Microwave Radiometer calibration with GPS radio occultation for the MiRaTA CubeSat mission

K. Cahoy, MIT AeroAstro
W. Blackwell, MIT Lincoln Laboratory
A. Marinan, MIT AeroAstro
N. Erickson, UMass-Amherst
R. Bishop, The Aerospace Corporation
T. Neilsen, Space Dynamics Laboratory
B. Dingwall, NASA Wallops Flight Facility

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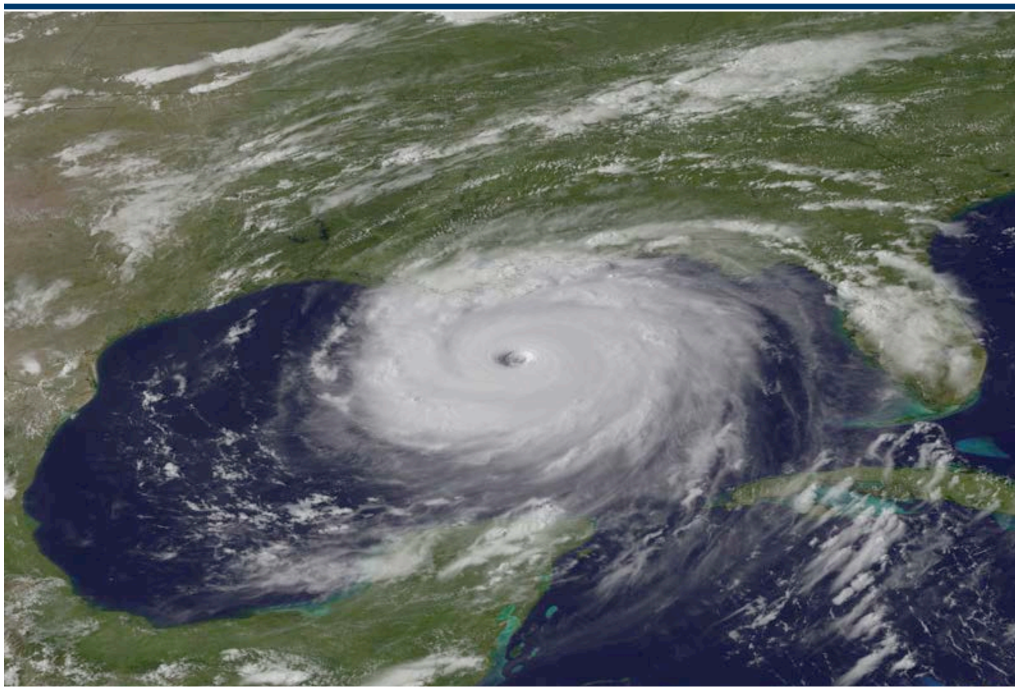
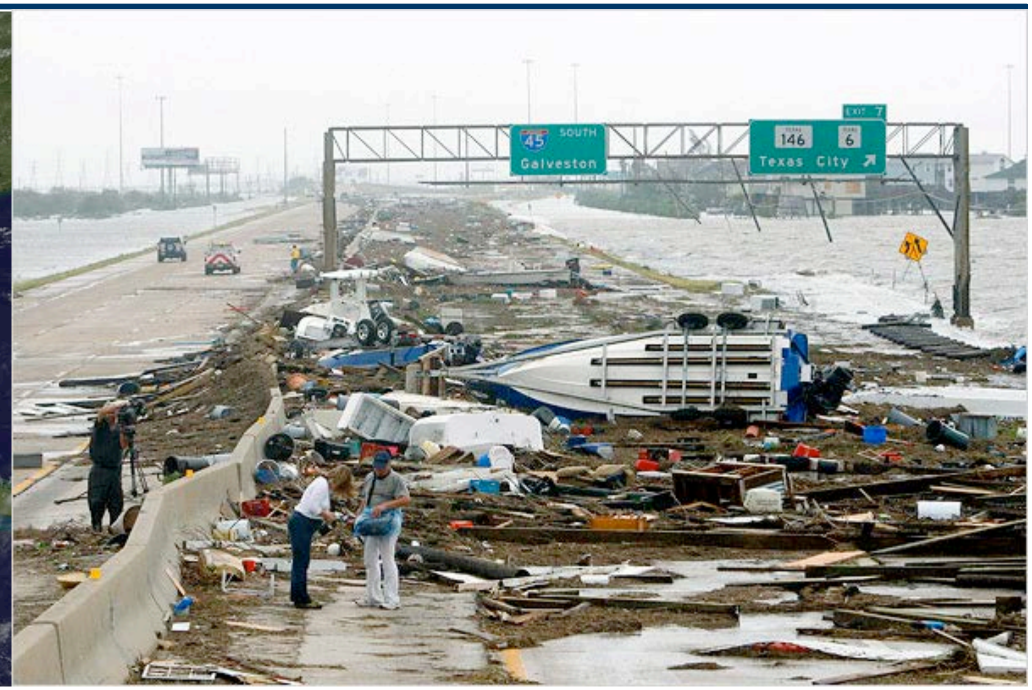
Our Ability to Predict the Weather Has Profound Societal and Economic Implications

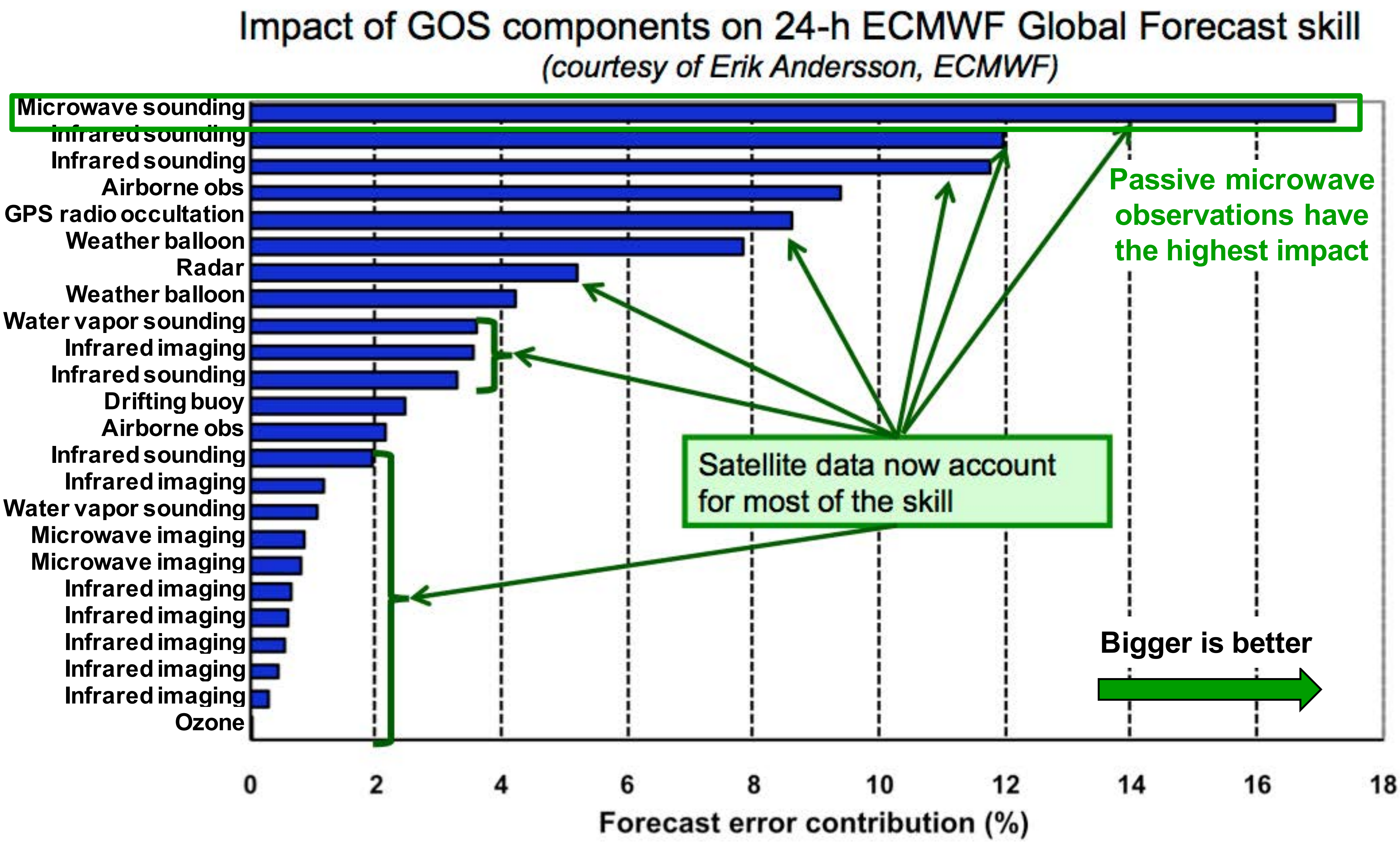




- **The US derives $32 B of value from weather forecasts annually[1]**
- **Earth observing satellites drive the forecasts**
- **Eternal quest for resolution: Spatial (vertical and horizontal), temporal, and radiometric**

[1]University Center for Atmospheric Research

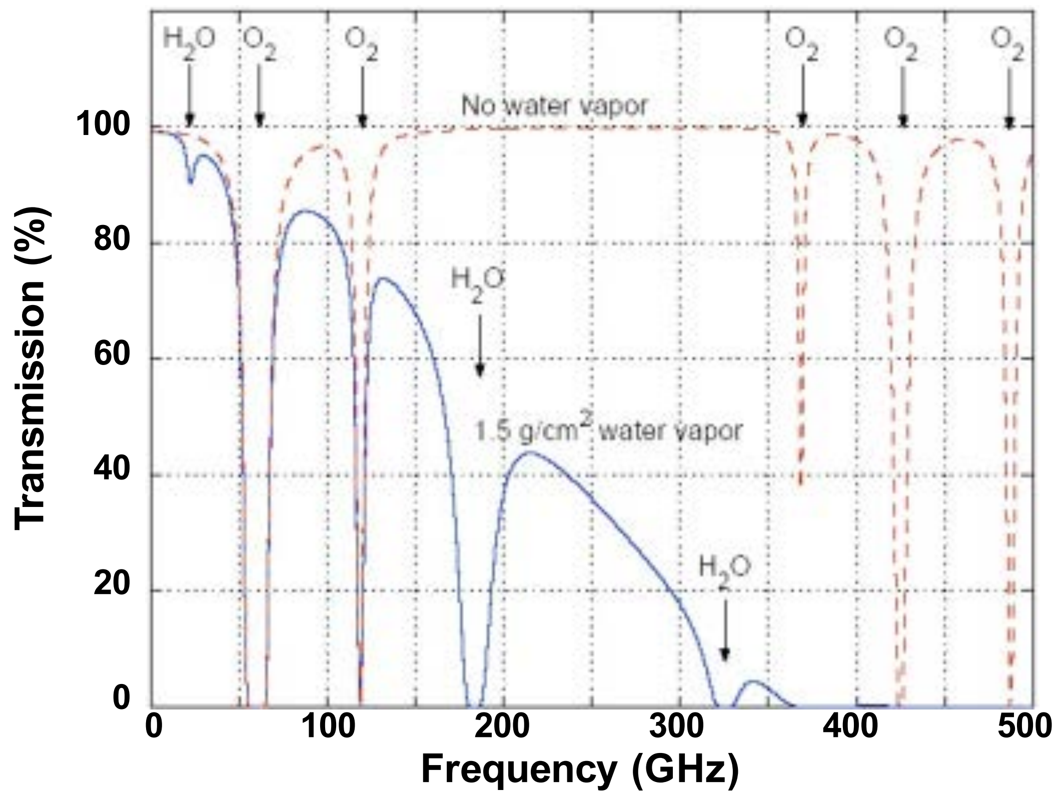
Satellites Provide the Most Forecast Skill



Microwave Atmospheric Sensing

Wavelength (meters)	Radio	Microwave	Infrared	Visible	Ultraviolet	X-ray	Gamma Ray
	10^3	10^{-2}	10^{-5}	$.5 \times 10^{-6}$	10^{-8}	10^{-10}	10^{-12}

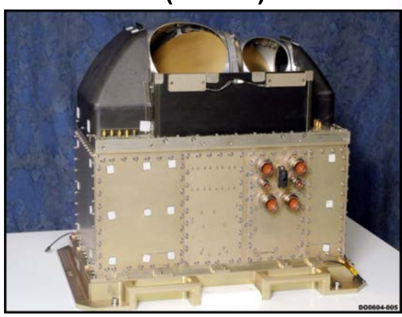
Cloud Penetration; Highest Forecast Impact



The frequency dependence of atmospheric absorption allows different altitudes to be sensed by spacing channels along absorption lines

New Approach for Microwave Sounding

Advanced Technology Microwave Sounder (ATMS)



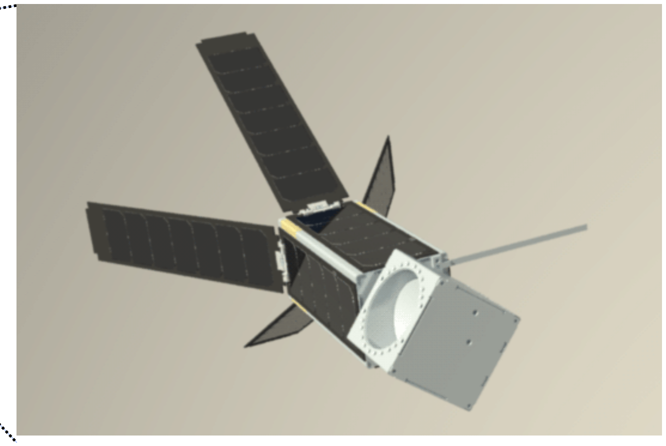
100 kg, 100 W

Suomi NPP Satellite (Launched Oct. 2011)

2100 kg NASA/GSFC

NPP: National Polar-orbiting Partnership

MicroMAS Satellite



4.2 kg, 10W, 34 x 10 x 10 cm

- Microwave sensor amenable to miniaturization (10 cm aperture)
- Broad footprints (~50 km)
- Modest pointing requirements
- Relatively low data rate

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Enabling the Next Generation: MicroMAS-1, MicroMAS-2, and MiRaTA

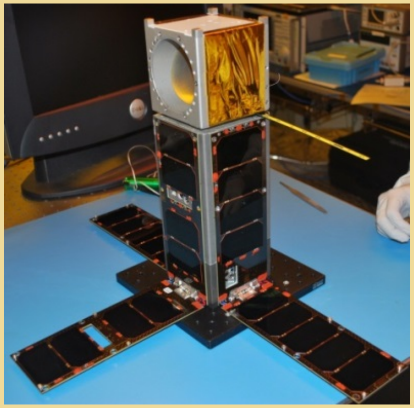
MicroMAS = Microsized Microwave Atmospheric Satellite
MiRaTA = Microwave Radiometer Technology Acceleration

MicroMAS-1

3U cubesat with 118-GHz radiometer

8 channels for temperature measurements

July 2014 launch, March 2015 release; validation of spacecraft systems; eventual transmitter failure

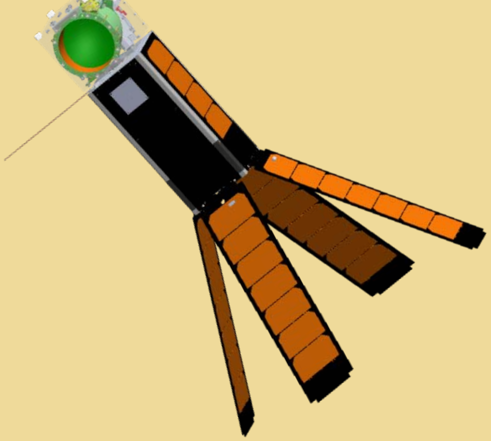


MicroMAS-2

3U cubesat scanning radiometer with channels near 90, 118, 183, and 206 GHz

12 channels for moisture and temperature profiling and precipitation imaging

Two launches in 2017

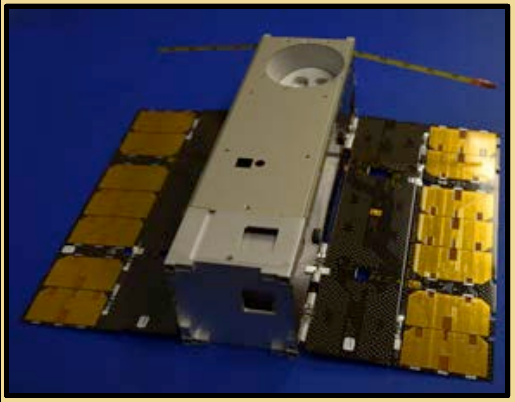


MiRaTA

3U cubesat with 60, 183, and 206 GHz radiometers and GPS radio occultation

10 channels for temperature, moisture, and cloud ice measurements

Early 2017 launch on JPSS-1



Next Generation: Constellations

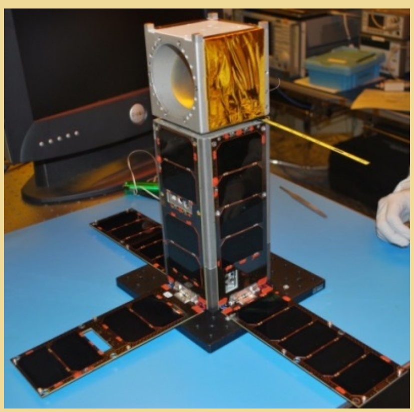
MicroMAS = Microsized Microwave Atmospheric Satellite
MiRaTA = Microwave Radiometer Technology Acceleration
Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS)

MicroMAS-1

3U cubesat with 118-GHz radiometer

8 channels for temperature measurements

July 2014 launch, March 2015 release; validation of spacecraft systems; eventual transmitter failure



MicroMAS-2

3U cubesat scanning radiometer with channels near 90, 118, 183, and 206 GHz

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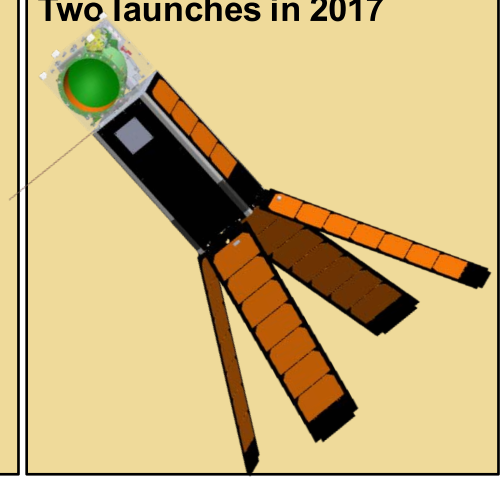

