Demonstration of High-frequency Airborne Microwave and Millimeter-Wave Radiometer (HAMMR) to Improve Spatial Resolution of Wet-Tropospheric Path Delay Measurements for Coastal and Inland Water Altimetry

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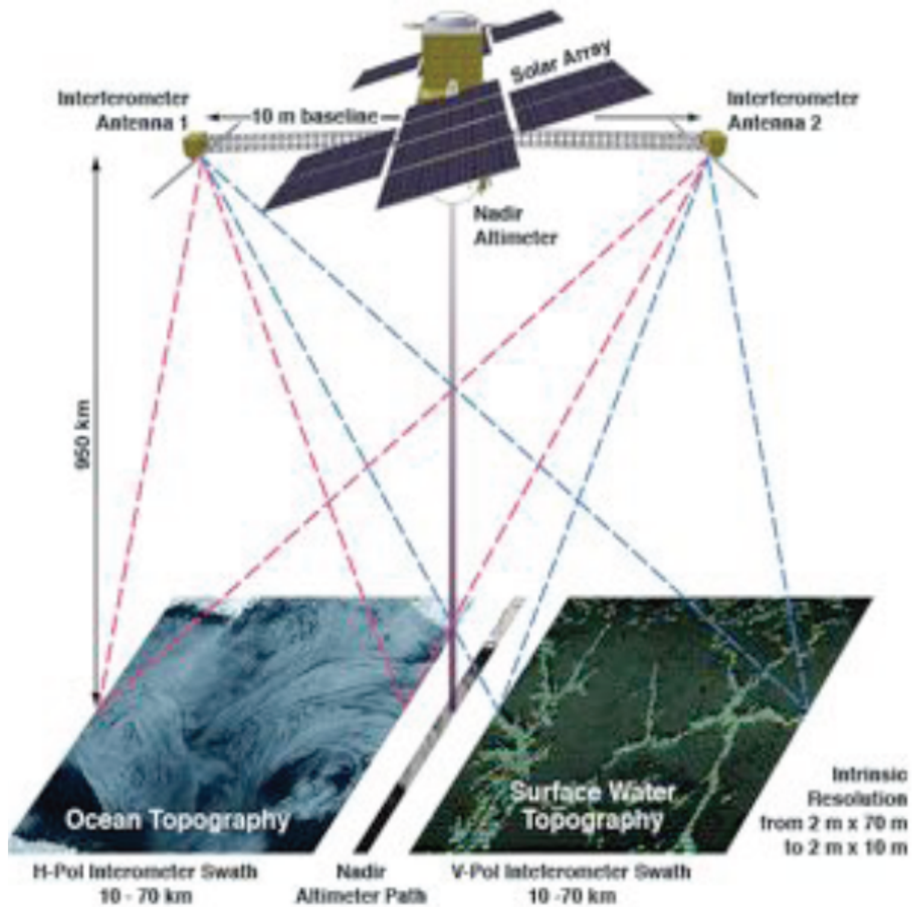
Surface Water and Ocean Topography (SWOT) Mission

- NASA/CNES/CSA Joint Mission from NRC Earth Science Decadal Survey Mission underway and planned for launch in Oct. 2020.
- Enhances capability and continues 22 years of high-precision sea level & surface topography measurements
- To make the first global survey of Earth's surface water, observe fine details of the ocean's surface topography, and measure how water bodies change over time
- Nadir altimeter and radiometer for wet-tropospheric correction
- Ka-band Radar Interferometer (KaRIn) with 120-km wide swath over 140 km

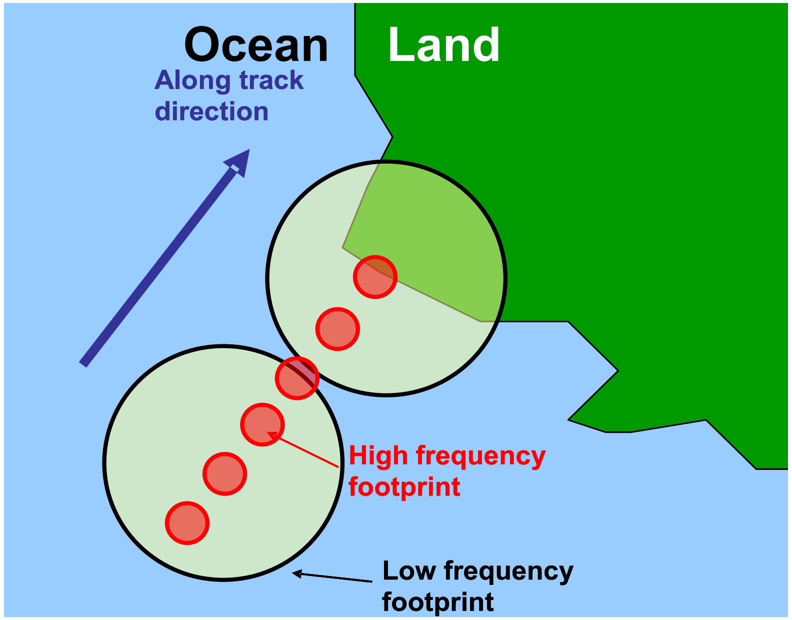


SWOT Science Objectives

- **NASA's Earth Science Focus Areas:**
  - Water & Energy Cycle
  - Climate Variability and Change
- **Oceanography Objectives:**
  - Characterize ocean mesoscale and sub-mesoscale circulation at horizontal resolution of 15 km with order of 1 cm height precision
    - Kinetic energy / Heat and carbon air-sea fluxes
    - Climate change and ocean circulation
    - Coastal and internal tides
- **Hydrology Objectives:**
  - To provide global height measurements of inland surface water bodies with area greater than 250 m^2 and rivers of width greater than 100 m with 10 cm height precision
  - To measure change in global water storage in inland water bodies and river discharge on sub-monthly to annual time scales

Scientific Motivation

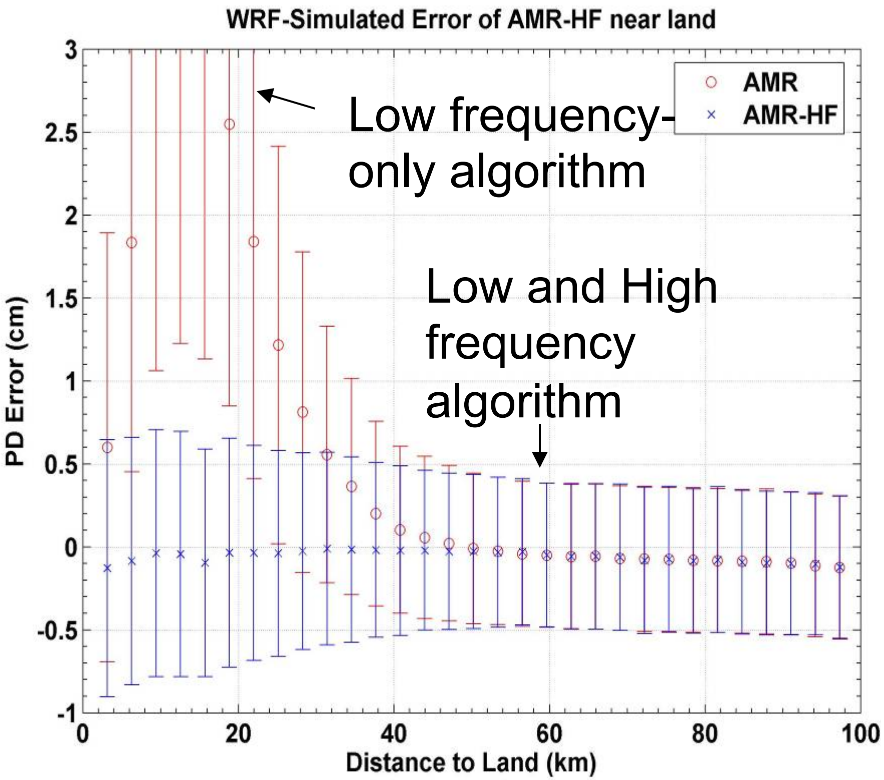
- Radar altimeter missions include nadir-viewing 18-34 GHz microwave radiometers to measure wet-tropospheric path delay. These radiometers, including the baseline for Jason Continuity of Service (CS) and SWOT, cannot provide sufficient measurements in coastal areas and over land.
- Error due to land incursion is unacceptable within 30-40 km of the coastlines.
- A second, high-frequency radiometer is under consideration for possible inclusion on Jason-CS mission by EUMETSAT/ESA/CNES/NOAA/NASA.

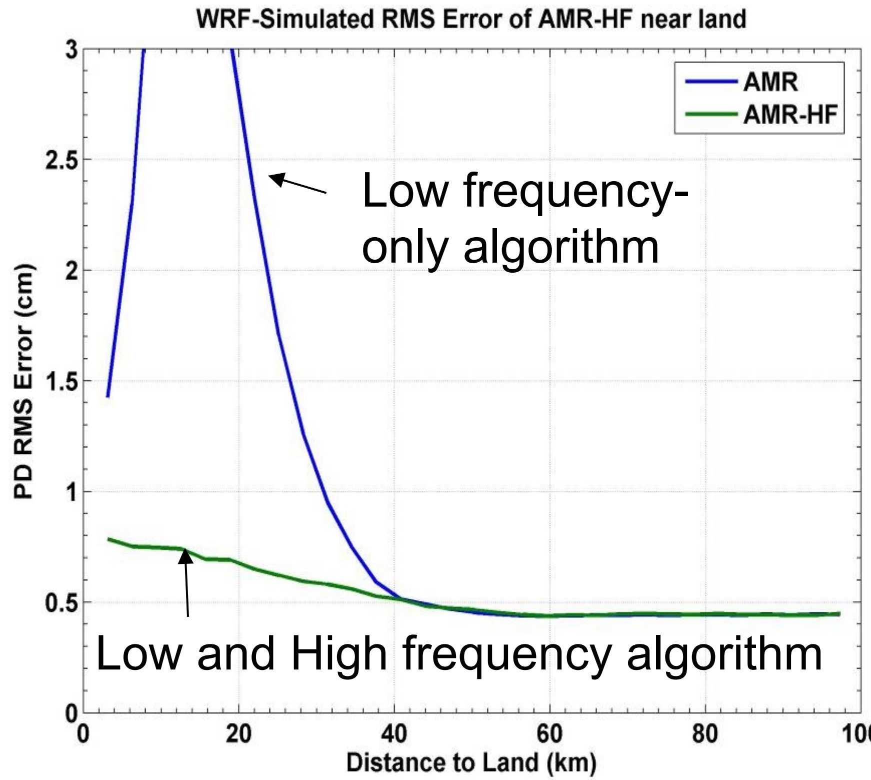


- Wide-band, high-frequency window channels at 90, 130 and 168 GHz provide an optimal frequency set to improve coastal retrievals.
- We have developed new algorithms for retrieval over inland water using ratios of window channels without the need for *a-priori* data.

