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Microwave Radiometer Technology Acceleration Mission (MiRaTA): Advancing Weather Remote Sensing with Nanosatellites

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ABSTRACT

The Microwave Radiometer Technology Acceleration (MiRaTA) is a 3U CubeSat NASA Earth Science Technology Office (ESTO) mission under development for a 2016 launch. Microwave radiometry and GPS radio occultation (GPSRO) measurements of all-weather temperature and humidity provide key contributions toward improved weather forecasting. The MiRaTA mission will validate new technologies in both passive microwave radiometry and GPS radio occultation: (1) new ultra-compact and low-power technology for multi-channel and multi-band passive microwave radiometers, and (2) new GPS receiver and patch antenna array technology for GPS radio occultation retrieval of both temperature-pressure profiles in the atmosphere and electron density profiles in the ionosphere. In addition, MiRaTA will test (3) a new approach to spaceborne microwave radiometer calibration using adjacent GPSRO measurements. Radiometer measurement quality can be substantially improved relative to present systems through the use of proximal GPSRO measurements as a calibration standard for radiometric observations, reducing and perhaps eliminating the need for costly and complex internal calibration targets. MiRaTA will execute occasional pitch-up maneuvers so that radiometer and GPSRO observations sound overlapping volumes of atmosphere through the Earth's limb. To validate system performance, observations from both microwave radiometer (MWR) and GPSRO instruments will be compared to radiosondes, global high-resolution analysis fields, other satellite observations, and to each other using radiative transfer models. Both the radiometer and GPSRO payloads, currently at TRL5 but to be advanced to TRL7 at mission conclusion, can be accommodated in a single 3U CubeSat. The current plan is to launch from an ISS orbit at ~400 km altitude and 52° inclination for low-cost

validation over a ~90-day mission to fly in 2016. MiRaTA will demonstrate high fidelity, well-calibrated radiometric sensing from a nanosatellite platform, thereby enabling new architectural approaches for mission implementation at lower cost and risk with more flexible access to space.

INTRODUCTION

The need for low-cost, mission-flexible, and rapidly deployable spaceborne sensors that meet stringent performance and operational requirements pervades the NASA Earth Science measurement programs, particularly the recommended NRC Earth Science Decadal Survey, "DS" missions [1] and core elements of the Climate-Centric Architecture, "CCA" [3]. Both the DS and CCA have explicitly identified the need for microwave radiometric observations for several recommended missions, such as PATH (Precipitation and All-weather Temperature and Humidity), ACE (Aerosol and Cloud Experiment), SWOT (Surface Water Ocean Topography), and SCLP (Snow and Cold Land Processes). Furthermore, the CCA highlighted the need "to assure the consistency of data across platforms and the traceability of data to recognized standards." MiRaTA will demonstrate and validate new low-cost and ultra-compact radiometer and GPS radio occultation technologies that address multiple program needs.

MiRaTA will validate ultra-compact, low-power core technology elements with cross-cutting applications. The elements are: 1a) a V-band (52-58 GHz) radiometer subsystem with ultra-compact (IF) spectrometer, 1b) a G-band (175-191 & 207 GHz) radiometer subsystem with wideband mixer front-end, and 2) a GPS radio occultation instrument for tropospheric observations whose measurements can contribute to radiometer calibration. These elements are functionally independent but highly synergistic, and all are readily accommodated in a single 3U CubeSat for low-cost validation. Any one of these three elements can be validated on-orbit even if both of the other two elements fail, thereby substantially lowering overall program risk.

These core technology elements would directly improve Earth Science Measurements in several ways. MiRaTA will demonstrate high-fidelity, well-calibrated radiometric sensing from very small satellite platforms, thereby enabling new architectural approaches for mission implementation at lower cost and risk with more flexible access to space. Demonstration of performance at lower cost and risk would enable constellation architectures that improve mission reliability, robustness, and data continuity by allowing a "distributed" earth observatory that could be fractionated over space and/or time. In addition, measurement quality can be substantially improved relative to present systems through the use of proximal GPSRO measurements as a calibration standard for radiometric observations, reducing and perhaps eliminating the need for costly and problematic internal calibration targets.

