Tropospheric Water and Cloud ICE (TWICE) 6U-Class Satellite Instrument: Enabling Observations of Cloud Ice Particle Sizes as well as Temperature and Humidity Profiles in the Upper Troposphere

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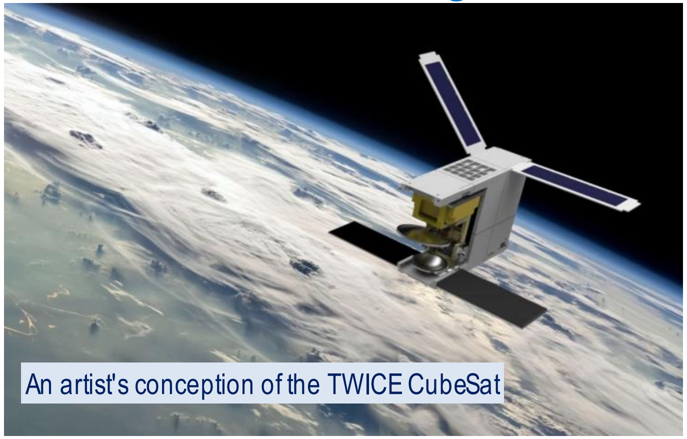
Tropospheric Water and Cloud ICE (TWICE) Scientific Motivation

TWICE Addresses Earth Science Decadal Survey:

- Science Question W-9: *What processes determine cloud microphysical properties and their connections to aerosols and precipitation?*
- Science Question C-5 A: *How do changes in aerosols (including their interactions with clouds which constitute the largest uncertainty in total climate forcing) affect Earth's radiation budget and offset the warming due to greenhouse gases?*

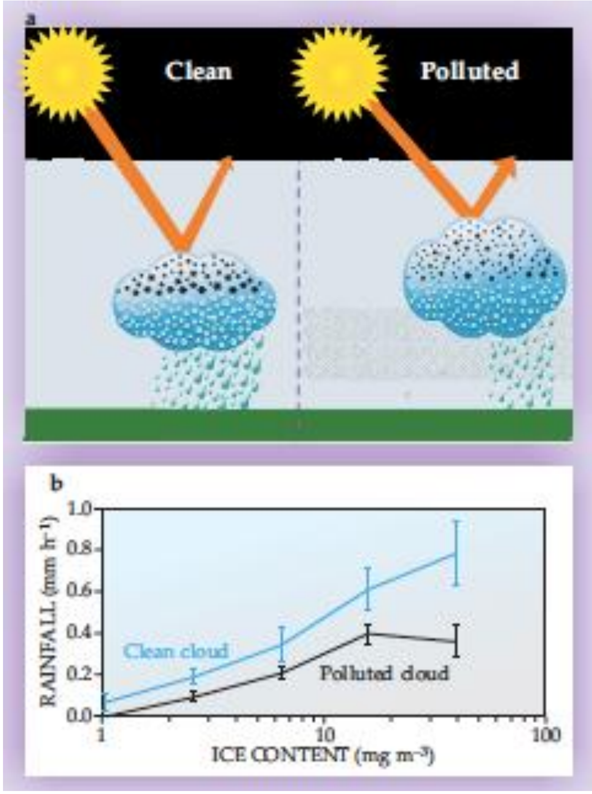
TWICE Scientific Objectives:

- Perform global observations of ice particle size information and water vapor profiles throughout the diurnal cycle
- Current understanding of upper tropospheric / lower stratospheric processes in general circulation models (GCMs) is limited. Such measurements can improve both weather and climate predictions as well as knowledge of their uncertainties.


An artist's conception of the TWICE CubeSat

Tropospheric Water and Cloud ICE (TWICE) Scientific Motivation

- **Aerosols and Clouds**
  - Clouds represent arguably the largest uncertainty in climate 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



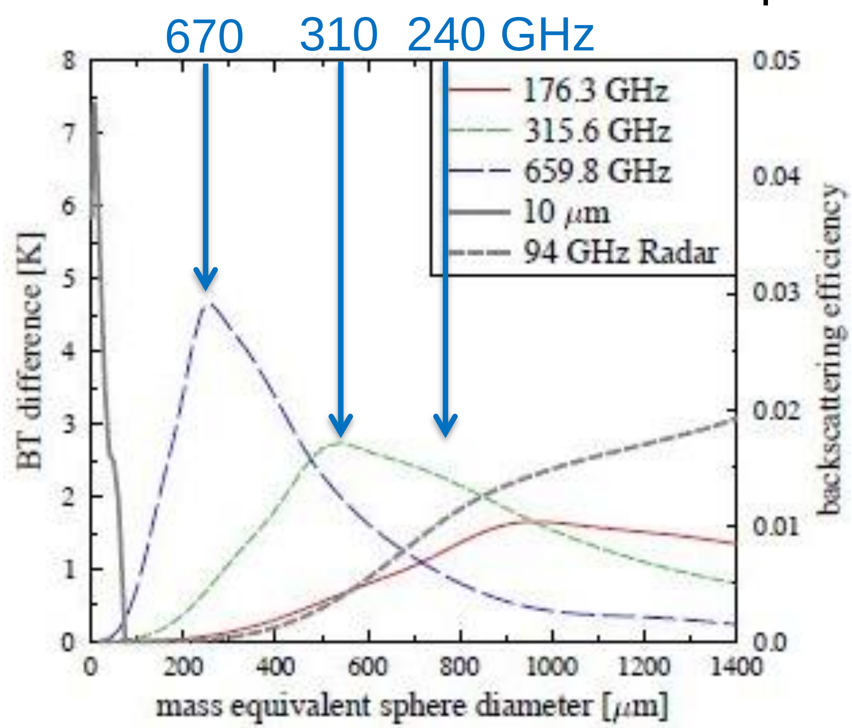
- **TWICE Radiometer Instrument**

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

TWICE Cloud Ice Particle Size Information

Sub-millimeter wave radiometry fills the sensitivity gap between infrared (cloud tops) and microwave (lower troposphere) measurements

