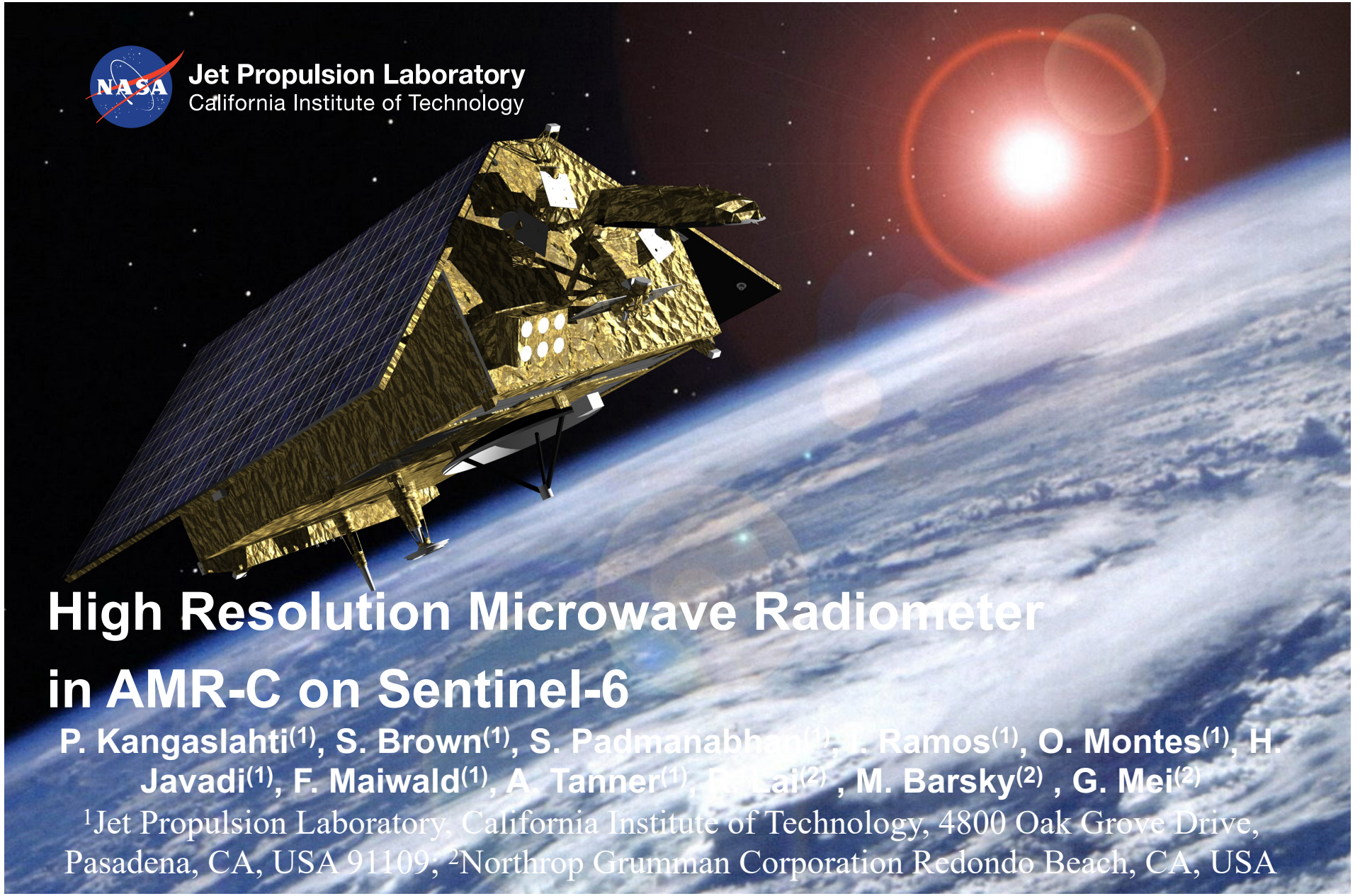

Jet Propulsion Laboratory
California Institute of Technology

High Resolution Microwave Radiometer in AMR-C on Sentinel-6

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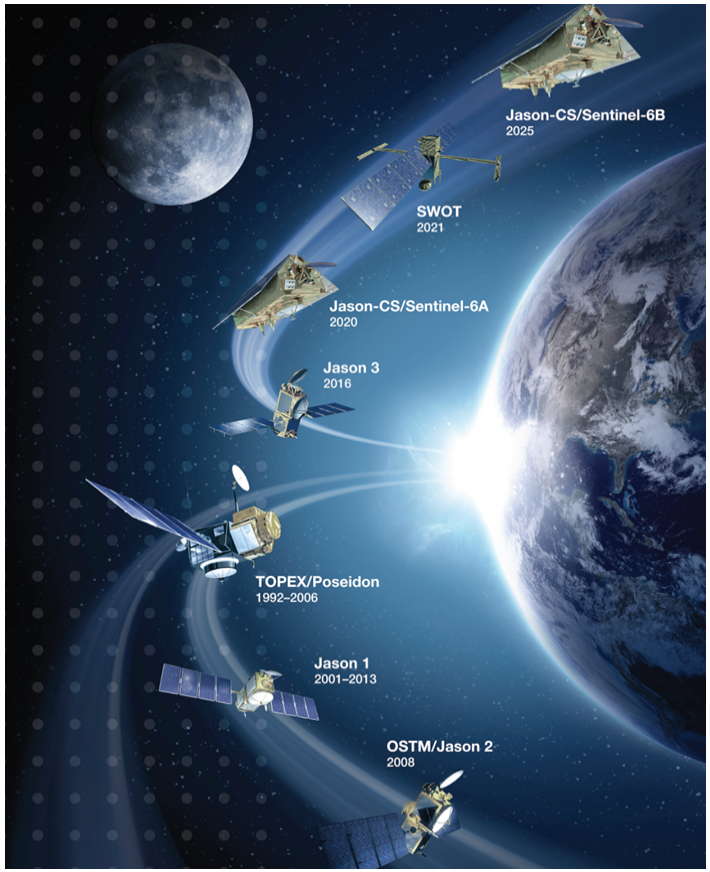
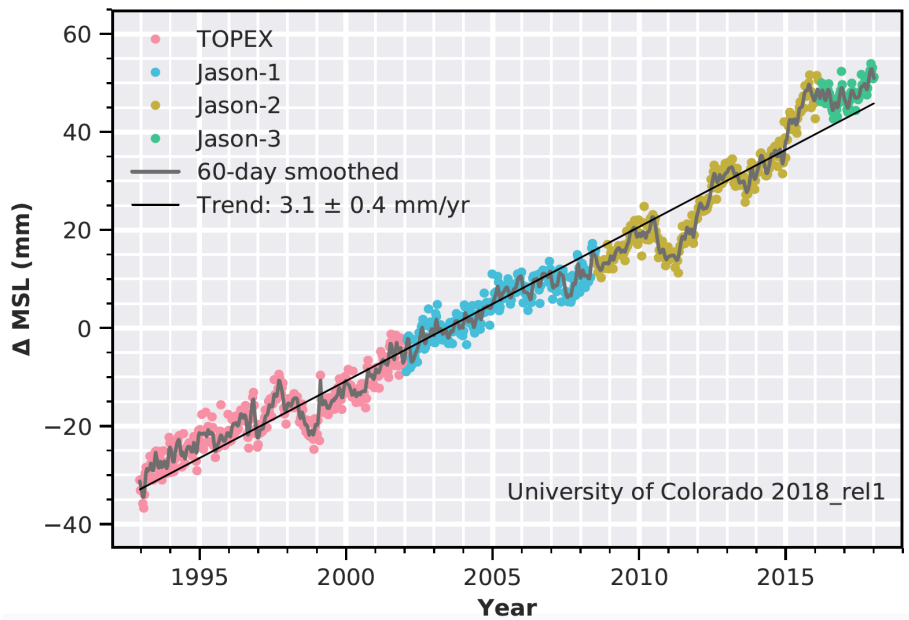
INTRODUCTION

- High Resolution Microwave Radiometer (HRMR) to improve atmospheric water vapor measurements near coastal boundaries in the Sentinel-6 ocean topography mission
- Sentinel-6 includes 18-34 GHz microwave radiometer for the water vapor measurement over the open ocean to correct the associated radio path delay in the radar measurement
- Near coastlines measurements challenging due to antenna beam contamination by warm landmasses leading to loss of topographic accuracy in these high science-value regions.
- Sentinel-6 added millimeter-wave “window” channels of 90, 130, and 168 GHz to improve the antenna beam resolution. These channels will extend the microwave retrievals closer to the coast under cloud-free conditions on an experimental basis.
- These radiometer channels have state-of-the-art performance in terms of sensitivity and stability due to the Low Noise Amplifier MMICs used, the internal calibration using Dicke-switched reference load, and injection of calibration noise signals from noise diodes.
- HRMR technology demonstrator could be fitted on the AMR-C instrument on the focal point of the antenna. This enabled the sharing of the reflector between the HRMR and AMR low-frequency channels.
