Tropospheric Water and Cloud ICE (TWICE): Millimeter-wave to Terahertz Radiometer Instrument for 6U-Class Nanosatellites

Steven C. Reising[1], Pekka Kangaslahti[2], Erich Schlecht[2], Xavier Bosch-Lluis[1], Mehmet Ogut[1], Sharmila Padmanabhan[2], Jonathan Jiang[2], Richard Cofield[2], Nacer Chahat[2], Shannon T. Brown[2], Yuriy Goncharenko[1], William Deal[3], Alex Zamora[3], Kevin Leong[3], and Gerry Mei[3]

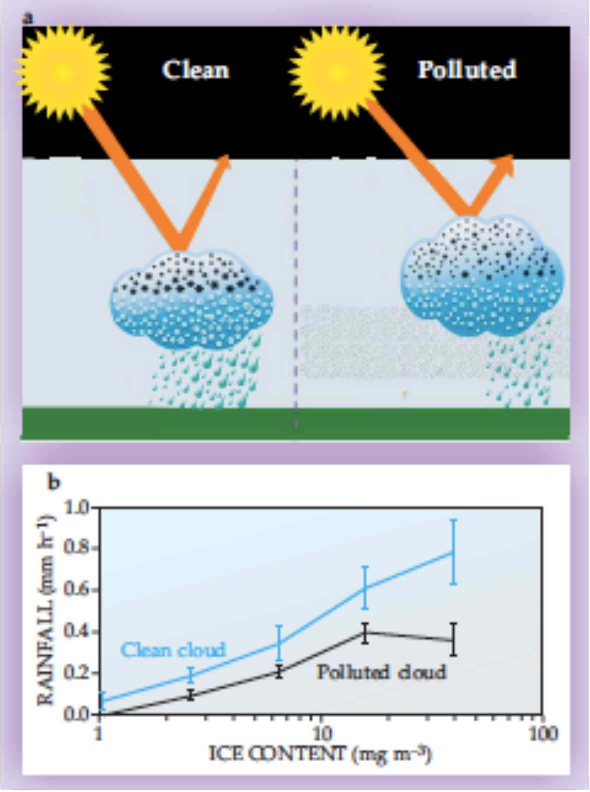
[1]Microwave Systems Laboratory, Colorado State University, Fort Collins, CO
[2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA
[3]Northrop Grumman Aerospace Systems, Redondo Beach, CA

TWICE Scientific Objectives

- **NASA's Earth Science Focus Areas:**
  - Climate Variability and Change
  - Water & Energy Cycle
- **Addressing Scientific Needs:**
  - To measure upper-tropospheric water vapor and cloud ice at a variety of local times to address limitations of current microwave sensors in sun-synchronous orbits
  - To 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.
  - To improve currently limited understanding of UTLS processes in general circulation models (GCMs), improving both climate predictions and knowledge of their uncertainties.

TWICE Scientific Motivation

- **Aerosols and Clouds**
  - Clouds represent the largest uncertainty in predictions of climate models.
  - 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

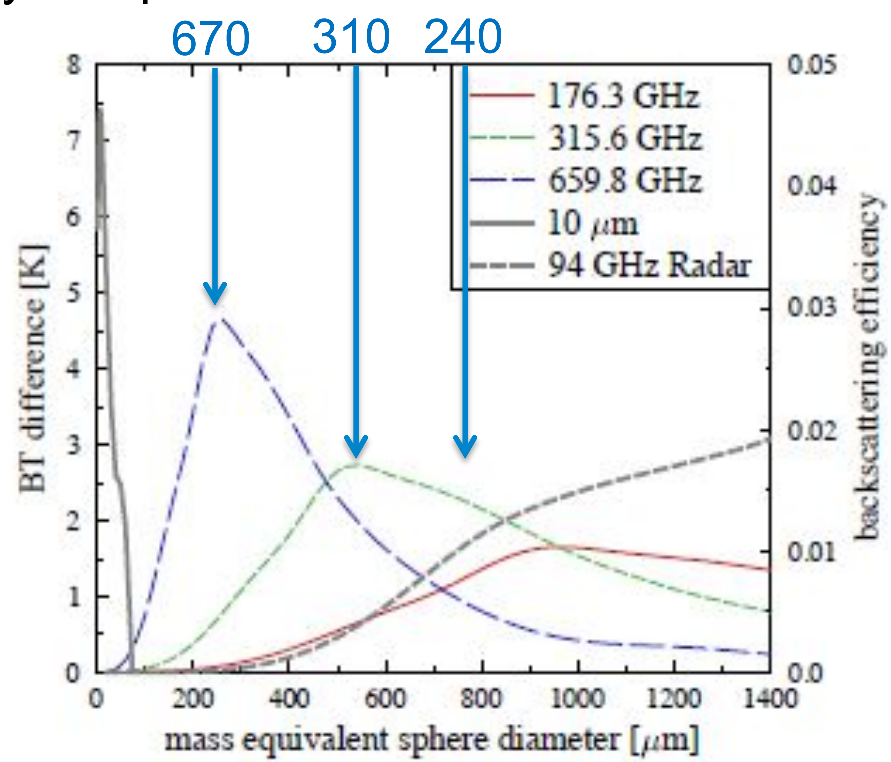


- **TWICE Radiometer Instrument**

  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 Ice Cloud Particle Size

- NASA's A-Train provides limited cloud particle size information.
  - CloudSat: 94-GHz radar (> 1 mm)
  - Aqua's MODIS: 10-μm infrared radiometer (< 100 μm)
- Sub-millimeter wave radiometry fill the gap by providing cloud particle size information between approximately 200 μm and 1 mm.
- High atmospheric opacity at sub-millimeter wavelengths allows the measurement of ice in high cirrus clouds through *scattering.*
- Measured brightness temperatures *decrease* due to ice particle scattering at sub-mm-wave frequencies.
- Figure at right shows brightness temperature decrease; adapted from Buehler et al., *QJRMS*, 2007.