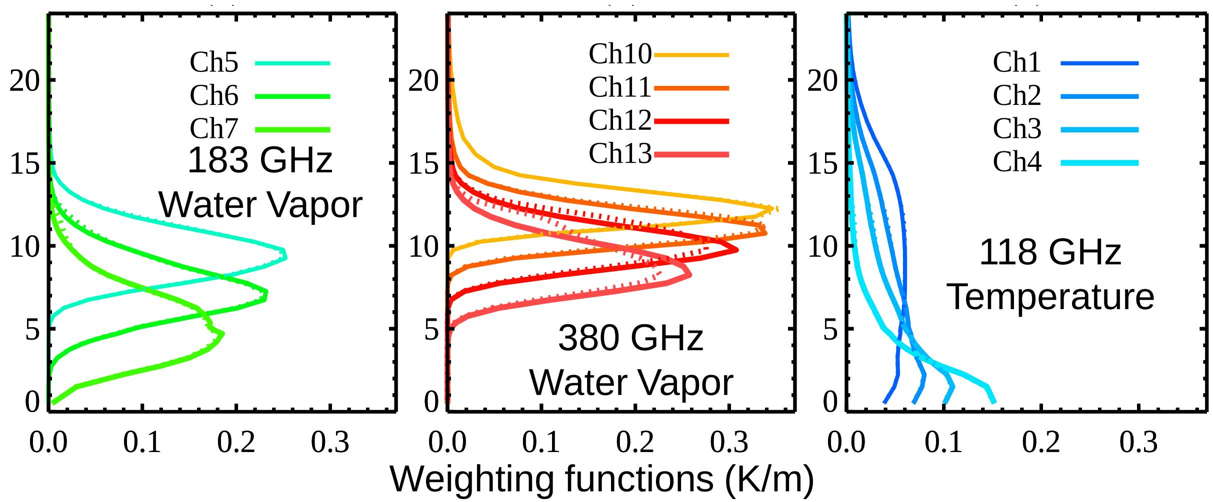
- NASA's A-Train provides limited cloud particle size information.
  - CloudSat: 94-GHz radar (particle sizes > 1 mm)
  - Aqua's MODIS: 10-µm infrared radiometer (particle sizes < 100 µm)
- Sub-millimeter wave provides ice particle size information between ~50 µm and ~1000 µm.
- High atmospheric opacity 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 for ICI MetOp SG-B.



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 temperature information using the O_2 absorption line.

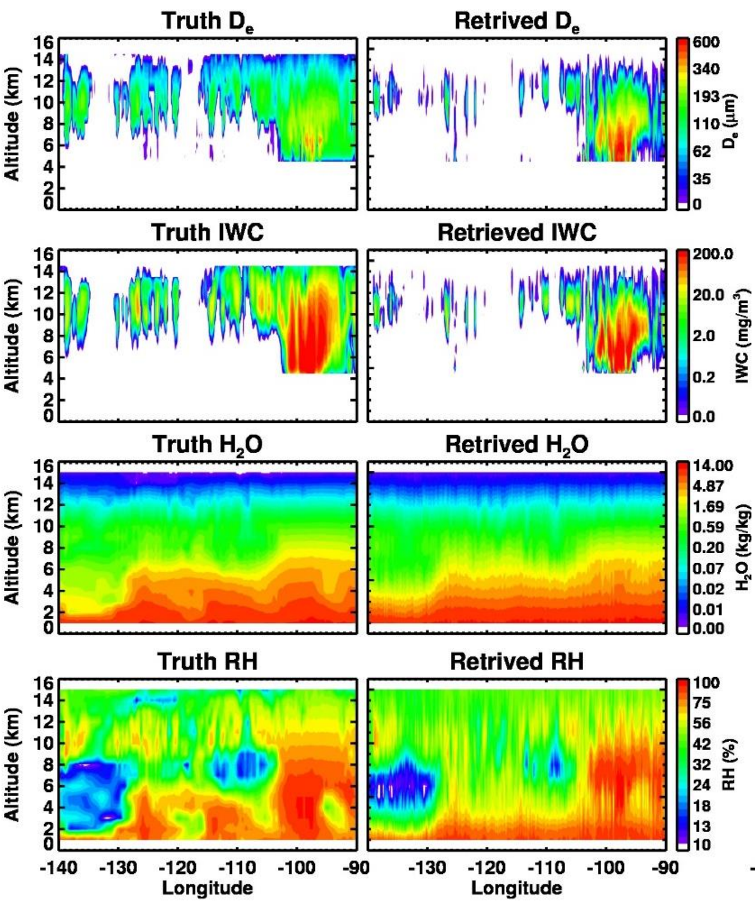
[Jiang et al., *Earth & Space Science, 4, doi:10.1002/2017EA000296, 2017]*



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

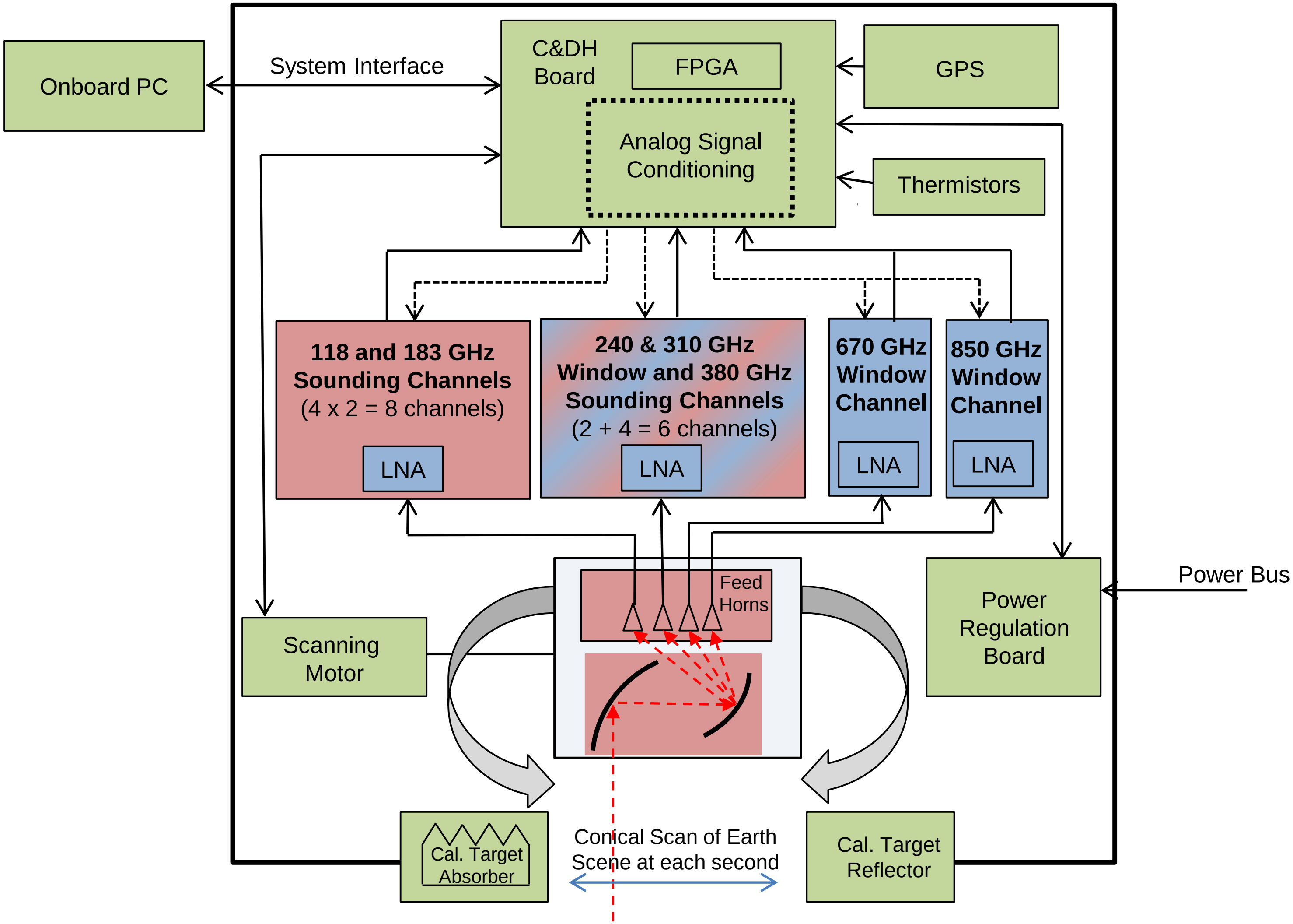
Retrieval of Cloud Ice, Humidity and Temperature Retrieval from TWICE

- We have developed and applied a Bayesian-based simulation and retrieval system [*Evans et al.*, 2002; 2012] for TWICE frequencies. Simultaneous retrievals are performed for these quantities:
- Cloud ice particle size (D_e), ice water content (IWC), water vapor content (H2O), and relative humidity (RH) profiles.
- Results show that the TWICE instrument is capable of retrieving ice particle size in the range of ~50 μm to 1000 μm 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 < 50% for IWC and < 20% for H_2O.