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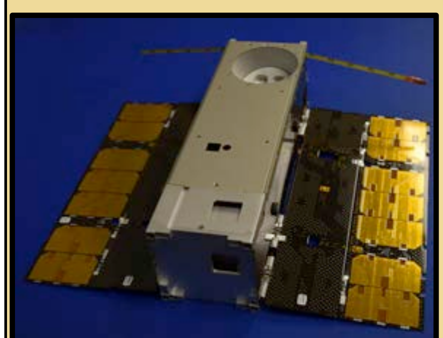


TROPICS

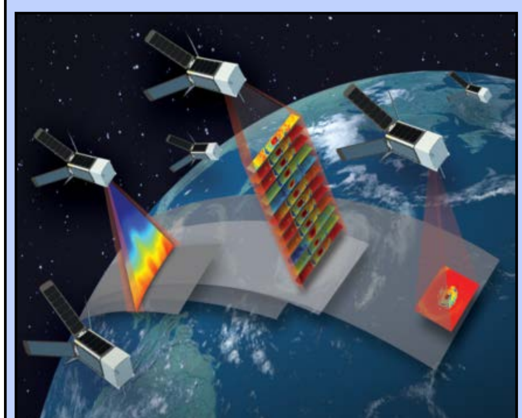
Selected for EVI-3

12 CubeSats (3U) in three orbital planes (600km/30°)

Temperature and moisture profiling and cloud ice measurements

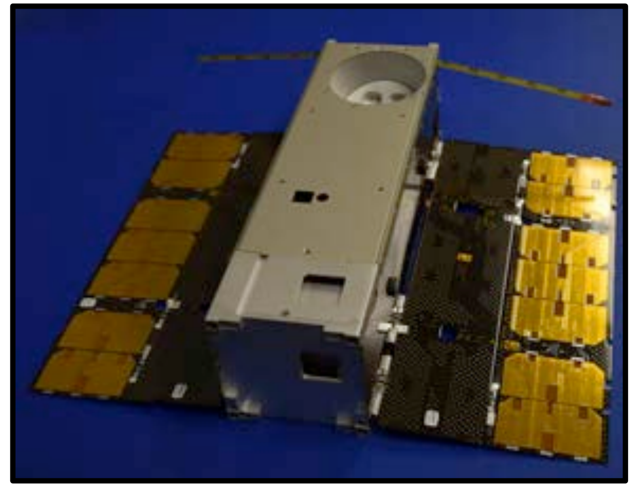
30-minute revisit

2019/2020 launch



Microwave Radiometer Technology Acceleration (MiRaTA)

- 3U (10 cm x 10 cm x 34 cm) tri-band radiometer
  - Temperature, water vapor, and cloud ice
  - ~60 GHz (temperature)
  - ~183 GHz (humidity)
  - ~207 GHz (cloud ice)
  - Absolute calibration better than 1 K
- Calibration proof of concept using limb measurements and GPS-RO
  - 60, 183, and 206 GHz; OEM628 GPS
- Funded by NASA Earth Science Technology Office (ESTO) InVEST program
- ~30-month build
- Launch in early 2017 (JPSS-1)
  - Permits direct comparisons with ATMS

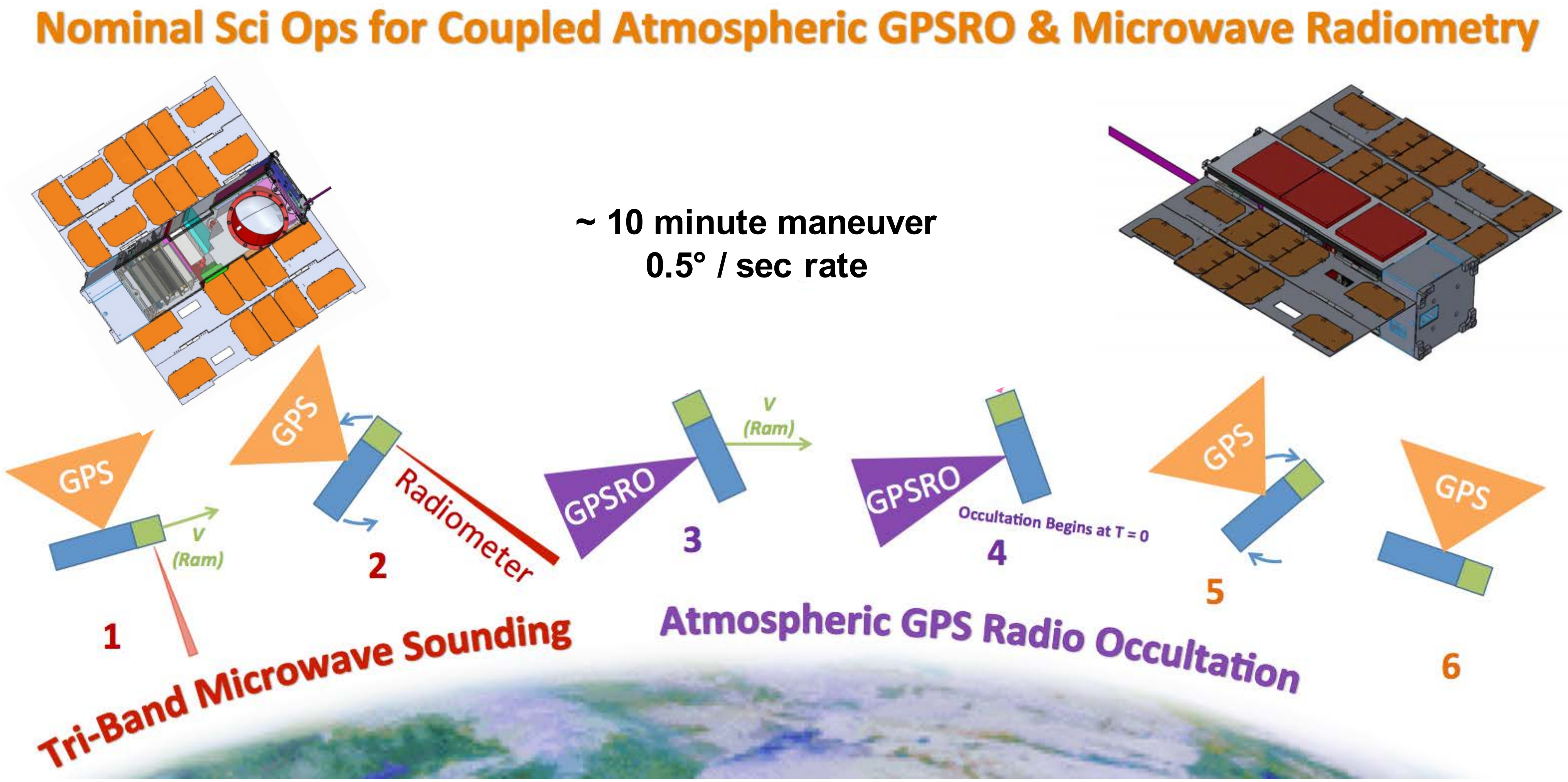


- 4.5 kg total mass
- 10 W avg power
- 10 kbps max data rate
- 0.5° pointing accuracy

TRL Advancement Criteria (TRL 5 to 7)

- **(1) IF spectrometer**
  - Verify that the V-band radiometric accuracy is within 1.5 K of the truth predictions
  - V-band end-to-end receiver temperature sufficient to yield 0.1K NEdT.
  - *Blackwell ACT10 "Hyperspectral Microwave Receiver" IFP module leveraged here*
- **(2) G-band mixer**
  - 2.0 K radiometric accuracy against ground truth predictions
  - End-to-end receiver temperature sufficient to yield 0.25 K NEdT.
  - *Blackwell ACT10 "Hyperspectral Microwave Receiver" mixer module leveraged here*
- **(3) GPS-RO receiver**
  - Evaluate GPS-RO temperature retrievals are within 1.5 K of the truth predictions
    - Truth measurements consist of combination of radiosondes and NWP measurements coupled with radiative transfer model
    - Direct radiance comparisons with operational passive microwave sounders will also be utilized for verification

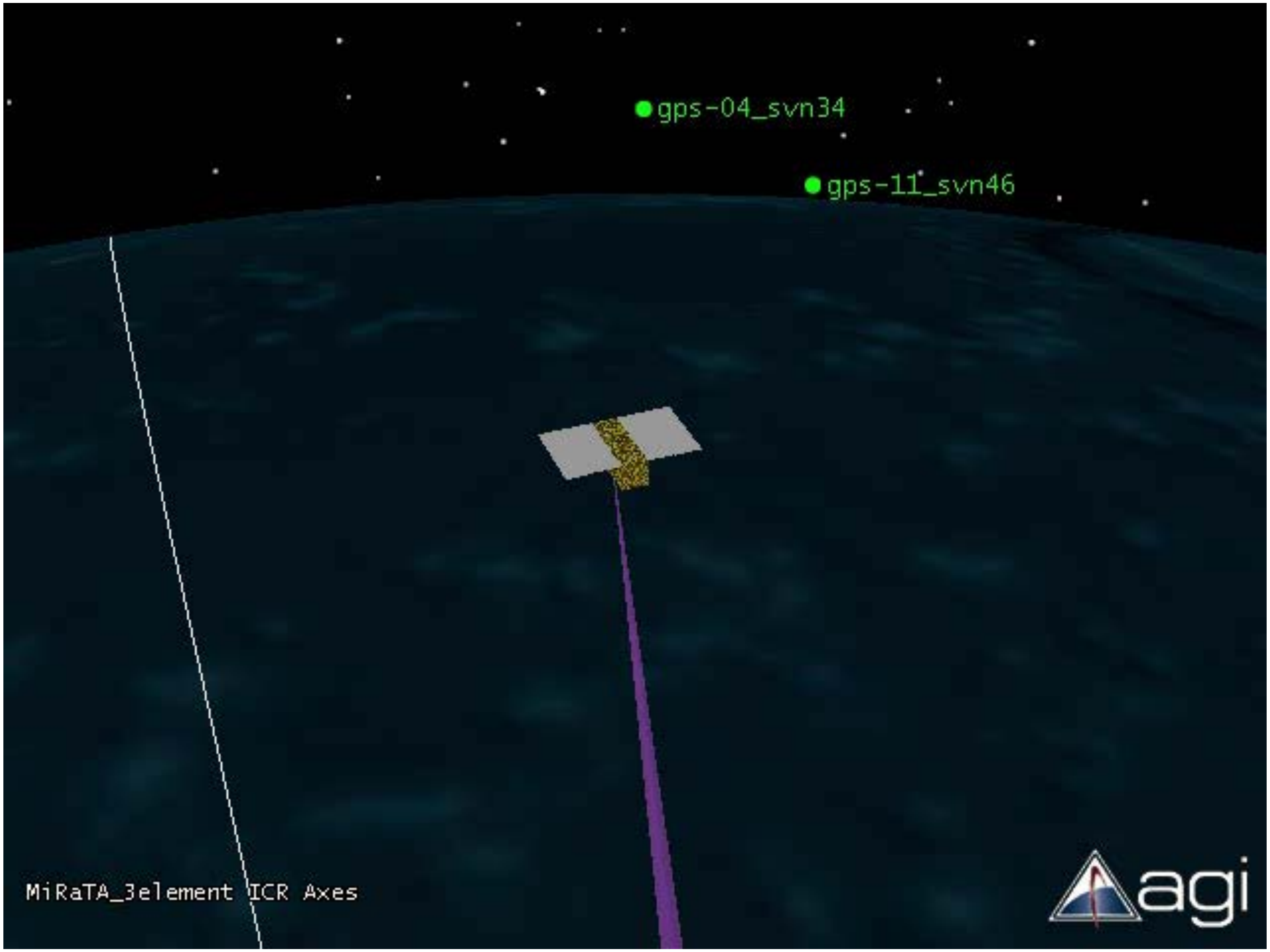
MiRaTA Calibration Maneuver



MiRaTA Pitch-Up Maneuver

Objective:

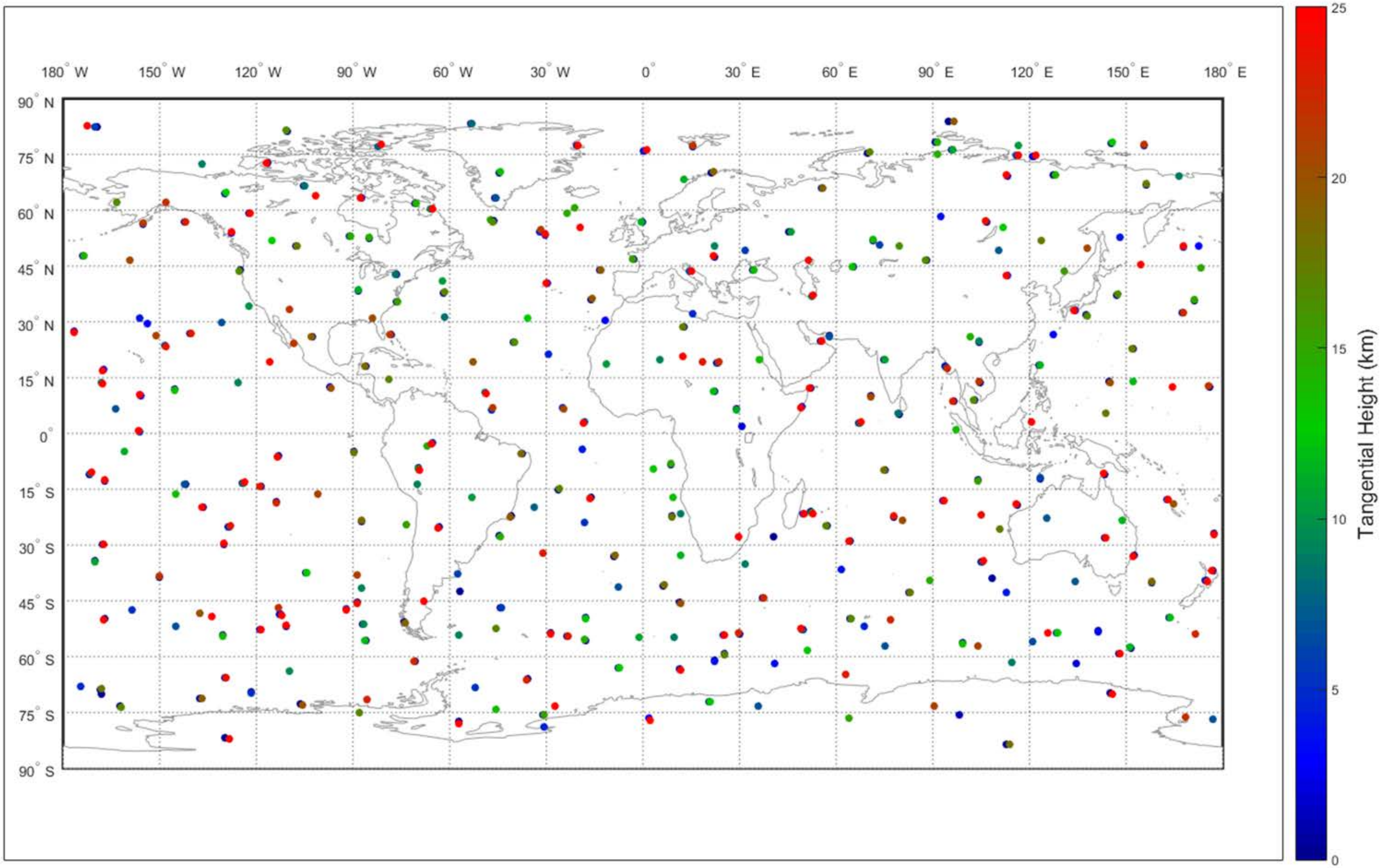
Collocate radiometric data and GPS RO temperature profile



Credit:

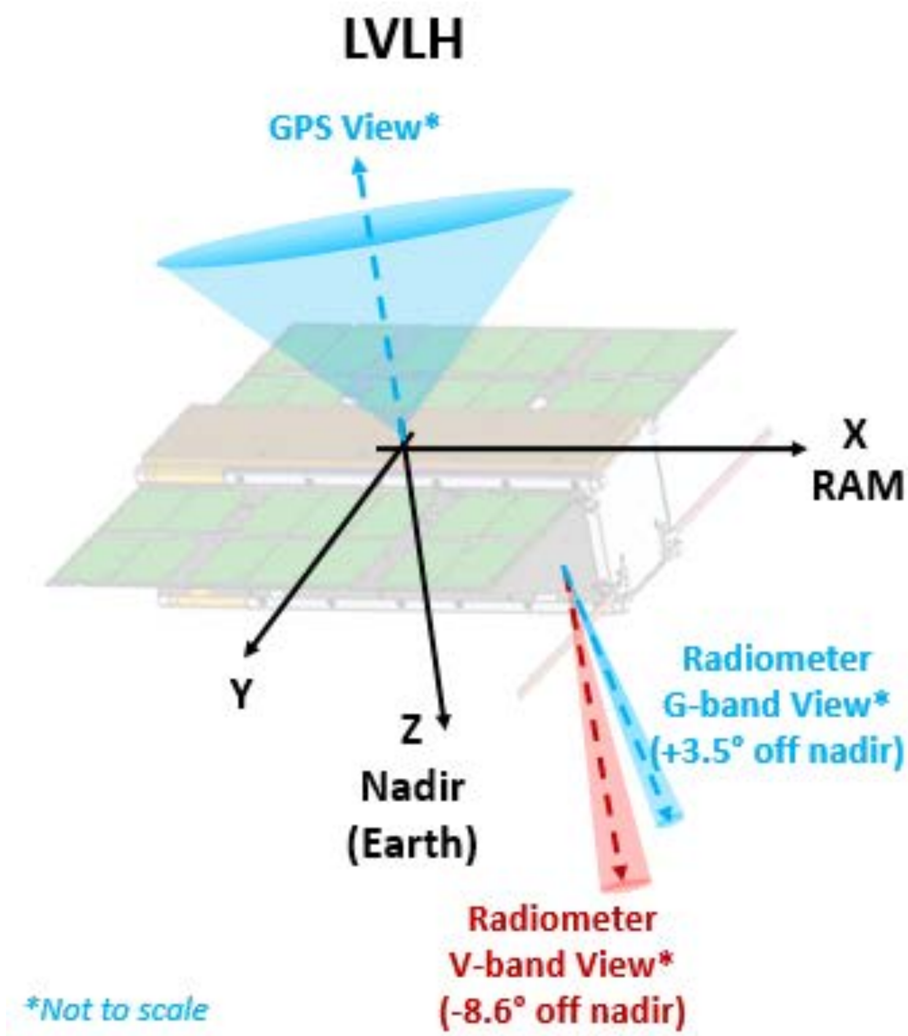
Annie Marinan (MIT SSL) & Weston Marlow (G95 & SSL)