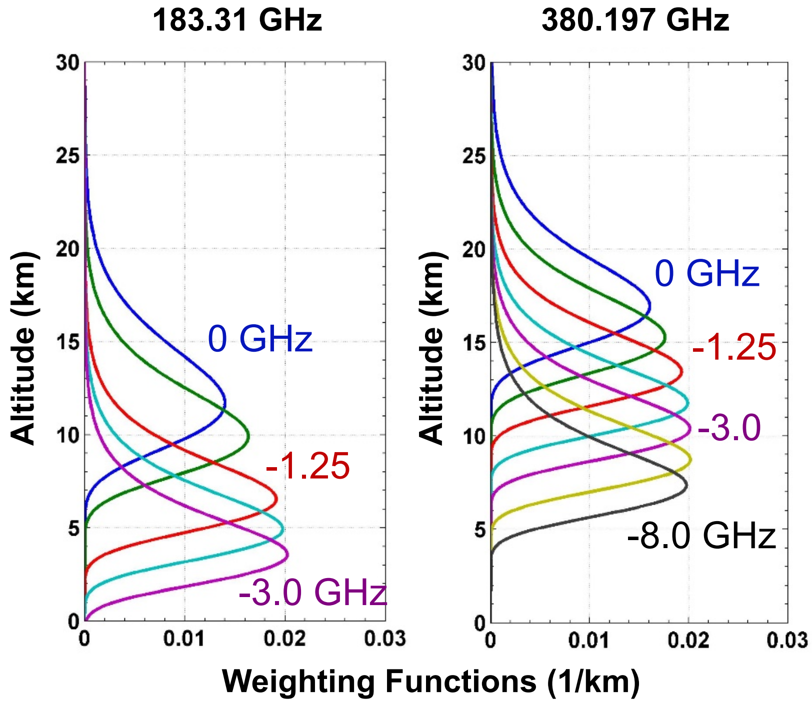


TWICE Water Vapor Profiling

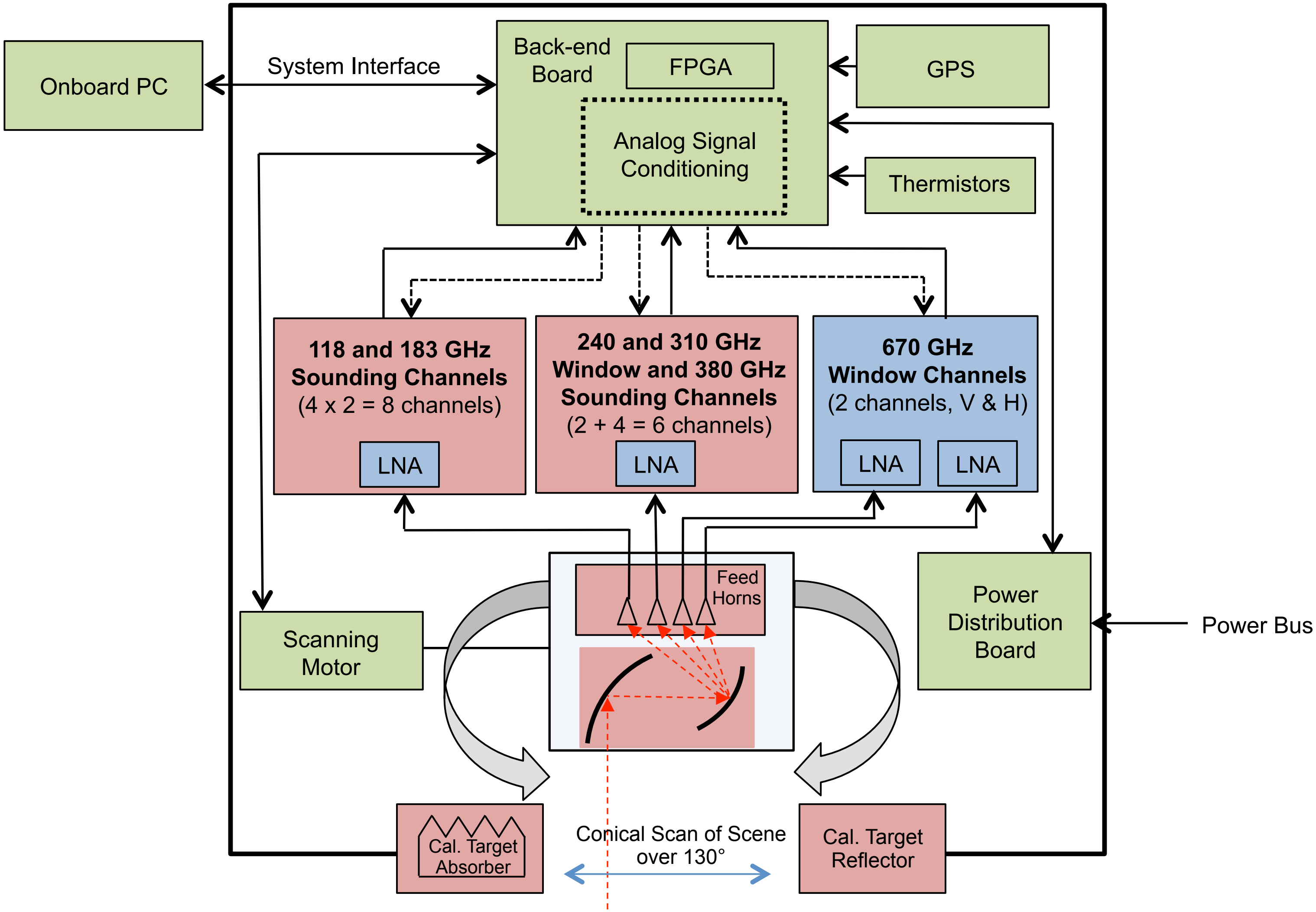
Water Vapor Sounding Channels:

- Measurements near two water vapor absorption lines provide profiling information through pressure broadening.
- 183 GHz and 380 GHz are chosen to retrieve water vapor in the troposphere and upper troposphere / lower stratosphere (UTLS).

- Water vapor weighting functions are shown at offsets of 0, 0.75, 1.25, 2, 3, 5 and 8 GHz below lines at 183.31 GHz (left) and 380.20 GHz (right).
- To constrain the water vapor retrievals, 118 GHz channels measure the tropospheric temperature profile using the O_2 absorption line.

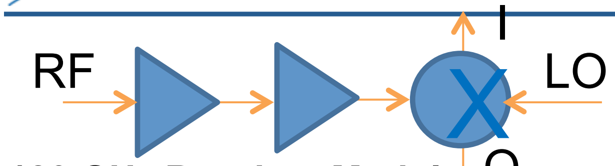


Tropospheric Water and Cloud Ice Instrument Block Diagram



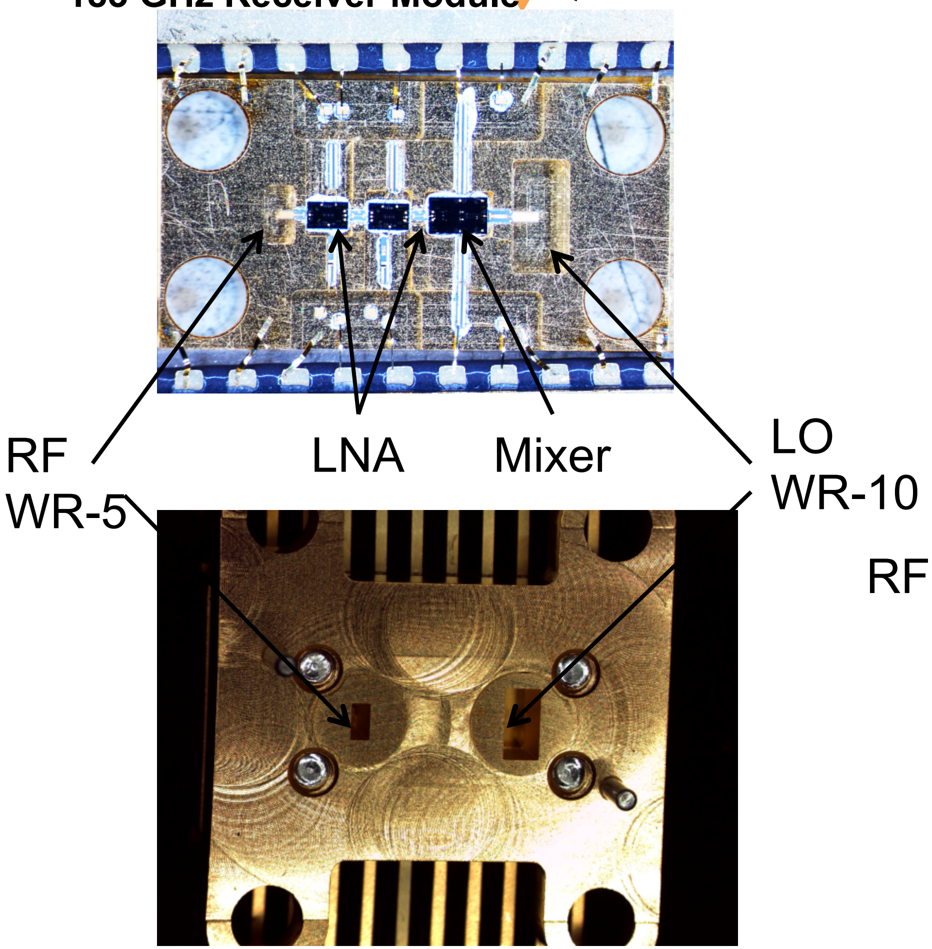
Green = CSU; Red = JPL; Blue = NGC;

