Enabling Observations of Temperature and Humidity Profiles and Cloud Ice Particle Size Distribution in the Upper-Troposphere/Lower-Stratosphere from 6U-Class Satellites: Tropospheric Water and Cloud ICE (TWICE)

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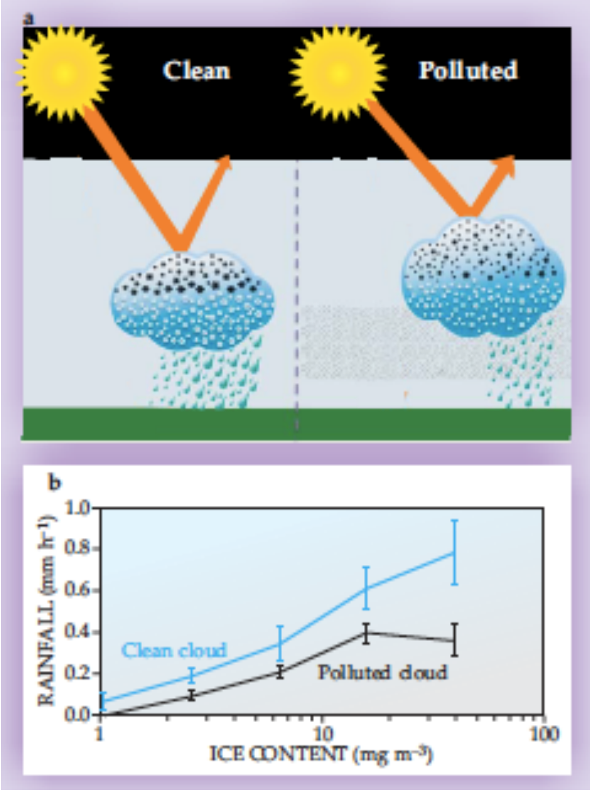
Tropospheric Water and Cloud ICE (TWICE) Scientific Objectives

- **NASA's Earth Science Focus Areas:**
  - Climate Variability and Change
  - Water & Energy Cycle
- **Addressing Scientific Needs:**
  - Measure water vapor and cloud ice at a variety of local times
    - Addresses limitations of current microwave sensors in sun-synchronous orbits
  - Enable global measurements throughout the diurnal cycle of:
    - water vapor profiles in the upper troposphere / lower stratosphere (UTLS)
    - cloud ice particle size distribution and ice water content in both clean and polluted environments.
  - Current understanding of UTLS processes in general circulation models (GCMs) is limited. Such measurements can improve both climate predictions and knowledge of their uncertainties.

TWICE Scientific Motivation

- **Aerosols and Clouds**
  - Clouds represent the largest uncertainty in climate model predictions.
  - Clouds in polluted environments tend to have smaller water droplets and ice crystals than those in cleaner environments (“first indirect effect”).
  - Polluted clouds are less likely to generate rainfall, increasing the cloud water content (“second indirect effect”) and are brighter (have higher albedo) than clean clouds

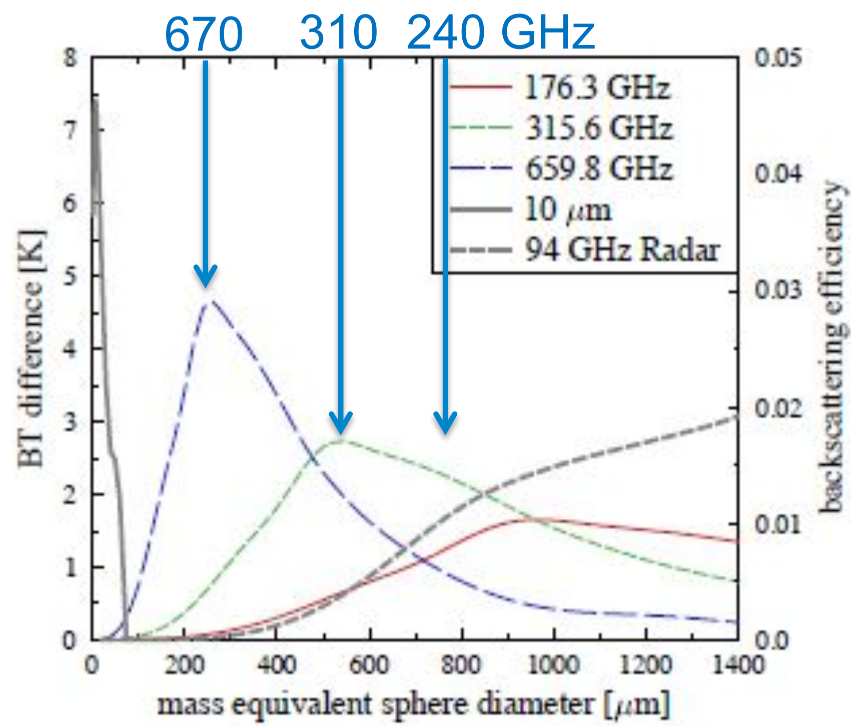


- **TWICE Radiometer Instrument**

  In tandem with other instruments providing aerosol information, the TWICE instrument:
  - Can provide cloud ice particle size information in both polluted and clean environments
  - Can determine the influence of aerosol pollution on cloud particle size spectrum

TWICE Cloud Ice Particle Size Information

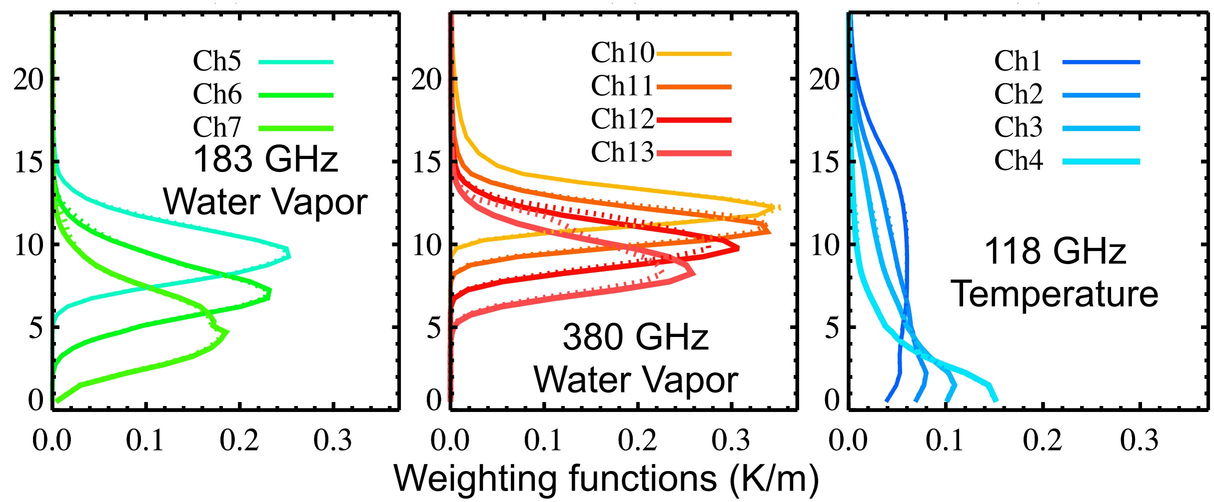
- NASA's A-Train provides limited cloud particle size information.
  - CloudSat: 94-GHz radar (Estimate particle size from IWC & T for particles > 1 mm)
  - Aqua's MODIS: 10-μm infrared radiometer (< 100 μm)
- Sub-millimeter wave radiometry can fill the gap by providing cloud particle size information between ~50 μm and ~1 mm.
- High atmospheric opacity at sub-millimeter wavelengths allows the measurement of ice in clouds above the freezing level through *scattering.*
- Measured brightness temperatures *decrease* due to ice particle scattering at sub-mm-wave frequencies.
- Modeled brightness temperature decrease due to scattering shown at right; adapted from S. Buehler et al., *QJRMS*, 2007.



