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

NASA ROSES Instrument Incubator Program

Presented by: Tim Durham[1], PI

Contributors: Kerry Speed[1], Art Olsen[1], Robert Lange[1], Paul Racette[2], Quenton Bonds[2], Ken Vanhille[3], Leung Tsang, Hans-Peter Marshall[4], Felix Miranda[2], Kevin Lambert[2]

Earth Science Technology Forum 2015
23-25 June 2015
Pasadena, CA

2 NASA   3 NUVOTRONICS   4 BOISE STATE UNIVERSITY

Importance of Snow

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

NASA WISM ROSES IIP Overview

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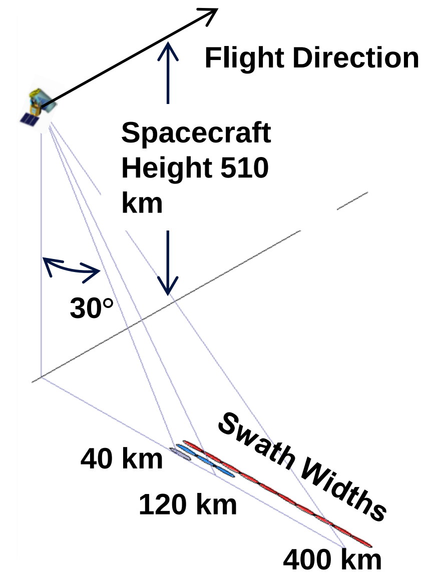
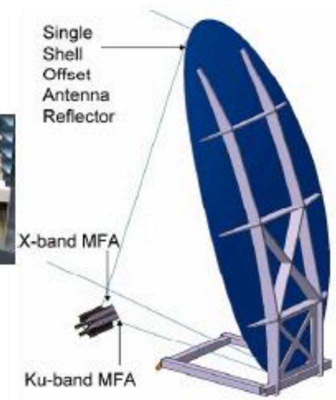
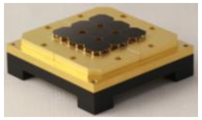
- Harris leading a NASA ROSES (Research Opportunities in Space and Earth Sciences) IIP (Instrument Incubator Program)
  - Currently in second round of funding
- Developing the science and technology needed to carry out a remote sensing mission to make snow measurements from both airborne and space platforms
- 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



[credits: EADS Astrium GmbH]

Existing Technology Feed Concept





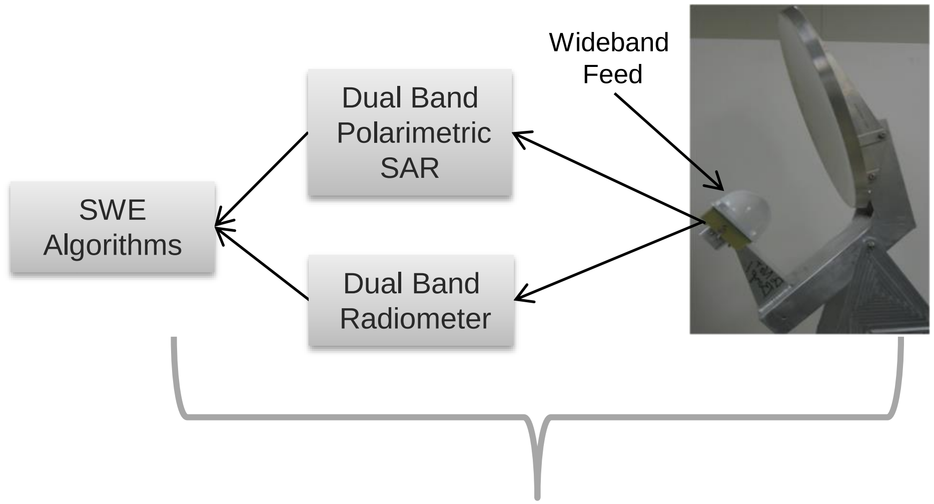
WISM IIP Feed

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

<u>Enhanced Multi-Band/Multi-Function Instrument</u>

- 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)

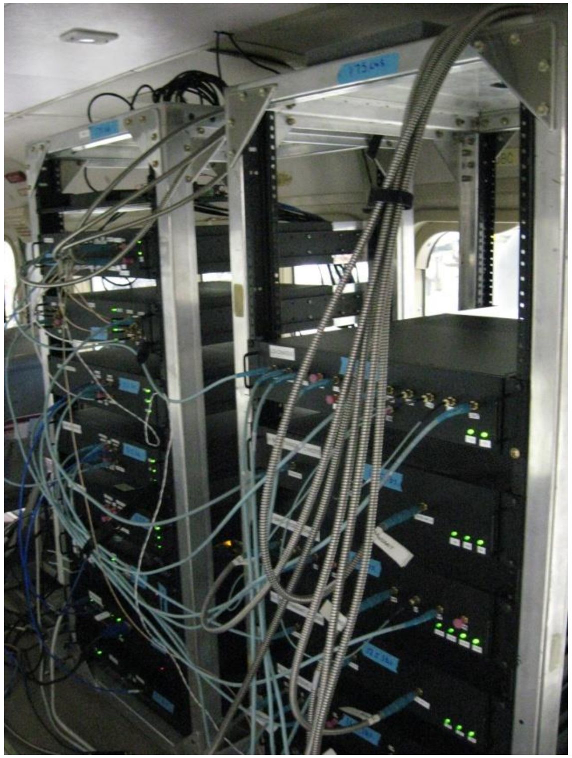


The Wideband Instrument for Snow Measurements (WISM)

Phase II Progress

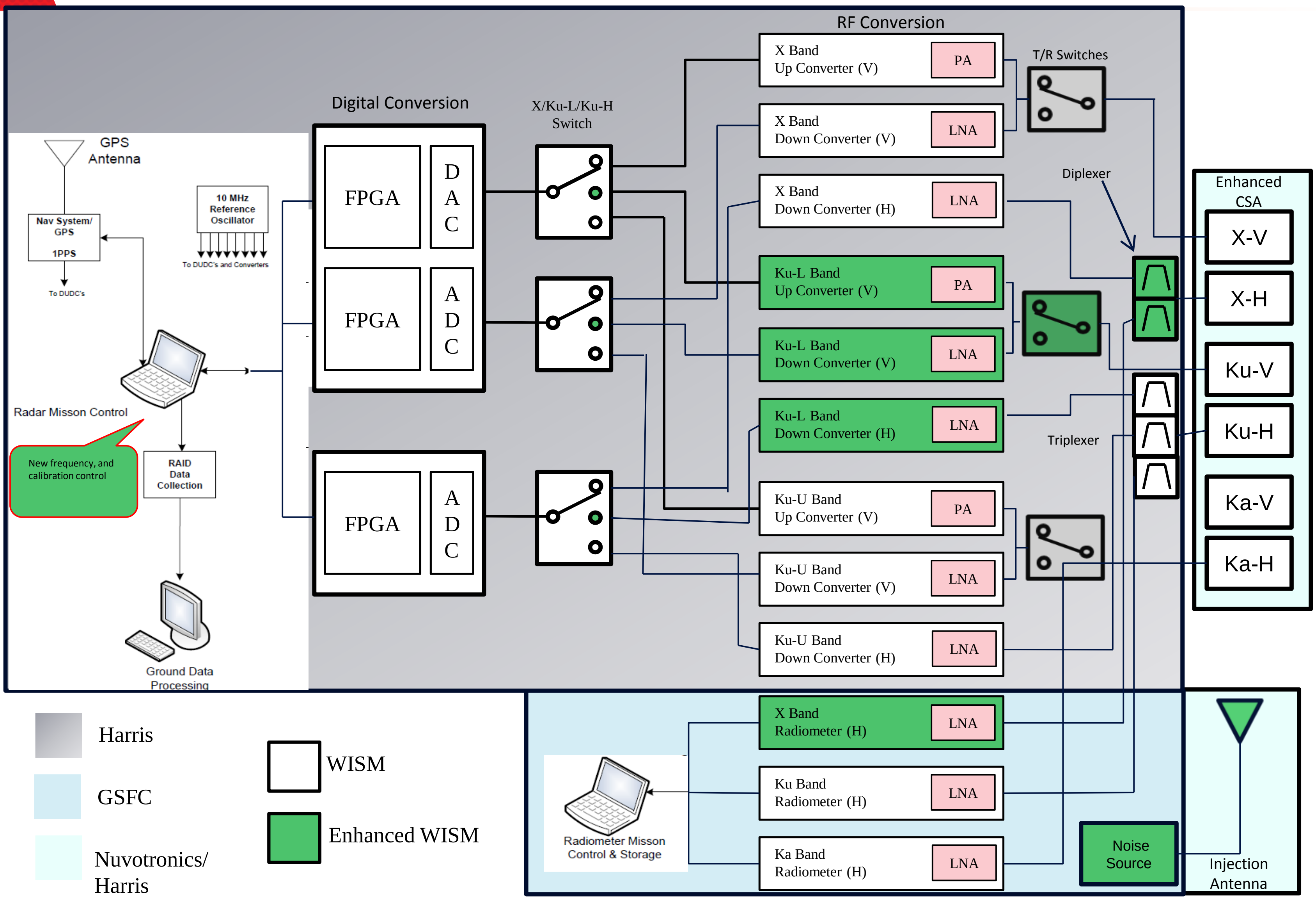
- Secondary antenna testing completed at GRC
  - Demonstrated wideband performance in the reflector
  - Patterns compare well with predictions
  - Gain consistent with expectations at three bands
  - Gain at X-band lower than expected but acceptable for tests