Temperature and Water Vapor Sounding Receivers near 118 and 183 GHz

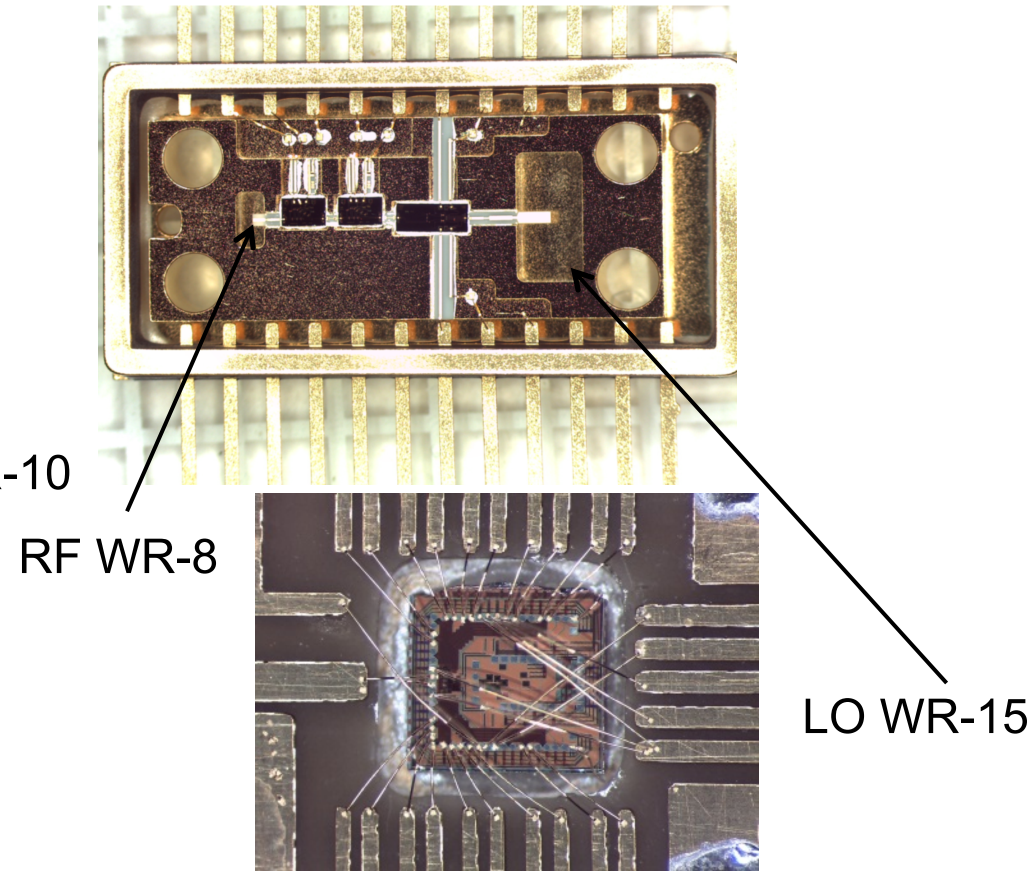


Technology previously developed for GeoSTAR and HAMMR

183 GHz Receiver Module



118 GHz Receiver Module



ASIC IF processor wire bonded to board

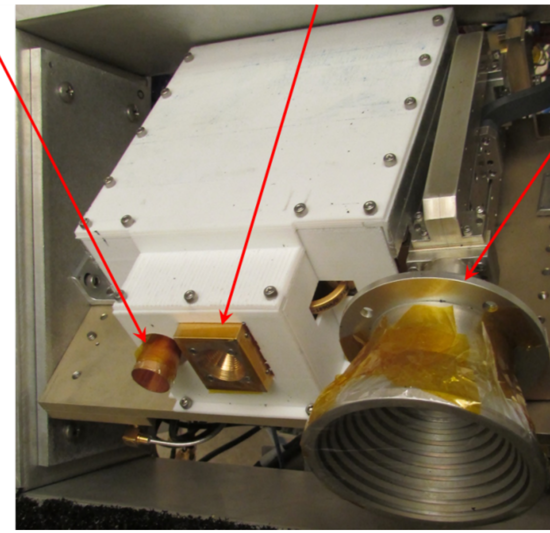
High-frequency Airborne Microwave and Millimeter-wave Radiometer

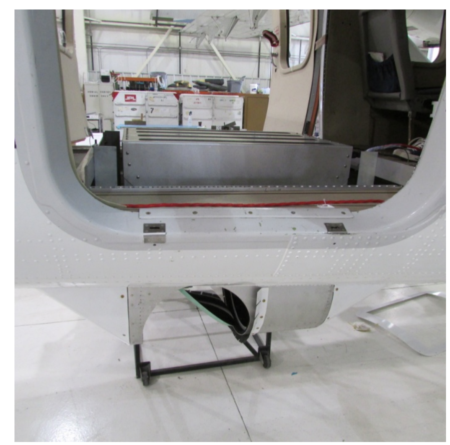
Temperature and humidity sounders were built for the HAMMR IIP-10 instrument, near 118 and 183 GHz, respectively.

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)



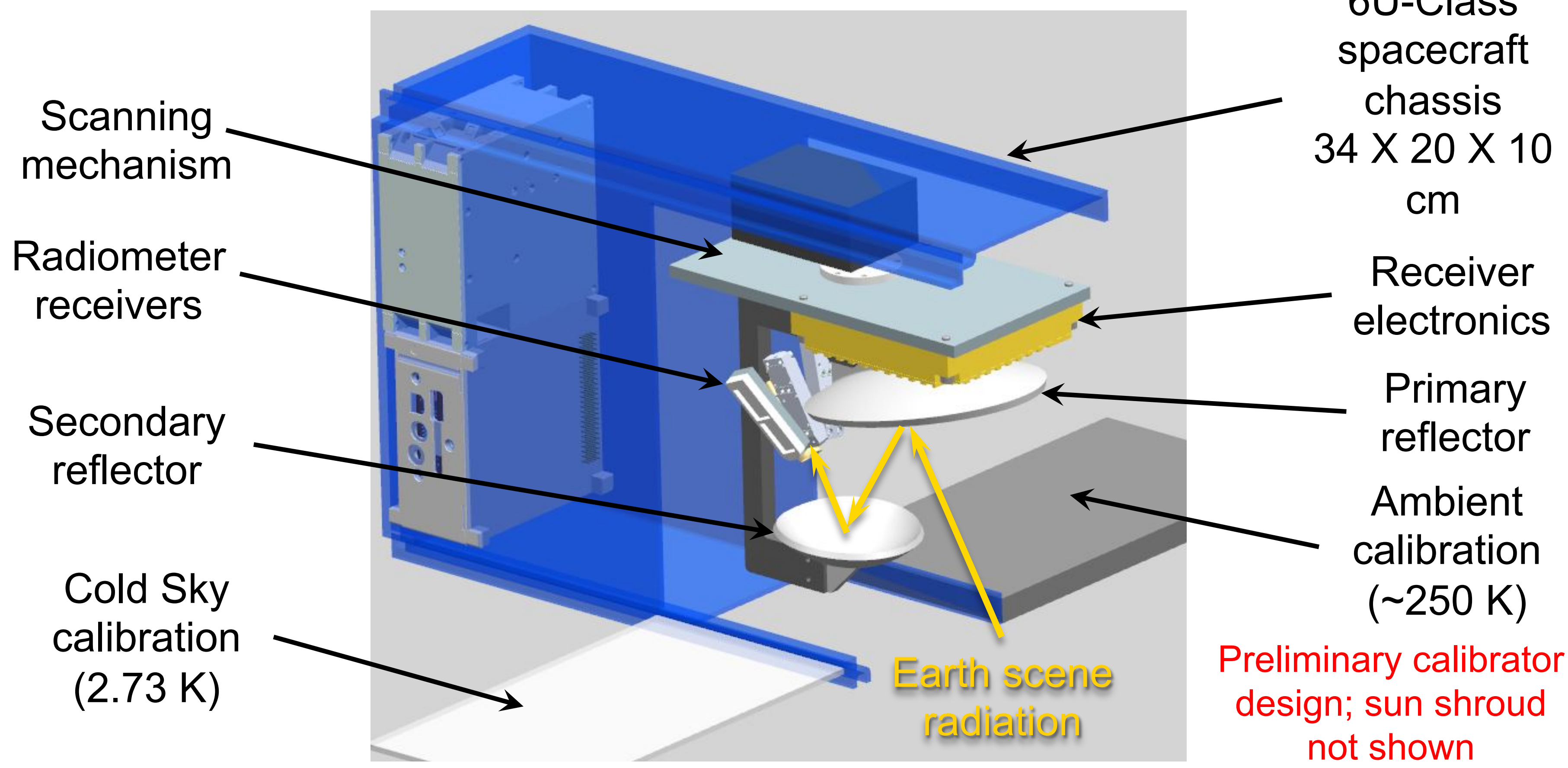


TWICE Measurement Frequencies

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	0.67
Mass (kg)	Proposed Spec.	0.6		0.5		0.3	0.5
	CBE	1.2		1.3		0.5	1.1