TWICE Water Vapor Profiling

- Measurements near water vapor absorption lines provide vertical profile information through pressure broadening.
- 183 GHz and 380 GHz were chosen to retrieve water vapor in the troposphere and upper troposphere / lower stratosphere (UTLS).
- To constrain the water vapor retrievals, 118 GHz channels measure information about the temperature profile using the O_2 absorption line.

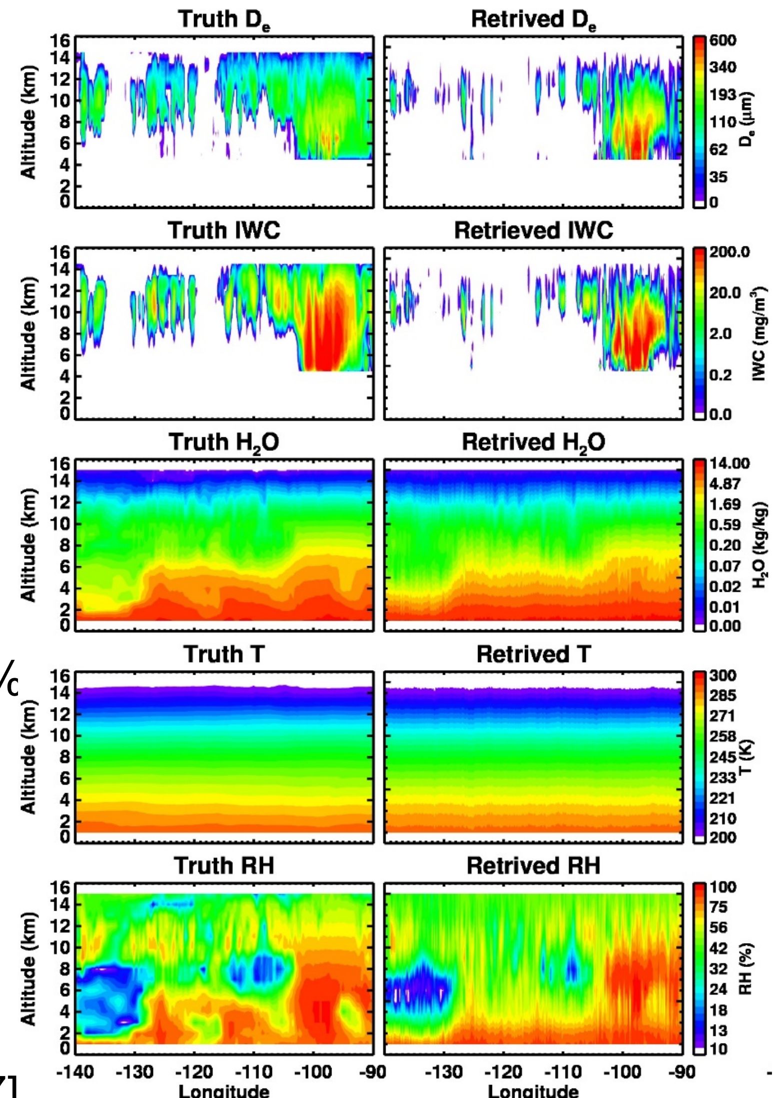
[J. Jiang et al., *Earth and Space Science*, in review, 2017].



Channel	Center frequency	±Offset frequency	Bandwidth
1	118.75	1.1	0.4
2	118.75	1.5	0.4
3	118.75	2.1	0.8
4	118.75	5.0	2.0
5	183.31	1.0	0.5
6	183.31	3.0	1.0
7	183.31	6.6	1.5
8	243.20	2.5	3.0
9	310.00	2.5	3.0
10	380.20	0.75	0.7
11	380.20	1.80	1.0
12	380.20	3.35	1.7
13	380.20	6.20	3.6
14	664.00	4.20	4.0

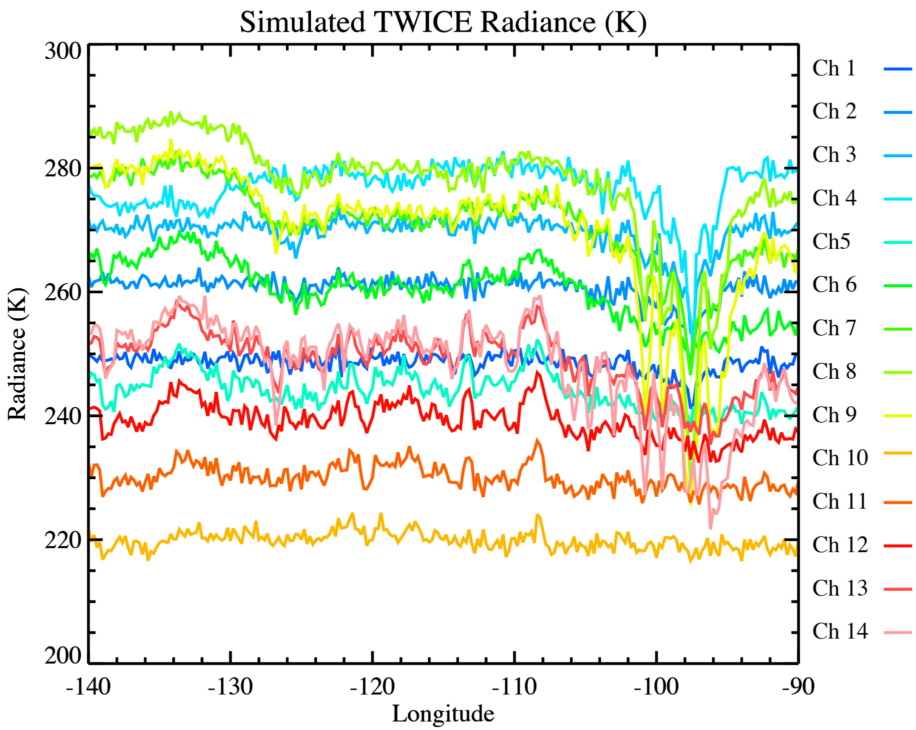
Simulation of Cloud Ice, Humidity and Temperature Measurements from TWICE

- We have developed a simulation and retrieval system based on Bayesian methodology [*Evans et al.*, 2002; 2012] for the 15 TWICE frequencies. Simultaneous retrievals are performed for the following quantities:
- Cloud ice particle size (D_e), ice water content (IWC), water vapor Content (H2O), temperature (T) profiles, and relative humidity (RH) profiles.
- Results show that the TWICE instrument is capable of retrieving ice particle size in the range of ~50 to 1000 ?m with better than 50% uncertainty, filling the gap in ice cloud particle size retrieval using existing space-borne remote sensing modalities.
- Uncertainties for other TWICE retrievals are about 1K for temperature, < 50% for IWC and < 20% for H_2O.