The MiRaTA radiometer and GPSRO sensors will offer significantly improved performance relative to current systems envisioned for the missions recommended by the Decadal Survey, including ACE, SCLP, SWOT, and PATH, as well as other planned Earth observation missions such as GPM (Global Precipitation Mission), JPSS (Joint Polar Satellite System) and others. For example, approximately 20 LEO CubeSats would provide average revisit rates better than 15 minutes over the entire globe (30 minutes in the tropics)[4], which substantially exceeds the coverage of present concepts [5].

Mission goals

The three-year MiRaTA program will validate radiometer and GPSRO instrument subsystems currently at TRL5: 1a) a six-channel ultra-compact V-band spectrometer (mated with a high-TRL 52-58 GHz front end), 1b) a G-band broadband mixer operating from approximately 175 to 210 GHz (mated with a high-TRL back end), and 2) a GPS radio occultation receiver that retrieves atmospheric profiles of temperature and humidity. The primary mission objective is to validate these subsystems independently to demonstrate state-of-the-art performance and achieve PATH objectives [5]: MiRaTA Objective 1) is to achieve absolute radiometric accuracy of 1.5 K (V-band radiometer; GPSRO) and 2.0 K (G-band radiometer) using comparisons to a comprehensive set of radiosondes and global analyses coupled with radiative transfer models [6]. MiRaTA Objective 2) is to achieve radiometric precision (noise equivalent delta temperature, NEdT) of 0.1 K at 55 GHz, 0.3/0.2/0.15 K at 183 ± 1/3/7 GHz, and 0.25 K at 207 GHz assuming 100 ms integration time and bandwidths given in the Payload section with the radiometer description. Finally, MiRaTA Objective 3) is to compare the radiometer and GPSRO measurements to demonstrate improved calibration of the radiometer using GPSRO as a reference. This mission will mark the first ever implementation of co-located radiometer and GPSRO sounding and the first CubeSat implementation of both temperature and humidity radiometric sounding and GPSRO atmospheric sounding. Therefore, not only will MiRaTA validate multiple subsystem technologies, but new sensing modalities will be demonstrated as well.

PAYLOAD OVERVIEW

The MiRaTA CubeSat will contain two complete instrument systems, a tri-band atmospheric sounder and a Compact TEC (Total Electron Count)/Atmosphere GPS Sensor (CTAGS). These two instruments will be operated in a manner to allow cross-comparison and cross-calibration.

Microwave Radiometer (MWR)

The tri-band microwave atmospheric sounder provides co-located observations over three frequency bands, 52-58, 175-191, and 206-208 GHz and comprises two radiometer subsystems as shown notionally in Figure 1. The specific frequency plan and radiometer design is ongoing, and slight modifications to the radiometer system are expected. Subsystem 1) is a V-band (52-58 GHz) receiver ("front end") with weakly coupled noise diode, low-noise MMIC amplifier, mixer, intermediate frequency (IF) preamplifier, and ultracompact IF spectrometer ("back end") with highly-scalable LTCC/SIW architecture [7] operating over the 23-29 GHz IF band to provide six channels with temperature weighting functions approximately uniformly distributed over the troposphere and lower stratosphere. Subsystem 2) is a broadband G-band mixer front end operating from 175.31 to 208.4 GHz with a conventional IF spectrometer back end with lumped element filters. The V-band front end and the G-band back end are currently at very high TRL, having been flown on several spaceborne systems [8] [9]. MiRaTA will advance the TRL for the ultracompact IF spectrometer back end and the broadband G-band mixer front end from TRL5 to TRL7.