- 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



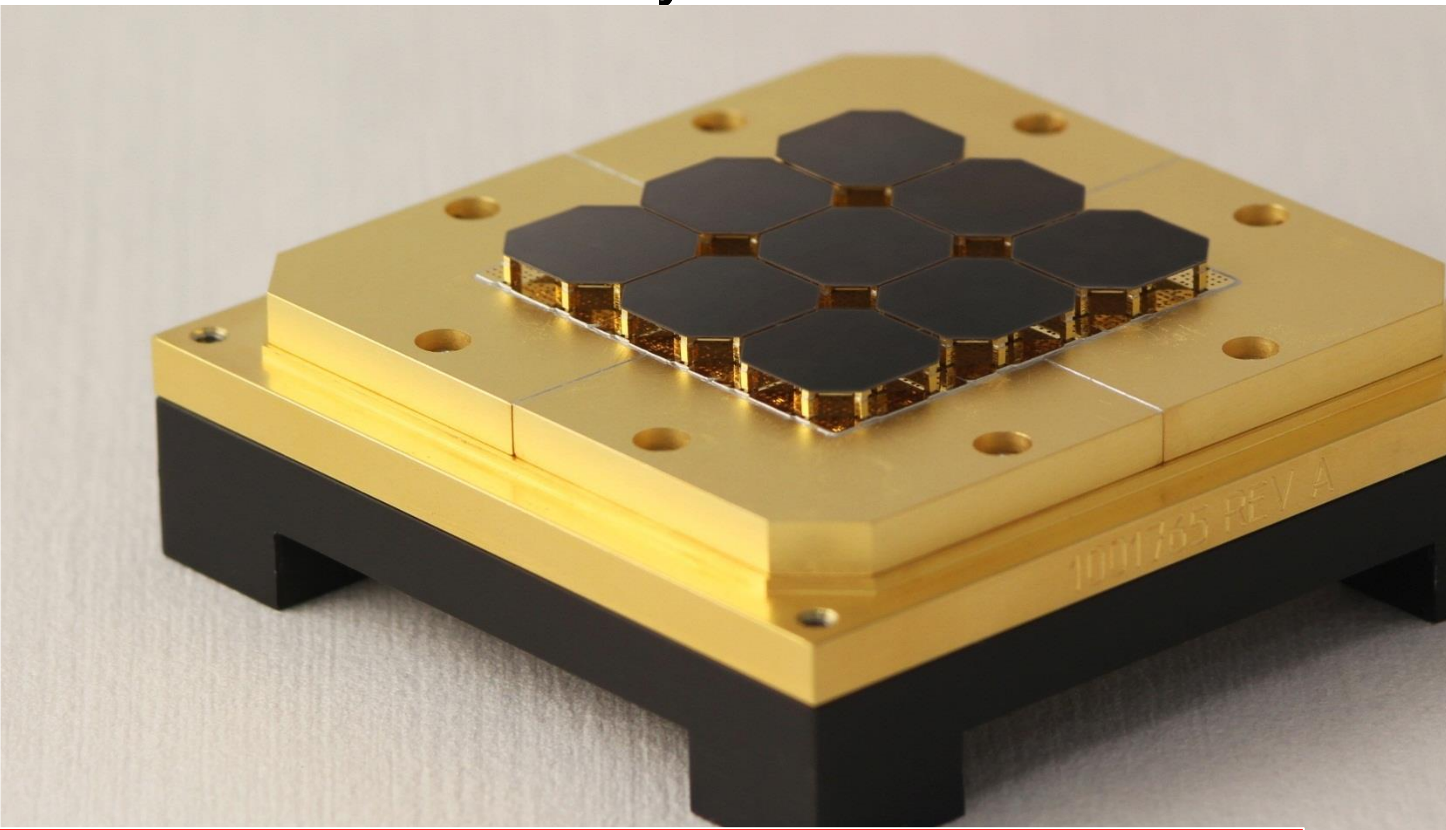
- First air campaign completed
  - Instrument successfully integrated into airplane
  - Four flights carried out over Grand Mesa, CO
  - Extensive concurrent ground measurements taken
  - Data processing nearing completion for all three instruments flown

Enhanced WISM Architecture



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 $10cm^3$

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

Snow depth measurement using FMCW Radar from skis and snowmobile

- 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

TOI Twin Otter Aircraft

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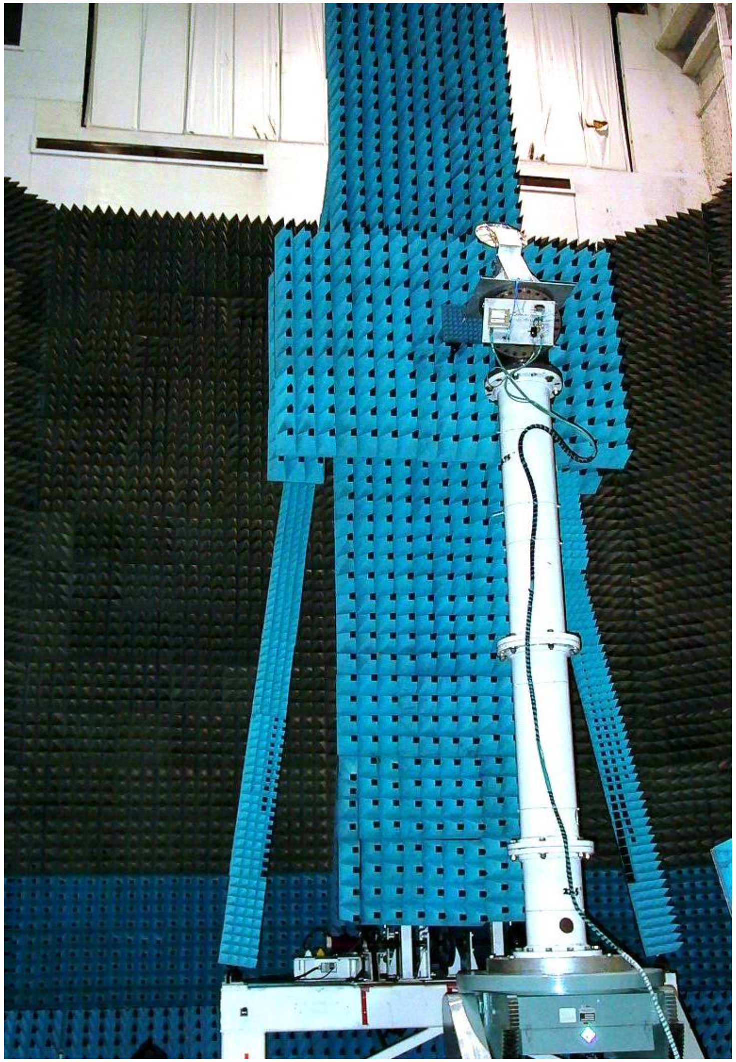
NASA GRC Planar Near-Field Range