[Jiang et al., *Earth & Space Science*, *4*, doi:10.1002/2017EA000296, 2017]

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

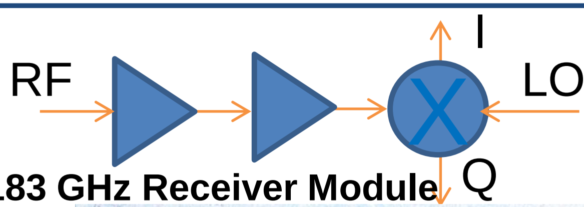
Temperature and Humidity Sounding Frequencies

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 (τ = 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 Radiometer	0.05	0.27
850 GHz Radiometer	0.05	0.27
Back-end Board	0.13	0.73
Power Regulation Board	0.13	3.00
C&DH Housing	0.50	
Optics	0.40	-
Calibration Target/Reflector	0.71	-
Scanning Motor	0.33	3.00
Totals	**3.24**	**14.46**

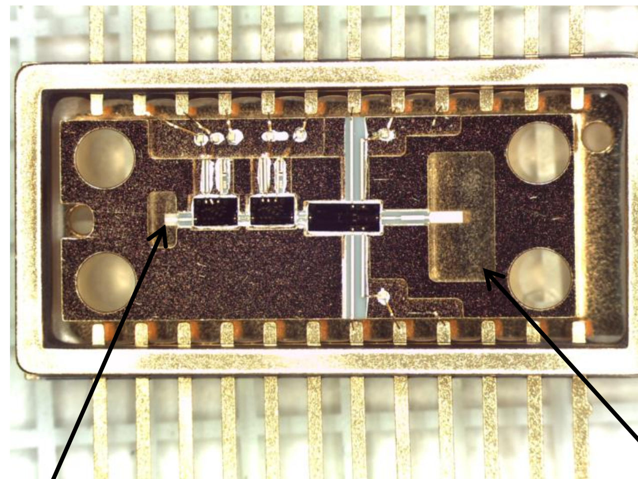
Millimeter-wave Radiometers for Temperature & Water Vapor Sounding



Technology developed and demonstrated for GeoSTAR and HAMMR airborne instruments

183 GHz Receiver Module

118 GHz Receiver Module

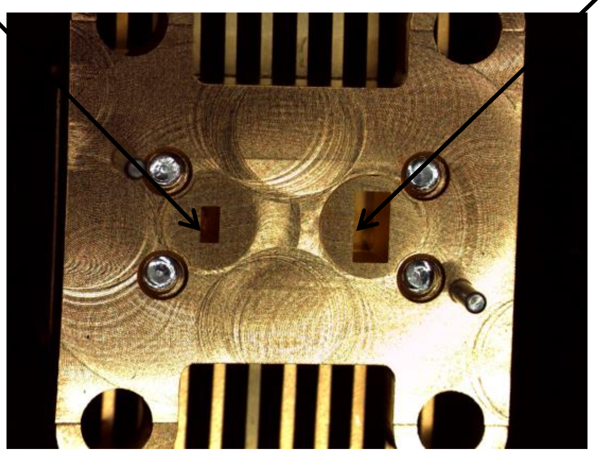


RF WR-5

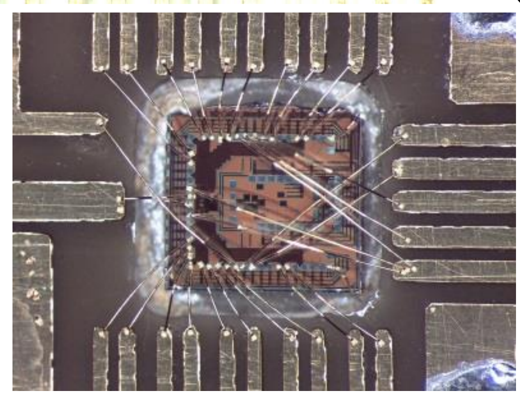
LNA

Mixer

LO WR-10



RF WR-8

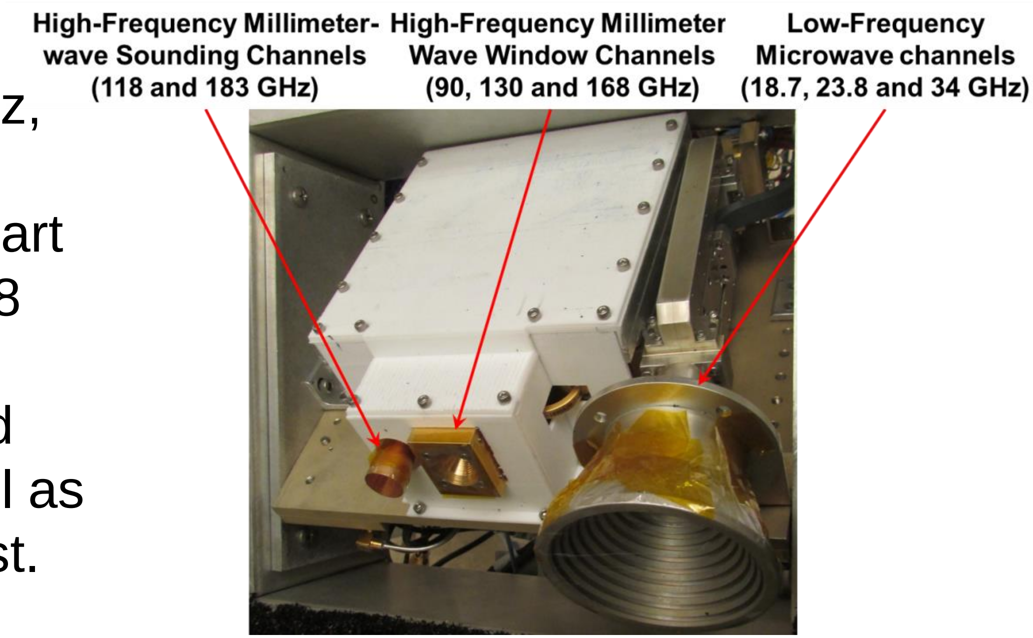


LO WR-15

ASIC IF processor designed by B. Razavi (UCLA)

High-frequency Airborne Microwave and Millimeter-wave Radiometer

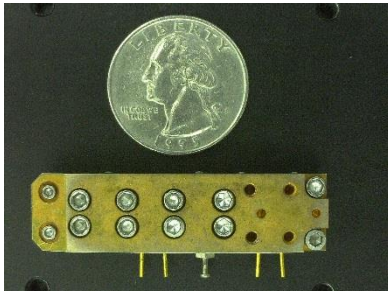
Temperature and humidity sounders near 118 and 183 GHz, respectively, have been successfully demonstrated as part of the HAMMR instrument for 68 flight hours aboard Twin Otter aircraft. Flights were conducted over inland water bodies as well as nearly the entire U.S. west coast.