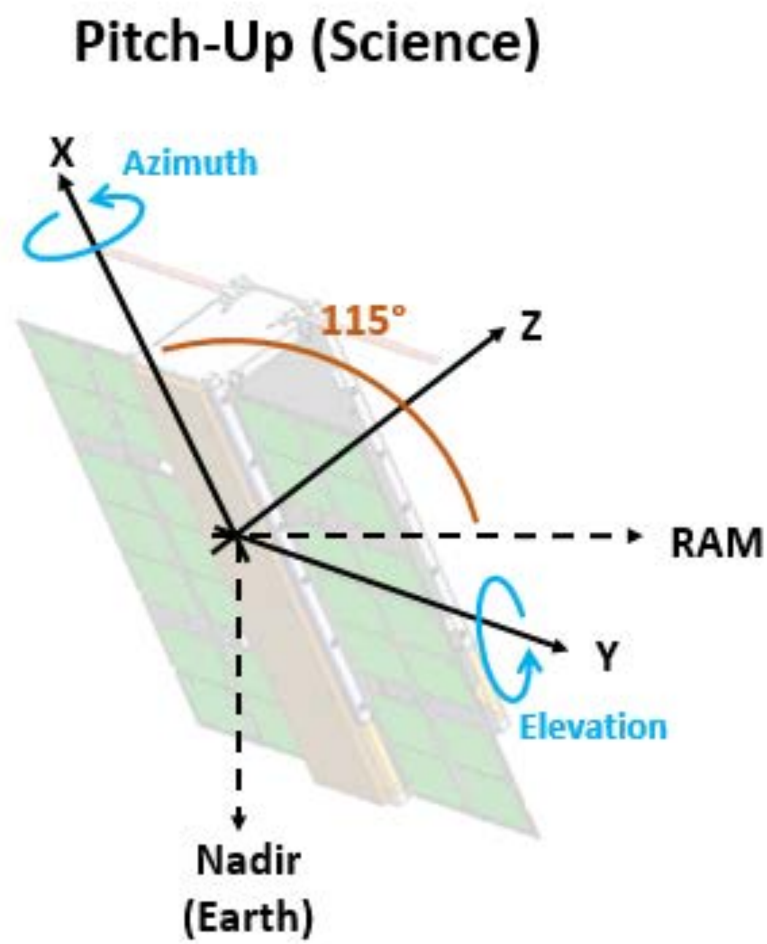
GPS-RO Opportunities for One Day



Setting GPS satellite, < 25 km tangent height

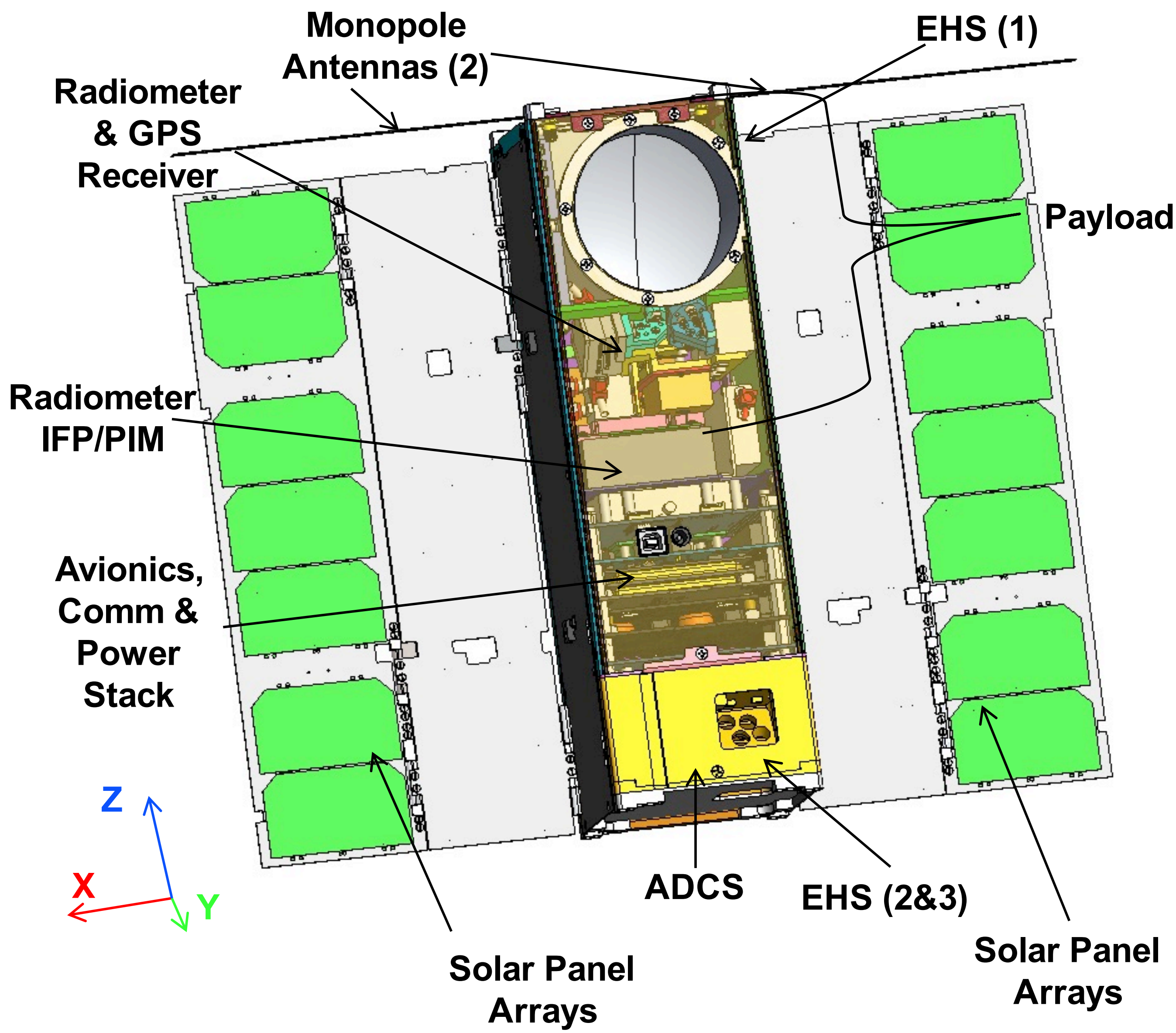
MiRaTA Sensor Viewing Geometries



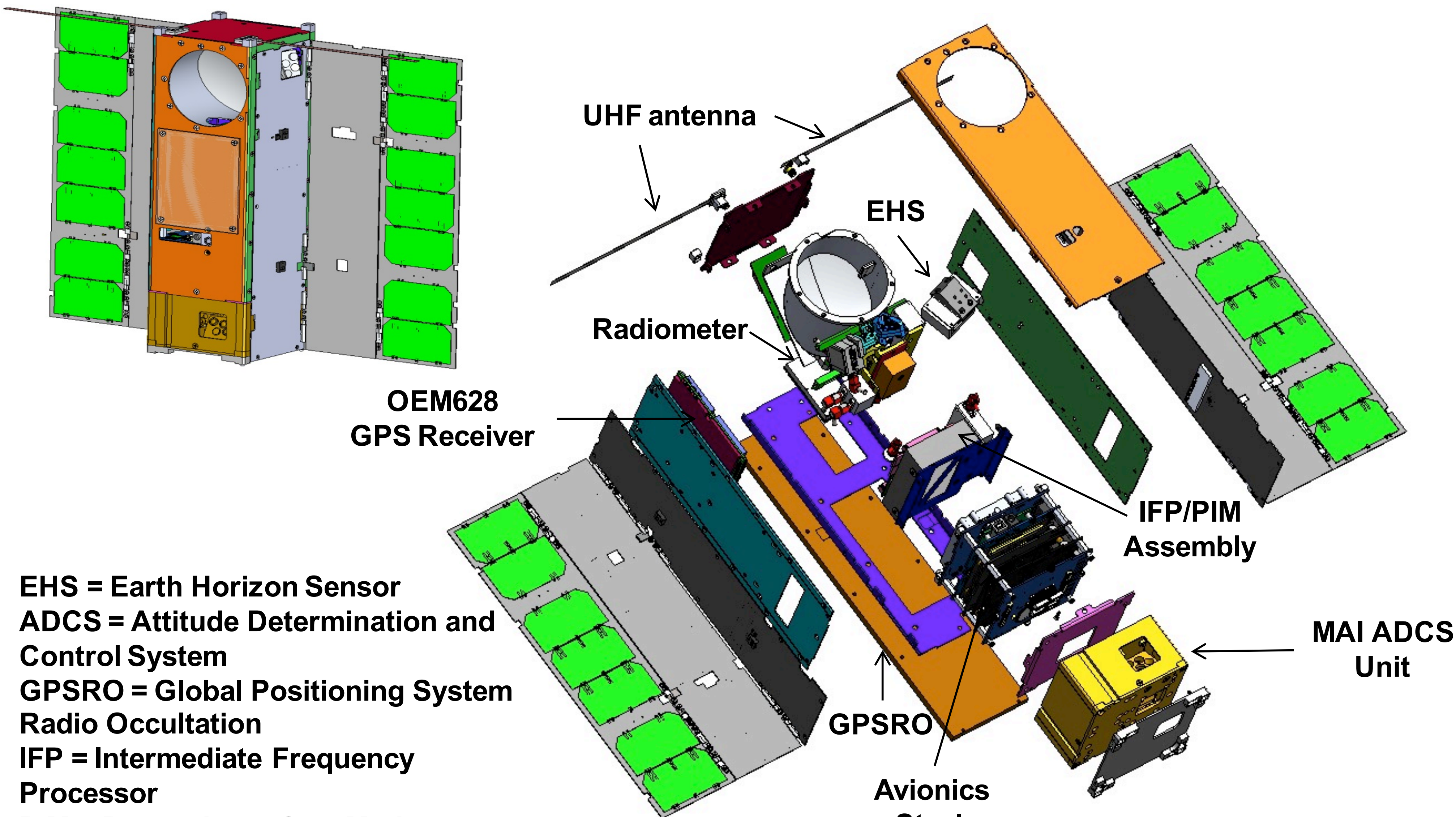


MiRaTA Spacecraft Overview

- **Payload**
  - Microwave Radiometer
  - GPS Radio Occultation receiver and Patch Antenna array (GPSRO or CTAGS)
- **Bus**
  - Cadet UHF Radio with Monopole UHF Antenna
  - Avionics Stack
    - With low data-rate UHF radio and antenna
  - Attitude Determination and Control System
  - Power system, batteries

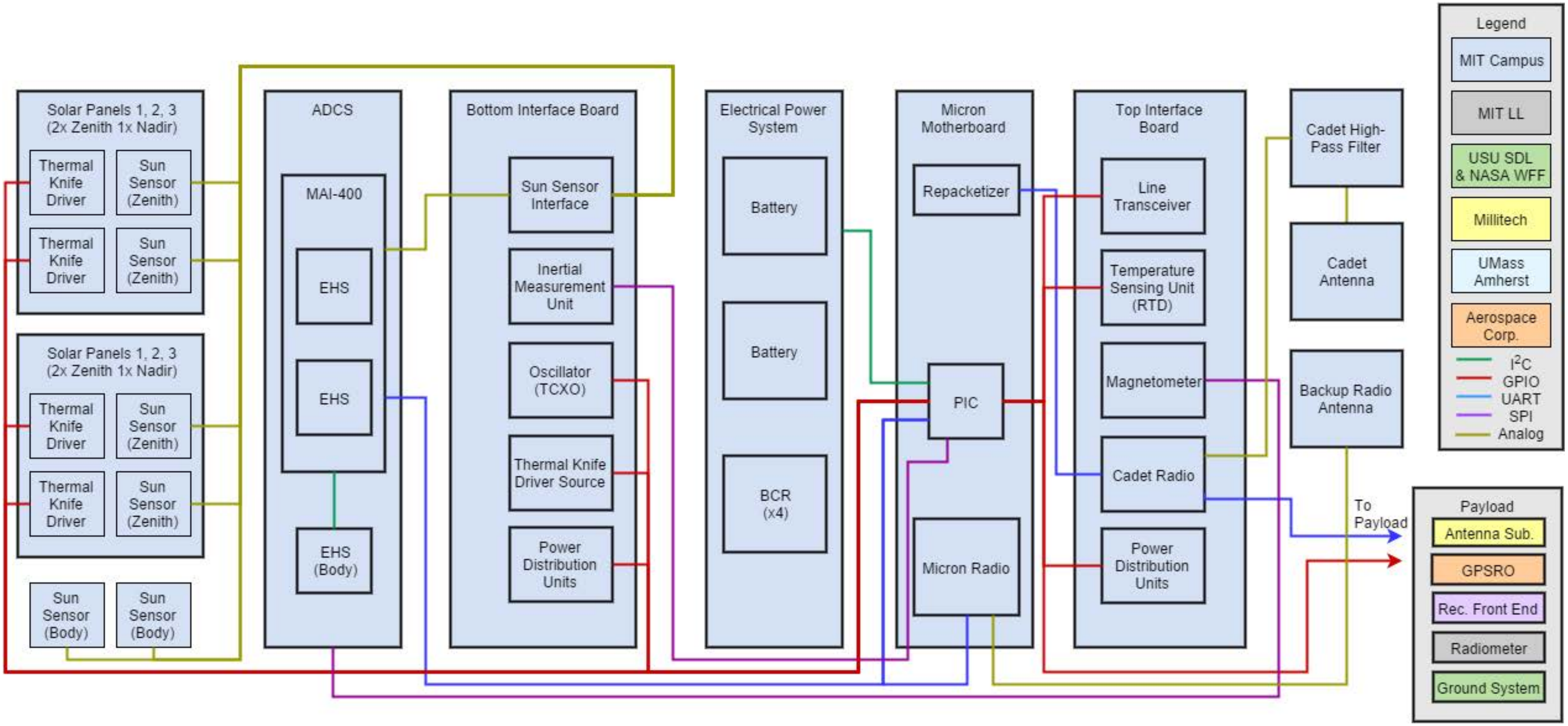


MiRaTA Space Vehicle Overview

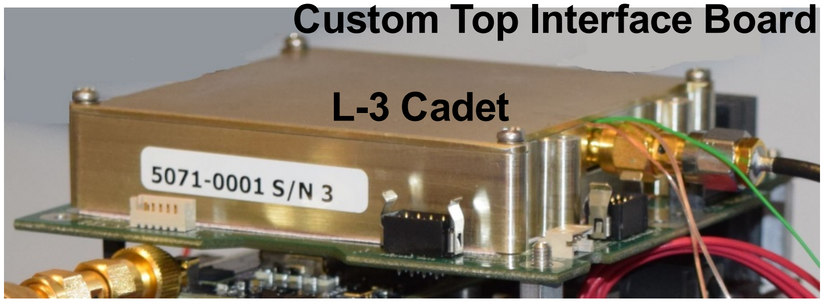


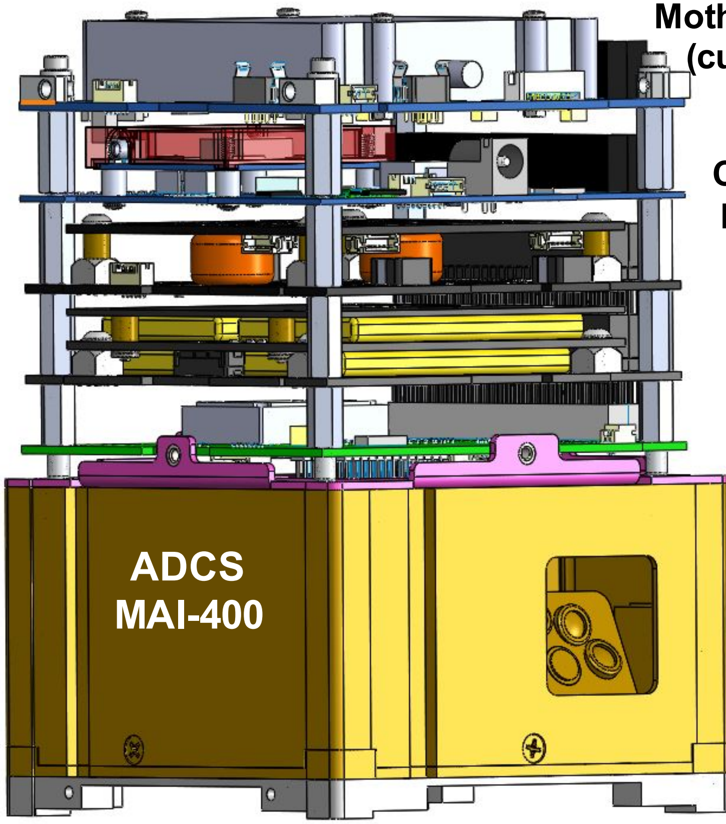
EHS = Earth Horizon Sensor
ADCS = Attitude Determination and Control System
GPSRO = Global Positioning System Radio Occultation
IFP = Intermediate Frequency Processor
PIM = Payload Interface Module

Systems: MiRaTA System Block Diagram



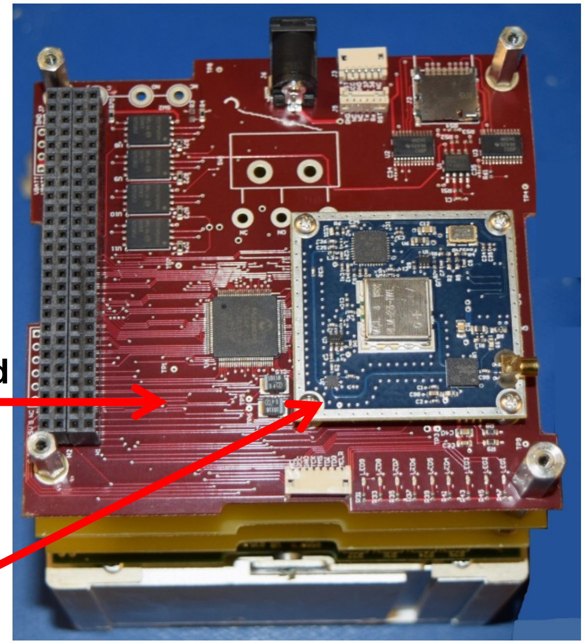
Bus Flight Hardware

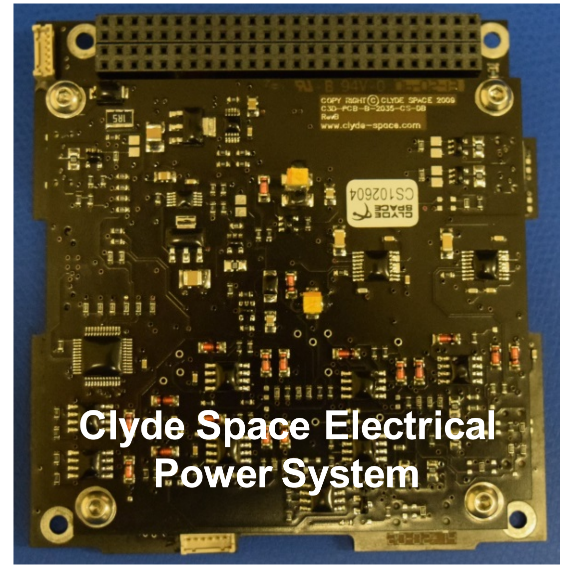




Micron
Motherboard
(custom)

