Air Campaign Results for the Wideband Instrument for Snow Measurements (WISM)

NASA ROSES Instrument Incubator Program
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50 to 80% of the yearly water supply in the Western United States is supplied by the seasonal snowpack. To effectively manage water resources, accurate measurement of the amount of water in the snowpack, the snow water equivalent (SWE), are needed on the very small spatial scales over which the snowpack varies.

Highly variable snowpack
Harris leading a NASA ROSES (Research Opportunities in Space and Earth Sciences) IIP (Instrument Incubator Program)
  - Currently in second round of funding

Developing the science and technology needed to carry out a remote sensing mission to make snow measurements from both airborne and space platforms

Snow and Cold Land Processes (SCLP) mission concept from NASA Decadal Survey uses four instruments to gather data on snow pack extent and characteristics (depth, density, snow water equivalent (SWE))

Existing antenna concept uses reflector antennas fed by individual feeds for each frequency/beam
  - Multi-element feeds produce offset beams

**Demonstrated** the technology to replace the feed manifold with a single array feed capable of supporting both SAR and radiometry
  - Performance improvement (i.e. co-boresighting)
  - Significant size, weight, power advantages

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Approach

• Combine active and passive sensing technologies in a single instrument
  – Built a multi-band radar/radiometer that utilizes the same antenna for six bands from X- to Ka- Band
  – Instrument is software reconfigurable for many important parameters
• Build wideband antenna
  – Implemented first version of Harris’ Current Sheet Array (CSA) antenna that operates from 8-40 GHz
  – Fabricated the array aperture and RF components in the antenna
  – Enhanced version to be built on second IIP
• Perform experiments
  – Ground based experiments in first IIP demonstrated antenna technology is compatible with wideband radars
  – Airborne experiments in second IIP will demonstrate science of snow measurement using active/passive combined sensing

Enhanced Multi-Band/Multi-Function Instrument
• X-band (Up-down, SAR)
• X-band (Down, radiometer, enhancement)
• Ku-band lower (Up-down, SAR, enhancement)
• Ku-band upper (Up-down, SAR)
• K-band (Down, radiometer)
• Ka-band (Down, radiometer)

The Wideband Instrument for Snow Measurements (WISM)
Phase II Progress

- Secondary antenna testing completed at GRC
  - Demonstrated wideband performance in the reflector
  - Patterns compare well with predictions
  - Gain consistent with expectations at three bands
  - Gain at X-band lower than expected but acceptable for tests

- Multi-band instrument completion
  - Radiometer
    - Design and build completed
    - Extensive lab testing performed at GSFC SIRF
    - Rooftop testing demonstrated performance with the WISM reflector
  - Radar
    - Upgrades completed
    - End-to-end signal path complete
    - System testing complete
  - System
    - Radar/Radiometer integration completed

- First air campaign completed
  - Instrument successfully integrated into airplane
  - Four flights carried out over Grand Mesa, CO
  - Extensive concurrent ground measurements taken
  - Data processing nearing completion for all three instruments flown
Enhanced WISM Architecture

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Antenna Feed: Final Assembly

- Two X-to-Ka-band antenna feeds delivered
- Total size is 2.8” by 2.8”

More than 12m of transmission line routing in a volume of 10cm³
WISM IIP Experiments

• Ground Experiments in 2010 IIP
  – Carried out by HP Marshall of Boise State University
  – Demonstrated use of wideband antenna for SWE measurements
  – Used 2-18 GHz ESM (Harris IR&D) and Alpha-Build (IIP) antennas
  – Utilized existing radars at Boise State to successfully measure snow depth and stratification

• Three Airborne Experiments planned for 2013 IIP
  – Goal is to demonstrate use of 8-40 GHz antenna for SWE measurements
    • Algorithms updated as required
  – Multi-band SAR and Radiometer test-bed
    • Add additional frequency to both
  – Use Twin Otter for airborne testing
NASA GRC Planar Near-Field Range

- 40’ x 40’ x 60’ test volume
- Vertical Scanner with 22’ x 22’ scan plane
- 15 ton capacity azimuth over elevation pedestal
- Removable sidewall, bridge cranes and drive in dock
- Nearfield Systems, Inc., transceiver, motion control, experiment and data processing software
- Transceiver frequency range 2-50 GHz
- Probe rotational stage for automated polarization control
Example Result: $K_u$-Band (Radar), Port JH1

**Principal Plane Pattern**

- Frequency: 17.20 GHz

**Directivity and Gain**

- Frequency (GHz): 16.8 to 19
- Gain: 30 to 35 dBi
- Directivity:

  - Co-pol
  - X-Pol

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Example Result: $K_a$-Band (Radiometer), Port JH1

Principal Plane Pattern

- Graph showing principal plane pattern for $36.50\text{ GHz}$
- Azimuth (deg) on the x-axis
- Normalized Magnitude (dB) on the y-axis

Directivity and Gain

- Graph showing directivity and gain over frequency (GHz)
- Frequency (GHz) on the x-axis
- dBi on the y-axis

Gain and Directivity plotted separately

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First WISM Flight Campaign

- Site Location: Grand Mesa, Colorado
  - SWE measured on ground by field crew lead by HP Marshall, underneath and simultaneous with flight lines.
  - Environment Canada Research colleagues joining ground crew
  - ~20 minutes from airport to target.
- Twin Otter Flight Requirements
  - Speed: ~100 knots/hr
  - Altitude: 3000 and 5000 ft. (radar/radiometer) and 1500 ft. (Lidar)
  - Endurance needed: 1 to 3 hours
- Three instruments total
  - WISM Radar
  - WISM Radiometer
  - Mini-ATM Lidar
- Flight Plans
  - Full campaign time span: 2/12/15-2/27/15
  - Flight dates: 02/21/15, 02/22/15 and 02/24/15 (2 flights)
  - 12 total flight hours over 4 flights.
  - Out and back flight lines over ground targets including corner reflectors, lakes and ground measurements.
Integration at TOI
First Flight

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50 km flight line chosen optimally for goals of WISM: simple topography, large non-forested openings, dynamic range of SWE

- Line minimized short-length scale variability, correlation length ~200m
- West half of line simple vegetation, smooth topography
- Eastern half more complex vegetation, steeper terrain
- Minimize risk of wet snow (high elevation mesa, 10,000+ ft)
- Snow over both ground and frozen lakes/reservoirs
Air Campaign Ground Observations

- 19 detailed snowpits along flight line (density, temperature, grain size, grain type, layer thickness profiles)
- 8000+ manual depth measurements
- 2 snowmobile radars profiled entire line multiple times, 10cm resolution
- Near-InfraRed Photography, SnowMicroPenetrometer, snow grain photos recorded snow microstructure at pits
- Storm layers sampled for oxygen isotopes to determine age and link precip events along line
- 16 Radar corner reflectors deployed and surveyed, 3 sizes
Accurate High-resolution Snow Observations Covering Large Dynamic Range

- 11-53cm range in SWE
- 30-165cm range in depth
- 100-448 kg/m^3 range in density
- New snow, small fine grained rounded snow, large faceted depth hoar
Terrain Characteristics

- Snow covered ground
- Snow covered Lakes
- Wide range of vegetation and snow conditions
Miniature Atmospheric Topographical Mapper

POC: Bradly Hood, WFF (ASRC)

Laser Altimeter that measures surface topography providing meter-scale roughness. Ability to measure snow depth given a digital elevation model.

Statistics:
- Riegl LiDAR – Q240i - 60
- Weight: LiDAR Pod – 30 lbs, Electronics shelf – 8 lbs, Harness – 2 lbs, GPS Antenna 1lb
- Power Consumption: ~60 Watts Peak, 28 VDC
- Integrated Novatel INS
- Operating Range: Up to 800 M depending on surface reflectivity
- TRL 6, UAS

Twin Otter (TO) Nadir Port
MiniATM RTD Computer and PSU mounted in TO
Sample color coded topographical map (Wallops Island)
- Using Waypoint Inertial Software
- Flight 4 data:
  - Figure 1: Raw GNSS data shows a rough flight path.
  - Figure 2: Analysis of the GNSS data shows good acquisition in green. The blue points are slightly less accurate due to the $60^\circ$ banked turn.
  - Figure 3: Analysis of the combined GNSS and IMU data fills gaps where GPS data was lost and gives a complete location and attitude solution.
LiDAR Data Summary

- Figure 6: visual representation of the data collected over the path of the flight line.

- Figures 7 and 9: Show 2D images of take off and landing and Grand Mesa.

- Figures 8 and 10: Show 3D images of the highlighted areas in 7 and 9.

