A New Cubesat Mission for High-Resolution Earth Atmospheric Sensing Using Combined Microwave Radiometry and GNSS Radio Occultation

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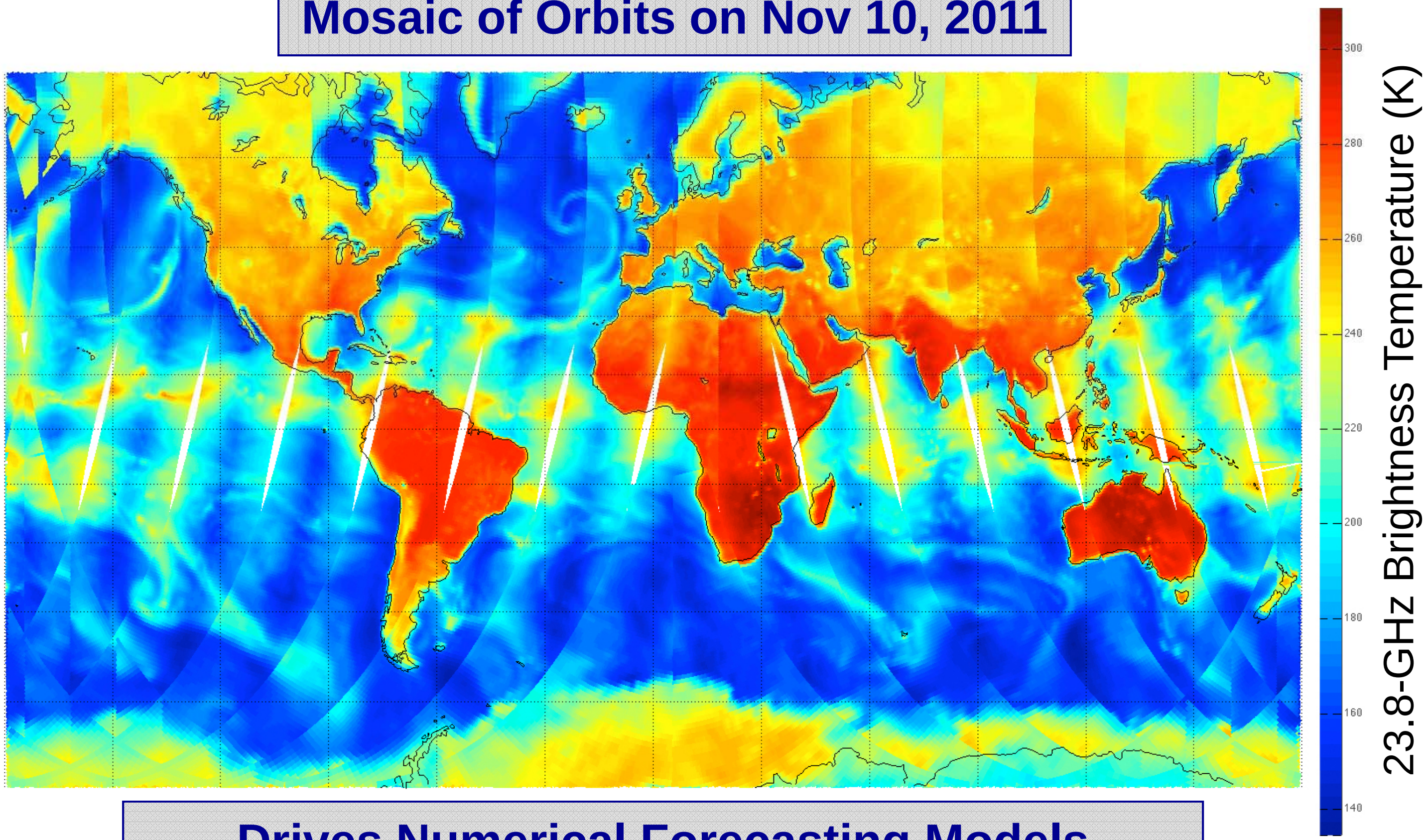
Outline

- **Introduction/Motivation**
- **Radiometer + GPS-RO calibration simulation results**
- **MiRaTA cubesat development**
- **Summary**

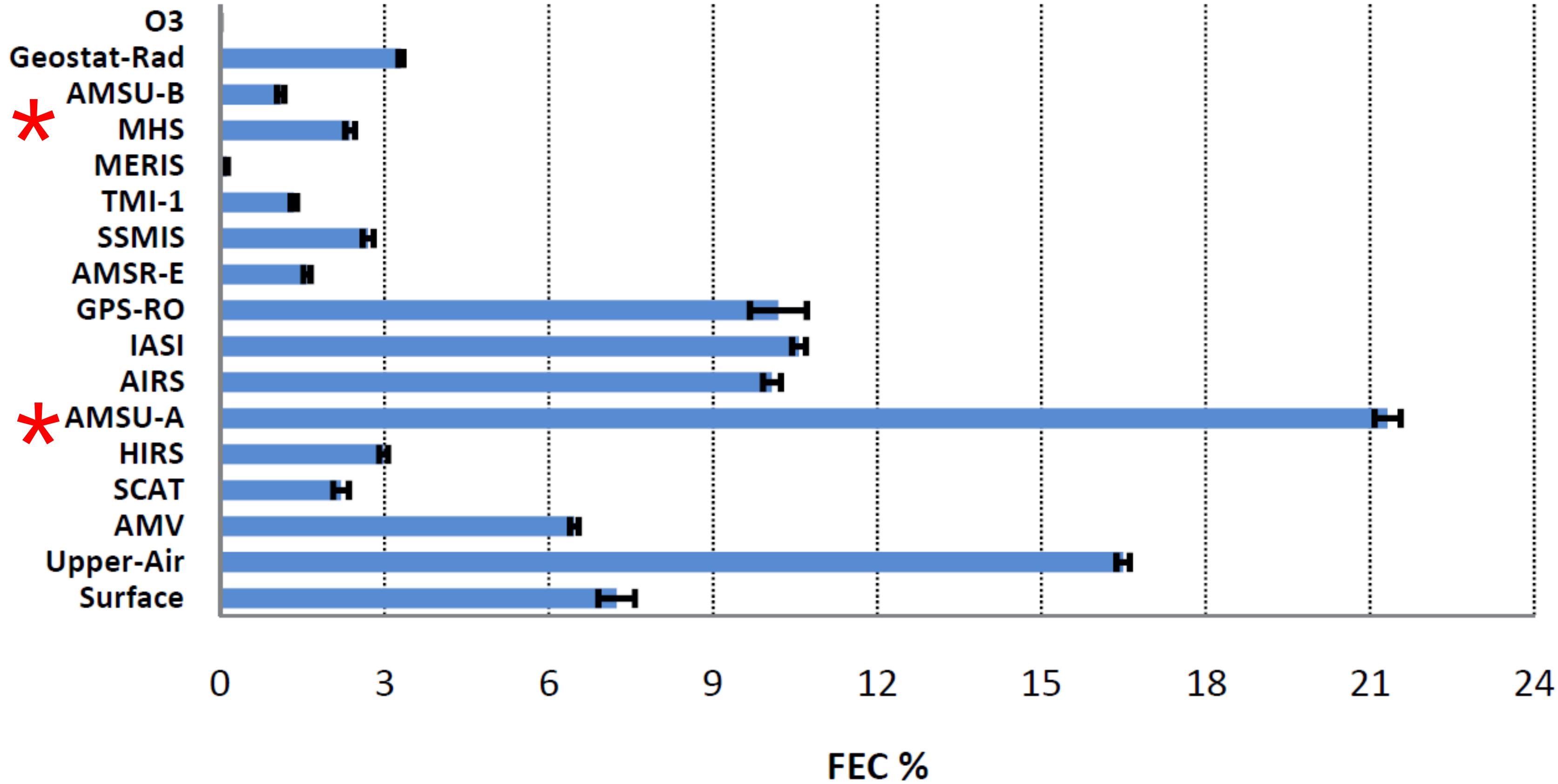
Need: All-Weather, High-Resolution, Persistent 3-D Observations of the Earth's Atmosphere

ATMS (S-NPP)
Mosaic of Orbits on Nov 10, 2011



Drives Numerical Forecasting Models
Monitoring of Severe Weather and Hurricanes
Hydrologic and Climate Studies