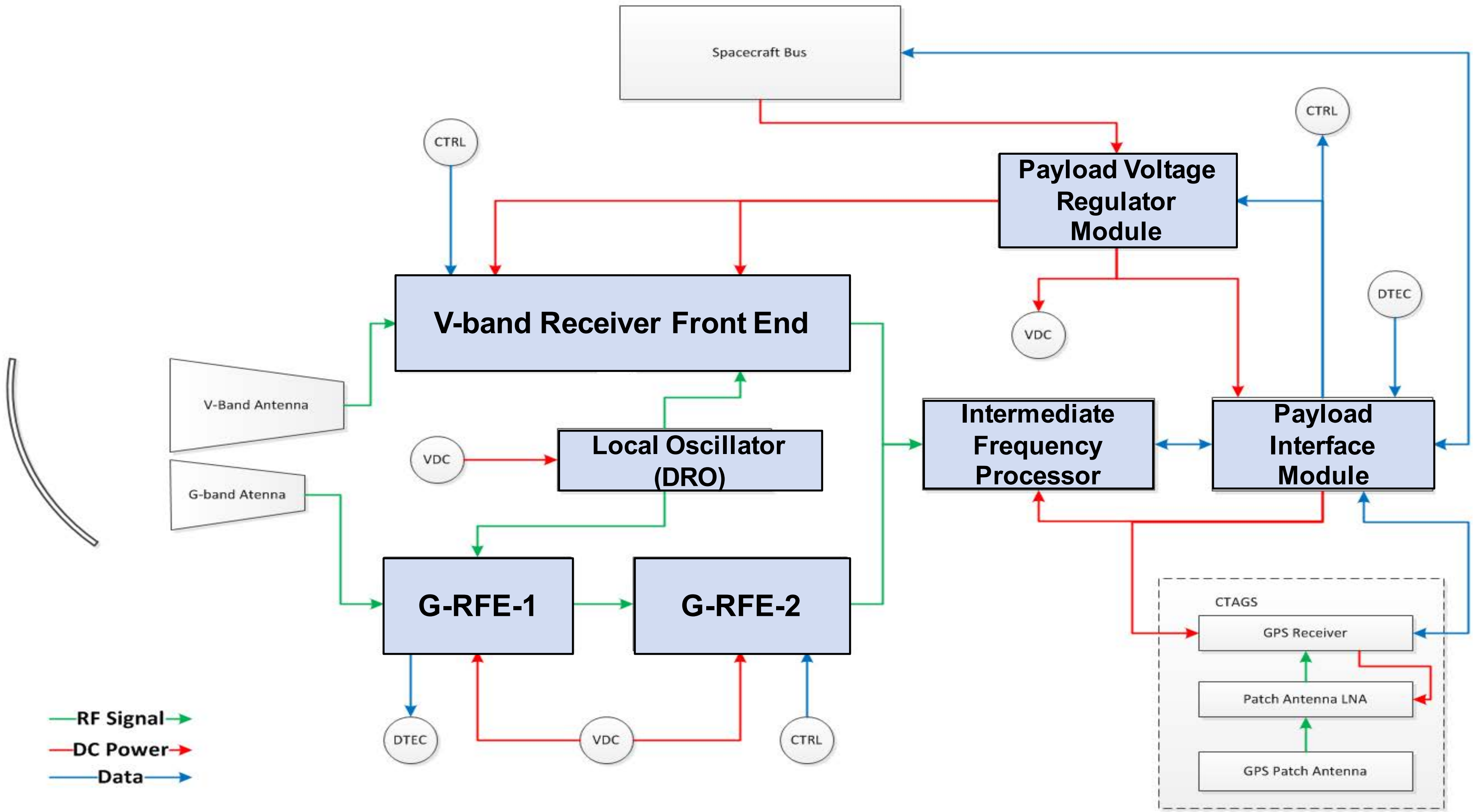
Custom
Micron
Radio





Custom Bottom Interface Board

Radiometer Payload: Block Diagram



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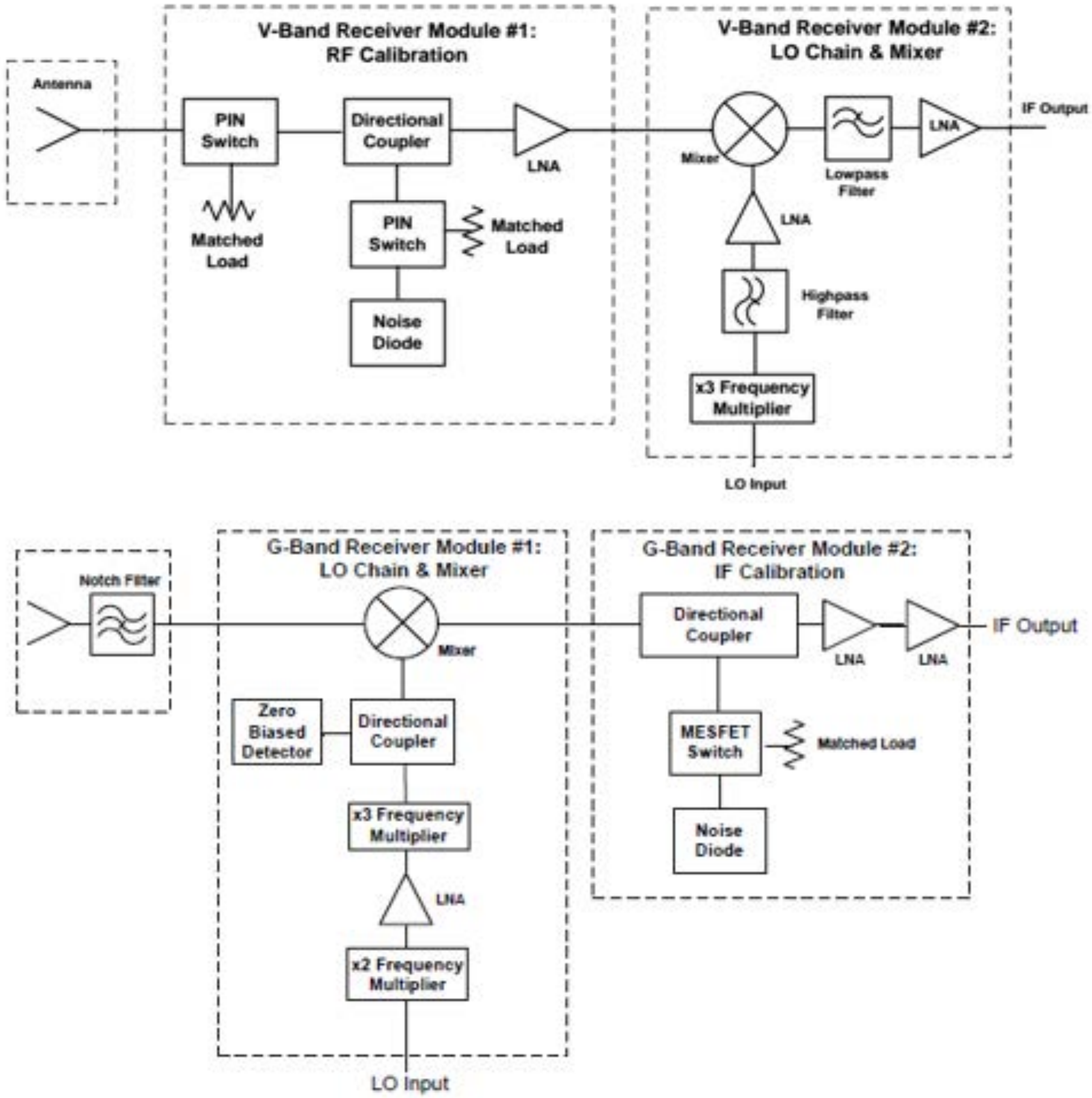
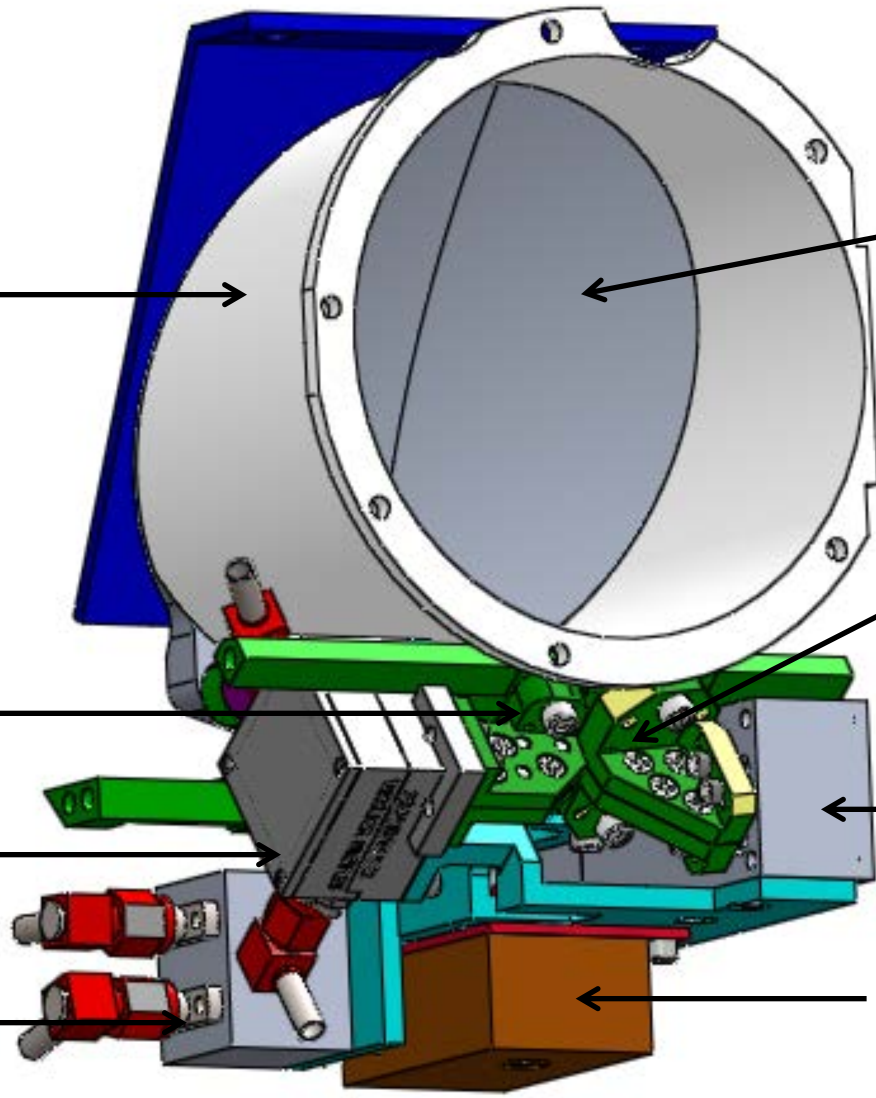
Payload: Radiometer Receiver Front End

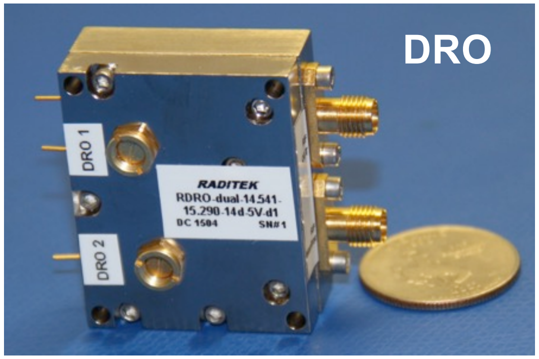


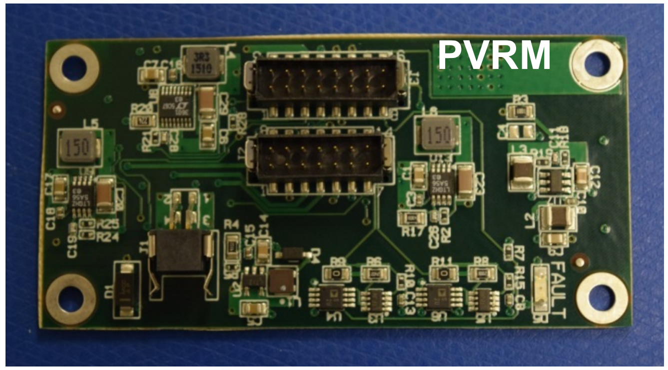
MiRaTA Radiometer System

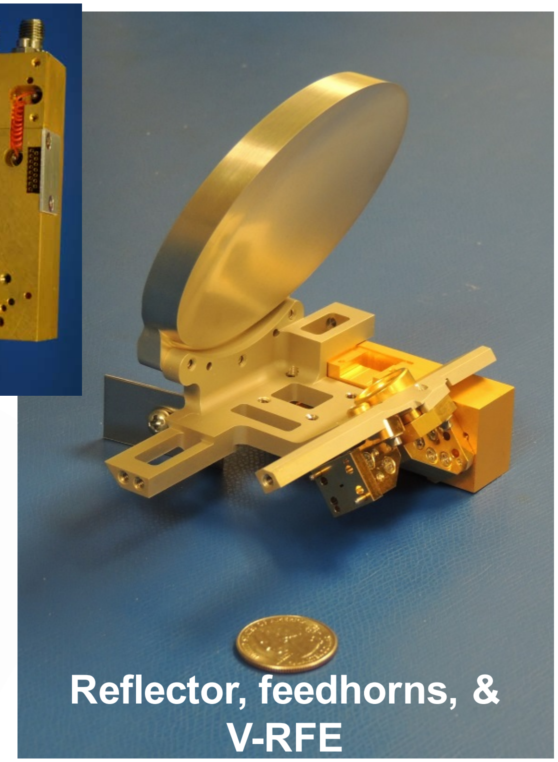


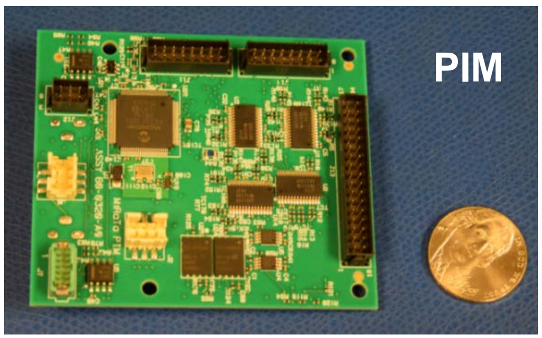
All flight radiometer hardware delivered

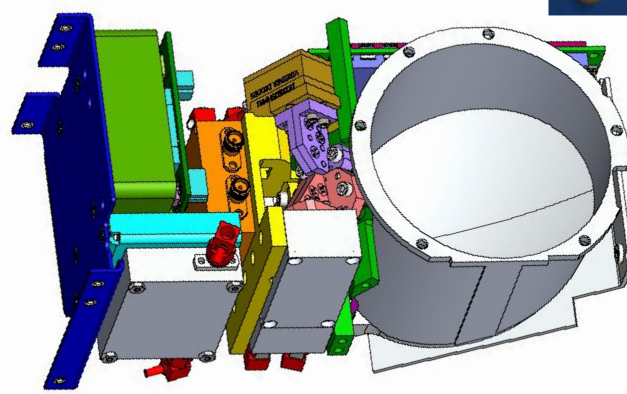
Radiometer Flight Hardware

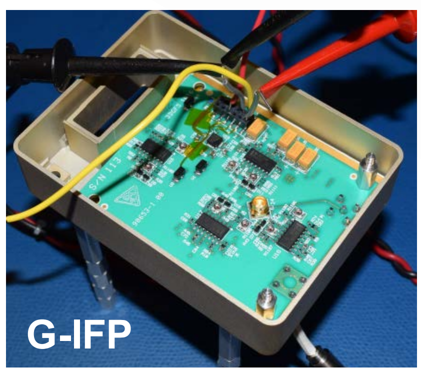


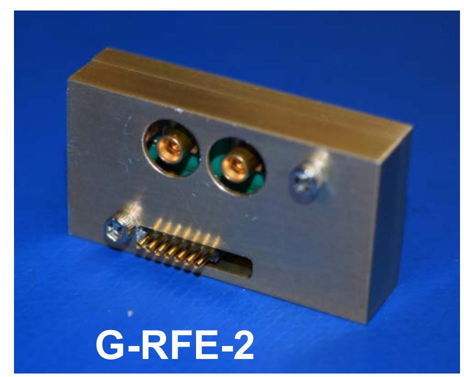






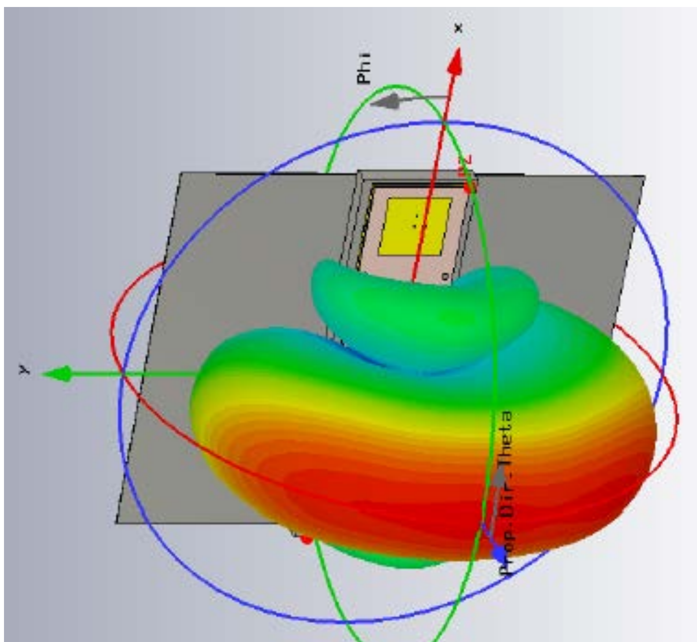




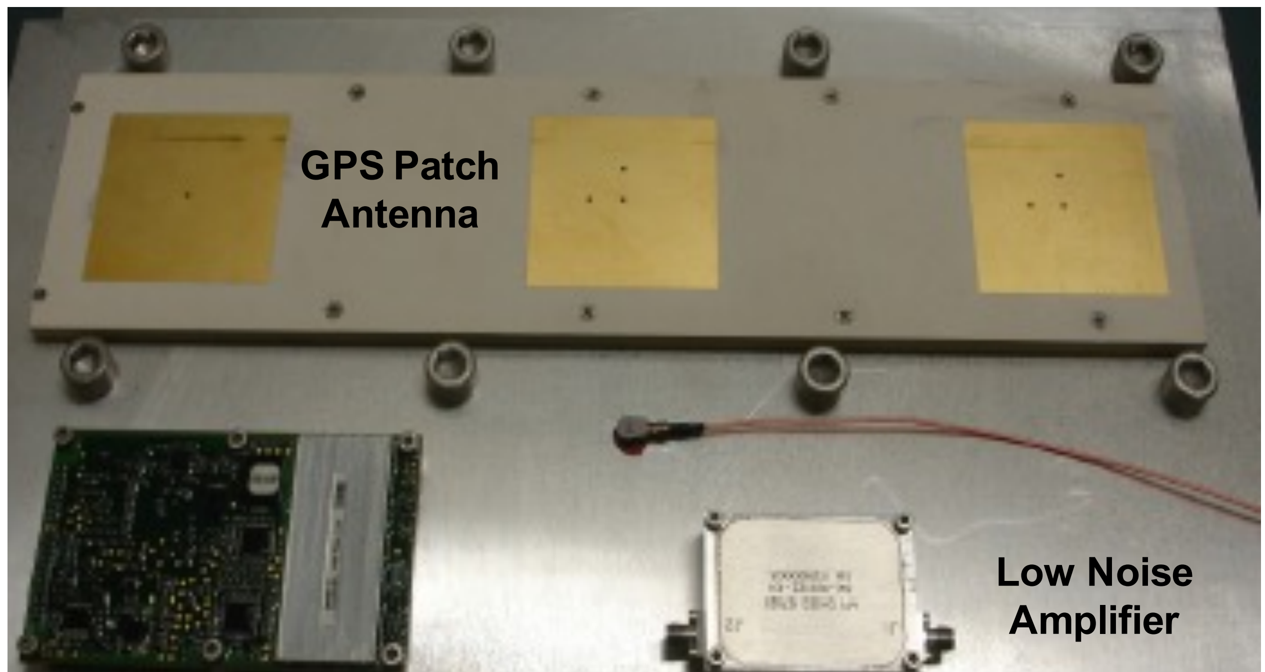


CTAGS Overview

- Provided by Aerospace Corp. to retrieve temperature profiles using GPS radio occultation (Dr. Rebecca Bishop)
- Aerospace performed TVac testing, vibration testing, & on-orbit simulations
- Delivered flight and flight spare in Mar. 2016