Wet Path Delay Retrieval in Coastal Zones

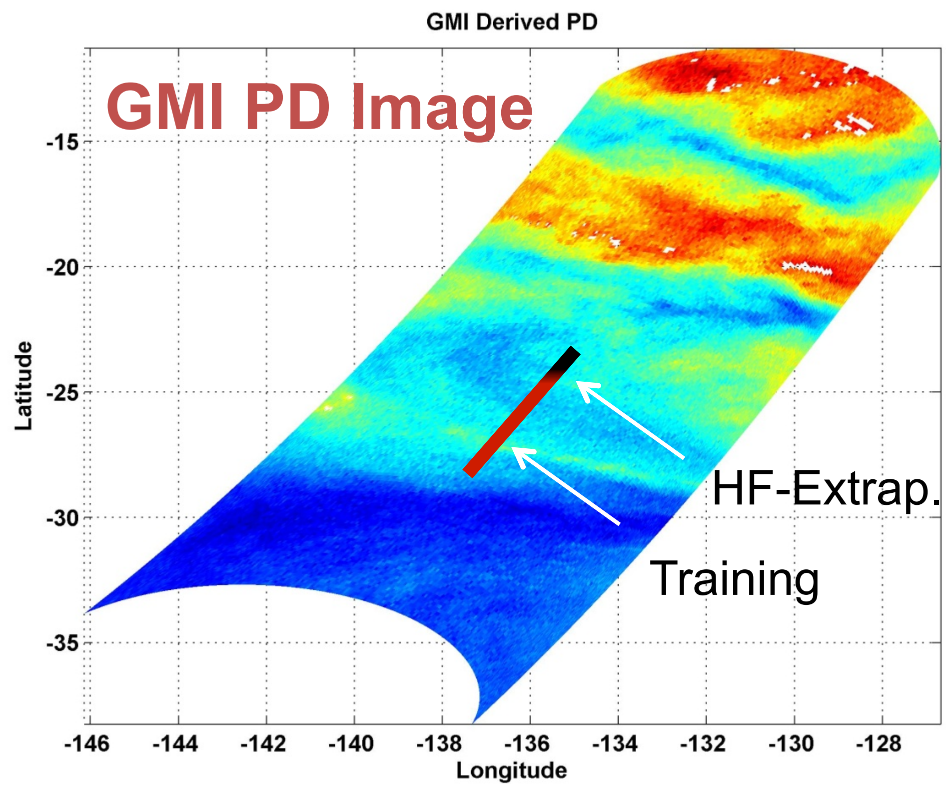
- A hybrid Bayesian retrieval algorithm, coupled with a high-resolution WRF model, was developed and applied to simulated brightness temperatures.
- Addition of high-frequency channels yielded wet path delay retrieval error of < 8 mm to within about 5 km of the coastlines.





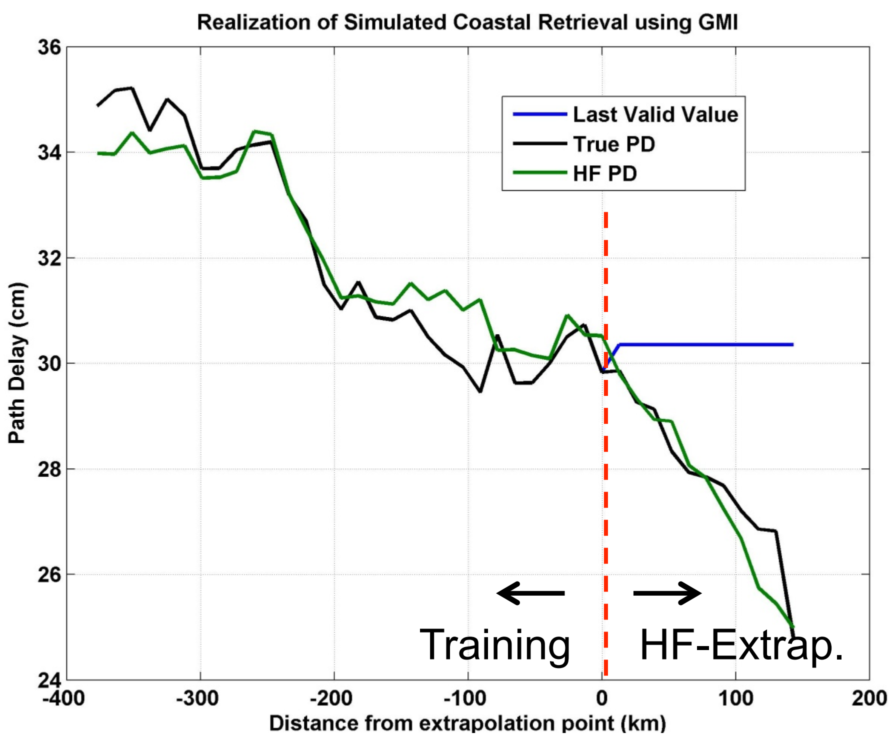
Application of Wet-Path Delay Retrieval Algorithm to GPM Microwave Imager

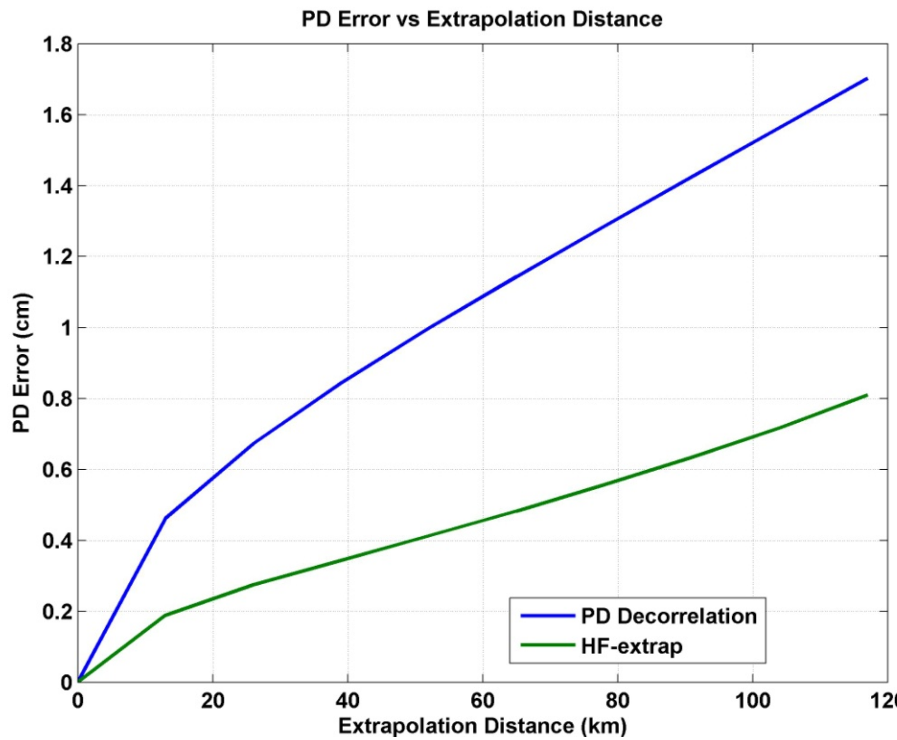
- The Global Precipitation Measurement Microwave Imager (GMI) has 18.7-37.0 GHz channels and also a high-resolution 90 GHz channel.
- GMI data used to evaluate algorithm performance in real atmospheres.
- Path delay computed from GMI low-frequency (18-37 GHz) channels.
- High-frequency (HF) coastal extrapolation algorithm applied to 90 GHz channel.
- 500 km segments extracted and used to evaluate algorithm.
  - 400 km used to dynamically train HF algorithm.
  - HF algorithm then applied to last 100 km and compared to low-frequency PD.



High-Frequency Algorithm Performance using GPM Microwave Imager

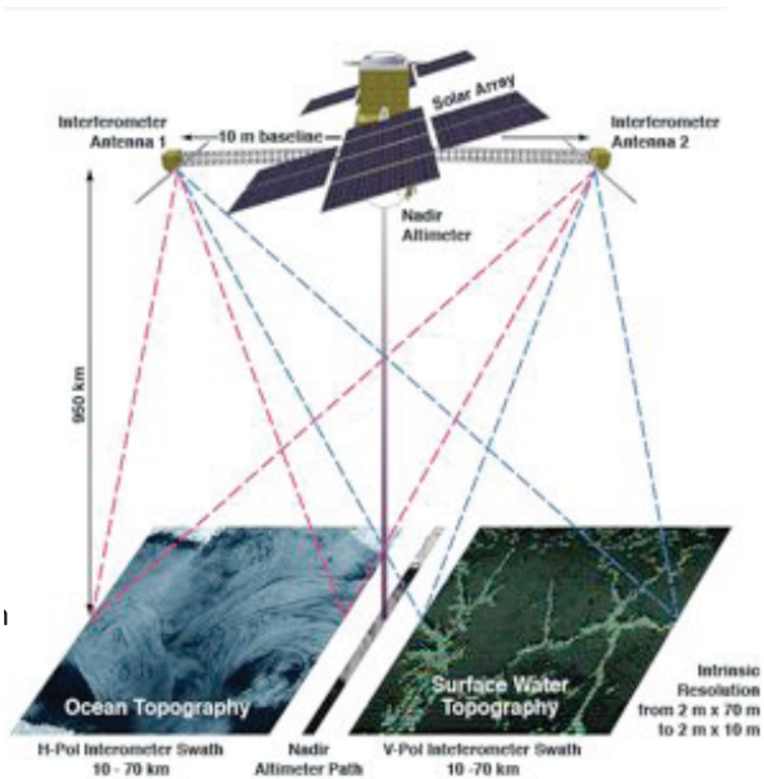
- HF Extrapolation algorithm using GMI 90 GHz channel compared to using last valid PD value to the coast
- Computed statistics for a large number of realizations, encompassing various atmospheric conditions
- Assuming a low-frequency radiometer that is contaminated at 50 km from the coast, HF algorithm decreases error from 10 mm to 4 mm.