- 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



WISM Secondary Antenna Measurements

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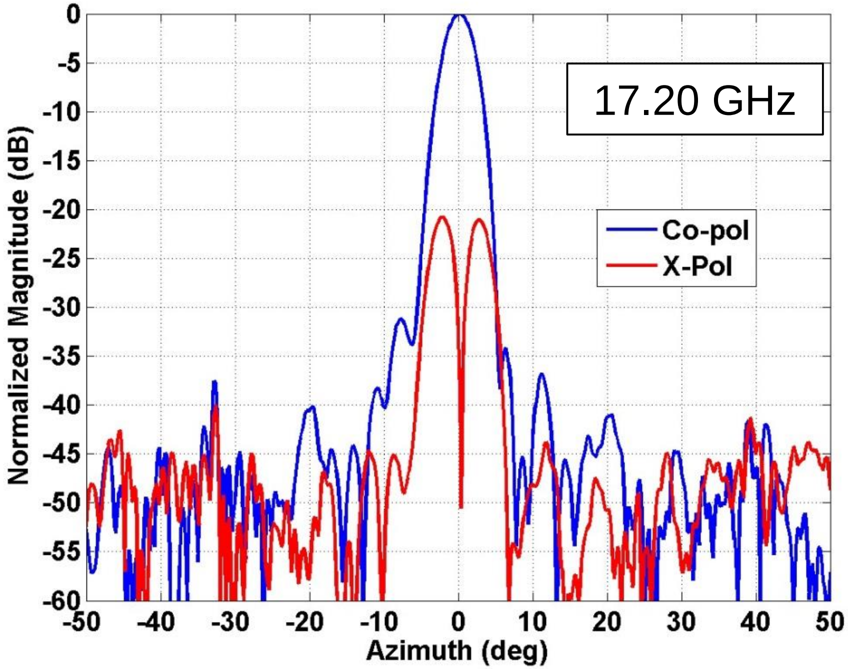
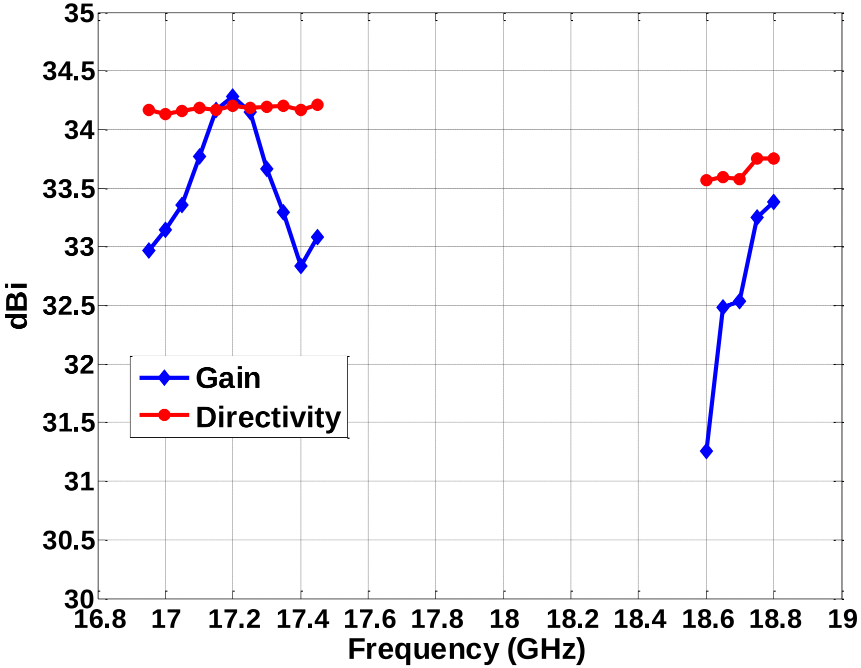
Example Result: K_u-Band (Radar), Port JH1