Forecast Error Contribution

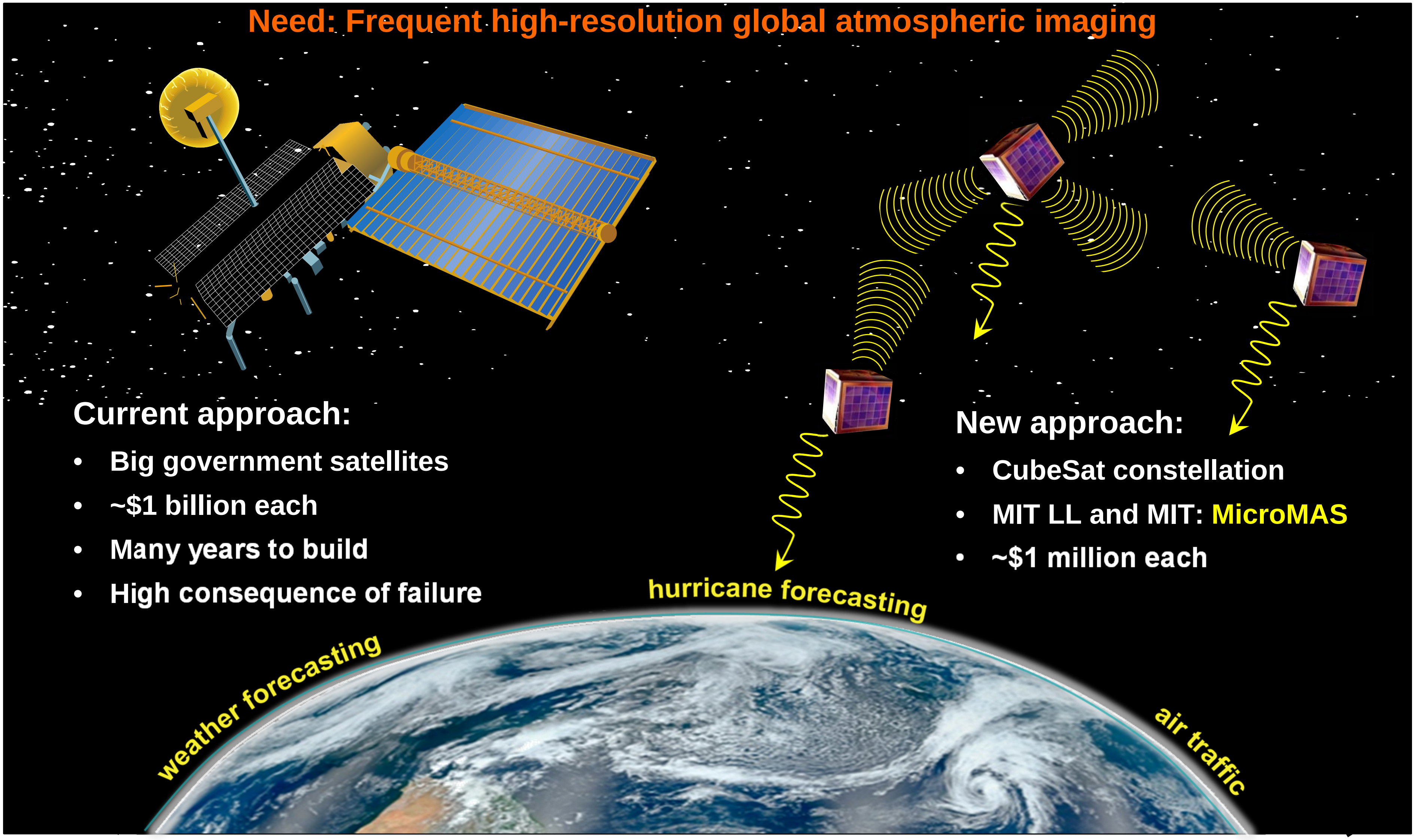


AMSU-A temperature sounding observations have the largest positive impact on forecast accuracy

AMSU-B/MHS observations are currently underutilized due to poor cloud screening

Figure courtesy Carla Cardinali, ECMWF

From Monolithic to Distributed Systems



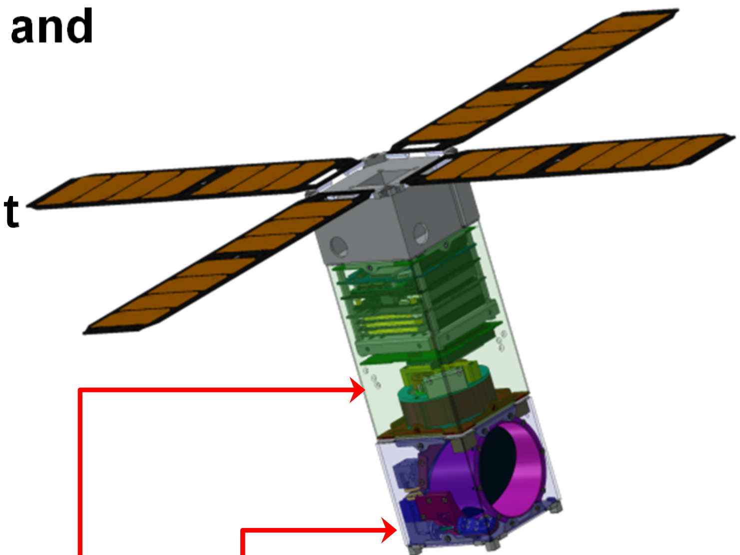
MicroMAS = Micro-sized Microwave Atmospheric Satellite

Slide adapted from P. Eremenko, DARPA F6 presentation, Feb. 2010

MicroMAS Mission

Launch a Single Satellite to Demonstrate the Core Element of a Transformative Sensing Architecture

- Synoptic sensing with focus on hurricanes and severe weather
- 51.6 deg. inclined orbit; ~400-km initial orbit altitude (released from ISS)
- One year mission lifetime objective
- Arrived at ISS on July 16th (Orb-2)
- Scheduled to be released on Sept. 5th, 2014
- MIT SSL building bus (2U)
- Lincoln providing single band sensor (1U)



3U CubeSat

CubeSat Calibration Challenges

- Blackbody calibration targets introduce packaging challenges (substantially reduces volume available for the antenna)
- Electronic calibration sources (diodes, transistors, amplifiers, etc.) are prone to instability and drift over long time scales

- Potential solution: Use limb measurements co-located to GPS-RO measurements to periodically calibrate the electronic calibration sources
  - GPS-RO is inherently very accurate and precise
  - Traceable to NIST standard
  - Antenna arrays can be accommodated on CubeSats to allow penetration down to mid/upper troposphere (to be confirmed by MiRaTA)

The Next Step: MiRaTA

- **MicroMAS senses temperature only**
  - **Need temperature + water vapor + cloud ice**
- **MicroMAS calibration is course (~1-2 K)**
  - **GPS-RO cross calibration offers 10X improvement**
- **MicroMAS calibration is not NIST-traceable**
  - **GPS-RO time reference is traceable to NIST standards**

MiRaTA: Microwave Radiometer Technology Acceleration

Calibration Using Co-located GPS Radio Occultation

- **The radiometer views the Earth's limb at different observing angles and multiple passbands providing radiance measurements per angle and channel**
- **A near coincidental and co-located GPS-RO refractivity profile is collected when a GPS satellite enters the CubeSat's Field of View across the limb**
- **The radiometer's transfer function (counts to brightness temperature) is derived based on a regression on an ensemble of simulated radiances and GPS-RO refractivity profiles**
- **Frequent calibration utilize the onboard noise diode, which can drift over the mission lifetime, and the GPS-RO calibration can periodically calibrate the noise source**