Patch antenna pattern



OEM628 GPS Receiver

Compact Total-Electron-Count and Atmospheric GPS Sensor (CTAGS)

Measurement Requirements and Enabling Technologies

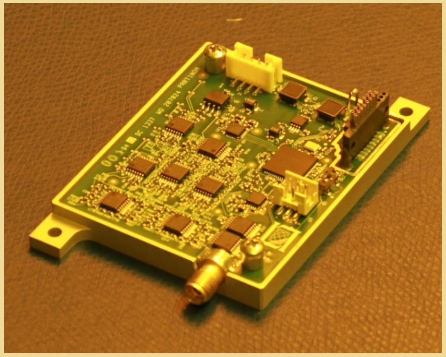
Temperature profile uncertainty of 2 K (RMS) in 50 km footprint needed to improve forecast accuracy

Six or more channels

Ultracompact spectrometer funded by NASA ESTO (ACT-10)

Low-temperature co-fired ceramic filters

Operation from 18-29 GHz



Sensitivity better than 0.3 K (RMS)

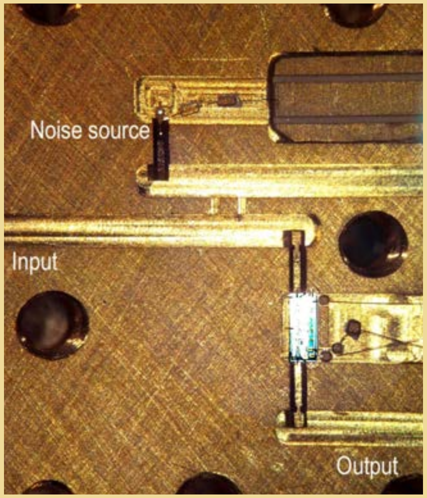
Receiver front-end electronics developed by UMass-Amherst

MMIC low-noise amplifiers and electronic calibration

Calibration accuracy better than 1 K (RMS)

Noise diode source provides periodic absolute calibration of radiometer

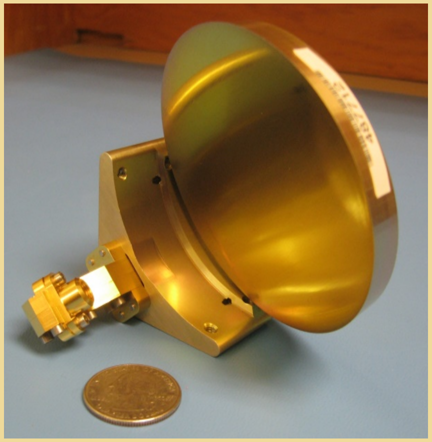
Highly stable; compact



Aperture ~9 cm Beam efficiency > 95%

Offset parabolic reflector system with scalar feed

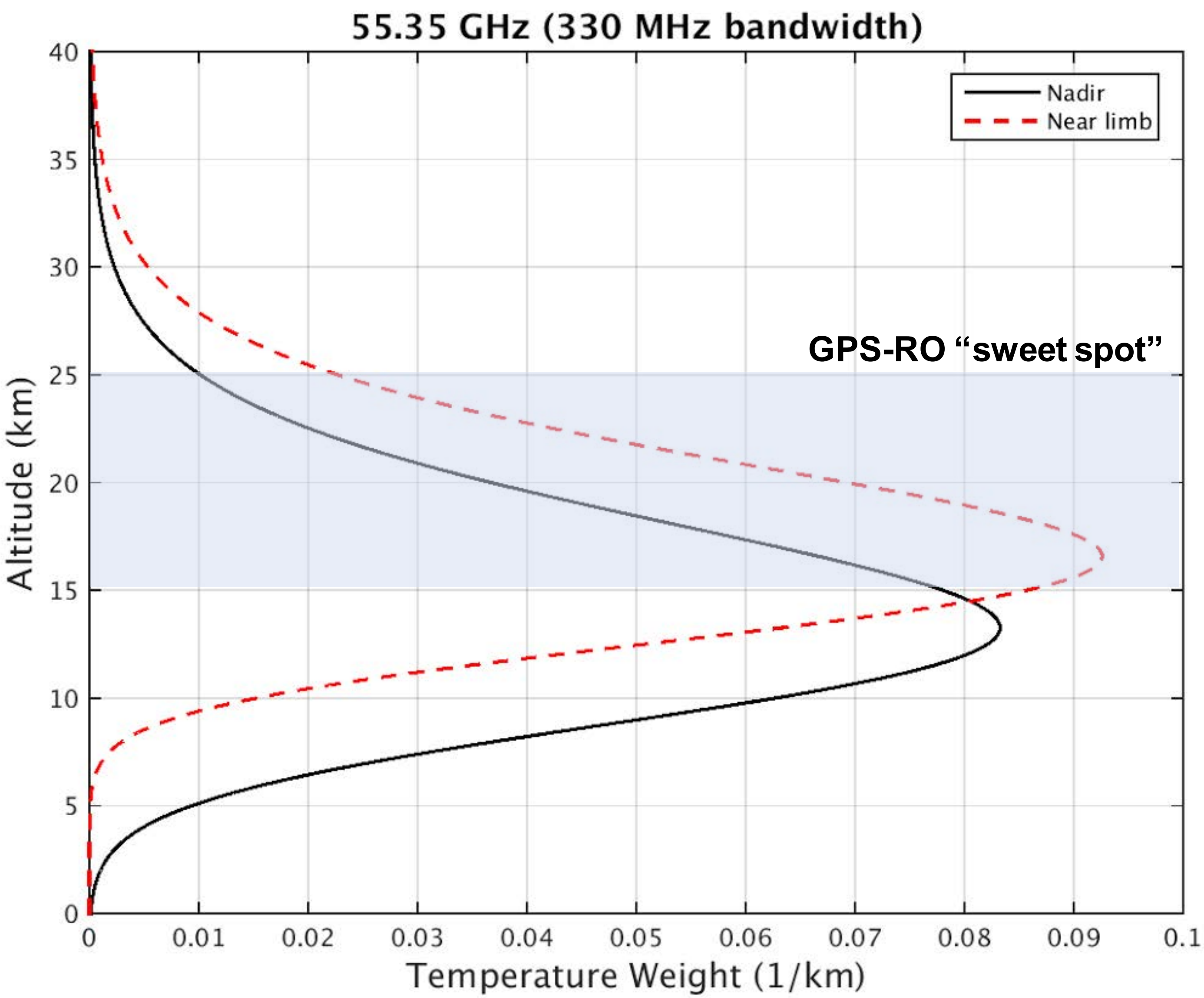
Lightweight, with 0.001" RMS surface tolerance



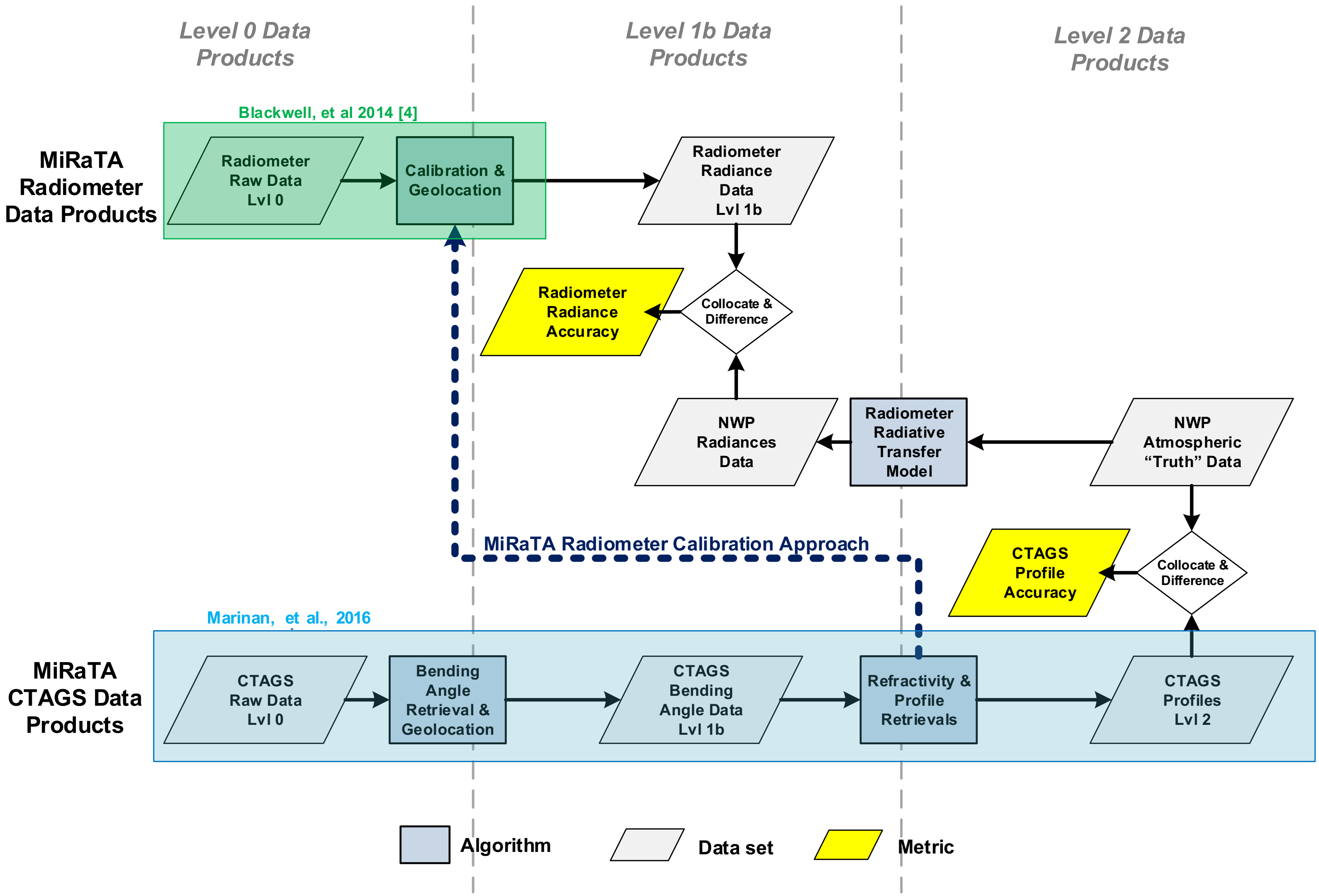
Channel Properties for MiRaTA Radiometers

Channel ID	Type	Center Frequency (GHz)	Bandwidth (MHz)	Weighting Function Peak Height (km)
V1	Single Side Band	50.30	180	0
V2		51.76	400	0
V3		52.80	400	2
V4		53.50	600	5
V5		54.40	400	8
V6		54.94	400	11
V7		55.50	330	13
V8		56.65	600	18
G1	Double Side Band	183.31 ± 1	500	7
G2		183.31 ± 3	1000	4
G3		183.31 ± 5	2000	2
G4		204.8	2000	1

Advantage of Limb Comparisons



MiRaTA Product Validation Approach



Approach – Co-located Radiometer and GPSRO

- Want to calibrate radiometer data using overlapping GPSRO measurements
- Execute a slow pitch (~ 0.5°/sec) maneuver once per orbit with a goal of obtaining > 100 spatially and temporally coincident radiometer and GPSRO scans of Earth's limb over a 90-day mission.
- For absolute radiometer calibration accuracy better than 0.25 K (50-60 GHz band), need:
  – GPSRO temperature precision better than 1.5 K (0.5 K goal)
  – GPSRO penetration to 20 km tangent height within 100 km of radiometer boresight

MiRaTA GPSRO Data Processing Flow

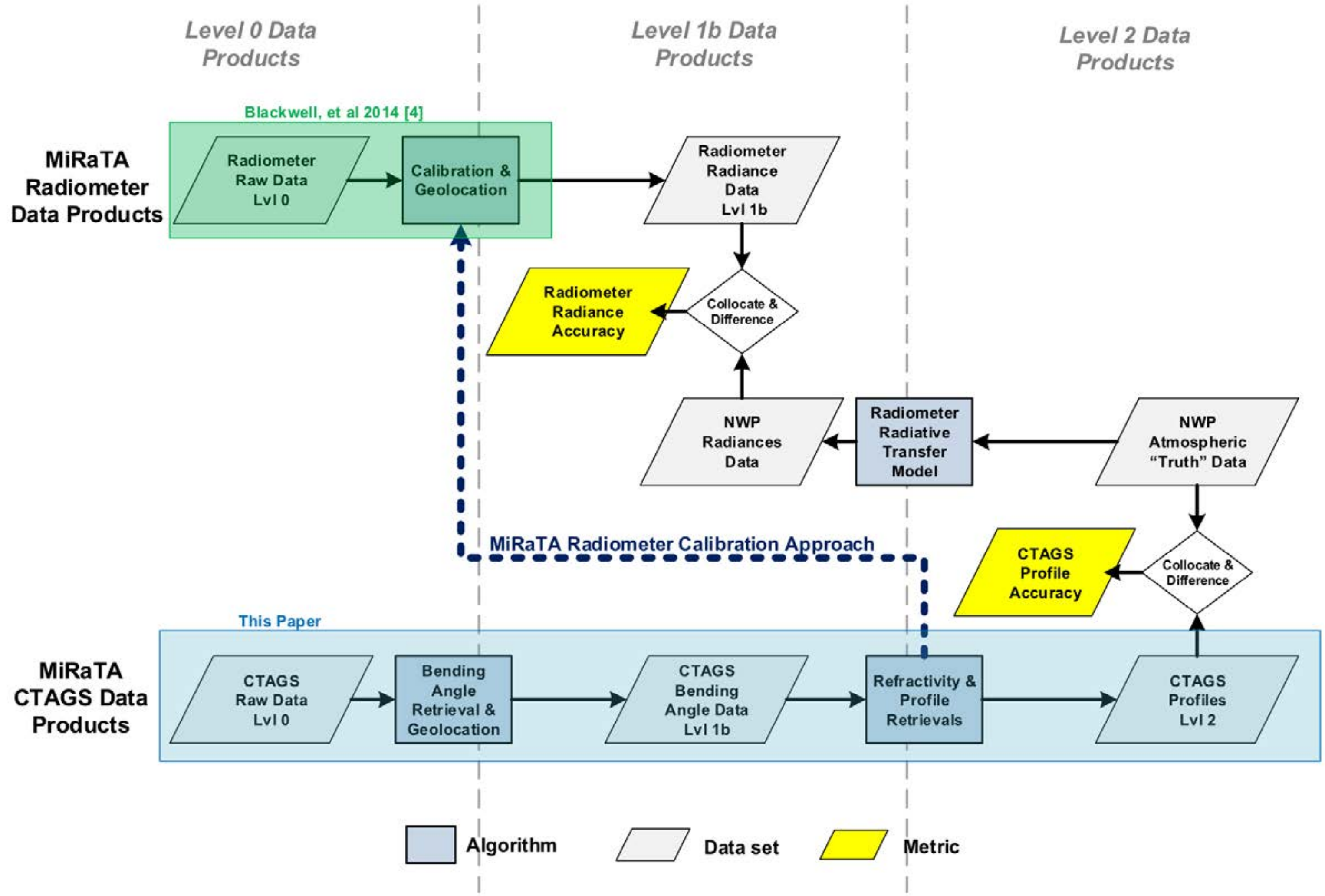
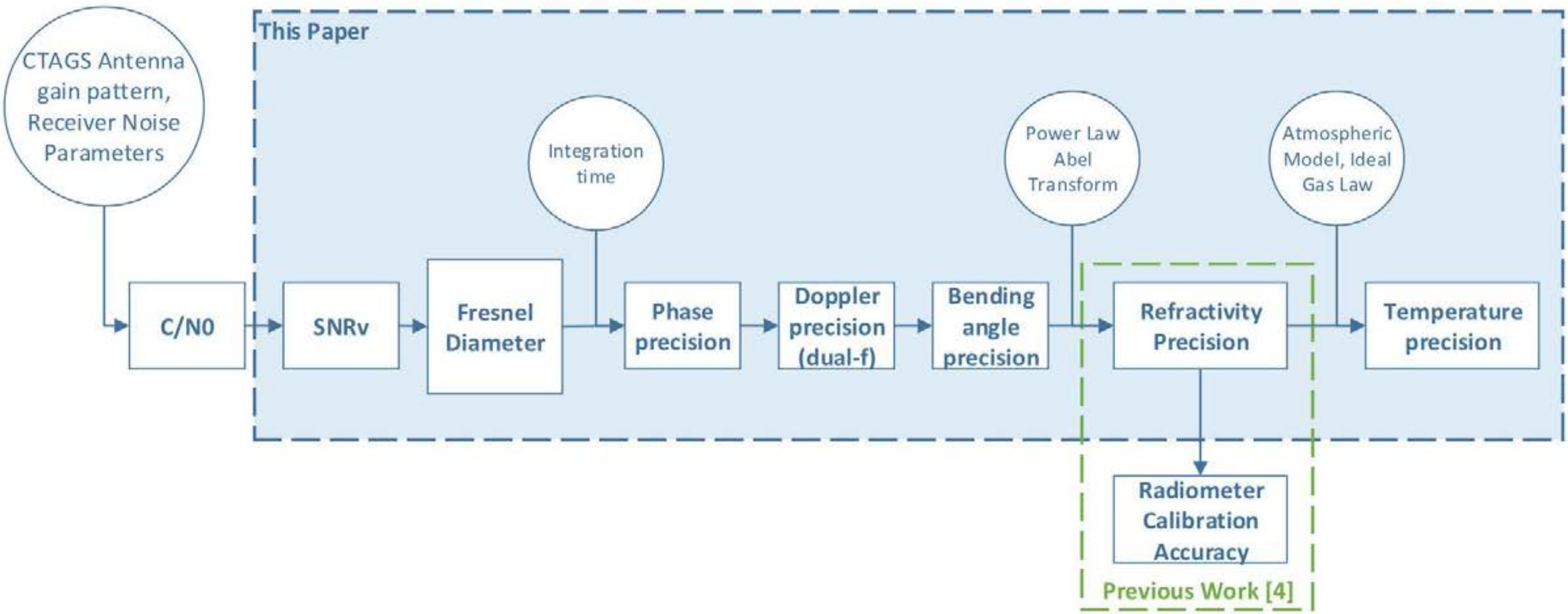