Principal Plane Pattern

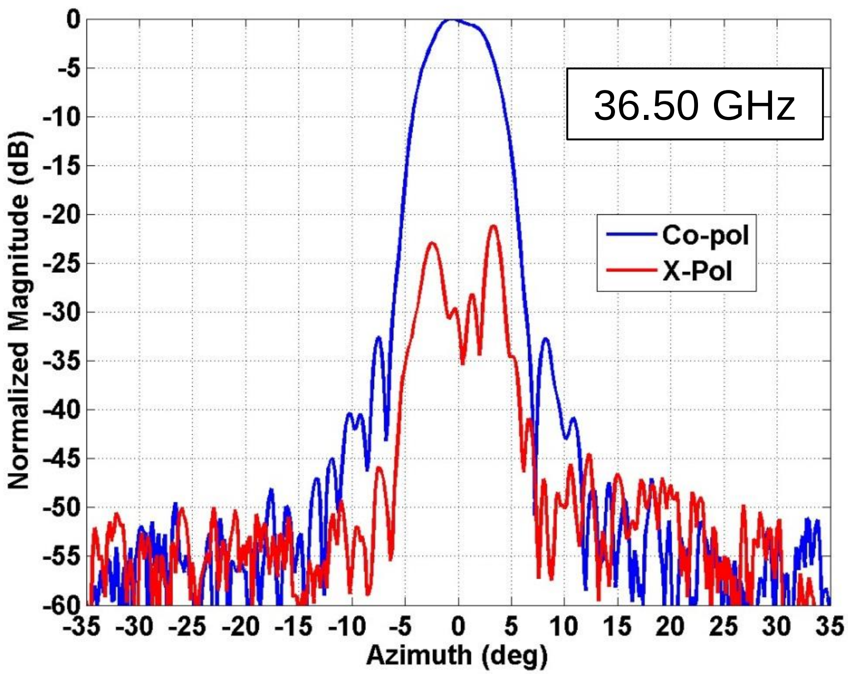


Directivity and Gain

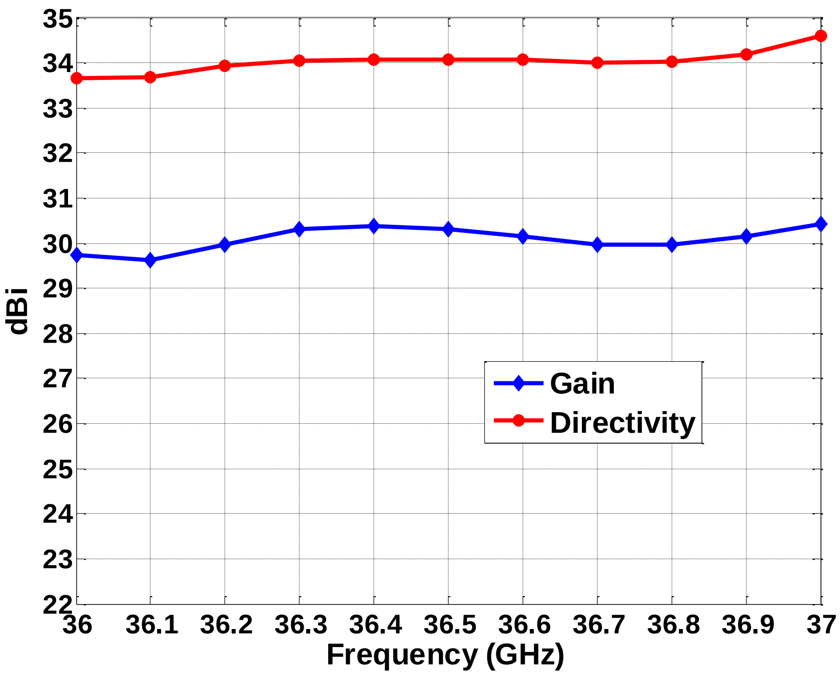


Example Result: K_a-Band (Radiometer), Port JH1

Principal Plane Pattern

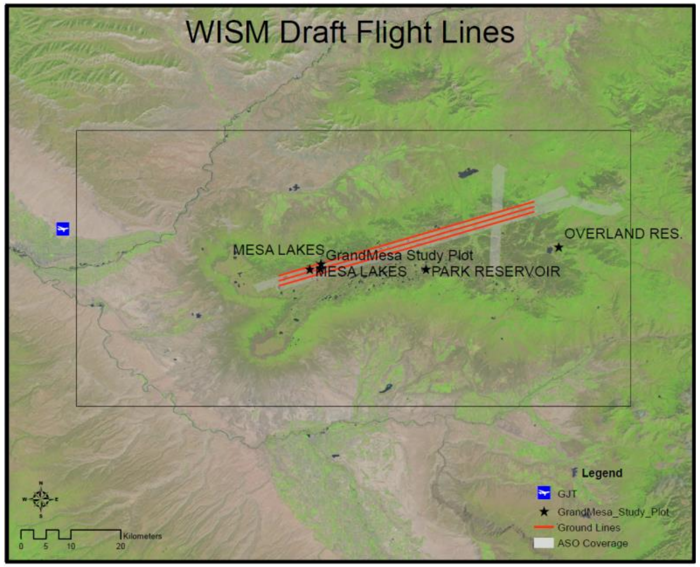


Directivity and Gain



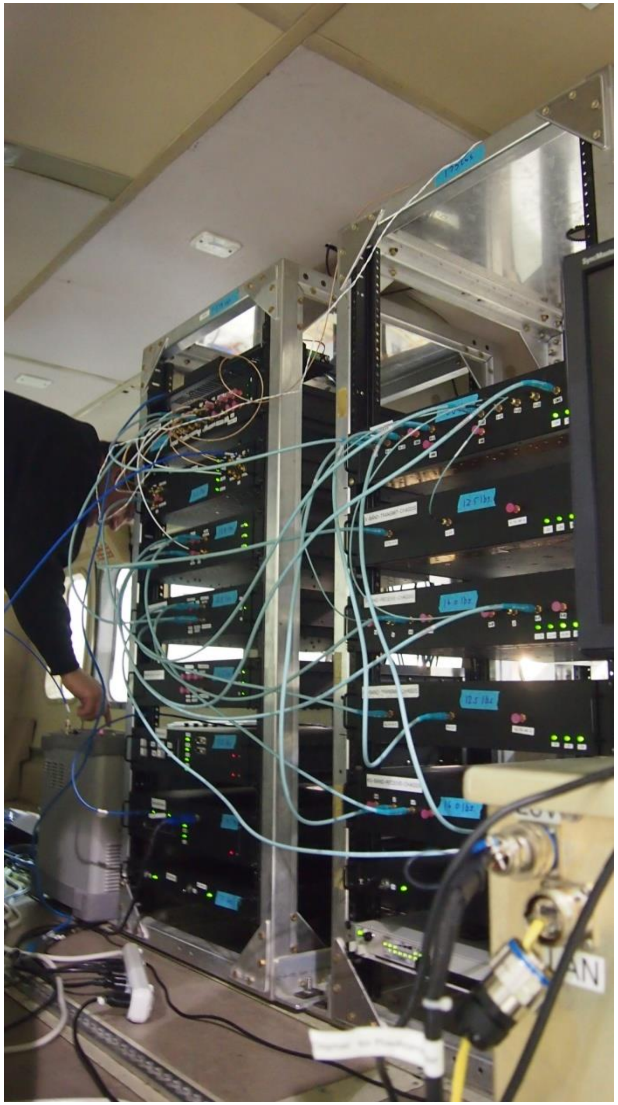
First WISM Flight Campaign

- 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.



Map of study area showing flight lines (red), ground stations (stars) and GJT airport.

Integration at TOI



NON-Export Controlled Information

First Flight

First Flight

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Second Flight

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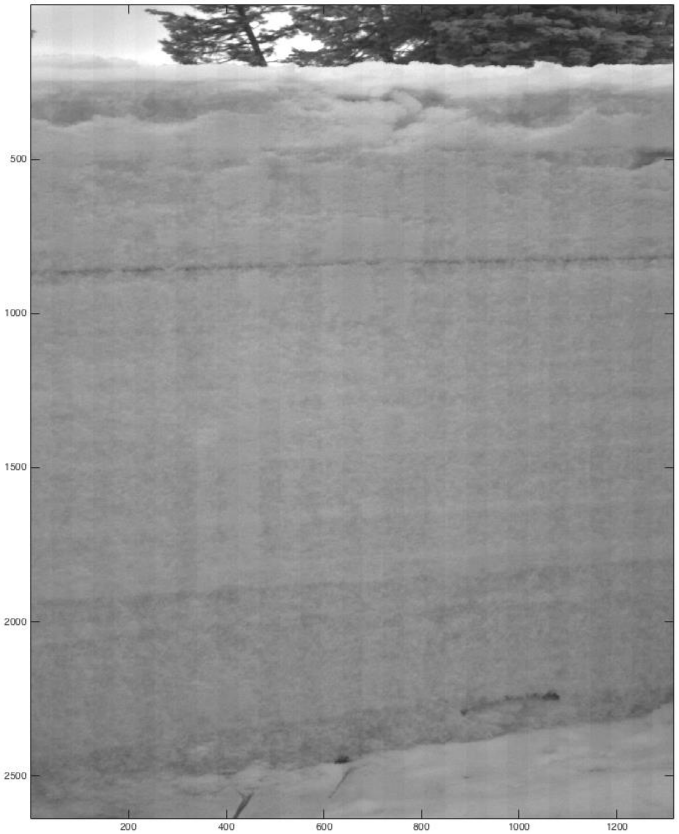
Air Campaign Ground Observations

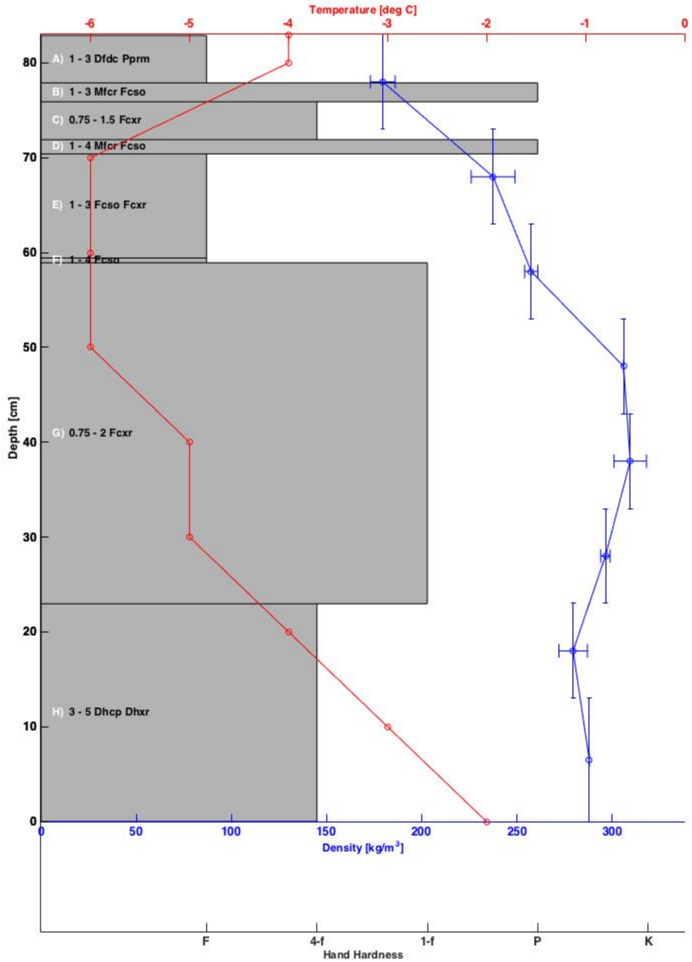
- 50 km flight line chosen optimally for goals of WISM: simple topography, large non-forested openings, dynamic range of SWE
- Line minimized short-length scale variability, correlation length ~200m
- West half of line simple vegetation, smooth topography
- Eastern half more complex vegetation, steeper terrain
- Minimize risk of wet snow (high elevation mesa, 10,000+ ft)
- Snow over both ground and frozen lakes/reservioirs