GPS Radio Occultation

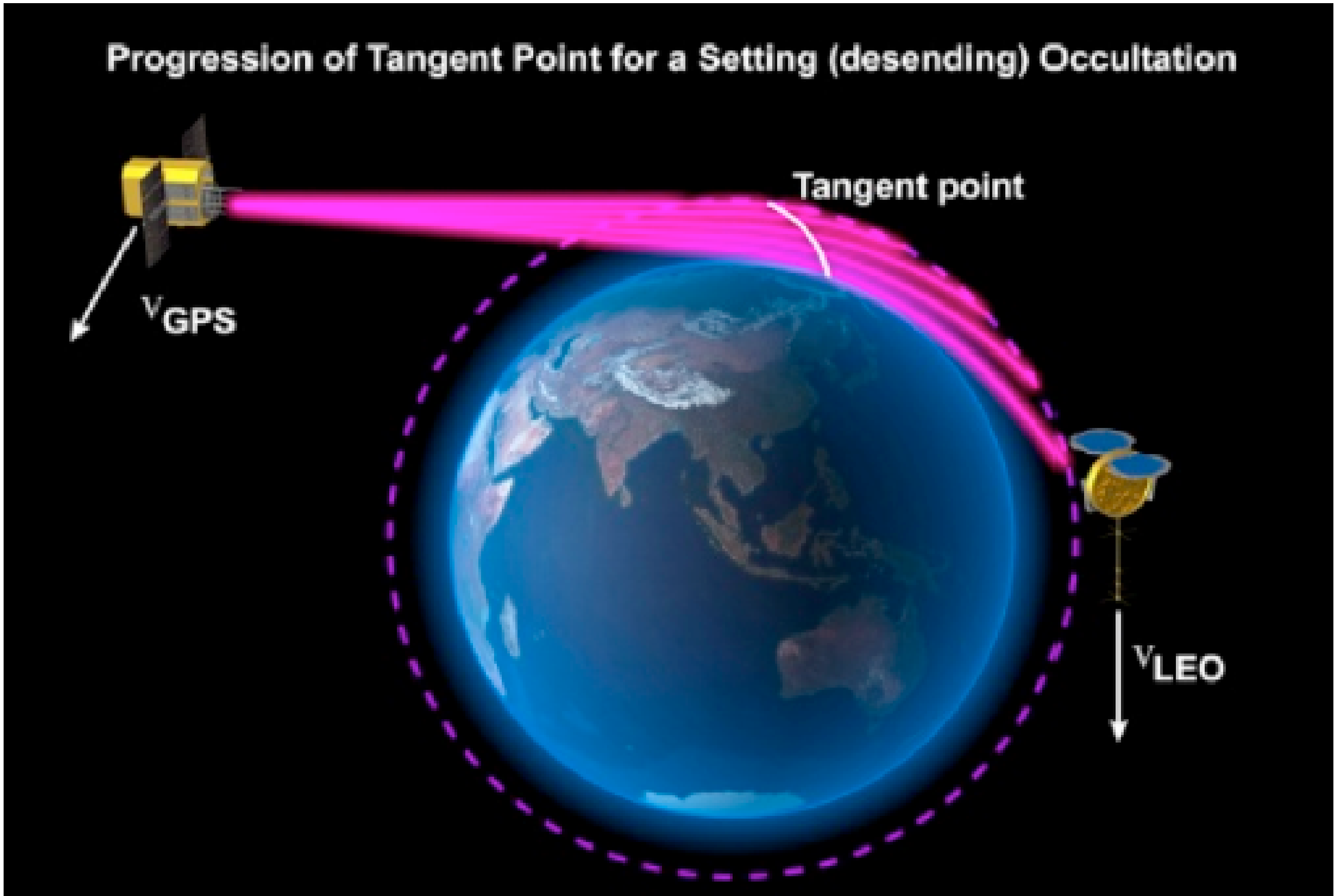
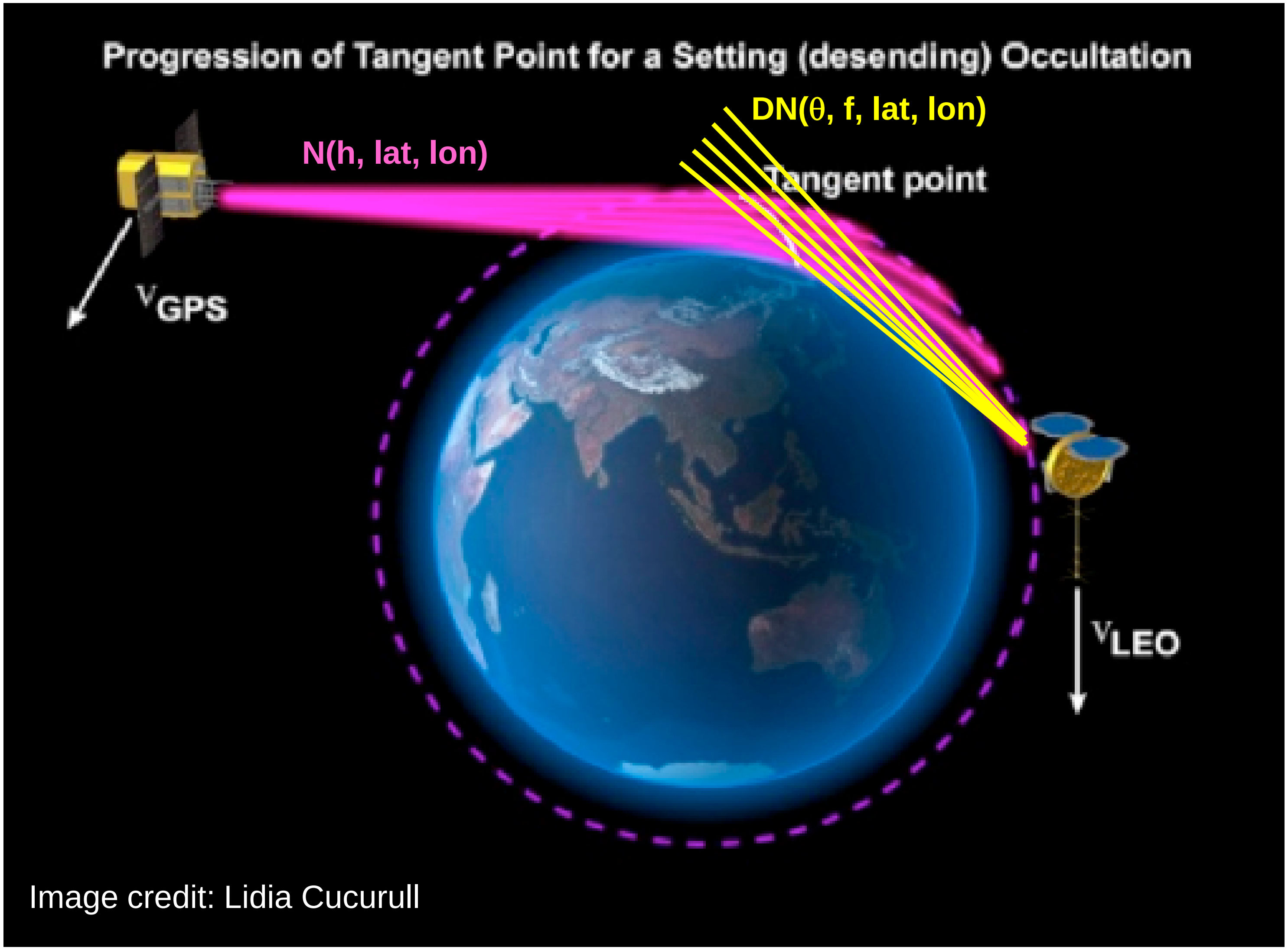


Image credit: Lidia Cucurull

GPS-RO + Radiometer



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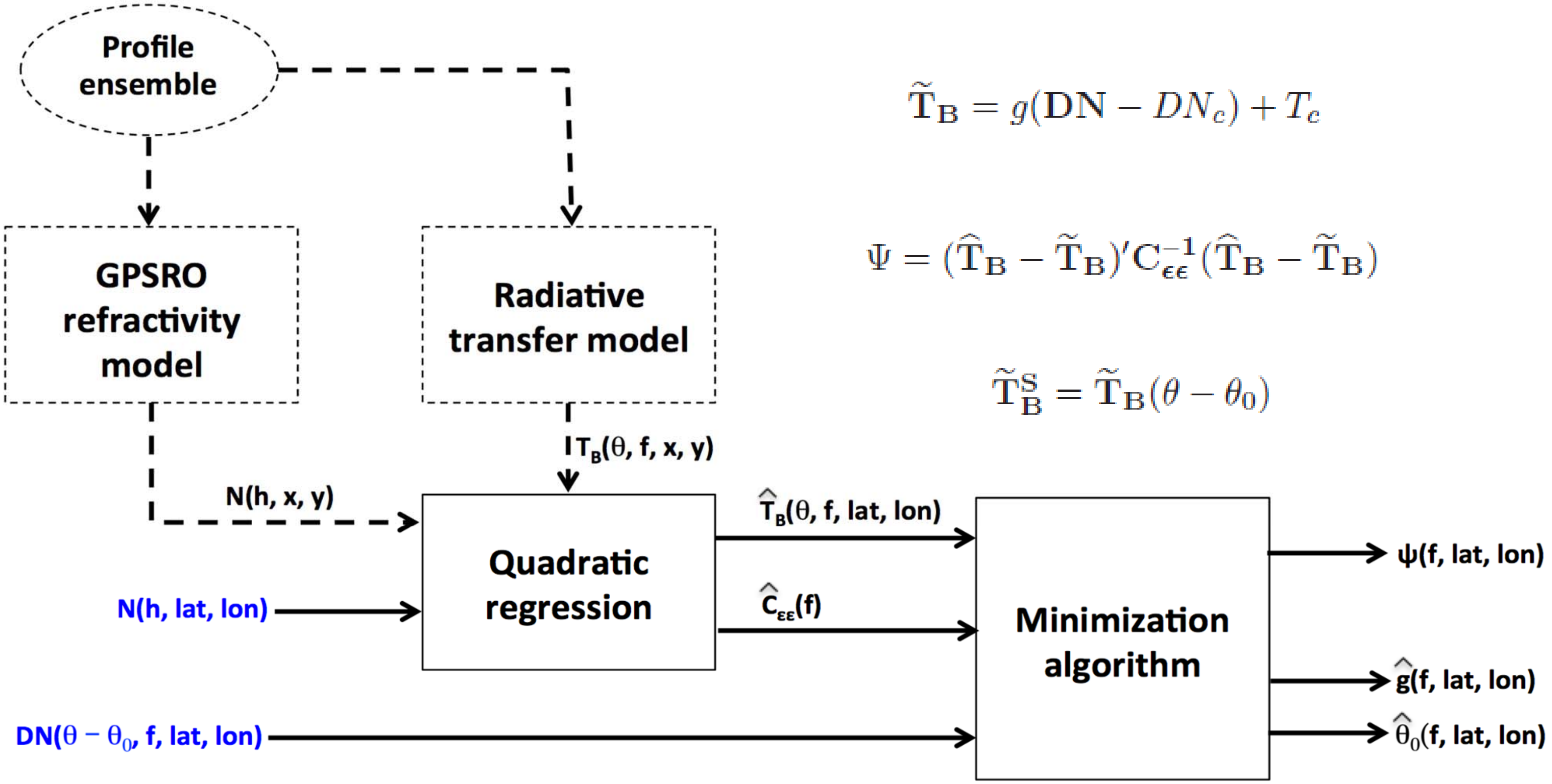
Block diagram of the GPS-RO microwave radiometer calibration procedure



$$\widetilde{\mathrm{T}}_{\mathrm{B}} = g(\mathrm{DN} - DN_c) + T_c$$

$$\Psi = (\widehat{\mathrm{T}}_{\mathrm{B}} - \widetilde{\mathrm{T}}_{\mathrm{B}})' \mathrm{C}_{\epsilon\epsilon}^{-1} (\widehat{\mathrm{T}}_{\mathrm{B}} - \widetilde{\mathrm{T}}_{\mathrm{B}})$$

$$\widetilde{\mathrm{T}}_{\mathrm{B}}^{\mathrm{S}} = \widetilde{\mathrm{T}}_{\mathrm{B}}(\theta - \theta_0)$$

