structure, DTM and DSM, ice/snow topography
GeoSAR	P- & X-band TopSAR	DTM and DSM	N/A	N/A
Intermap	P-band PolSAR & X-band TopSAR	Sub-canopy feature mapping & DSM		

UAVSAR Overview

- NASA Earth Science Division's facility instrument suite; supporting ~500 flight hours of R&A requests per year
- Three radar bands (one per pod):
  - L-band polarimetric repeat-pass InSAR
  - P-band (AirMOSS) pol. repeat-pass InSAR
  - Ka-band (GLISTIN-A) single-pass InSAR
- Accommodation: pod-based radar mounted to bottom of G-III (AFRC and JSC)
  - G-III has precision autopilot to repeat tracks to within 5 m tube

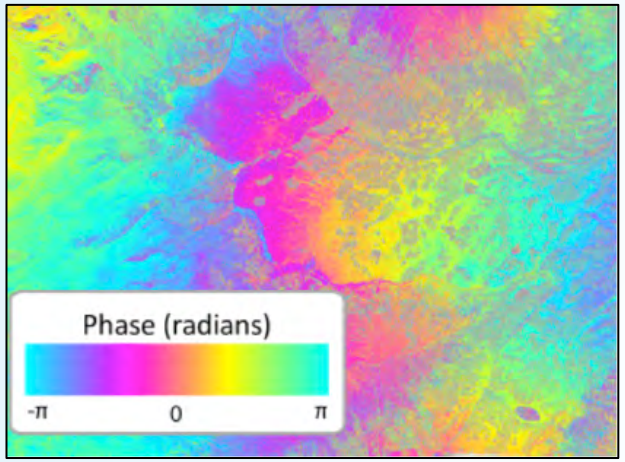
	P-band (AirMOSS)	L-band	Ka-band (GLISTIN-A)
Wavelength (cm)	70	24	0.8
Polarization	Quad-pol	Quad-pol	Horizontal
Peak Transmit Power (kW)	2.0	3.1	0.08
Maximum Duty Cycle	10%	8%	10%
Slant Range Resolution (m)	7	1.8	1.8
Azimuth Resolution (m)	0.8	0.8	0.25
Nominal Range Swath (km)	22	22	10
Noise Equivalent Sigma0 (dB)	< -40	< -50	TBD
Radiometric Accuracy (dB)	< 1 abs.	< 1 abs.	TBD
Height Precision (30x30 m posting)	N/A	N/A	0.1 – 0.5 m

JSC G-III

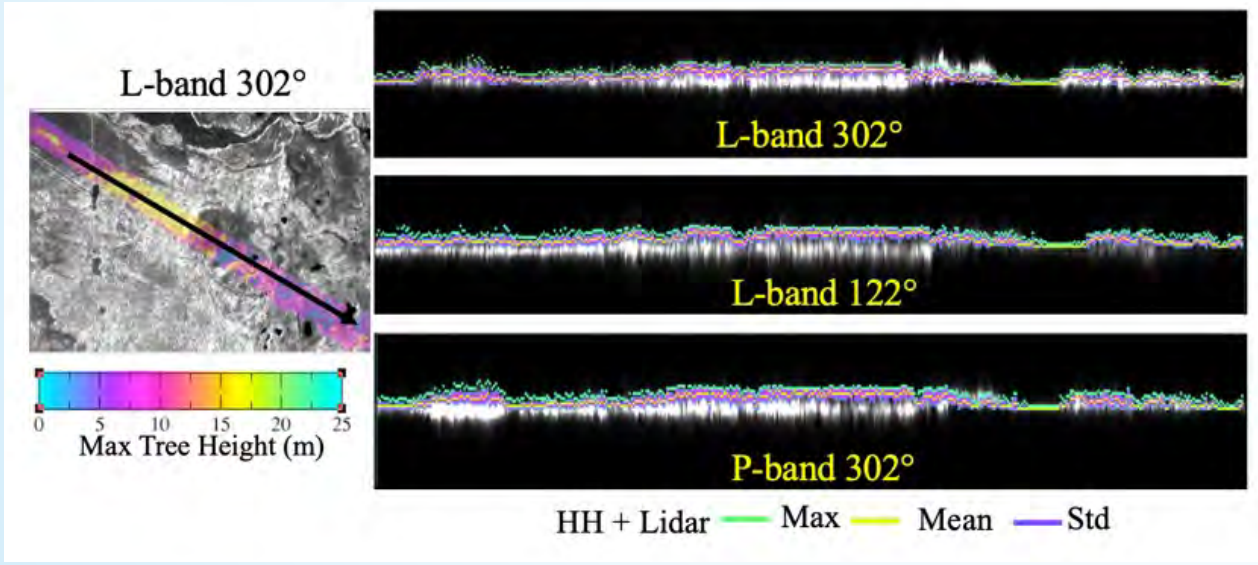
Non-pressurized pod with air inlets for cooling the radar electronics

AFRC G-III

UAVSAR Examples



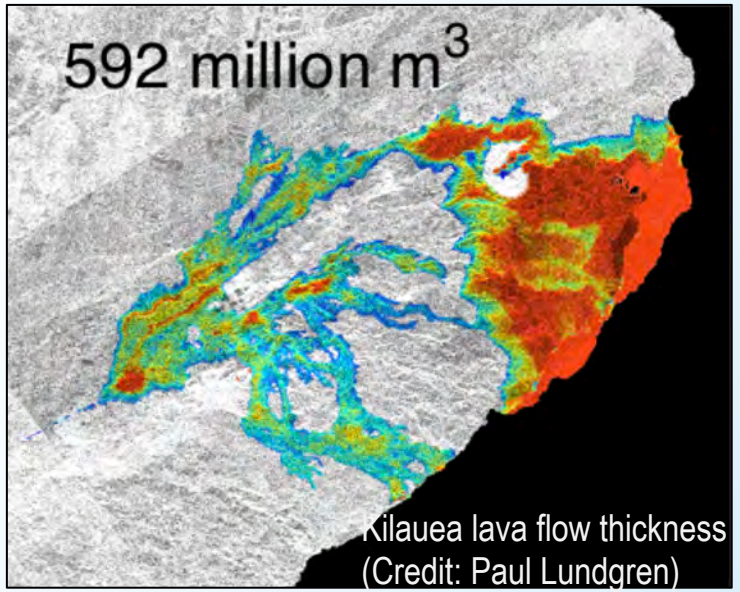
L-band false color phase change image over Cameron Pass, showing phase change due to snow accumulation



Multi-Frequency L and P-band Tomography

Greenland Glaciers
Ka-band TopSAR

Kilauea volcano
Ka-band
TopSAR



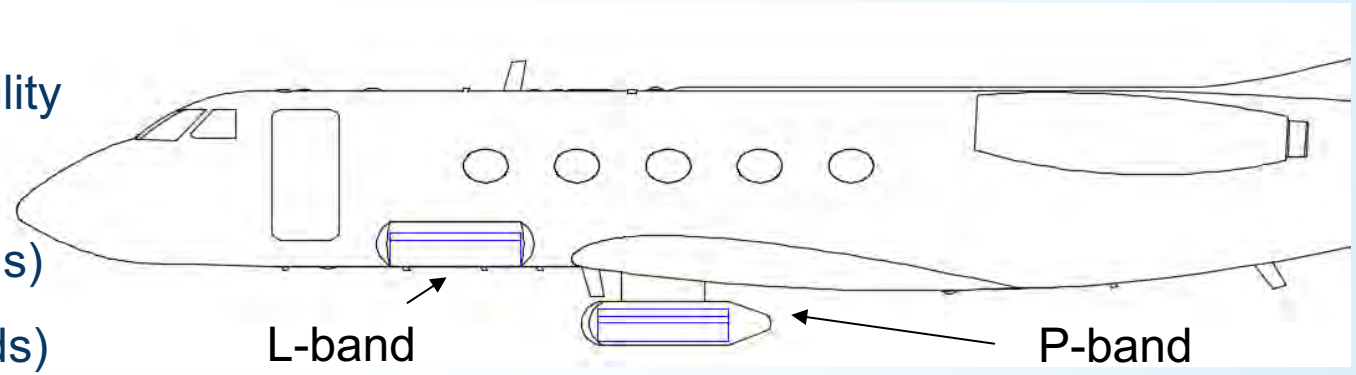
UAVSAR-NextGen Vision

Objectives

- Ensure robustness of current capabilities
- Modernize UAVSAR capabilities so that it could be a testbed to push the envelope of future technologies that will enable future decadal surveys to make new measurements

Options

- Simultaneous multi-frequency capability
- Repeat-pass S-band InSAR
- Single-pass L-band InSAR (wing pods)
- Single-pass X-band InSAR (wing pods)
- Bistatic/Multi-static mode
- Operate on G-III and G-V, and other platforms with comparable performance
- Camera, radiometer (for water vapor)?
- What else?



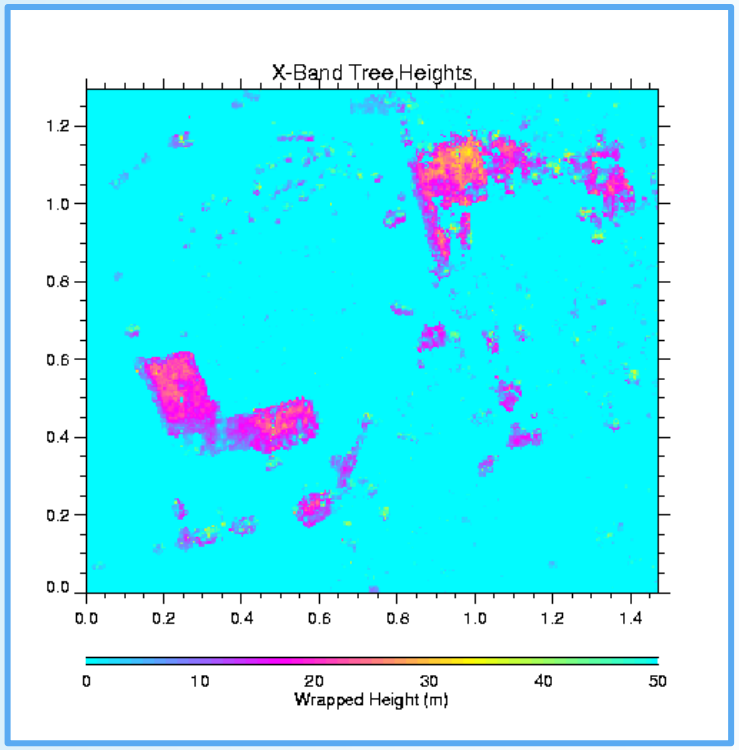
GeoSAR Overview

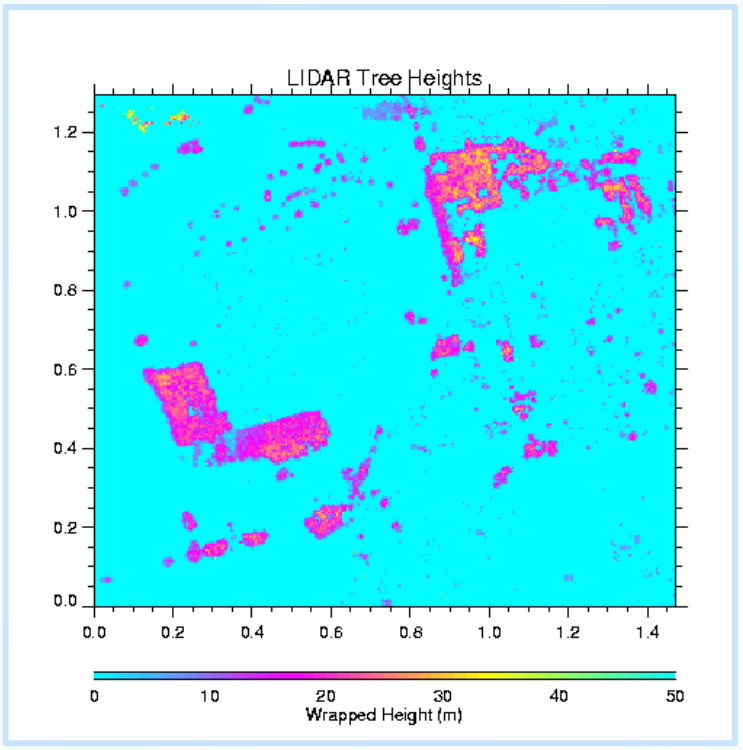
GeoSAR is an interferometric airborne radar mapping system that uses two frequencies to generate digital elevation models (DEMs) and orthorectified radar reflectance maps near the tops of trees as well as beneath foliage.

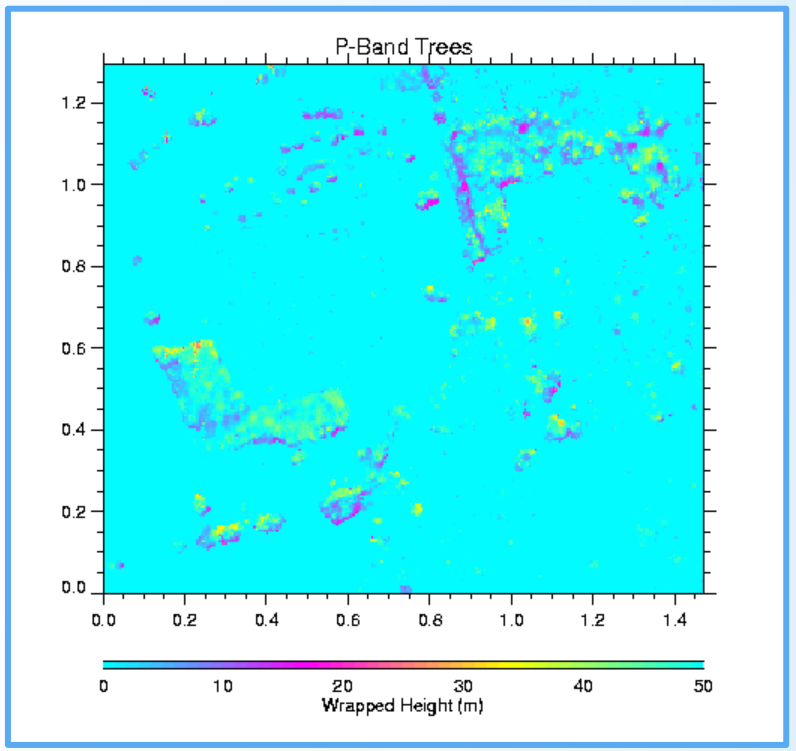
Note: GeoSAR is currently mothballed by Phoenix Air

	P-band	X-band
Wavelength (cm)	86	3
Polarization	Quad pol	VV
Peak transmit Power (kw)	4	8
Antenna baseline (m)	20	2.5
Horizontal spacing (m)	1.25 - 5	1.25 -5
Ground swath (km)	12-14 per side	12-14 per side
DEM height accuracy (m)	1-3 (rel.) 2-5 (abs.)	0.5-1.2 (rel.) 1-3 (abs.)

Comparing LIDAR, X, and P-band Tree Heights







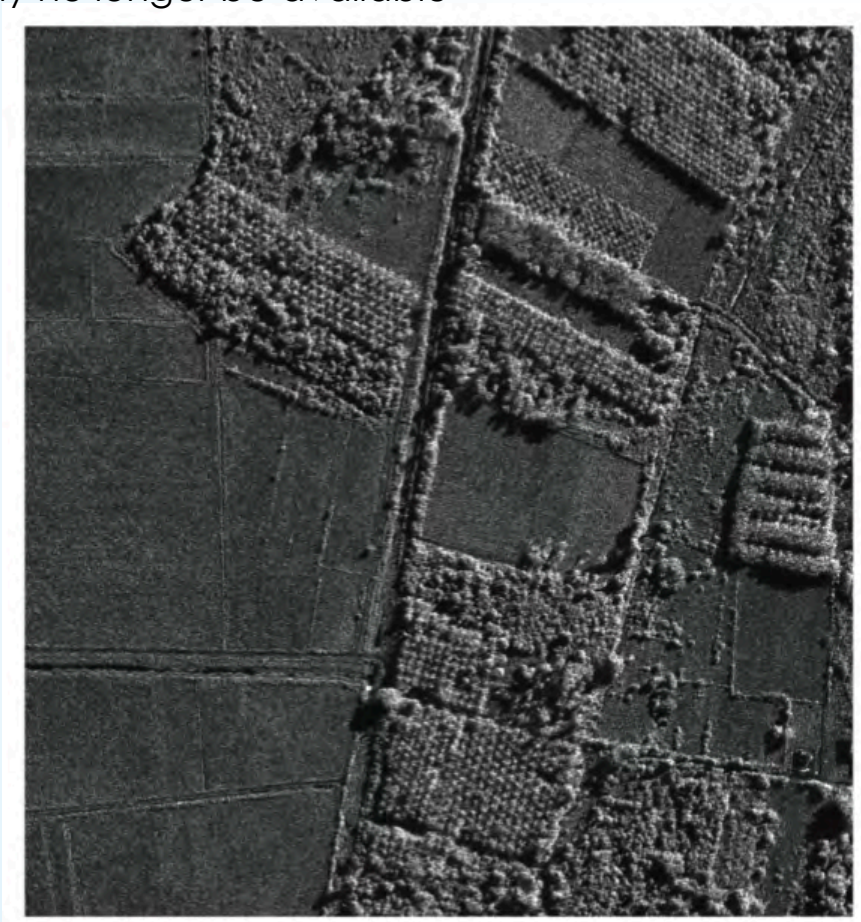
X-band and lidar tree heights are comparable, whereas P-band "tree heights" are quite different due to foliage penetration

Credit: Scott Hensley of JPL

Intermap Overview

X-band IFSAR imagery (left) shows high resolution (50 cm) surface details and features. P-band SAR imagery (right) is capable of foliage penetration to reveal infrastructure, wires, fences, and cables.