Figure 1: Ground processing and validation flow for the MiRaTA mission data products

Deriving Temperature Precision

- **Based on method presented by Hajj et al., 2002**
  - **Kursinski, 1997**
  - **Hinson, 2010**



Note: Radiometer calibration calculations done by Lincoln Laboratory

Deriving Temperature Precision

- **Antenna Gain: 9.7 dB (L1), 9.4 dB (L2)**
- **From the receiver datasheet, 0.5 mm phase precision at 20 Hz**

$$\langle \delta\phi(\tau)^2\rangle^{\frac{1}{2}} = \frac{\lambda}{2\pi}(2SNR_0\tau)^{-\frac{1}{2}}$$

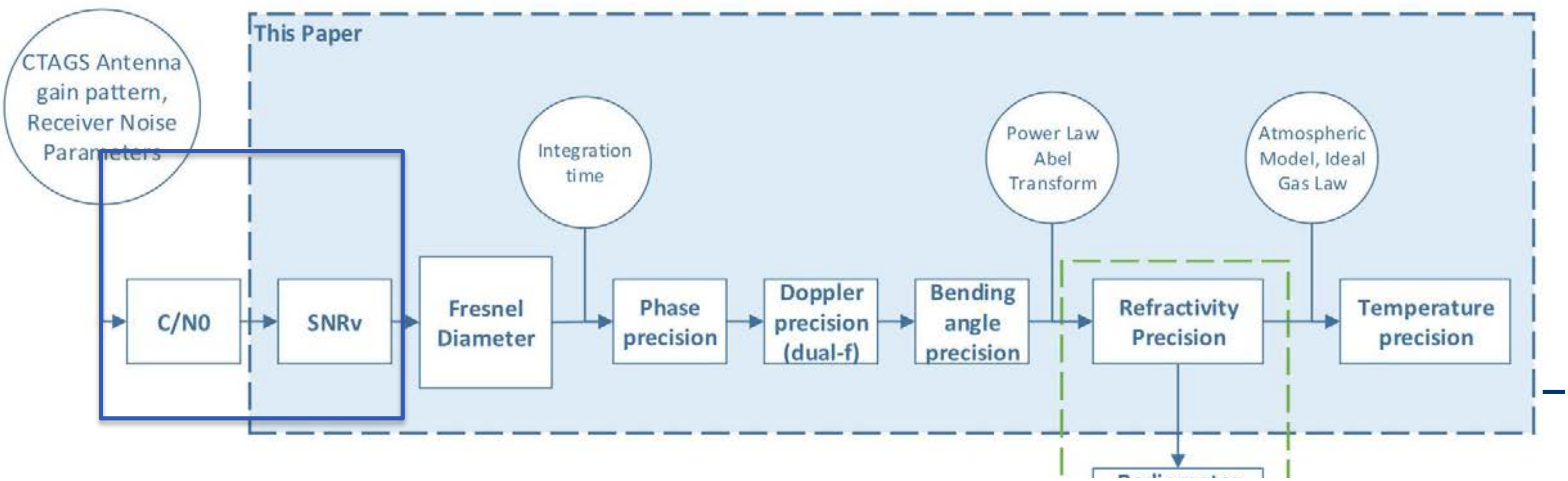
$\langle \delta\phi^2\rangle^{\frac{1}{2}}$ is the rms phase error (units of length)

λ is the sampling frequency (L1 or L2)

τ is the integration time

SNR_0 (W/W) is the power signal to noise ratio based on a 1-second integration time ($SNR_0 = SNR_{v_0}^2$, where SNR_{v_0} is the voltage signal to noise ratio in a vacuum)

The 1-second L1 SNRv of the receiver is 271 V/V (174 V/V for L2)



Deriving Temperature Precision

- **From free-space SNR and atmospheric loss, calculate Fresnel zone (~1.4 km)**
- **Determine time it takes for signal to travel one Fresnel zone**
- **Recalculate phase precision based on integration time**

For the receiver SNR_{v_0} the average Fresnel zone value for MiRaTA is 1.4 km.

The average integration time for the MiRaTA orbit (440 km x 811 km) is 0.5s

This corresponds to a 0.16 mm phase precision (0.32 mm for L2)

$T = 2Z_F / V =$ integration time

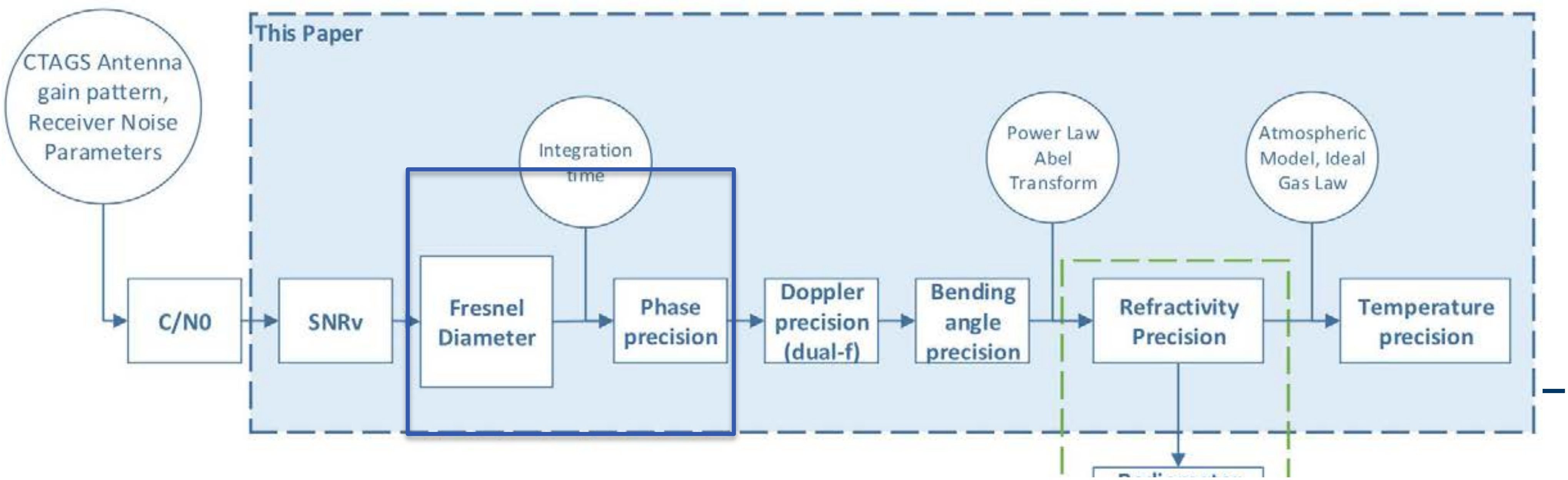
$Z_F =$ Fresnel zone diameter

$\lambda =$ sampling wavelength

$D_t =$ distance from tangent point to Tx

$D_r =$ distance from tangent point to Rx

$V =$ vertical rate of link



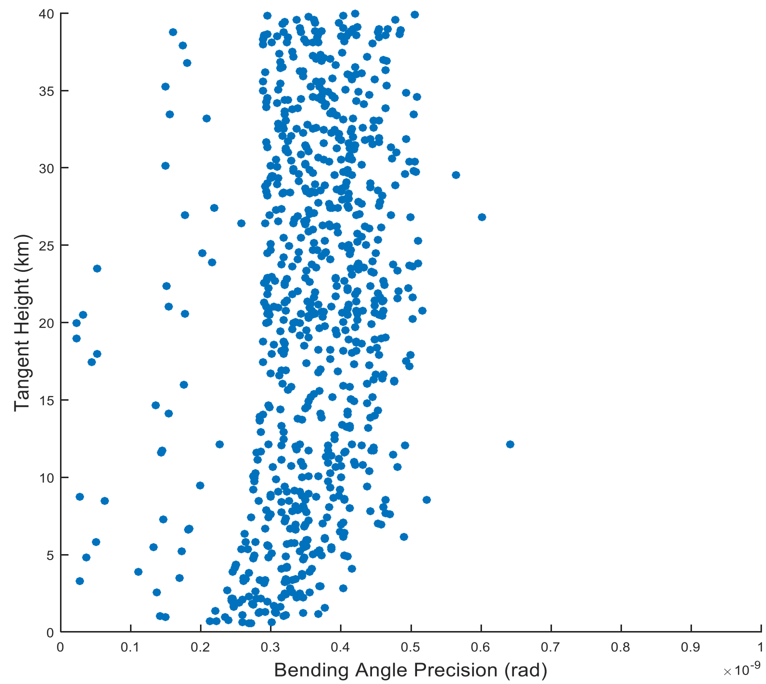
Deriving Temperature Precision

- Doppler noise calculated from phase precision

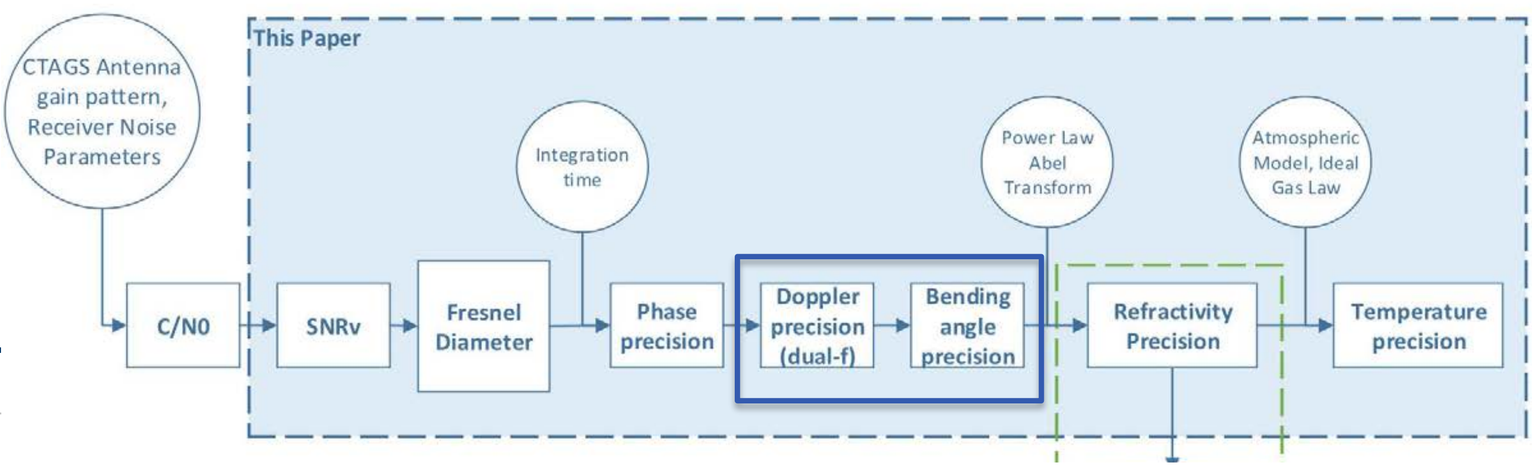
$$\sigma_{Doppler} = \frac{\sigma_\phi \sqrt{12}}{\Delta N^{3/2}}$$

$$\sigma_\alpha = \frac{\lambda \sigma_{Doppler}}{V_0}$$

$$\sigma_{\alpha_{neut}}^2 = (2.54)^2 \sigma_{\alpha_1}^2 + (1.54)^2 \sigma_{\alpha_2}^2$$



- Neutral bending angle calculation takes into account both L1 and L2



Deriving Temperature Precision

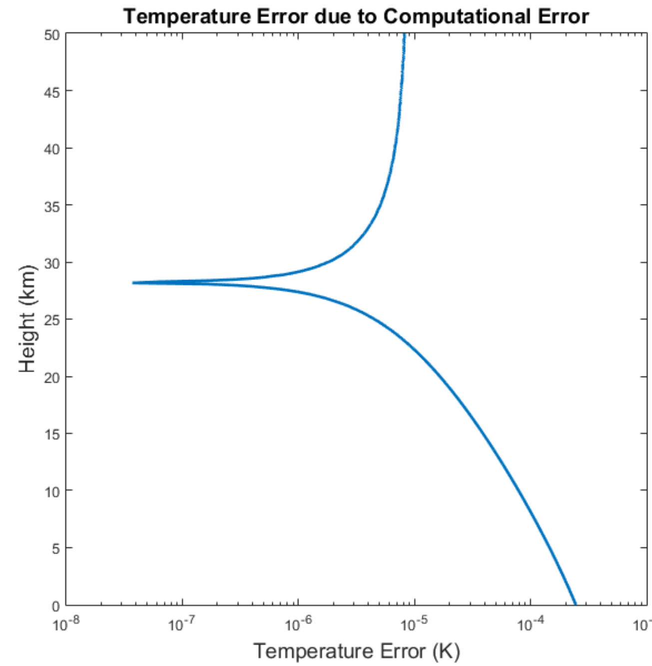
- **Abel transform converts bending angle to atmospheric refractivity**
- **Bending angle (exponential with height) represented with power-law approximation**
- **Abel transform of power law has analytic solution**
- **Calculate contribution of numerical calculation to retrieval error**
  - **Several orders of magnitude below expected measurement errors**

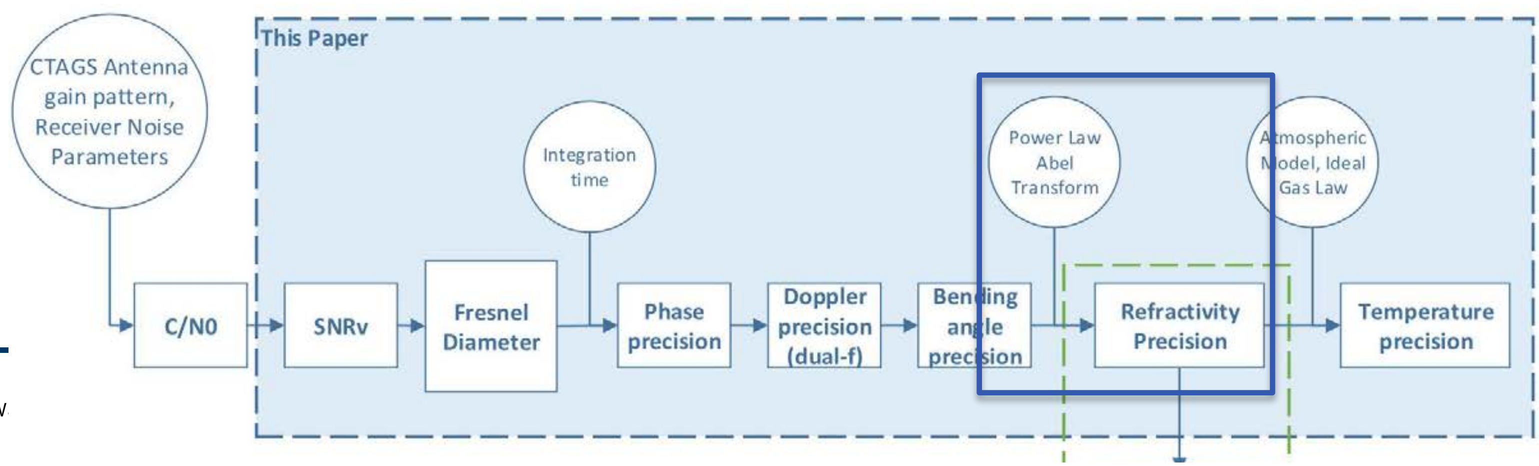
$$\ln \mu_j = \frac{1}{\pi} \int_{a_j}^{\infty} \frac{\theta(a)\, da}{\sqrt{a^2 - a_j^2}}$$