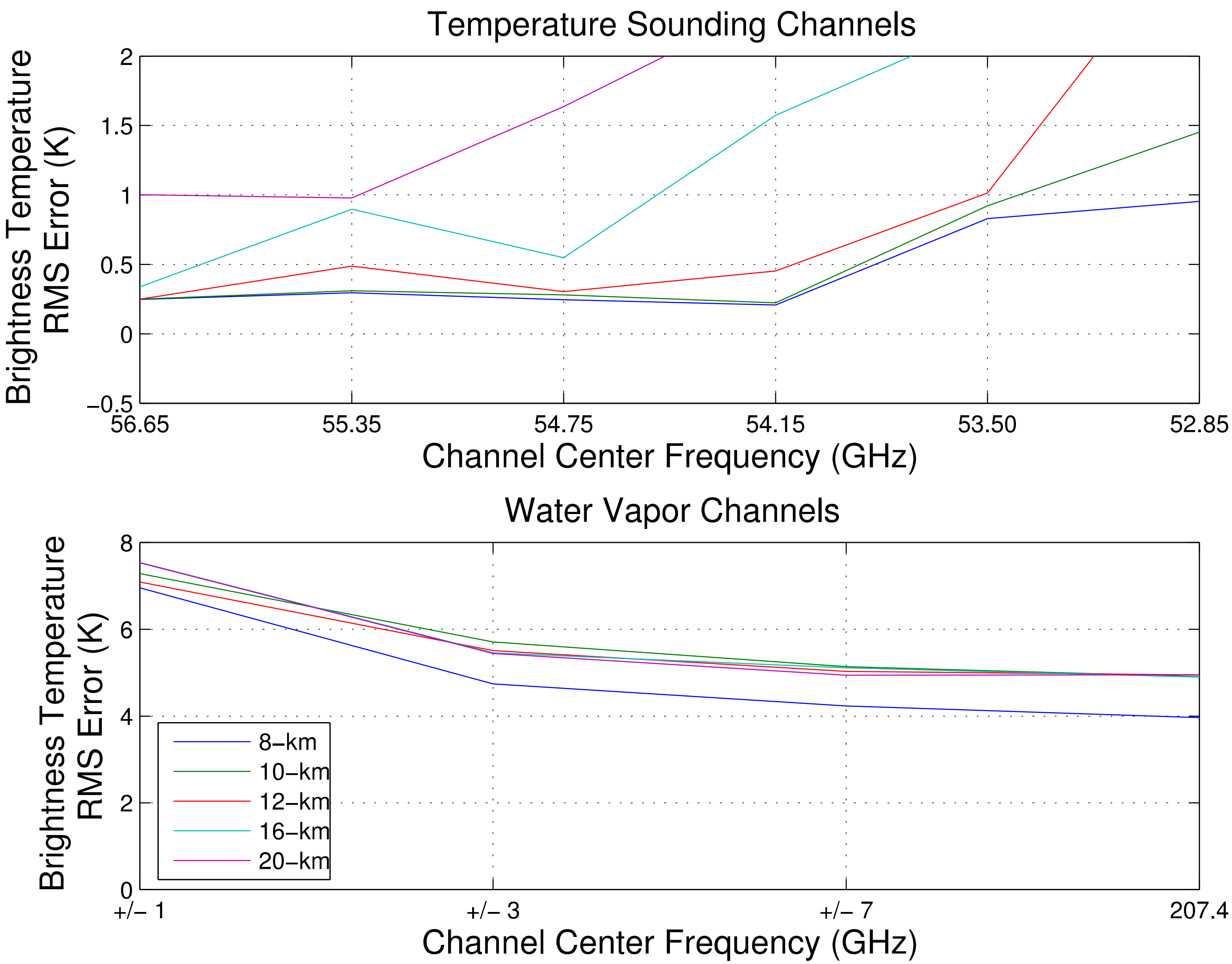
BLACKWELL *et al.*: RADIOMETER CALIBRATION USING COLOCATED GPSRO MEASUREMENTS

IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING, VOL. 52, NO. 10, OCTOBER 2014

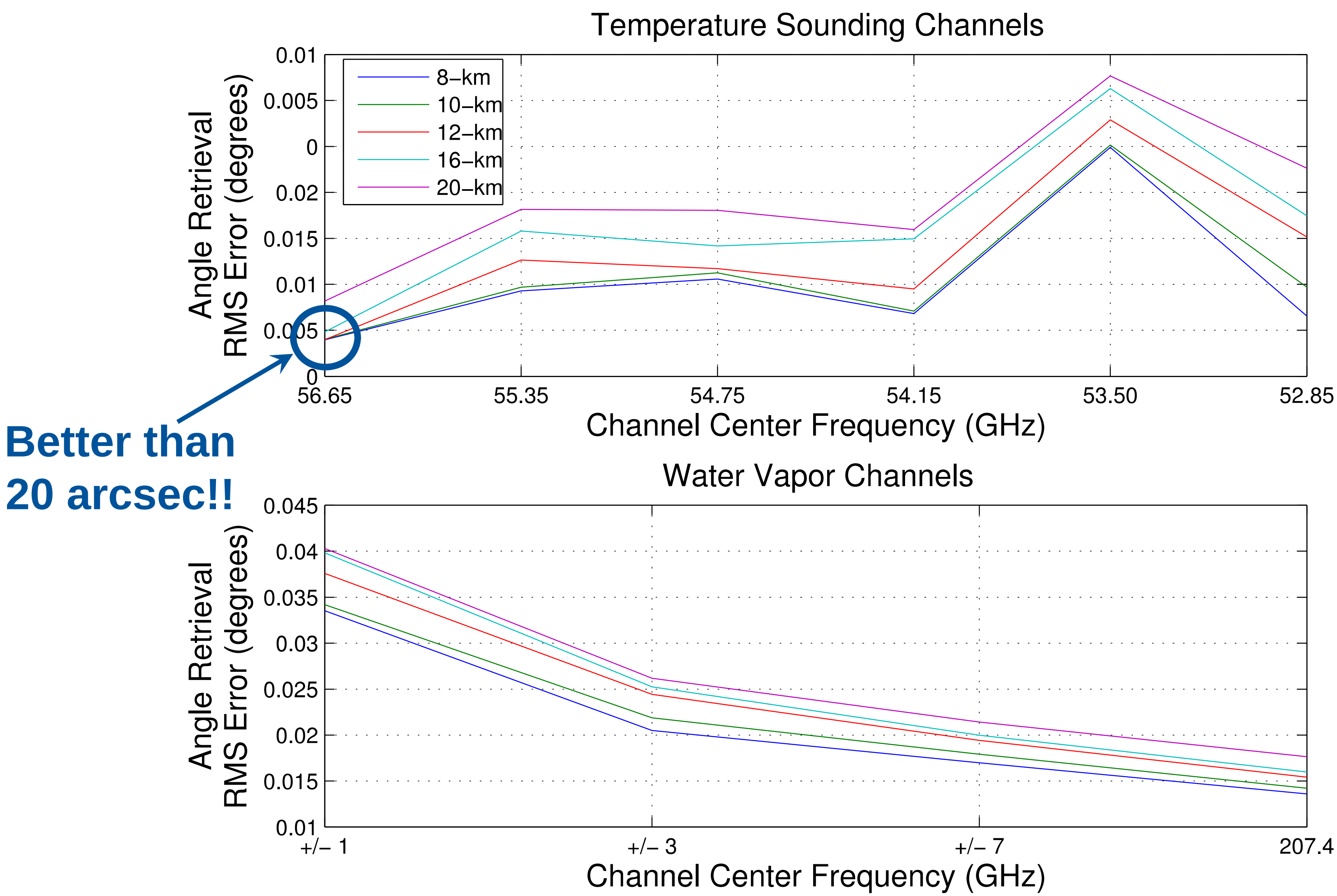
Simulation Assumptions

- 400 km orbit altitude
- 5.0° FWHM (V-band); 1.25° FWHM (G-band)
- 0.1° angular spacing (~4 kHz radiometer sample rate at 60 RPM!!)
- 200 angles used for V-band (55 to 75 degree scan angle)
- 40 angles used for G-band (67 to 71 degree scan angle)
- “gain” (K/count) mean of 0.02 with 0.0012 standard deviation

RMS Calibration Error
(Angle Offset Retrieved from Obs)



Angle Retrieval RMS Error



Observations and Caveats

- **Multichannel approaches possible if diode drift is correlated with frequency**
- **Method assumes that scan angle errors are constant over the scan (negligible jitter)**
  - **Appears to be valid based on testing of the MicroMAS scanning assembly**
- **Relatively high radiometer sample rates are required unless an onboard star tracker is used**
  - **5 kHz used for MicroMAS (one channel) and MiRaTA (all channels)**
  - **Minimal impact on data rate, as only a small angular sector is needed**