- HRMR provides kilometer-scale footprints to enable correction of propagation delay of the radar signal in the coastal regions for ocean topography measurements.

Sentinel-6 AMR-C

- The Advanced Microwave Radiometer – Climate Quality (AMR-C) is part of the European Sentinel-6 A/B series of two Earth-observing satellites which will be launched in 2020 and 2025 successively
- AMR-C radiometer instruments have an internal calibration system which enables higher radiometric stability accomplished by moving the secondary reflector between well-defined loads
- allows continuing the study of the ocean circulation, climate change and sea-level rise for over a decade with the effect that the slope of the sea-level change can be determined.

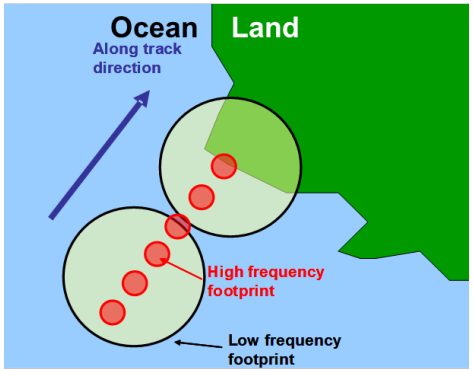


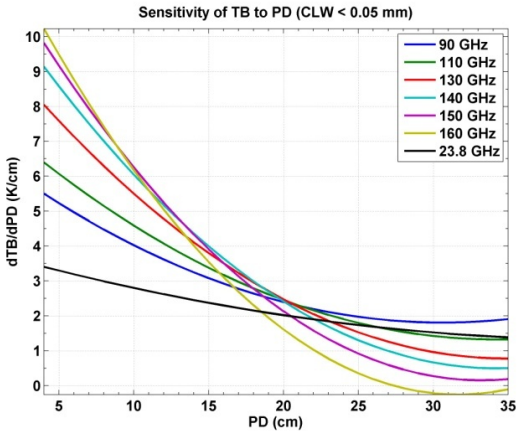


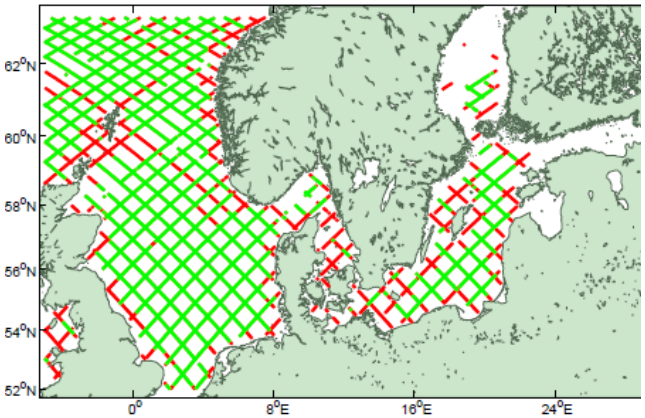
Global mean rise of sea-level over time (removed the seasonal variation of +/-7.5mm) from TOPEX throughout Jason-3

Sentinel-6 AMR-C HRMR

- HRMR shares the same primary reflector as the low frequency channels => improved resolution
- HRMR in the focal point of the primary reflector and the waist of the main beam of the AMR formed by the secondary reflector in the internal calibration system
- Required a stand-alone thermal control system (radiator and heaters), constrained by the limited volume between the secondary reflector mechanism, the focal point and the AMR beam waist
- Direct detection radiometer architecture to minimize the power and number of millimeter-wave modules in the unit (HRMR-RF) that is mounted at the focal plane.