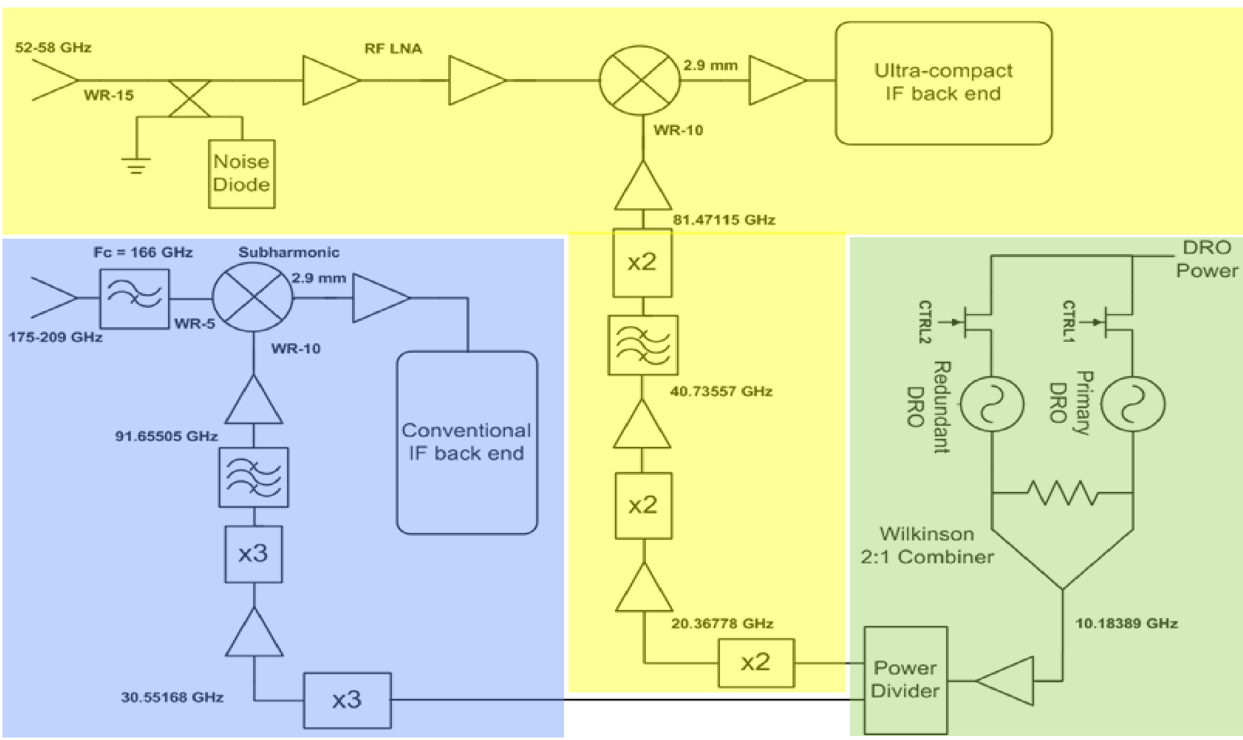

Figure 1: The MiRaTA tri-band, 10-channel microwave atmospheric sounder provides all-weather temperature, humidity, and cloud ice measurements for weather forecasting and climate studies. The V-band (yellow) and G-band (blue) receiver systems are completely independent, with a redundant dielectric resonator oscillator (green) common to both.

GPS Radio Occultation

GPS radio occultation (GPSRO) measurements have been used extensively to improve weather forecasting and assessments of climate [10]. Temperature profile accuracies approaching 0.1 K are achievable in the upper troposphere and lower stratosphere [11], and recent work has presented techniques for probing down to the boundary layer [12]. GPS-RO measurements are well-calibrated due to their fundamental dependence on time delays, which can be traced to National Institute of Standards and Technology (NIST) standards [13].

However, GPSRO measurements have relatively sparse geospatial coverage. When the COSMIC/FORMOSAT-3 constellation was at peak operational capacity, it provided approximately 2,000 occultation profiles per day, compared with over 3,000,000 soundings per day for ATMS (Advanced Technology Microwave Sounder).The MiRaTA mission will demonstrate the combined use of passive microwave sounding and GPSRO observations to leverage the benefits of both in order to achieve highly accurate calibration with dense geospatial sampling.

Furthermore, we investigate a new method of two-point calibration, where the traditional calibration points of cold sky and warm internal calibration target (ICT) are replaced with cold sky and a warm noise diode turned on and off against cold sky. The noise from the diode is sufficiently strong that a weak coupler can be used and avoids the need for a switch as the noise diode is always in the signal path, but only produces noise when energized with an appropriate bias current (usually on the order of 5-10 mA). The noise diode is periodically calibrated with GPSRO measurements to mitigate any drift [14] . In addition to offering improved calibration, this method also dispenses with the need for an ICT, which can be bulky, susceptible to errors, and often drives the design of the radiometer antenna and scanning system. GPSRO instrumentation is very compact and places no restrictions on the design of the radiometer. CubeSat class spacecraft (3U, about 10 x 10 x 30 cm and 4.0 kg) can now accommodate both radiometers and GPSRO systems on the same spacecraft, offering a low-cost, high-performance sounding platform.

