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

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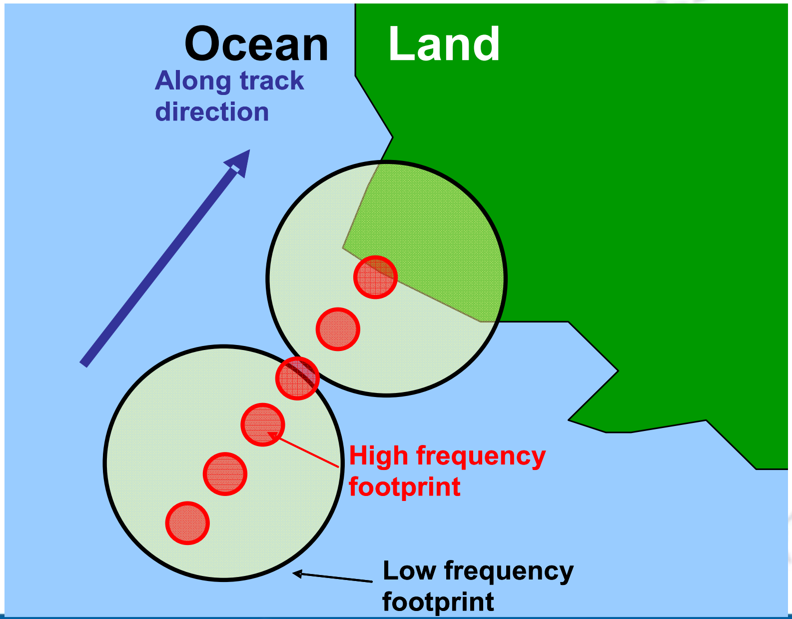
Scientific Motivation

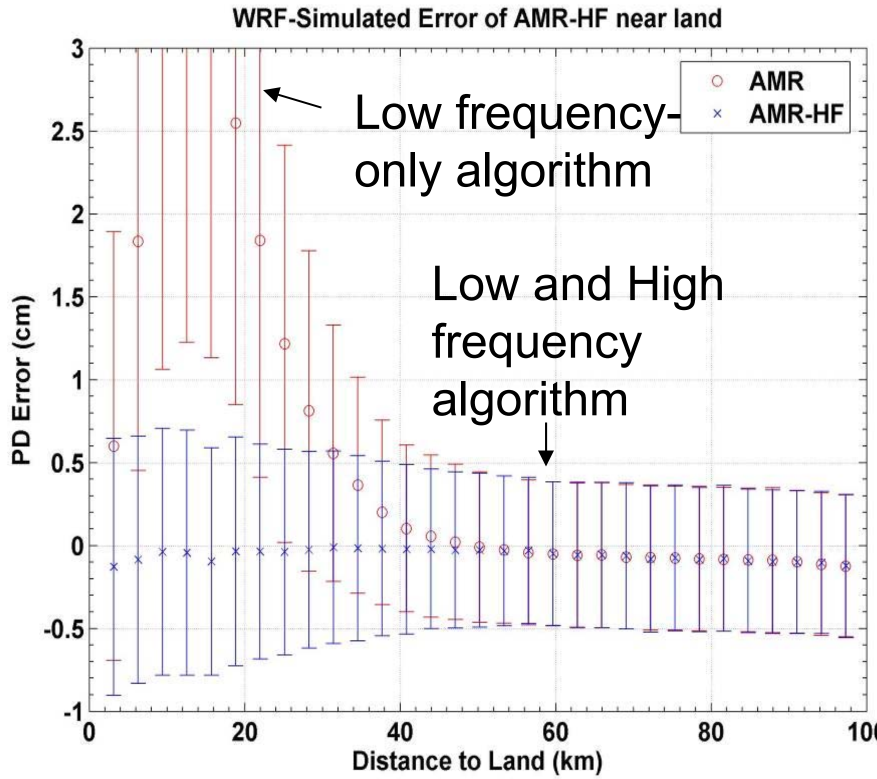
- Radar altimeter missions include nadir-viewing 18-34 GHz microwave radiometers to measure wet-tropospheric path delay. These radiometers, including those for the SWOT and Jason-CS baseline missions, cannot provide sufficient measurements in coastal areas and over land.
- Error due to land incursion is unacceptable within 30-40 km of the coastlines.
- OSTST 2012 meeting recommended for Jason-CS: “The most significant benefit would be […] for the second radiometer to resolve km-scale water vapour to improve coastal altimetry and inland hydrology applications.”

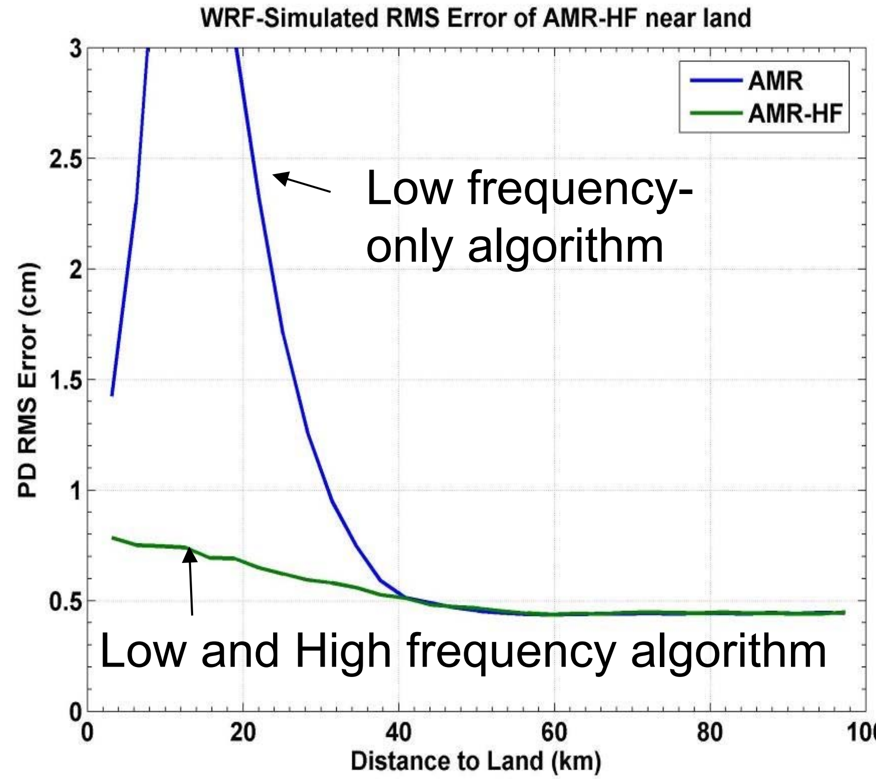


- High-frequency, wide-bandwidth millimeter-wave window channels at 90, 130 and 168 GHz provide an optimal frequency set to improve coastal retrievals.
- We have developed new algorithms for retrieval over inland water using ratios of window channels without the need for *a-priori* data.

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 less than 8 mm to within 3 km from the coasts.