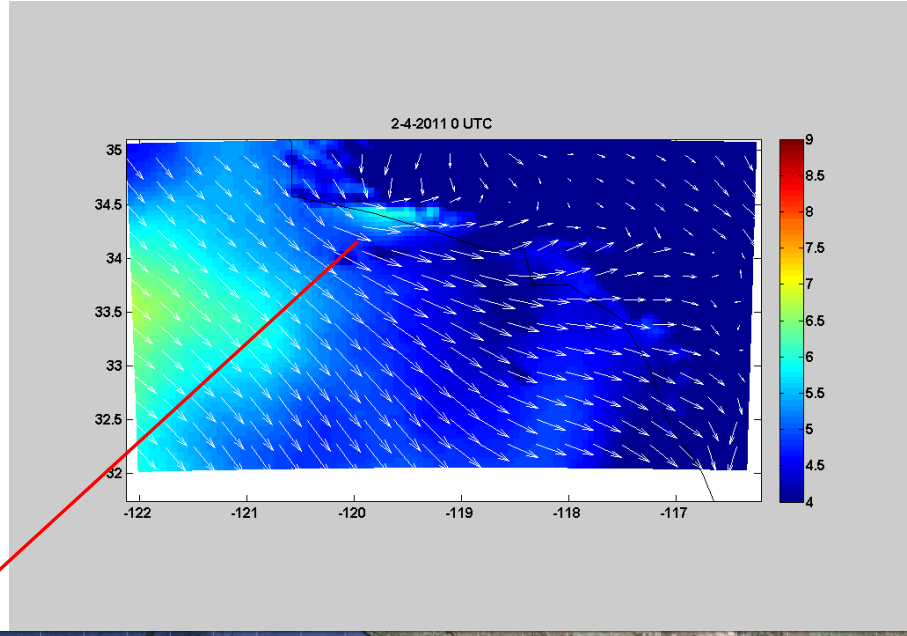


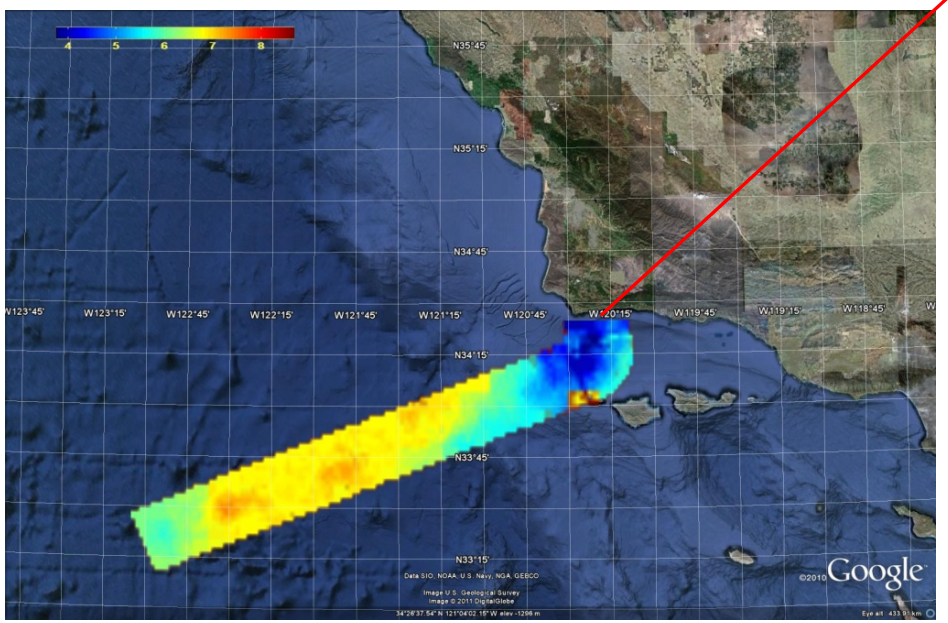


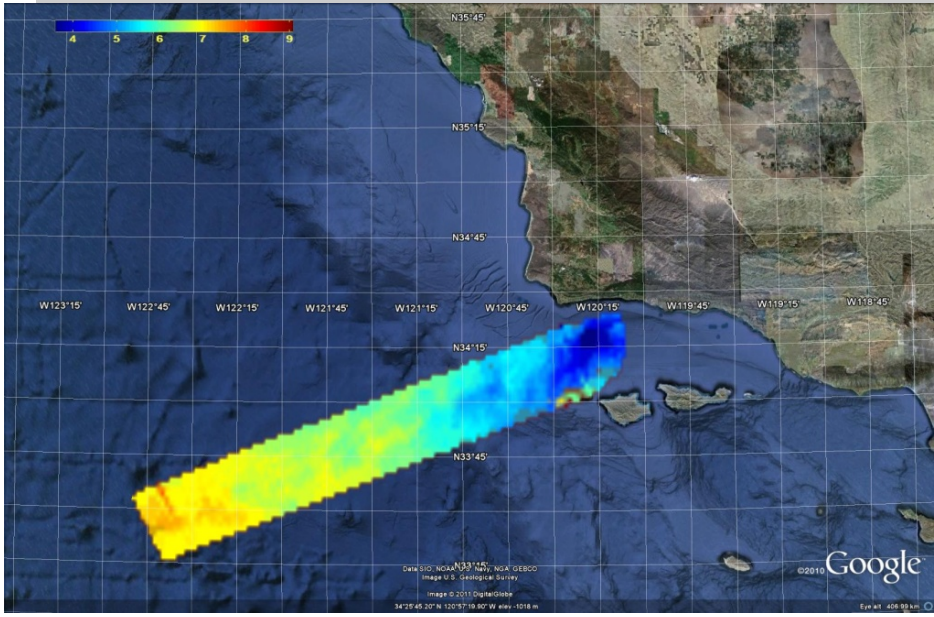


Example: Off-shore Winds

- Certain areas can result in large systematic biases
- Example of Santa Ana winds off California coast
  - **~3-4 cm bias in the path delay at the coast**

