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

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November 4, 2016

This work is sponsored by the National Aeronautics and Space Administration. Opinions, interpretations, conclusions, and recommendations are those of the authors and are not necessarily endorsed by the United States Government.
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

Impact of GOS components on 24-h ECMWF Global Forecast skill
(courtesy of Erik Andersson, ECMWF)

Passive microwave observations have the highest impact

Satellite data now account for most of the skill

Bigger is better
Microwave Atmospheric Sensing

The frequency dependence of atmospheric absorption allows different altitudes to be sensed by spacing channels along absorption lines.
New Approach for Microwave Sounding

Suomi NPP Satellite
(Launched Oct. 2011)

- Advanced Technology Microwave Sounder (ATMS)
- 2100 kg
- NASA/GSFC

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

NPP: National Polar-orbiting Partnership

NEROC- 5
KLC, ADM, WJB  11/4/2016
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
- 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

**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

Nominal Sci Ops for Coupled Atmospheric GPSRO & Microwave Radiometry

~ 10 minute maneuver
0.5° / sec rate
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

OEM628 GPS Receiver  
UHF antenna  
Radiometer  
MAI ADCS Unit  
IFP/PIM Assembly  
Avionics Stack  
GPSRO
Bus Flight Hardware

Custom Top Interface Board

L-3 Cadet

Micron Motherboard (custom)

Custom Micron Radio

ADCS MAI-400

IMU

Custom Bottom Interface Board

Clyde Space Electrical Power System

Clyde Space Battery
Payload: Radiometer Receiver Front End
MiRaTA Radiometer System

All flight radiometer hardware delivered
Radiometer Flight Hardware

DRO

PVRM

V-RFE

PIM

Reflector, feedhorns, & V-RFE

V-IFP

G-IFP

G-RFE-1

G-RFE-2
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
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

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

55.35 GHz (330 MHz bandwidth)

Altitude (km)

Temperature Weight (1/km)

Nadir
Near limb

GPS-RO “sweet spot”
MiRaTA Product Validation Approach

Level 0 Data Products

- MiRaTA Radiometer Raw Data Lvl 0
  - Calibration & Geolocation
  - Radiometer Radiance Data Lvl 1b
    - Radiometer Radiance Accuracy
      - Collocate & Difference
        - Radiometer Radiative Transfer Model
          - NWP Radiance Data
  - MiRaTA Radiometer Calibration Approach
    - [Blackwell, et al 2014](#)

Level 1b Data Products

- CTAGS Bending Angle Data Lvl 1b
  - Refraction & Profile Retrievals
    - CTAGS Profiles Lvl 2
      - CTAGS Profile Accuracy
        - Collocate & Difference
  - MiRaTA CTAGS Data Products
    - [Marinan, et al., 2016](#)

Level 2 Data Products

- NWP Atmospheric “Truth” Data
  - MiRaTA Radiometer Calibration Approach

Algorithm Data set Metric
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

![Diagram showing the data processing flow for MiRaTA GPSRO data products. The flow includes steps from Level 0 Data Products to Level 2 Data Products, with specific milestones such as Radiometer Raw Data, Calibration & Geolocation, Radiometer Radiance Data, Radiometer Radiative Transfer Model, Radiometer Radiance Accuracy, CTAGS Profile Accuracy, NWP Radiance Data, and NWP Atmospheric "Truth" Data.]

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)

\(\lambda\) is the sampling frequency (L1 or L2)

\(\tau\) 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 $SNR_v$, 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)

\[
T = \frac{2Z_F}{V} = \text{integration time}
\]

\[
Z_F = \text{Fresnel zone diameter}
\]

\[
\lambda = \text{sampling wavelength}
\]

\[
D_t = \text{distance from tangent point to Tx}
\]

\[
D_r = \text{distance from tangent point to Rx}
\]

\[
v = \text{vertical rate of link}
\]
Deriving Temperature Precision

- Doppler noise calculated from phase precision

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

\[ \sigma_\alpha = \frac{\lambda \sigma_{\text{Doppler}}}{V_0} \]

\[ \sigma_{\alpha_{\text{neut}}}^2 = (2.54)^2 \sigma^2_{\alpha_1} + (1.54)^2 \sigma^2_{\alpha_2} \]

- 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 Inputs**

Altitude (km):
- [400 500 600 700]

Inclination (deg):
- [0 30 60 98]

Numbers of satellites:
- [1 3 6]

**External Input:** GPSRO antenna 60 deg HPBW

**GPSRO Model (MATLAB/STK)**

- Max Gain
- Gain Pattern
- Field of View

**Parametric Model**

Lookup table with:
- Total number of occultations
- Angle of accesses (mean, std dev)
- Range of accesses (mean, std dev)

For various altitudes and inclinations

**Outputs**

- Access Intervals
- Numbers of Occultations
- Revisit Rate
- Link Budget Analysis

**External Input**

Altitude (km):
- Satellite Altitude

Inclination (deg):
- Satellite Inclination

Numbers of satellites:
- GPS Position and Velocity
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

<table>
<thead>
<tr>
<th></th>
<th>400 km</th>
<th>500 km</th>
<th>600 km</th>
<th>700 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>80%</td>
<td>84%</td>
<td>87%</td>
<td>89%</td>
</tr>
<tr>
<td>30°</td>
<td>60%</td>
<td>63%</td>
<td>66%</td>
<td>69%</td>
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<tr>
<td>60°</td>
<td>62%</td>
<td>65%</td>
<td>68%</td>
<td>71%</td>
</tr>
<tr>
<td>98°</td>
<td>69%</td>
<td>72%</td>
<td>75%</td>
<td>77%</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th></th>
<th>400 km</th>
<th>500 km</th>
<th>600 km</th>
<th>700 km</th>
</tr>
</thead>
<tbody>
<tr>
<td>0°</td>
<td>36820</td>
<td>36570</td>
<td>36180</td>
<td>35530</td>
</tr>
<tr>
<td>30°</td>
<td>31150</td>
<td>31830</td>
<td>32330</td>
<td>32510</td>
</tr>
<tr>
<td>60°</td>
<td>33480</td>
<td>34490</td>
<td>35190</td>
<td>35600</td>
</tr>
<tr>
<td>98°</td>
<td>38780</td>
<td>39560</td>
<td>39990</td>
<td>40240</td>
</tr>
</tbody>
</table>

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

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

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Date</th>
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<tr>
<td>Award “Start”</td>
<td>Dec. 20, 2013</td>
</tr>
<tr>
<td>NSSC Approval</td>
<td>Feb. 12, 2014</td>
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<tr>
<td>Funds distributed</td>
<td>Mar. 14, 2014</td>
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<tr>
<td>Project Kickoff with Subs</td>
<td>Apr. 2014</td>
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<tr>
<td>System Requirements Review</td>
<td>June 2, 2014</td>
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<tr>
<td>System PDR</td>
<td>Oct. 22, 2014</td>
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<tr>
<td>System CDR</td>
<td>June 1-3, 2015</td>
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<tr>
<td>Deadline to complete testing reports</td>
<td>Nov. 11, 2016</td>
</tr>
<tr>
<td>Mission Readiness Review</td>
<td>Dec. 6, 2016</td>
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<tr>
<td>CubeSat Delivery</td>
<td>Jan. 10, 2017</td>
</tr>
<tr>
<td>Launch</td>
<td>March, 2017*</td>
</tr>
</tbody>
</table>

* 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

VDI 183X6DSHMR1 1-04 Performance

Noise Temperature (K)

LO Power (mW)