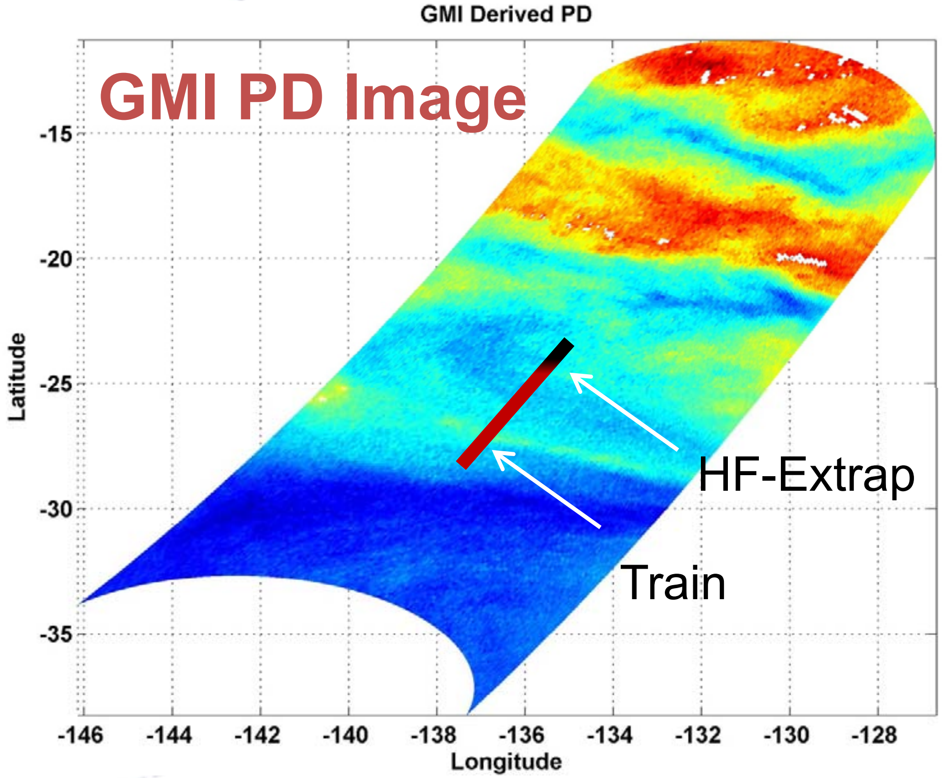




Application of Wet-Path Delay Retrieval Algorithm to GMI

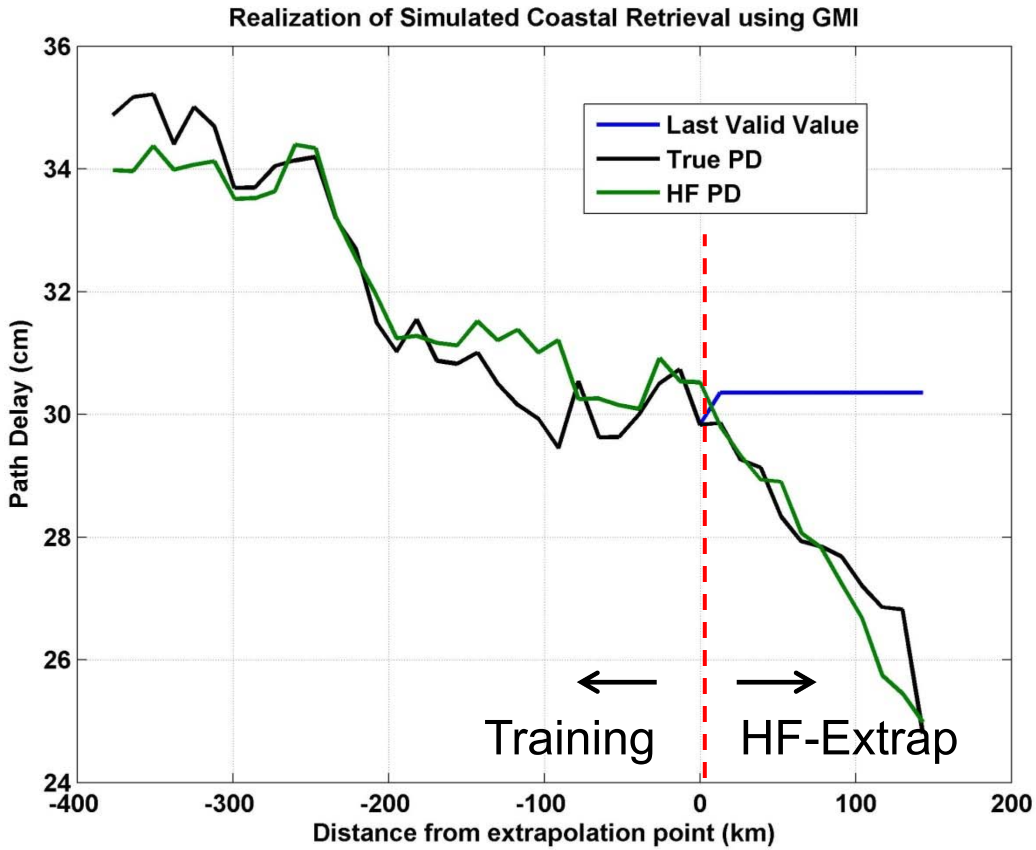
- The Global Precipitation Measurement Microwave Imager (GMI) has 18.7-37.0 GHz channels and also a high-resolution 90 GHz channel.
- GMI data used to evaluate algorithm performance in real atmospheres.

- 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.



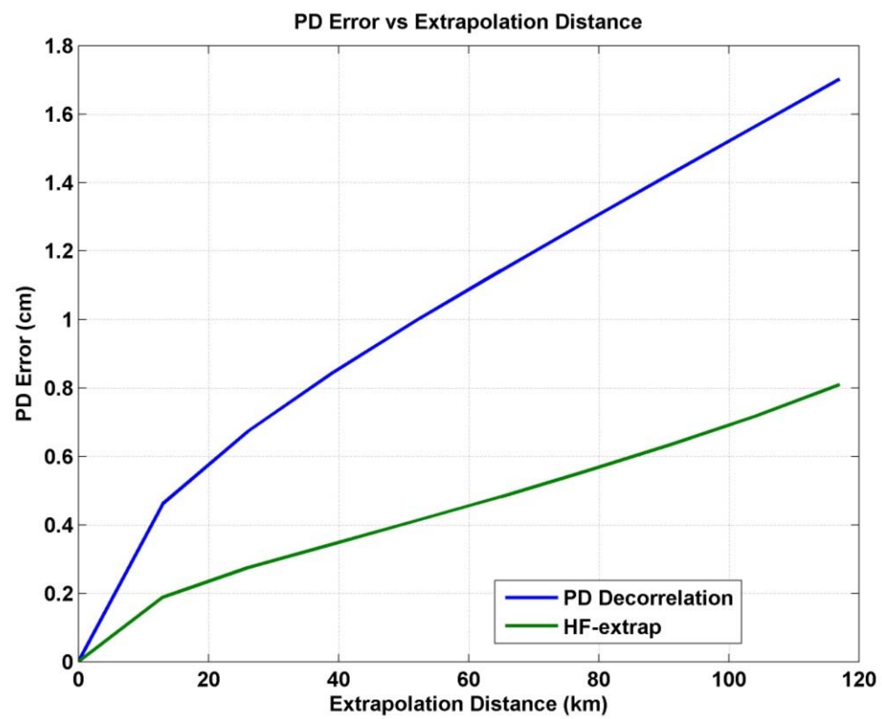
Example Realization of High-Frequency Algorithm

- HF Extrapolation algorithm using GMI 90 GHz channel is compared to using last valid PD value to the coast.



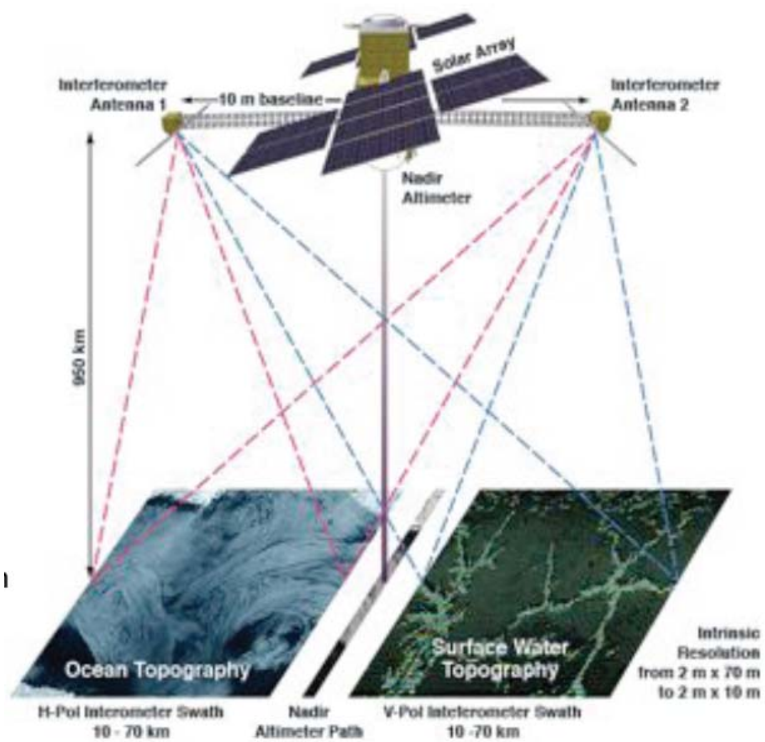
High-Frequency Algorithm Performance using GMI

- Computed statistics for a large number of realizations, encompassing various atmospheric conditions
- HF algorithm shows significant reduction in PD variance
- Assuming a low-frequency radiometer that is contaminated at 50 km from the coast, the HF algorithm reduces the error from 10 mm to 4 mm.
- More details will be given by Shannon Brown next Tuesday at OSTST: "Potential for High Resolution Wet Path Delay Measurements using High Frequency Radiometers on Future Altimetry Missions"