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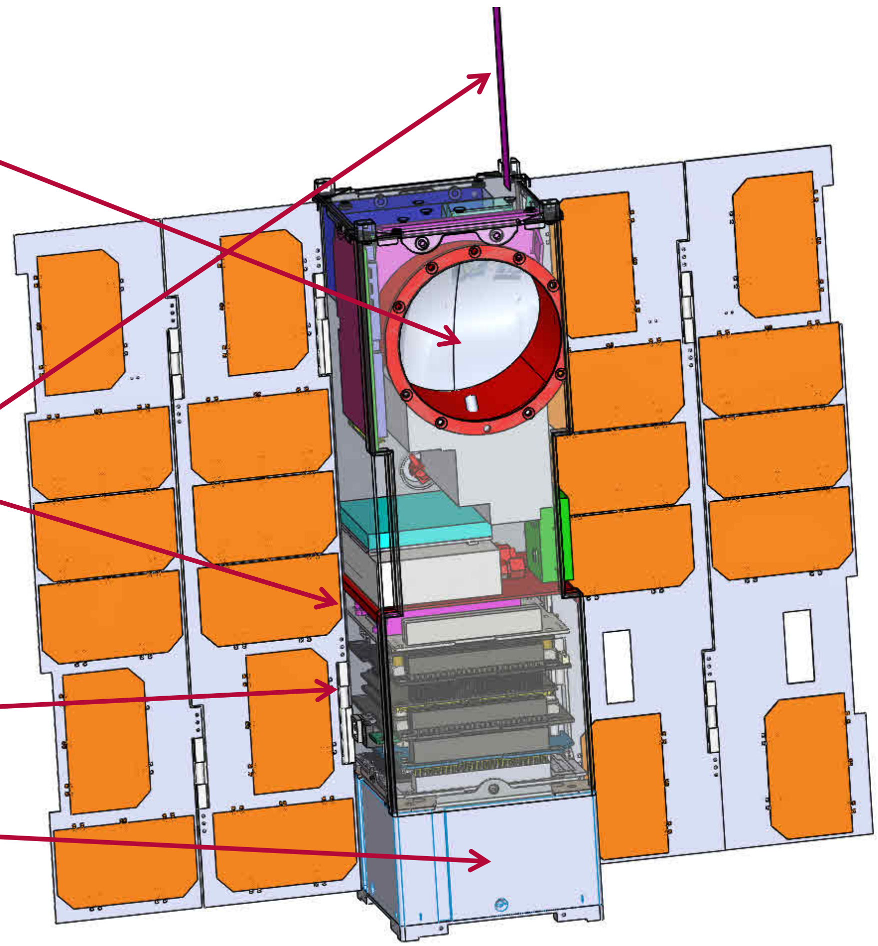
MiRaTA Bus

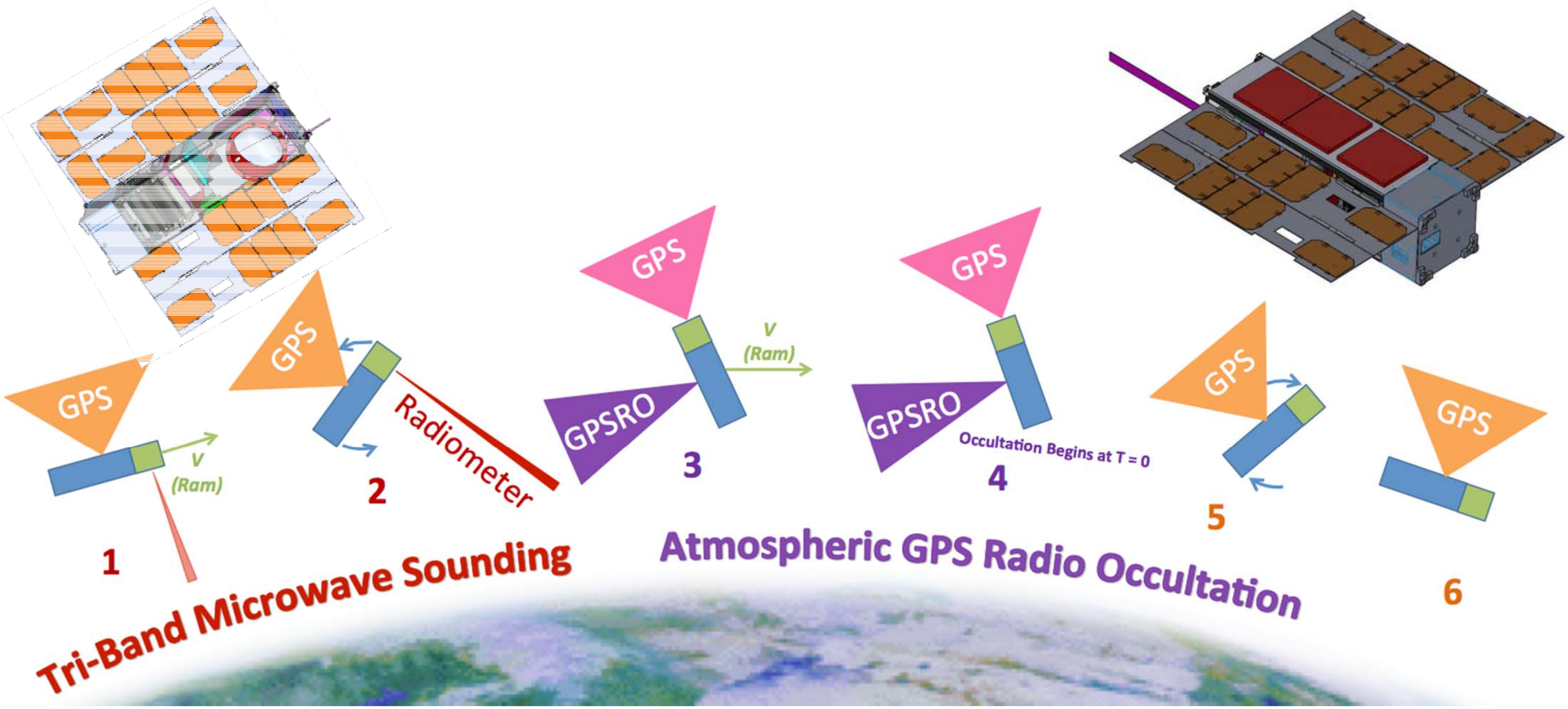
- **Payload**
  - Tri-band microwave radiometer
  - GPS radio occultation receiver with patch antenna array (on back)
- **Bus**
  - L-3 Cadet UHF Nanosatellite Radio with spring tape antenna*
  - Pumpkin PIC24F motherboard with Salvo RTOS*
  - Clyde Space EPS, battery, and double-sided deployed solar panels*
  - MAI-400 reaction wheels + Earth Horizon Sensors*
  - Custom interface boards



*** MicroMAS heritage**

MiRaTA Calibration Maneuver

Nominal Sci Ops for Coupled Atmospheric GPSRO & Microwave Radiometry



~ 20 minute maneuver
0.5° / sec rate

Spacecraft Requirements

Mission Success Criteria:

- At least 100 radiometer limb scans
- Radiometric precision consistent with T_R(V-band) = 500K and T_R(G-band) = 1500K
- Radiometric accuracy of 1.5 K (V-band) and 2.0 K (G-band)
- GPSRO temperature retrieval RMS error meeting JPSS requirements (approximately 1.5K RMS) [21] down to 20 km, threshold, and 10 km, goal).

Spacecraft Requirements:

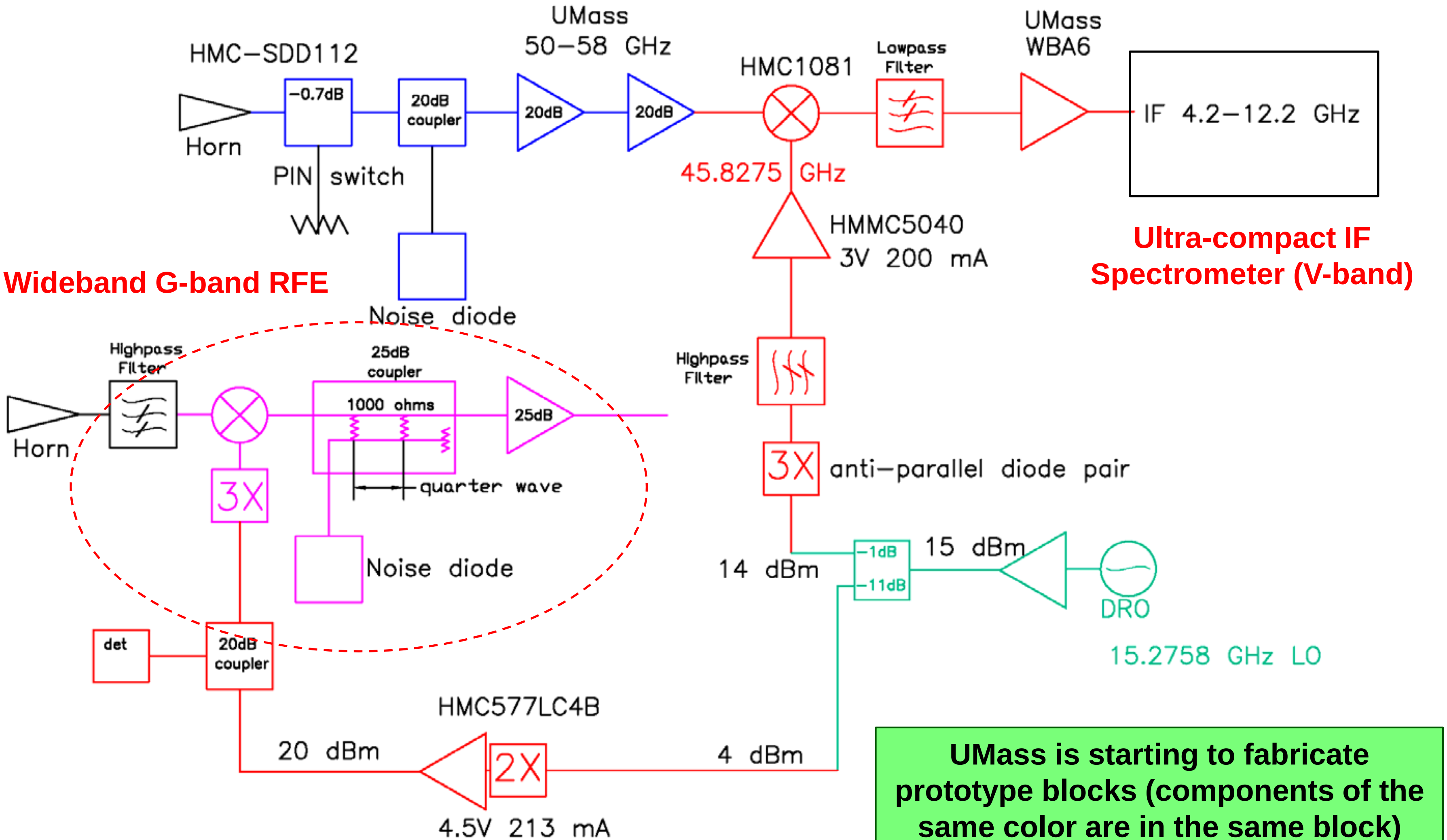
Requirement	Rationale
Pointing control of 2.5 degrees (1σ) threshold, 1.0 degree goal	Required to ensure co-location of radiometer and GPSRO measurements to within approximately 100 km
Pointing knowledge of 1.0 degrees (1σ) threshold, 0.5 degree goal	Required to permit geolocation of the observations to within approximately 10% of the footprint size
Minimum pitch rate of 0.5 degrees/sec	Ensure radiometric stability over the ~30 seconds of the limb scan for the G-band system (the V-band system will use a noise diode for calibration stability)
Minimum average data rate of approximately 5 kbps.	Required to transmit all observational and engineering data/metadata
Power systems shall provide: 5.5W to radiometer (10 min per orbit, 0.5W standby), 3.2W to CTAGS (20 min per orbit, 0.5W standby), 4.15W to spacecraft (always), and 10W for comm. transmit (<1 min per orbit)	Power for technology validation demonstration and survival
Minimum 90 day mission lifetime from 300-390 km orbit at 52° inclination	Time needed to fulfill objectives with >100% margin