[J. Jiang et al., *Earth & Space Science*, in review, 2017]

Results of Simulation of Cloud Ice and Humidity Measurements from TWICE



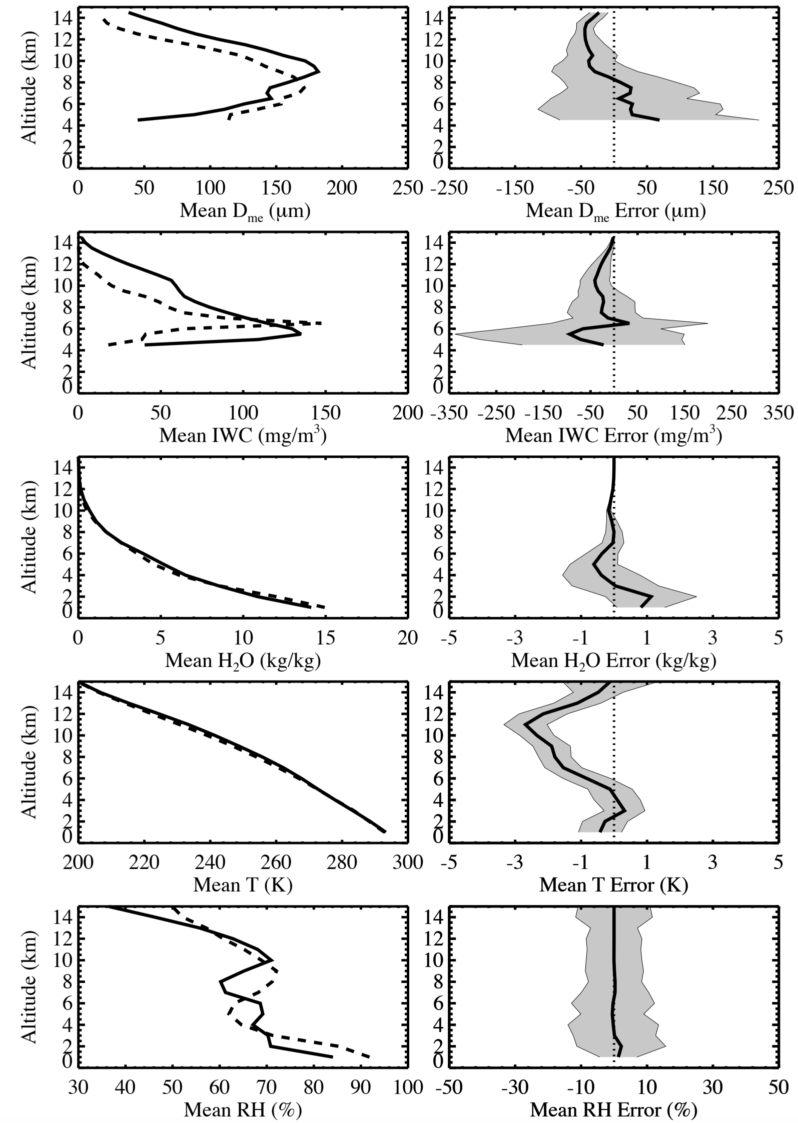
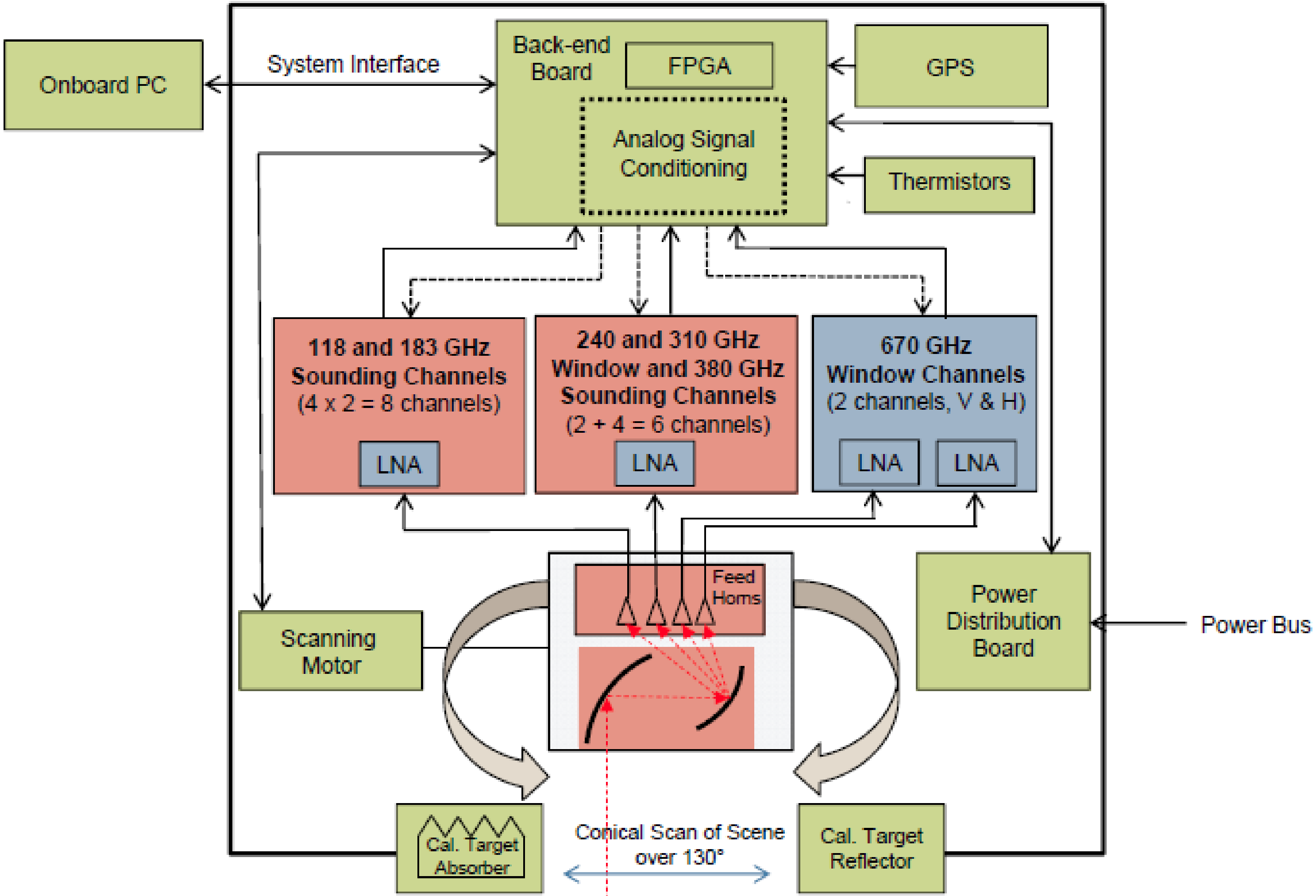


Figure above: The simulated radiance brightness temperatures as "seen" by the TWICE frequency channels as it "flies" over a set of "truth" profiles provided by a WRF model output.

Figure at right: Left column shows the mean truth (solid) and mean retrieved (dashed) profiles of D_{me}, IWC, H_2O, T, and RH. Right column shows the mean retrieval error and RMS error of the mean profiles.

Tropospheric Water and Cloud Ice Instrument Block Diagram



Green = CSU; Red = JPL; Blue = NGC;

TWICE Instrument Measurement Frequencies and Specifications

Quasi-Window Frequencies (3) for Cloud Ice Particle Sizing

Temperature and Humidity Sounding Frequencies

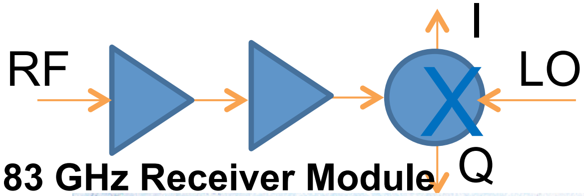
Parameter							
Channel Center Frequency		118 GHz sounder	183 GHz sounder	240 GHz	310 GHz	380 GHz sounder	670 GHz
Channel Bandwidth		Offset frequencies from +10 MHz to +8.5 GHz	Offset frequencies from -10 MHz to -8.5 GHz	10 GHz	10 GHz	Offset frequencies from -10 MHz to -8.5 GHz	20 GHz
Passband Ripple (max)		± 2 dB	± 2 dB	± 2 dB	± 2 dB	± 2 dB	± 5 dB
System Noise Figure (goal: minimize)		≤ 7 dB	≤ 7 dB	≤ 7 dB	≤ 7 dB	≤ 7 dB	≤ 13 dB
NEDT (? = 1s) (K)		< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
DC Power (W)	**Proposed Spec.**	8		0.6		4	0.6
	CBE	4.53		0.35		2.31	0.54
Mass (kg)	**Proposed Spec.**	0.6		0.5		0.3	0.5
	CBE	0.55		0.1		0.3	0.09