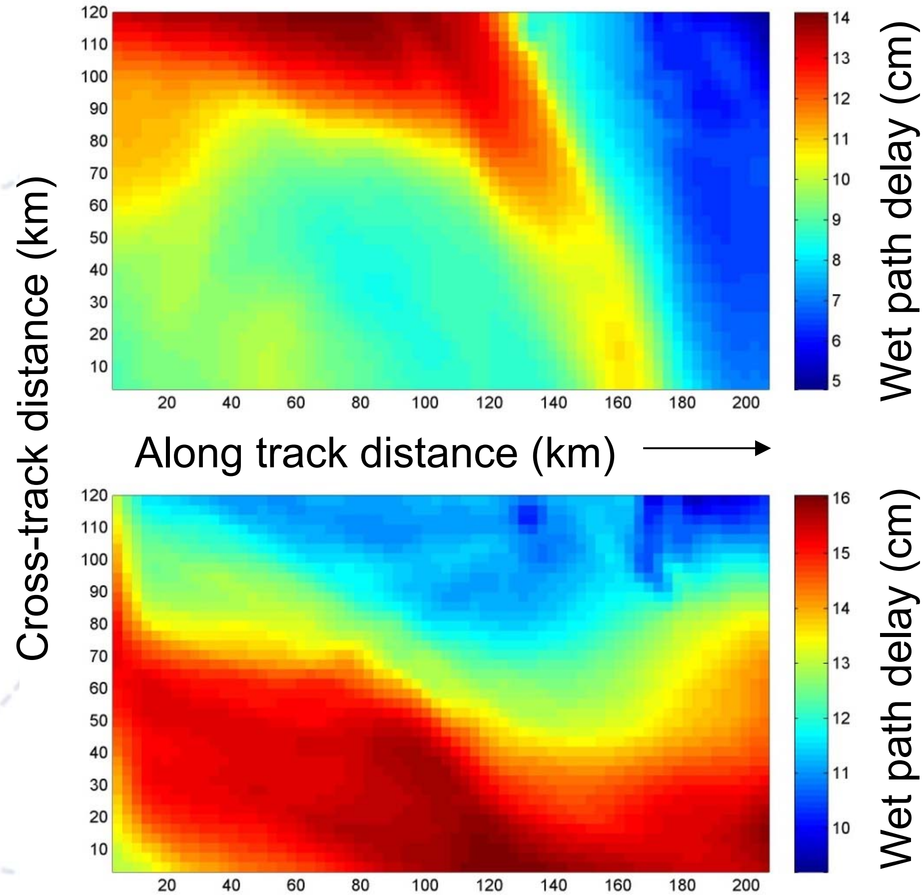


Understanding Swath-Scale Water Vapor Variability

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



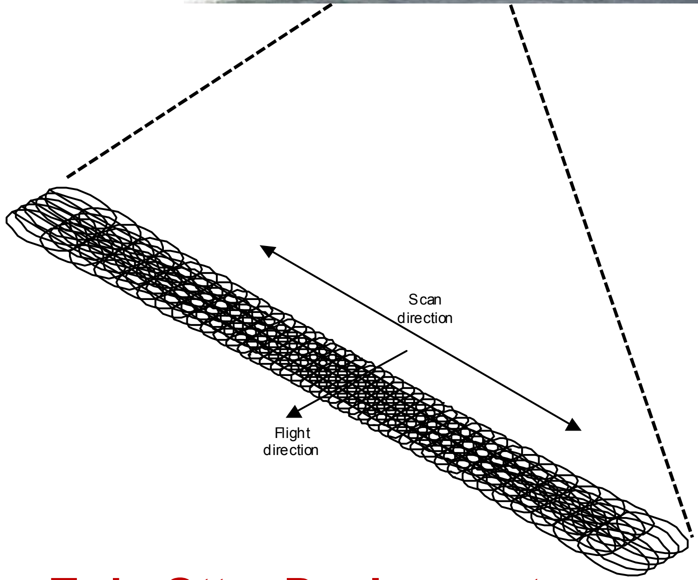
Model wet-path delay fields from Weather Research and Forecasting (WRF) model



High-Frequency Airborne Microwave and mm-Wave Radiometer

CSU and JPL have designed and fabricated the High-Frequency Airborne Microwave and mm-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 to extend the wet-tropospheric path delay correction much closer to the world's coastlines
3. Demonstrate millimeter-wave radiometer that can be directly integrated into future altimetry space missions
4. Provide an airborne calibration and validation instrument in support of the SWOT and Jason-CS mission, complementary to JPL's AirSWOT

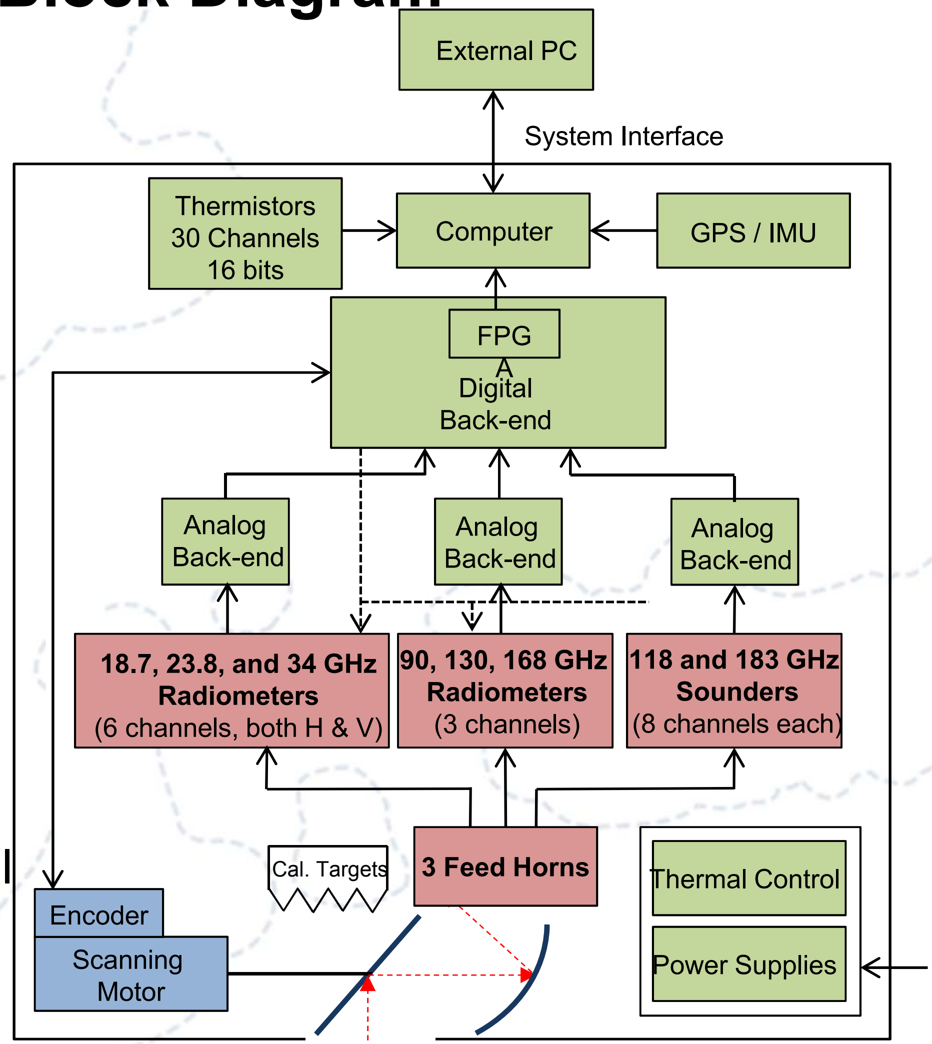


Twin Otter Deployment:

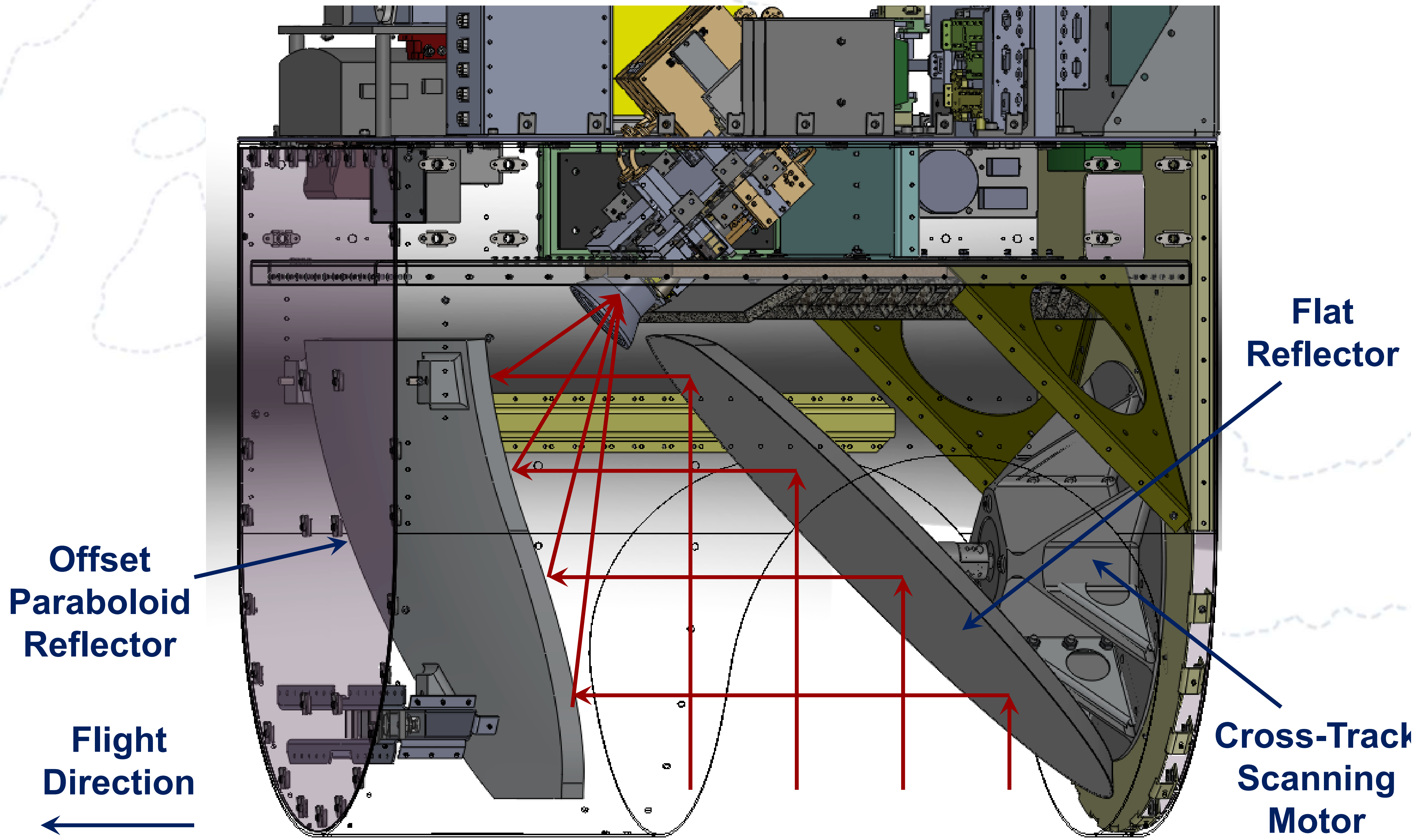
- Altitude: 3 km
- Swath Width: 6 km
- Scan Rate: 60 rpm