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

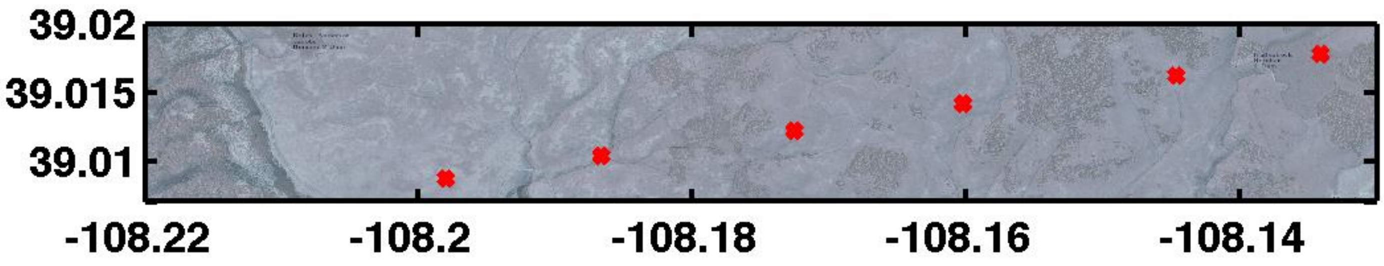
Accurate High-resolution Snow Observations Covering Large Dynamic Range



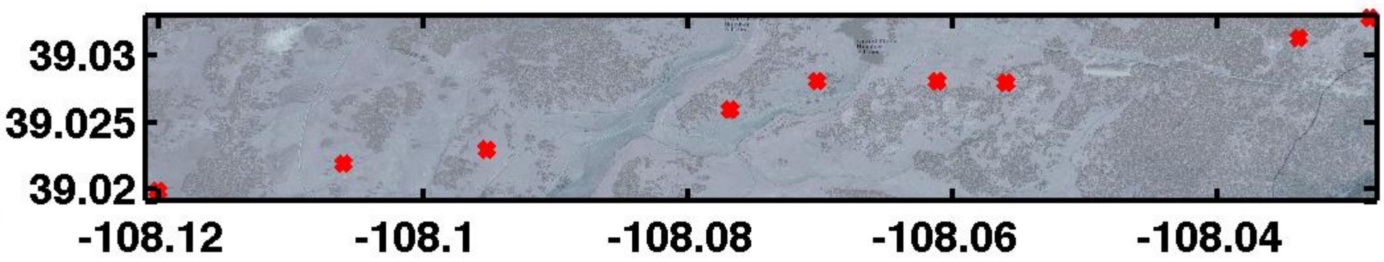


- 11-53cm range in SWE
- 30-165cm range in depth
- 100-448 kg/m^3 range in density
- New snow, small fine grained rounded snow, large faceted depth hoar

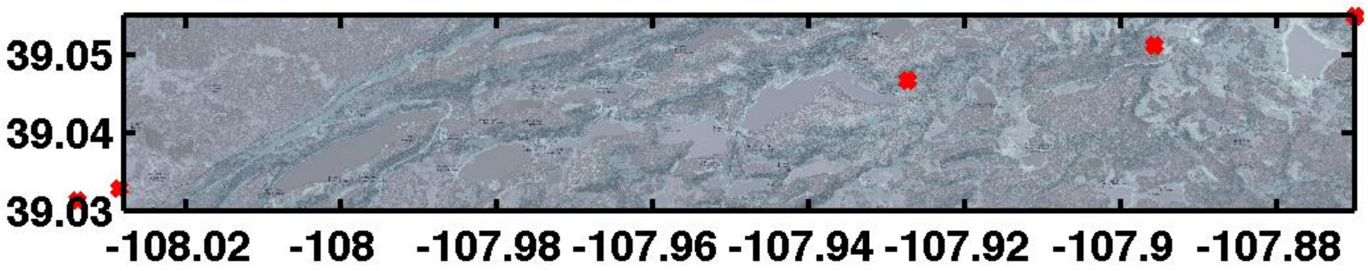
Terrain Characteristics



Snow covered ground



Snow covered Lakes



Wide range of vegetation and snow conditions

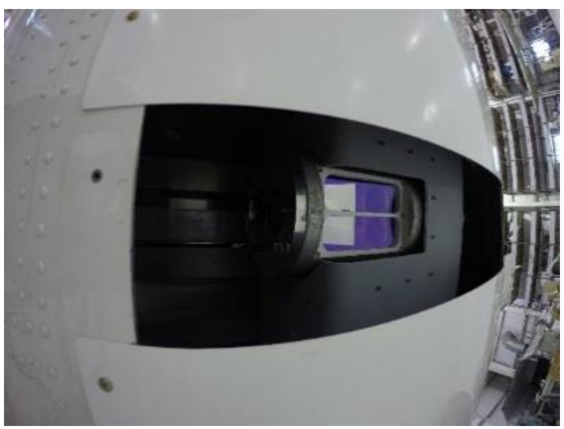
Miniature Atmospheric Topographical Mapper

POC: Bradly Hood, WFF (ASRC)

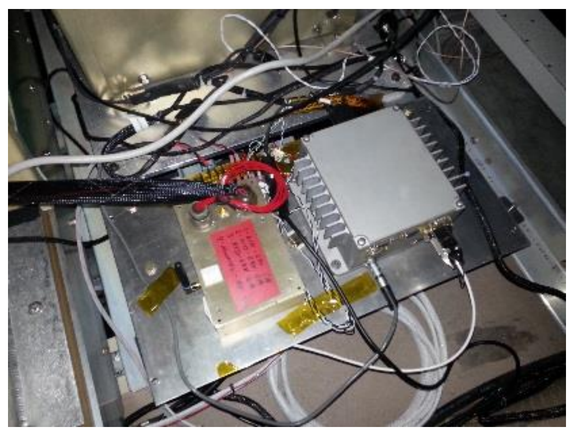
Laser Altimeter that measures surface topography providing meter-scale roughness. Ability to measure snow depth given a digital elevation model.

Statistics:

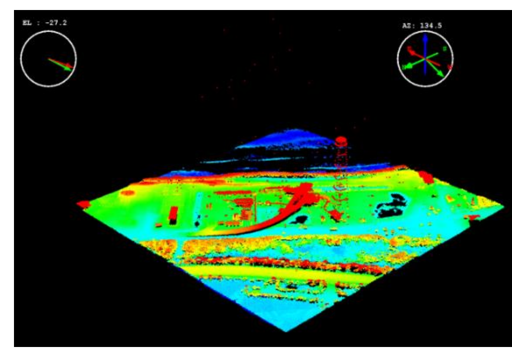
- Riegl LiDAR – Q240i - 60
- Weight: LiDAR Pod – 30 lbs, Electronics shelf – 8 lbs, Harness – 2 lbs, GPS Antenna 1lb
- Power Consumption: ~60 Watts Peak, 28 VDC
- Integrated Novatel INS
- Operating Range: Up to 800 M depending on surface reflectivity
- TRL 6, UAS



Twin Otter (TO) Nadir Port



MiniATM RTD Computer and PSU mounted in TO



Sample color coded topographical map (Wallops Island)

Mini-ATM Navigation Data Summary

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- 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 60^0 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.