TWICE Instrument for 6U-Class Spacecraft

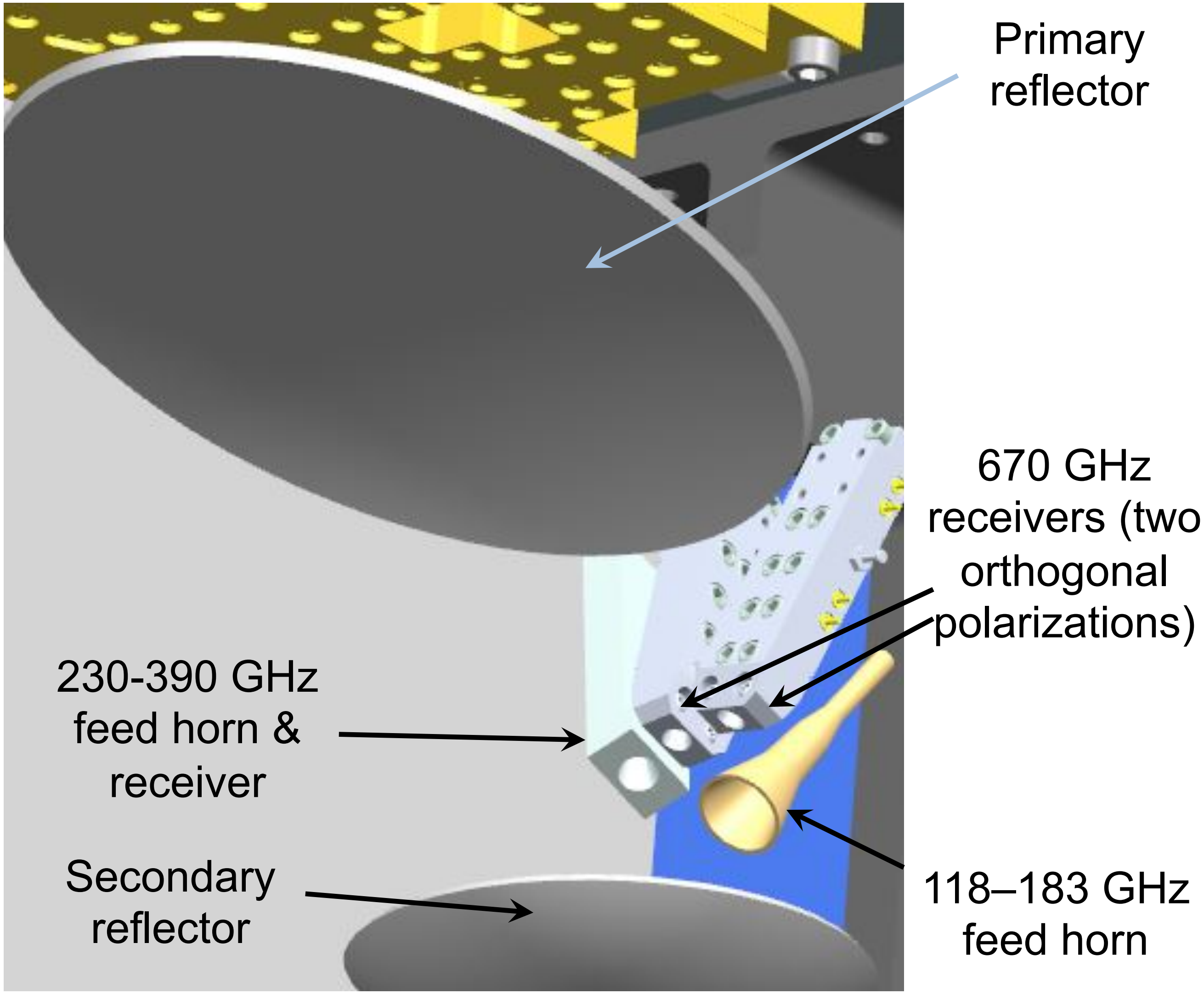
- Three frequency bands in one quasi-optical subsystem
- Conical scanning with 9.5-cm primary reflector
- Cold sky and ambient target calibration each scan (60 rpm)



Preliminary calibrator design; sun shroud not shown

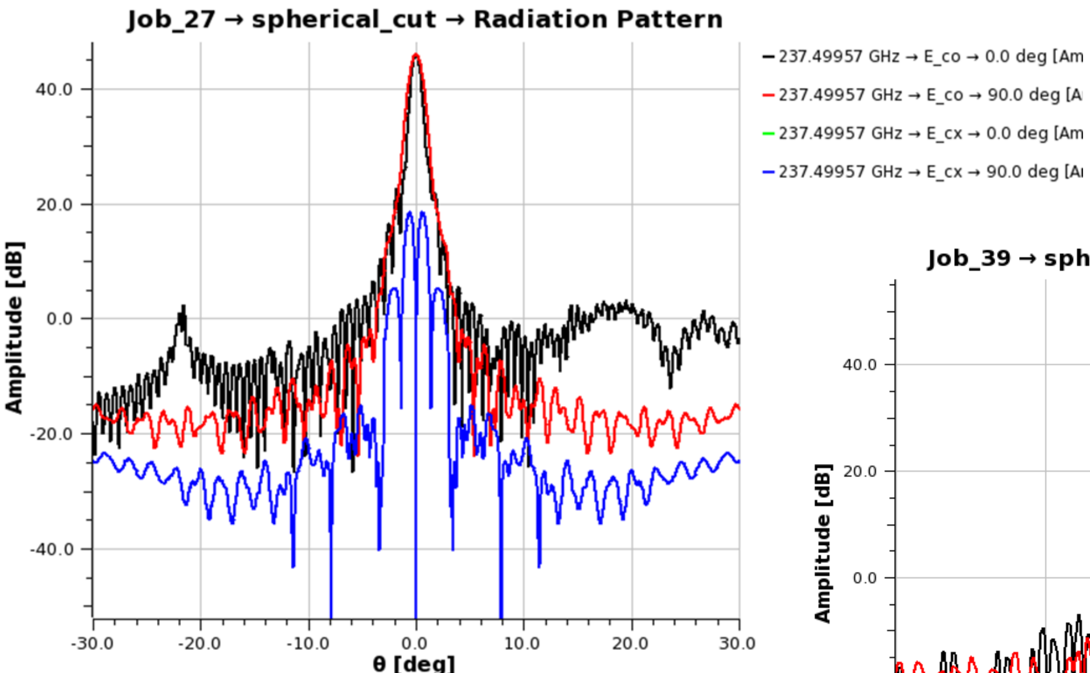
TWICE Instrument Optics

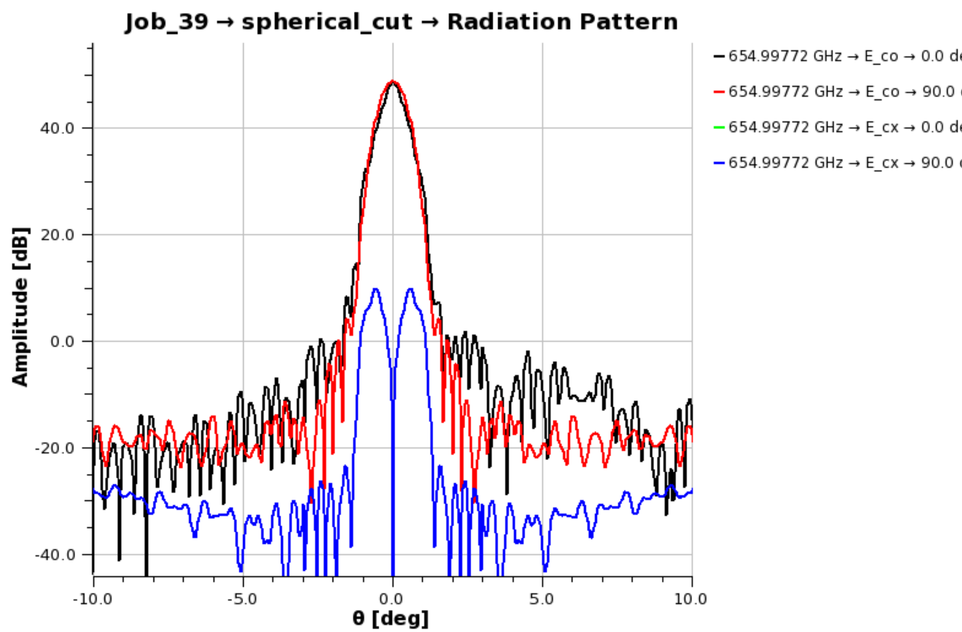
- Large focal plane enabled by oversized secondary reflector.
- 230–390 GHz and 670 GHz horns fabricated inside front-end modules to minimize waveguide loss
- 118–183 GHz horn outside of front-end to minimize blockage of other feed horns.
- Feed horns angled so that the tightest spacing is at the feed horn apertures, leaving space for receivers and wiring behind the feed horns.