Note: P-band may no longer be available



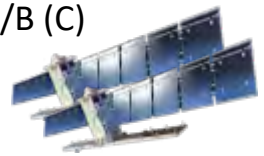
Information from intermap website

SAR Systems used for geodetic imaging

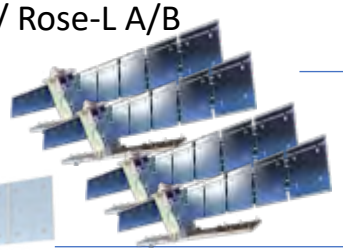
Present (2018-2020)

2020-2030

Sentinel-1A/B (C)



Sentinel-1 C/D / Rose-L A/B

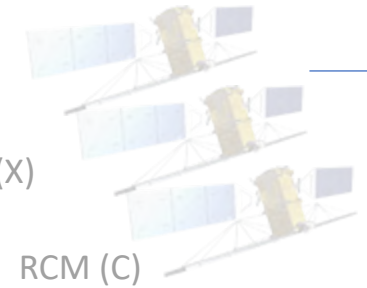


ALOS-4 (L)

ALOS-2 (L)

- **Open raw/SLC data access**
- **Global high area coverage rate**

RADARSAT2 (C)



PAZ (X)

Biomass (P)

TerraSARs (X)

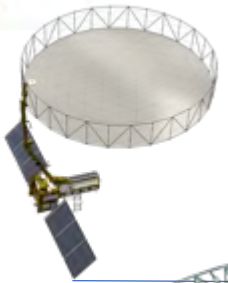
SAOCOM1-A/B (L)

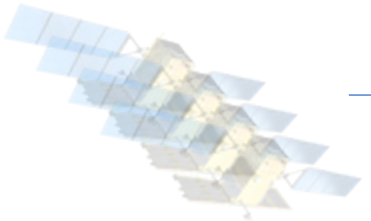
RCM (C)

COSMO-SkyMeds (X)

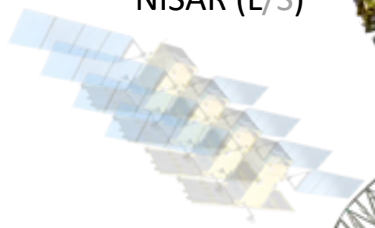
NovaSAR (S)

NISAR (L/S)

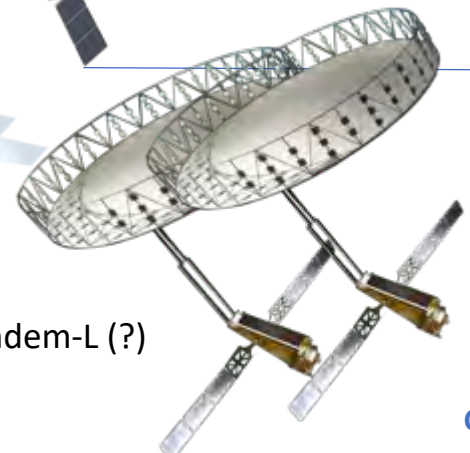




CSK-NG (X)



RISAT-1A (C)



ASNARO-2 (X)

Iceye (X)

Tandem-L (?)

Other Commercial Constellations (?)

Others…

Others…

Credit: Batu Osmanoglu

G-PoR – Government Agency SAR Satellites

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

DEM

Vegetation structure?

* Under formulation ** On hold

Note: Not all agencies/satellites are included. Reason for not including missions may be due to perceived lifetime, and data access.

Only Copernicus has a commitment for continuity past 2027, *however for the purpose of analysis, we assume all these capabilities exist in 2027*

Credit: Batu Osmanoglu

C-PoR – Commercial SAR Satellites

Company*	Mission	Band	First Launch	Swath (km)	Inclination	# Sat. (Now/2027)
Iceye, Finland	Iceye	X	2018	30	97.68°	4/18
Surrey Sat. Tech. Ltd., UK	NovaSAR	S	2018	20	97.5°	1/? (1)
NEC, Japan	Asnaro-2	X	2018	12	97.4°	1/? (1)
Capella Space, CA	Denali	X	2018	40	~90°	1/36
Urthecast SAR, 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

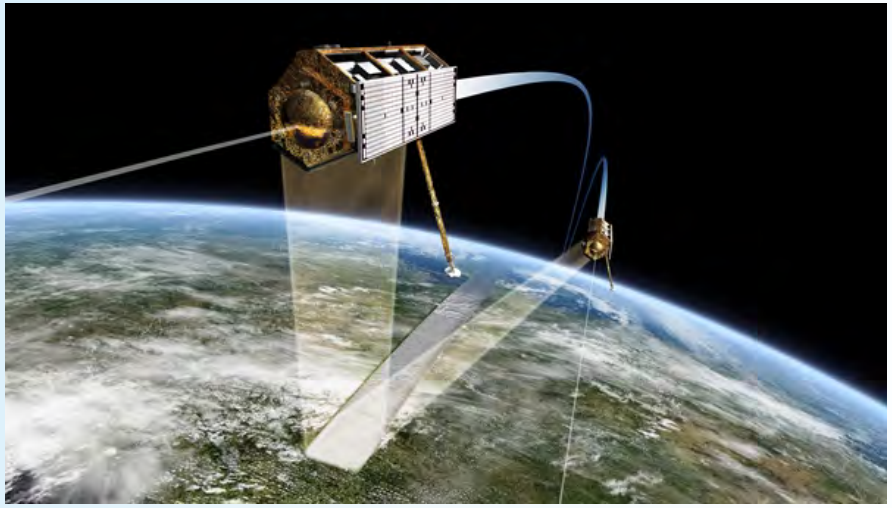
* Not all companies/satellites are included. Reasons for not including may be due to lack of technical information.

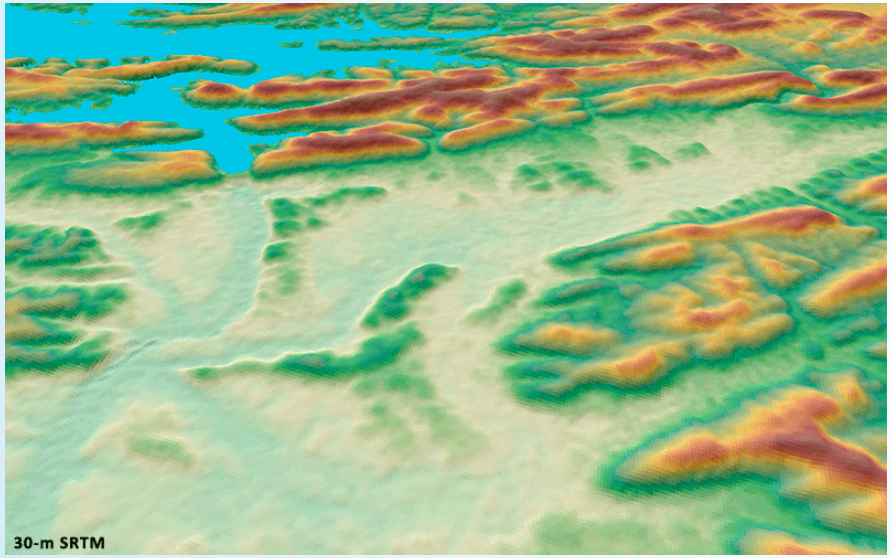
? Missing information. Assumptions are shown in parenthesis.

Commercial data users may be able to order *20km wide X-band data every 10 minutes anywhere on Earth* if a similar capacity to what's shown is realized.

Credit: Batu Osmanoglu

Operational Spaceborne InSAR for Topography Mapping -- TanDEM-X (DLR & AirBus)





- Consists of two TerraSAR-X satellites, launched in 2007 and 2010 respectively, flying in formation separated by a few hundred meters
- Spacecraft mass: 1220 kg
- DEM with 12-m horizontal resolution
  - Height accuracy: < 2 m relative (slopes ≤ 20%), < 4 m absolute
  - Absolute horizontal accuracy: < 10 m
- Copernicus DEM 90-m posting is open access
  - Copernicus may release 30-m posting DEM soon
- AirBus' WorldDEM was completed in 2016 features 12-m resolution, and is available for purchase
  - Price per Sq Km: $6.25
  - ($77k per 1º tile at the equator, $65k per 1º tile at 32º latitude)
- DLR has no plans for next generation TanDEM-X

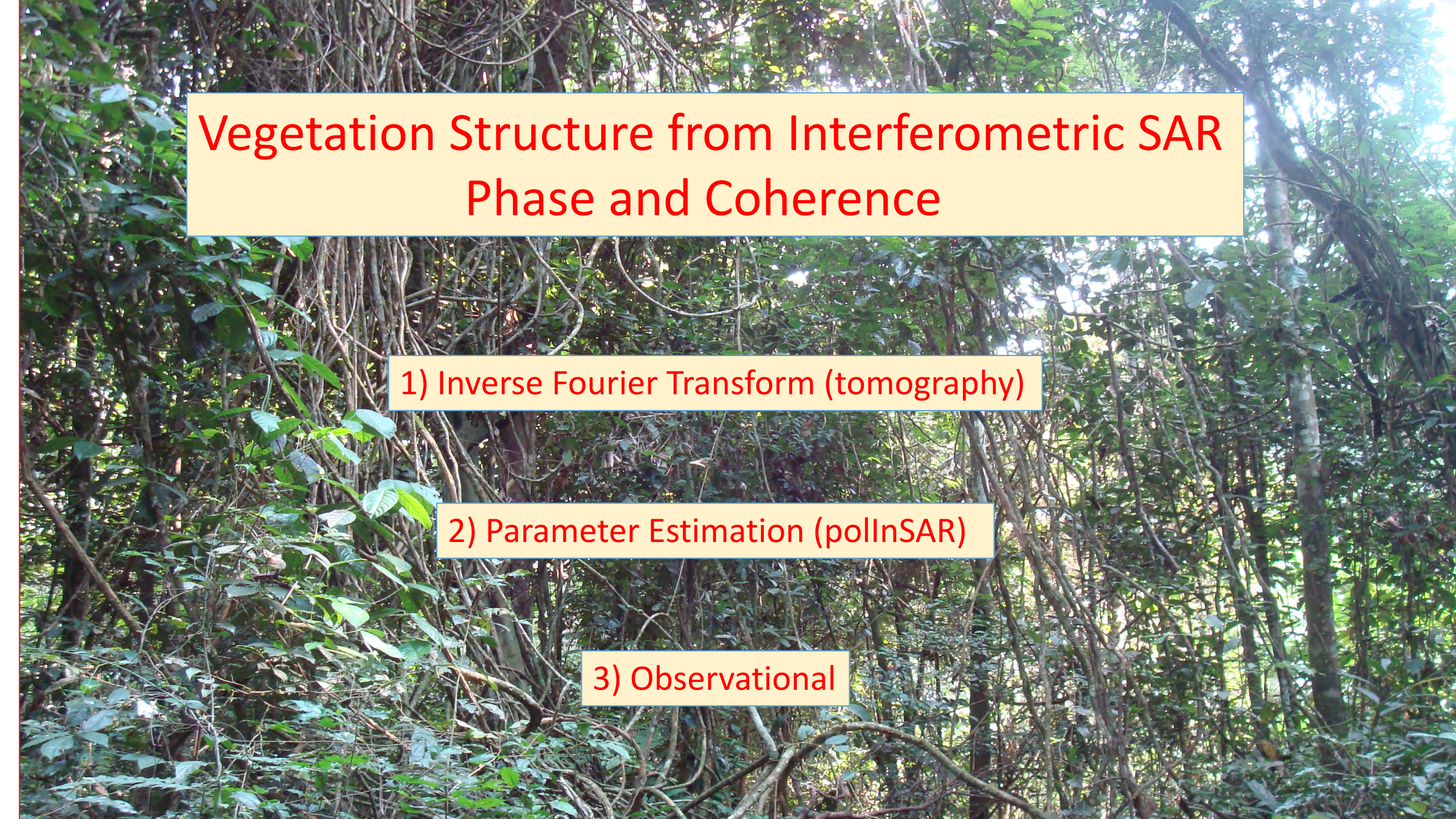
Future Spaceborne InSAR for Topography Mapping

- Rose-L (ESA)
- Commercial satellite constellations may provide targeted surface elevation mapping with X-band SAR
- Constellation of multiple small satellites at L-band?
  - One transmitting satellite and multiple receive-only satellites

Where are the technology gaps?

- Measurement needs: high-frequency observations over a range of spatial scales and resolutions
- Technology gaps:
  - What is the most efficient observation approach to retrieve vegetation structure that meets accuracy aspiration?
  - Is there a radar solution that can measure snow depth that meets accuracy aspiration?
  - Are there lightweight and compact radar payload (<100 kg) that can be launched on small satellites?
  - Is there an efficient solution to provide hourly revisit observations of specific events?
- Possible solutions?
  - Lightweight deployable antenna
  - Miniaturized electronics suitable for small satellites
  - HALE platform to provide targeted long duration observations over specific events
- What are needed to fill the gaps?
- What new strategies can be employed?

Thank You!
yunling.lou@jpl.nasa.gov
stv-leads@list.jpl.nasa.gov


Vegetation Structure from Interferometric SAR Phase and Coherence
1) Inverse Fourier Transform (tomography)
2) Parameter Estimation (polInSAR)
3) Observational

Vegetation Structure from Interferometric SAR Phase and Coherence

$$Fundamental\ InSAR\ Observation \equiv \gamma\left(\kappa_z(\vec{B})\right) = \quad e^{i\phi_0 \int_0^{hv} f(z) \exp i\kappa_z z\, dz}$$

$$Phase = \arg[(\gamma\left(\kappa_z(\vec{B})\right)] \qquad Coherence \equiv |\gamma\left(\kappa_z(\vec{B})\right)|$$

Vegetation Structure from Interferometric SAR: Phase and Coherence

$$Fundamental\ InSAR\ Observation \equiv \gamma\left(\kappa_z(\vec{B})\right) = e^{i\phi_0}\int_0^{h_v} f(z)\exp i\kappa_z z\ dz$$

$$Phase = \arg[(\gamma\left(\kappa_z(\vec{B})\right)] \qquad Coherence \equiv |\gamma\left(\kappa_z(\vec{B})\right)|$$

Vegetation Structure from Interferometric SAR

1) Inverse Fourier Transform—Tomography

$$\gamma\left(\kappa_z(\vec{B})\right) = e^{i\phi_0}\int_0^{h_v} f(z)\exp i\kappa_z z \; dz$$

$$\mathrm{f}(z) = Profile(z) \approx \int_{-\infty}^{\infty}\gamma(\kappa_z)\exp(-i\kappa_z z)\, d\kappa_z$$

Large number of κ_z (baselines) required

Vegetation Structure from Interferometric SAR:

2) Parameter Estimation—PolInSAR

Pick ϕ_{0m}, h_{vm} and simple $f(z; P_m)$, *and make model observations for several* κ_z (baselines)

$$\gamma(\kappa_z)_m = e^{i\phi_{0m}} \int_0^{h_{vm}} f_m(z; P_m) \exp(i\kappa_z z) dz$$

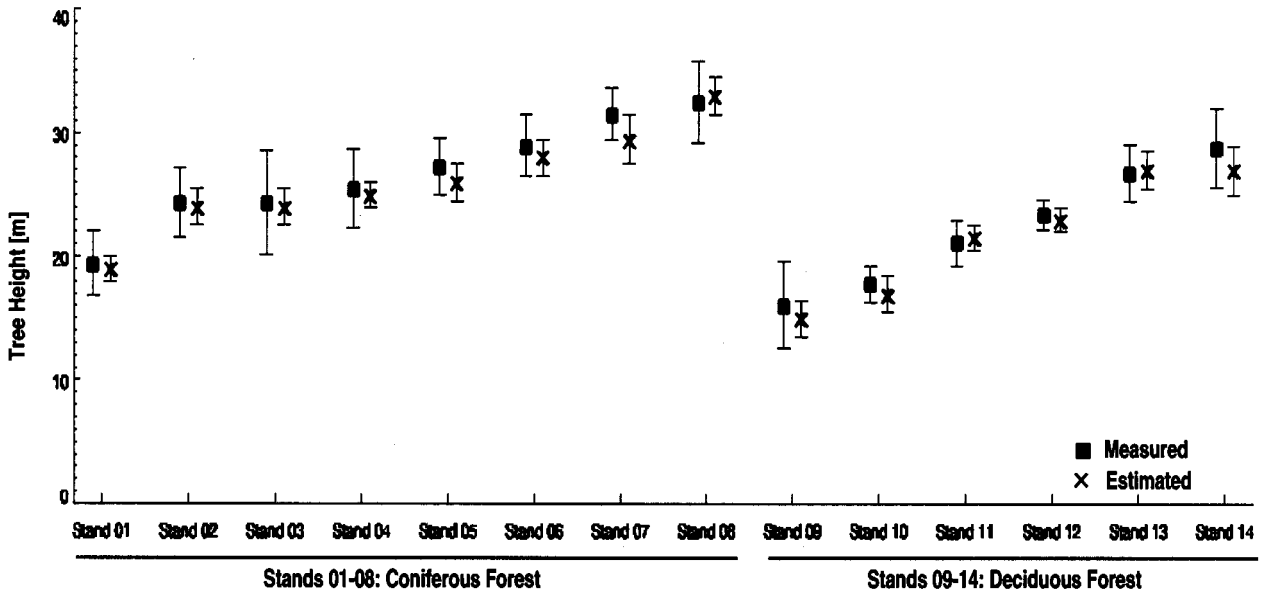
Minimize $(Data - Model)^2$ by adjusting model parameters

At minimum data-model, arrive at best model estimates: h_{vm}, ϕ_{0m}, and $f_m(z; P_m)$

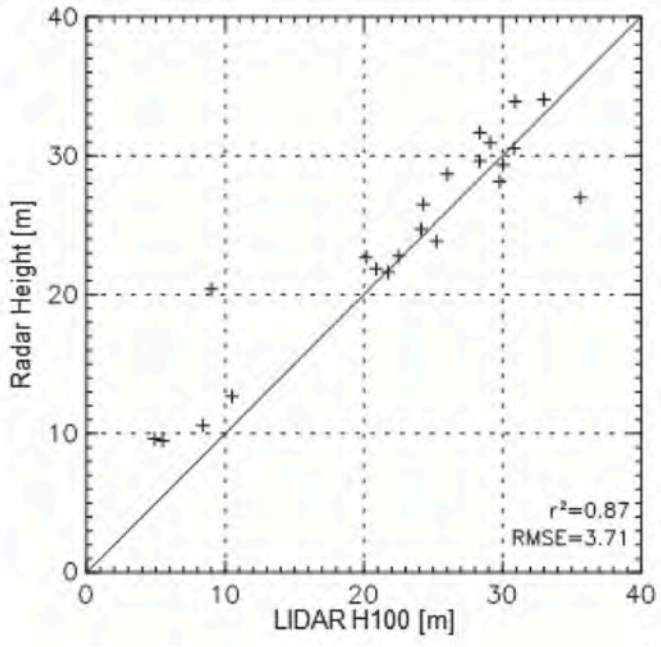
Vegetation Structure from Interferometric SAR:

2) Parameter Estimation—PolInSAR

Arrive at best model estimates: h_{vm}, ϕ_{0m}, and $f_m(z; P_m)$



Papathanassiou, Cloude 2001
(temperate) L-band

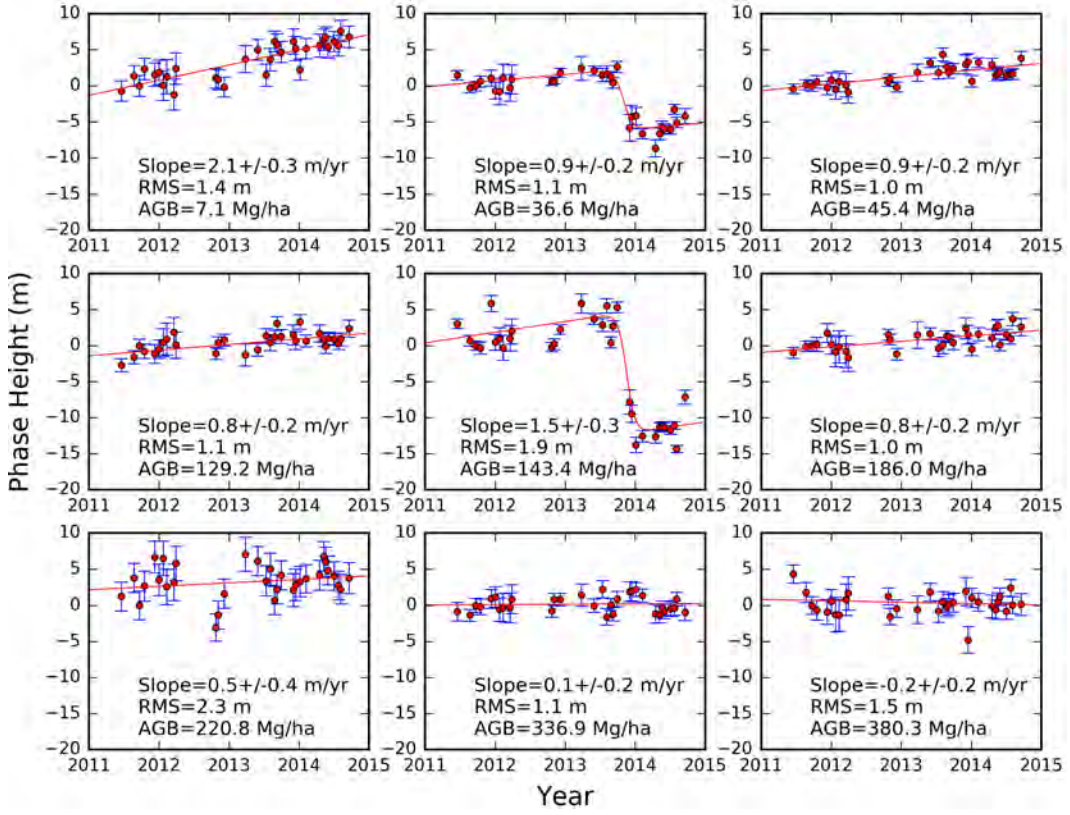


Kugler et al. 2015
(temperate) L-band

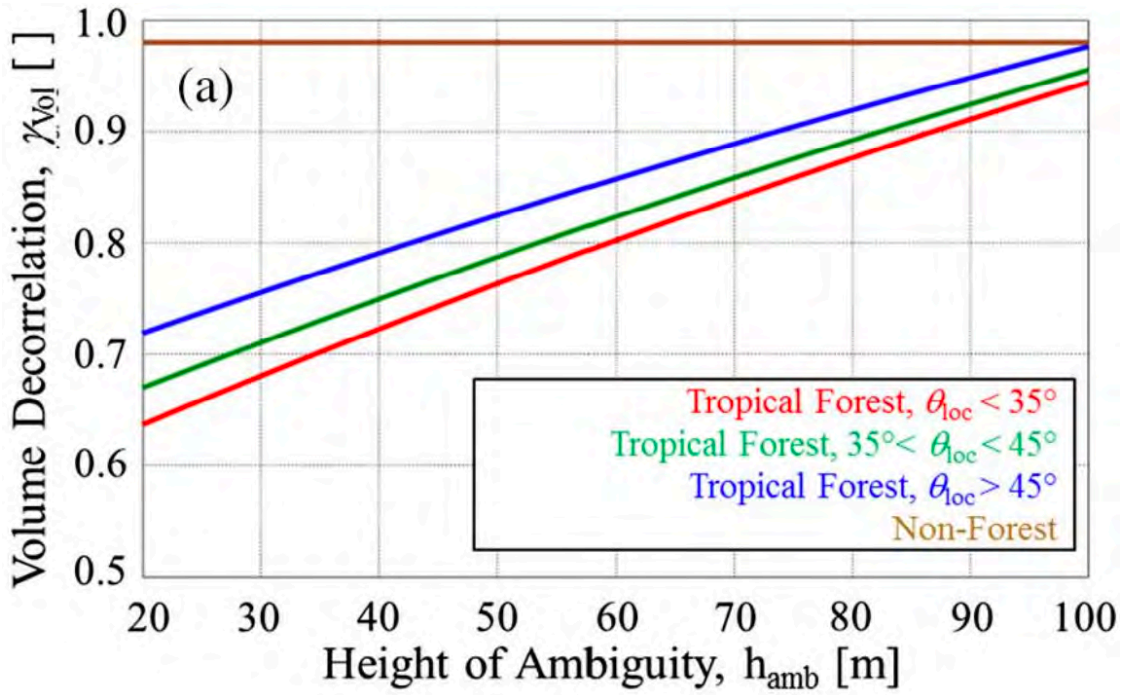
Vegetation Structure from Interferometric SAR:

3) Observational

Use (nearly) raw observations



Treuhaft et al. 2017
InSAR Phase



Martone et al. 2018
InSAR Coherence

Vegetation Structure from Interferometric SAR: Technology Gaps Examples

- What are the optimal observational modes (tomography, param estimation (mod), observational) for **measuring biophysical parameters** (e.g. biomass, leaf area density) and their rates of change?

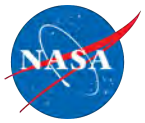
- At which Fourier frequencies (κ_z, baselines) and rf frequencies should these optimal modes be implemented?

- Need airborne L- and X-band fixed baseline to answer the above, along with field and lidar

Surface Topography and Vegetation Structure mapped via TomoSAR

Marco Lavalle (JPL)

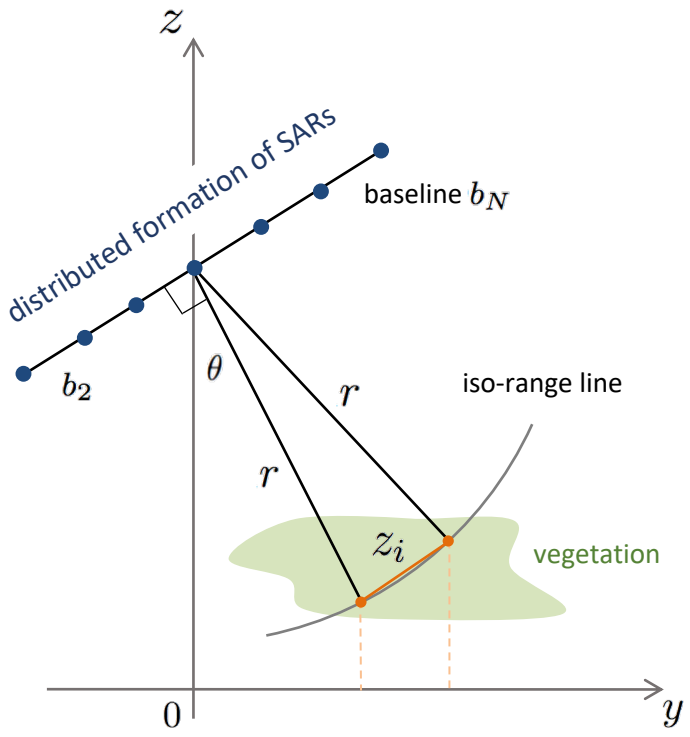
with inputs from the DARTS, UAVSAR, and STV teams



Jet Propulsion Laboratory, California Institute of Technology

Single-pass Tomographic SAR: TomoSAR

- Single-pass TomoSAR is achievable with a distributed formation of SAR satellites – one (or more) transmits and all receive
- In single-image SAR, echoes from scatterers at same range *r* are mixed
- In TomoSAR, signals *s* received at distinct orbital locations carry spatial harmonics proportional to height *z* of the scatterers
- Phase history is used to recover the height of the scatterers via spectral estimators (e.g. Fourier, Capon) or other algorithms



$$\mathbf{s}(n) = \sum_{m=1}^{N_s} \sqrt{\sigma_m}\mathbf{x}_m(n) \odot \mathbf{a}(z_m) + \mathbf{g}(n) \quad n = 1, ..., N_l$$

$$P_F(z_m) = \frac{\mathbf{a}^\dagger(z_m)\widehat{\mathbf{R}}_s\,\mathbf{a}(z_m)}{N^2}$$

3D structure

$$\widehat{\mathbf{R}}_s = \frac{1}{N_l}\sum_{n=1}^{N_l}\mathbf{s}(n)\mathbf{s}^\dagger(n)$$

covariance matrix

$$\mathbf{a}(\omega) = \begin{pmatrix} 1 \\ e^{j\omega b_2} \\ \vdots \\ e^{j\omega b_N} \end{pmatrix}$$

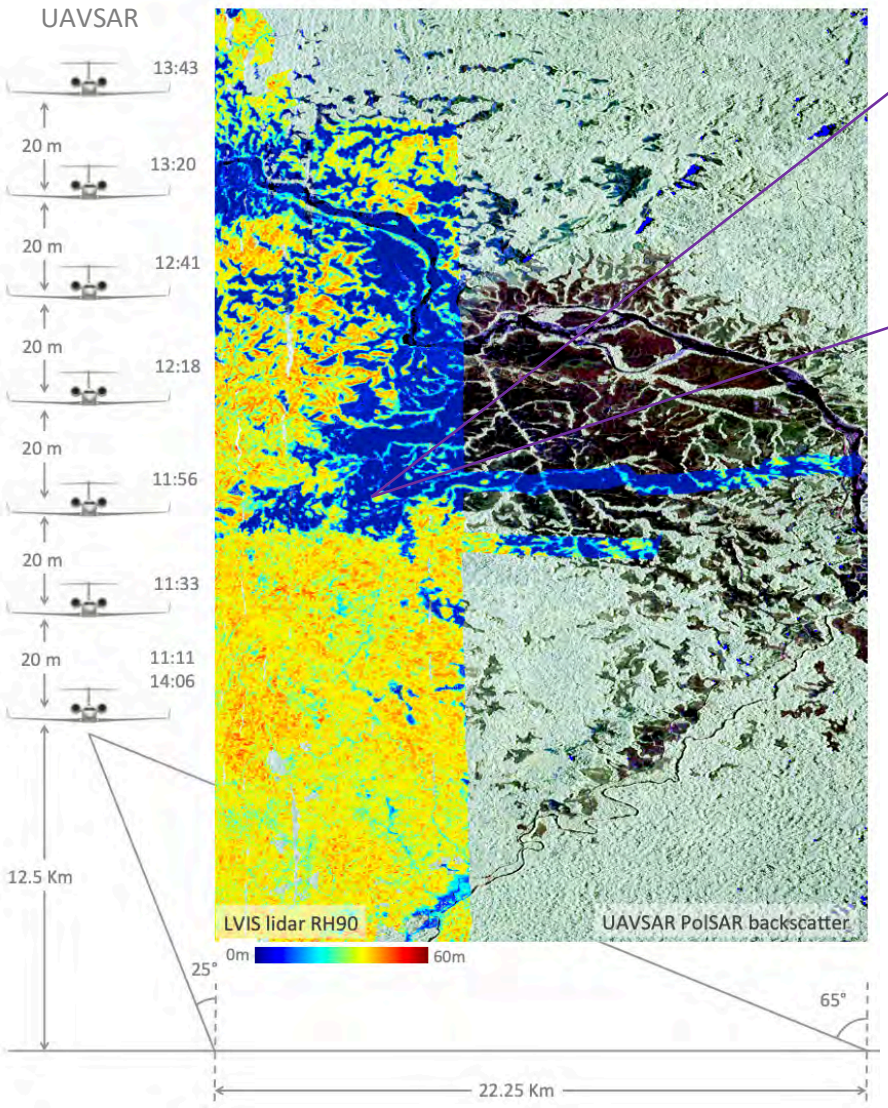
steering vector

$$\omega(z) = \frac{4\pi z_i}{\lambda r} = \frac{4\pi z}{\lambda r \sin\theta}$$

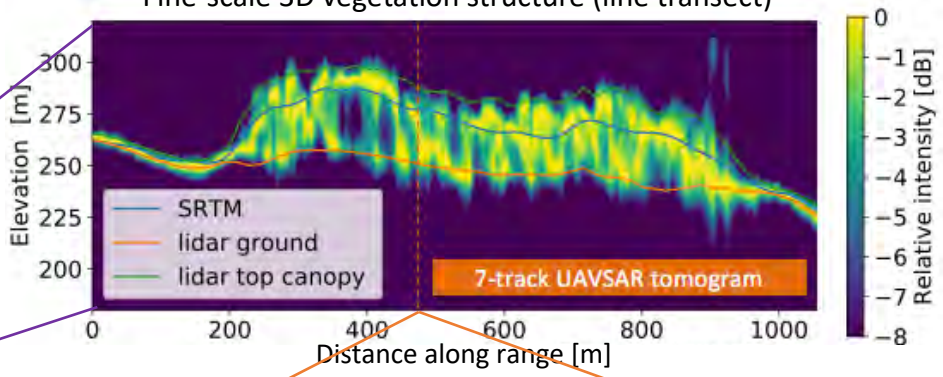
spatial frequency (also called k_z)

TomoSAR proof with JPL airborne experiment

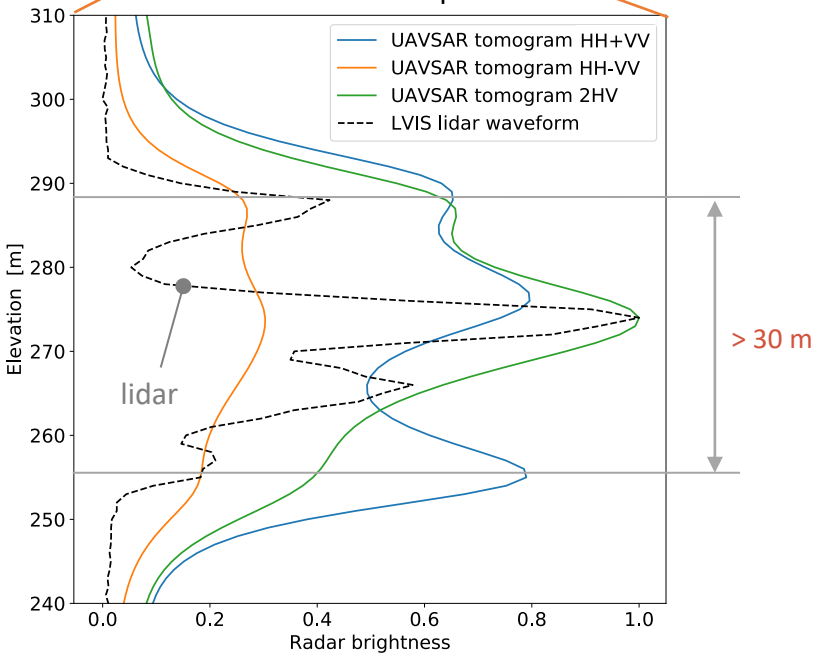
2016 AfriSAR Airborne Campaign (Gabon)



Fine-scale 3D vegetation structure (line transect)

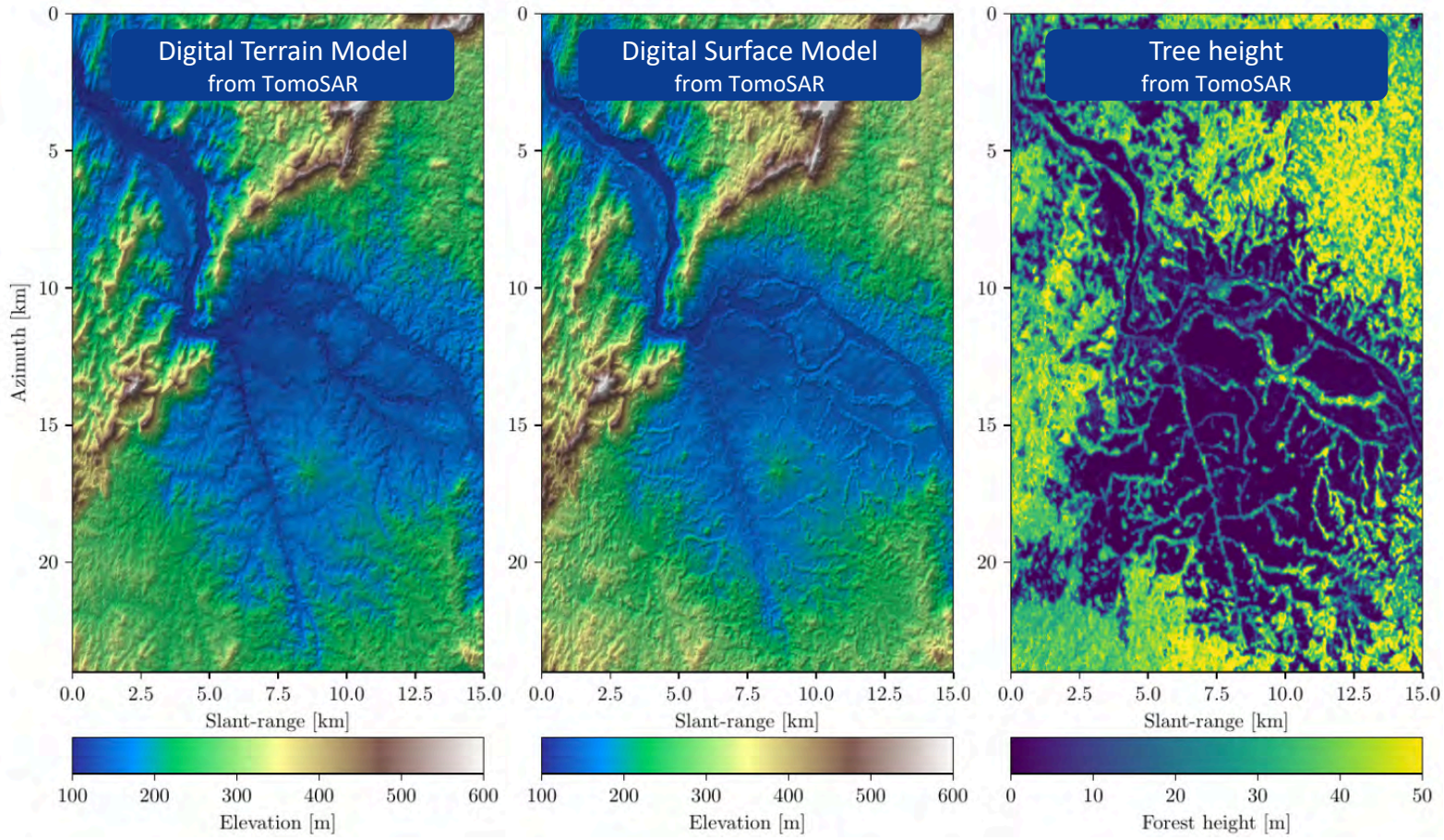


20m x 20m vertical profile



marco.lavalle@jpl.nasa.gov

DTM, DSM and Tree height mapping from L-band radar tomograms

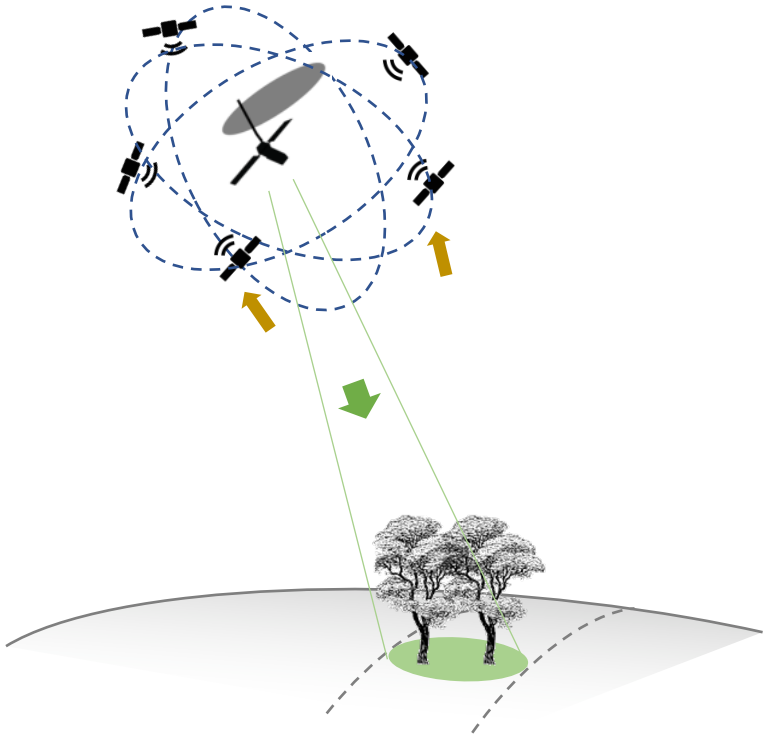


Shiroma G.H.X. and M. Lavalle, "Digital Terrain, Surface, and Canopy Height Models From InSAR Backscatter-Height Histograms," in *IEEE Transactions on Geoscience and Remote Sensing*, Jan 2020. [link]

marco.lavalle@jpl.nasa.gov

Technology challenges for spaceborne TomoSAR

1. Optimal observation geometry configuration with realistic spacecraft orbits



2. Accurate distributed relative cm-level localization

3. Mutual signal phase synchronization

4. Small-Sat compatible, light-weight deployable antenna and compact radar electronics

5. Integrated system performance encompassing system and science requirements

6. End-to-end SAR processing applied to multi-static tomographic validation data

7. Robust and wide-applicable conversion of tomograms into L3 biophysical products (e.g. biomass, LAI) and synergy with lidar