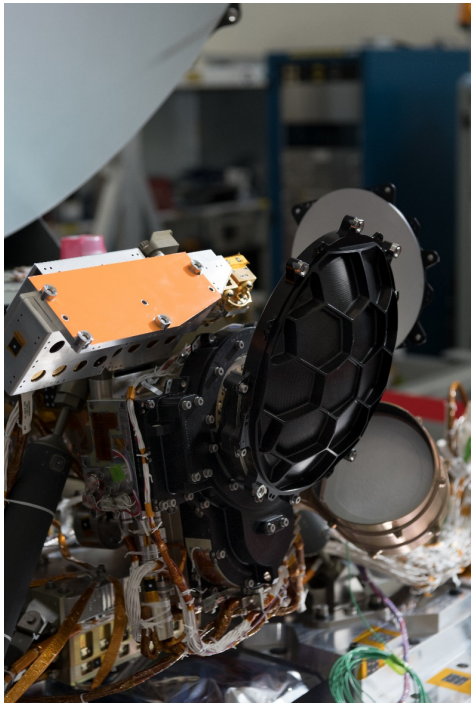


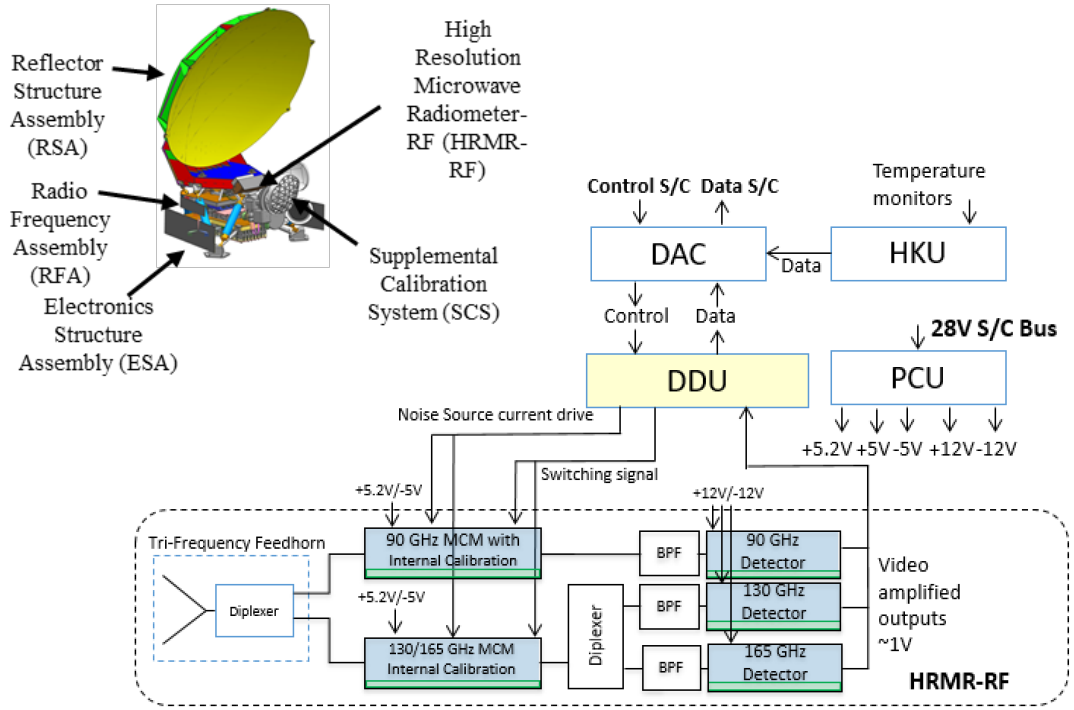




HRMR System Description

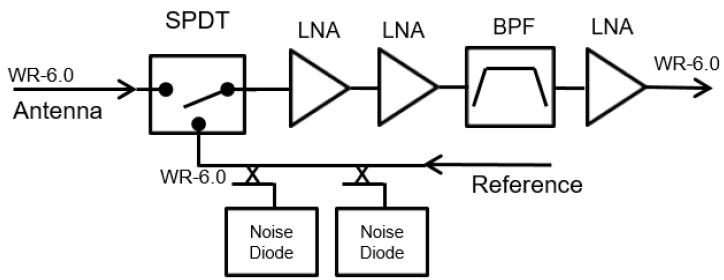
- HRMR-RF millimeter-wave modules have both chip and wire technology for millimeter-wave functionality and printed circuit boards with surface mount components for bias, switching and video amplification functions
- Electronics are housed in separate units on the thermally controlled electronics deck (ESA)
- The Digitizer and Driver Unit (DDU) includes the ADC's that digitize the analog signals from HRMR-RF and current driver circuitry for the noise diodes in HRMR-RF
- Data Acquisition and Control (DAC) unit, a HouseKeeping Unit (HKU), and Power Controller (PCU) serve as the interface to the spacecraft
- DAC was updated to have two operating modes, the traditional AMR and the fast switching mode for use with HRMR-RF