Calibration of the Microwave Radiometer with GPSRO

Absolute calibration of spaceborne microwave scanning instruments for high-fidelity atmospheric research is immensely challenging and difficult to fully trace to a reference standard [15], although recent work has shown promise to establish brightness temperature standards with uncertainties of approximately 0.7 K [16]. As a direct result of these calibration challenges, bias corrections of up to several Kelvins are routinely used [17]. Problems associated with reflector emissivity and internal calibration target (ICT) contamination have been reported [13]. Previous comparisons of AMSU-A observations that were co-located to COSMIC/FORMOSAT-3 GPSRO observations indicated biases as large as 1.92 K [10].

The CCA recommends improved radiometer calibration, which is profoundly challenging even in flagship-class systems such as ATMS and the Global Precipitation Mission (GPM) Microwave Imager GMI, and even more so for a CubeSat radiometer. Several approaches have been proposed that fall far short of climate-quality calibration. Noise diodes can be used to inject a calibration signal into the radiometer with relatively low loss, however, the signal drifts appreciably [14]. Internal matched loads can be switched into the radiometer signal path, but the switches add loss (>2dB at 183 GHz [18]), precluding their use in systems that require coverage of large areas on short time scales, such as PATH. Perhaps most importantly, neither approach permits complete "through-the-antenna" calibration. The GPSRO and MWR approach directly addresses these challenges to offer climate-quality, through-the-antenna calibration of CubeSat radiometers. The concept is to use noise-diodes on short time scales and co-located GPSRO measurements on longer time scales to calibrate the noise diode to very high accuracy and stability. This technique could be implemented operationally using radiometer cross-track scanning and sideward-looking GPSRO observations (available every ~15 minutes) to permit simultaneous limb sampling. Calibration to “GPSRO measurements of opportunity” are insufficiently coincident in space and time to allow high-fidelity radiometer calibration.

An innovation within the MiRaTA technology validation program is the use of the Earth's limb as a brightness temperature reference. There are several key benefits to this approach: 1) nearly the entire dynamic range of the radiometers is covered with each scan of the limb as shown in Figure 2, permitting extensive calibration (note hot and cold calibration sources in Figure 2) and validation with relatively few scans (readily collected over a 60-day validation period); 2) the largest sources of validation error in the non-opaque radiometer channels are surface emissivity and boundary layer temperature variability, and these are minimized to negligible levels because of increased absorption due to the longer line-of-sight associated with the limb viewing geometry; 3) the regions of maximum sensitivity (vs. altitude) of the radiometer and GPSRO observations are very closely aligned in the upper troposphere and lower stratosphere; 4) the path through the atmosphere of the radiometer and GPSRO line-of-sight is almost identical, minimizing co-location error; and 5) the shape of the limb brightness temperature distribution with angle can be used to estimate radiometer boresight direction with very high accuracy.