SNOW ACCUMULATION VIA RADAR TECHNIQUES

H.P. Marshall, Boise State University
SnowEx2020 Project Scientist
hpmarshall@boisestate.edu

What is SnowEx?

SnowEx is a NASA-sponsored, multi-year field experiment, which includes extensive surface-based observations to evaluate how to best combine different remote sensing technologies to accurately observe snow throughout the season in various landscapes.

SnowEx Science Plan (Available at: go.osu.edu/snowex-sp)

- Lists sensing techniques, categories & priorities
- Defines and articulates **gaps** in SWE retrieval capability

1. Forest snow
2. Mountain snow
3. Tundra snow
4. Prairie snow
5. Maritime snow
6. Snow surface energetics
7. Wet snow

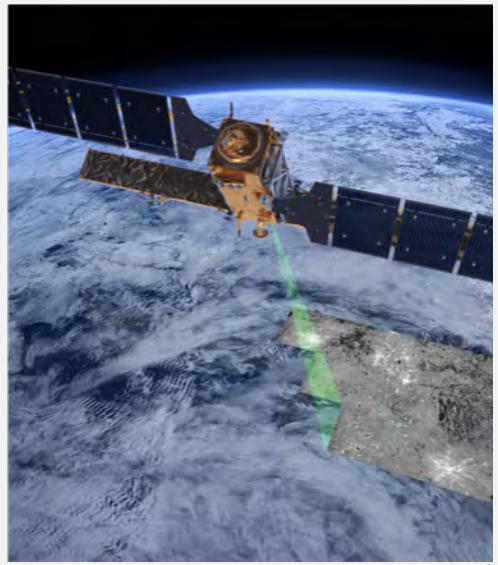
SnowEx 2020

The SnowEx 2020 Campaign consists of coordinated airborne and field-based experiments in the Western U.S.

1. **A time series experiment with UAVSAR**
   - L-band Interferometric Synthetic Aperture Radar
   - Test in range of snow climates and during accumulation & melt
   - 13 sites, spanning 5 states
   - December 20, 2019 to March 12, 2020, with weekly to bi-weekly aircraft overflights and field campaigns
2. **A detailed experiment on Grand Mesa, Colorado**
   - SWE retrieval from active and passive microwave sensors
   - Surface temperature observations from Thermal IR
   - 5-day snow-off campaign November 4-8, 2019
   - 19-day snow-on campaign January 27 –February 14, 2020

MEASURING SNOW ON THE GROUND WITH RADAR

- 250 MHz – 35 GHz have been shown to provide useful snow information, depending on conditions
- Ground-based (mobile and tower), Airborne, and Satellite radar have been components of SnowEx and other field efforts
- Inversion approaches are either based on ***amplitude*** (backscatter at multiple frequencies and/or polarizations), or on radar ***time of flight*** (InSAR and ultrawideband)

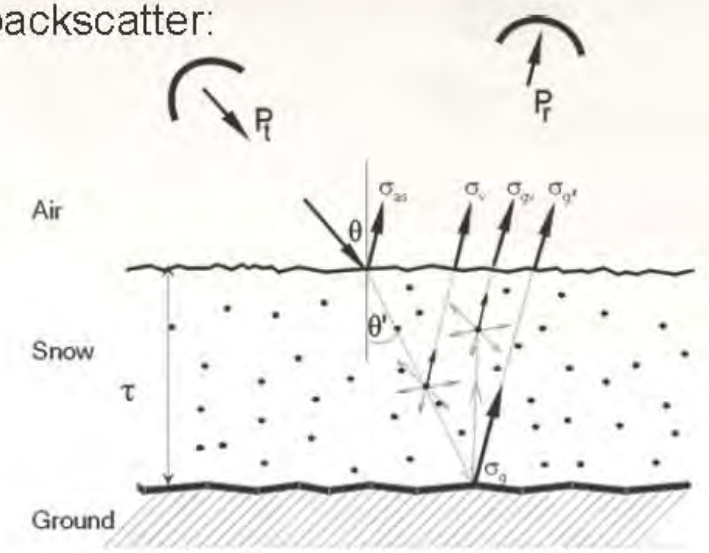


VOLUME SCATTERING APPROACH

Measurement principle: radar backscatter

Main parameters relevant for snow backscatter:

- Snow water equivalent
- Grain size
- Soil background signal
- Liquid water content (if melting)

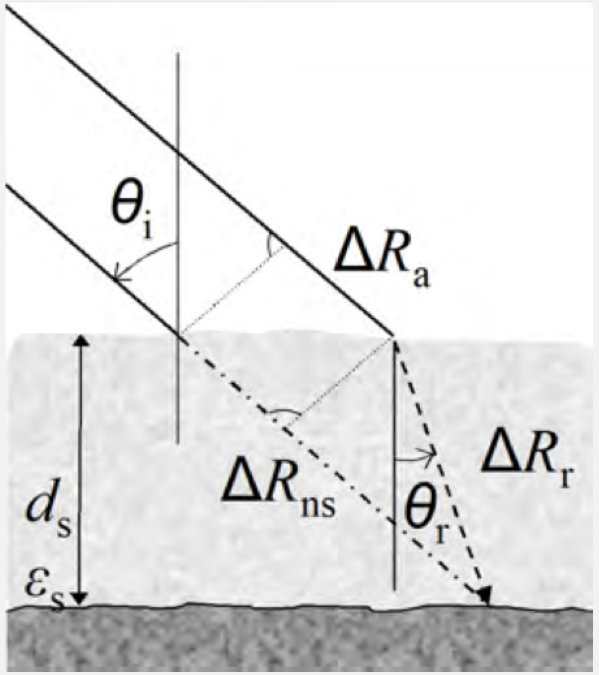


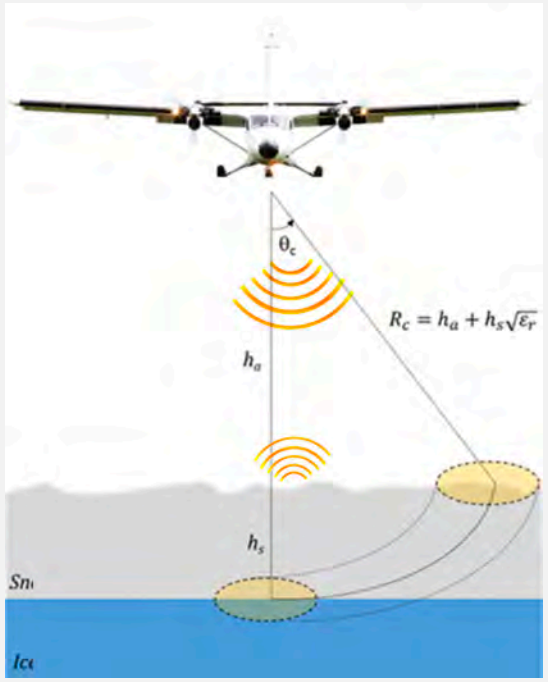
Backscatter contributions:
Volume, surface, and interaction terms

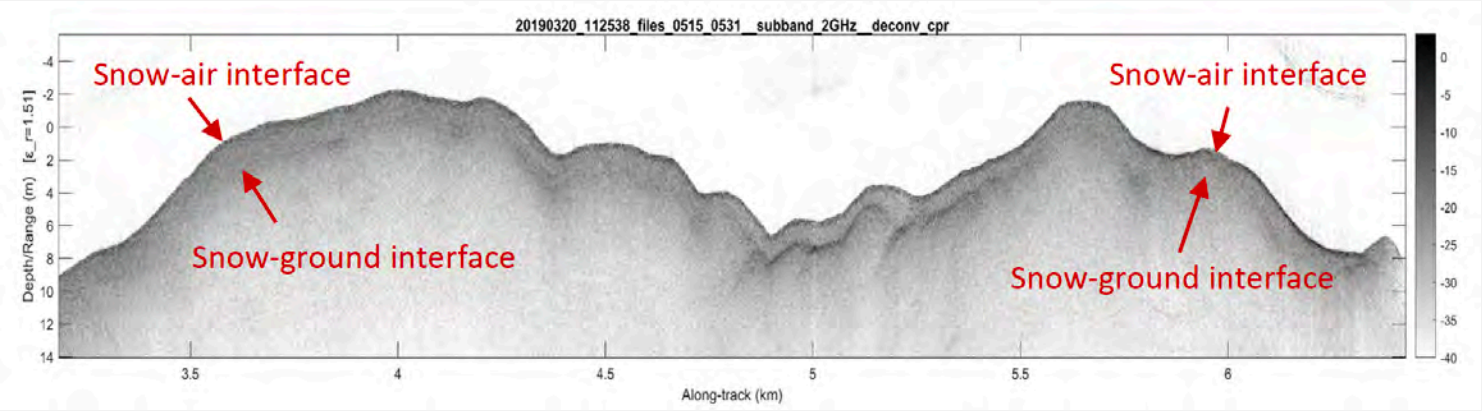
$$\sigma^0 = \sigma^{as} + \sigma^{v} + \sigma^{gv} + \sigma^{g'}$$

- **X and Ku-band volume scattering:** approach was mission concept for NASA CLPX and ESA CoreH2O. X-band backscatter primarily from snow-ground interface, Ku-band backscatter from volume scattering of grains.
- **Dual Ku-band volume scattering:** 13 and 17 GHz to help with sensitivity to grain size. Canadian Space Agency currently in Phase 0 for Ku-band SAR mission for snow.
- **ESA Sentinel C-band SAR at VH:** shows surprising correlation with snow depth across the Northern Hemisphere [Lievens et al., 2019]. Field and modeling experiments underway to explain physics.

TRAVEL-TIME APPROACH

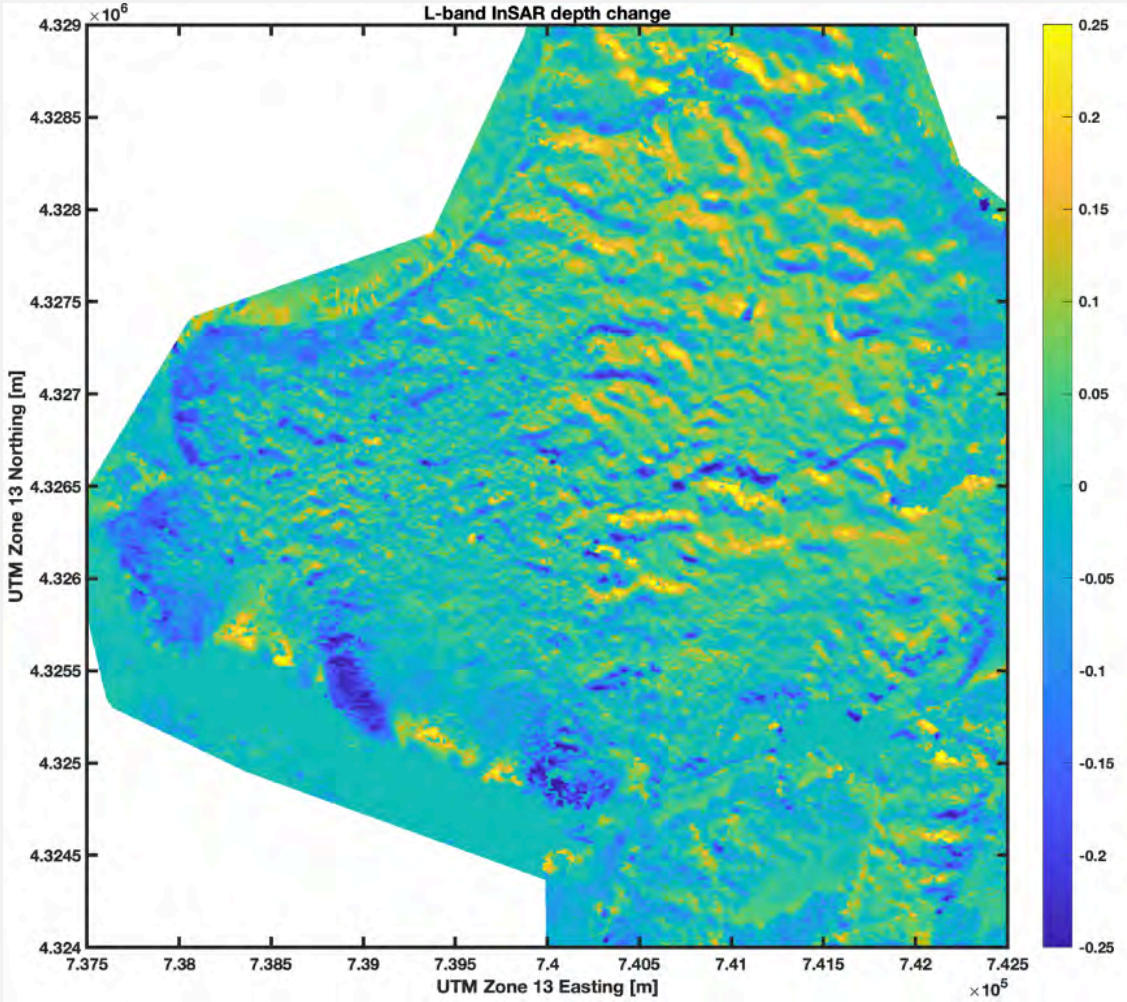


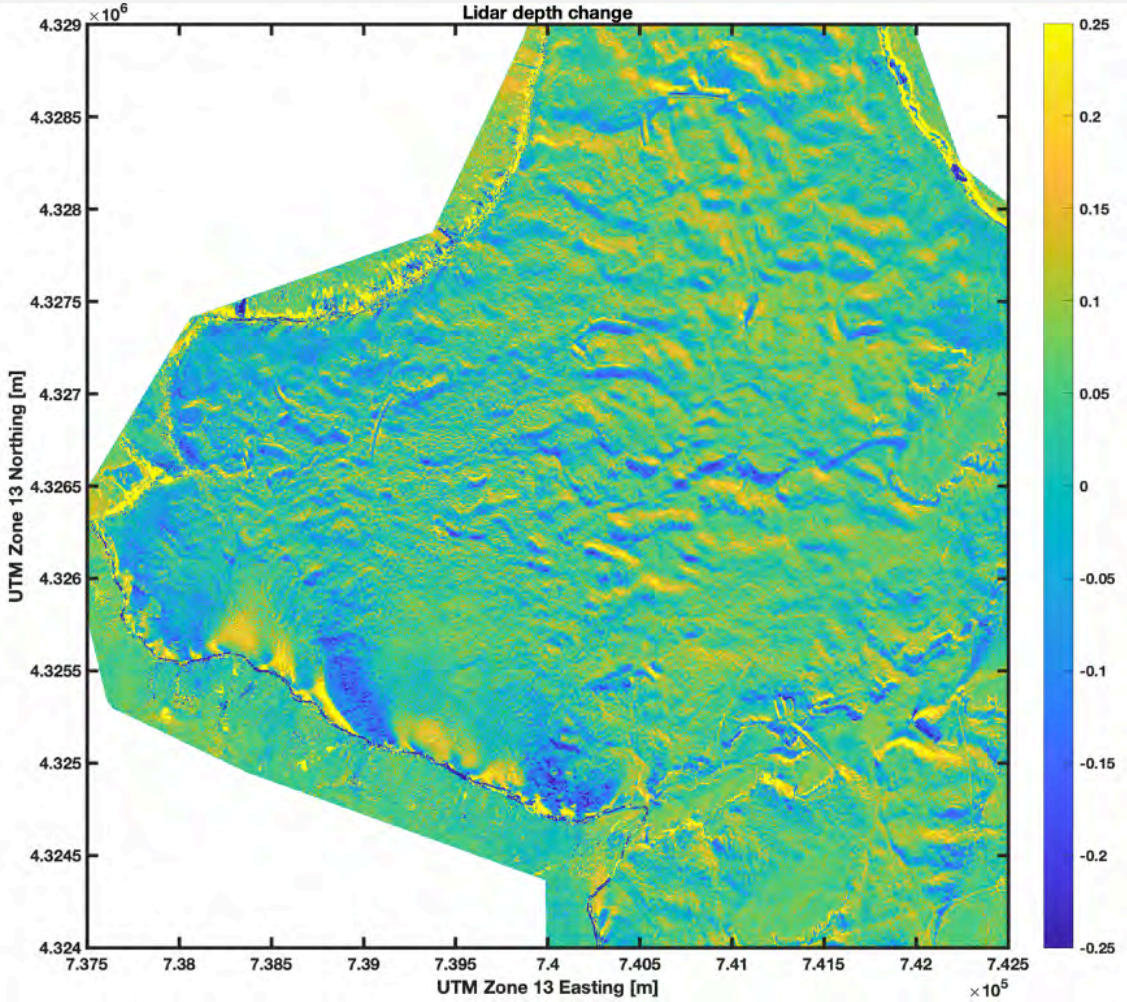




- **35Ghz single pass Ka-band InSAR:** GLISTIN-A experiments [e.g. Moller et al, 2018]. Similar to airborne LiDAR, this approach tracks the surface elevation of the snow surface, which is differenced from snow-free conditions to get snow depth.
- **2-18 GHz ultrabroadband FMCW:** University of Alabama and CRESIS. Nadir pointing, resolves surface reflection, internal stratigraphy, ground reflection. Travel-time through snow used to invert for depth/SWE.
- **1.4 GHz repeat pass L-band InSAR:** Snow is mostly transparent, primary return from snow-ground interface. Change in phase related to change in depth/SWE.
- **300 MHz P-band Signals of Opportunity:** Similar to L-band InSAR, except transmitted signal from existing satellites. Shown to resolve depth/SWE in dry snow from changes in phase of reflection from ground, and in wet snow can track location of snow surface [Shah et al., 2017]