MAI-400 + IR EHS
GPS POD

L-3 Cadet UHF Nanosatellite Radio
NASA WFF 18 m dish

Clyde Space 20 Wh battery, EPS, double-sided deployed panels

Radiometer (UMass-Amherst & MIT LL)



UMass is starting to fabricate prototype blocks (components of the same color are in the same block)

Summary

- GPS Radio Occultation offers a new, high-performance calibration standard for passive microwave radiometry
- Combines precision of GPS-RO with dense spatial coverage of cross-track-scanning passive sounders
- Simulation study presented using GPSRO refractivity to initialize radiometer gain optimization routing
- Performance simulations indicate absolute calibration accuracies approaching 0.1K are achievable
- MiRaTA CubeSat mission is being formulated to demonstrate these results (2016 launch)
- MicroMAS CubeSat mission (early Sept. 2014 ISS release) will demonstrate these results in one channel using GPSRO "measurements of opportunity"

Backup Slides

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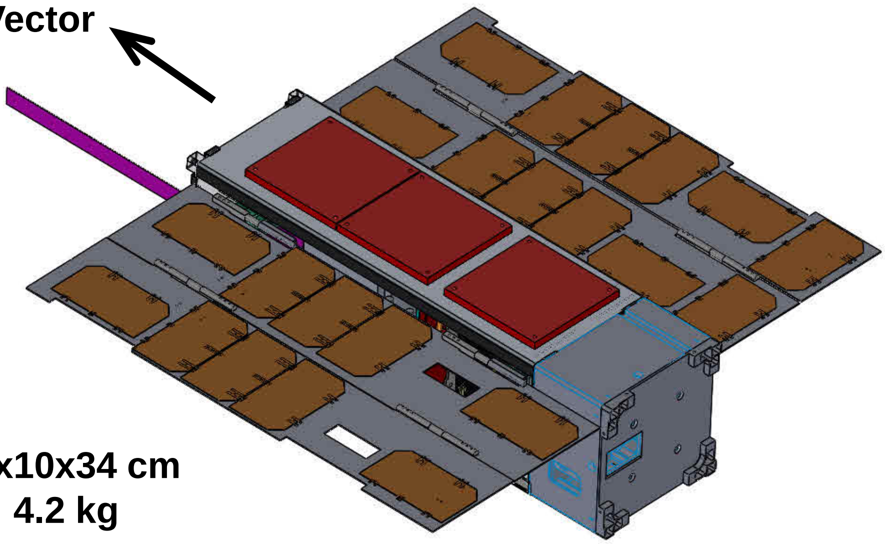
MiRaTA (2016 Launch)

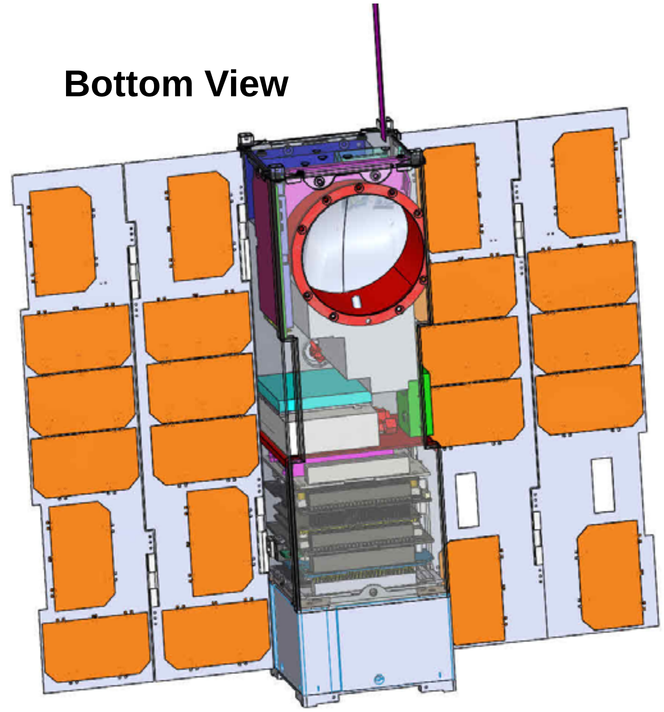
Velocity Vector

Top View



10x10x34 cm
4.2 kg

Bottom View

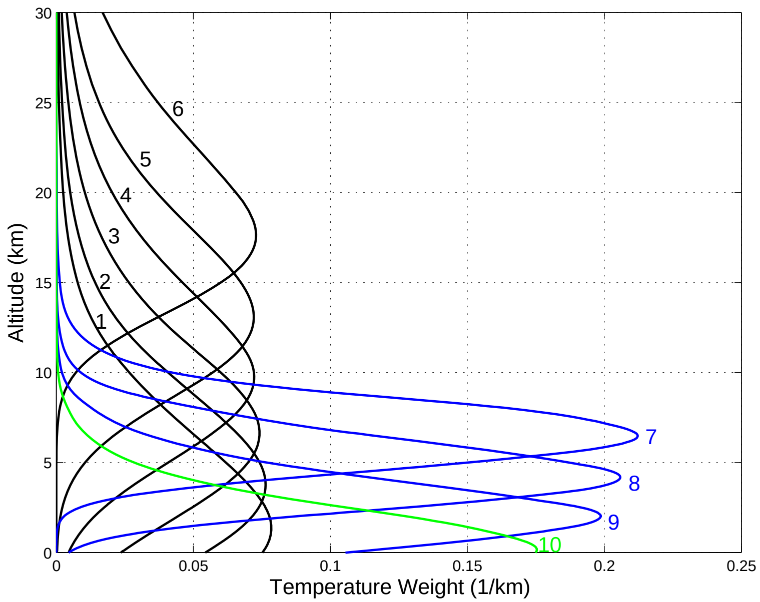


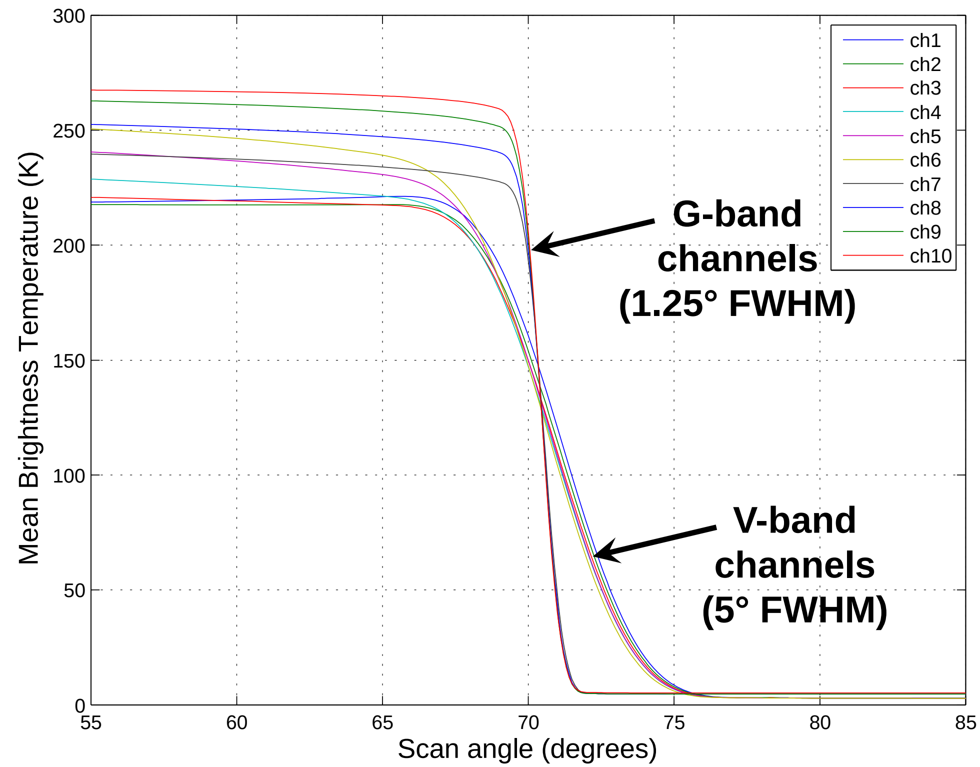
MiRaTA
Microwave Radiometer Technology Acceleration