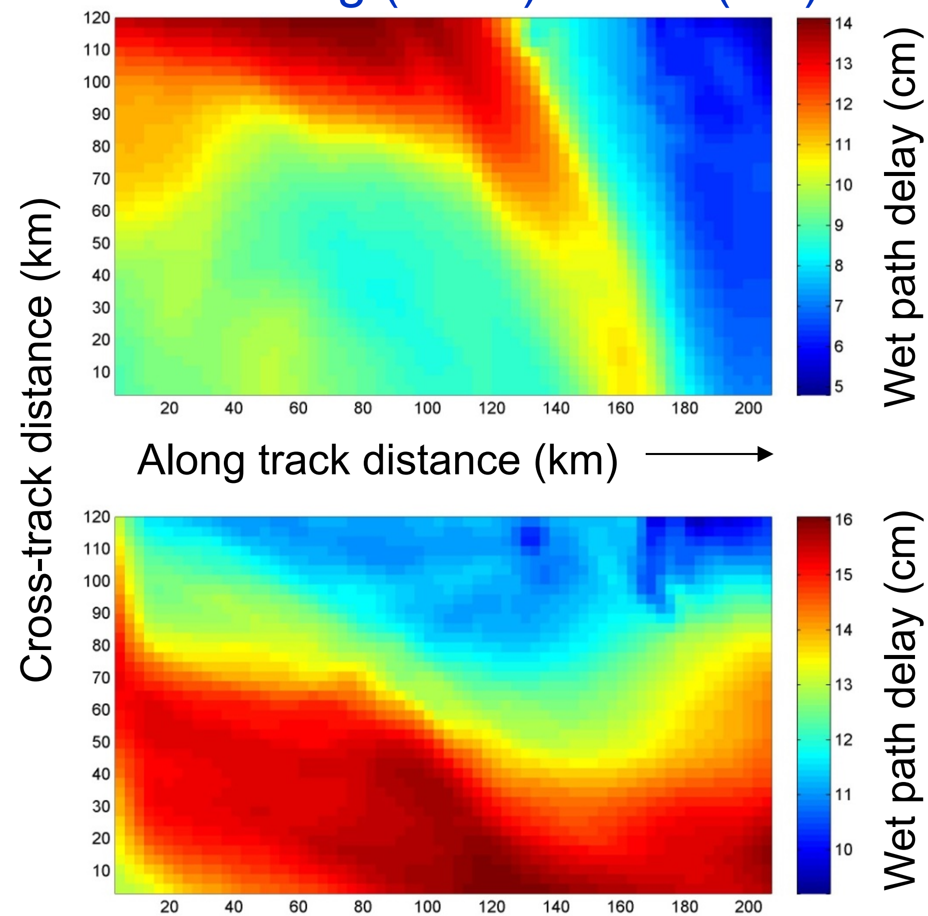


Understanding Swath-Scale Water Vapor Variability

SWOT baseline mission includes only nadir radiometer, highlighting the need to characterize small-scale water vapor variability to understand errors across the 120-km wide swath over 140 km.



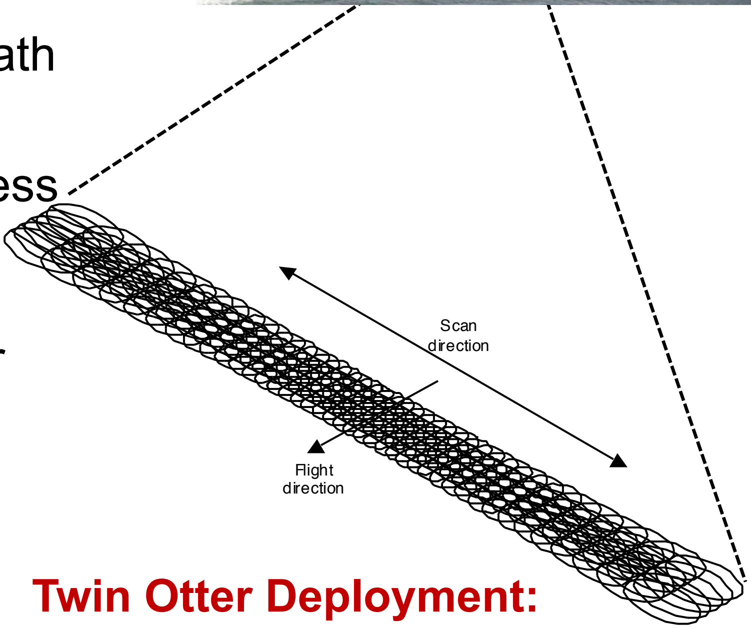
Model path delay fields from Weather Research and Forecasting (WRF) model (cm)



High-Frequency Airborne Microwave and mm-Wave Radiometer

Under support from NASA ESTO's Instrument Incubator Program 2010, we have developed and built the High-frequency Airborne Microwave and Millimeter-wave Radiometer (HAMMR) operating from 18.7 to 183 GHz, and demonstrated its operation on a Twin Otter aircraft. HAMMR will:

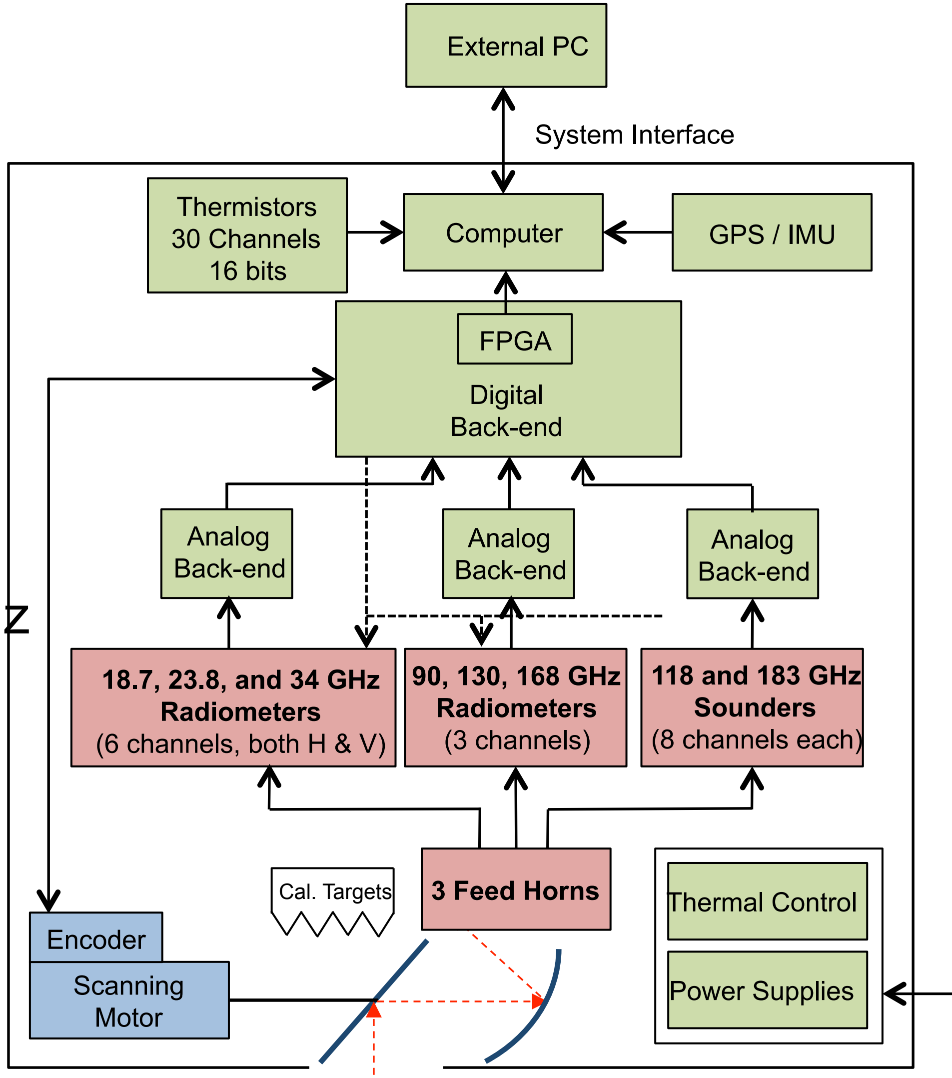
1. Provide high-resolution measurements of wet-path delay from aircraft on the order of 100-m scales
2. Provide high-frequency millimeter-wave brightness temperatures to test algorithms to extend wet-tropospheric path delay correction closer to the world's coastlines and explore the potential over inland water
3. Demonstrate high-frequency millimeter-wave radiometers that can be directly integrated into future altimetry space missions
4. Provide an airborne calibration and validation instrument in support of the SWOT mission, complementary to JPL's AirSWOT