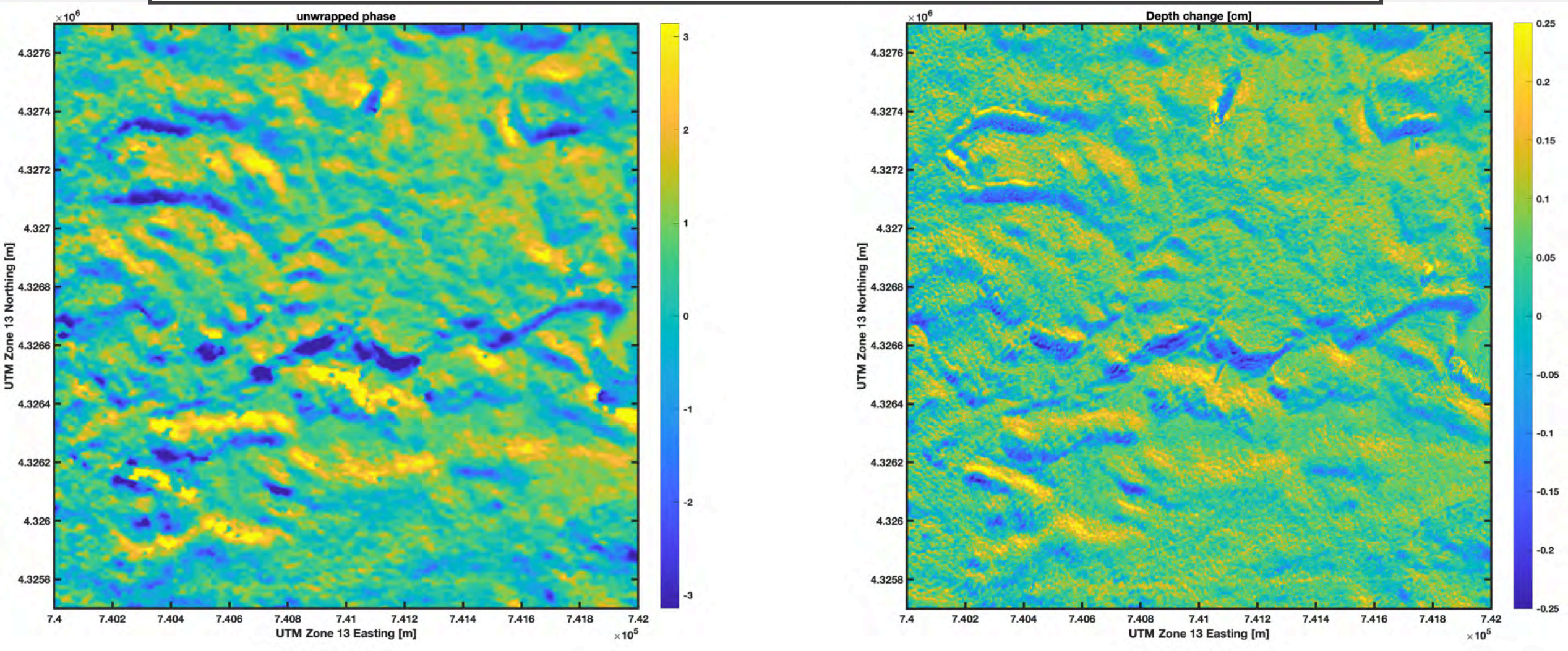
RECENT L-BAND INSAR RESULTS FROM SNOWEX 2020





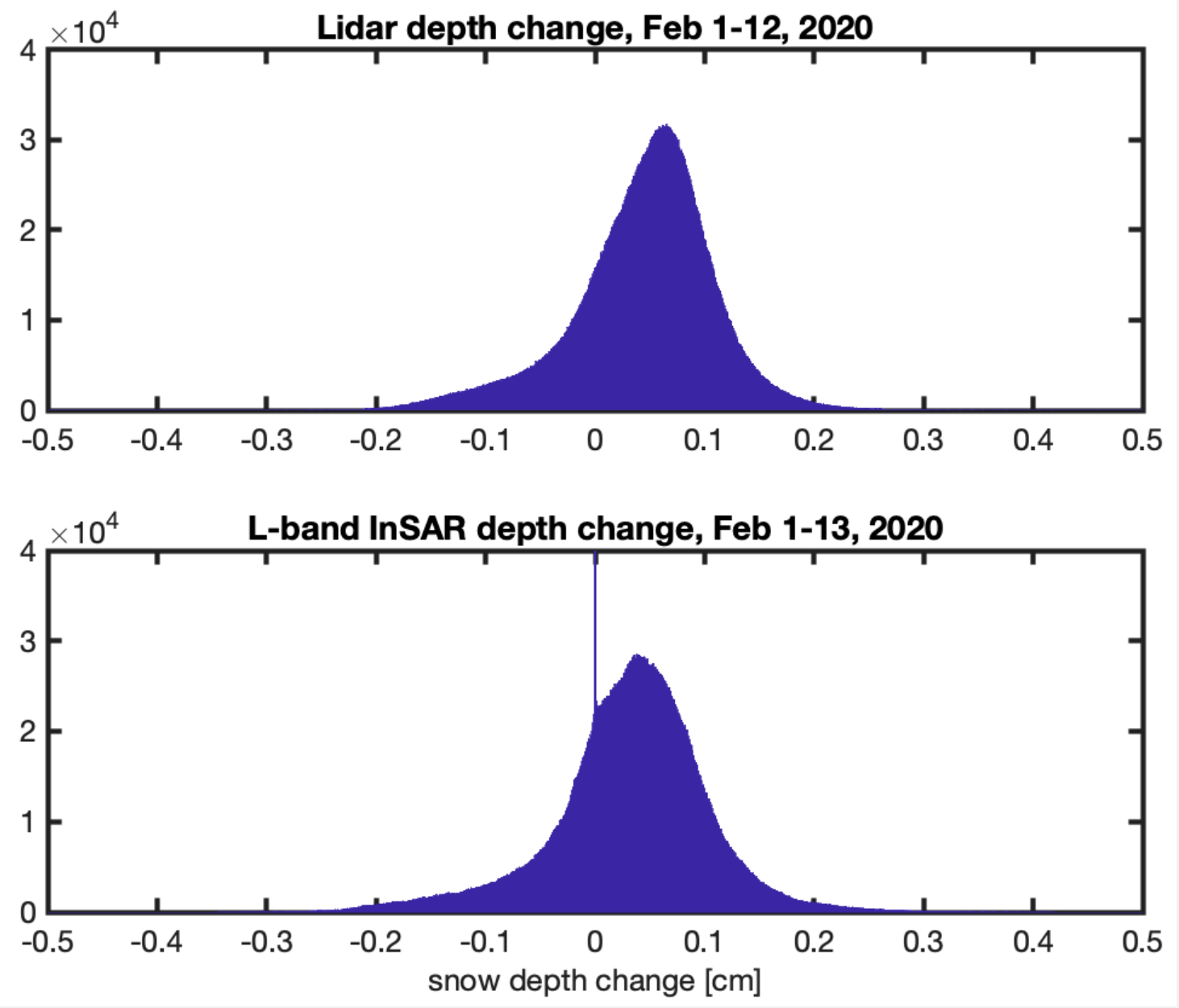
- UAVSAR pair from Grand Mesa, Feb 13 - Feb 1, 2020
- Quantum Spatial Inc (QSI) lidar flights for depth change, Feb 12-Feb 1, 2020
- Lidar accuracy ~3-5cm per flight, expected ~6-10cm accuracy for depth/depth change products
- UAVSAR depth inversion uses phase change and incidence angle, with measured surface density (200 kg/m^3). No tunable parameters!

RECENT L-BAND INSAR RESULTS FROM SNOWEX 2020



- Zoom in on 2km x 2km region with dynamic range in depth
- R-value = 0.76, RMSD=4.7cm depth, 0.9cm SWE
- Independent high-resolution spatial snow information is critical for evaluation of radar approaches

RECENT L-BAND INSAR RESULTS FROM SNOWEX 2020



- Independent field observations of depth change show a mean depth change of 9cm over this period
- In these conditions (surface density ~200 kg/m^3), 360 deg phase change can capture 46cm depth change. Reference location and surface density estimate required.
- Correlation loss after 3-12 weeks depending on conditions, much shorter in vegetation
- SnowEx2021 focused on capturing larger SWE/depth changes, and exploring transition between dry and wet snow
- Technique shows promise for defining snow accumulation patterns
- More work needed to define limitations in vegetation and steep topography

IDEAL AIRBORNE RADAR PLATFORM FOR SNOW?

- Ideal frequency for snow varies widely with snow conditions
- Volume scattering at Ku-band has been primary snow radar mission concept since turn of century. Complexities remain primarily due to sensitivity to grain size; only works in dry snow
- Recent C-band shows volume scattering signal at VH, helps explain loss in L-band coherence. Physics still needed to explain.
- L-band InSAR and P-band SoOp have shown promise recently, and not sensitive to grain size. Needs more validation in range of conditions, especially transition to wet snow.
- Ka-band InSAR can be used to measure depth in deep mountain snowpacks

Some Possibilities for snow:

- L-band and Ka-band InSAR on same aircraft
- Separate depth sensor: Integrated lidar or optical camera system for Structure from Motion (SfM)
- Wide frequency range: ultrabroadband FMCW SAR, to observe frequency dependence on backscatter
- Additional receivers for reflectometry from SoOp (GNSS, satellite radio, etc)

Altimetric Measurement Using Signals of Opportunity Reflectometry

Rashmi Shah
Jet Propulsion Laboratory, California Institute of Technology
Rashmi.shah@jpl.nasa.gov
09/10/2020

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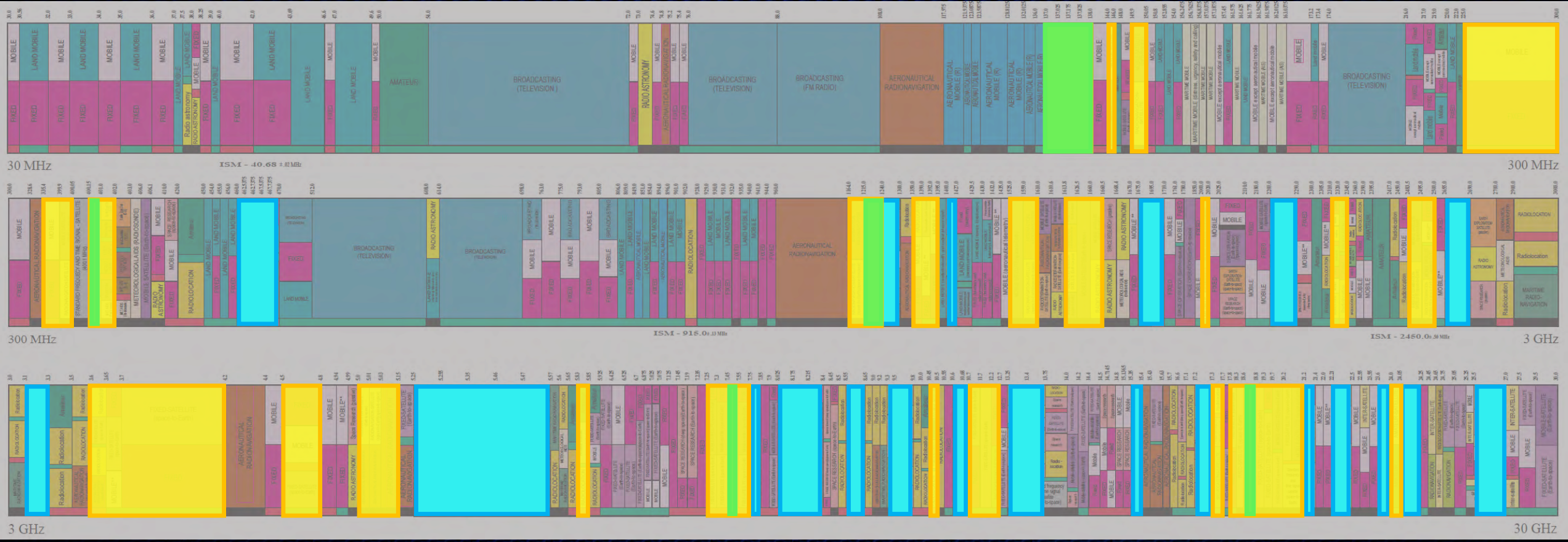
Outline

- Signals of Opportunity Concept
- Snow Measurement Using SoOp
- Ocean Altimetry Measurement Using SoOp
- Summary

The Electromagnetic Spectrum: *Valuable Real Estate*

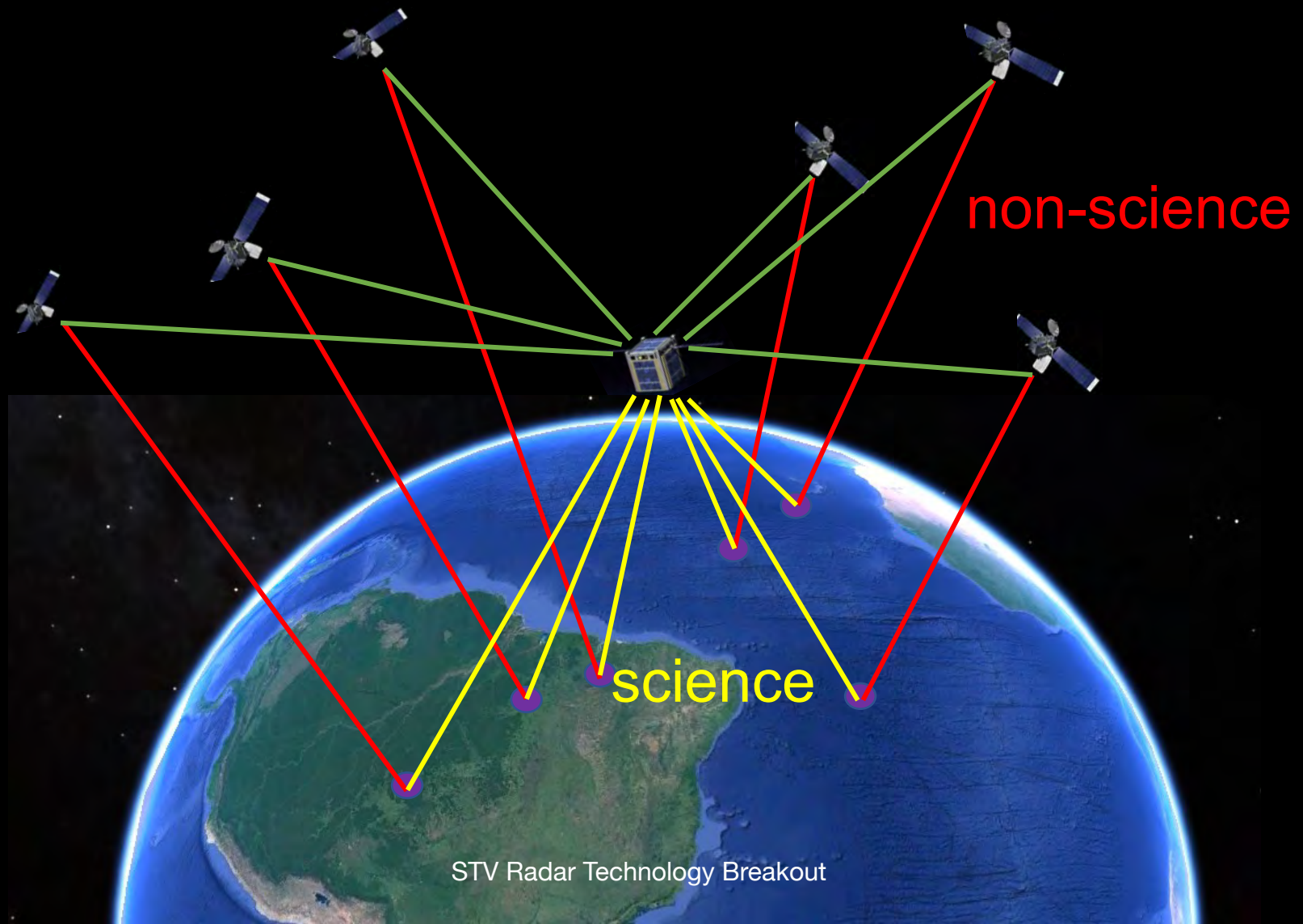
Two Windows on the Earth



Science Optical Window Comm/Nav Microwave Window Shared

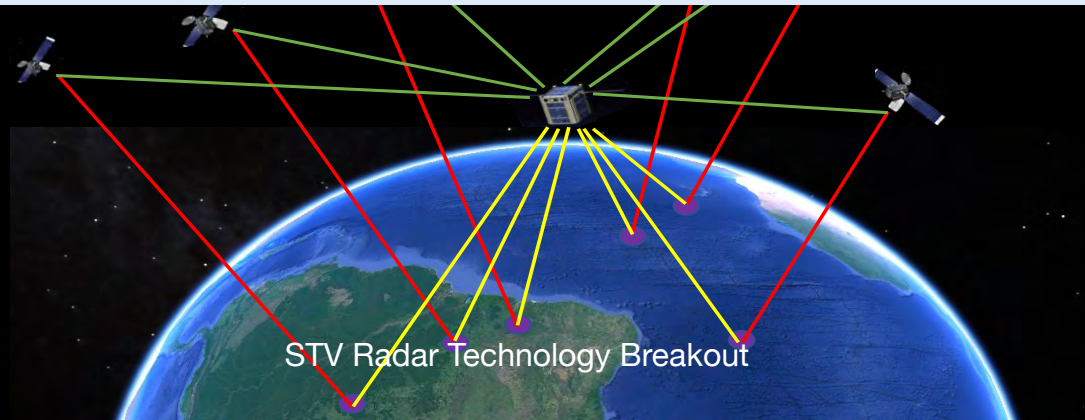
Signals of Opportunity (SoOp)