$\mu =$ refractivity

$\theta =$ bending angle

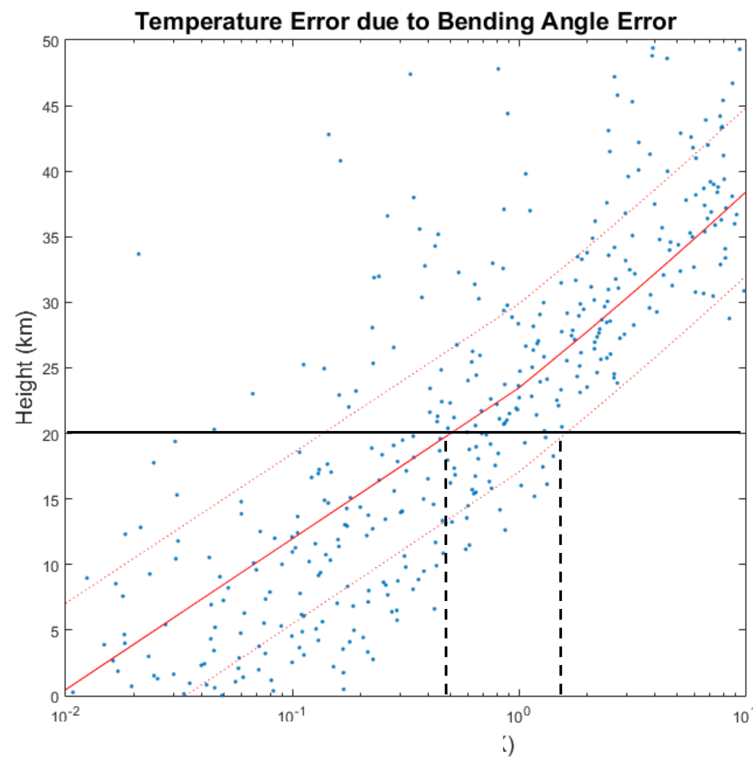
$a =$ impact factor

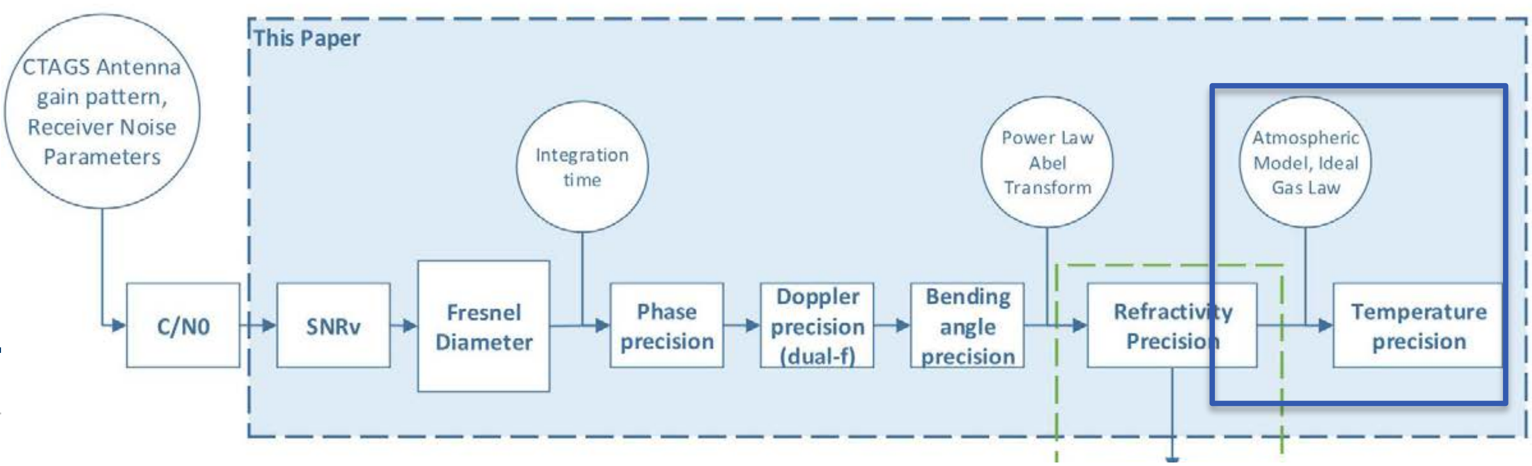




Deriving Temperature Precision

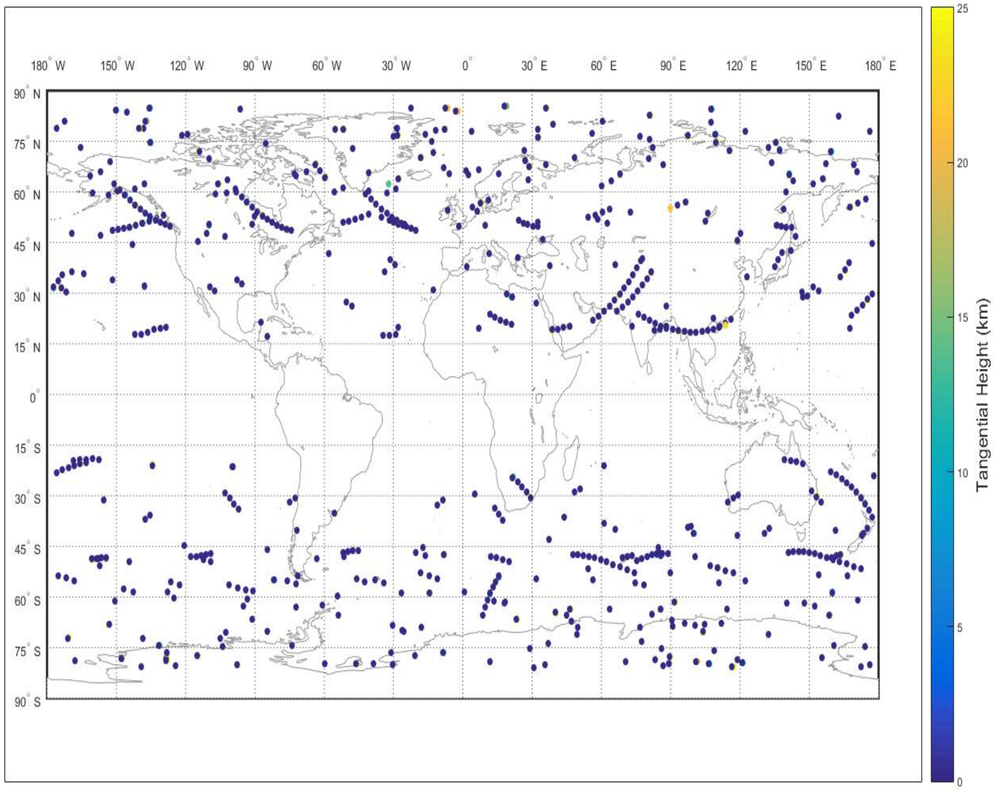
- From refractivity, get air density
  - Integrate density to get pressure
    - Ideal gas law for temperature
- Propagate bending angle error through all calculations to derive temperature error
  - Best-fit: ~0.5 degrees at 20 km
  - 95% confidence: 0.1 - 1.7 degrees at 20 km





Path Forward (MiRaTA)

- **Identify how many overlapping observations we can acquire over the mission lifetime (mission requirement: 100)**
  - **Preliminary results (over 3 months)**
    - **> 500 overlapping accesses**
    - **5-6 opportunities per day**
  - **MiRaTA ADCS driving additional satellite rotation that may impact the total number of overlapping occultations**
- **Estimate how many might fall within required temperature precision (most likely a Monte Carlo approach)**



CubeSat GPSRO – Global Coverage Approach

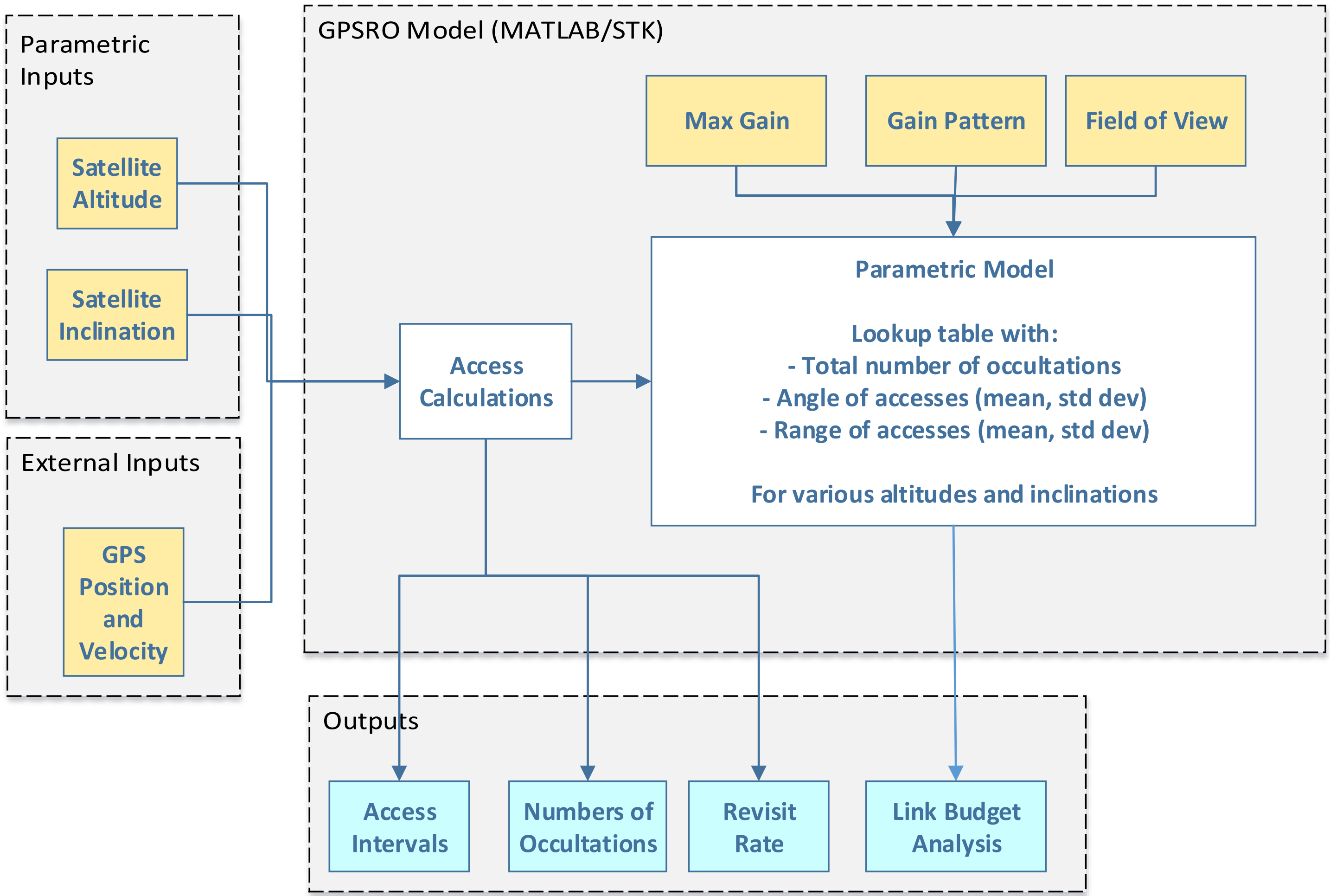
External Input: GPSRO antenna 60 deg HPBW

External Inputs

Altitude (km):
[400 500 600 700]

Inclination (deg):
[0 30 60 98]

Numbers of satellites:
[1 3 6]



Access Opportunities for GPSRO by Orbit

- Percent Time with >= 4 GPS Satellites in View
  - Driven by requirement for position knowledge and reference satellites
- Total number of occultation opportunities
  - Assuming 60 degree HPBW receiving antenna field of view
- Analysis run over 3 months (Jan – Apr 2016) across tradespace of orbit parameters

	400 km	500 km	600 km	700 km
0°	80%	84%	87%	89%
30°	60%	63%	66%	69%
60°	62%	65%	68%	71%
98°	69%	72%	75%	77%

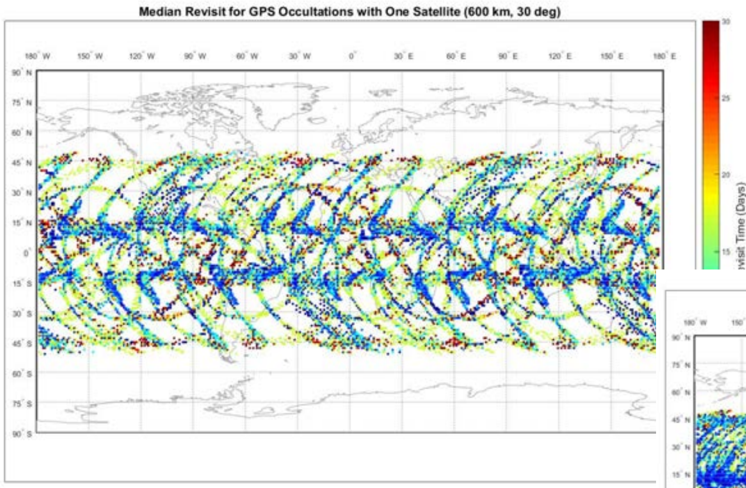
%Time (out of 3 months) with 4 GPS satellites in view

	400 km	500 km	600 km	700 km
0°	36820	36570	36180	35530
30°	31150	31830	32330	32510
60°	33480	34490	35190	35600
98°	38780	39560	39990	40240

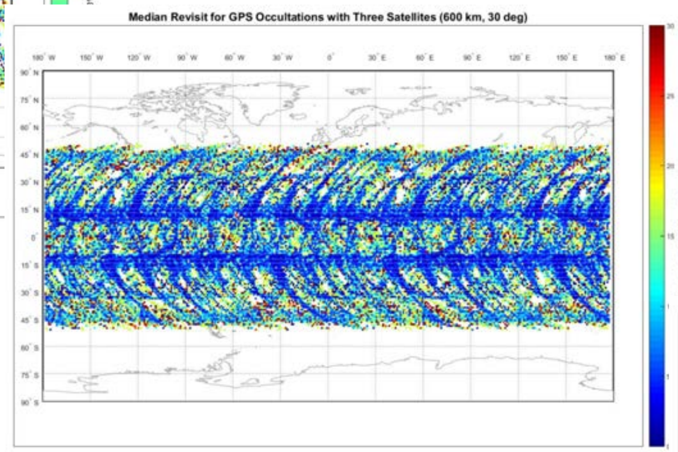
Number of GPS RO occultation opportunities below 200 km tangent height

In general, equatorial or polar orbits (i.e. not mid-latitude) offer more GPS access and occultation opportunities

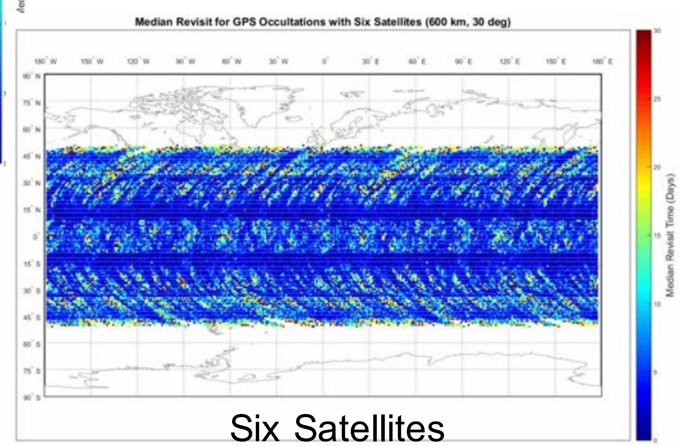
Revisits, Multiple GPSRO Satellites per Plane



One satellite



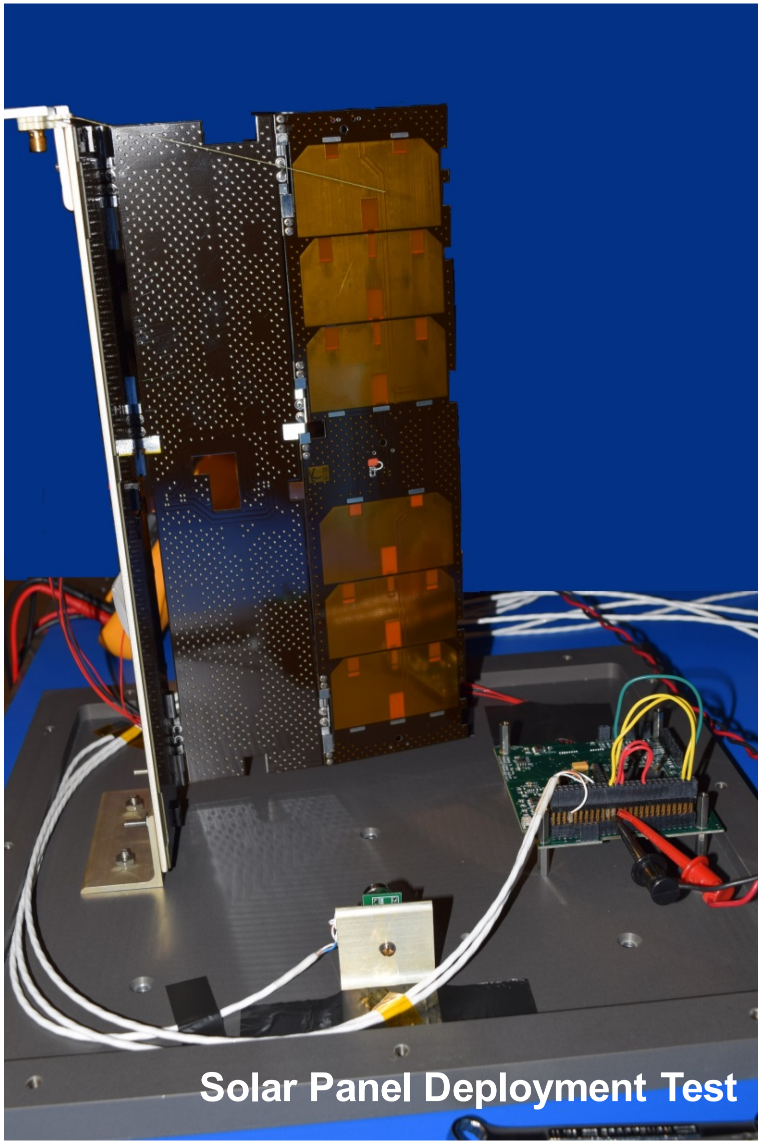
Three Satellites

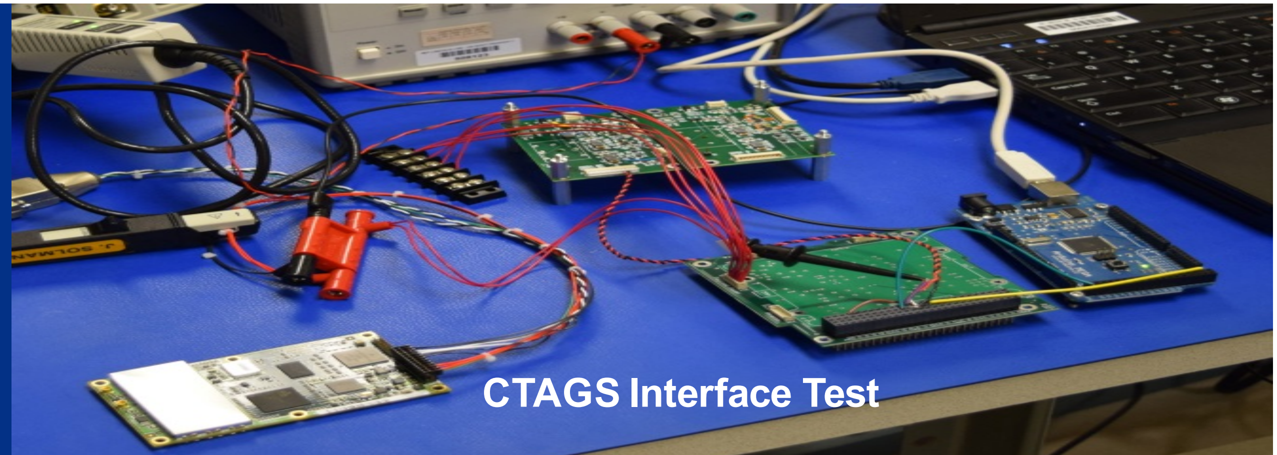


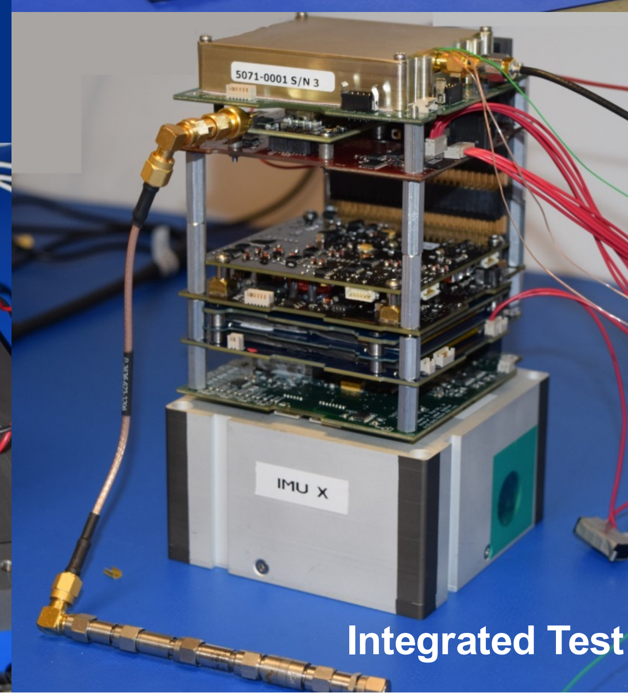
Six Satellites

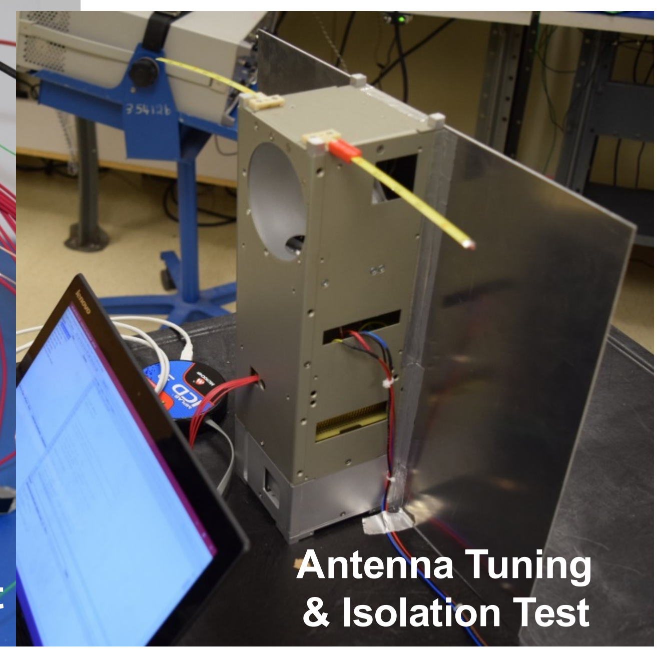
Moving toward weekly/daily measurement updates (ideally hourly revisits)