Mass and Power Consumption for each TWICE Subsystem

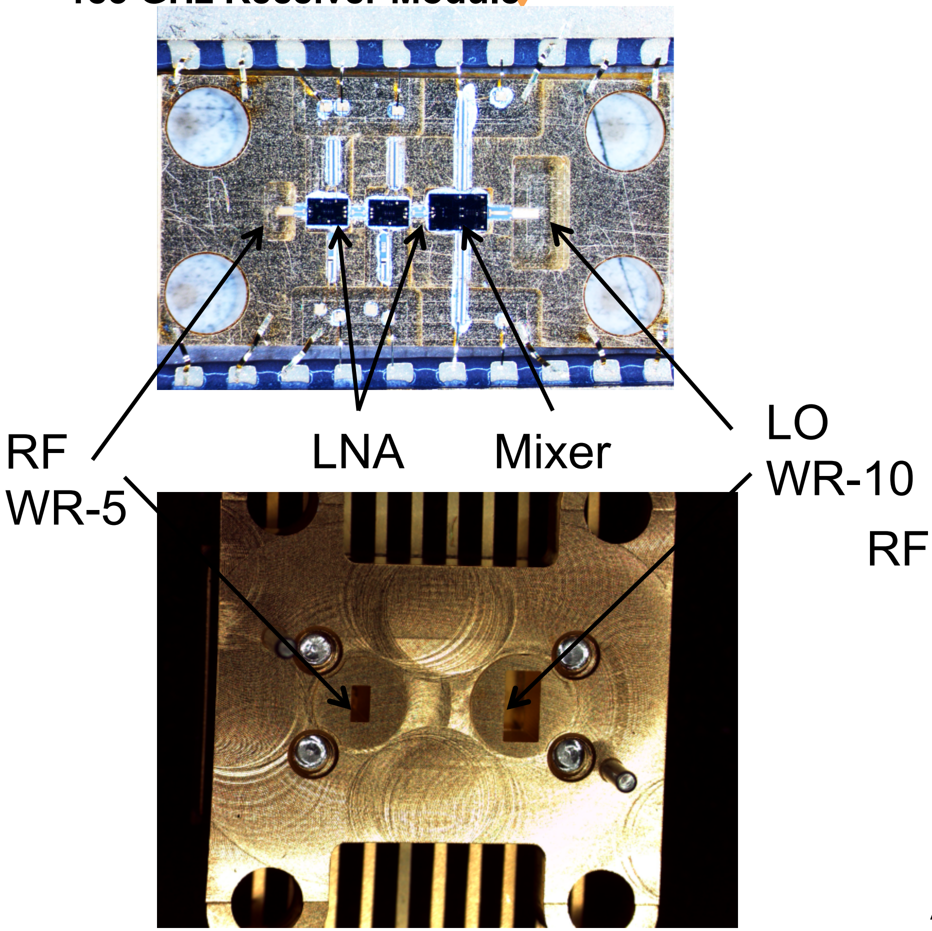
Subsystem	Mass (kg)	Power (W)
118-183 GHz Sounder	0.55	4.53
240 GHz & 310 GHz Radiometers	0.1	0.35
380 GHz Sounder	0.3	2.31
670 GHz Radiometers (H&V)	0.09	0.54
Back-end Board	0.13	0.73
Power Regulation Board	0.13	3.00
Optics	0.40	-
Calibration Target/Reflector	0.71	-
Scanning Motor	0.33	1.00
Totals	**2.74**	**12.46**

Millimeter-wave Radiometers for Temperature & Water Vapor Sounding

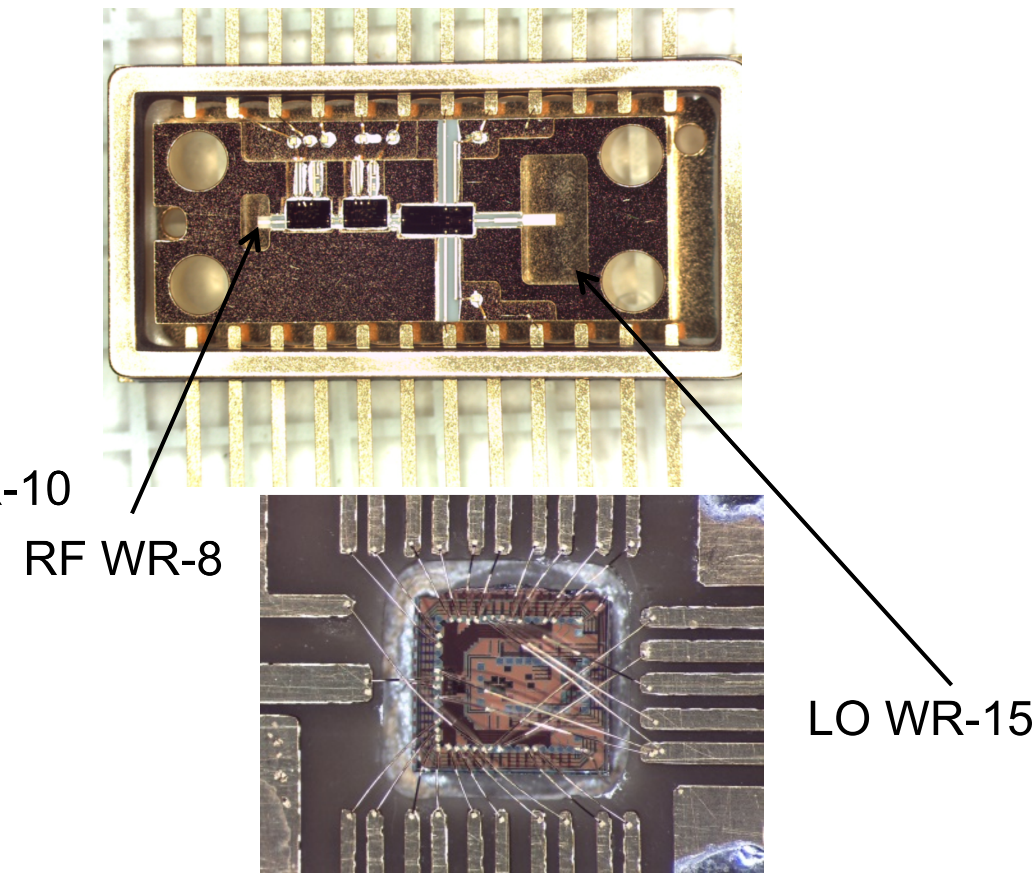
Technology developed and demonstrated for GeoSTAR and HAMMR airborne instruments