Reflectometry

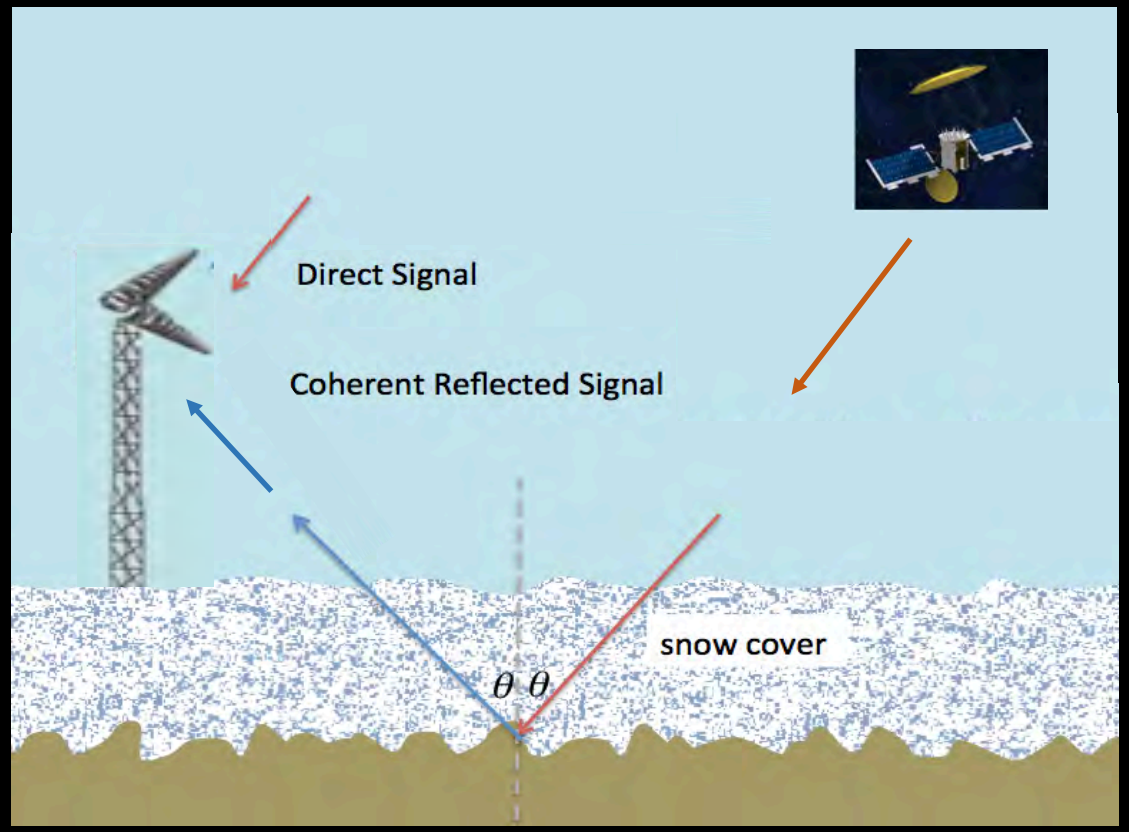


Signals of Opportunity (SoOp)
Advantages

- **Operate on any frequency where a transmitter exists**
- Strong, coherent transmitted signal (in a sense “active”)
- Forward scatter - high SNR
- Low SWaP enables small satellite constellations
- Resolution set by transmitting signals’ bandwidth or transmitting signals’ frequency
- Fundamental observation is time/frequency/phase (not radiometry) or power (requires radiometric calibration)



Snow and Soil Measurement Principle



$$R \simeq R(f, \textit{Soil Moisture})$$

$$\phi_s \simeq \mathrm{a} \cdot f \cdot SWE$$

ϕ_s = phase change

f = frequency

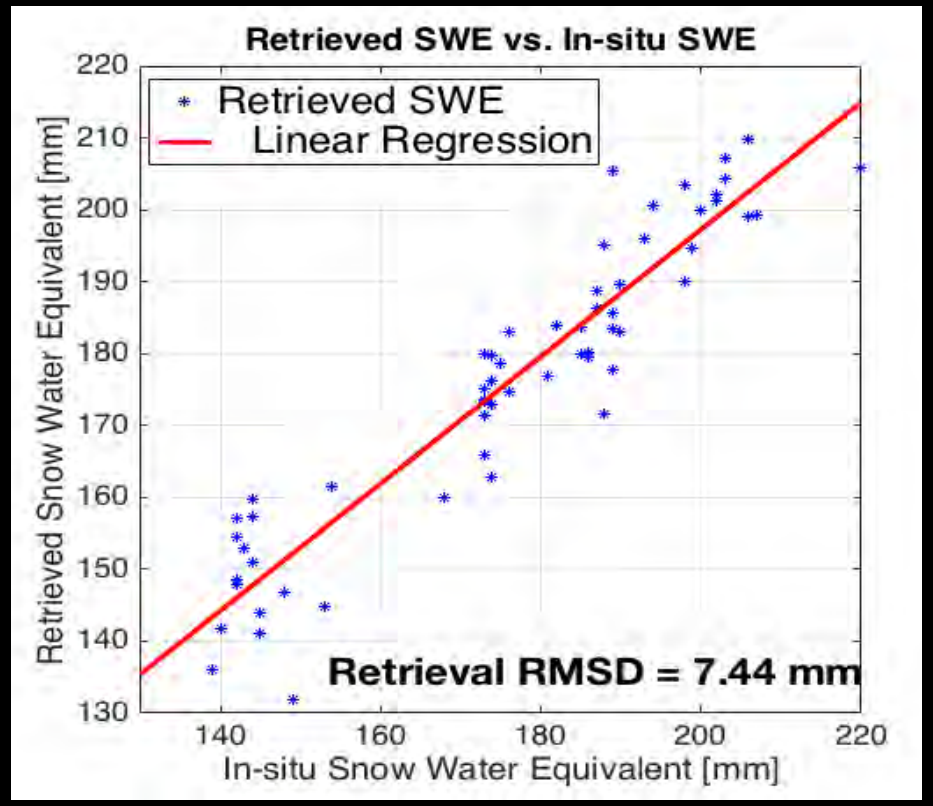
a : depends on θ

R = Reflectivity

Yueh et al., 2017

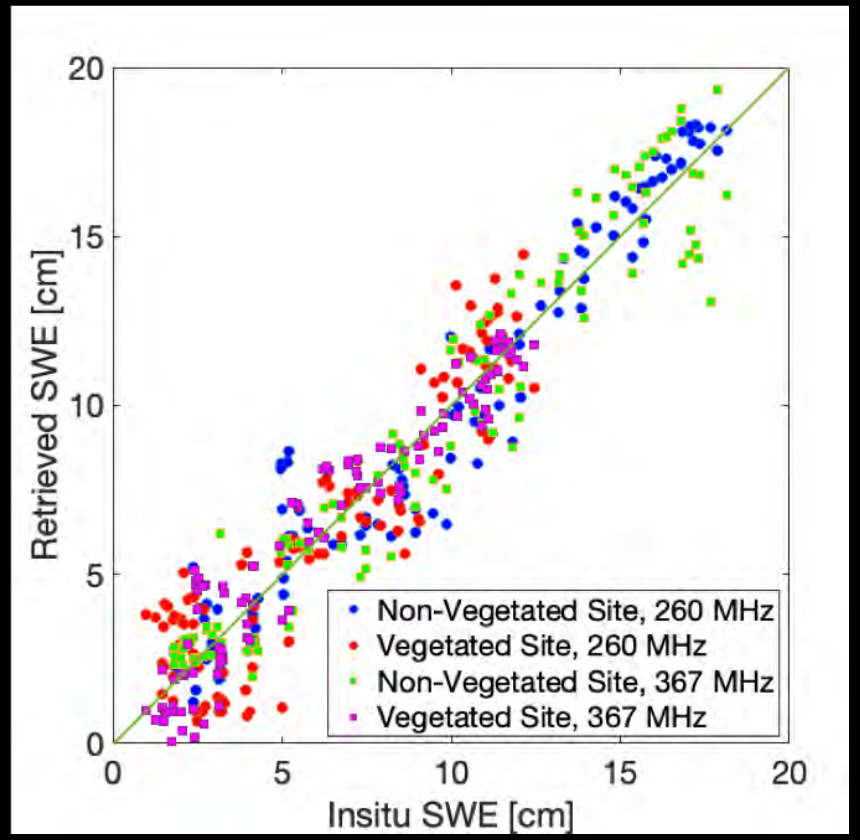
Snow Retrieval Demonstration

260 MHz



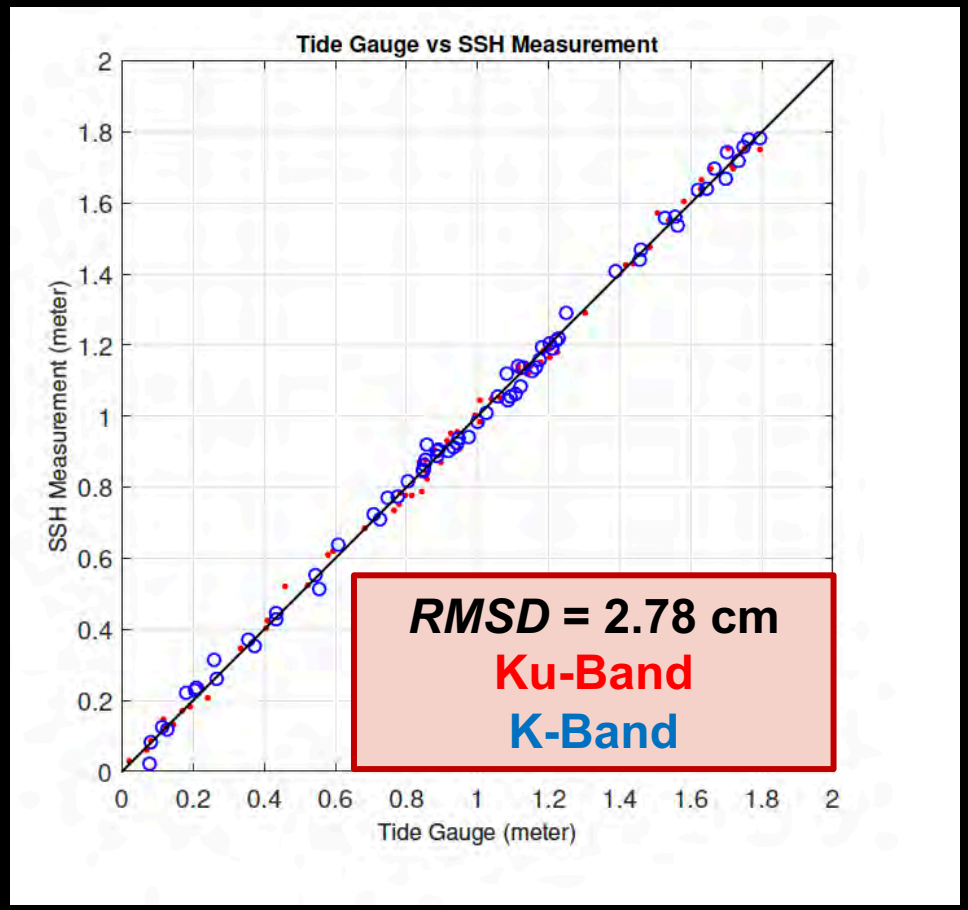
Shah et al., 2017

260 MHz and 370 MHz



Ocean Altimetry Measurement

Platform Harvest



$$\sigma_H = \frac{c}{2\sin\epsilon \boxed{BW}\sqrt{N_{IN}}}\sqrt{\left(1+\frac{1}{SNR}\right)^2+\left(\frac{1}{SNR}\right)^2}$$

Use of 400 MHz wide DirecTV spectrum ➔ SoOp is coherent over wide bandwidth

Ho et al., 2019

Summary and Future Use

Reflectometry – a “passive” way of doing bistatic radar

- Navigation (GNSS) signal special properties enabled the first reflectometry demonstrations (late 90’s)
- Expansion of reflectometry broadly to “Signals of Opportunity” opens this technique to nearly all microwave frequencies penetrating the Earth’s atmosphere.

- Potential Future Uses
  - Use multifrequency approach to measure vegetation attenuations at different depths
  - Use interferometric technique using multiple platform to measure topography
  - Use backscatter rather than forward scatter to improve on resolution

National Aeronautics and Space Administration

NASA

EXPLORE EARTH

The HALE UAS Capability Assessment and Demonstration Project

Matthew Fladeland, Airborne Science Manager
Earth Science Division
NASA Ames Research Center

September 10, 2020

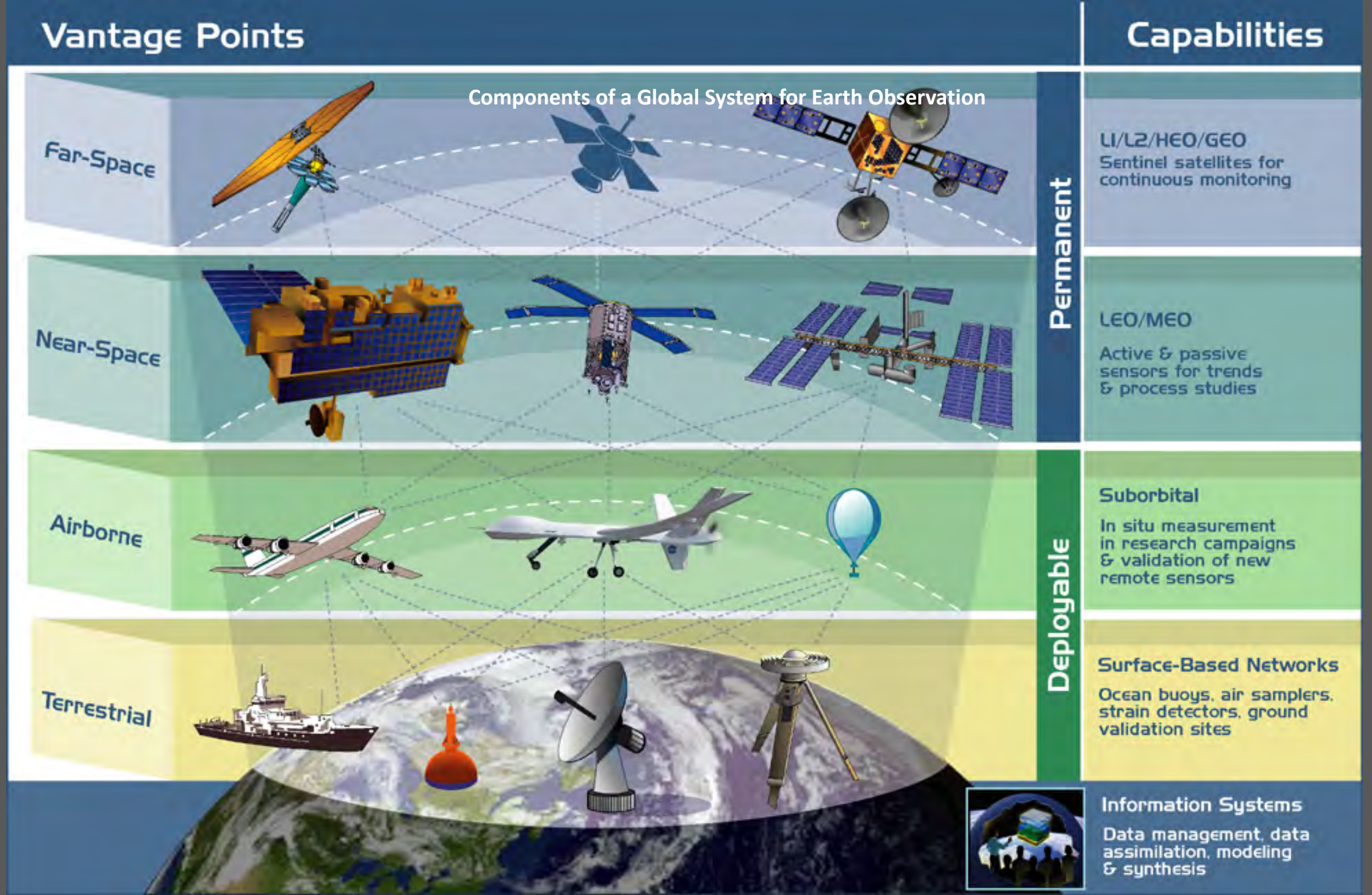
Surface Vegetation and Topography Radar Sub-Group

Overview

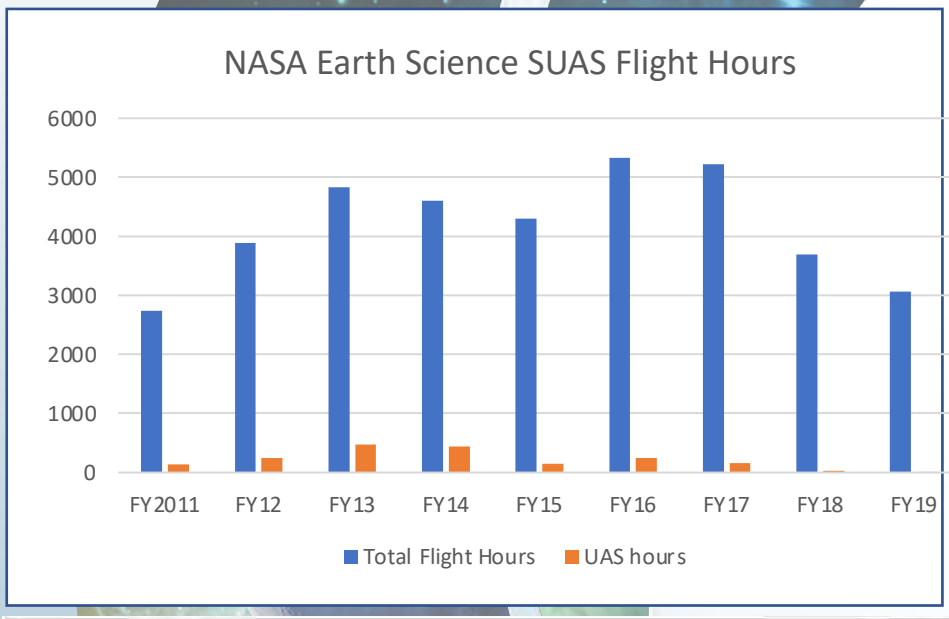
- Airborne Science Program
- Requirements for unmanned aircraft
- Capabilities, considerations, and roles of UAS
- High Altitude Long Endurance UAS (HALE)
- Conclusions