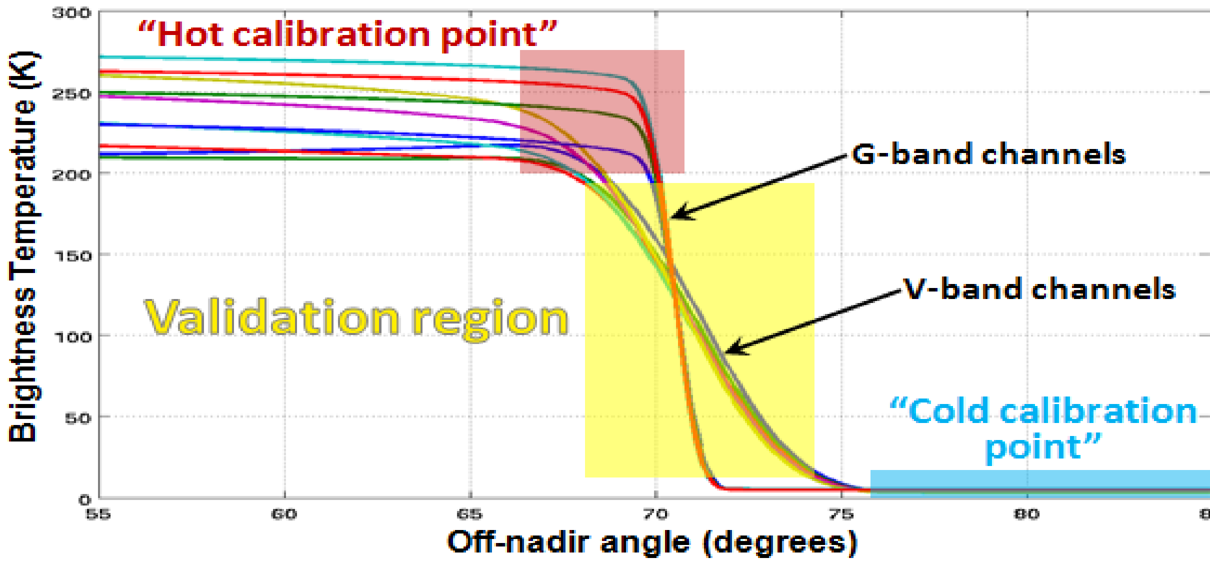

Figure 2: Representative brightness temperature as a function of scan angle near the Earth's limb for the MiRaTA channels. With knowledge of the atmospheric state, which will be provided with very high accuracy (~0.25K (Ho, Schreiner, & Zhou, Using SI-traceable Global Positioning System radio occultation measurements for climate monitoring, 2009)) by the GPSRO measurements, this distribution can be calculated to very high accuracy (~0.3K) by a limb-optimized radiative transfer model **[6]**.

CONCEPT OF OPERATIONS

MiRaTA baselines a launch from the ISS into a nominal orbit of ~400 km and 52° inclination. With a maximum mass of 4.5 kg, the mission lifetime should exceed 90 days. A simulation was also performed to assess mission lifetime from a ~400 km initial orbit (ISS) and considered worst-case drag configurations presented by the solar arrays during the pitch maneuver. Orbit decay to 300km (minimum useable altitude) occurs in >90 days. The 90 days includes a 30-day early orbit checkout (EOC) phase and a 60-day validation phase. EOC activities commence after launch and deployment and include solar panel deployment, ground communication, detumbling (estimated to be < 2 days), checkout of the attitude determination and control system (ADCS), slew to nominal flight orientation, monitoring of telemetry, and checkout of the GPS PNT (position, navigation, time), GPSRO, V-band radiometer, and G-band radiometer instruments. The validation phase will then commence with the major objective being to obtain ~100 validation-quality earth limb scans of radiometer and GPSRO data. Once this goal is achieved (which optimistically could be in as few as seven days, but conservatively there is significant schedule margin in the validation phase), additional opportunities for radiometric imagery will be sought (hurricanes, for example), and roll mode (scanning) will be initiated.

The MiRaTA Mission Operations Team (MOT) will have a Mission Operations Center (MOC) at MIT LL that will connect to the NASA Wallops Flight Facility, and USU SDL will use a software-defined radio ground station with the 18.3-m UHF antenna dish at Wallops. This arrangement was used successfully with the Dynamic Ionosphere CubeSat Experiment **(**DICE) mission [19] and is also planned for the Microsized Microwave Atmospheric Satellite, MicroMAS [20]

The primary MiRaTA mission ConOps is summarized in Figure 3. The MiRaTA spacecraft will perform a slow pitch up/down maneuver once per orbit to permit the radiometer and GPSRO observations to sound overlapping volumes of atmosphere through the Earth's limb, where sensitivity, calibration, and dynamic range are optimal. These observations will be compared to radiosondes [21], global high-resolution analysis fields [22], other satellite observations (ATMS/Cross-track Infrared Sounder [8], etc.) and with each other (GPSRO and radiometer) using transfer models [6].