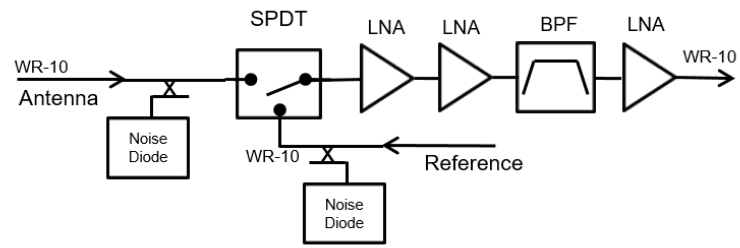


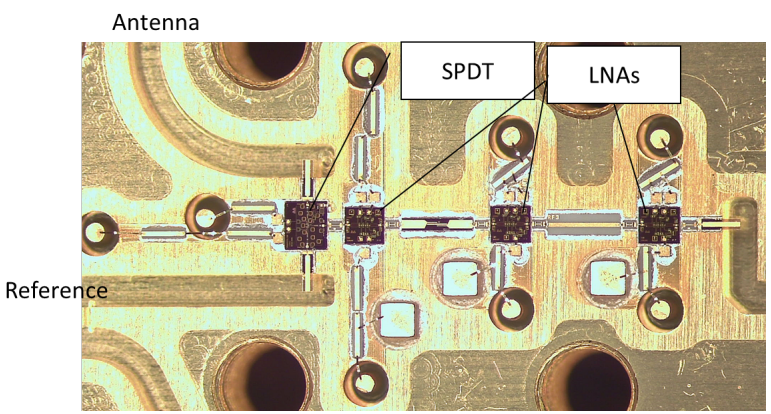


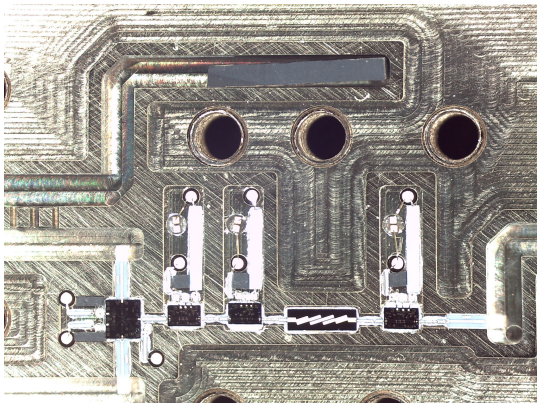
HRMR-RF Description

- The HRMR-RF includes the Tri-Frequency Feedhorn, 90 GHz Multichip Module (MCM), a shared 130/168 GHz MCM, Diplexer to split the 130 and 168 GHz signals, Bandpass Filters (BPF) to define the detection bands and 90, 130 and 168 GHz Detectors
- Millimeter-wave modules were built using custom-designed MMICs by wirebonding the interconnects
- MCMs include the LNA MMICs, noise diodes that are coupled to the signal paths and single-pole-double-throw (SPDT) switch MMICs for the Dicke switching function
- MCMs include noise diodes that provide stable calibration signals when turned on, waveguide couplers for the noise signals and waveguide loads for blackbody noise reference signals