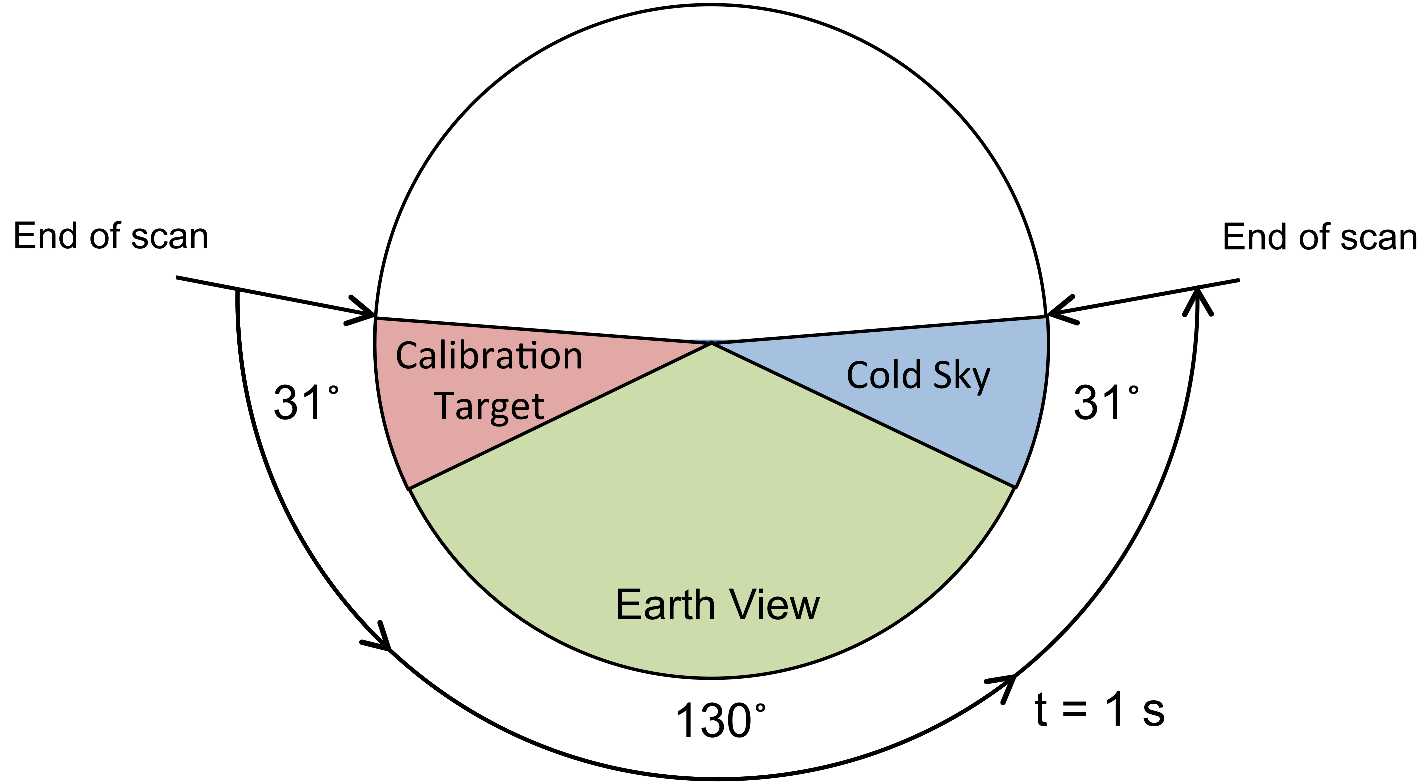
TWICE Feed Horn Patterns Simulated in Optical Subsystem

- 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 Scanning and Calibration Strategy

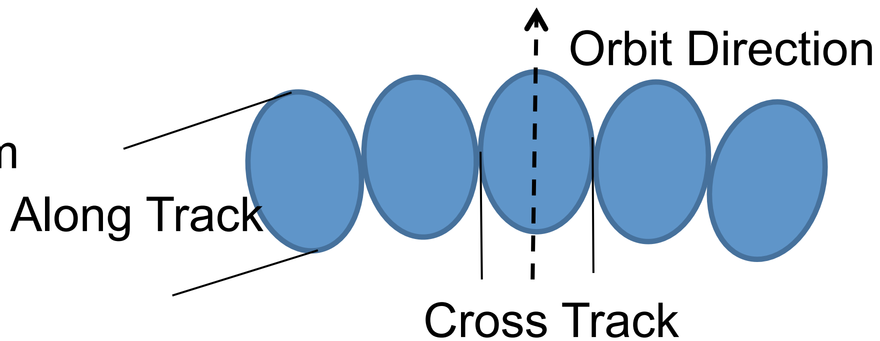


- Zero angular speed at each end of scan
- Total Time to scan 192˚ = $T_{acceleration} + T_{scene} + T_{deceleration}$ = 1 s
- Contiguous footprint sampling is desired

TWICE Surface Footprint Size for 400 km Orbit

Channel Center Frequency (GHz)	Antenna 3-dB Beamwidth (deg)	Cross-Track Footprint (km)	Along-Track Footprint (km)
118	1.56	16.0	24.2
183	1.17	11.9	18.1
240	0.77	7.8	11.8
310	0.64	6.5	9.9
380	0.56	5.8	8.7
670	0.62	6.3	9.6

- Swath width = 749 km
- Scan-to-scan along-track displacement at 30 RPM = 7.2 km