- **Funded by NASA Earth Science Technology Office**
- **First demonstration of CubeSat Atmospheric GPSRO**
- **First CubeSat tri-band radiometer (9-cm aperture)**
- **First demonstration of radiometer + GPSRO**
- **Based largely on MicroMAS (MIT/LL/UMASS) and CTECS (Aerospace)**

MiRaTA Spectral Characteristics

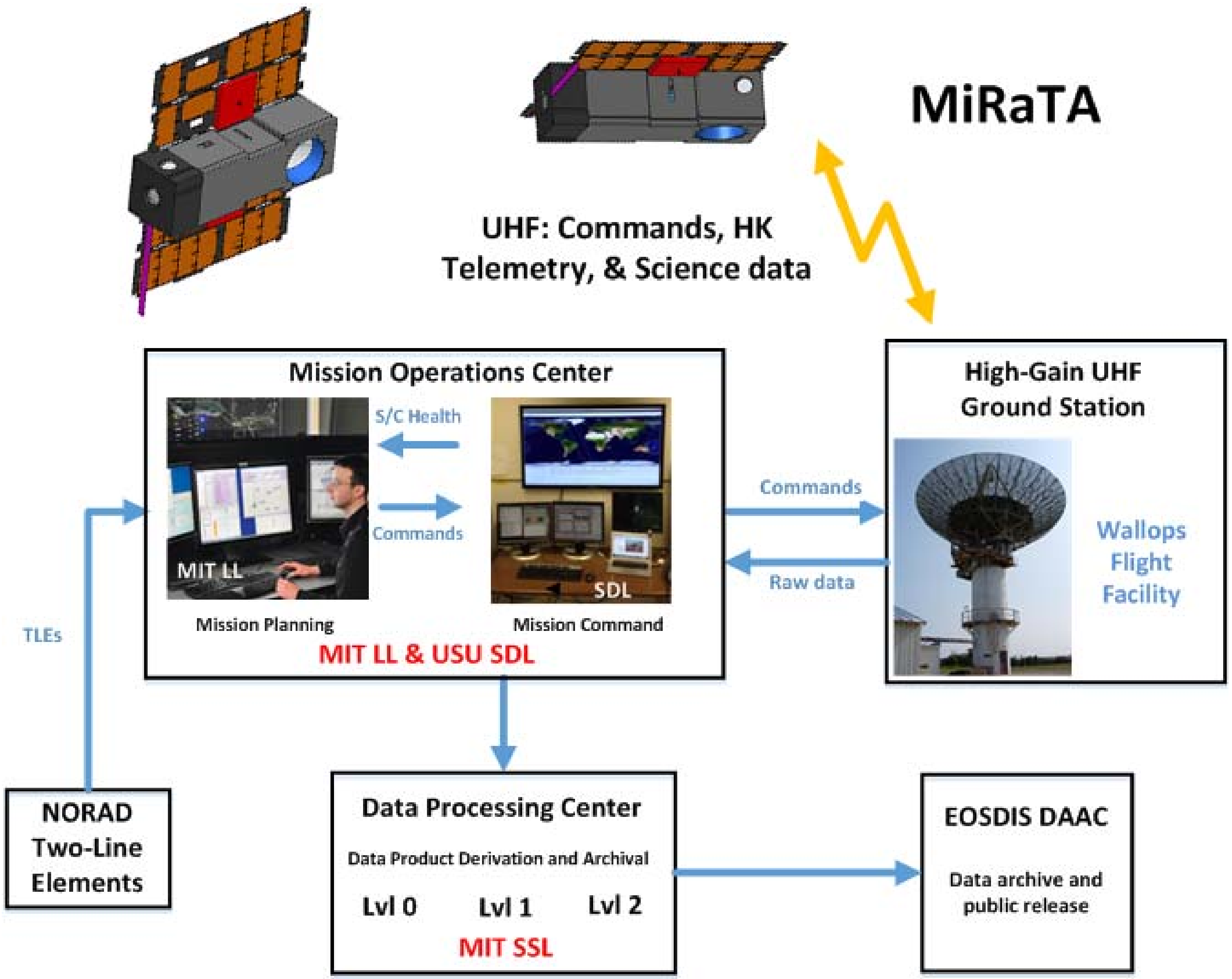
Channel #	Center Frequency (GHz)	Bandwidth (MHz)
1	52.85	600
2	53.50	600
3	54.15	600
4	54.75	600
5	55.35	600
6	56.00	600
7	183.31 ± 1	500
8	183.31 ± 3	1000
9	183.31 ± 7	2000
10	207.4	2000



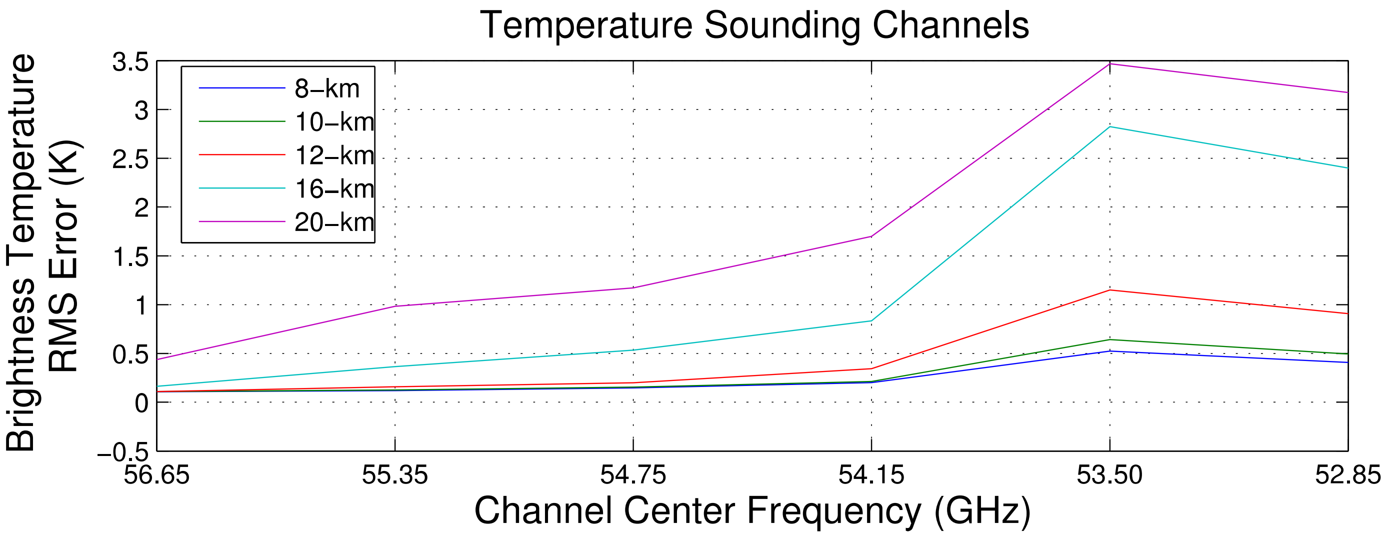


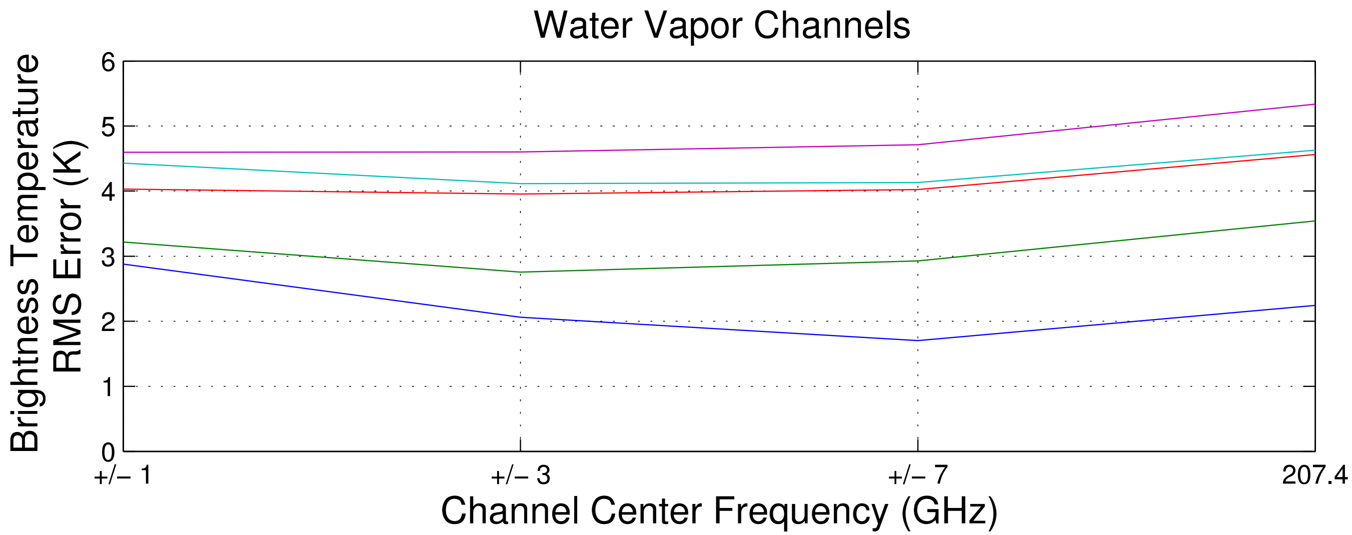
$dT_B/d\theta > 100$!!