HAMMR 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

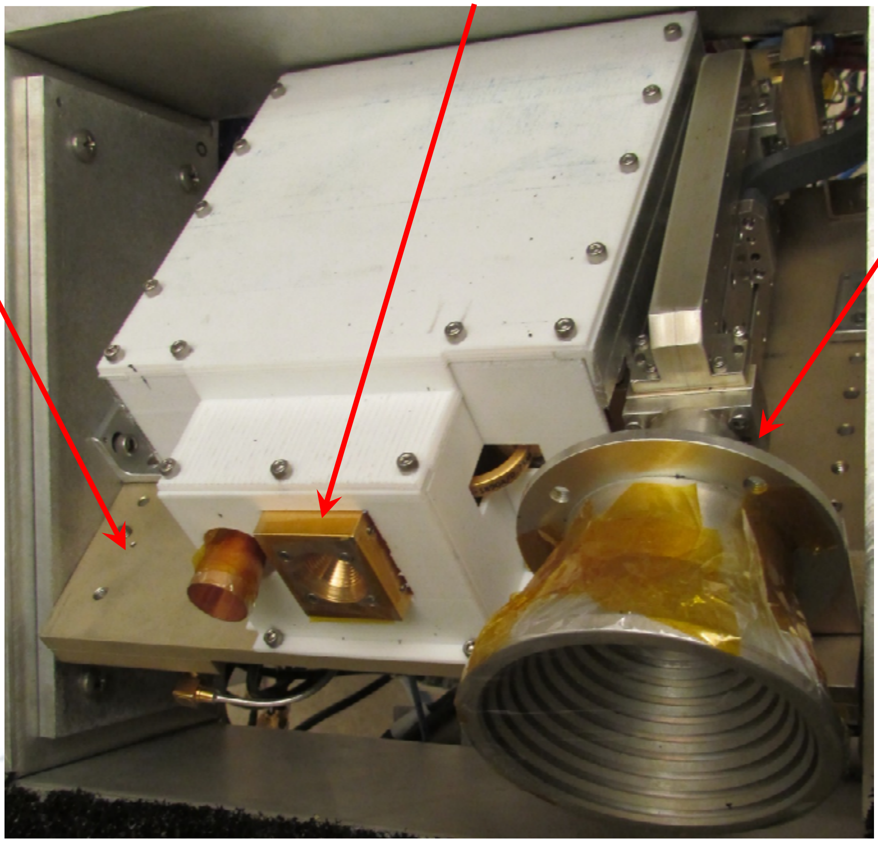

Flat Reflector
Offset Paraboloid Reflector
Flight Direction
Cross-Track Scanning Motor

Three Feed Horn Antennas for Three Frequency Channel Sets

High-Frequency mm-Wave Sounding Channels (118 and 183 GHz)

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

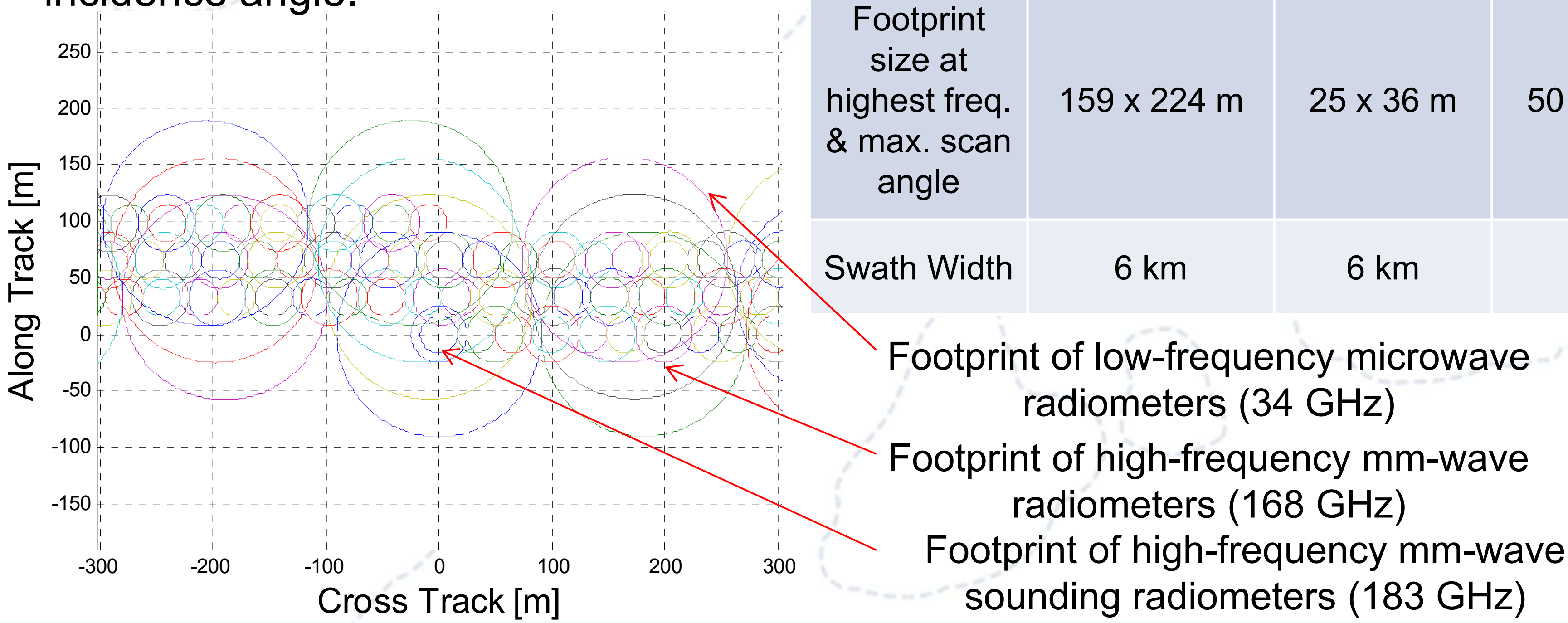
Low-Frequency Microwave channels (18.7, 23.8 and 34 GHz)