Twin Otter Deployment:
- Altitude: 3 km
- Swath Width: 6 km
- Scan Rate: 60 rpm

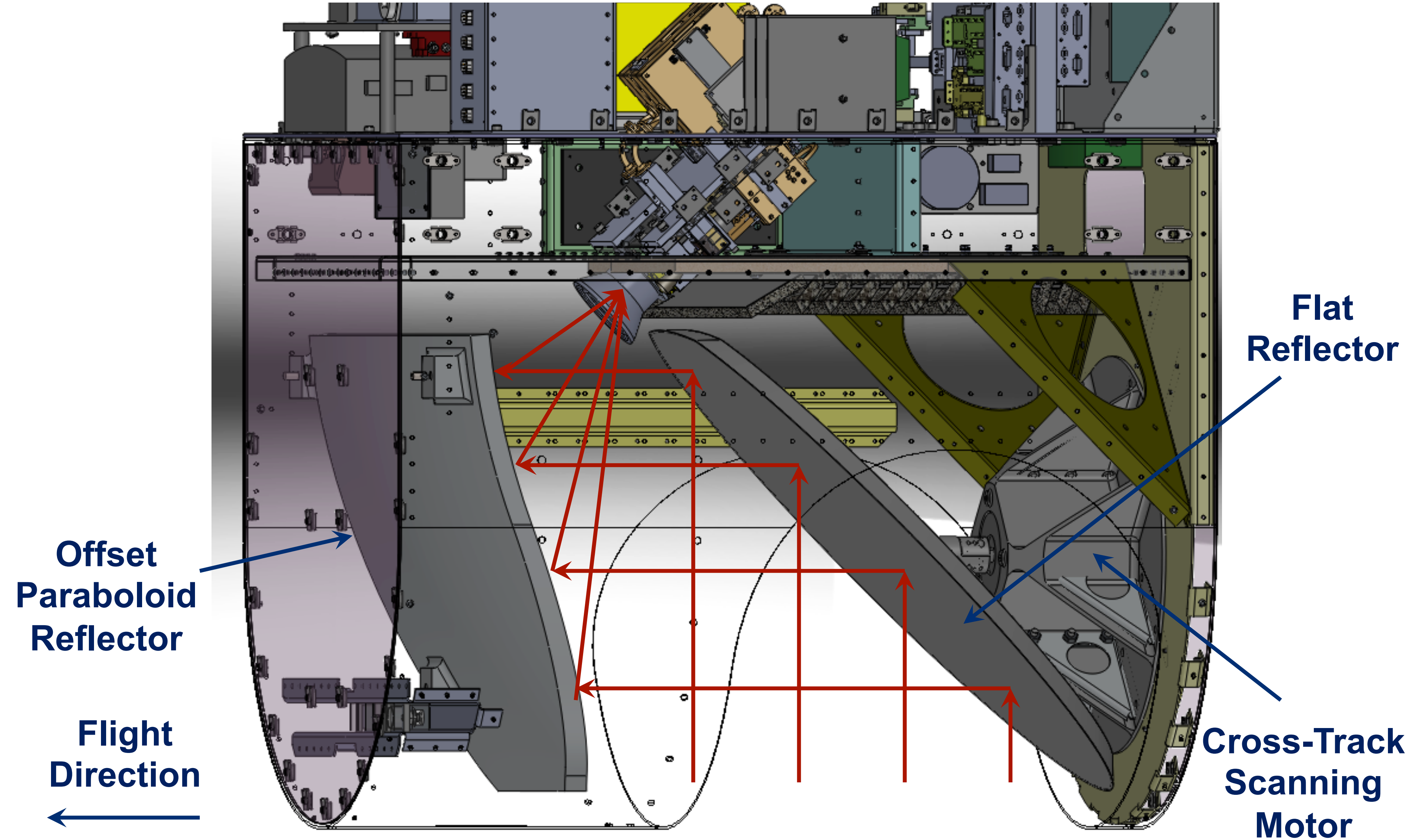
Wide-Band Airborne Radiometer System Block Diagram

- Low-frequency microwave channels
  - 18.7, 23.8 and 34.0 GHz
- High-frequency millimeter-wave window channels
  - 90, 130 and 168 GHz
- High-frequency mm-wave sounding channels
  - ASIC analog spectrometer with 8 bands each near 118 and 183 GHz
- Analog and digital back-end w/ FPGA
  - Radiometer signal conditioning, integration & sampling
  - Timing of Dicke switching and internal calibration
  - Temperature control and monitoring



Green: CSU; Red: JPL; Blue: NCAR

Wide-Band Airborne Radiometer System Design

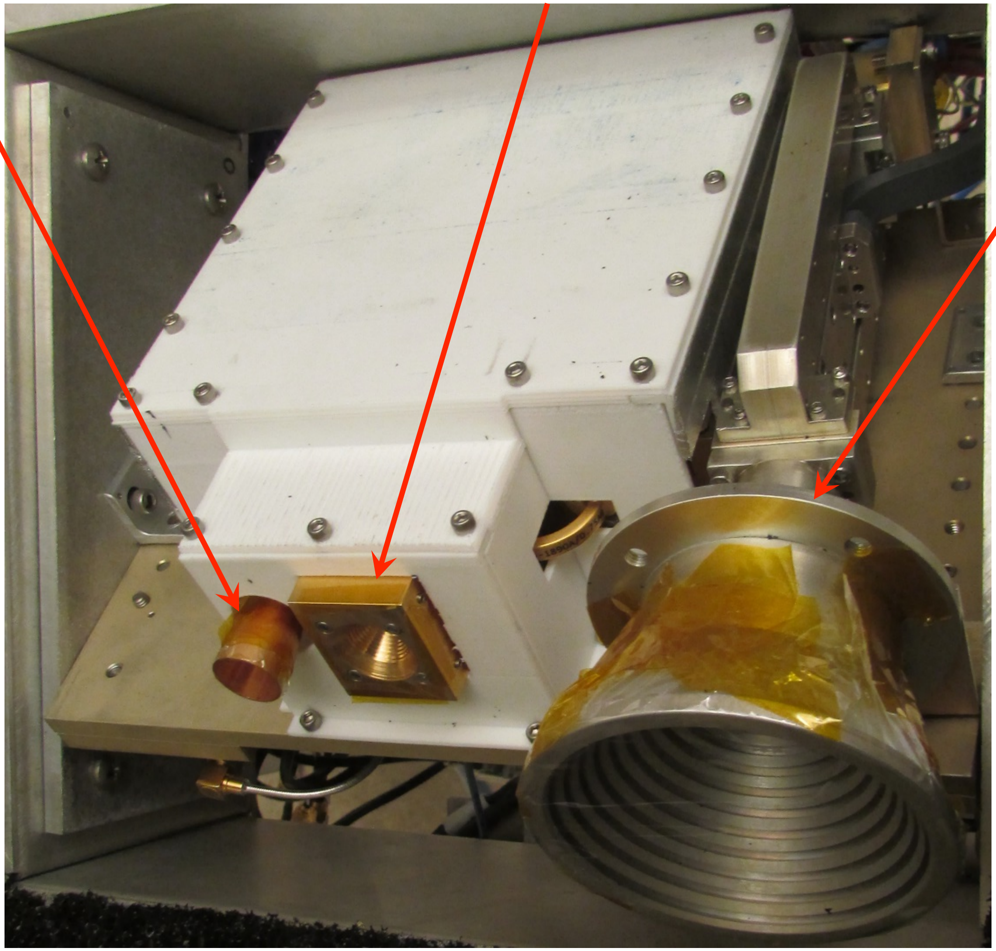


Three Feed Horn Antennas for Three Frequency Channel Sets

High-Frequency Millimeter wave Sounding Channels (118 and 183 GHz)

High-Frequency Millimeter Wave Window Channels (90, 130 and 168 GHz)

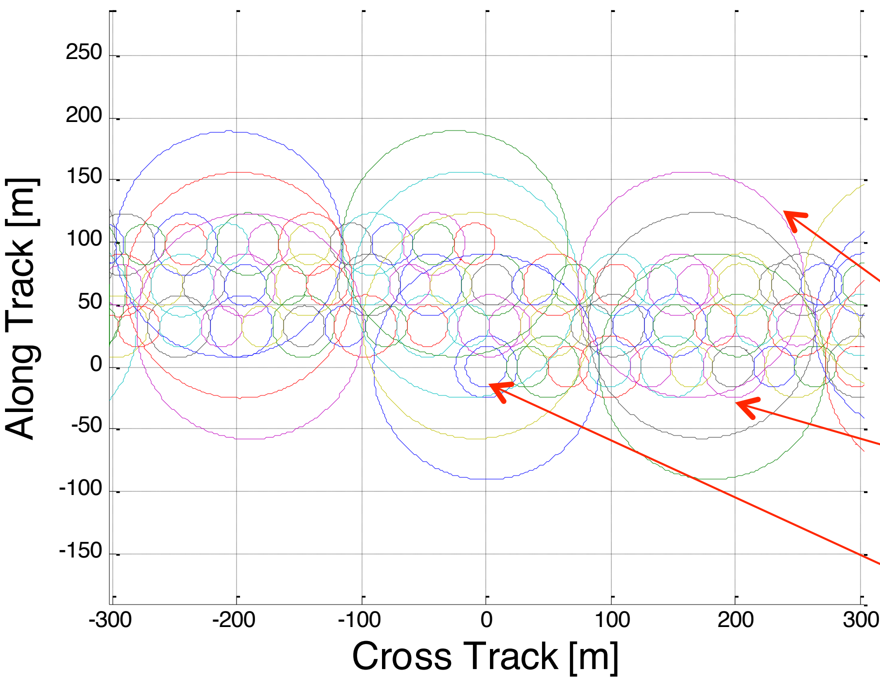
Low-Frequency Microwave channels (18.7, 23.8 and 34 GHz)



Sampling and Data Rates

Sampling rates were chosen to ensure contiguous along-track sampling using Twin Otter aircraft specifications of 3 km altitude (unpressurized), 33 m/s ground speed, 60 rpm scan rate, and scene observations from -45° to 45° incidence angle.