- Adding base station data will further improve accuracy
Radar – Radiometer Interference Testing

Confirmed that the radar will not interfere with or damage the radiometer despite common antenna
Calibrated Brightness Temperature ($T_B$)  
**Ex. Flight 1; 1500Ft Pass1 Eastbound**

### Science Measurements

- **Calibration measurements**
  - Pre-flight Measurements
    - Two black bodies separated by ~20 K
    - Sky views at 0 and 45 degrees zenith using large metallic reflector
  - Aircraft 60 degree banks for in-flight sky measurements
  - Detailed antenna pattern measurements
  - Characterization of front-end RF components

- **Data Processing Programs**
  - Remove 1.2 kHz radar transmit pulses
  - Noise removal (~30s periodic spikes from data system, 2.5% data loss)
  - Filter and down sample from 100kHz to ~20 Hz
  - House keeping data (scale, filter, synchronize)
  - Calibrates noise sources via hot and cold internal calibration standards, then calibrates scene (snow) via noise source and cold standard

- **Preliminary analysis**: eastbound scene-snow data (Ku-band shown)
  - Raw radiometer data (7 states, 80% scene duty cycle)
  - Preliminary calibration will be improved with Enhanced WISM
• Airborne Stripmap Synthetic Aperture Radar operating at X and Ku bands with 10 meter resolution
• Single polarization transmit (V) dual polarization receive (H,V)
• SAR images are formed via post-processing algorithms

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platform Altitude</td>
<td>457 (1500), 914 (3000), 1524 (5000)</td>
<td>meters (feet)</td>
</tr>
<tr>
<td>Platform Speed</td>
<td>45</td>
<td>m/sec</td>
</tr>
<tr>
<td>X-Band Center Frequency</td>
<td>9.75</td>
<td>GHz</td>
</tr>
<tr>
<td>Ku-Band Center Frequency</td>
<td>17.2</td>
<td>GHz</td>
</tr>
<tr>
<td>Transmit Bandwidth (LFM)</td>
<td>27.1</td>
<td>MHz</td>
</tr>
<tr>
<td>Slant Range Resolution</td>
<td>6.7</td>
<td>m</td>
</tr>
<tr>
<td>Ground Range Resolution</td>
<td>10.0</td>
<td>m</td>
</tr>
<tr>
<td>Azimuth Resolution</td>
<td>10.0</td>
<td>m</td>
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</tbody>
</table>
**RADAR Post Processing**

**Data Pre-Conditioning**

1. **NAV Data File**
   - Interpolate NAV Data to Pulse Time Stamp
   - Pulse Baseband Conversion
   - Pulse Data Matched Filter & Window
   - Baseband Pulse With Navigation Interpolated Data File (float)

2. **Raw RADAR Packet Data File**
   - Pulse Extraction From Ethernet Packets
   - Raw RADAR Packet Data File
   - NAV Interpolated Pulse File (16 bit Samples)

3. **USGS DEM Map**
   - USGS DEM Map
   - Calculate R₀, Vᵣ For Aperture
   - Configure SAR Data Structure
   - Apply Platform Orientation Configure Grid/Mesh
   - Compute SAR Algorithm
   - Calculate σ₀

4. **Calculate SAR Aperture # Pulses/Image**
   - Form 2D Range/Azimuth SAR signal array
   - Form NAV Data array Per Aperture

**SAR Data Processing**

**Validation Underway**

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Scattering Coefficient Estimation

\[
\sigma_0 = \frac{P_{ave} G_T G_R \eta^2 \delta_r}{8 \pi \lambda R^3 \nu kTFL_{sys} SNR}
\]

- Transmitter EIRP
- Range Resolution
- Scattering Coefficient
- Accurate Range Estimate using USGS DEM Map and Navigation Position Data
- Velocity from NAV Data Estimate
- Equipment Calibration Factors
- Derived from Matched Filter Signal Plus Noise Output Level
# Air Campaign Data Summary

<table>
<thead>
<tr>
<th>Date</th>
<th>Flight #1 (GigaBytes)</th>
<th>Flight #2 (GigaBytes)</th>
<th>Flight #3 (GigaBytes)</th>
<th>Flight #4 (GigaBytes)</th>
<th>Data Summary Per Polarization (Gigabytes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>2/21/2015</td>
<td>2/22/2015</td>
<td>2/24/2015</td>
<td>2/24/2015</td>
<td></td>
</tr>
<tr>
<td>Purpose</td>
<td>Snow Science</td>
<td>Engineering Airport Flight</td>
<td>Snow Science + Airport (5000)</td>
<td>Snow Science</td>
<td></td>
</tr>
<tr>
<td>Altitude</td>
<td>1500, 3000</td>
<td>1500, 3000</td>
<td>1500, 3000, 5000</td>
<td>1500, 3000, 5000</td>
<td></td>
</tr>
<tr>
<td>Ku-Band H-Pol Data Volume</td>
<td>0</td>
<td>34.5</td>
<td>301</td>
<td>475.8</td>
<td>811.3</td>
</tr>
<tr>
<td>Ku-Band V-Pol Data Volume</td>
<td>0</td>
<td>34.5</td>
<td>300.3</td>
<td>474.4</td>
<td>809.2</td>
</tr>
<tr>
<td>X-Band H-Pol Data Volume</td>
<td>0</td>
<td>16.6</td>
<td>33.3</td>
<td>49.7</td>
<td>99.6</td>
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<tr>
<td>X-Band V-Pol Data Volume</td>
<td>0</td>
<td>89.7</td>
<td>97.7</td>
<td>464.4</td>
<td>651.8</td>
</tr>
<tr>
<td>GPS/INS Data Volume (MB)</td>
<td>44.2</td>
<td>47.3</td>
<td>105.5</td>
<td>47.1</td>
<td>2.44</td>
</tr>
<tr>
<td>Total Per Flight (Gigabytes)</td>
<td>0.044</td>
<td>175.4</td>
<td>732.4</td>
<td>1464.3</td>
<td><strong>2372.2</strong></td>
</tr>
</tbody>
</table>
Example Ku-Band Range Pulse Return