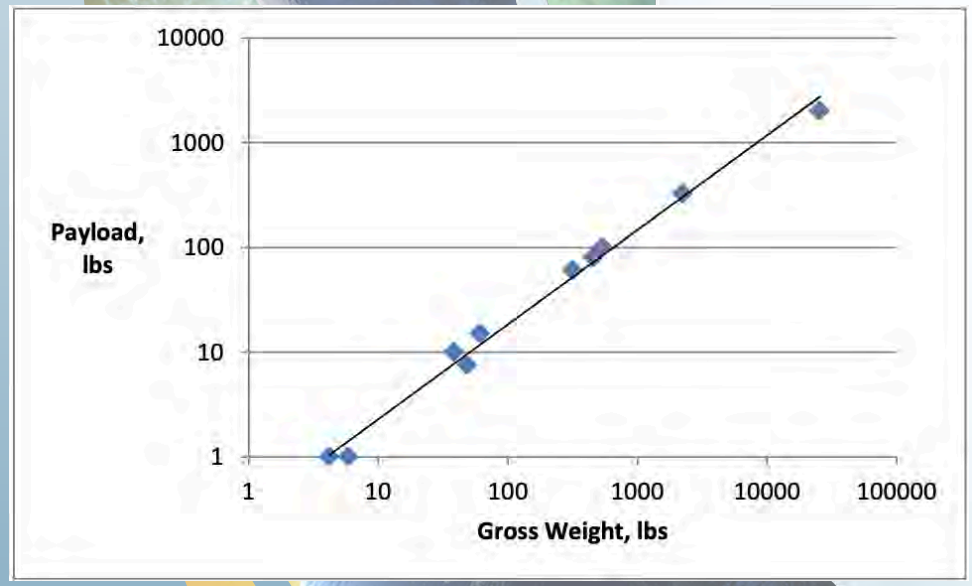
National Aeronautics and Space Administration

Airborne Science Program


Components of a Global System for Earth Observation
Vantage Points
Capabilities
Far-Space
Near-Space
Airborne
Terrestrial
Permanent
Deployable
L1/L2/HEO/GEO
Sentinel satellites for continuous monitoring
LEO/MEO
Active & passive sensors for trends & process studies
Suborbital
In situ measurement in research campaigns & validation of new remote sensors
Surface-Based Networks
Ocean buoys, air samplers, strain detectors, ground validation sites
Information Systems
Data management, data assimilation, modeling & synthesis

NASA UAS Categories and Roles



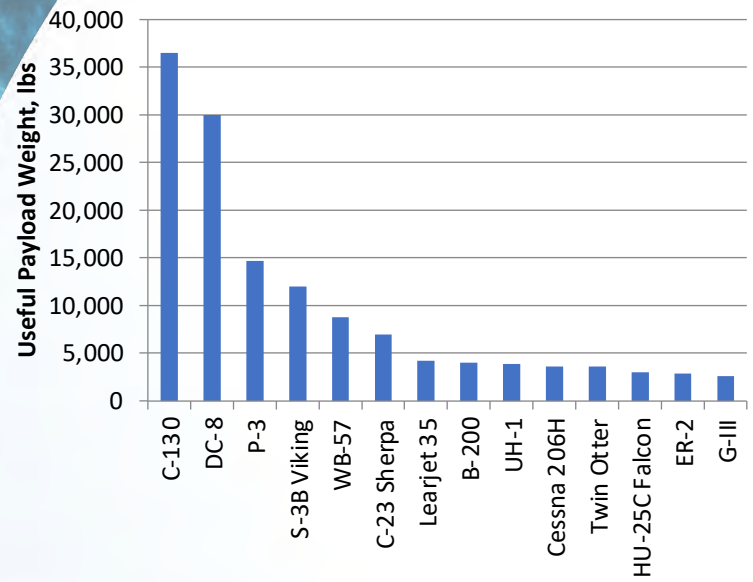


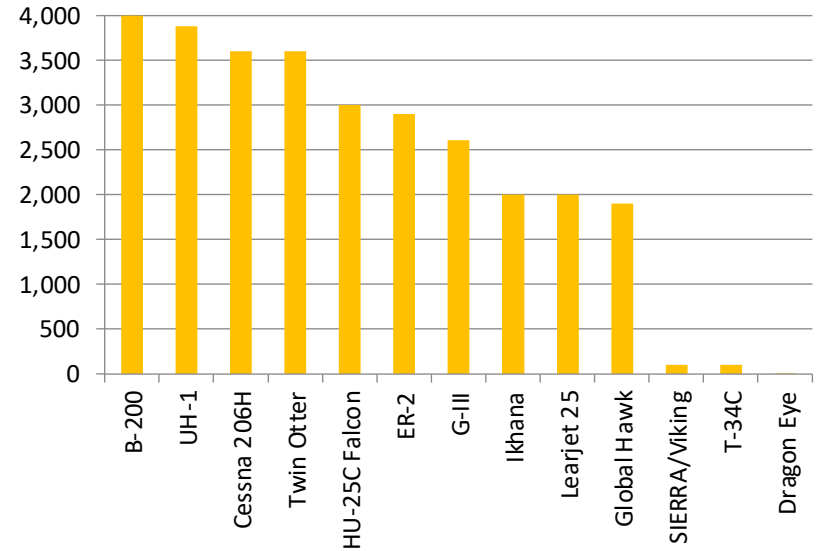
Category 1 – 55lb. Or less GTOW; Less than 10lb payloads; several miles of range; less than 1 hr flight duration; local measurements
- eg. High resolution gas sampling; high resolution remote sensing
- Access to airspace under FAA MOA and Part 107

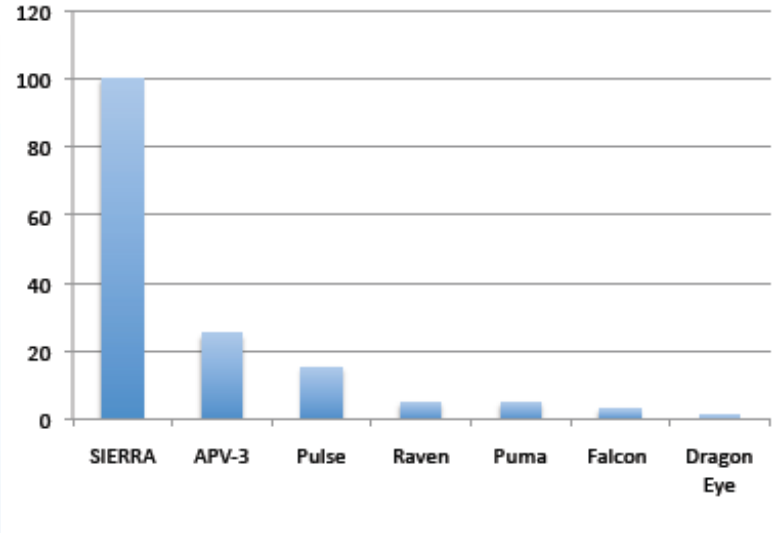
Category 2 – 55-330 lbs; 75~payload; fixed wing and single rotor UAS; local to regional measurements
- Enables longer range and altitude
- Small scale HAPS/HALE UAS fall into this category
- Access to airspace via FAA COA
- Chase plane or ground based radar needed for BVLOS

Category 3 – 330+ lbs; 100+ lbs of payload; regional measurements
- restricted to remote regions or line of site (ie. local measurements)
- Access to airspace via FAA COA
- Routine access to National Airspace not available

Comparing available payload mass for conventional and unmanned aircraft







NASA has a long history with UAS: 1989-2007

1989 – First Community Workshop on using UAVs for Earth Science

1993 – DOE/ARM UAV Program: first demonstration flight of a science payload on a UAV

1994 – Perseus UAV selected for participation in ASHOE/MAESA

1994 - 2003 – NASA Environmental Research Aircraft and Sensor Technology (**ERAST**) program

1997 – Pathfinder+ and DAISY: first NASA science payload flown on solar powered UAV

1999 – NASA ERAST and DOE ARM UAV Hawaii Experiment

2000-2002 – NASA UAV Science Demonstration Program (**UAVSDP**)

2001 – First Response Experiment (FiRE) successfully combines Altus, remotely operated sensors and advanced information technologies to provide geo-registered imaging to Internet

2001 – Pathfinder+ demonstrates high resolution imaging during flights over Kauai coffee plantation

2002 – Altus UAV used with manned aircraft in CAMEX-4 (**Altus Cumulus Electrification Study**)

2003 – Formation of UAV Application Center at NASA Research Park

2004 – First use of SAVDS radar and short range tracking for detect-and-avoid

2005 - First Altair remote sensing missions

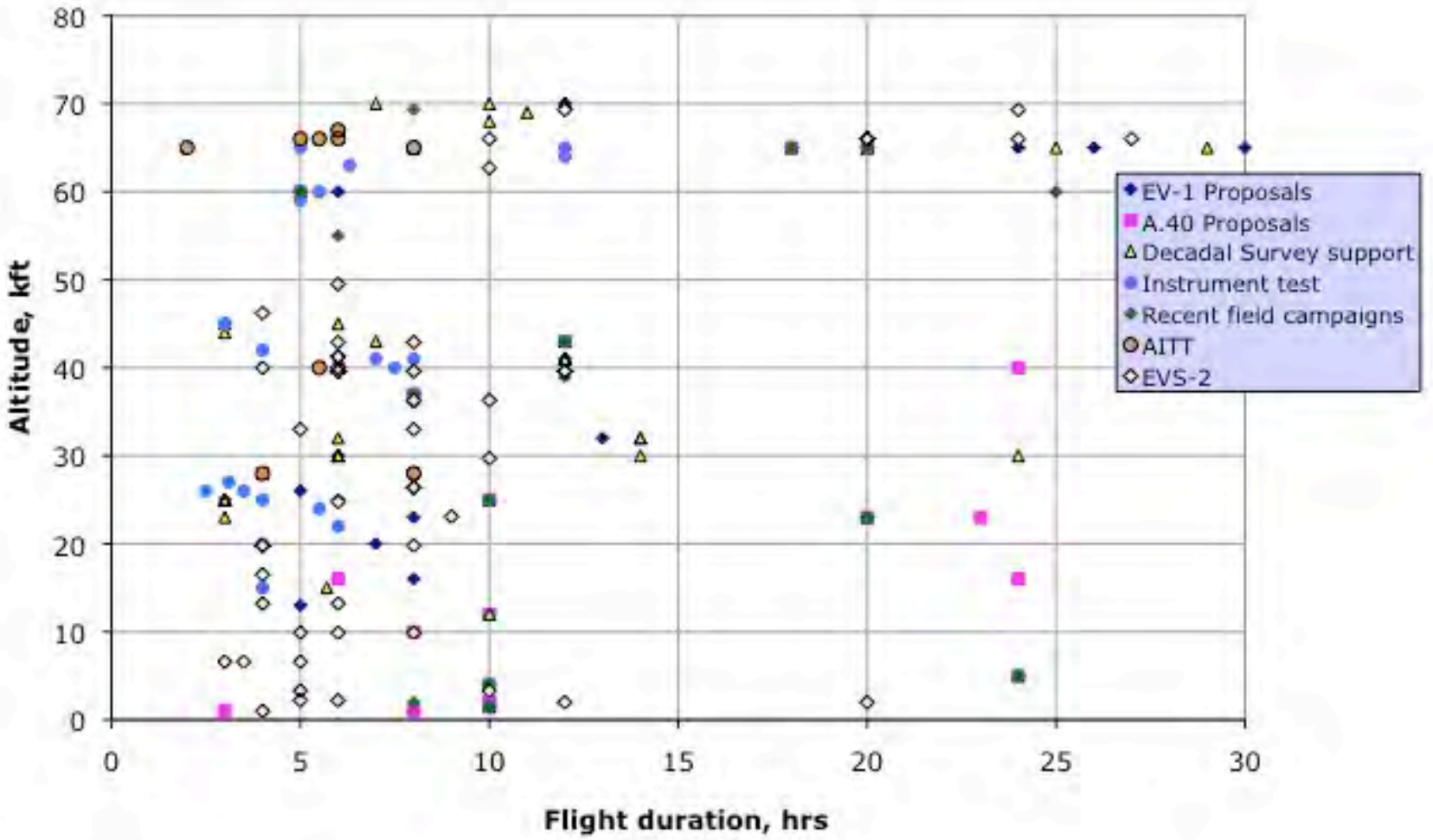
2005 - 2 SIERRA UAV acquired from NRL

2006 – Interagency small UAV fire demo at Fort Hunter Liggett

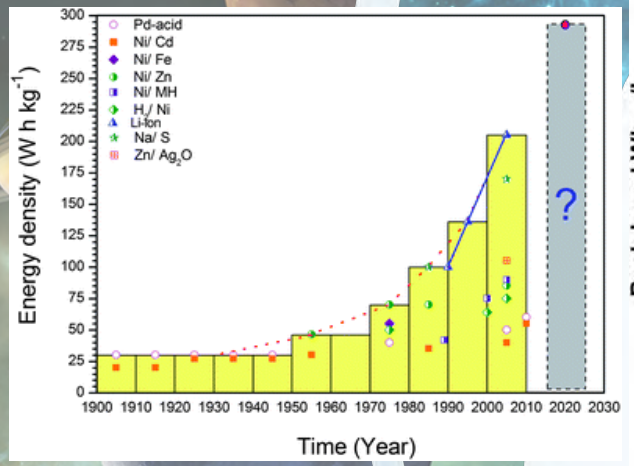
2006 – Maldives stacked UAVs Campaign

2007 – NOAA / NASA flight of Aerosonde into Hurricane Noel

Science Community Requirements for High Altitude Long Endurance Airborne Measurements persist



Why don’t we already have HAPS?



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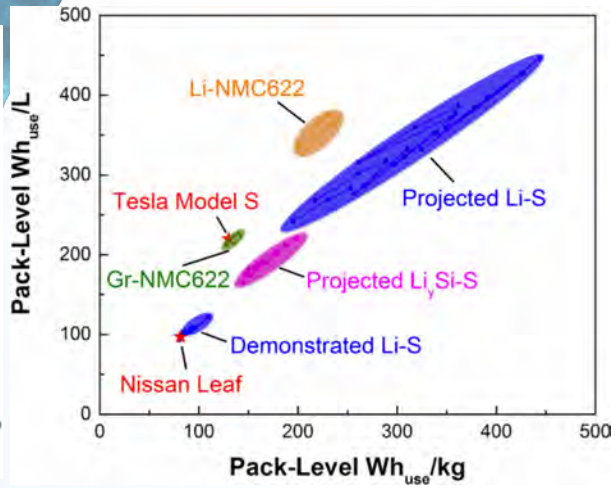

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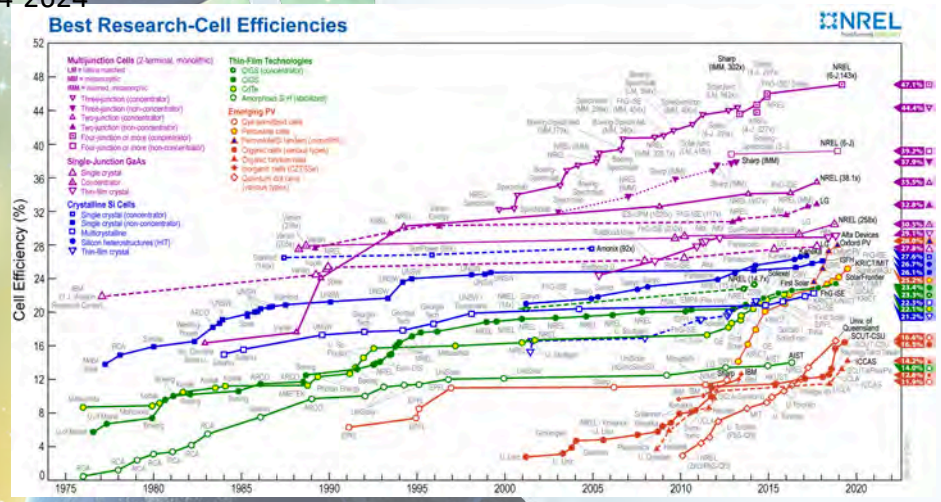
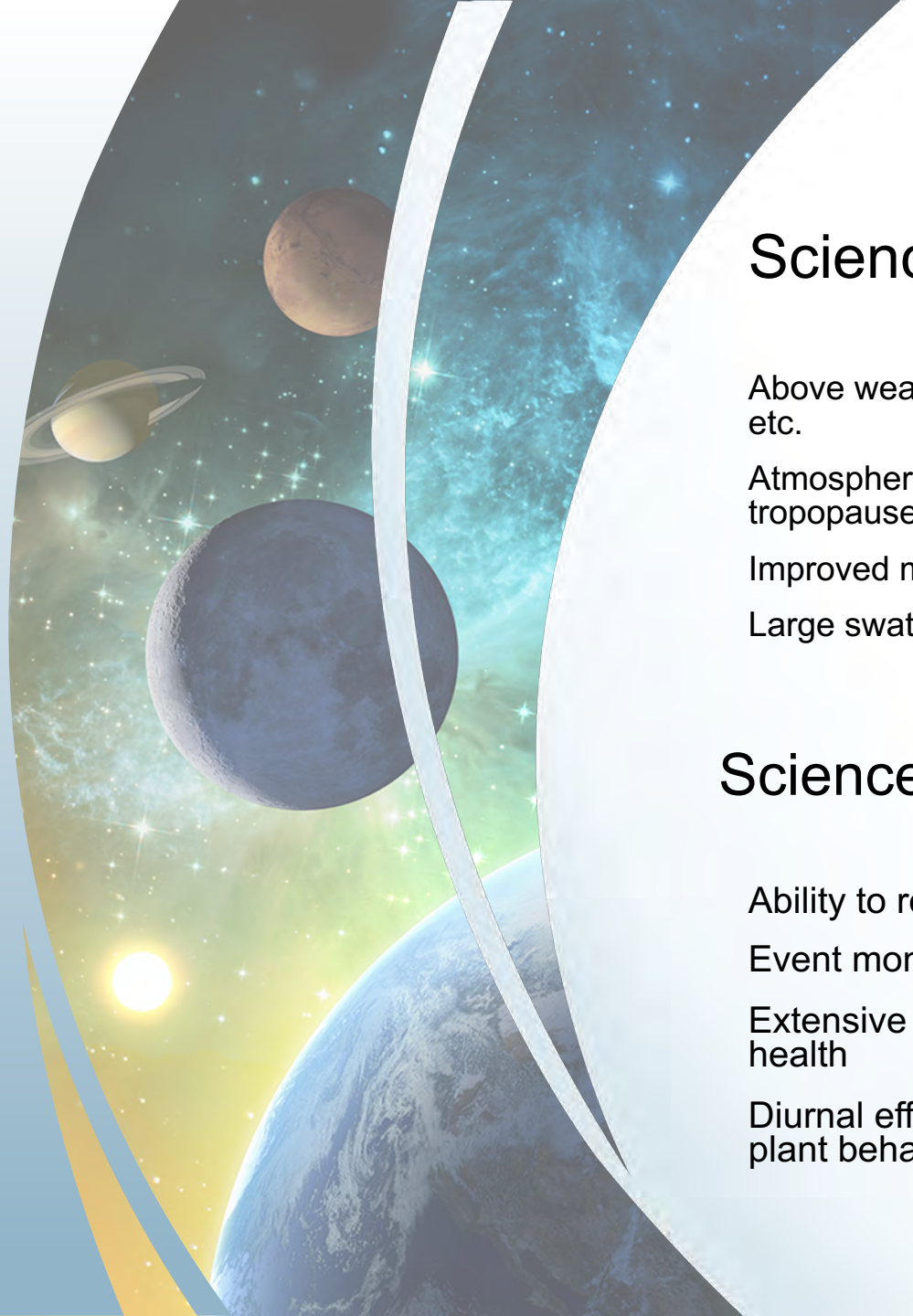


Batteries – only recently have batteries reached the power density and recharge cycles necessary for HAPS propulsion. New battery chemistries including Li-Sulphur are also making the aircraft safer.