183 GHz Receiver Module



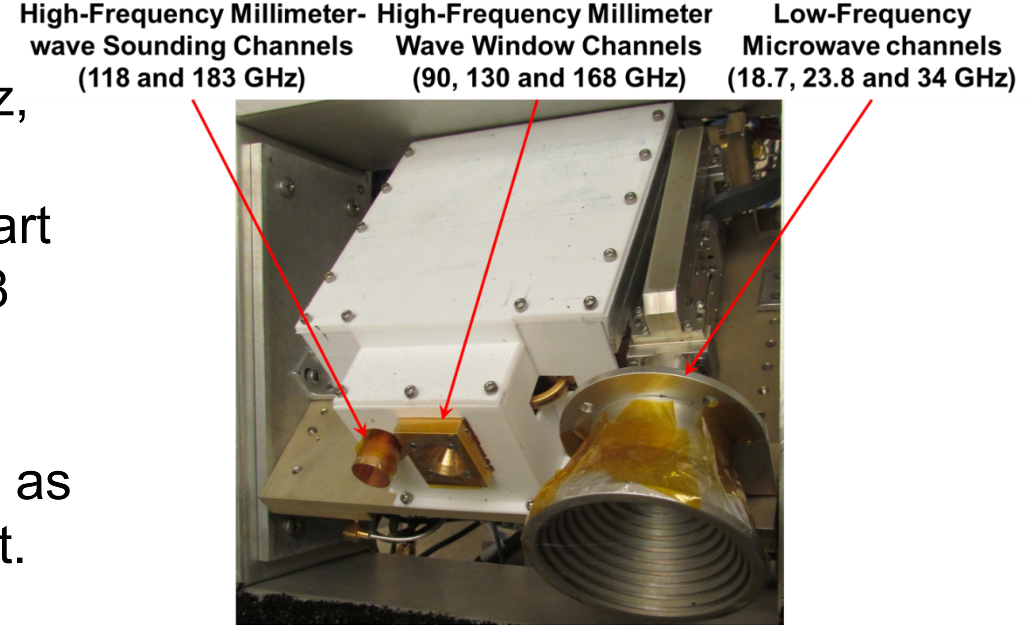
118 GHz Receiver Module

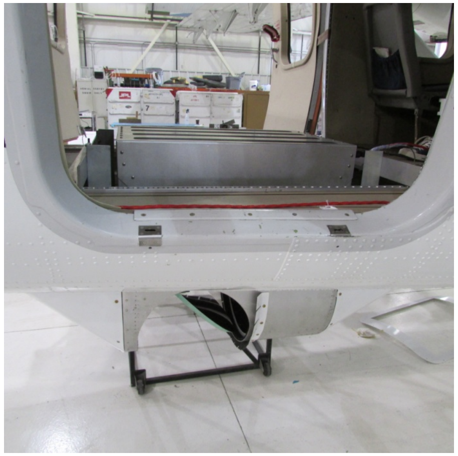


ASIC IF processor designed by B. Razavi (UCLA)

High-frequency Airborne Microwave and Millimeter-wave Radiometer

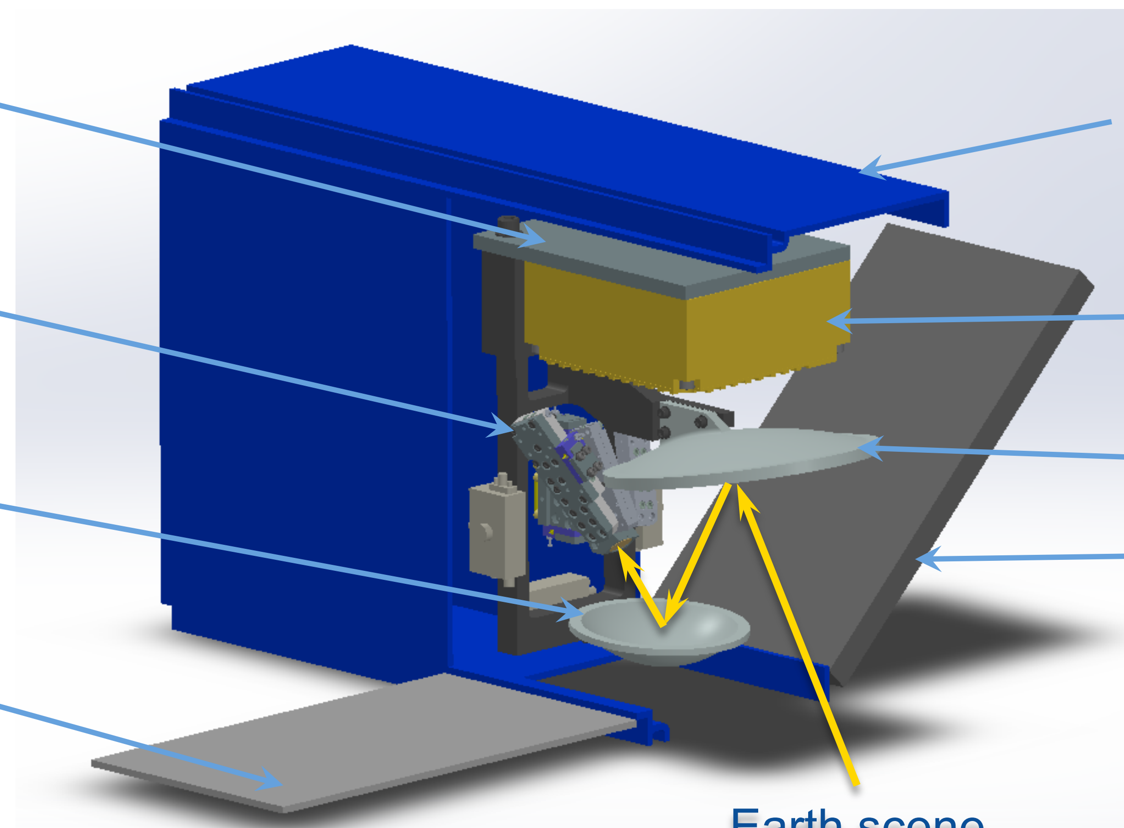
Temperature and humidity sounders near 118 and 183 GHz, respectively, have been successfully demonstrated as part of the HAMMR instrument for 68 flight hours aboard Twin Otter aircraft. Flights were conducted over inland water bodies as well as nearly the entire U.S. west coast.





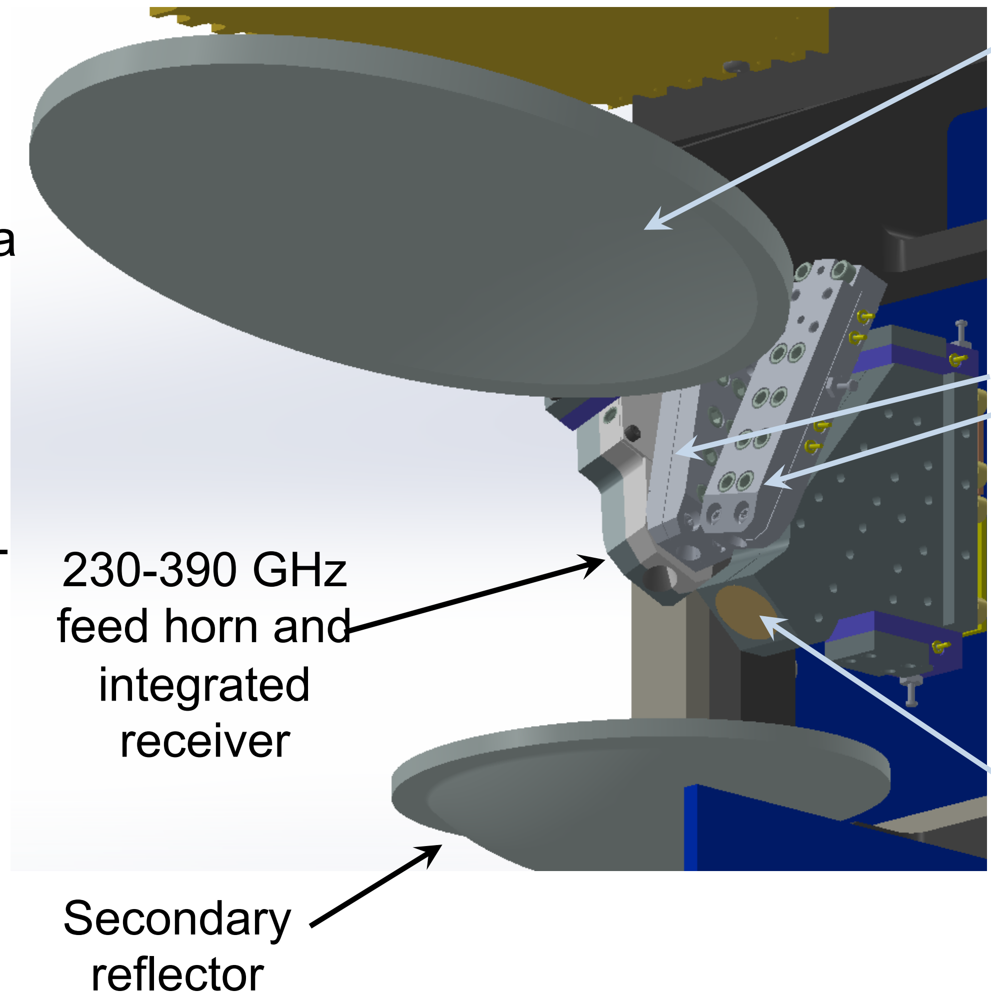
TWICE Instrument for 6U-Class Satellites