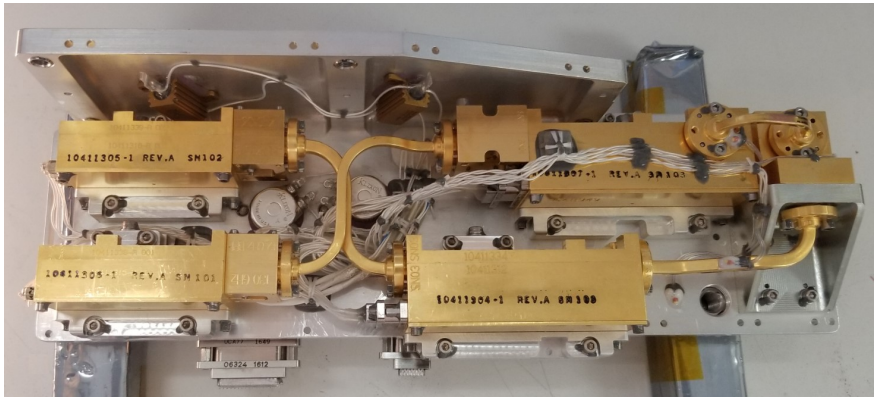


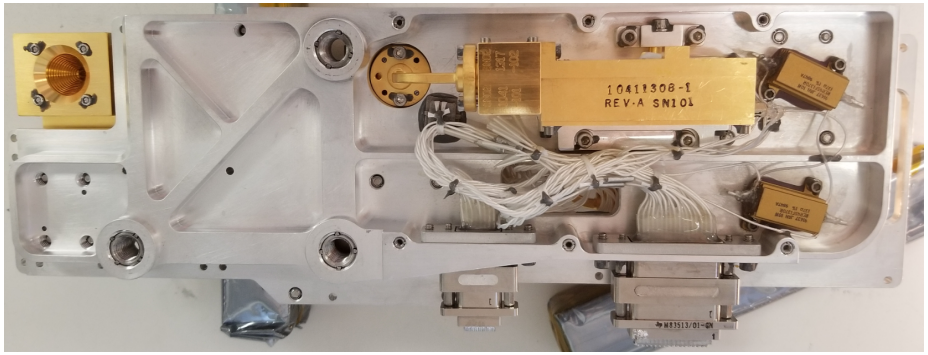




HRMR-RF Description

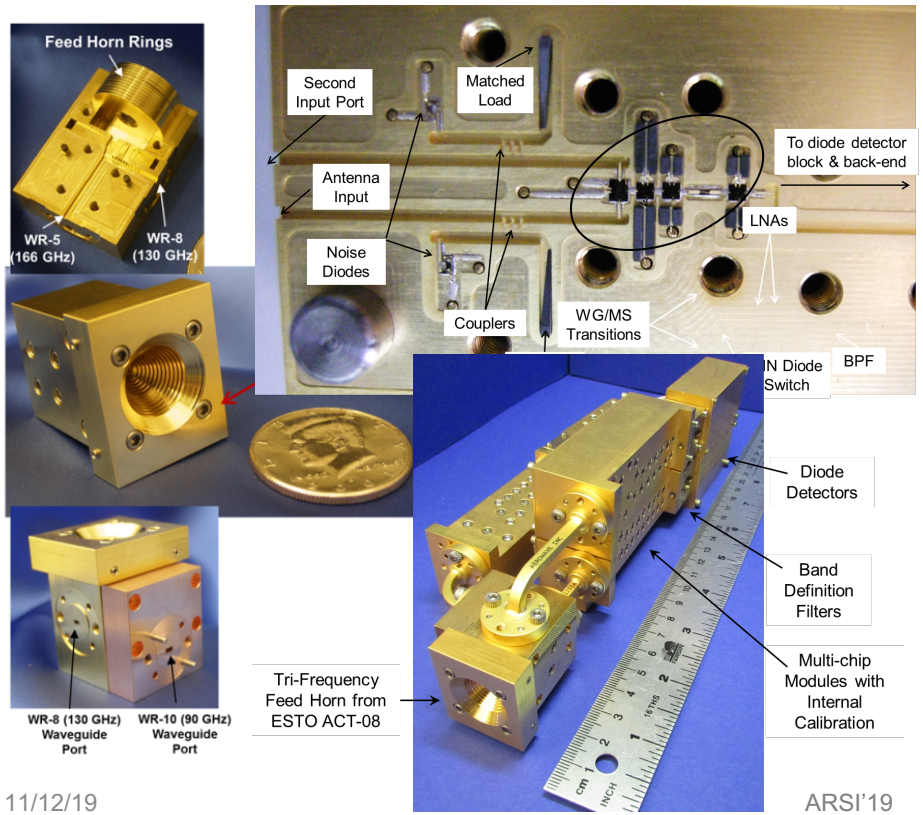
- The detector modules had waveguide inputs and waveguide to microstrip probes. For the 90 GHz channel, we used Keysight low barrier Schottky detector diode that was mounted with beam leads. The higher frequency detector modules included Virginia Diodes low barrier Schottky detector diodes that were flipped on substrates
- high sensitivity detection of 1-2 mV/μW. The detected signal was amplified with 2-stage low noise operational amplifier circuits assembled using OP27 amplifiers. Each detector module had about 1 V analog output
- The diplexer after the 130-168 GHz MCM split the signal to the two channel defining BPFs and detector modules
- At 90 GHz the signal was routed directly from the MCM to the 90 GHz BPF and detector module. All connections were made with bent waveguides to minimize thermal stresses in the system and avoid stressing the waveguide joints in vibration

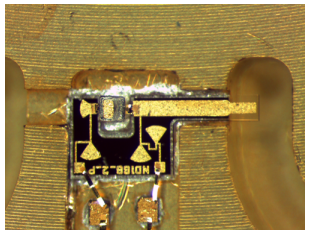


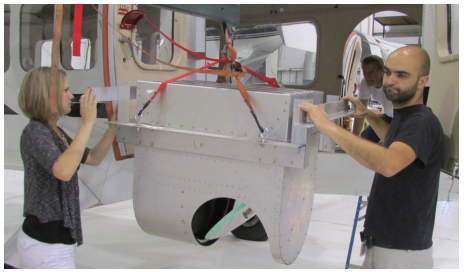


HRMR-RF Technology Development History

- The tri-frequency feedhorn, SPDT MMIC's, noise sources and MCMs developed in NASA's Earth Science Technology Office's (ESTO) Advanced Component Technology (ACT) project *(Advanced Component Development to Enable Low-Mass, Low-Power High-Frequency Radiometers for Coastal Wet-Tropospheric Correction on SWOT, PI Steven Reising CSU)*
- The ACT project was followed by ESTO Instrument Incubator Project (IIP) demonstration of the complete airborne system *(Development of an Internally-Calibrated Wide-Band Airborne Microwave Radiometer to Provide High-Resolution Wet-Tropospheric Path Delay Measurements for SWOT, PI Steven Reising CSU)*







HRMR Performance

- The HRMR instrument relies on the LNAs to provide a low noise temperature for the system (T_{sys}) and the wide frequency bandwidth (B) to improve sensitivity
- All three channels operate at atmospheric window channels making the 10 GHz detection bandwidths feasible
- The LNAs and the Schottky detectors add 1/f-noise in the signal that can be mitigated with the SPDT switch in front. It rapidly switches between the internal waveguide load reference signal and the antenna signal to provide samples of both at frequency above the 1/f-noise corner frequency
- Dicke switching improves the stability of the measurement allowing longer integration time (τ), but on the other hand half the time is reference observations so the sensitivity will be reduced by a factor of 2. The sensitivity NEDT of the Dicke switched radiometer is

$$NEDT = 2 * \frac{T_{sys}}{\sqrt{B\tau}}$$

- HRMR switched the SPDT switch at a rate of 2 kHz and integrated the antenna and reference signals for 125 ms of total time
- To maintain the same data rate as the lower frequency AMR instrument the DAC transmitted one data packet every 62.5 ms. Every other of these is an antenna measurement and every other a reference measurement
- The half beam size integration for the nadir pointing instrument is 0.25 s for the 130 and 168 GHz channels and 0.5 s for the wider beamwidth 90 GHz channel
- Dicke switching provided the required stability over 60 s which allows calibration with the lower frequency AMR instrument over the open ocean so that measurements for the final 50 km before coastal crossing can be provided by HRMR.