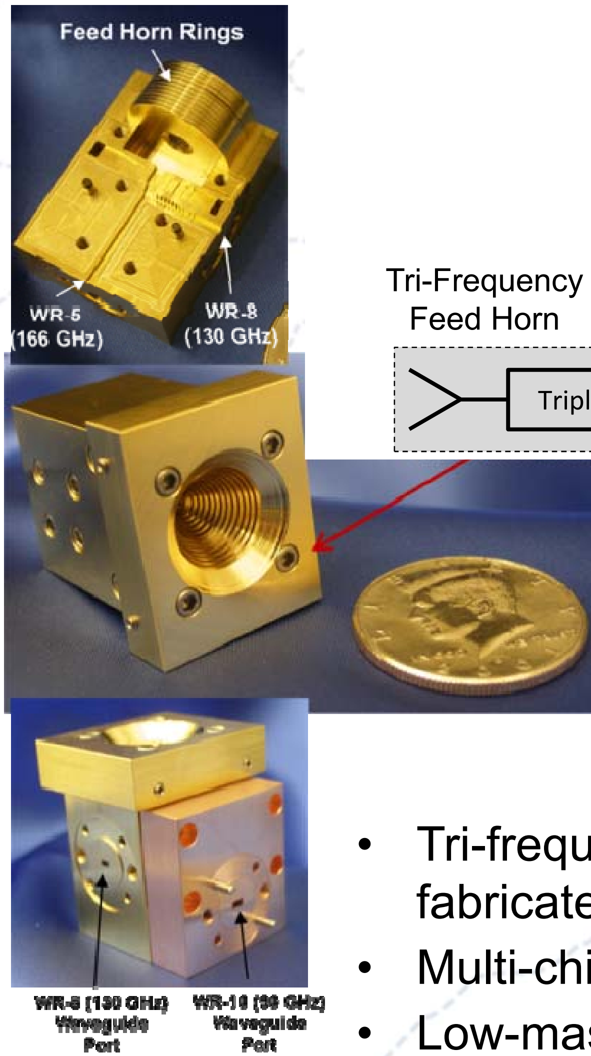
HAMMR Footprints and Sampling Rates

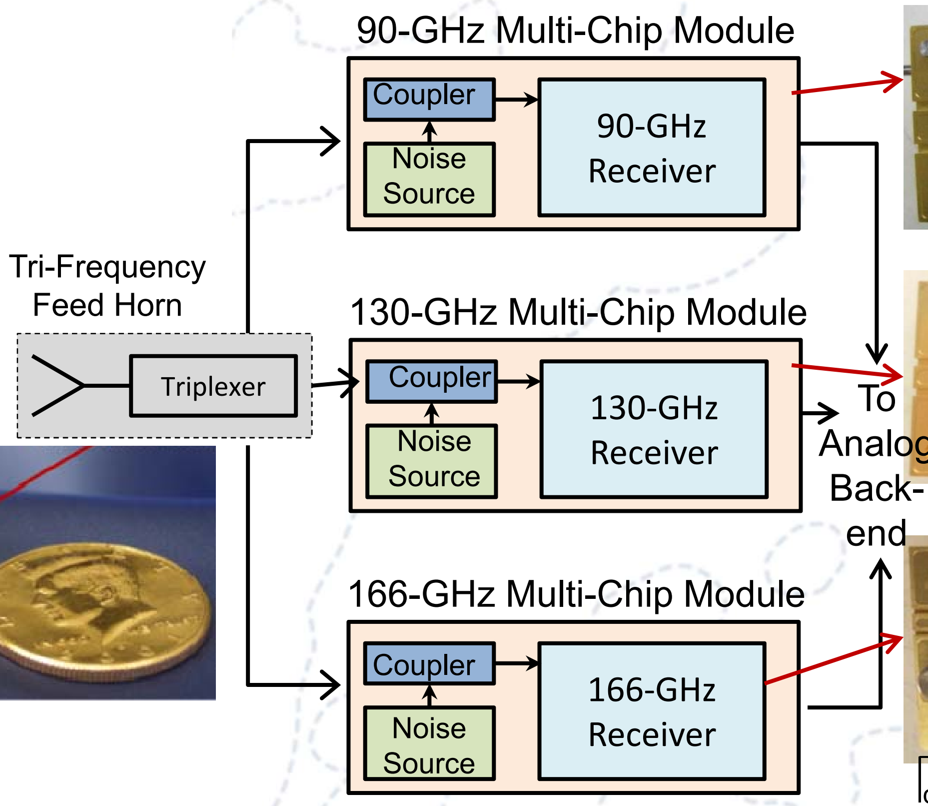
Sampling rates were chosen to ensure contiguous along-track sampling using Twin Otter aircraft specifications of 3 km altitude, 33 m/s ground speed, 60 rpm scan rate, and scene observations from -45° to 45° incidence angle.

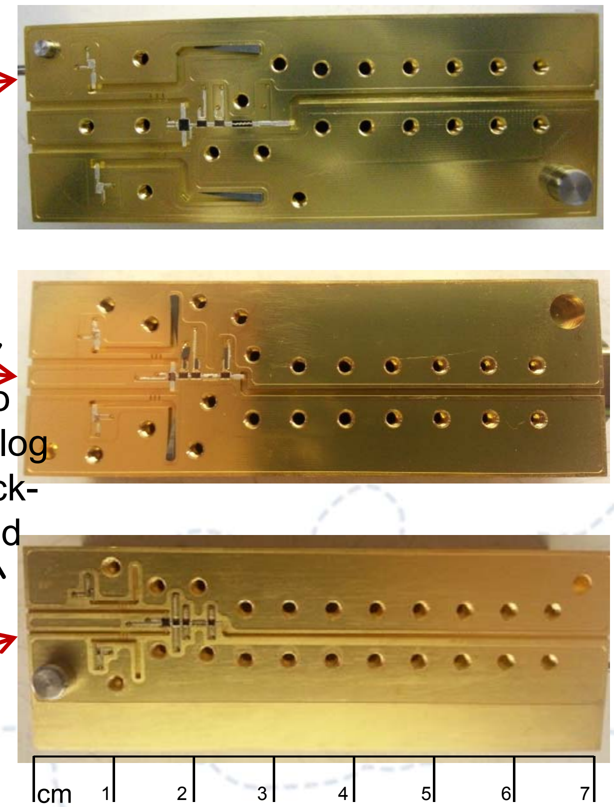
	Microwave Radiometers (Quasi-H & V)	mm-Wave Window Channels	mm-Wave Sounding Channels
Number of Channels	6	3	16
Sample Rate	5 kHz	10 kHz	370 Hz
Footprint size at highest freq. & max. scan angle	159 x 224 m	25 x 36 m	50 x 70 m
Swath Width	6 km	6 km	6 km



HAMMR High-frequency Millimeter-wave Window Channels



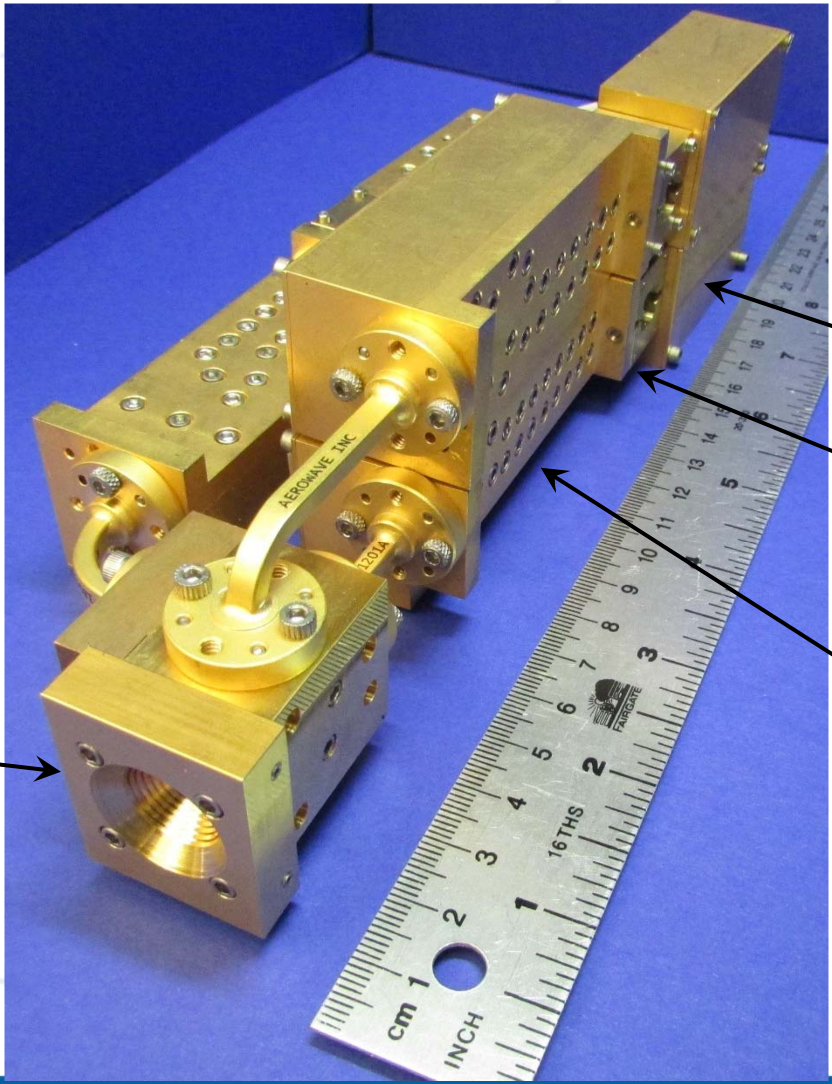




- Tri-frequency feed horn and integrated triplexer designed and fabricated for NASA ACT-08 project
- Multi-chip modules with integrated internal calibration
- Low-mass, low-power direct-detection architecture

High-frequency mm-Wave Radiometers at 90, 130 & 168 GHz

Tri-Frequency Feed Horn for 85 to 175 GHz (based on scaled version of AMR horn)