- Three frequency bands in one Gregorian quasi-optical subsystem
- Conical scanning with 9.5-cm primary reflector
- Cold sky and ambient target calibration each scan (60 rpm)



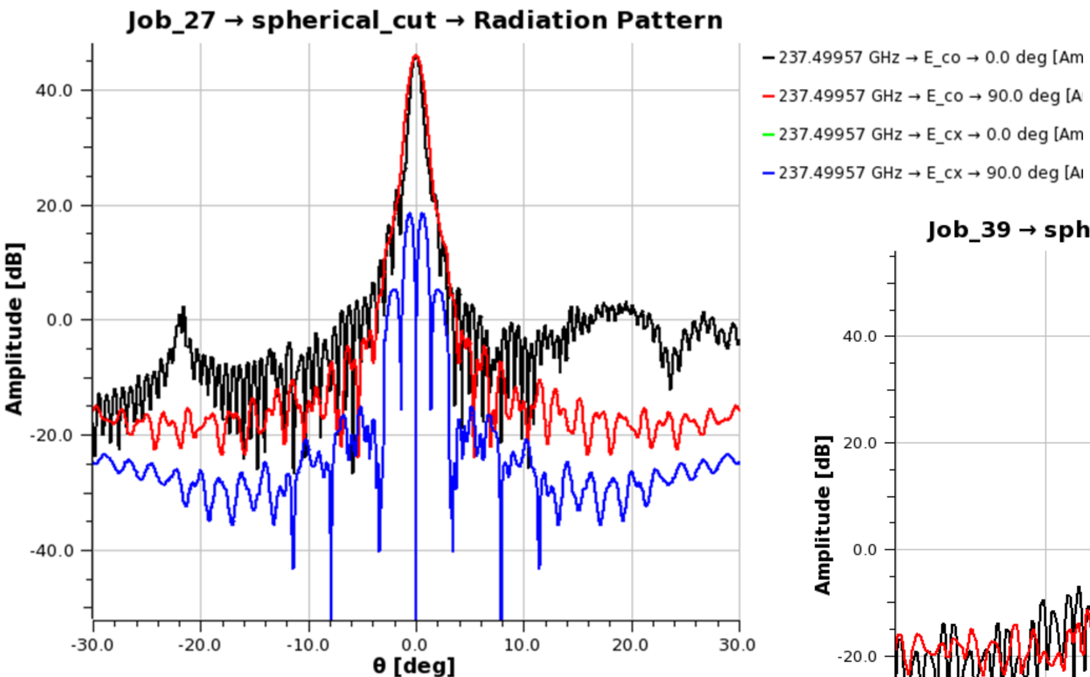
TWICE Instrument Quasi-Optics Design

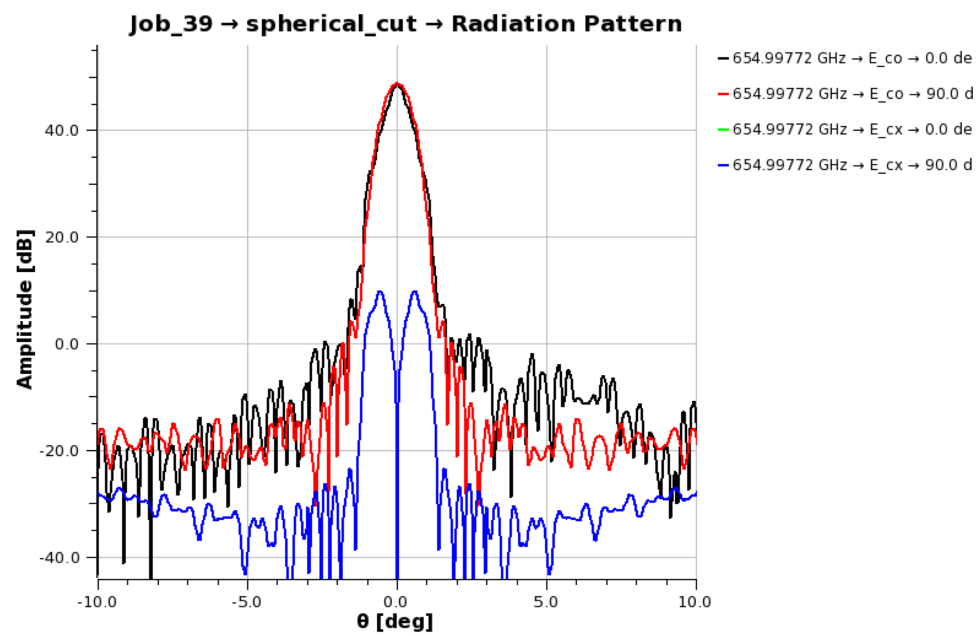
- Large focal plane enabled by oversized secondary reflector.
- Feed horns angled to minimize the total area of the antenna beams on the primary reflector.
- Four feed horns, all fabricated inside front-end modules to minimize waveguide loss:
    - 670 GHz (two orthogonal polarizations),
    - 230–390 GHz
    - 118–183 GHz