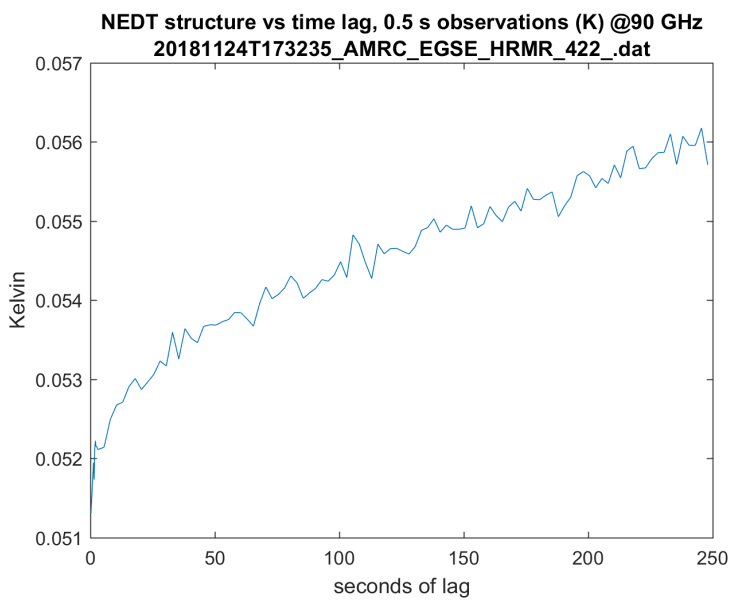
HRMR Performance

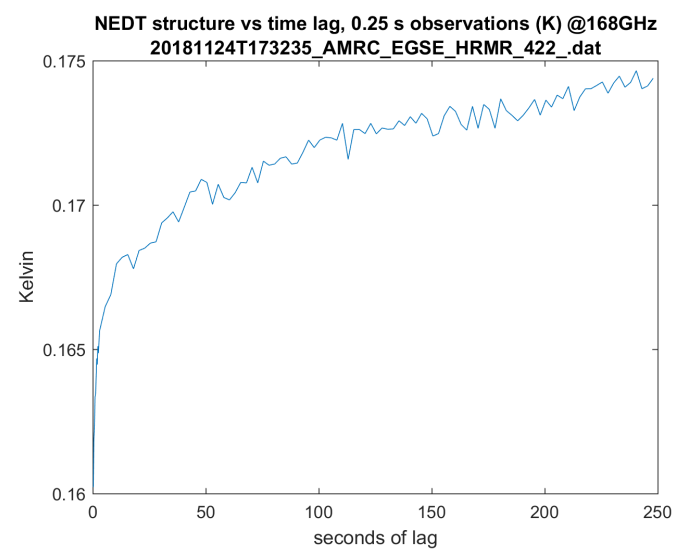
- The HRMR instrument was characterized for its performance and the instrument sensitivity over the 60 s period looking at an ambient target, and calibrating the noise temperature of the receiver with an ambient and liquid nitrogen immersed target
- The receiver sensitivity is calculated with 0.25 s integration time for 130 and 168 GHz channels and 0.5 s integration time for the 90 GHz channel. All results apply over the 60 s period
- stability structure plots for the 90 and 168 GHz channels, as computed from the standard deviation of the difference between observations of a constant brightness temperature scene separated in time by a time lag, d, in

$$S(d) = \sqrt{\langle (T_B(t+d) - T_B(t))^2 \rangle / 2}$$

where <> is the expectation operator.

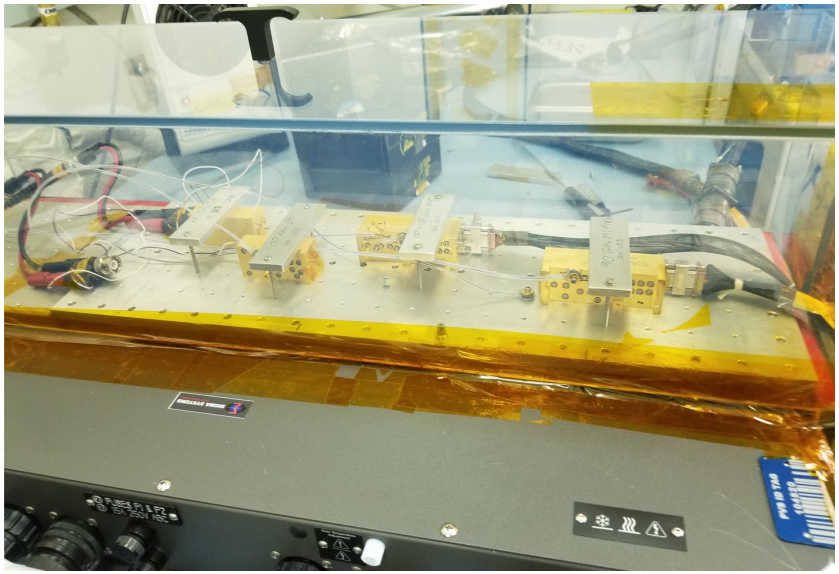
Frequency Channel	**Receiver Noise Temperature**	**Receiver Sensitivity**
Unit:	K	K
90 GHz	990	0.05
130 GHz	1750	0.12
168 GHz	3240	0.17