	Microwave Radiometers (Quasi-H & V)	mm-Wave Window Channels	mm-Wave Sounding Channels
Number of Channels	6	3	16
Sample Rate	5 kHz	10 kHz	370 Hz
Footprint Dimensions at highest frequency & maximum scan angle	159 x 224 m	25 x 36 m	50 x 70 m
Swath Width	6 km	6 km	6 km

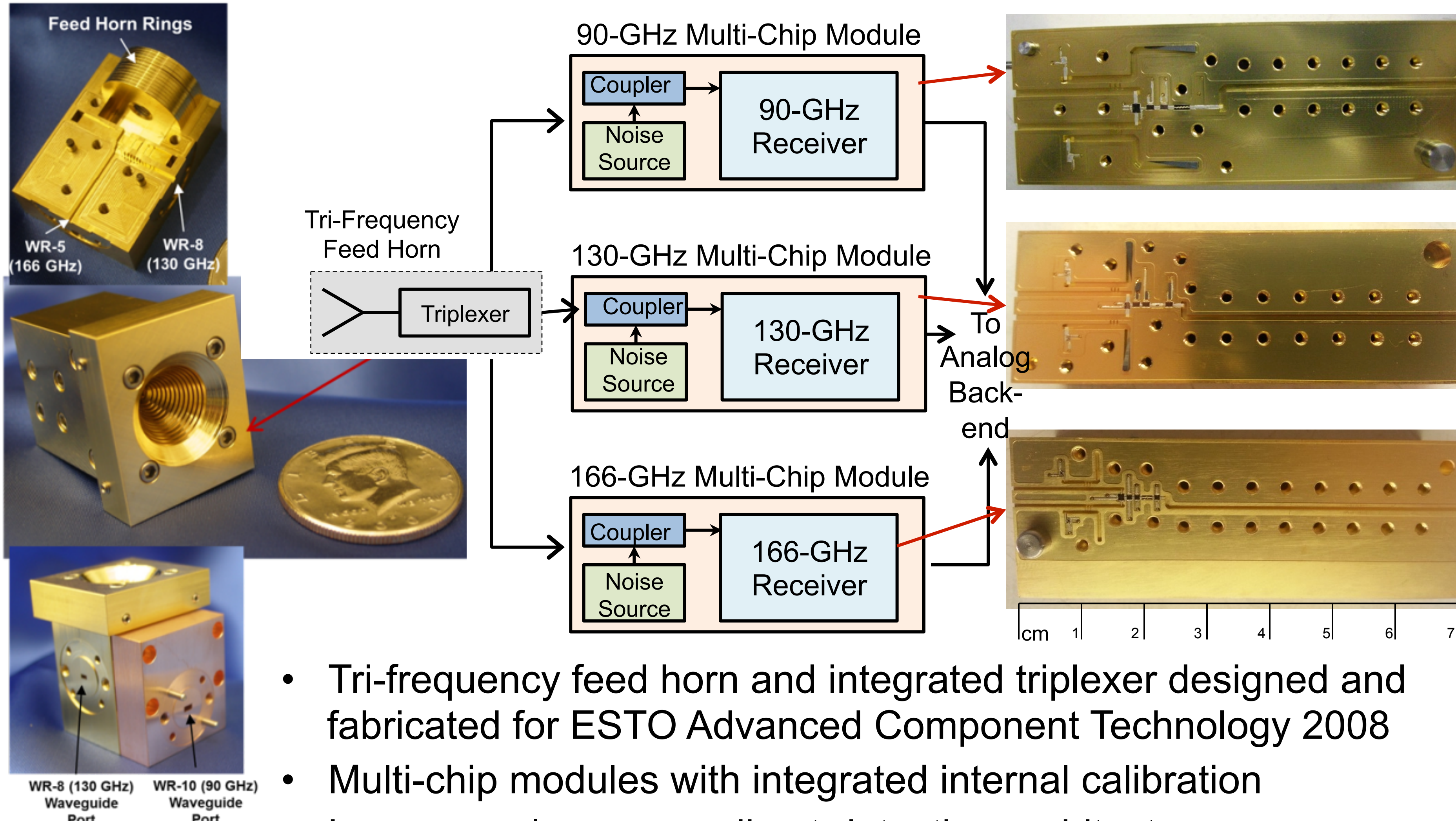


Footprint of low-frequency microwave radiometers (18-34 GHz)

Footprint of high-frequency mm-wave radiometers (90-175 GHz)

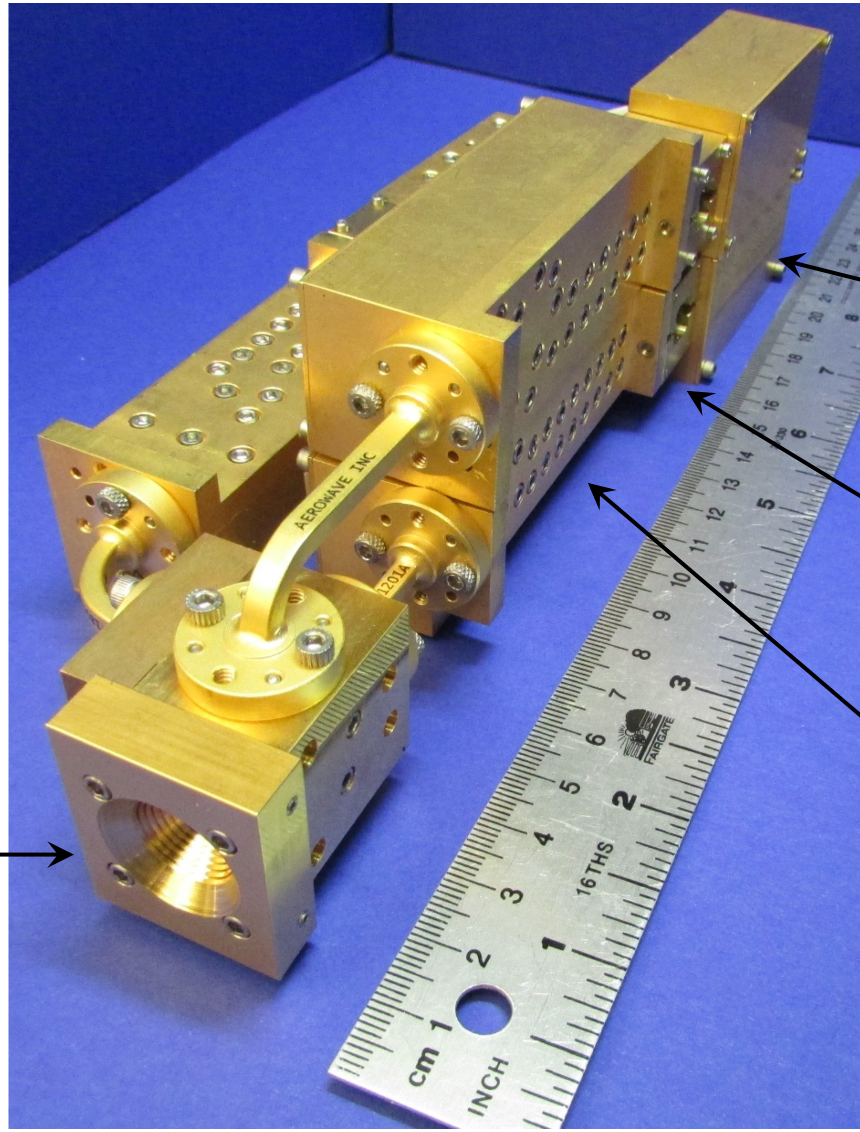
Footprint of 118 and 183 GHz sounding radiometers

High-Frequency Millimeter-Wave Window Channels



- Tri-frequency feed horn and integrated triplexer designed and fabricated for ESTO Advanced Component Technology 2008
- Multi-chip modules with integrated internal calibration
- Low-mass, low-power direct-detection architecture