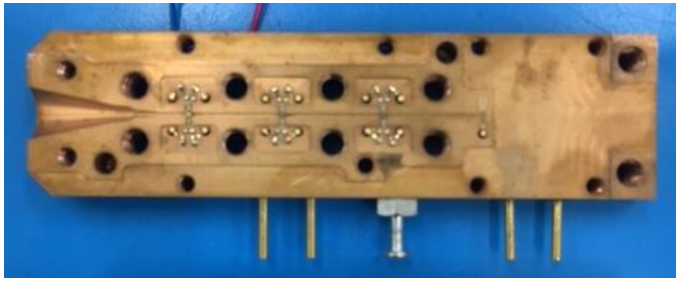


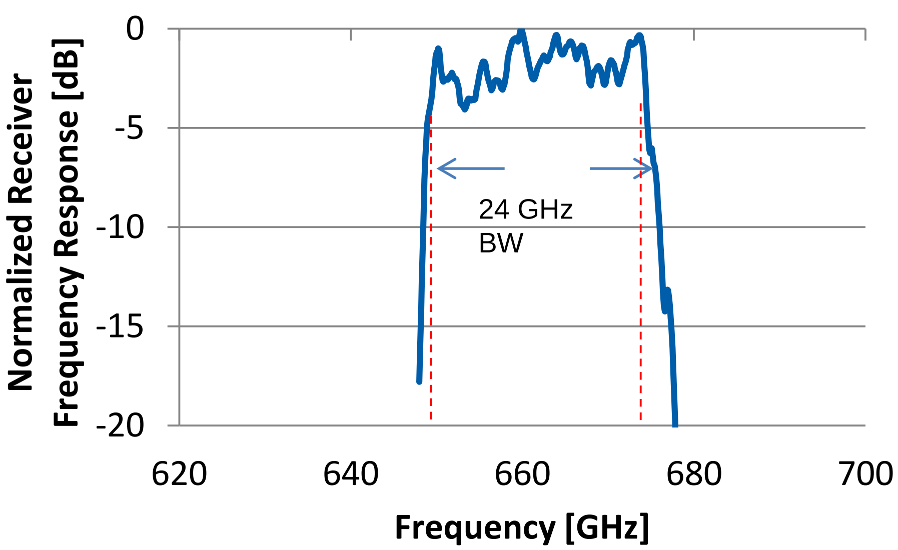
670 GHz Integrated Receiver Measured Response

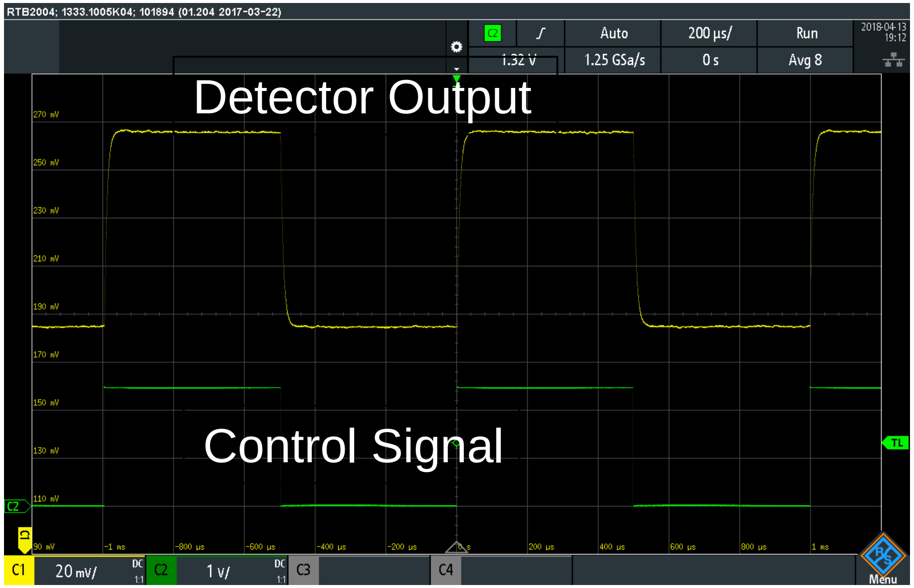
Integrated 670 GHz Receiver

- 10.6 dB measured noise figure
- 270 mW DC Power
- First stage bias is "chopped" to reduce 1/f noise
- 3-LNAs and 2 bandpass filters
- GaAs Schottky Detector (VDI)
- Integrated Video Circuit