Solar panels – improved efficiency, flexibility, and low mass

Strong, Light-weight materials are required to sustain wind gusts

Low SWAP avionics have only recently become available



Science from high altitude (60-70,000ft)

Above weather: satellite simulation, observe storm formation, deploy dropsondes etc.

Atmospheric composition: chemistry and dynamics in the stratosphere and at the tropopause; pollution tracking

Improved measurements of key climate drivers: clouds, aerosols and radiation

Large swath imaging: coastal zones, cryosphere monitoring, terrestrial ecology

Science with long duration flight (24-36+hrs)

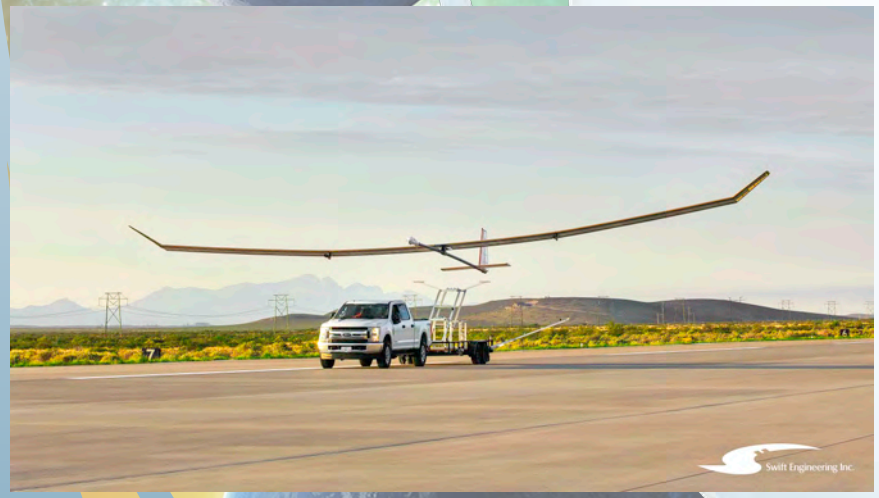
Ability to reach remote locations and loiter: oceans, ice, forests, islands

Event monitoring: storms, flooding, fires, volcanic activity, pollution events

Extensive mapping: Earth surface/topography, terrestrial imagery, vegetation health

Diurnal effects: green house gases, atmospheric composition and dynamics, plant behavior, animal behavior

Swift Engineering
High Altitude Long Endurance UAS

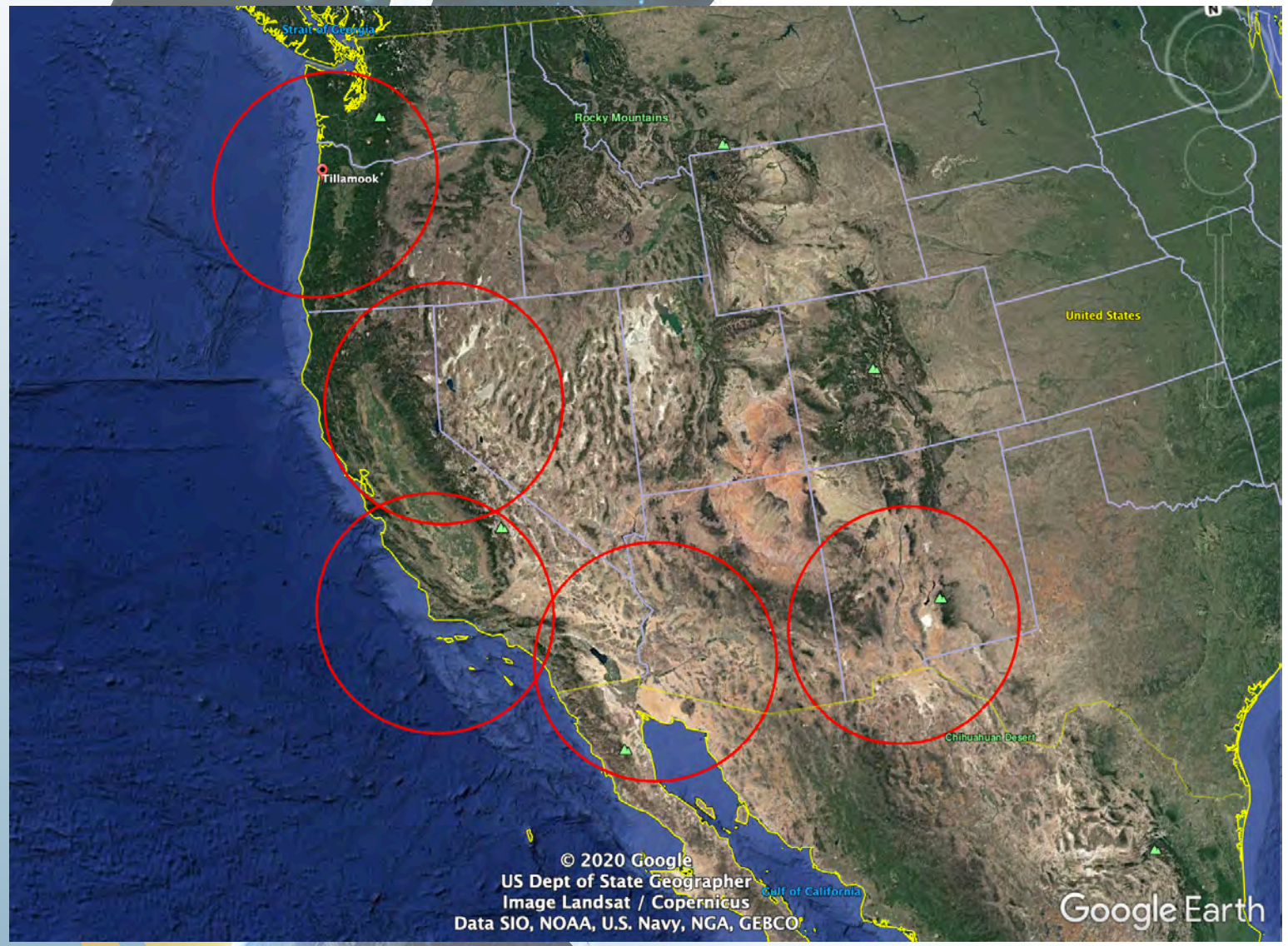


The Swift HALE UAS first flight took place at SpacePort America in New Mexico on July 7th, 2020

The flight lasted for 2 hours and enabled to team to do several L/D maneuvers as well as climb test to validate performance models.

This prototype was developed through NASA SBIR Phase II funding in cooperation with NASA Ames

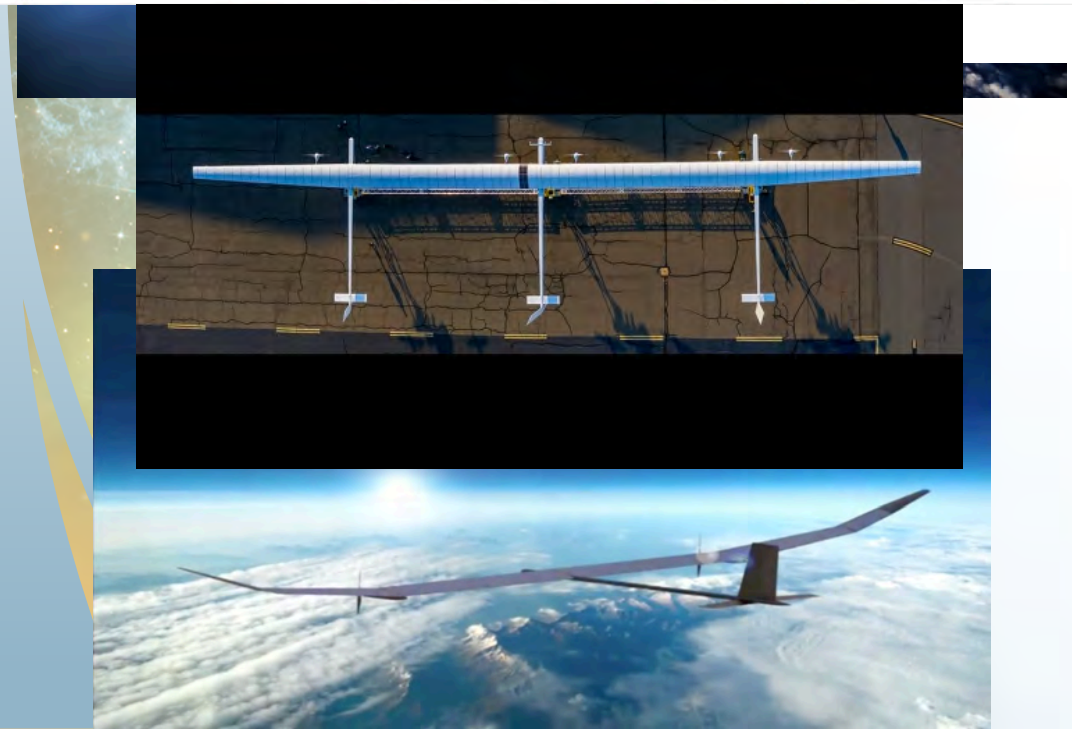
A Phase II-E in partnership with USFS, and USGS will demonstrate a long endurance remote sensing mission in summer 2021 following additional envelope expansion flights later this year.



Range rings represent approximate coverage area for 1 HALE for 200nm radius daily operations.

Current launch and recovery locations in discussion include:

- SpacePort America, New Mexico
- Yuma Proving Grounds, Arizona
- Vandenberg AFB, California
- Reno Stead Airport, Nevada
- Tillamook UAV test site



Other HALE UAS under development

Airbus Zephyr Program

Status: Operational; new ops base in Australia

Capability: GTOW 165lbs and 71ft wingspan; ~10-20lb payload; Zephyr-T under development with ~50lb payload

HAPSMOBILE

Status: Low altitude test flights completed; COA issues for flights over Lanai

Capability: 260 ft wingspan; 6 month endurance; payload ~ 100lbs. Total investment to date: $126 million.

Aurora Odysseus Program

Status: Under Development; **Indefinitely delayed**

Capability: 65,000 ft cruising altitude for 3 months carrying ~50lbs of payload with 250 watts of continuous payload power and a wingspan of 74 m. (ref. Jane's)

Prismatic

Status: 2 Prototypes produced; Flight testing in early 2020

Capability: 300+lb GTOW; 100+ft wingspan; 30lb payload; 1 year endurance; 55 kts

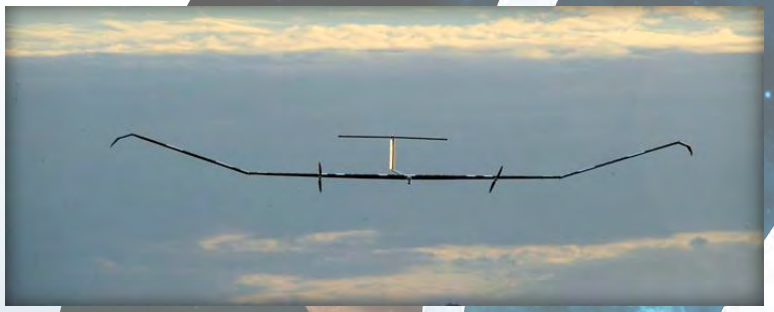
$1.5B in investments in 2018.

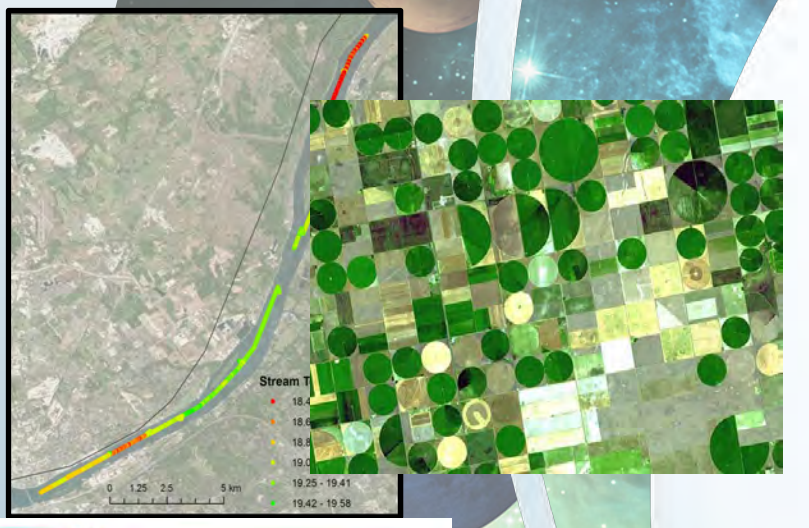
SCEYE One and Two

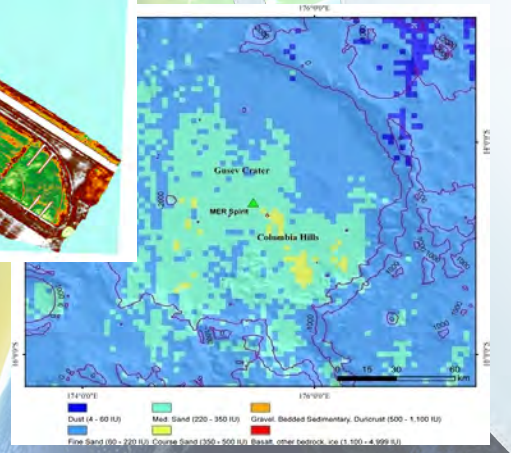
Status: Subscale prototypes flown; Oct 2020 testflights

Capability: 250ft airship 100+kg payload; 10kw Power; station-keeping at 65kft altitude for months to a year; 18 kts

HAPS mission concepts

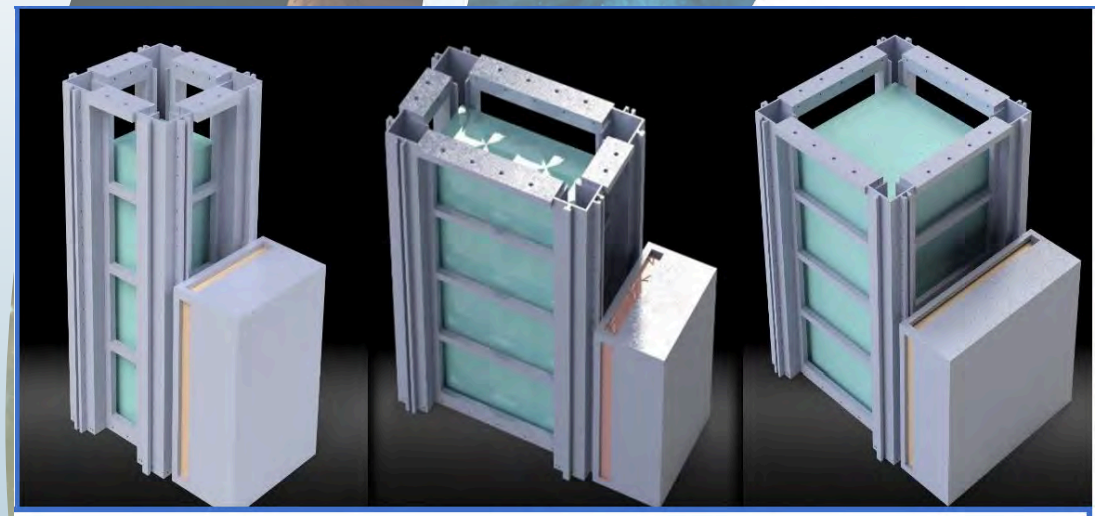






- NASA Designated Observables Architecture study teams for Surface Deformation and Change (SDC) as well as Surface Biology and Geology (SBG) have included HAPS in their studies.
  - SDC: SAR on HAPS might inform on episodic, fast moving phenomemon in between satellite overpasses
  - SBG: imaging spectrometers on HAPS could provide additional intraday to intramonth data for specific regions during green-up, and green-down or after disturbances, in order to augment satellite data
- Disaster monitoring – loitering over fire or volcano with SAR and optical MWIR/LWIR for gas
- Coastal zone imaging – Fluid Lensing and MIDAR demonstrations - Evapotranspiration, Crop Health, And Water Resources In Irrigation-dependent Agriculture
- Using Temperature To Identify At-risk Stream Environments: Studying Agricultural Drainage, Conservation Management, And Sensitive Ecosystems
- Thermal Inertia, Manning's *N*, Glacial Processes, And Sediment Transport Analysis
- UTLS chemistry – understanding water vapor and other fluxes into the stratosphere

Xcube: leveraging cubesat standards to facilitate airborne testing



3U, 6U, and 12U XCube Carriers

- USRA and Ames Airborne Sensor Facility is supporting a CalPoly student team in designing a CubeSat payload carrier for “suborbital platforms”
- Goals is to create a standardized interface for science payloads to reduce barriers for science data collection and instrument testing
- CubeSat Carrier will be modular so it can be scaled accordingly for different payload bays and aircraft.
- Integration and testing planned on the NASA ER-2, SIERRA but is portable to other aircraft

Conclusions

- Given technology advances and significant government and commercial investment over the past decade, HALE UAS will be operational and available to science within the next 3-5 years
- HALE UAS will enable loitering over local to regional targets to provide geostationary like measurements with improved spatial and temporal resolution
- NASA is supporting partnerships and collaborations with industry to validate technologies and capabilities, develop concepts of operations, and refine cost estimates for various missions sets.
- Aeroenvironment, Prismatic (BAE Systems), SCEYE and Swift Engineering all have very promising technologies