High-frequency Millimeter-wave Radiometers at 90, 130 & 168 GHz



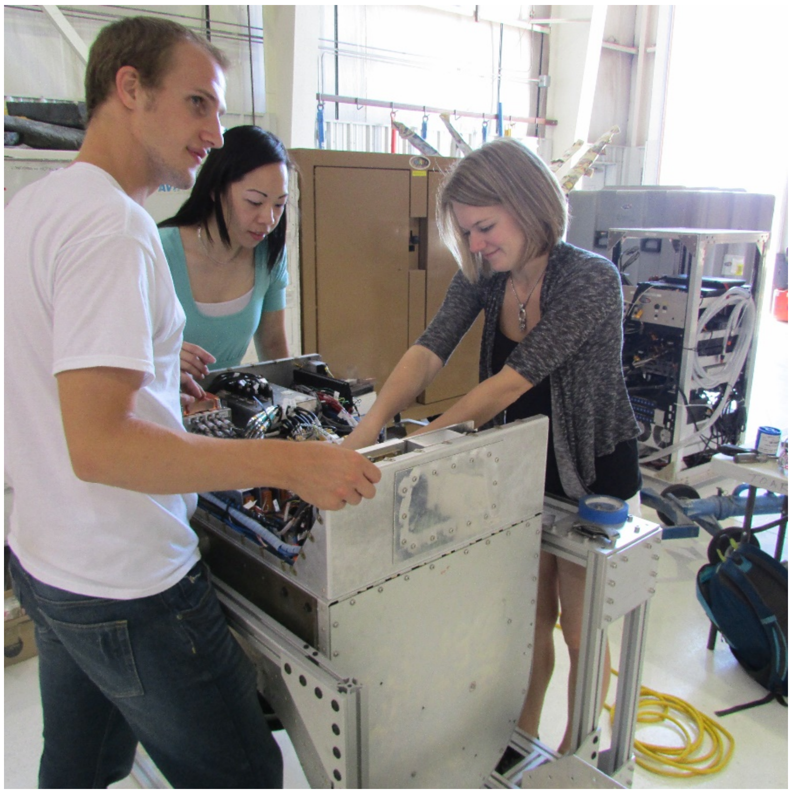
Diode Detectors

Band Definition Filters

Multi-chip Modules with Internal Calibration

Tri-Frequency Feed Horn from ESTO ACT-08

HAMMR Integration in Twin Otter
Grand Junction, CO, July 8, 2014



HAMMR Integration in Twin Otter
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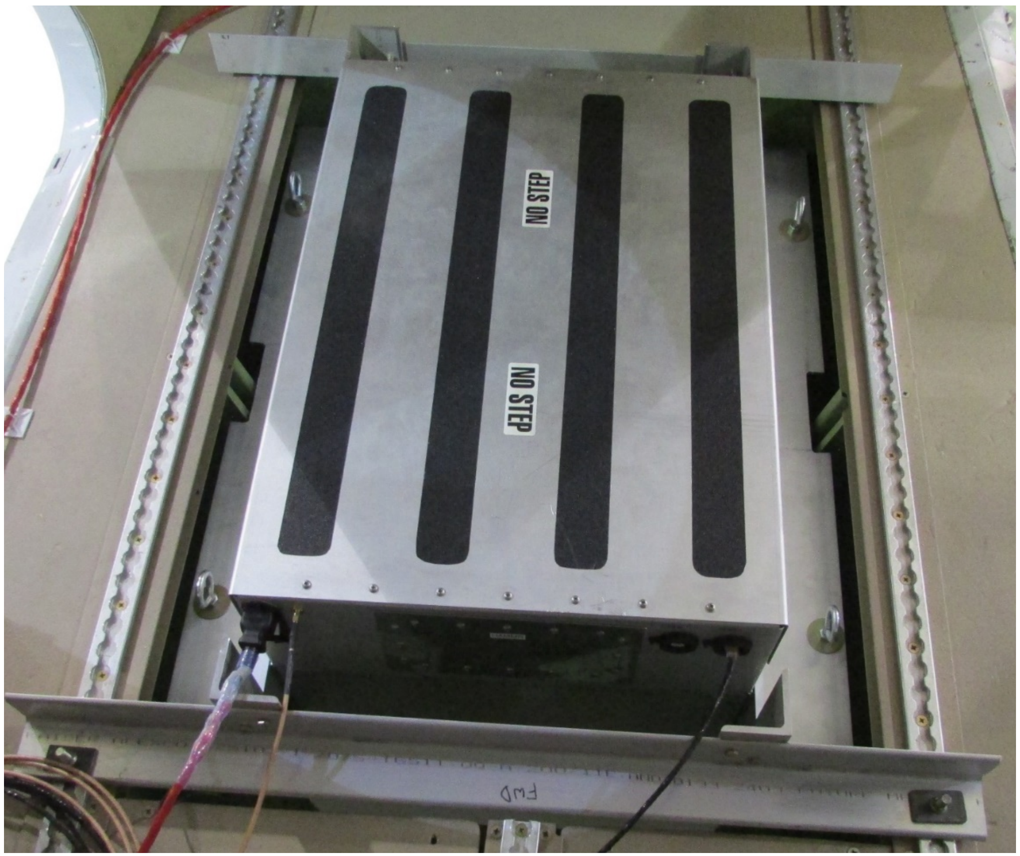
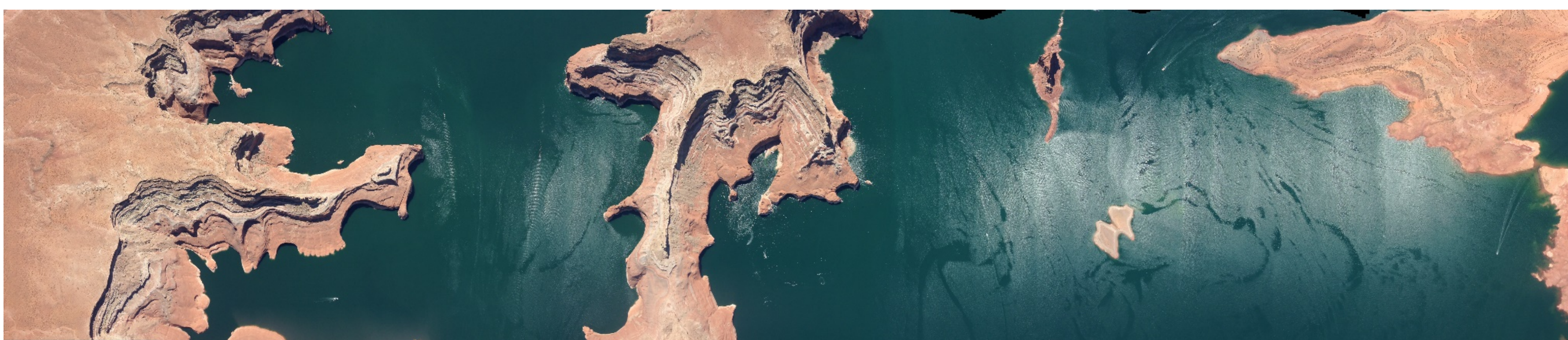


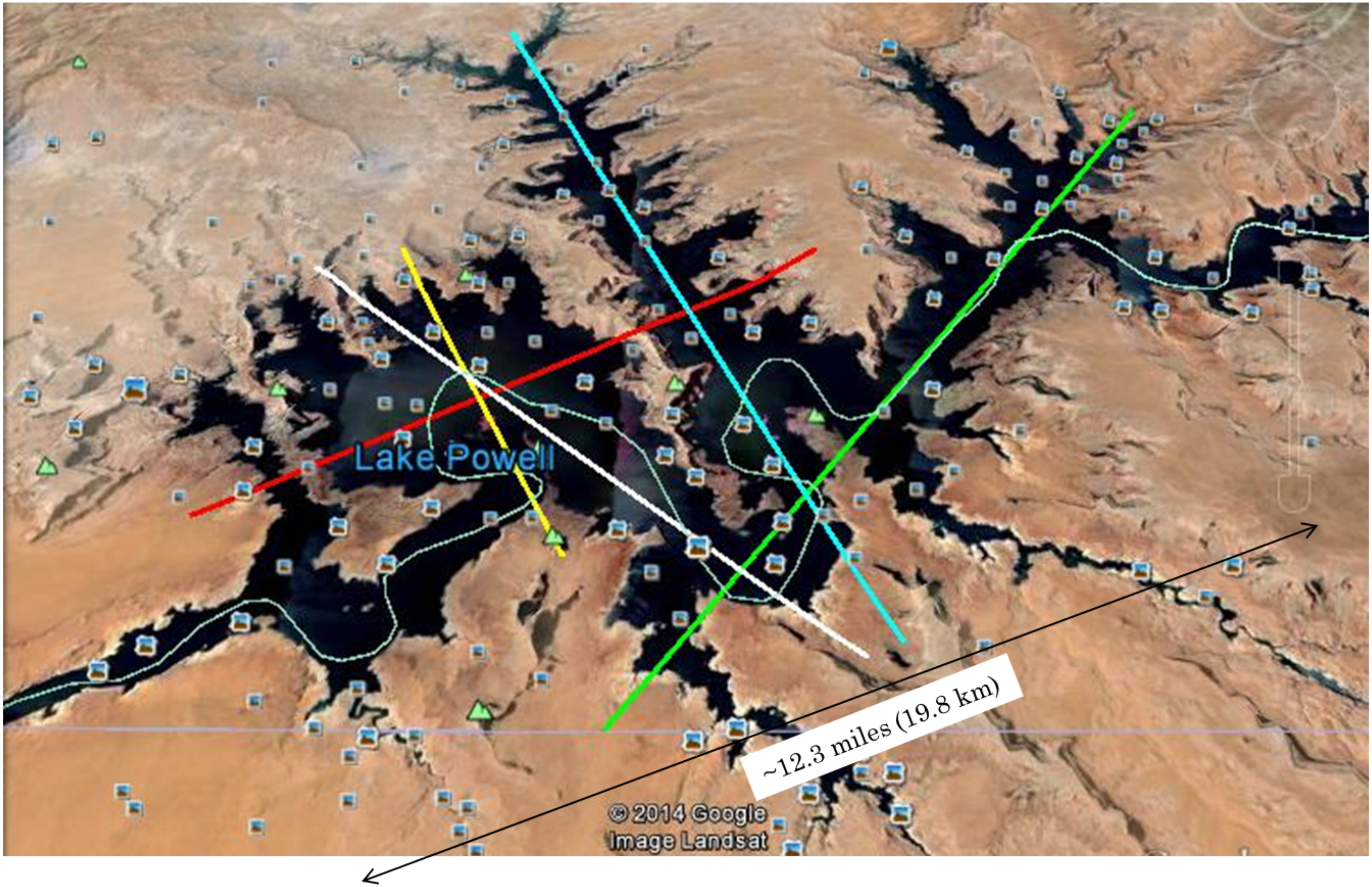
Summary of HAMMR Flights from Grand Junction, Colorado, July 2014

- Successful completion of 14 flight hours over 3 days
  - First day over Blue Mesa Reservoir, Colorado
  - Second and third days over Lake Powell, Utah and Arizona
- HAMMR instrument and subsystems worked well
- Physical temperatures throughout radiometer system were stable
- HAMMR radiometer channel subsystems performed very well
- Cross-track scanning was very stable; aerodynamics and turbulence were not a problem
- Ambient and LN_2 calibration was performed using an external target before and after each flight