- Peaks in matched filter response indicate images of transmit pulses
- Returns are occurring at the correct time
- SAR processing will sort pulses into resolution “bins” for SWE extraction
<table>
<thead>
<tr>
<th>WISM Enhancement</th>
<th>Instrument component affected (responsible organizations):</th>
<th>Implementation</th>
<th>Science/Performance Justification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Add additional radar frequency of operation at 13.6 GHz (Ku Band)</td>
<td>Radar (Harris)</td>
<td>Additional up/down converters, digital hardware and software modifications</td>
<td>Obtain data at additional frequency to reduce sensitivity of SWE inversion to grain size</td>
</tr>
<tr>
<td>Add X-band receiver to radiometer</td>
<td>Radiometer (GSFC)</td>
<td>Repackage radiometer to accommodate receiver, diplexer, electronics</td>
<td>Improve sensitivity of passive measurements to thick snowpack, add band overlapping radar frequencies</td>
</tr>
<tr>
<td>Through-the-antenna noise injection</td>
<td>Radiometer (GSFC)</td>
<td>Modulated broadband external noise source injected to include CSA feed</td>
<td>Calibrate thermal emission due to front end losses</td>
</tr>
<tr>
<td>Improve radar calibration</td>
<td>Radar (Harris, BSU)</td>
<td>External calibration with corner reflectors, noise floor calibration using injected noise, analysis supporting improved calibration</td>
<td>Achieve radar scattering measurement accuracies that correspond to cm level SWE measurement accuracy</td>
</tr>
<tr>
<td>Lower loss in CSA ahead of radiometer receiver</td>
<td>CSA Feed (Harris, Nuvotronics, GRC)</td>
<td>Reduce loss in waveguide (see text): improve component designs (i.e., splitters, baluns) and integrate into antenna; investigate active component integration (i.e., switches, LNAs) into antenna</td>
<td>Improves radiometer measurement by lowering front-end losses</td>
</tr>
<tr>
<td>Improve Beam Efficiency at radiometer bands (goal of &gt; 95%)</td>
<td>Reflector (Harris)</td>
<td>Shape reflector for improved efficiency</td>
<td>Improves radiometer measurement accuracy by reducing extraneous noise</td>
</tr>
<tr>
<td>Improve aperture efficiency (goal of &gt;85%)</td>
<td>CSA Feed (Harris, Nuvotronics, GRC)</td>
<td>Control aperture amplitude distribution (investigate symmetrically scalable CSA)</td>
<td>Reduces instrument power consumption and lowers ambiguity due to reflected power</td>
</tr>
<tr>
<td>Step scan capability to provide multiple beams</td>
<td>CSA Feed, Radar/radiometer electronics (Harris, GSFC)</td>
<td>Perform analysis of step scan options; possible limited implementation for airborne demonstration</td>
<td>Provides more coverage area per pass for airborne measurements; required for global coverage from space</td>
</tr>
</tbody>
</table>
Conclusions of the Work Performed

• Secondary measurements demonstrated wideband antenna performance in reflector system
  – Meets requirements for active/passive remote sensing
  – Reduces SWaP considerably over competing technologies
  – Allows for co-boresighting of beams

• Dual band radar development COTS parts and existing software to achieve performance goals within budget
  – Several improvements made to original design to enhance effectiveness
    • Power supply
    • Thermal control
    • EMI shielding
    • Window radome
  – Instrument remains intact for future tests/experiments
  – Enhancements made on this IIP will demonstrate reconfigurability

• Dual band radiometer developed that is compatible with integration into the radar system
  – Near simultaneous sensing with all four sensors