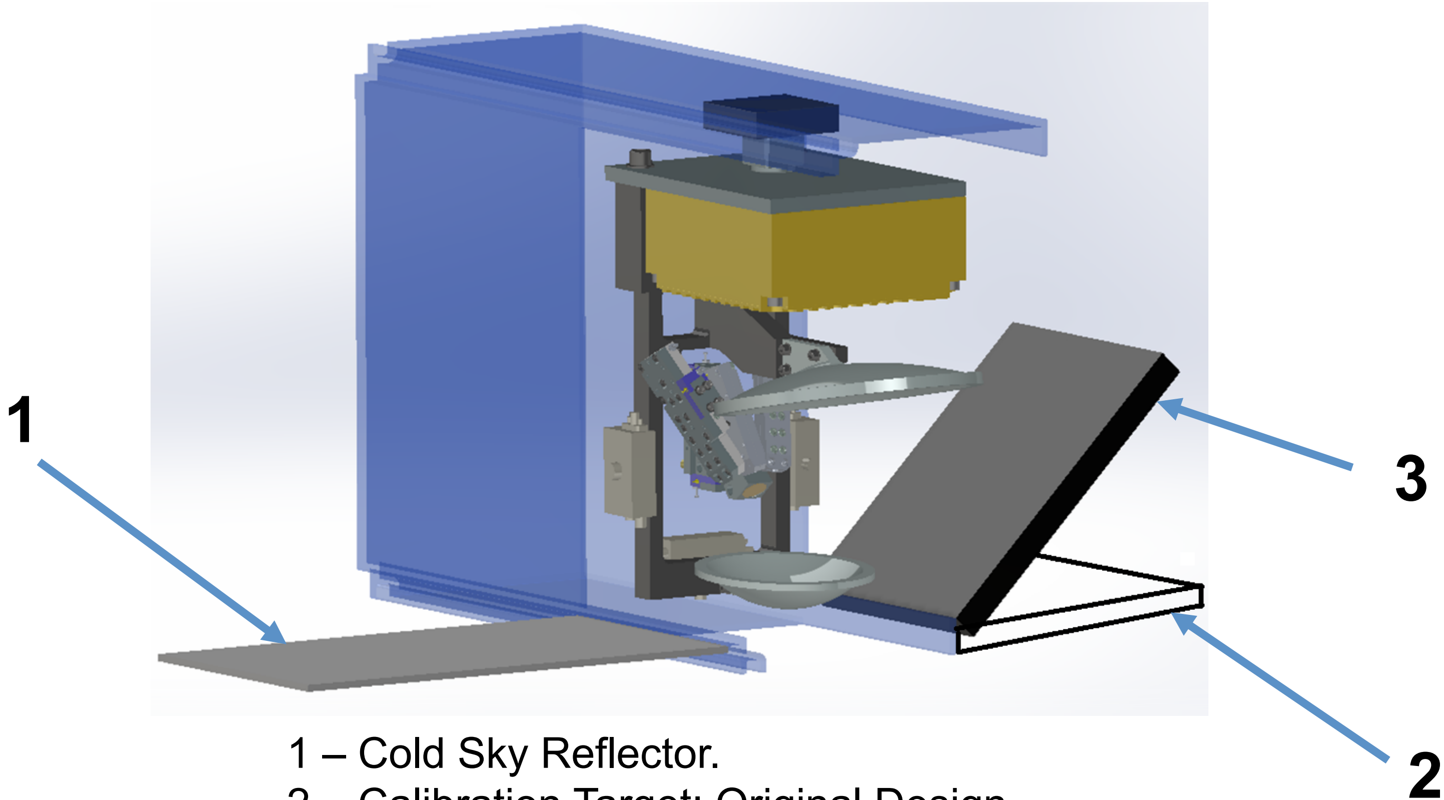
TWICE Feed Horn Patterns Simulated in Optical Subsystem

- All frequencies simulated, achieving main beam efficiencies > 90 %
- Half-power bandwidths from 1.5° to 0.6° across frequency range
- Corresponds to 16 km to 6 km footprint size (cross-track) from 400-km altitude





TWICE Calibration Target Design



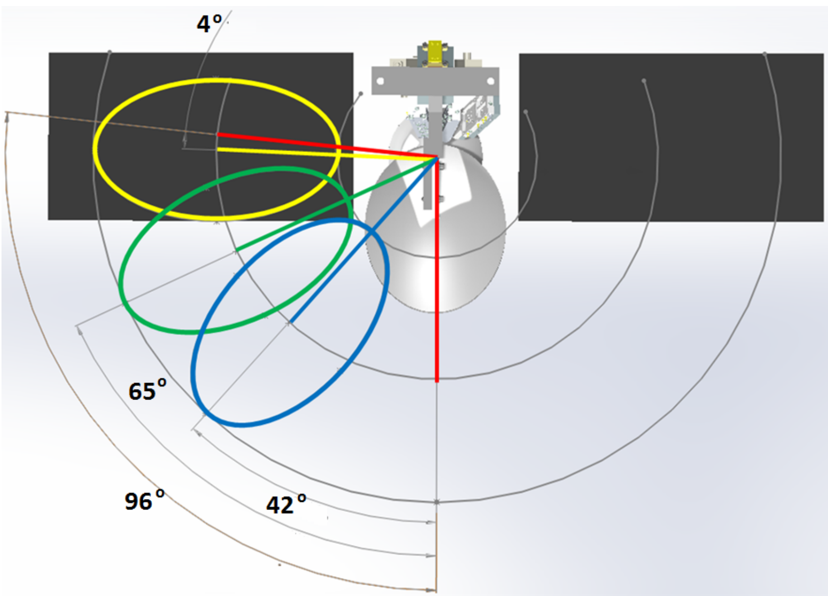
1 – Cold Sky Reflector.
2 – Calibration Target: Original Design.
3 - Calibration Target: Modified Design.

Advantages of modified design:

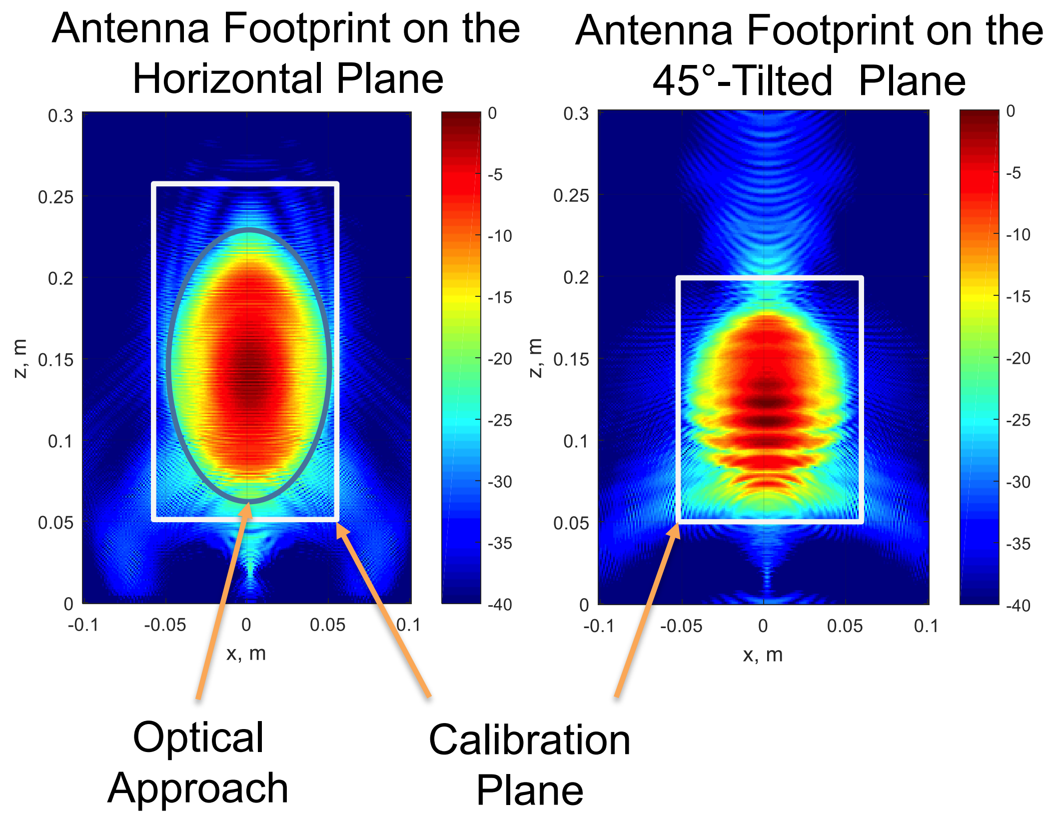
- Reduces size of antenna footprint,
- Partially shades target from solar intrusion,
- Reduces thermal inhomogeneity.