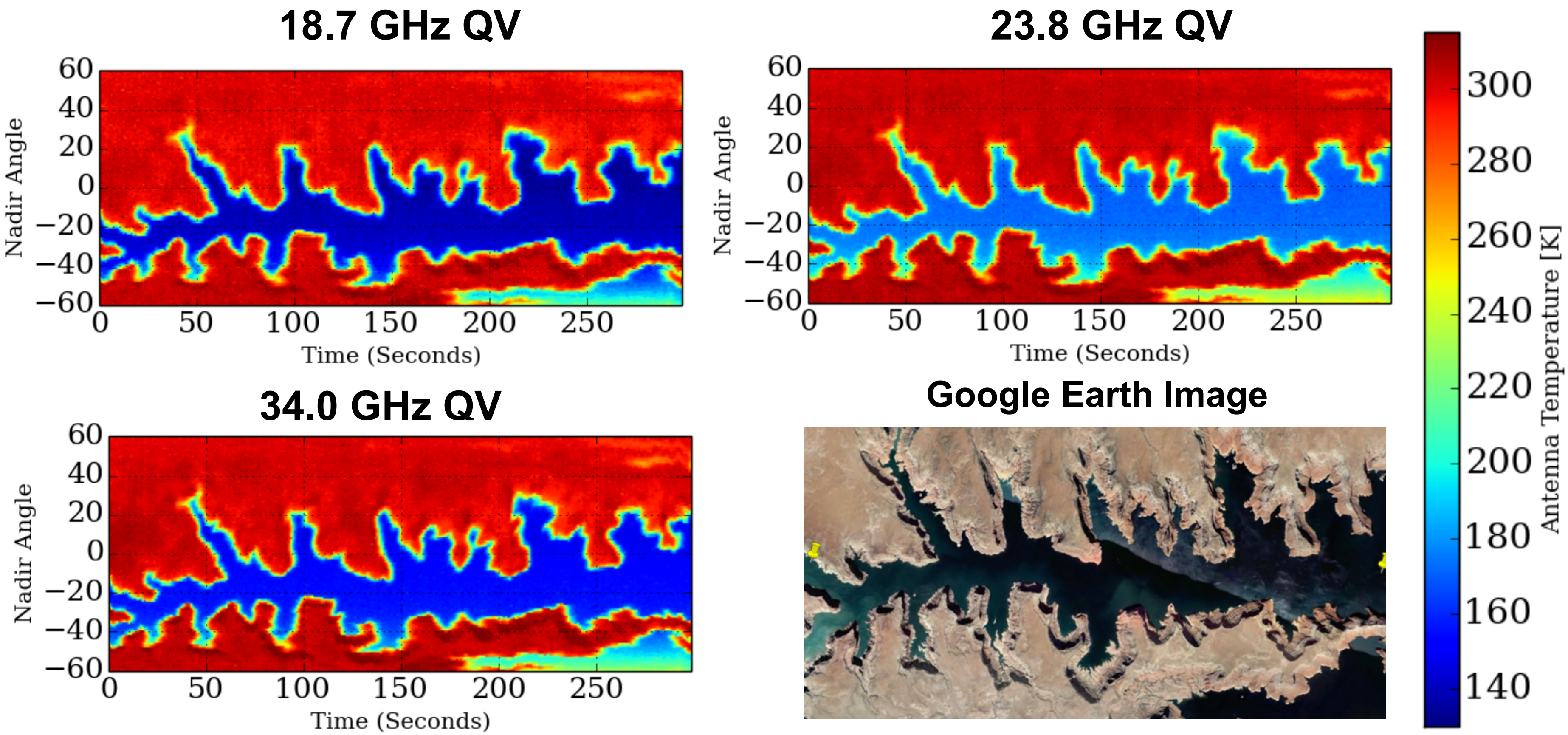
HAMMR Flights over Lake Powell, Utah and Arizona, July 10-11, 2014



Flight Lines over Lake Powell, Utah and Arizona, July 10-11, 2014

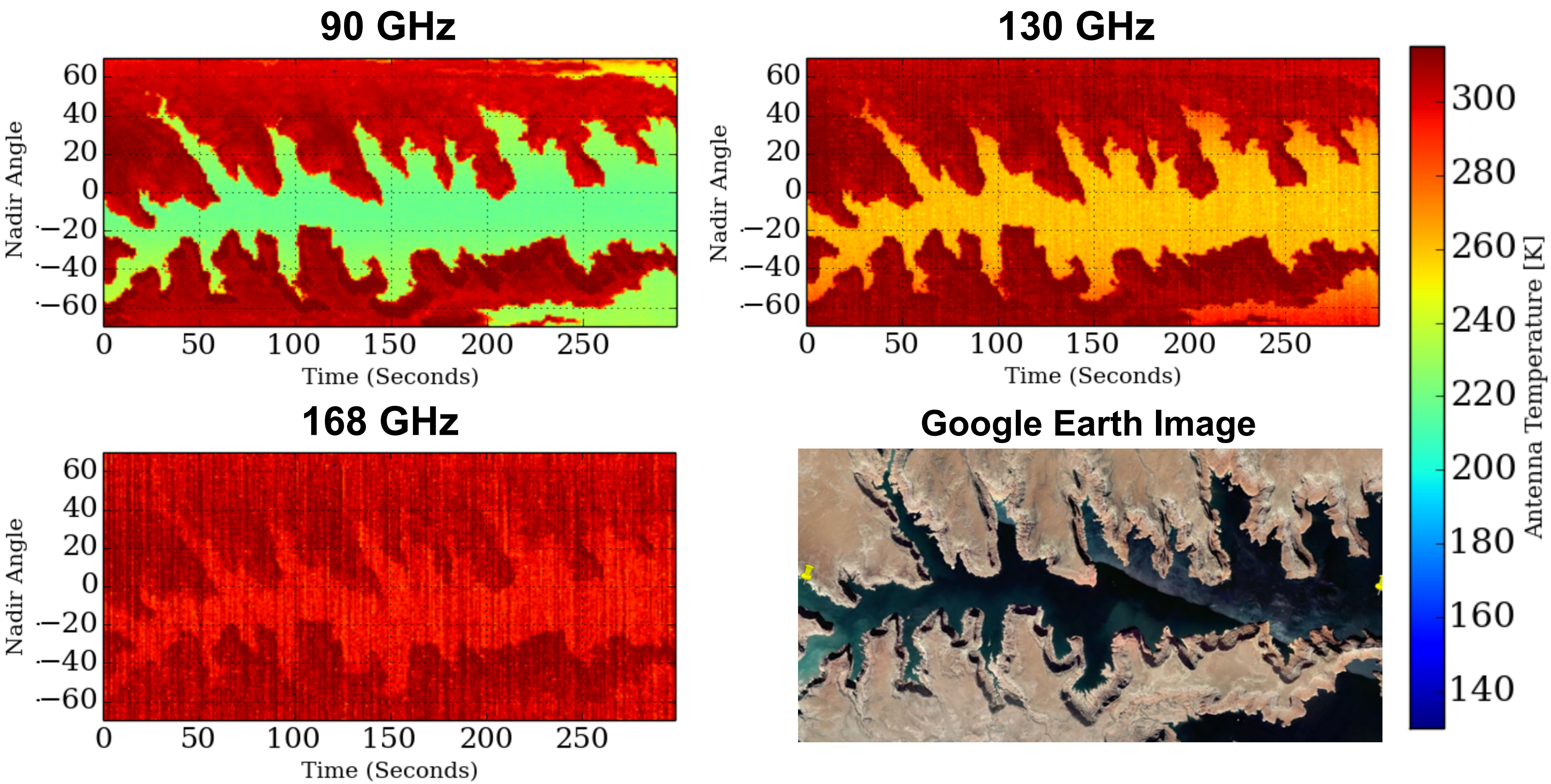


Low-Frequency Microwave Radiometer Measurements



Measurements were performed over Lake Powell, Utah on July 11, 2014.