MiRaTA Ground Segment

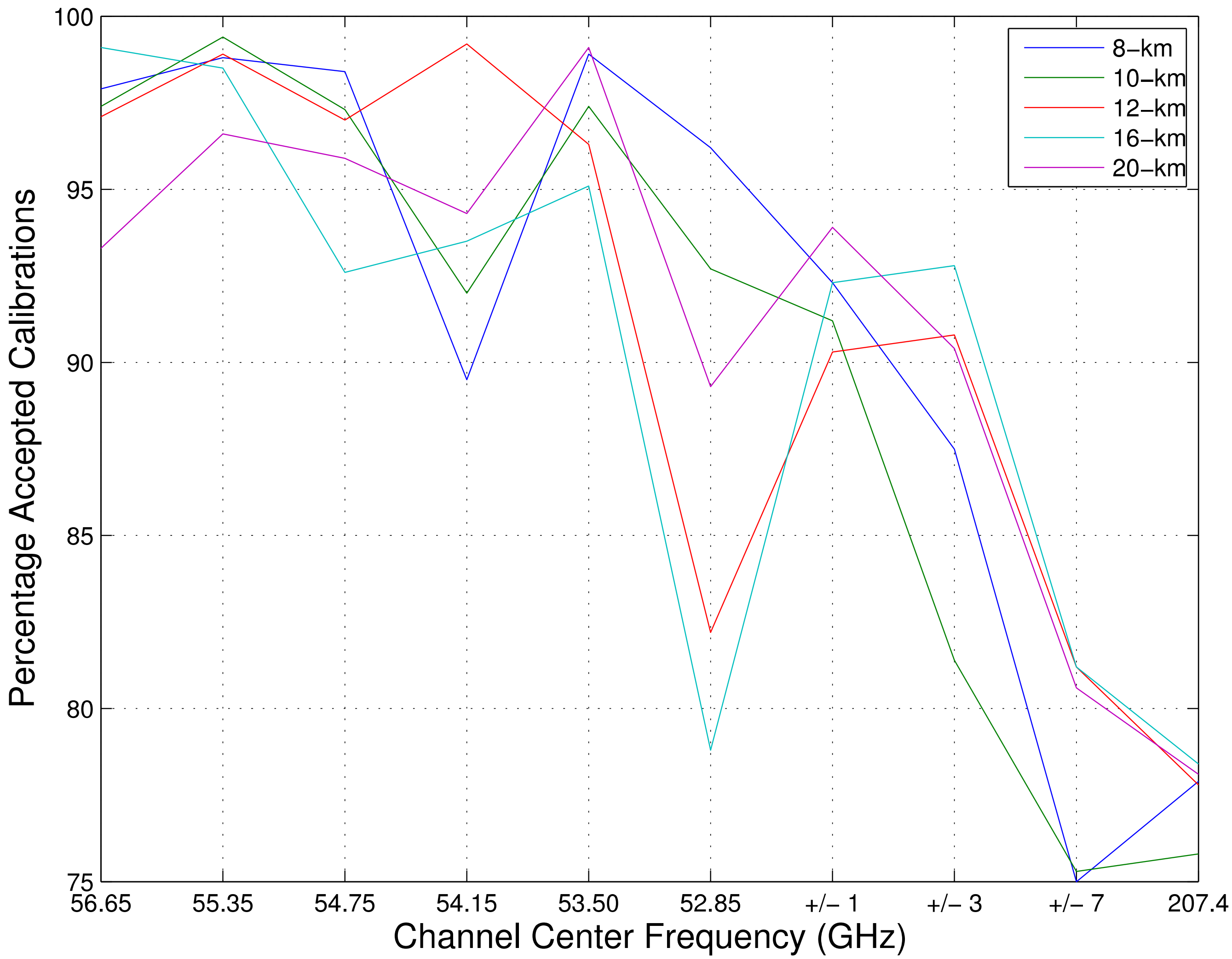


RMS Calibration Error (Perfect Angle Knowledge)

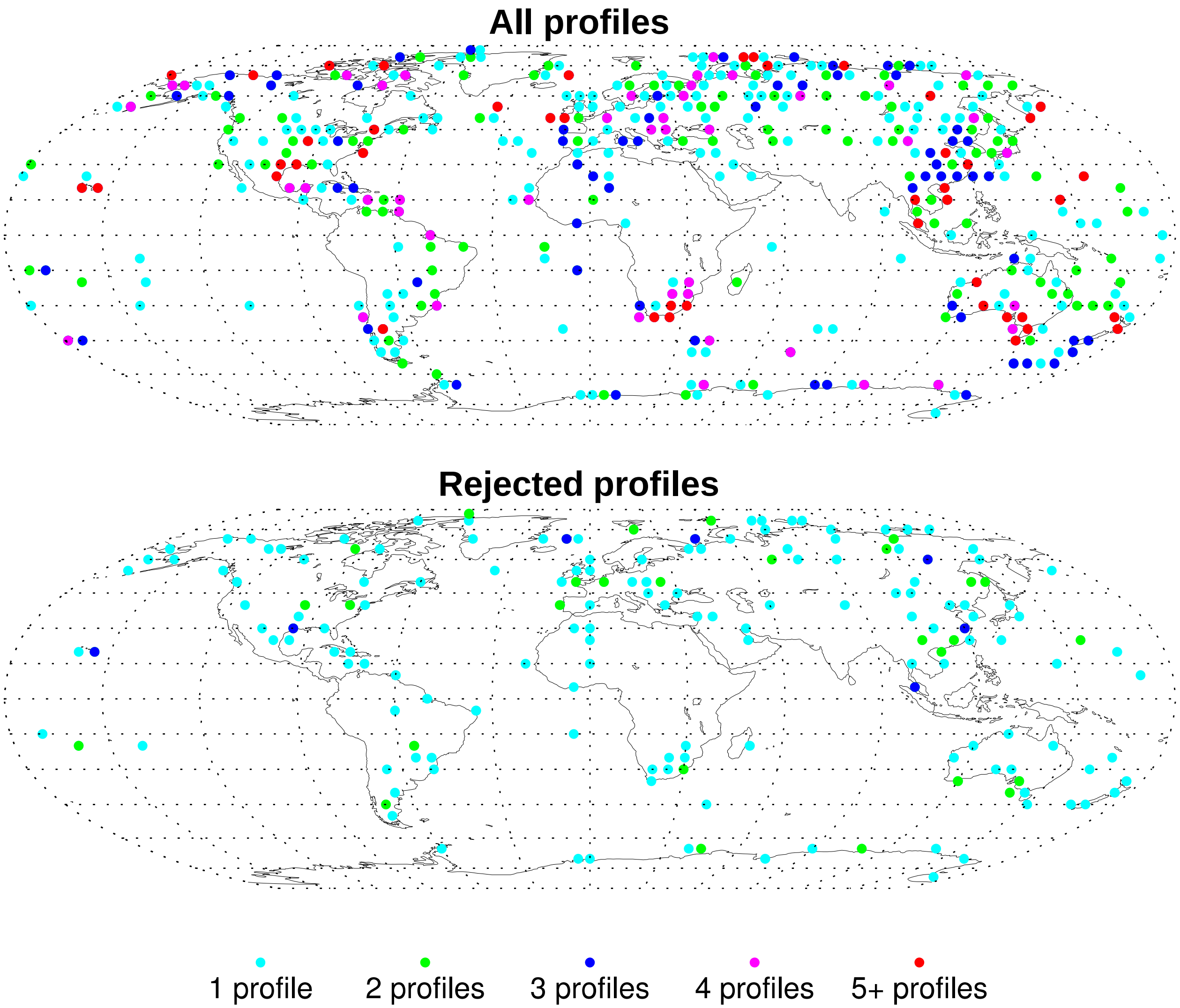




Percentage of Accepted Calibrations



Geograpical Locations of Profiles



MiRaTA Performance Versus State-of-the-Art (ATMS)

	ATMS	MiRaTA
Volume (m^3)	0.17	0.003
Mass (kg)	75	4
Sensor power (W)	100	8.7
Sensor cost ($M)	>100	~2
Share of spacecraft cost ($M)	>100	~1
Share of launch cost ($M)	20	0.221
Impact of launch failure	Severe degradation	Rapidly replaceable
Antenna beamwidth (deg) @ 55/183 GHz	2.2/1.1	5/1.25
Receiver noise temperature (K)	500,1800 (55/183 GHz)	500,1800 (55/183 GHz)
G-band mixer bandwidth	~15 GHz	~25 GHz
23.8/31.4/89/166-GHz channels	Yes	No
Cloud ice channel (207.4 GHz)	No	Yes
On-orbit electronic calibration	No	Yes (V-band)
On-orbit calibration accuracy	1.5K/2.0K	1.5K/2.0K
Temperature profile RMS error	~2.0K	~1.5K

Validation Methdology

- High-fidelity, independent ground truth needed to verify radiometer calibration accuracy
- Multiple proven validation techniques will be used
- Cross calibrations with ATMS/AMSU
- Cross calibration with COSMIC GPS-RO
- Comparisons with radiosondes and global NWP models