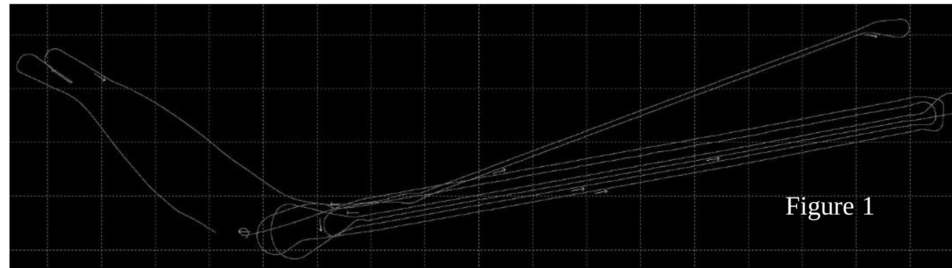


Figure 1

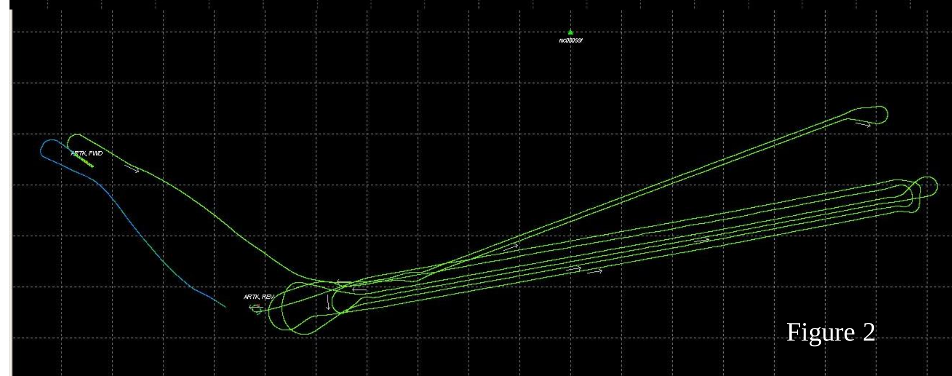


Figure 2

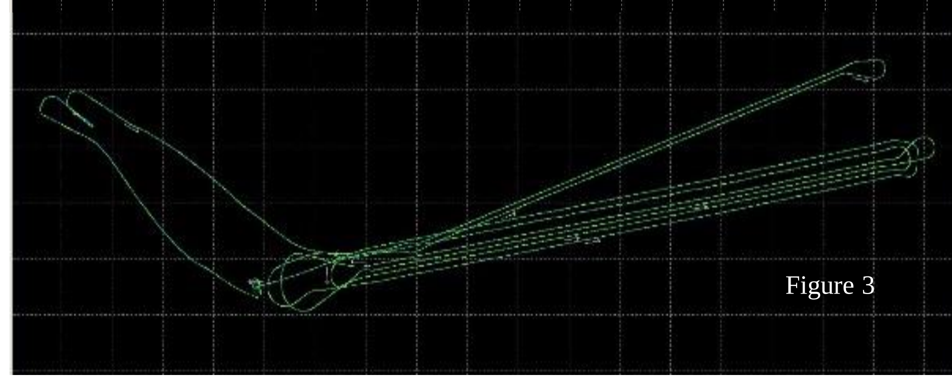


Figure 3

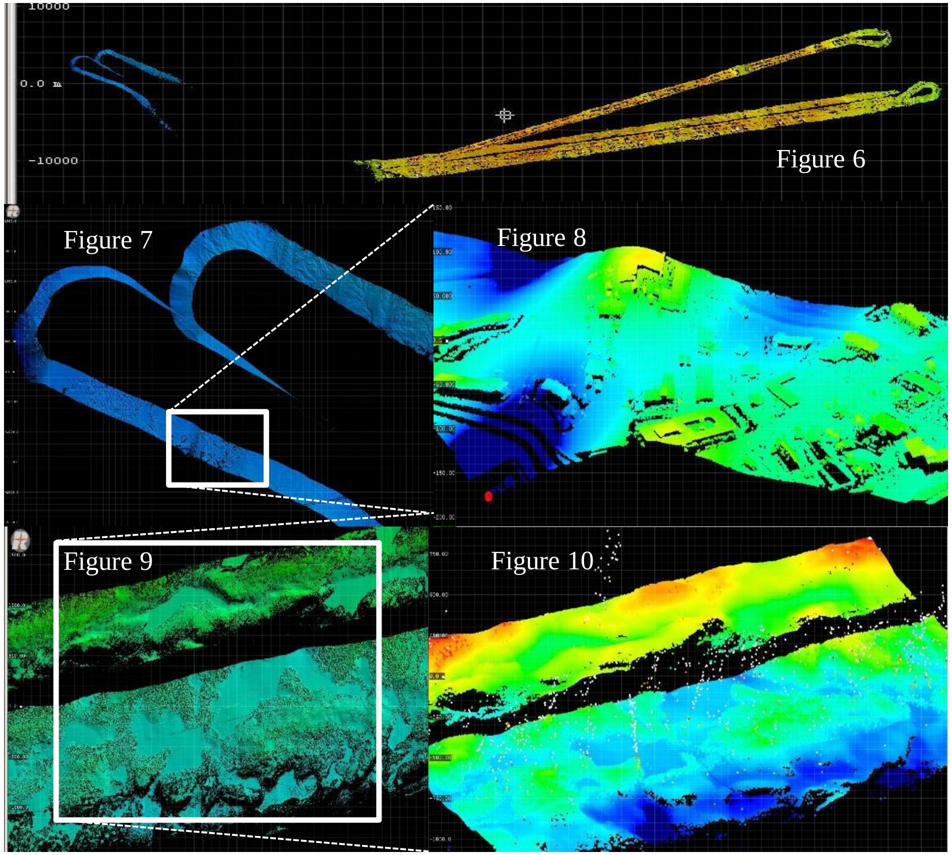
LiDAR Data Summary

- 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.

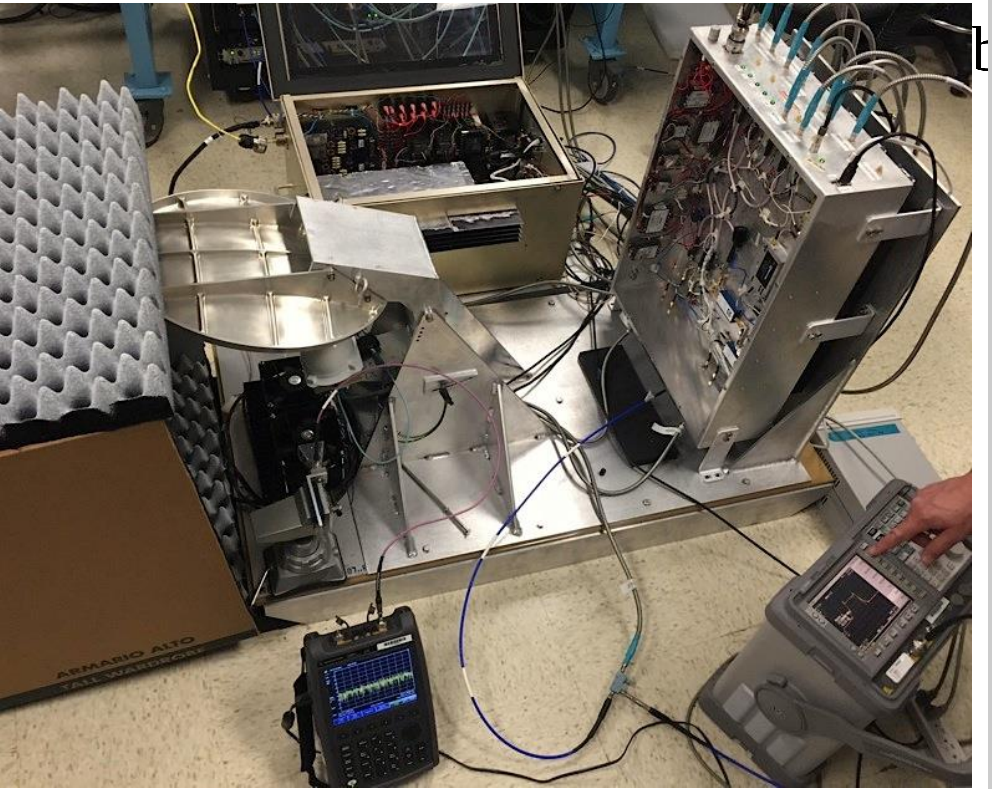
- Adding base station data will further improve accuracy