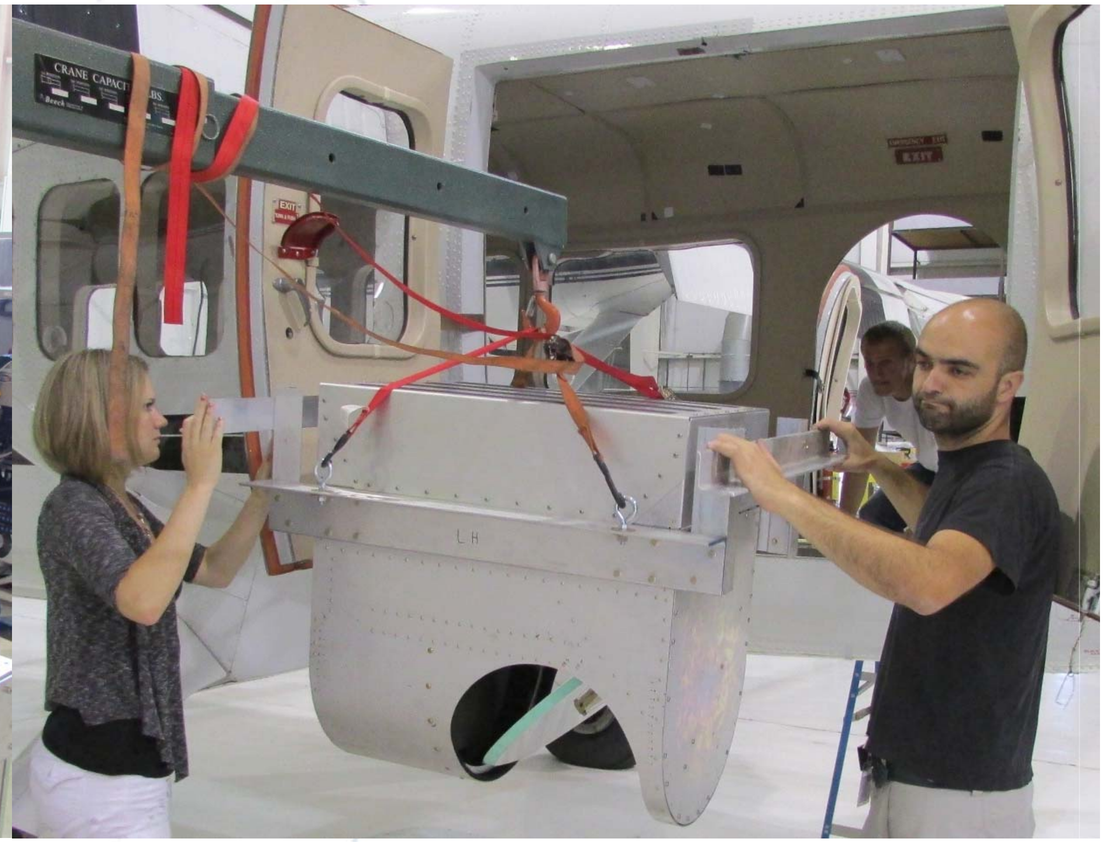


Diode Detectors

Band Definition Filters

Multi-chip Modules with Internal Calibration

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



HAMMR Integration in Twin Otter Aircraft, Grand Junction, CO
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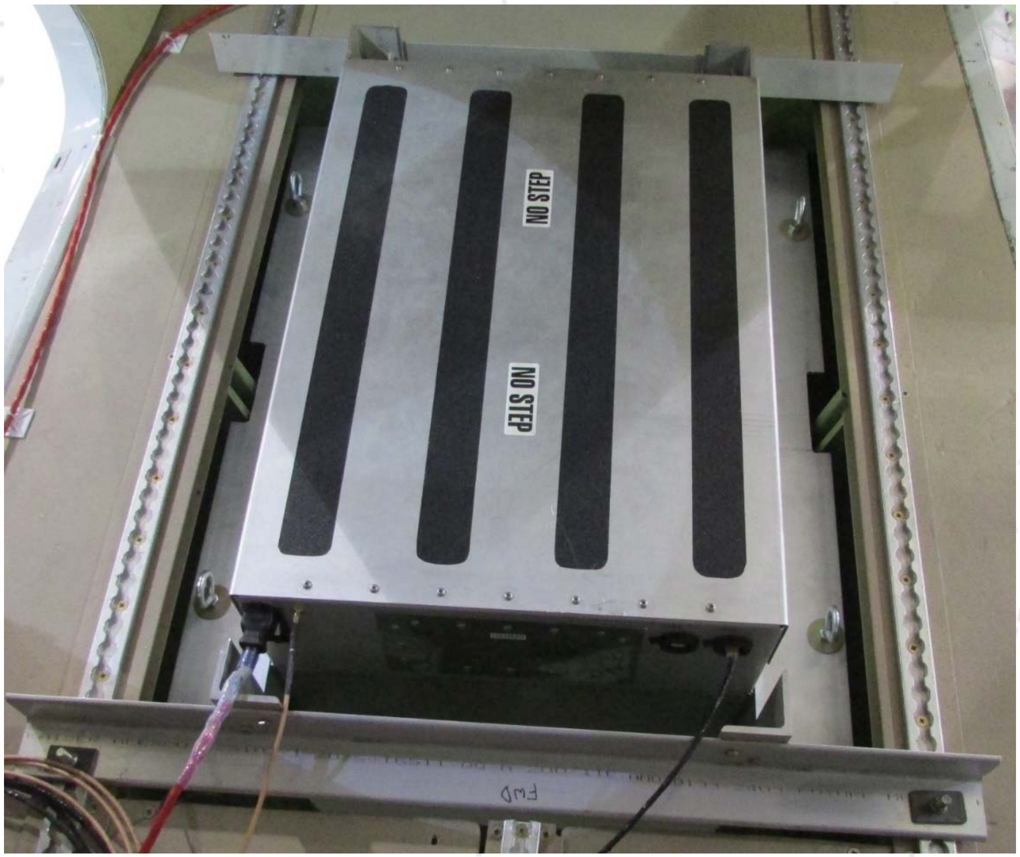
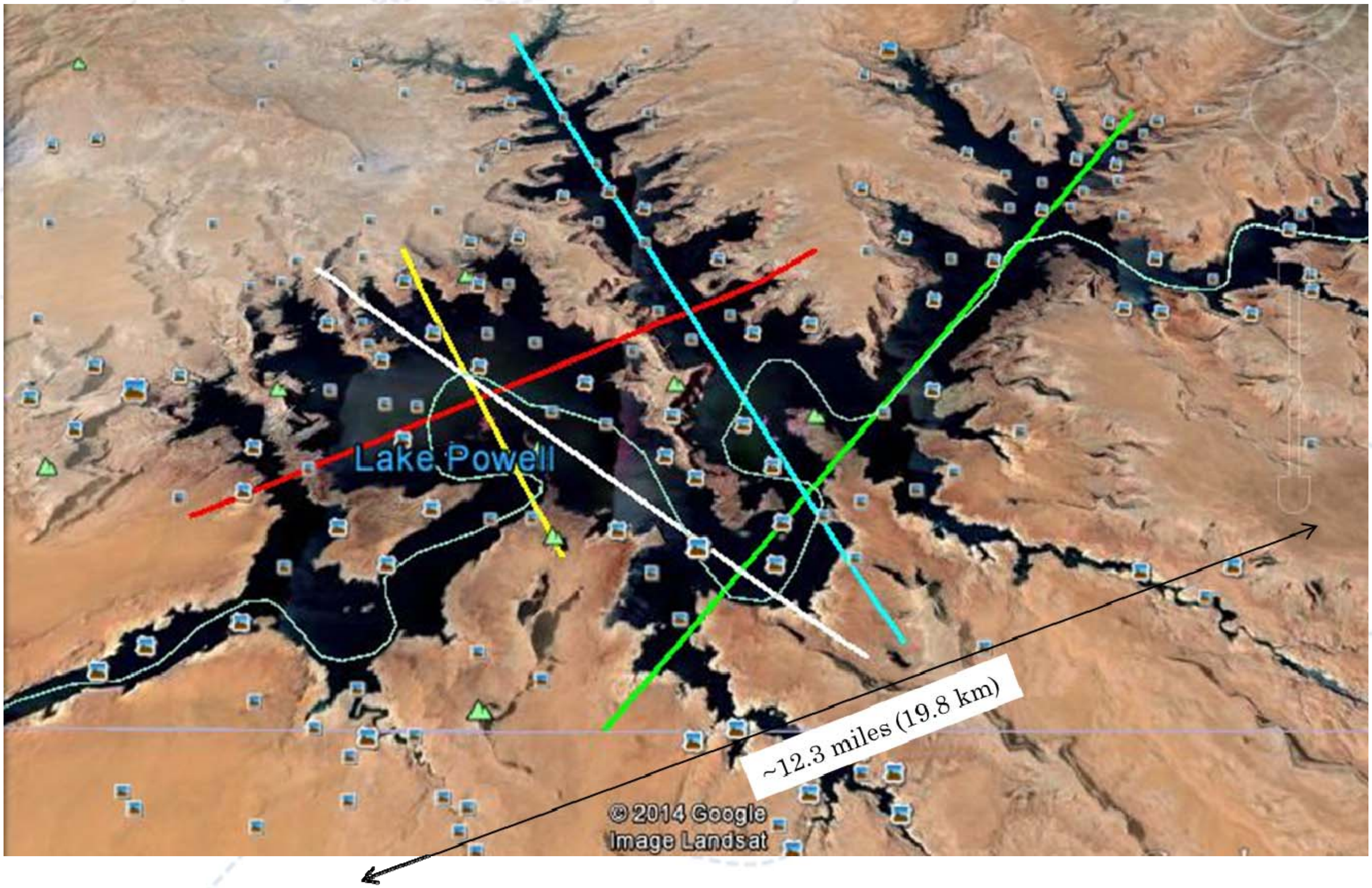