TWICE Near Field Antenna Pattern Simulations

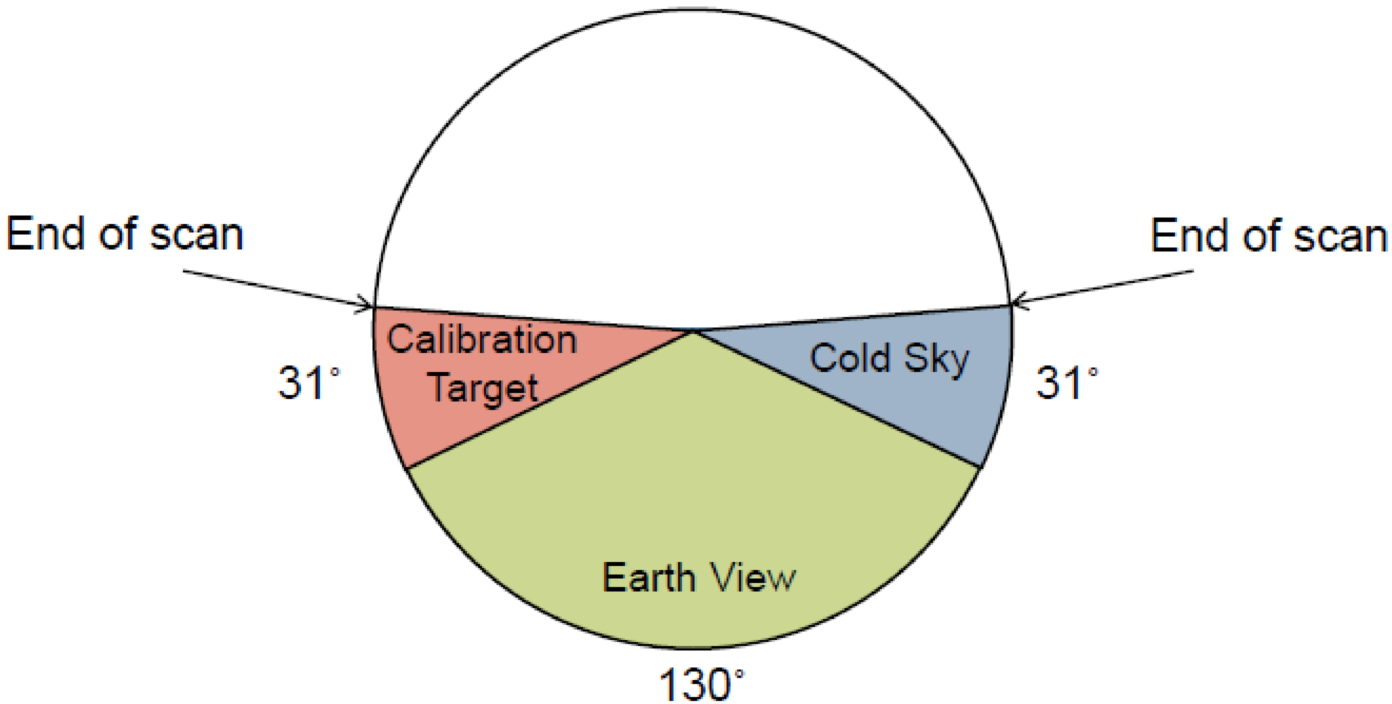
Antenna Near-Field Footprint (Optical Approach)



Antenna near-field footprint near 118 GHz



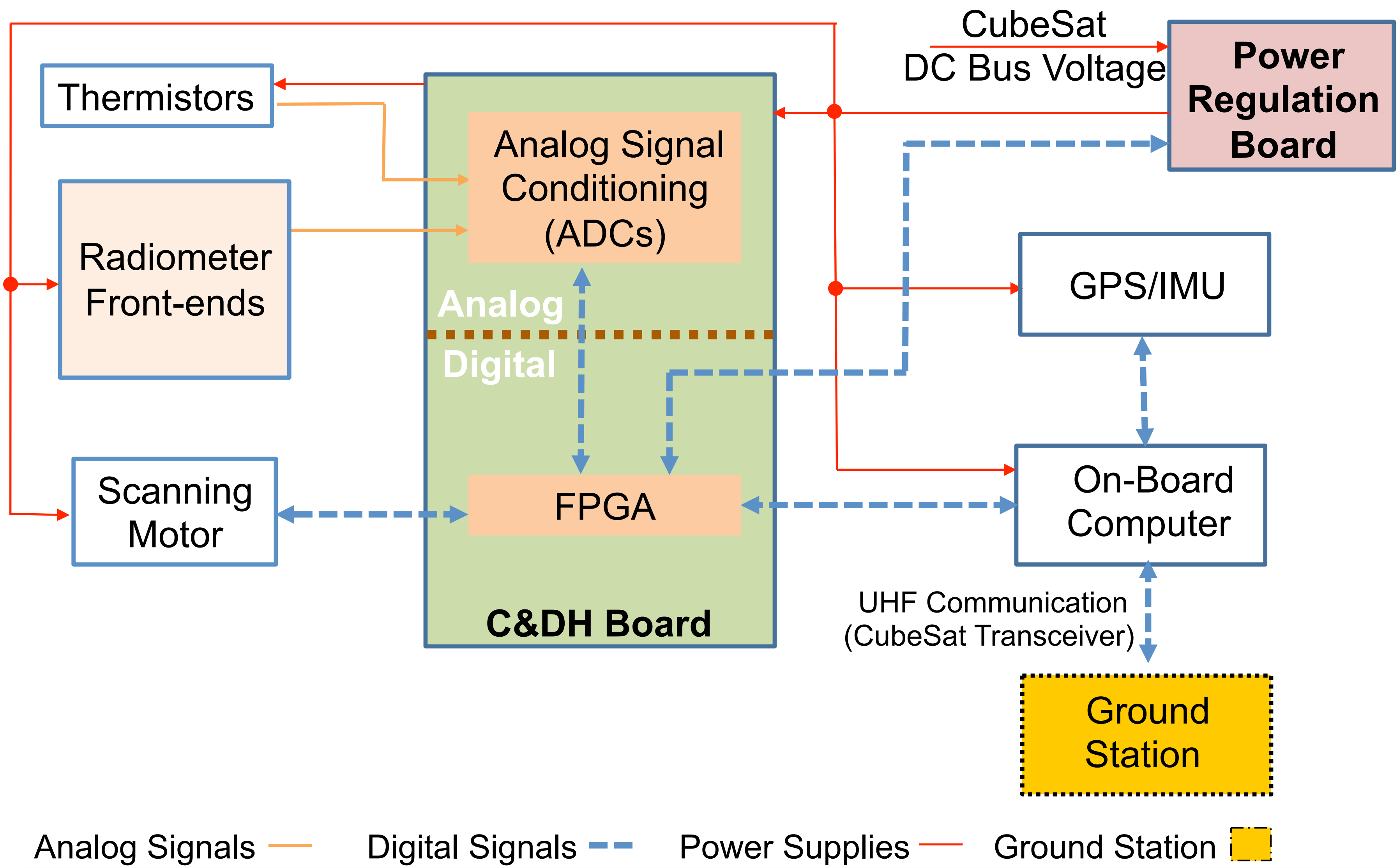
TWICE Conical Scanning and Calibration Strategy



Constant angular speed: 30 RPM

- Zero angular speed at each end of scan
- Total Time to scan 192° = $T_{acceleration} + T_{scene} + T_{deceleration}$ = 1 s
- $T_{scan\ revisit}$ = 1 s
- Contiguous footprint sampling is desired

TWICE Instrument Top-Level Interface Control Diagram



TWICE Summary

- The Tropospheric Water and Cloud ICE (TWICE) is a 6U-Class satellite instrument under development to enable global measurements of upper-tropospheric/lower stratospheric (ULTS) cloud ice and water vapor at a variety of local times.
- These global measurements are expected to improve currently limited understanding of general circulation model (GCM) cloud processes, improving both climate predictions and knowledge of their uncertainty.
- Cloud ice particle sizing is needed in both clean and polluted clouds to study the indirect effects of aerosols throughout the diurnal cycle.
- TWICE will perform measurements at 15 frequencies from 118 GHz to 670 GHz to yield ice cloud particle size information and total ice water content as well as atmospheric profiling of temperature and water vapor.
- Conical scanning will preserve the polarization basis and enable external calibration at all 15 frequencies using cold sky and an ambient target.
- The TWICE instrument will meet the size, weight and power (SWaP) requirements for deployment in a 6U-Class satellite.

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