Sampling Time and Data Rate

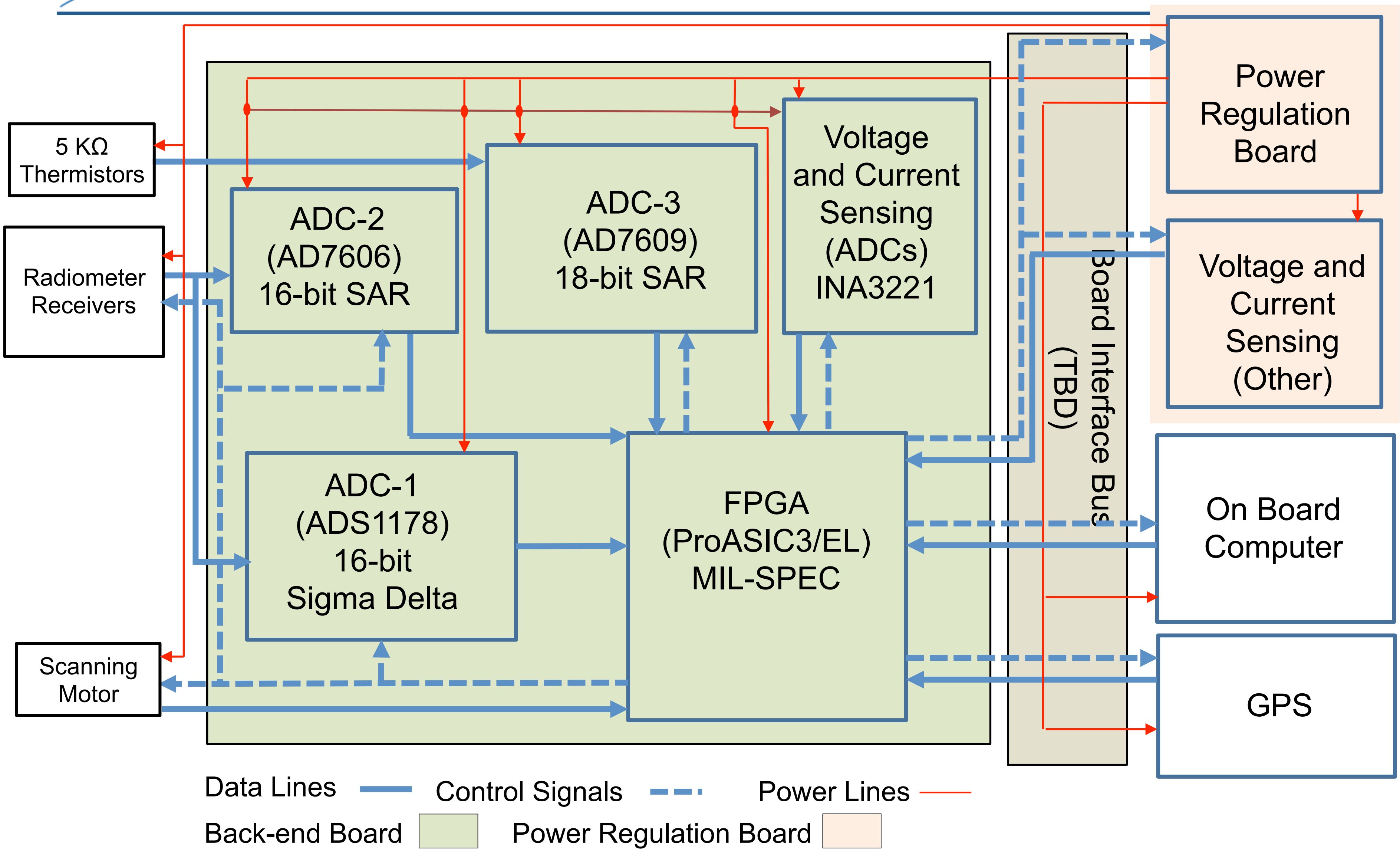
Channel Center Frequency (GHz)	Number of Channels	Number of Footprints per Scan	Sampling Time		Data Rate for each Frequency (kbps)
			Footprint Time (ms)	Sampling Time (ms)	
118	4	59	16.9	13.6	4.71
183	4	79	12.7	13.6	4.71
240	1	120	8.3	6.8	2.35
310	1	144	6.9	6.8	2.35
380	4	163	6.1	6.8	9.41
670	2	148	6.8	6.8	4.71

Total Data Rate = 28.2 kbps

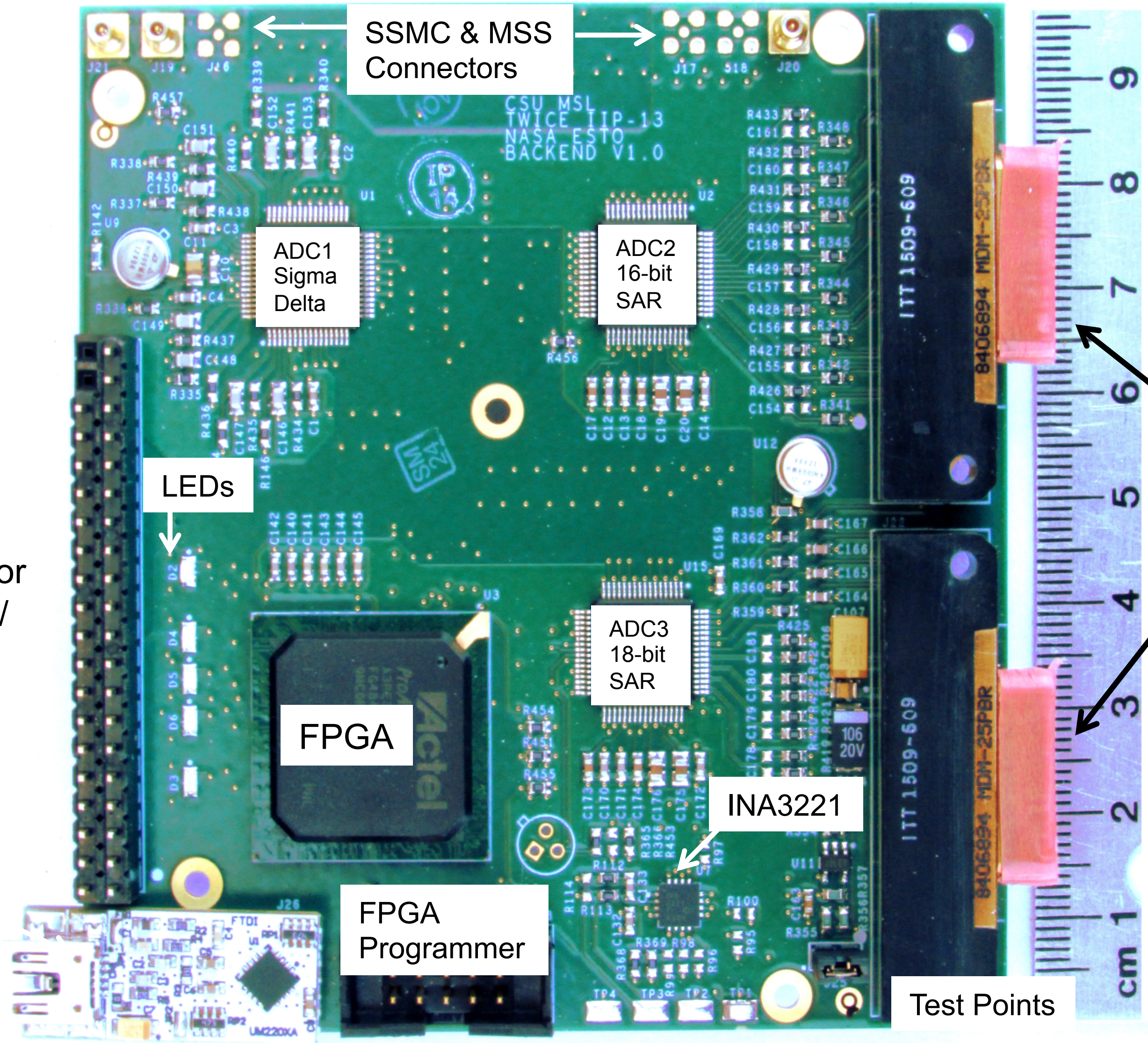
Note: 16 bits per sample for each channel

- Lossless data compression may be used to reduce the radiometer data rate to fit within the budget for satellite-to-ground communications.