Summary of HAMMR Flights from Grand Junction, CO in July

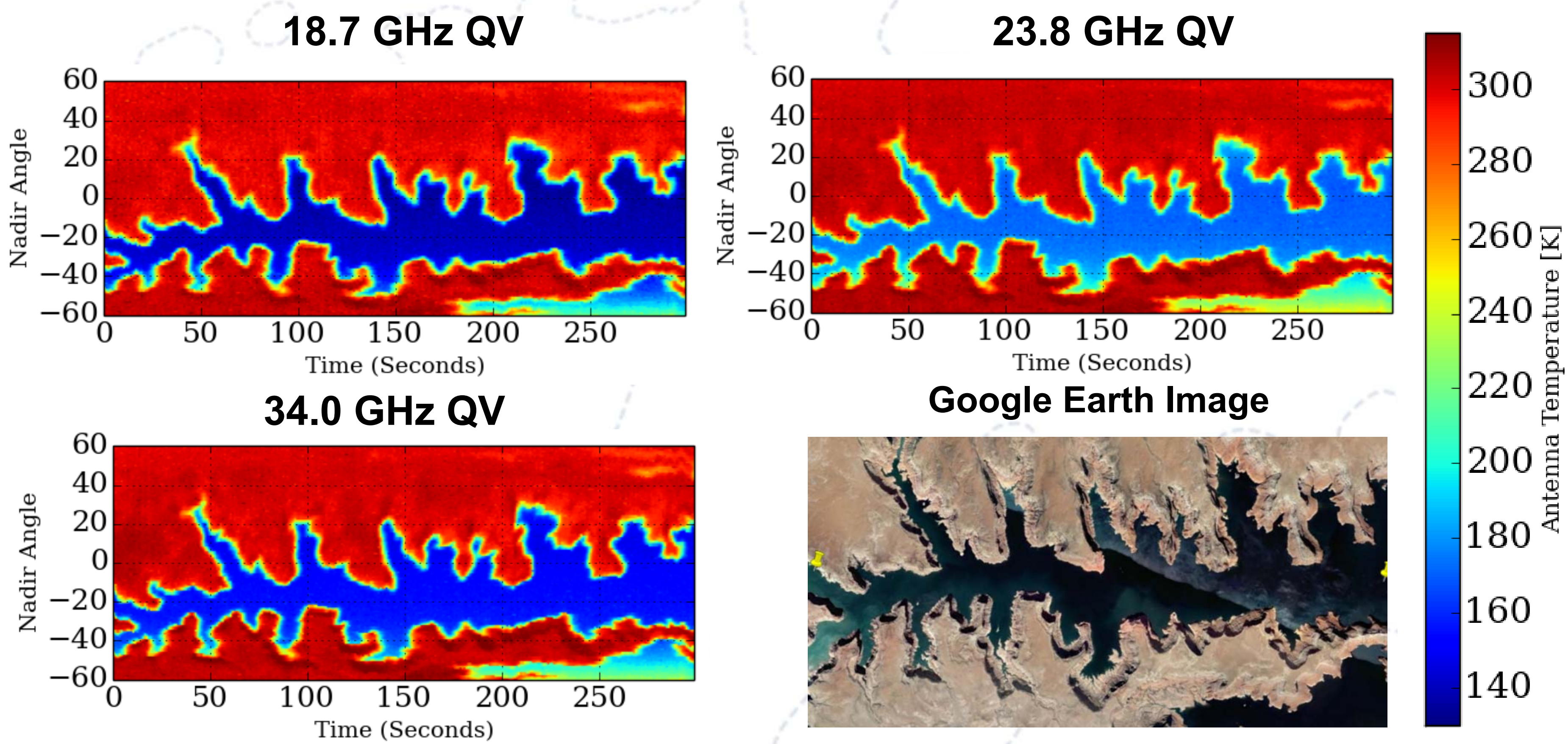
- Successful completion of 14 flight hours over 3 days
  - One day over Blue Mesa Reservoir, Colorado
  - Two days of flights over Lake Powell, Utah and Arizona
- Physical temperatures throughout radiometer system were stable
- HAMMR radiometer channel subsystems performed very well
- Cross-track scanning was very stable
- Ambient and LN_2 calibration performed using an external target before and after each flight