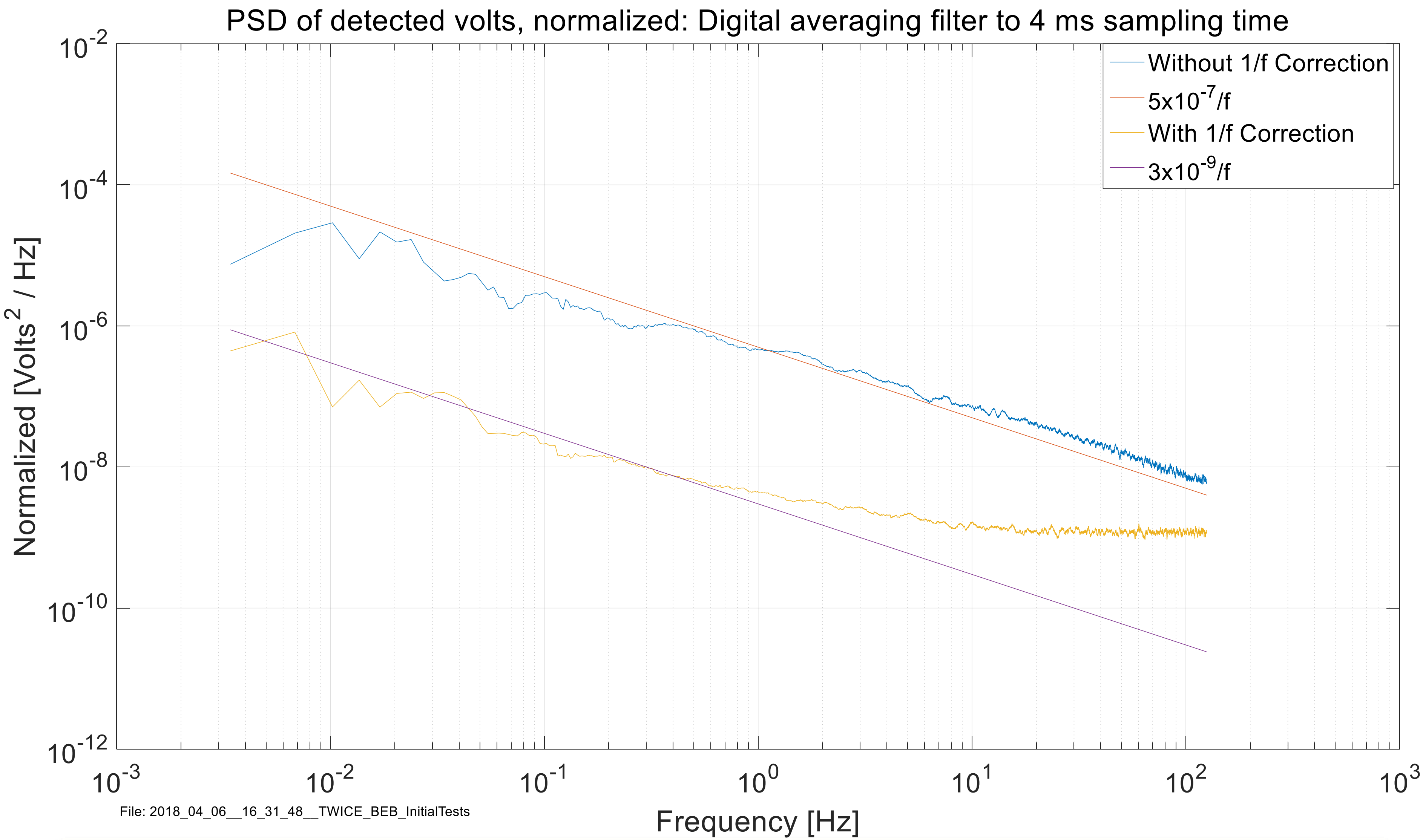








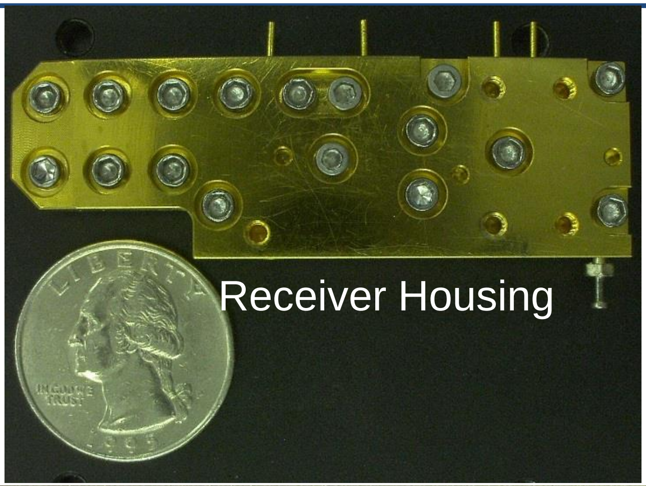
Demonstration of 1/f Noise Mitigation Technique for 670-GHz Receiver

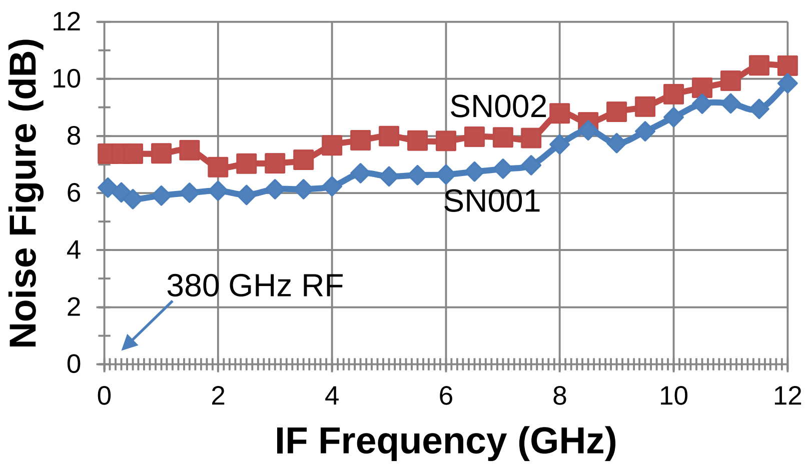


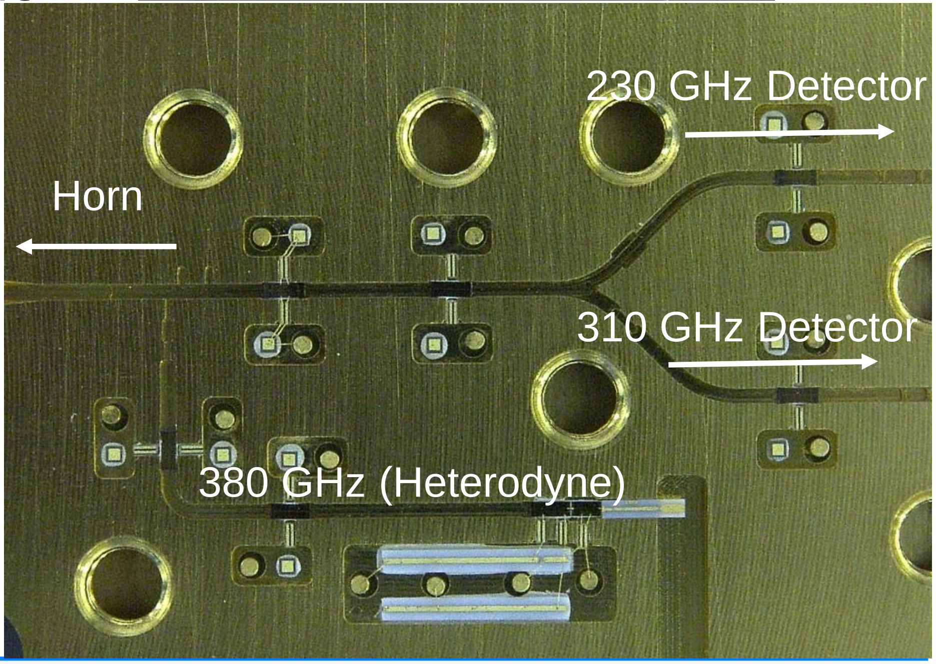
230 to 380 GHz Integrated Receiver

Integrated Receiver:

- 240 GHz direct detection receiver
- 310 GHz direct detection receiver
- 380 GHz Heterodyne receiver
- Highly compact with single horn antenna
- Front-end LNA-based receiver (before 380 GHz mixer)
- Integrated diplexers and bandpass filters