TWICE Back-end Subsystem



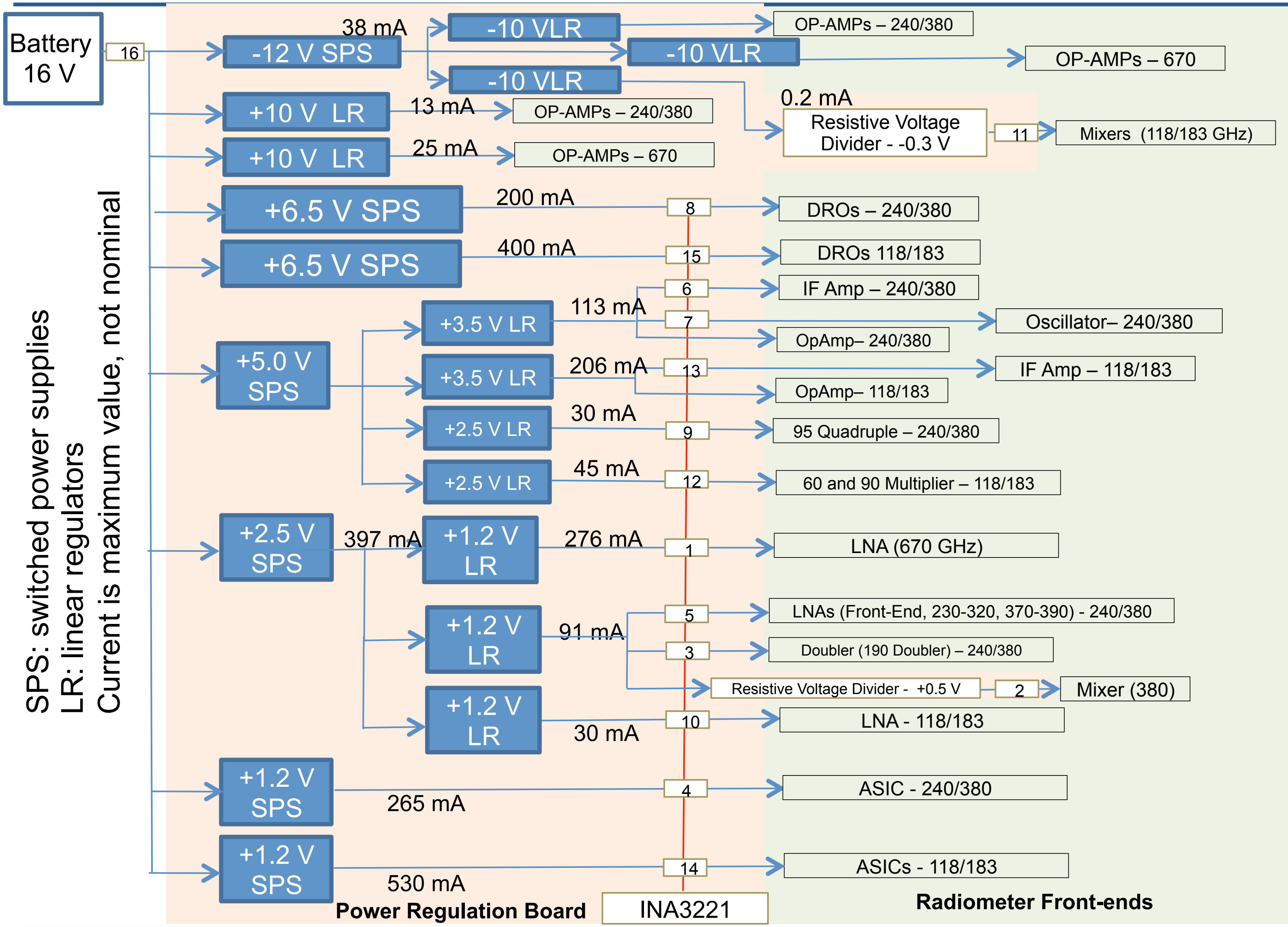
TWICE Back-end Board Prototype



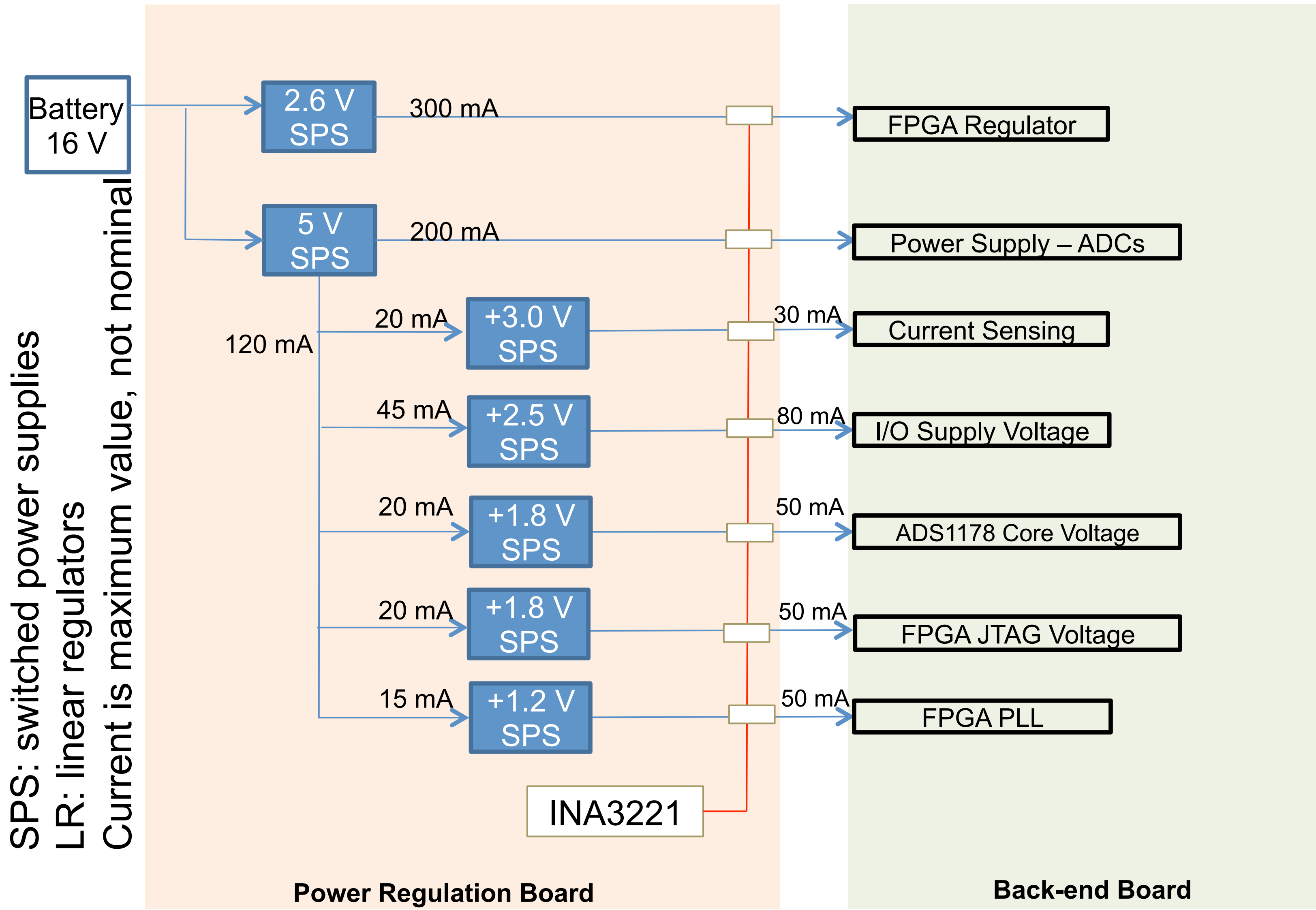
Power Regulation Board Design Constraints

Parameter	Specification
Power Efficiency	High to reduce power loss (~ 75%)
Dimensions	~ 9.5 x 9 cm
In Orbit of 350-450 km, 30° to 91° inclination	• Tolerant to thermal cycling • Resistant to single-event burnout (SEB)
Other Specifications	• Reliable • Low noise • Low output voltage swing • Provide the necessary voltages with required current ratings to all subsystems in TWICE • Include switches to turn on or off each radiometer channel • Monitoring current and voltage of selected regulators • Stackable with the already designed back-end board (PC-104)