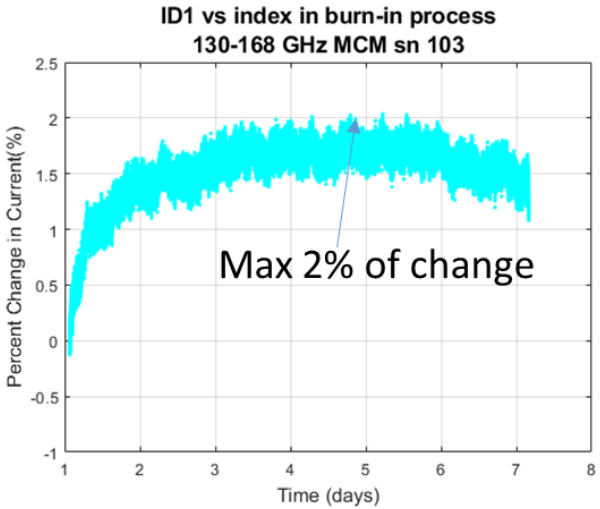




HRMR Performance

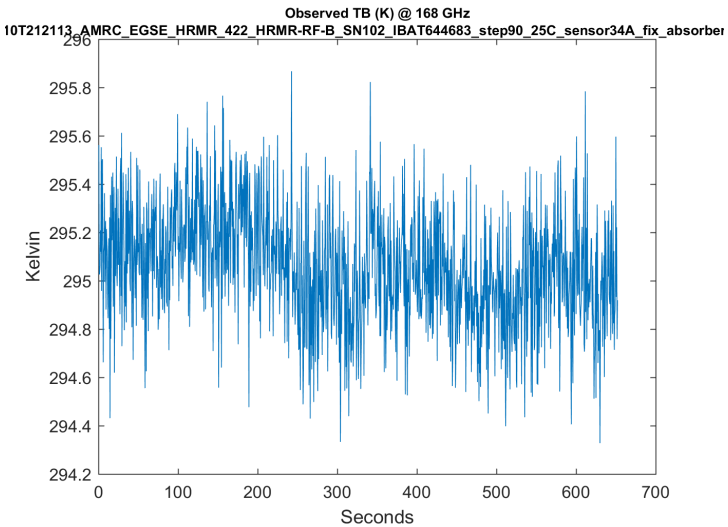
- The results were the same for both AMR-C instruments, except for the 168 GHz channel that was slightly less stable over the 60 s period resulting in a maximum deviation of 0.34 K over 60 s of measurement
- The noise diodes provided 100 K to 400 K calibration signals for the radiometer channels depending on the frequency
- The HRMR instrument was built as a technology demonstration without imposing science requirements on it. This allowed less oversight in the assembly and test phase, but overall the same processes were followed as with the main AMR instrument
- The electronics parts were procured to the same space flight standards as for the AMR, however, the chip and wire components were procured commercially. The assembled chip and wire modules underwent 168 hours at 125 deg C burn-in to find any early failures on the commercial parts.

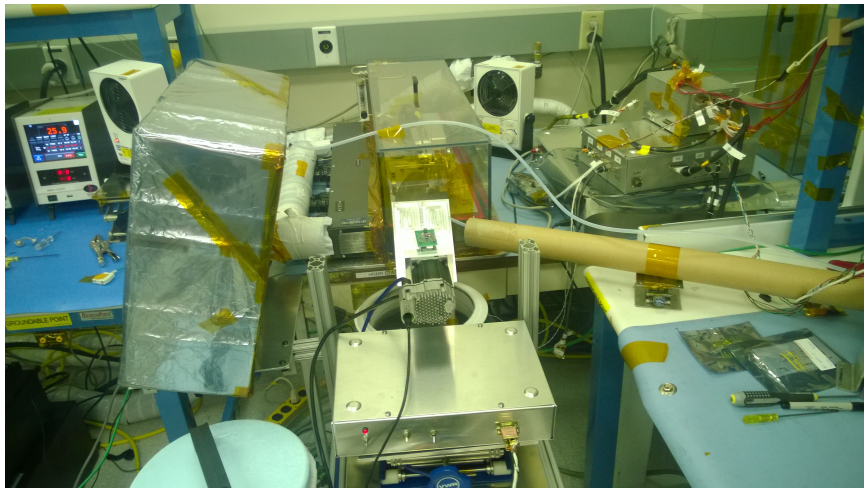




HRMR Environmental Testing

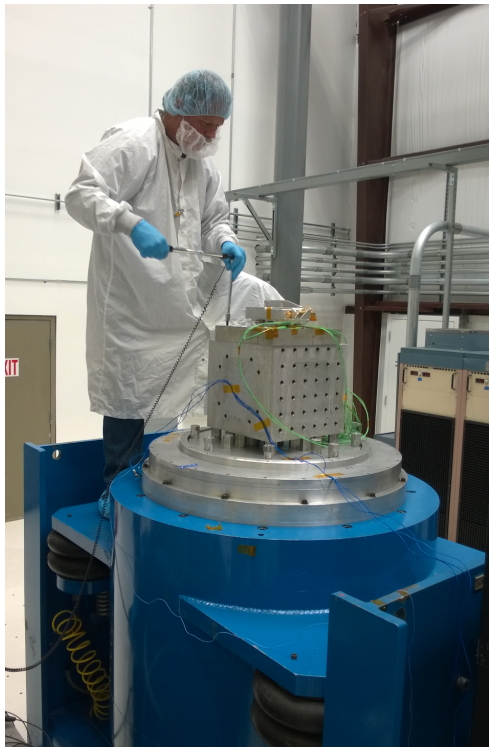
- The assembly and initial test phase was followed by three thermal ambient testing cycles at +65/-20 deg C
- continuously following the radiometric performance of the system and the supply currents
- Hot and cold starts were included in the test cycle





HRMR Environmental Testing

- After the thermal cycles, the units were vibration tested to reduce risk before the main instrument II&T cycle. No failures were observed in these tests
- Testing cycle was completed with radiometric thermal testing within the operating temperature range of +10 to +40 deg C
- The AMR-C instruments completed Instrument Integration and Test (II&T) at JPL and the first one was integrated to the Sentinel-6 spacecraft



Conclusion

- HRMR was developed as a technology demonstrator for the Sentinel-6 missions
- Will provide the radiometric calibration of water vapor caused path delay error in the coastal regions. This will benefit the coastal altimetry science, and mature the HRMR instrument technology
- The technology demonstrators met the performance goals and are ready for launch installed in the primary AMR instruments
- The technology demonstrator development was preceded by investments by NASA ESTO ACT and IIP programs to develop and mature the technology from initial concepts to components and airborne instruments
- The technology investment was key in achieving the mass of 2.5 kg, 2.1 W power consumption and volume of 2000 cm3 for the HRMR-RF subsystem, and therefore the accommodation of it on the focal point of the primary antenna.

Acknowledgement

This work was carried out at the Jet Propulsion Laboratory, California Institute of Technology under contract with NASA. Government sponsorship acknowledged.

We would like to acknowledge the technology development collaboration with Professor Steve Reising and his group members from Colorado State University in the NASA ESTO funded technology programs

Special thanks to the assembly team of Mary Soria, Arlene Baiza, Heather Lim, Bradley Drake, Erika Hernandez and Jo Tillis.

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AMR-C
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