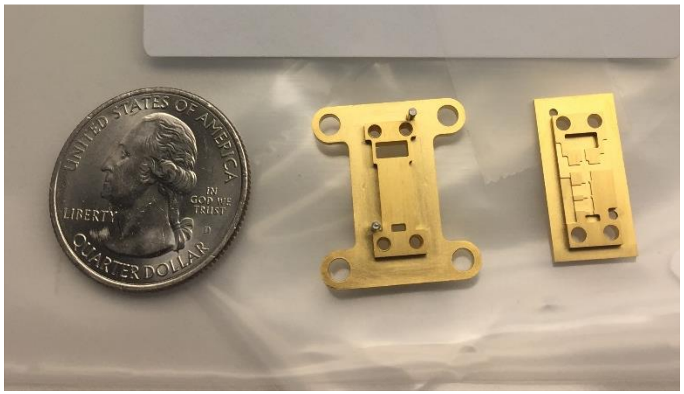




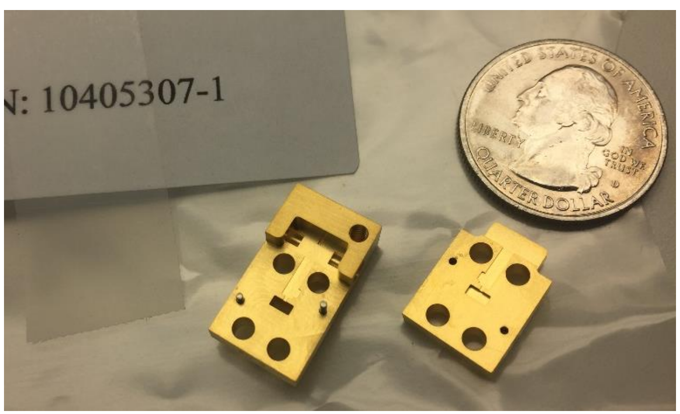


118 and 183 GHz Receiver

- Feed horn machined inside the split block with diplexer for 118 and 183 GHz
- 118 GHz and 183 GHz receiver modules



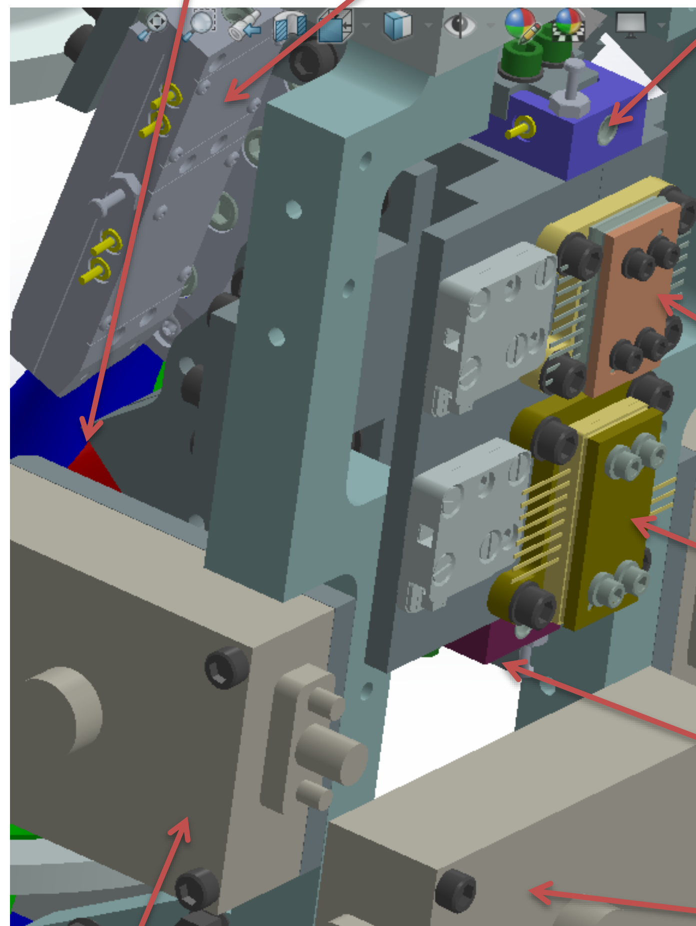
- LO multipliers for receiver modules
- DROs provide LO signals to multipliers



Modeled beam from feed horn for 118 and 183 GHz

670 GHz receiver

91.66 GHz X4 multiplier



183 GHz Receiver Module

118 GHz Receiver Module

59.38 GHz X2 multiplier

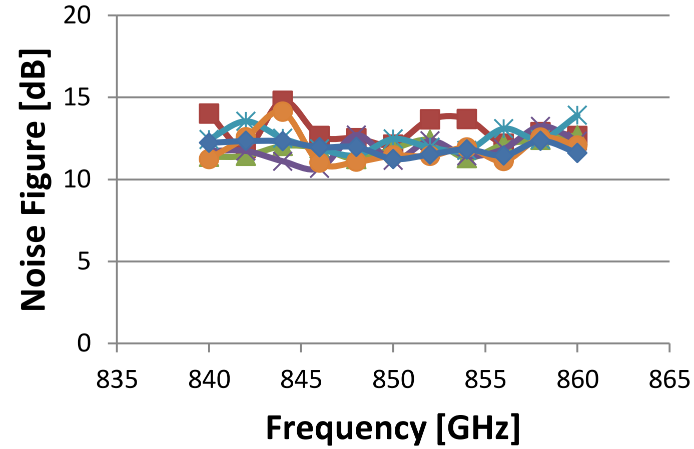
DRO: LO Source at 29.69 GHz

DRO: LO Source at 22.914 GHz

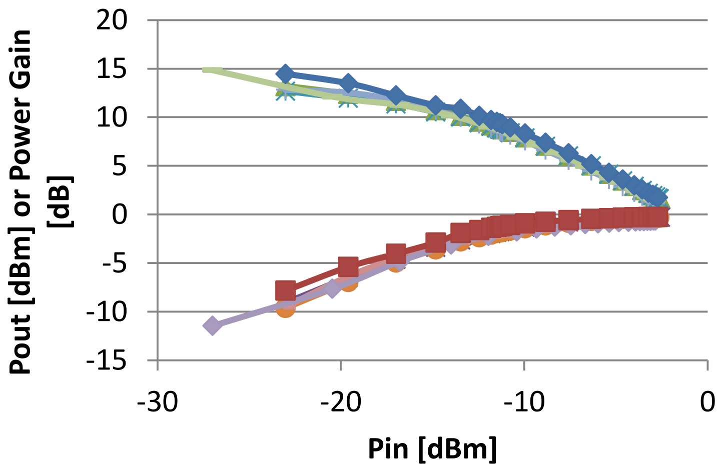
850 GHz LNA Readiness

- Adding a channel near 883 GHz would substantially improve sensitivity to small cloud ice particles (down to ~20 μm).
- Northrop Grumman has developed and demonstrated an 850 GHz LNA under other projects.

