Synthetic Aperture Radar for STV Overview

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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

SRTM (TopSAR)

UAVSAR (Polarimetric DInSAR)

DEM of Okmok, Alaska

Pol. composite of Mondah Forest

SRTM used two antennas with cross-track baseline to map topography
## Radar Bands of Interest

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

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

Microwave interacts most strongly with objects the size of the wavelength

Leaves reflect X-band wavelength but not L-band

---

Rosen, 2009
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

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

**Instruments**

- **UAVSAR (NASA)**: P- & L-band polarimetric DInSAR, Ka-band HH TopSAR. Capabilities include surface deformation change detection, vegetation structure, volcano topography, and ice/snow topography.
- **GeoSAR**: P- & X-band TopSAR. Capabilities include DTM and DSM.
- **Intermap**: P-band PolSAR & X-band TopSAR. Capabilities include 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

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

592 million m$^3$

Kilauea lava flow thickness
(Credit: Paul Lundgren)
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

<table>
<thead>
<tr>
<th></th>
<th>P-band</th>
<th>X-band</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (cm)</td>
<td>86</td>
<td>3</td>
</tr>
<tr>
<td>Polarization</td>
<td>Quad pol</td>
<td>VV</td>
</tr>
<tr>
<td>Peak transmit Power (kw)</td>
<td>4</td>
<td>8</td>
</tr>
<tr>
<td>Antenna baseline (m)</td>
<td>20</td>
<td>2.5</td>
</tr>
<tr>
<td>Horizontal spacing (m)</td>
<td>1.25 - 5</td>
<td>1.25 -5</td>
</tr>
<tr>
<td>Ground swath (km)</td>
<td>12-14 per side</td>
<td>12-14 per side</td>
</tr>
<tr>
<td>DEM height accuracy (m)</td>
<td>1-3 (rel.)</td>
<td>0.5-1.2 (rel.)</td>
</tr>
<tr>
<td></td>
<td>2-5 (abs.)</td>
<td>1-3 (abs.)</td>
</tr>
</tbody>
</table>
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
SAR Systems used for geodetic imaging

Present (2018-2020)

- Sentinel-1A/B (C)
- ALOS-2 (L)
- RADARSAT2 (C)
- TerraSARs (X)
- COSMO-SkyMeds (X)
- RISAT-1A (C)
- ASNARO-2 (X)
- Others...

2020-2030

- Sentinel-1 C/D / Rose-L A/B
- ALOS-4 (L)
- PAZ (X)
- RCM (C)
- NovaSAR (S)
- CSK-NG (X)
- Iceye (X)
- Others...

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

Biomass (P)

NISAR (L/S)

Tandem-L (?)

Other Commercial Constellations (?)

Credit: Batu Osmanoglu
### G-PoR – Government Agency SAR Satellites

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

* 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.
# C-PoR – Commercial SAR Satellites

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

* 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
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 1° tile at the equator, $65k per 1° tile at 32° 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!

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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**

\[
\gamma(\kappa_z(\vec{B})) = e^{i\phi_0} \int_0^{h_B} f(z) \exp(ik_z z) dz
\]

**Phase**

\[
\text{Phase} = \arg[\gamma(\kappa_z(\vec{B}))]
\]

**Coherence**

\[
\text{Coherence} \equiv |\gamma(\kappa_z(\vec{B}))|
\]
Vegetation Structure from Interferometric SAR: Phase and Coherence

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

Phase $= \arg(\gamma(\kappa_z(\vec{B})))$  Coherence $\equiv |\gamma(\kappa_z(\vec{B}))|$
Vegetation Structure from Interferometric SAR

1) Inverse Fourier Transform—Tomography

\[
\gamma(\kappa_z(\vec{B})) = e^{i\phi_0} \int_0^{h_v} f(z) \exp(i\kappa_z z) \, dz
\]

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

Large number of \(\kappa_z\) (baselines) required
2) Parameter Estimation—PolInSAR

Pick $\phi_0$, $h_v$, and simple $f(z; P_m)$, and make model observations for several $\kappa_z$ (baselines)

$$\gamma(\kappa_z)_m = e^{i\phi_0} \int_0^{h_v} f_m(z; P_m) \exp(i\kappa_z z) dz$$

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

At minimum data-model, arrive at best model estimates: $h_v$, $\phi_0$, and $f_m(z; P_m)$
2) Parameter Estimation—PolInSAR

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

Papathanassiou, Cloude 2001
(tempereate) L-band

Kugler et al. 2015
(tempereate) 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 ($\kappa_z$, 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
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

\[
s(n) = \sum_{m=1}^{N_s} \sqrt{\sigma_m} x_m(n) \odot a(z_m) + g(n) \quad n = 1, \ldots, N_t
\]

\[
P_{F}(z_m) = \frac{a^\dagger(z_m) \hat{R}_s a(z_m)}{N^2}
\]

\[
\hat{R}_s = \frac{1}{N_t} \sum_{n=1}^{N_t} s(n)s^\dagger(n)
\]

\[
a(\omega) = \begin{pmatrix}
1 \\
\exp(\j z_2 b_2) \\
\vdots \\
\exp(\j z_N b_N)
\end{pmatrix}
\]

\[
\omega(z) = \frac{4\pi z_i}{\lambda r} = \frac{4\pi z}{\lambda r \sin \theta}
\]
TomoSAR proof with JPL airborne experiment

2016 AfriSAR Airborne Campaign (Gabon)
DTM, DSM and Tree height mapping from L-band radar tomograms

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
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)
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
\[
\sigma^0 = \sigma^{ss} + \sigma^{sv} + \sigma^{vs} + \sigma^{vv}
\]

- **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**: GLISTINA 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!
• 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
Independent field observations of depth change show a mean depth change of 9cm over this period.

In these conditions (surface density \( \sim 200 \text{ kg/m}^3 \)), 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 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

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09/10/2020

Outline

• Signals of Opportunity Concept
• Snow Measurement Using SoOp
• Ocean Altimetry Measurement Using SoOp
• Summary
The Electromagnetic Spectrum: \textit{Valuable Real Estate}

\textbf{Two Windows on the Earth}

![Electromagnetic Spectrum Diagram](image-url)
Signals of Opportunity (SoOp) Reflectometry

non-science

science
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

\[ R \approx R(f, \text{Soil Moisture}) \]

\[ \phi_s \approx a \cdot f \cdot SWE \]

\( \phi_s \): phase change  
\( f \): frequency  
\( a \): depends on \( \theta \)  
\( R \): Reflectivity

Yueh et al., 2017
Snow Retrieval Demonstration

Shah et al., 2017

260 MHz

Retrieved SWE vs. In-situ SWE

Retrieved SWE
Linear Regression

Retrieval RMSD = 7.44 mm

260 MHz and 370 MHz

Shah et al., 2017
Ocean Altimetry Measurement

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

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

Platform Harvest

RMSD = 2.78 cm
Ku-Band
K-Band

Ho et al., 2019
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
EXPLOR\textsc{e} EARTH

The HALE UAS Capability Assessment and Demonstration Project

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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
Components of a Global System for Earth Observation

Far-Space
- Sentinel satellites for continuous monitoring

Near-Space
- Active & passive sensors for trends & process studies

Airborne
- In situ measurement in research campaigns & validation of new remote sensors

Terrestrial
- Ocean buoys, air samplers, strain detectors, ground validation sites

Deployable

Permanent

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?

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
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 the 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
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.

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

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$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 phenomenon 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
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