HAMMR Flights over Lake Powell, Utah, July 9-11, 2014

HAMMR Flight Lines over Lake Powell, Utah, July 9-11, 2014

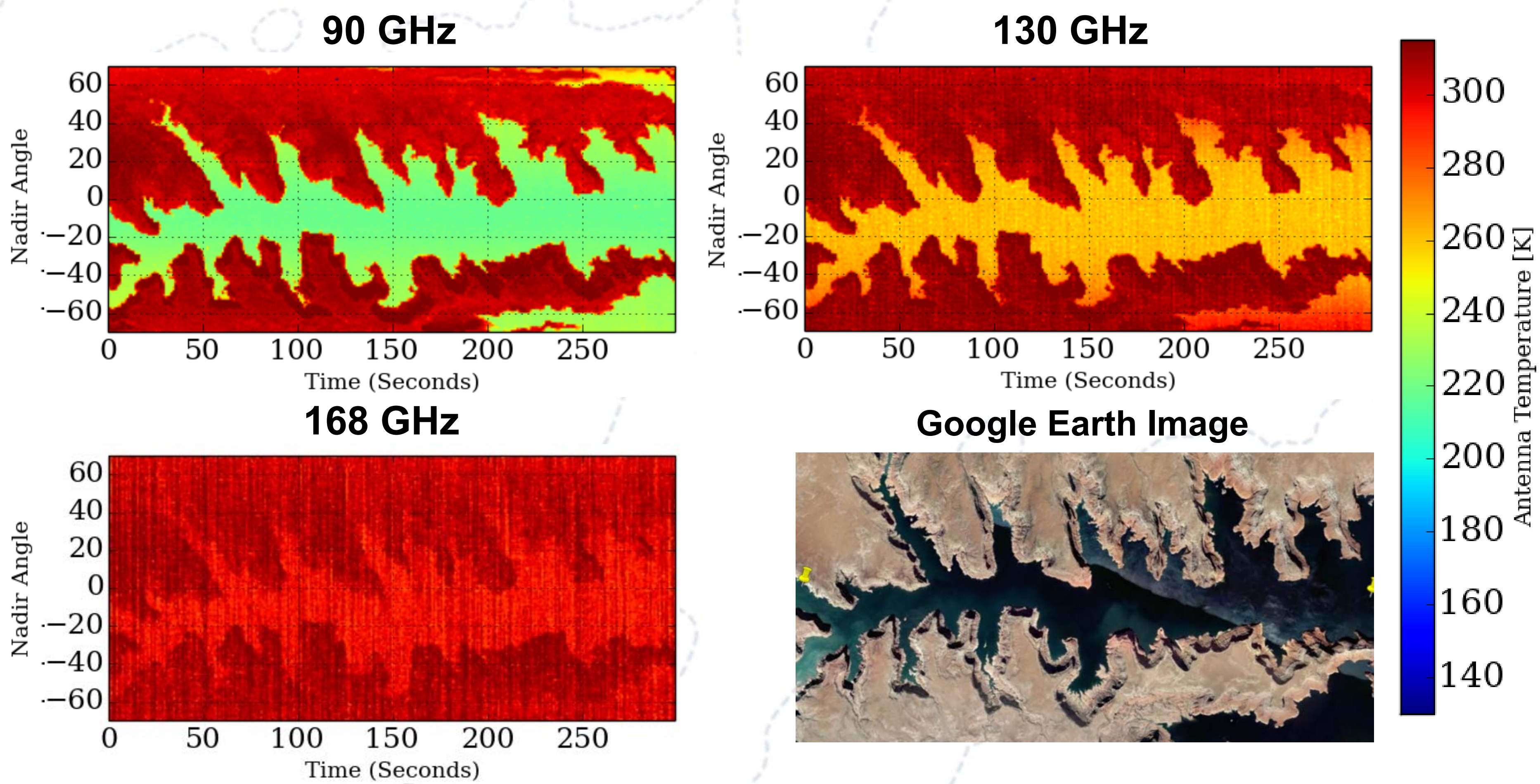


Low-Frequency Microwave Radiometer Measurements



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

High-Frequency Millimeter-wave Radiometer Measurements

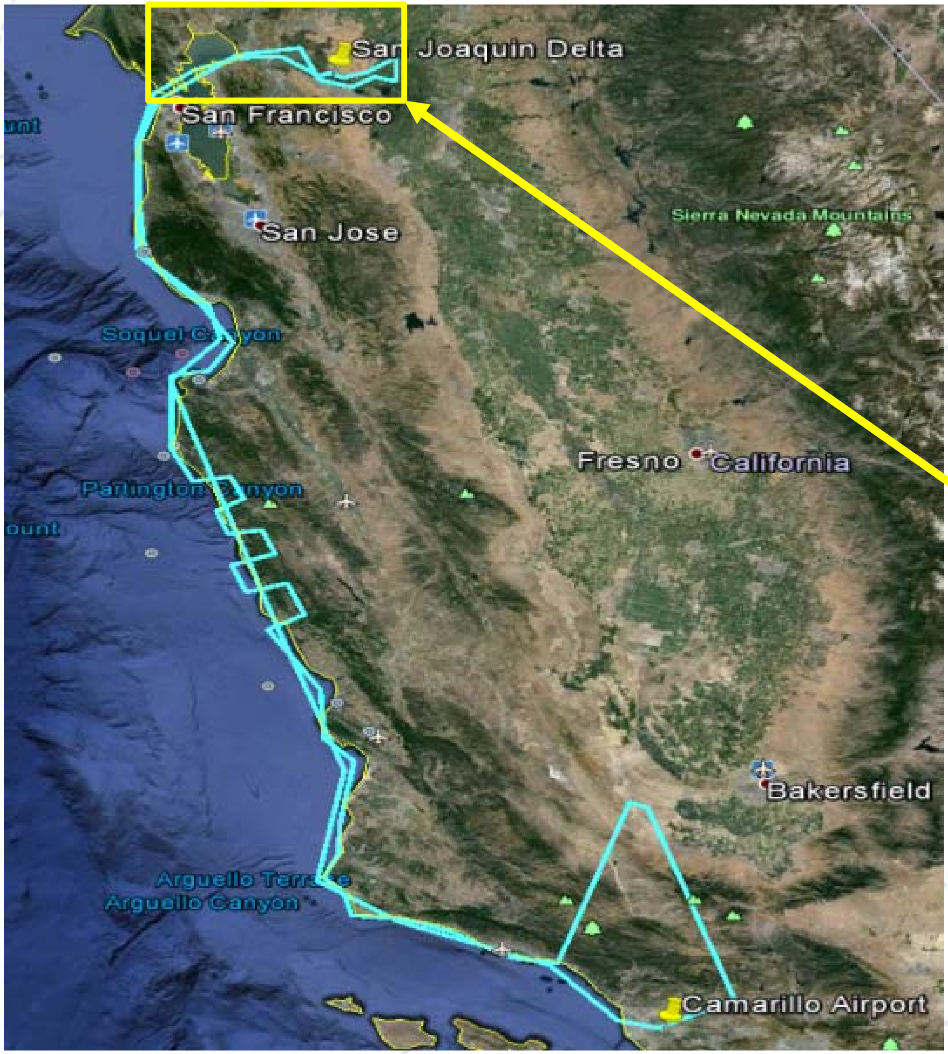


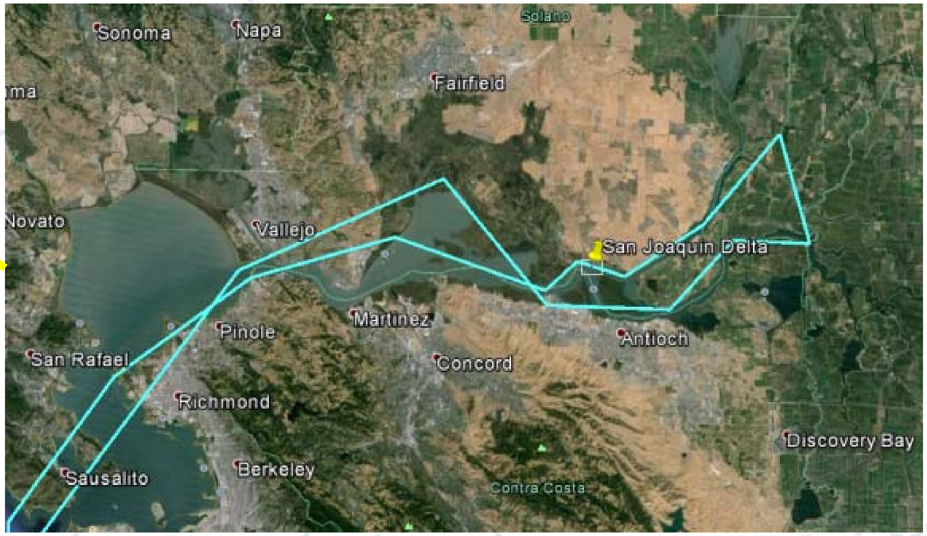
Measurements were performed over Lake Powell, Utah on July 11, 2014.

Future Plans for HAMMR Data Processing and Applications

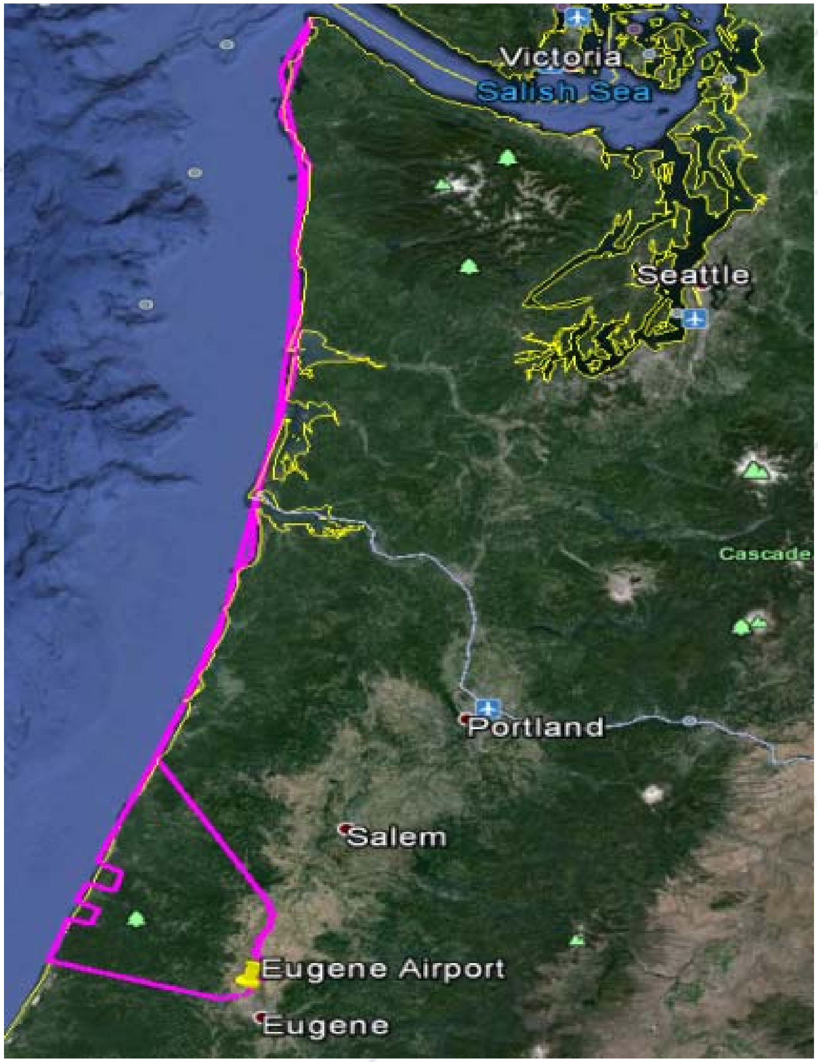
- Improve calibration of L1a antenna temperatures from microwave and mm-wave window channels using Dicke matched load and internal noise sources (two per channel)
- Complete data processor to convert L1a antenna temperatures to L1b geolocated brightness temperatures by accounting for the antenna pattern, location and aircraft attitude
- Retrieve microwave channel wet-path delay using baseline algorithms and use them to train mm-wave window channel wet-path delay algorithm. Then compare results with those from microwave channels to determine precision of higher-frequency product.
- Determine statistics of water vapor spatial variations for U.S. west coast measurements. Examine 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
- Maximum of 8 flight hours per day
- Total of 45 flight hours, including ferry flights between Grand Junction, CO, Camarillo, CA, and Eugene, OR

Summary

- Conventional altimeters with nadir-viewing 18-34 GHz microwave radiometers to measure wet-tropospheric path delay have limited accuracy within ~40 km of land.
- The addition of high-frequency mm-wave (90, 130 and 168 GHz) radiometers to ocean altimetry missions is expected to improve spatial resolution of wet-path delay retrievals near the coasts and may enable retrievals over inland water.
- High-frequency Airborne Microwave and mm-Wave (18-183 GHz) Radiometer (HAMMR) was successfully demonstrated on the Twin Otter in July 2014. HAMMR will:
  - Provide high-resolution measurements of tropospheric water vapor spatial variability at approximately 100-m spatial scales from aircraft
  - Provide high-frequency millimeter-wave brightness temperature measurements to extend the wet-tropospheric path delay correction much closer to the world's coastlines
  - Demonstrate millimeter-wave window channel radiometers 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