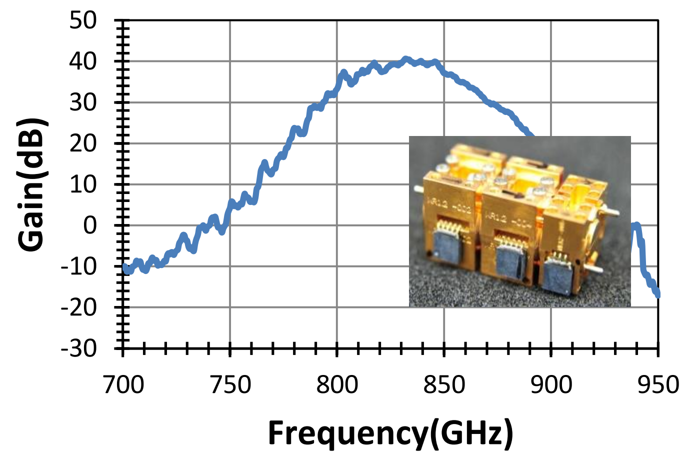
LNA Noise Figure



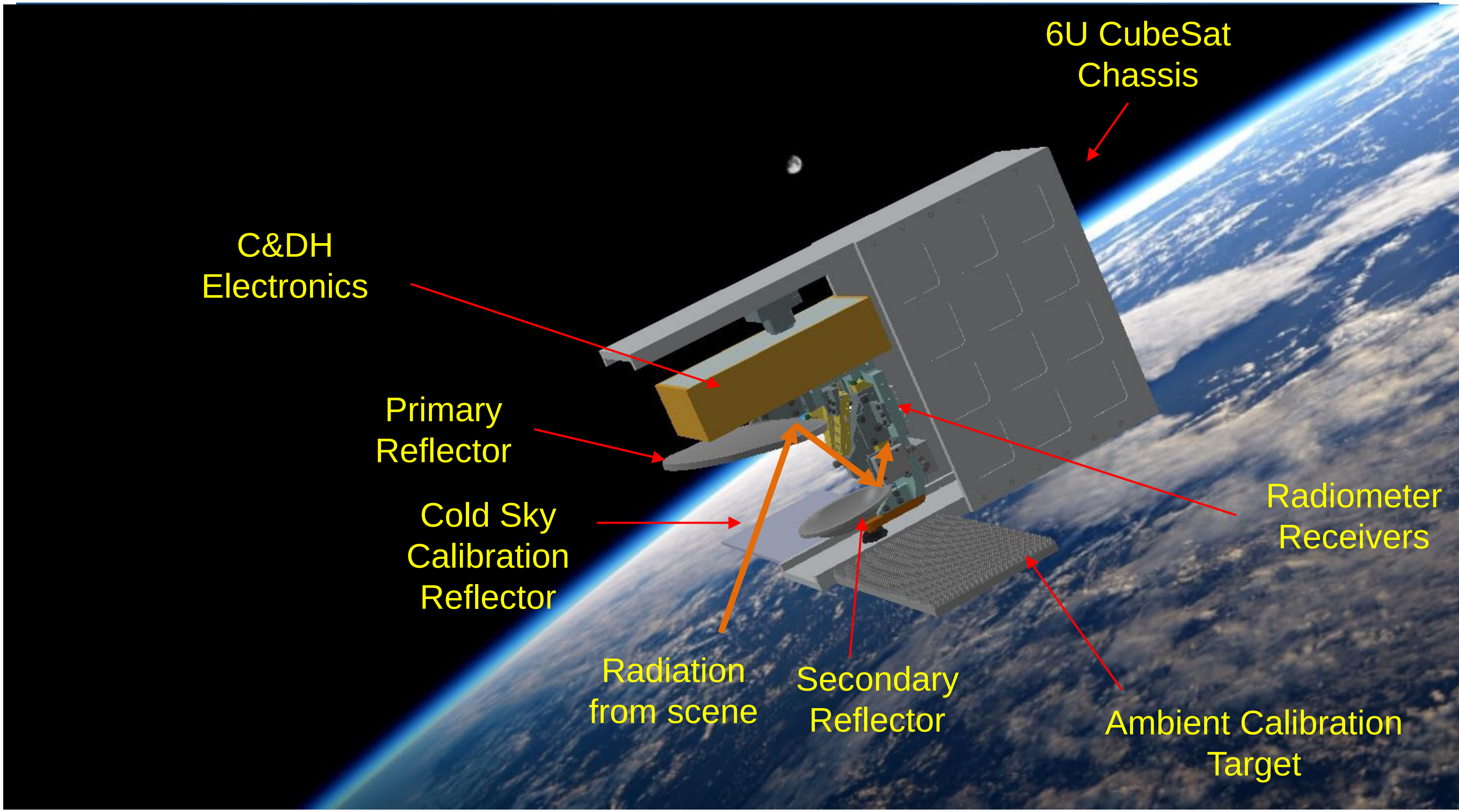
Saturated Power Characteristics



Three cascaded amplifier gain



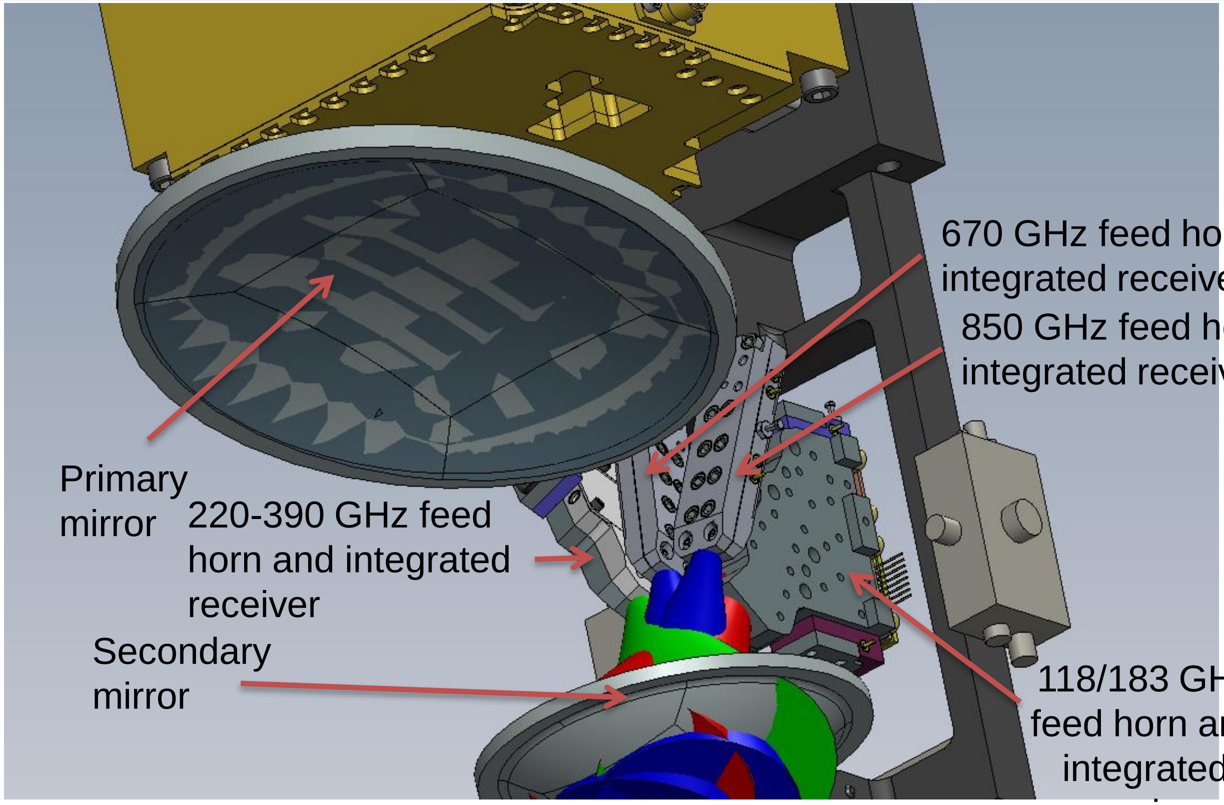
TWICE Instrument for 6U-Class Satellites