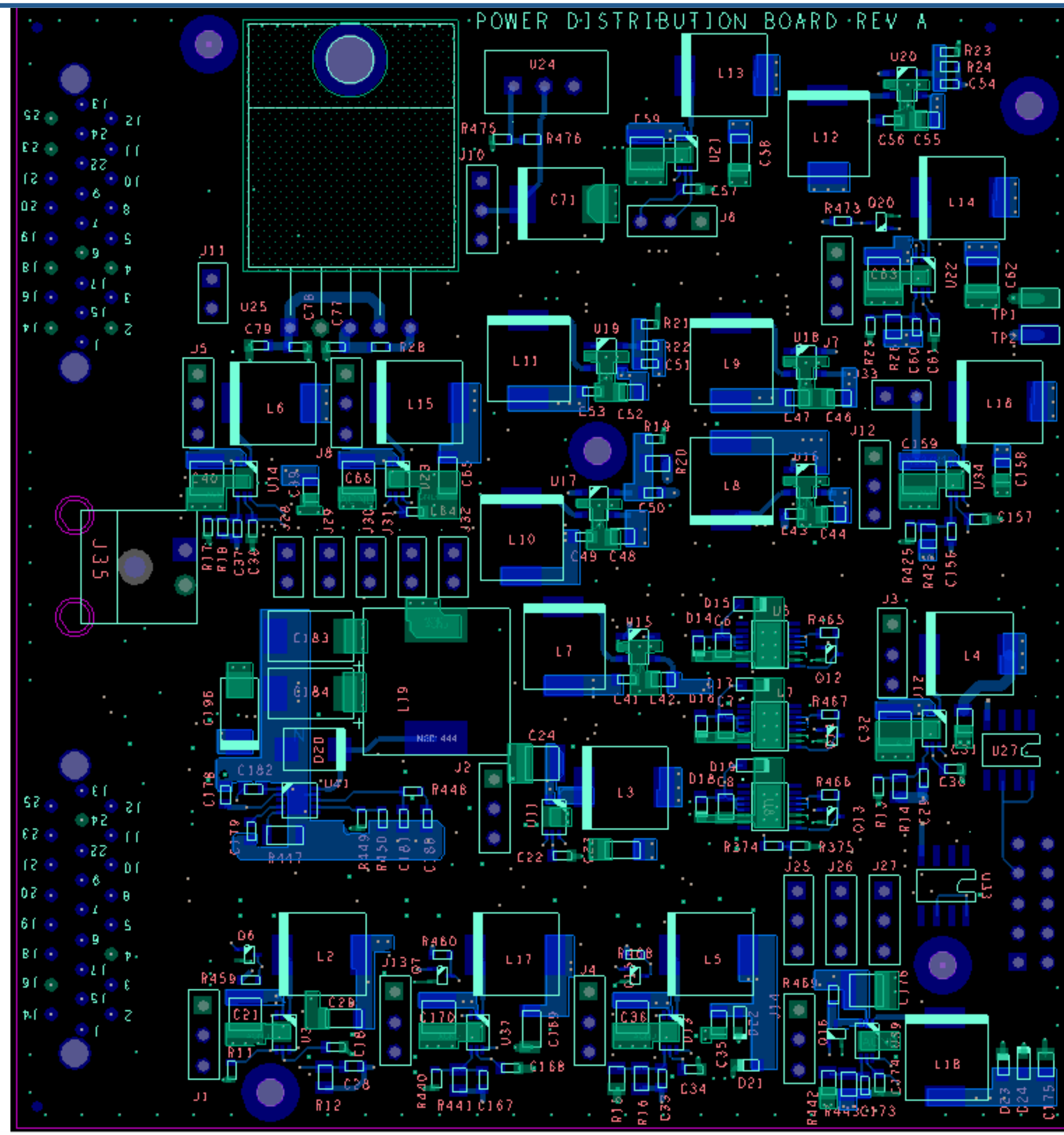
Front-end Power Regulation Diagram



Back-end Power Regulation Diagram



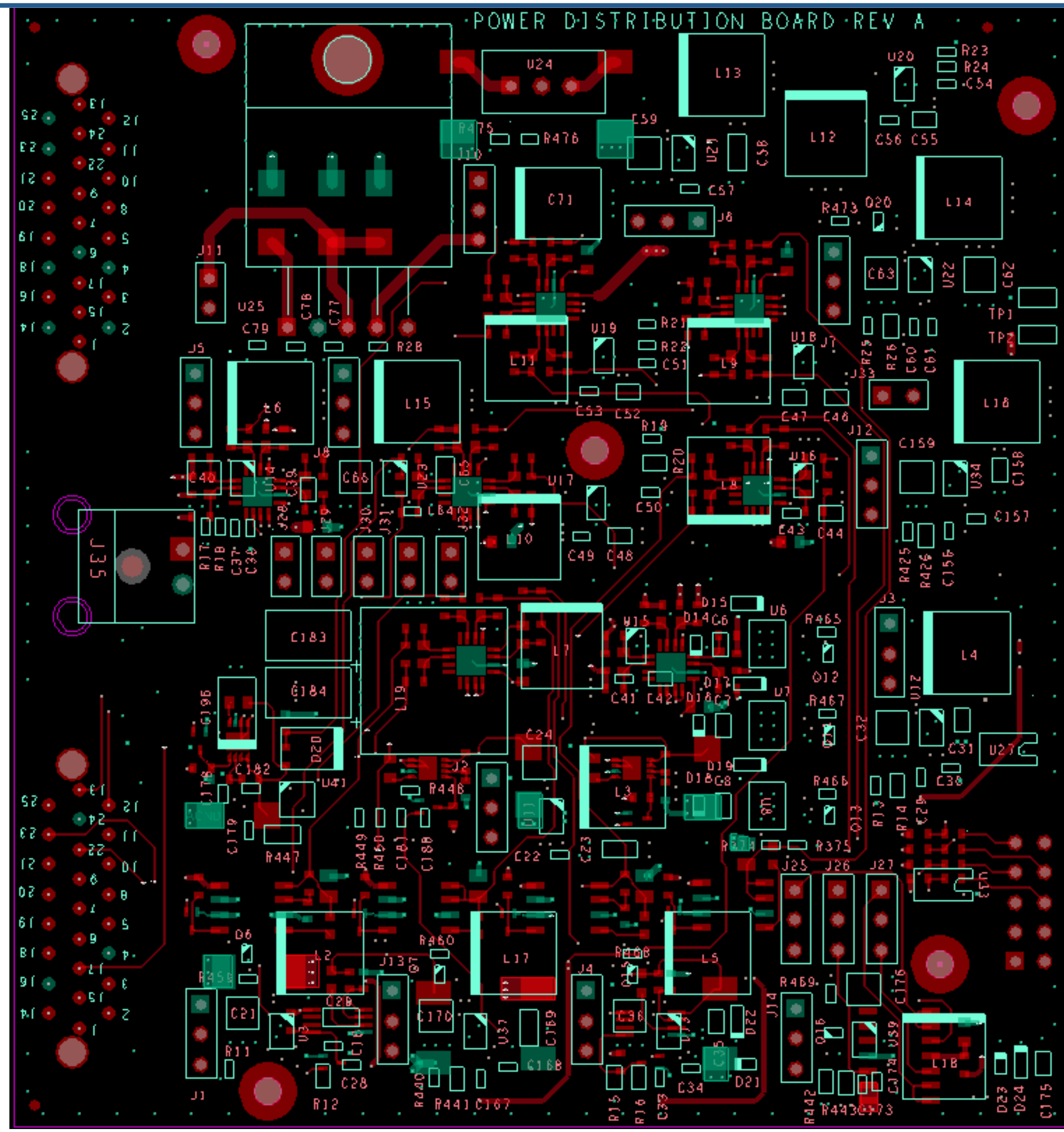
Power Regulation Board: Top Layer Layout (of 8)



- All switching regulators and most linear regulators as well as Micro-D and power connectors are on this layer.

Power Regulation Board: Bottom Layer Layout (of 8)

- Current Sensing Devices
- Some linear regulators (all negative linear regulators)
- PC-104 connector
- Back-end – Power Regulation Board communication signals.



Back-end Design Status

- Fabricated, populated and successfully tested TWICE back-end boards (4 each) for complete electrical functionality.
- Successfully tested VHDL design for on-board FPGA, including communication with external laptop.
- Demonstrated simultaneous data acquisition from all 3 ADCs and current sensing device demonstrated, with standard deviation of noise from each ADC of less than one count.
- Performed single-event latchup (SEL) tests at Texas A&M University (TAMU) Radiation Effects Facility, with CSU postdoc and Ph.D. student, and two JPL experts on radiation testing attending.
- 16-bit sigma-delta ADC (ADC1178) on evaluation boards were tested at room temp. using a Silver (Ag) ion beam with linear energy transfer (LET) level of 42.2 MeV-cm^2/mg at low flux levels of 10^2-10^3 ions/(cm^{2}s)
- Destructive SEL events were observed on two ADS1178 ADCs.
- Planning is underway to test SAR ADCs at TAMU's facility.

TWICE Instrument Mass and Power Summary by Subsystem

Subsystem	Mass (kg)	Power (W)
118-183 GHz Sounder	1.16	4.53
380 GHz Sounder	0.54	2.31
240 GHz & 310 GHz Radiometers	1.27	0.35
670 GHz Radiometers (H&V)	1.10	0.67
Back-end Board	0.13	0.73
Power Regulation Board	0.13	3.91
Quasi-optics	1.74	-
Calibration Target/Reflector	0.71	-
Scanning Motor	0.33	0.50
Totals	7.3	13.0

Summary

- The Tropospheric Water and Cloud ICE (TWICE) instrument is under development to enable global measurements of upper-tropospheric/lower stratospheric (ULTS) cloud ice and water vapor at a variety of local times.
- Such global measurements are expected to improve currently limited understanding of UTLS processes in general circulation models (GCMs), 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 water vapor profiling in the troposphere and UTLS.
- Conical scanning will preserve the polarization basis and enable external calibration at all 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.