Testing Overview


Solar Panel Deployment Test

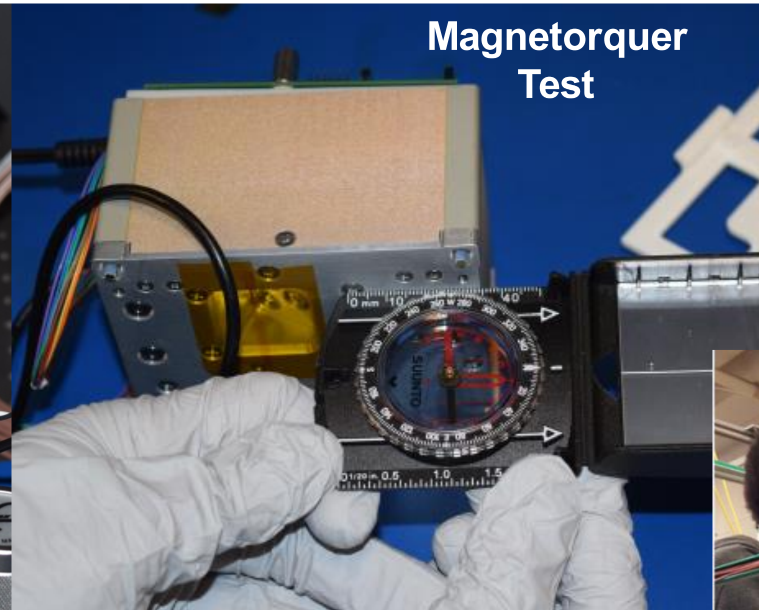

CTAGS Interface Test


Integrated Test


Antenna Tuning & Isolation Test

ADCS Testing Overview

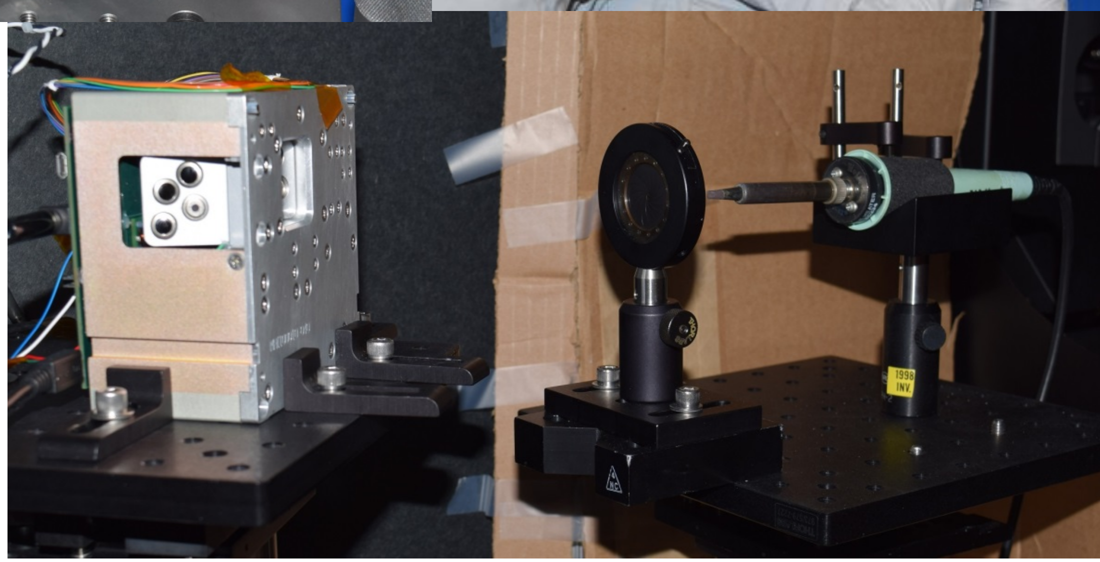
Earth Horizon Sensor Blackbody Response Test



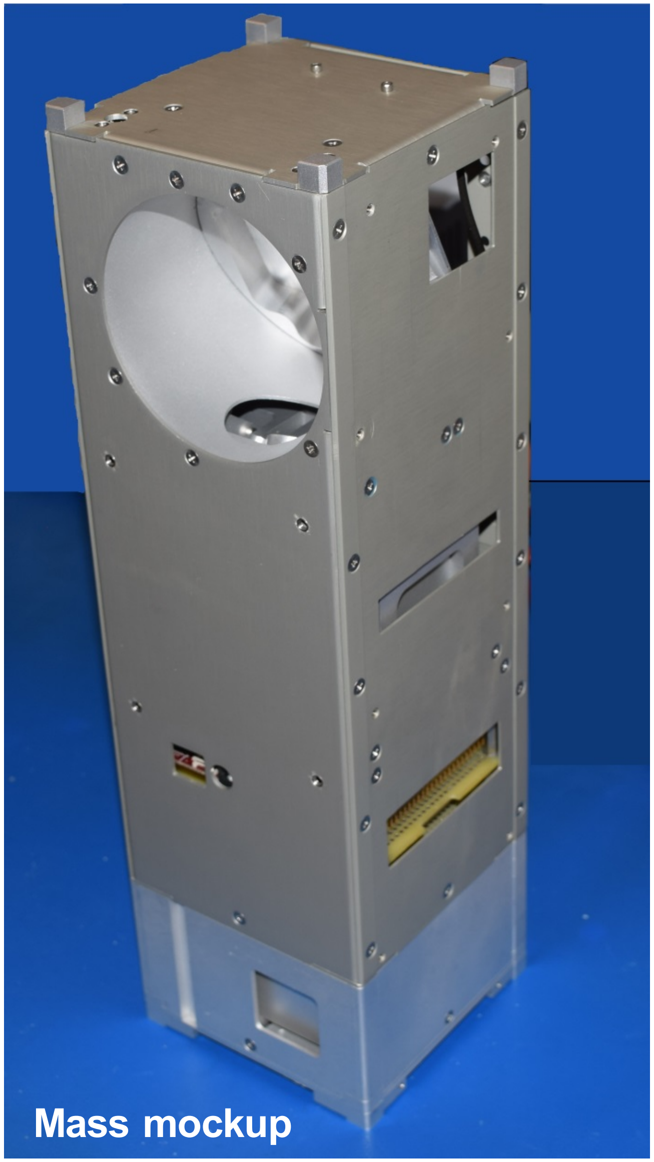
Magnetorquer Test

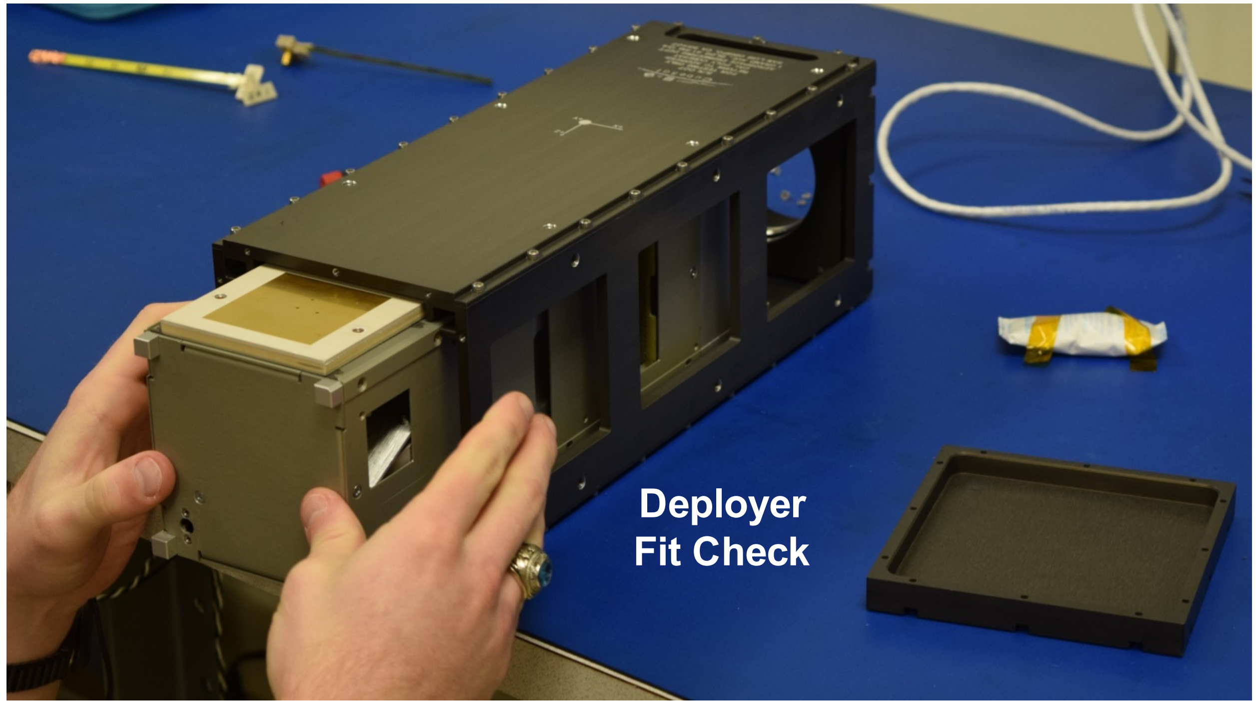
Magnetometer Testing in Helmholtz Cage

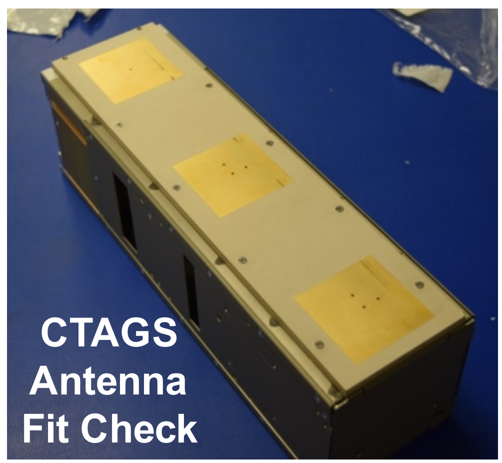
Earth Horizon Sensor Narrow & wide FOV Characterization

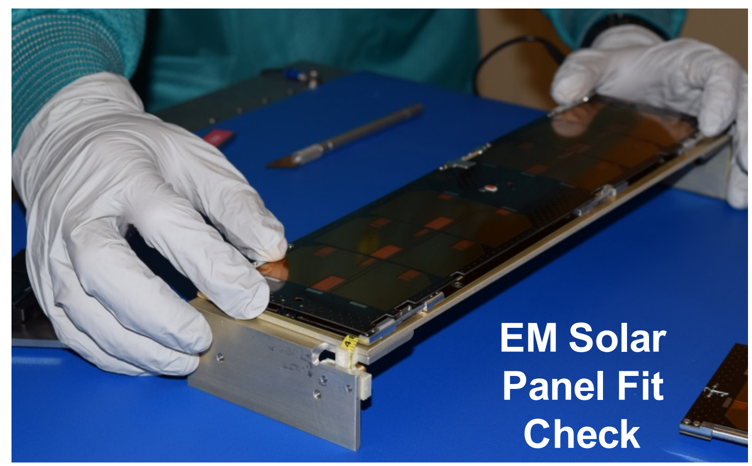


Space Vehicle Fit Checks









Volume & mass risks are low, but with slim margins

MiRaTA Manifested on ELaNa 14

- Launch on a Delta II with JPSS-1
- Inclination – 97.73 degrees
- Orbit – ~811km x ~440km
- LTAN - 13:20:35
- JPSS-1 launch in Jan. 2017

MiRaTA Key Dates

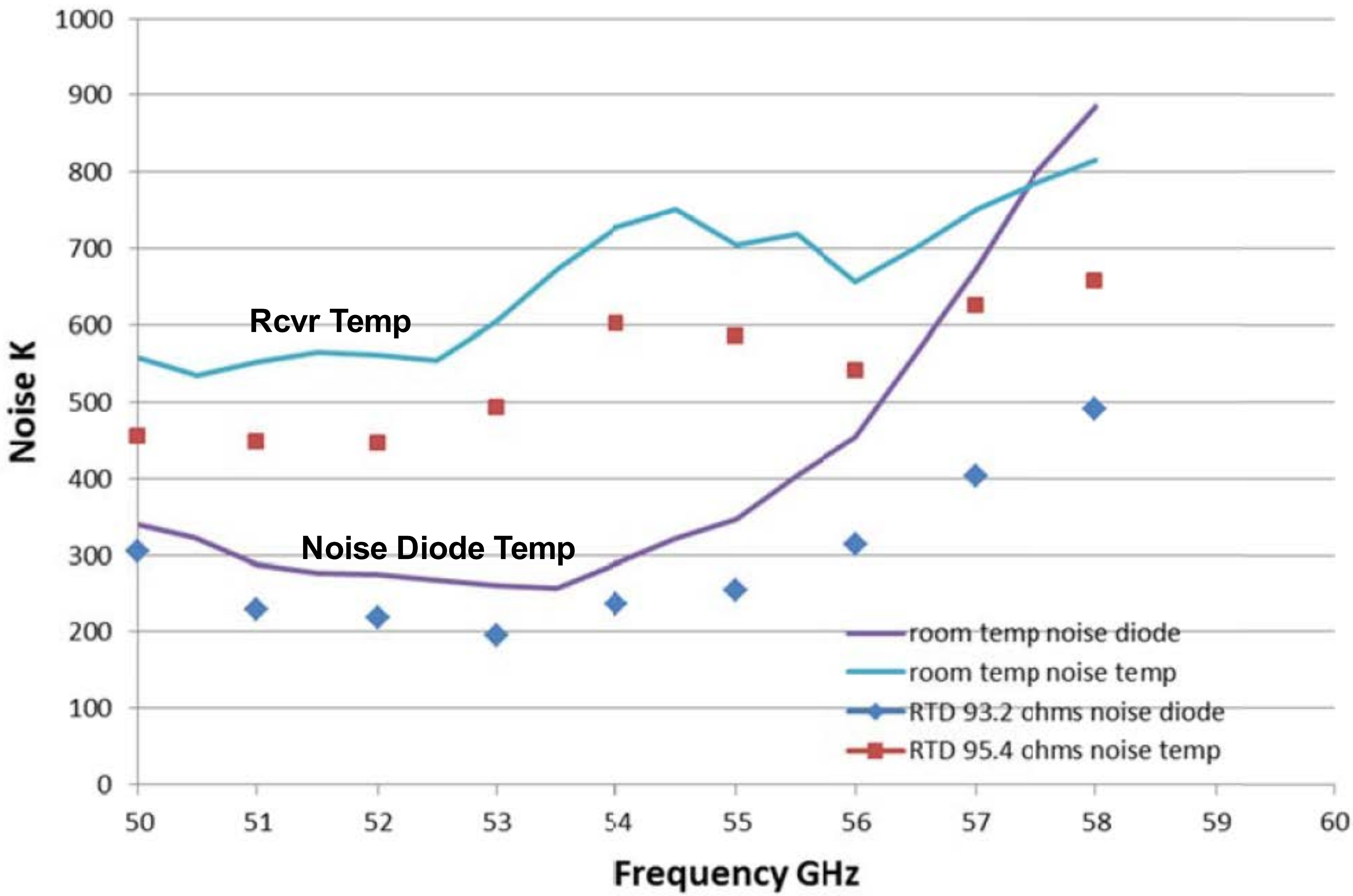
Milestone	Date
Award "Start"	*Dec. 20, 2013*
NSSC Approval	*Feb. 12, 2014*
Funds distributed	*Mar. 14, 2014*
Project Kickoff with Subs	*Apr. 2014*
System Requirements Review	*June 2, 2014*
System PDR	*Oct. 22, 2014*
System CDR	*June 1-3, 2015*
Flight-ready Spacecraft Integrated	*Oct. 26*, 2016
Deadline to complete testing reports	Nov. 11, 2016
Mission Readiness Review	Dec. 6, 2016
CubeSat Delivery	Jan. 10, 2017
Launch	March, 2017*

*** ELaNa-XIV launch with JPSS-1**

Summary

- MiRaTA will provide multi-band radiometry and GPS-RO in a single 3U cubesat
  - Temperature, moisture, and cloud ice with high absolute accuracy
- Flight hardware build is complete, system testing underway
- TVAC complete, currently undergoing vibration and shock test
- March 2017 launch on JPSS-1
- MiRaTA is a critical pathfinder for the TROPICS constellation
  - Multi-band radiometry
  - Electronic calibration
  - Spacecraft maneuvers for mission capability

MiRaTA V-band Front-End Performance (Includes PIN Switch and Noise Injection)



MiRaTA G-band Front-End Performance