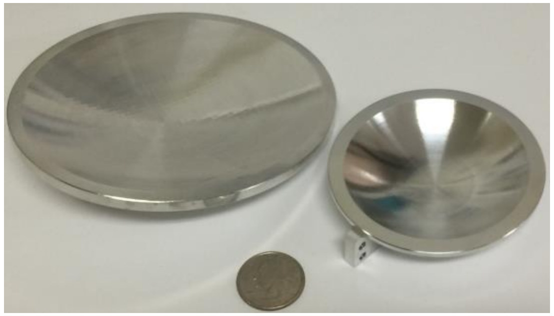


- Four frequency bands in one Gregorian quasi-optical subsystem
- Conical scanning of the Earth scene with 9.5-cm primary reflector

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:
  - 850 GHz
  - 670 GHz
  - 230–390 GHz
  - 118–183 GHz



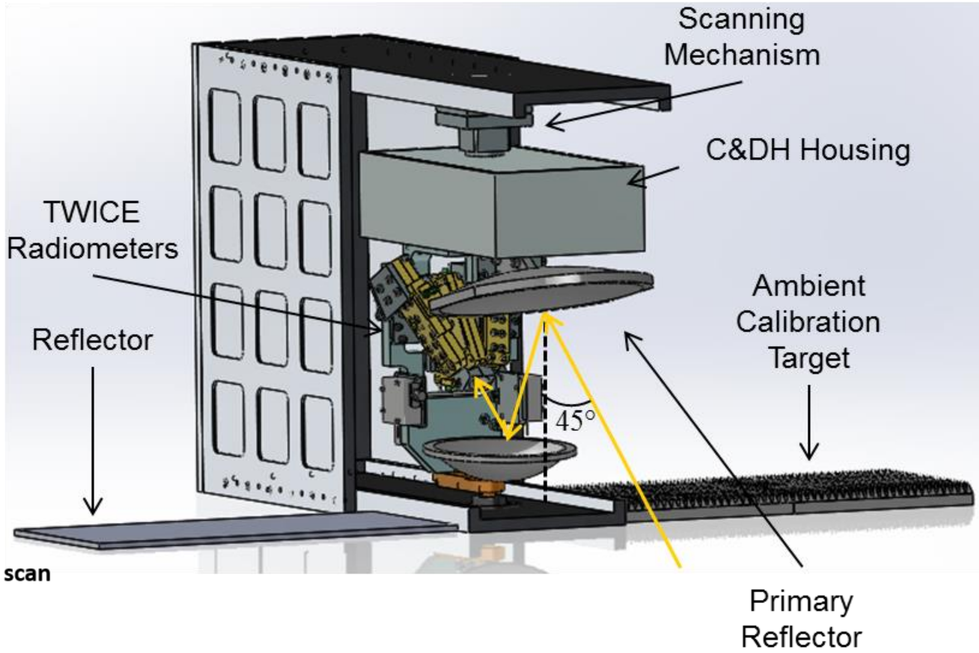


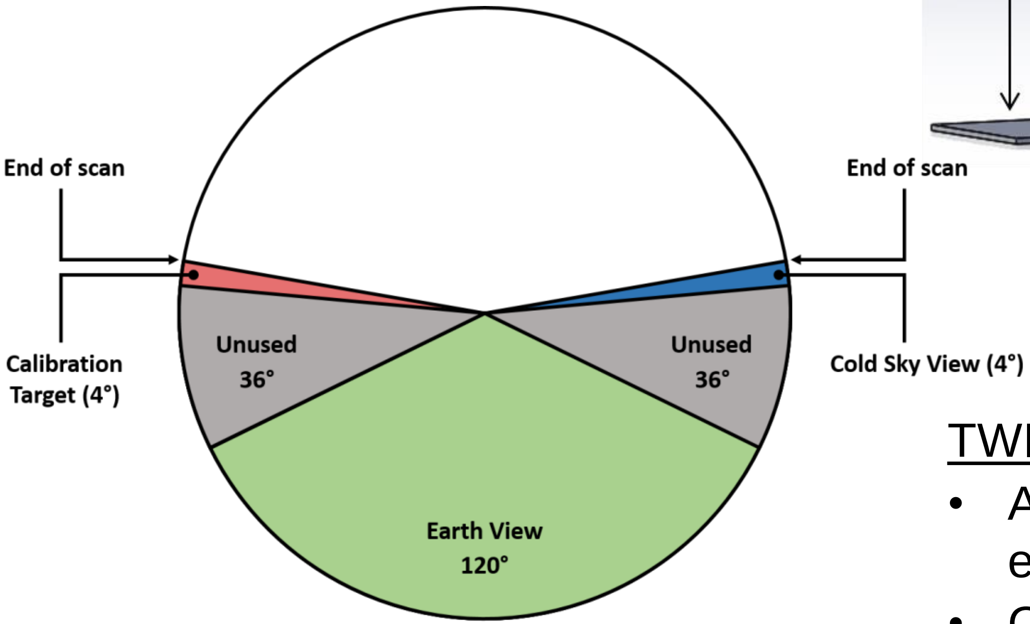
Primary and Secondary Reflectors for TWICE

TWICE Scanning and Calibration Strategy

TWICE Scanning Design

- Conical scanning of the Earth scene
- Ambient target and cold sky references measured at the beginning and end of each scan for end-to-end calibration
- Primary reflector has 45° look angle.





- Total time to scan 200° = $T_{acceleration} + T_{scene} + T_{deceleration} = 1\ s$
- $T_{scan\ revisit} = 1\ s$

TWICE Scanning Requirements

- Acceleration or deceleration from end of scan to Earth view range
- Constant angular velocity over the Earth view range

TWICE Sampling Time and Radiometric Resolution

Frequency (GHz)	Cross-Track Footprint Size (km)	Number of Footprints per Scan (N_{FP})	Sampling Time (ms)		Radiometric Resolution Per Pixel (K)
			Radiometer Footprint Time	Footprint Sampling Time	
118	19	46	10.31	8.00	0.12
183	12	72	6.51	8.00	0.15
240	13	67	7.06	4.00	< 0.1
310	10	87	5.43	4.00	< 0.1
380	8	108	4.34	4.00	0.35
670	5	173	2.71	4.00	0.3
850	5	173	2.71	4.00	0.4

- The samples acquired by the ADC during one footprint sampling time are averaged to yield one sample per footprint.
- The receivers centered at 240, 310, 670 and 850 GHz have wide bandwidths that improve radiometric resolution.

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 particle size and water vapor profile information 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 16 frequencies from 118 GHz to 850 GHz to yield cloud ice particle size information, total ice water content and water vapor profiles.
- Conical scanning will preserve the polarization basis and enable end-to-end calibration at all 16 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.