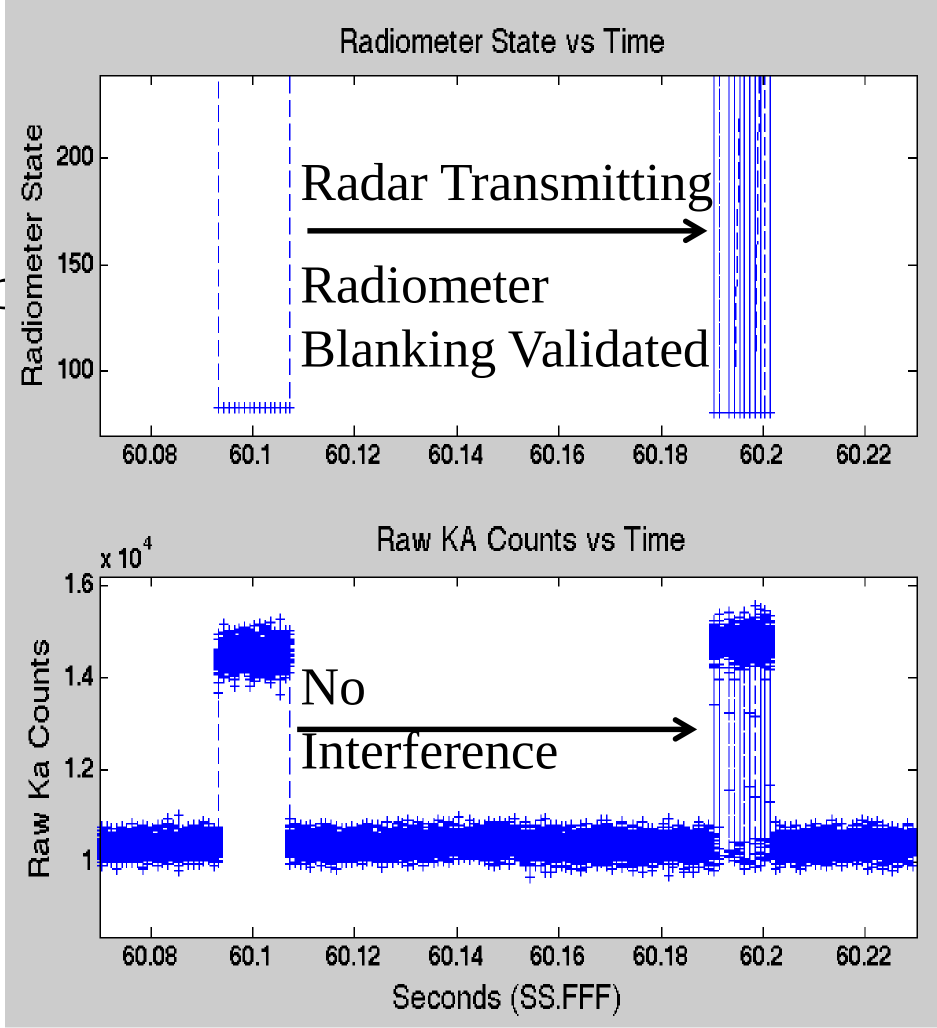


Full Instrument (Radar-Radiometer-Antenna) I&T at Harris

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

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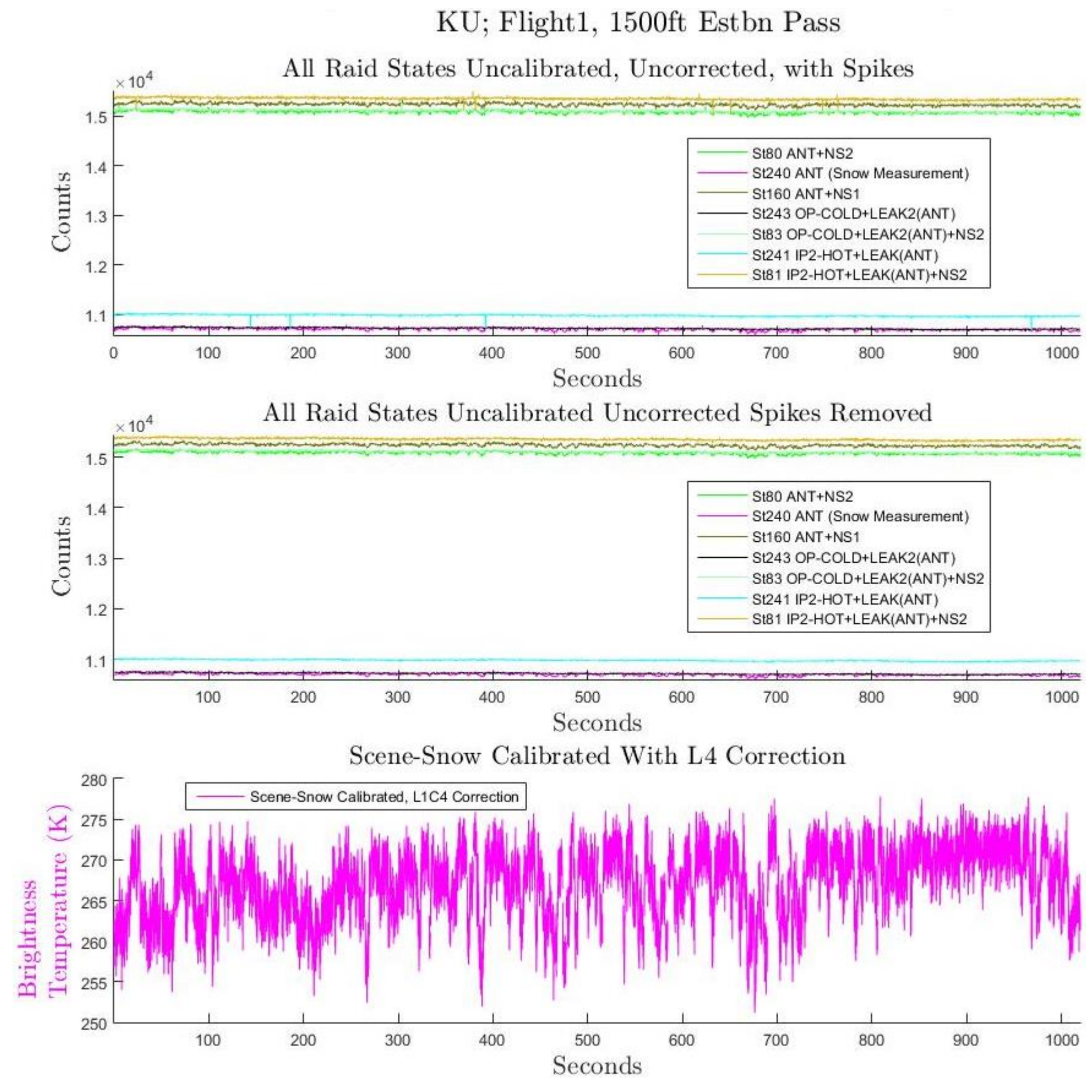
Science Measurements

- 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**



SAR System Description & High Level Requirements

- 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

Parameter	Value	Units
Platform Altitude	**457 (1500), 914 (3000, 1524 (5000)**	**meters (feet)**
Platform Speed	**45**	**m/sec**
X-Band Center Frequency	**9.75**	**GHz**
Ku-Band Center Frequency	**17.2**	**GHz**
Transmit Bandwidth (LFM)	**27.1**	**MHz**
Slant Range Resolution	**6.7**	**m**
Ground Range Resolution	**10.0**	**m**
Azimuth Resolution	**10.0**	**m**

RADAR Post Processing

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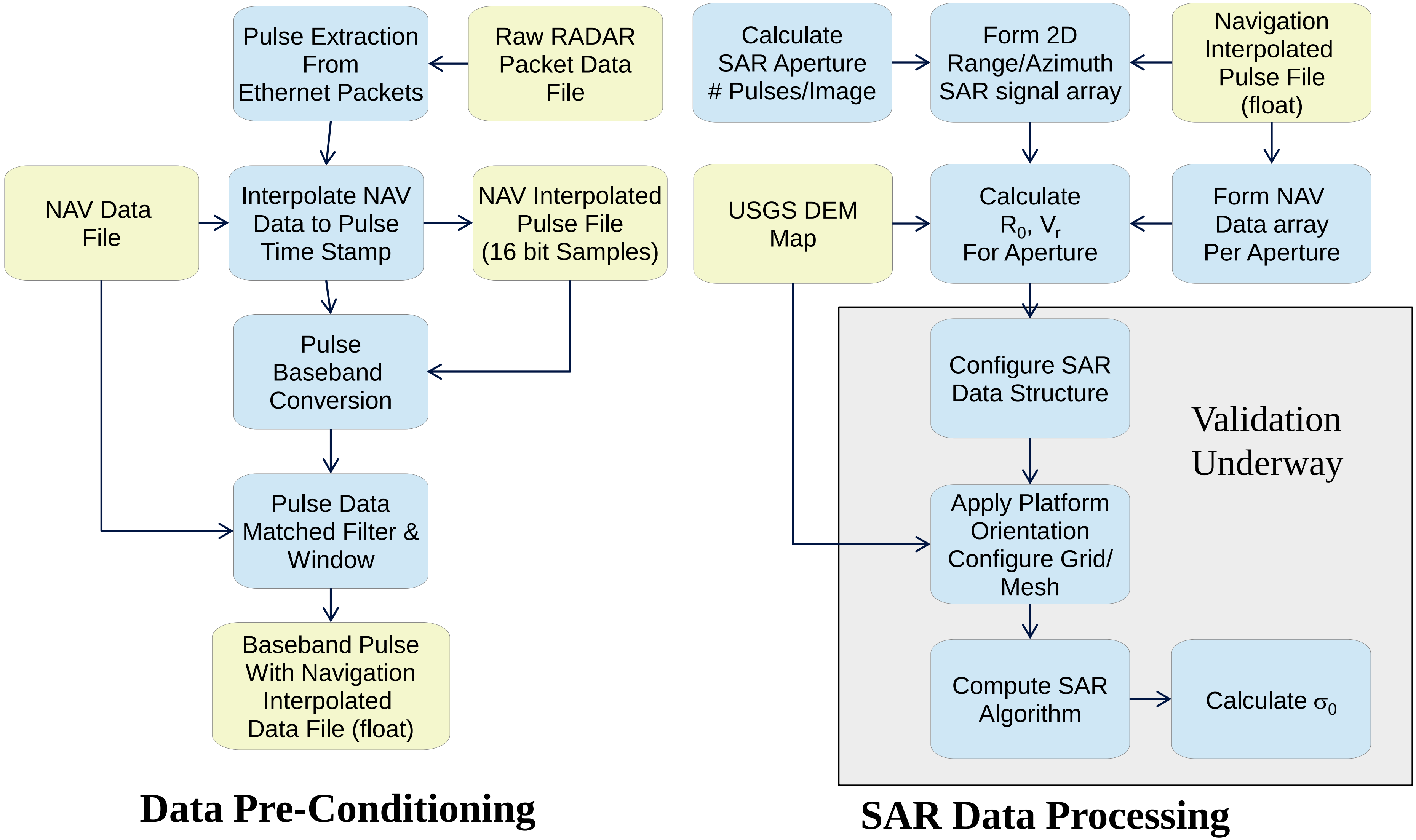