High-Frequency Millimeter-wave Radiometer Measurements

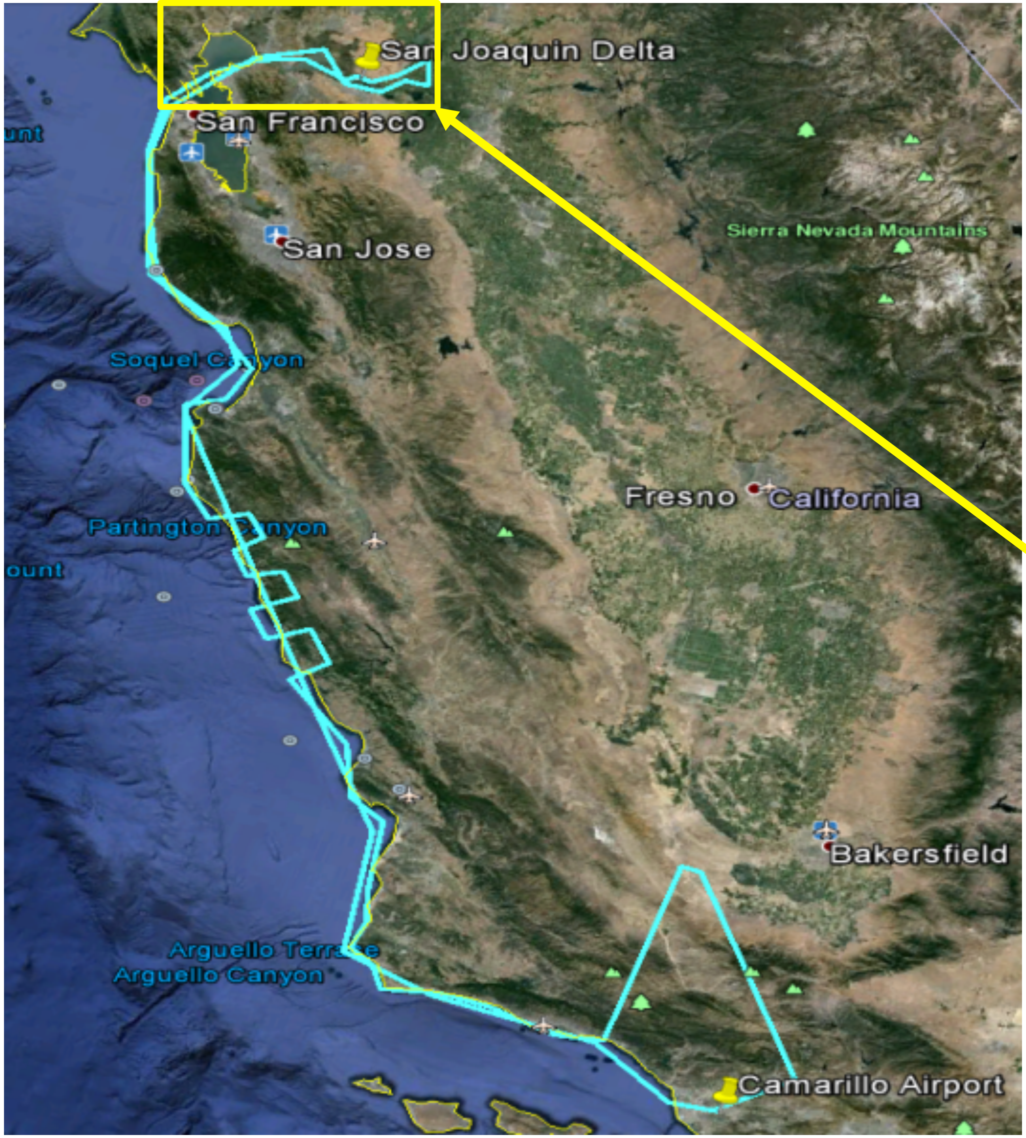


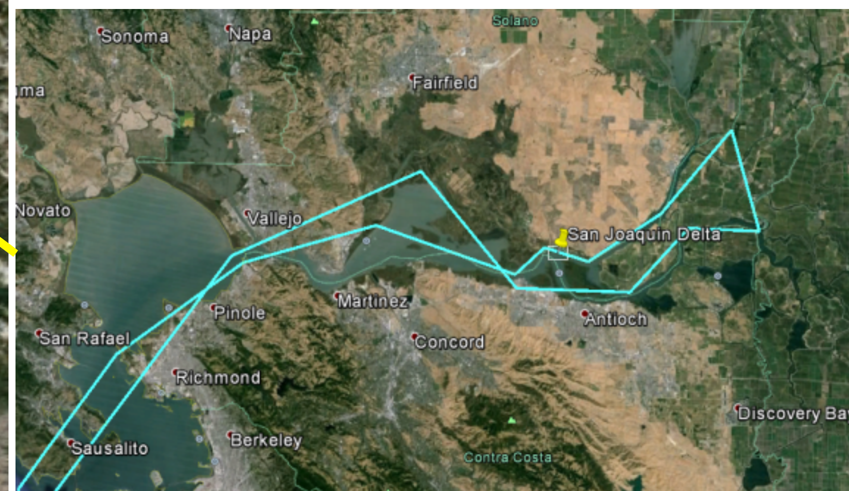
Measurements were performed over Lake Powell, Utah on July 11, 2014.

Future Plans for HAMMR Data Processing and Applications

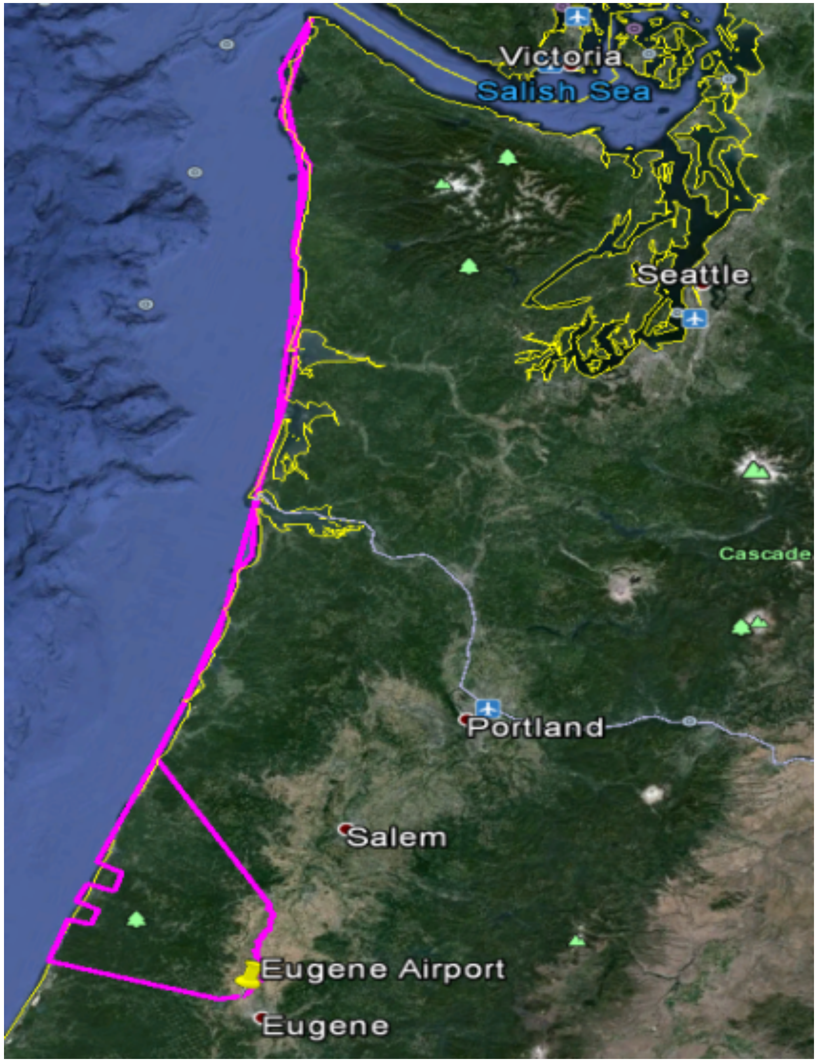
- Improve calibration of L1a antenna temperatures from microwave and mm-wave window channels using Dicke matched load and internal noise sources (two per mm-wave window channel)
- Complete data processor to convert L1a antenna temperatures to L1b geolocated brightness temperatures by accounting for the antenna pattern, location and aircraft attitude
- Retrieve microwave channel wet-path delay using baseline algorithms and use to train mm-wave window channel wet-path delay algorithm to extrapolate retrievals to land. Finally, compare mm-wave retrievals with microwave channel retrievals to determine precision of high-resolution wet-tropospheric correction.
- Determine statistics of small-scale water vapor spatial variation during U.S. west coast campaign, including effects of grid resolution
- Assess added value of humidity and temperature sounding channels

Preliminary HAMMR Flight Plan along Southern California Coast





Preliminary HAMMR Flight Plan for Oregon & Washington Coasts

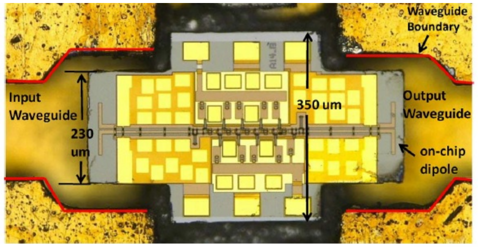


Flight Campaign Goals:

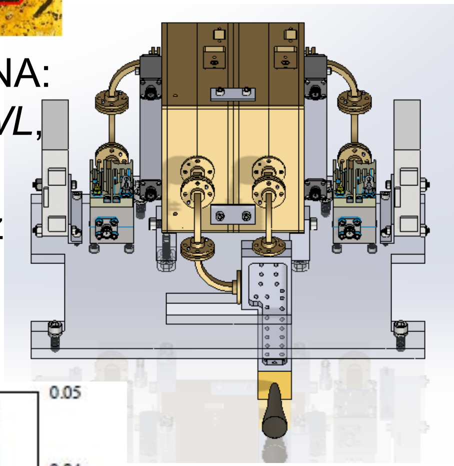
- Measure water vapor variability in the coastal zone and over inland water
- Measure under a wide variety of weather conditions over land & ocean
- Perform on-shore and off-shore flight segments to detect any scan bias
- Limited to max. altitude of 10,000 ft MSL in unpressurized cabin and a maximum of 8 flight hours per day
- Total of 45 flight hours, including ferry flights between Grand Junction, Colorado, Camarillo, California, and Eugene, Oregon

Tropospheric Water and Cloud ICE (TWICE) IIP-13

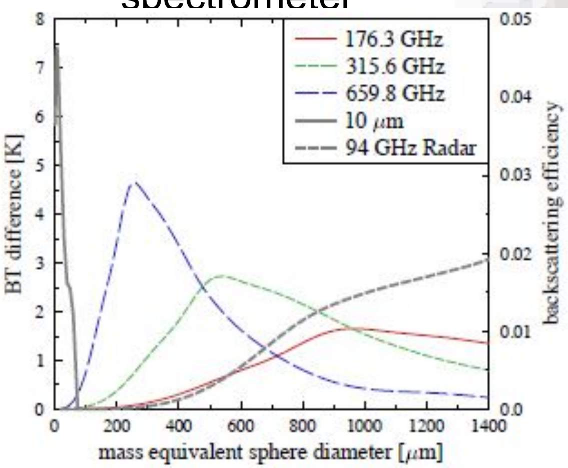
- **Objectives:**
  - Develop wide-band millimeter and sub-millimeter wave radiometer to measure upper-tropospheric water vapor, cloud ice particle size distribution and water content at a variety of local times
  - Demonstrate advancement of state of the art of sub-millimeter wave radiometers to InP HEMT MMIC LNA front ends up to 660 GHz
  - Reduce size, mass and power consumption to enable deployment on a 6U CubeSat platform
- **Frequency Channels:**
  - Cloud ice particle sizing at window channels of 240, 310 and 660 GHz (dual-pol) using direction-detection radiometers.
  - Upper tropospheric water vapor sounding near 118 GHz, 183 GHz and 380 GHz with offsets up to 8 GHz, all based on an ASIC analog spectrometer developed for HAMMR.



660 GHz InP HEMT LNA: Deal et al., *IEEE MCWL*, 2012.



HAMMR 118 & 183 GHz profiling radiometer with ASIC-based spectrometer



Ice particle sizing based on Buehler et al., *QJRMS, 2007.*

Summary

- Conventional altimeters with nadir-viewing 18-34 GHz microwave radiometers to measure wet-tropospheric path delay have limited accuracy within 30-40 km of land.
- The addition of high frequency (90-175 GHz) radiometers to ocean altimetry missions is expected to improve spatial resolution of wet-path delay retrievals near the coasts and enable retrievals over inland water.
- High-frequency Airborne Microwave and mm-Wave (18-183 GHz) Radiometer (HAMMR) was successfully demonstrated on a Twin Otter this July. HAMMR will:
  - Provide high-resolution measurements of spatial variability of tropospheric water vapor on 100-m scales from aircraft
  - Provide high-frequency millimeter-wave brightness temperature measurements to extend wet-tropospheric path delay correction closer to the world's coastlines and explore the potential over inland water
  - Demonstrate millimeter-wave radiometer technology that can be directly integrated into future altimetry space missions
  - Provide an airborne calibration and validation instrument in support of the SWOT and Jason-CS missions that is complementary to JPL's AirSWOT

Thanks to George Komar, Parminder Ghuman and Keith Murray at NASA ESTO for their continued support through the ACT and IIP programs!