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Scattering Coefficient Estimation

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Transmitter EIRP

Range Resolution

Scattering Coefficient

$$\sigma_0 = \frac{P_{ave} G_T G_R \eta^2 \delta_r}{8\pi\lambda R^3 \upsilon\, kTF\, L_{sys} SNR}$$

Derived from Matched Filter Signal Plus Noise Output Level

Accurate Range Estimate using USGS DEM Map And Navigation Position Data

Velocity from NAV Data Estimate

Equipment Calibration Factors

Air Campaign Data Summary

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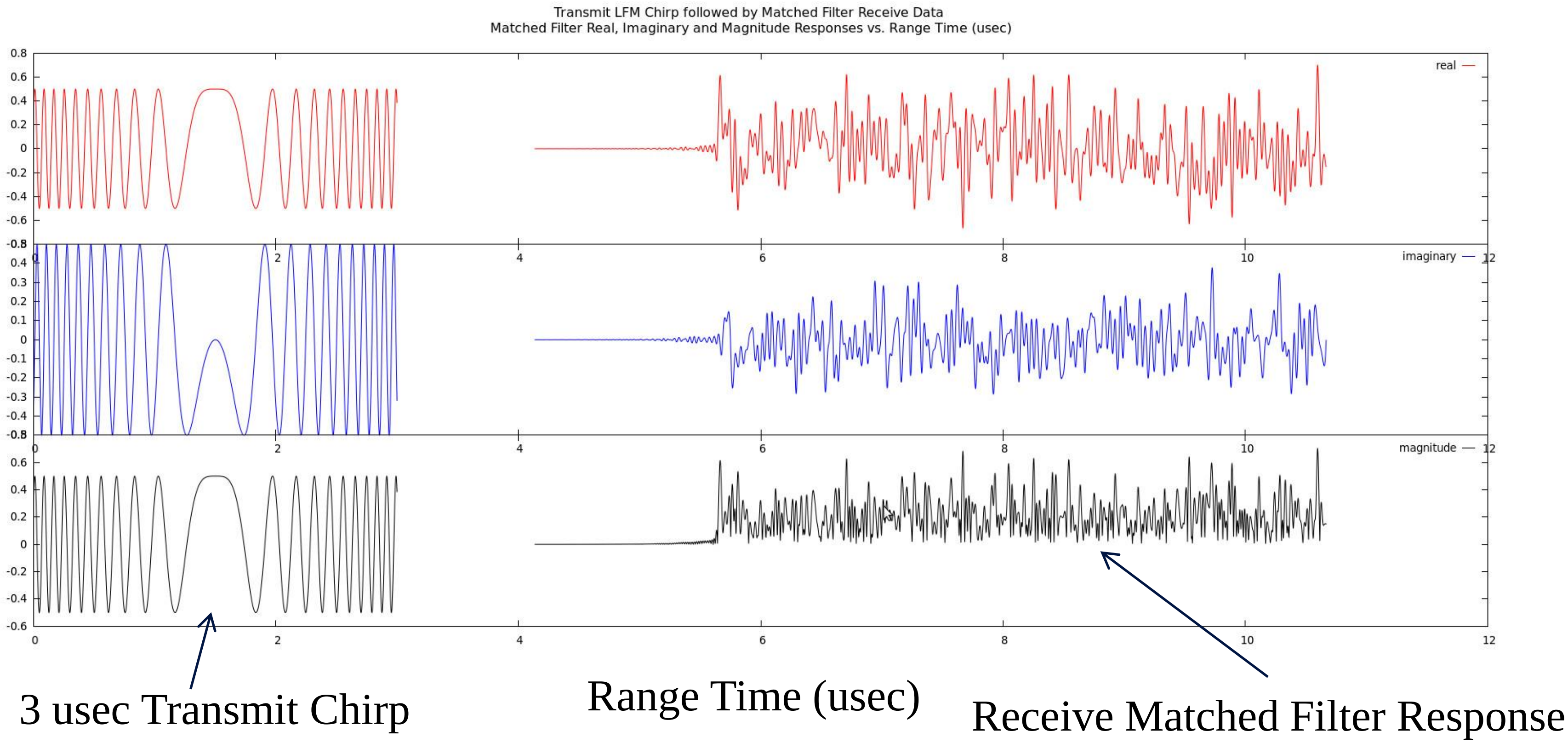
	Flight # 1 (GigaBytes)	Flight #2 (GigaBytes)	Flight #3 (GigaBytes)	Flight #4 (GigaBytes)	Data Summary Per Polarization (Gigabytes)
Date	2/21/2015	2/22/2015	2/24/2015	2/24/2015	
Purpose	Snow Science	Engineering Airport Flight	Snow Science + Airport (5000)	Snow Science	
Altitude	1500, 3000	1500, 3000	1500,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

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

2013 IIP WISM Enhancements

WISM Enhancement	Instrument component affected (responsible organizations):	Implementation	Science/Performance Justification
Add additional radar frequency of operation at 13.6 GHz (Ku Band)	Radar (Harris)	Additional up/down converters, digital hardware and software modifications	Obtain data at additional frequency to reduce sensitivity of SWE inversion to grain size
Add X-band receiver to radiometer	Radiometer (GSFC)	Repackage radiometer to accommodate receiver, diplexer, electronics	Improve sensitivity of passive measurements to thick snowpack, add band overlapping radar frequencies
Through-the-antenna noise injection	Radiometer (GSFC)	Modulated broadband external noise source injected to include CSA feed	Calibrate thermal emission due to front end losses
Improve radar calibration	Radar (Harris, BSU)	External calibration with corner reflectors, noise floor calibration using injected noise, analysis supporting improved calibration	Achieve radar scattering measurement accuracies that correspond to cm level SWE measurement accuracy
Lower loss in CSA ahead of radiometer receiver	CSA Feed (Harris, Nuvotronics, GRC)	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	Improves radiometer measurement by lowering front-end losses
Improve Beam Efficiency at radiometer bands (goal of > 95%)	Reflector (Harris)	Shape reflector for improved efficiency	Improves radiometer measurement accuracy by reducing extraneous noise
	CSA Feed (Harris, Nuvotronics, GRC)	Control aperture amplitude distribution (investigate symmetrically scalable CSA)	
Improve aperture efficiency (goal of >85%)	CSA Feed (Harris)	Reduce unit cell spacing and optimize unit cell design	Reduces instrument power consumption and lowers ambiguity due to reflected power
Step scan capability to provide multiple beams	CSA Feed, Radar/radiometer electronics (Harris, GSFC)	Perform analysis of step scan options; possible limited implementation for airborne demonstration	Provides more coverage area per pass for airborne measurements; required for global coverage from space

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