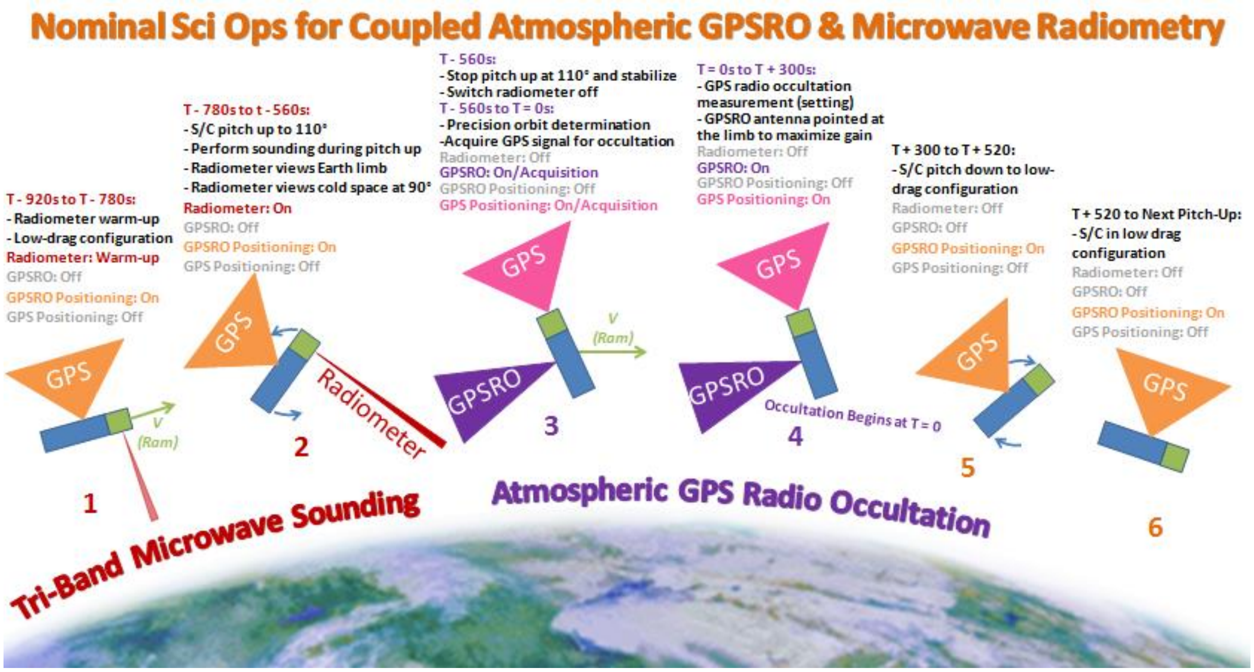

Figure 3: The MiRaTA primary mission validation concept of operations (ConOps) is shown above. A slow pitch maneuver (~0.5°/sec) is used to scan the radiometer fields of view through the Earth's limb and subsequently direct the CTAGS field of view through the same atmosphere to catch a setting occultation. The entire maneuver takes about 20 minutes and is performed once per orbit over a 60-day validation period (approximately 1000 total scans).

In addition to the advantages mentioned previously, this ConOps permits the radiometer and GPSRO systems to be powered on at different times in the maneuver, thus minimizing the potential for interference. Communications transmissions will be performed when the radiometer and GPSRO systems are powered down. A comprehensive orbital simulation was performed to assess the availability of high-quality setting occultations, and we expect a minimum of five such opportunities per orbit.

Summary of Mission Goals

- At least 100 radiometer limb scans
- NEdT of 0.1 K at 55 GHz, 0.3/0.2/0.15 K at 183 ± 1/3/7 GHz, and 0.25 K at 207 GHz
- 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) down to 20 km, threshold, and 10 km, goal) (JPSS, 2011).

Table 1. High-level spacecraft requirements to achieve mission goals

s	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: 5.5 W to MWR (10 min per orbit, 0.5 W standby), 3.2 W to GPSRO (20 min per orbit, 0.5 W standby), 4.15 W to spacecraft (always), and 10 W for comm. transmit (<1 min per orbit)	Power for technology validation demonstration and survival
Minimum 90 day mission lifetime from 300-400 km orbit at 52° inclination	Time needed to fulfill objectives with >100% margin

DETAILED PAYLOAD DESCRIPTION

Microwave Radiometer

The ultra-compact back-end spectrometer used in the MiRaTA V-band radiometer is shown in Figure 4 The spectrometer has been fabricated using low-temperature co-fired ceramic (LTCC) technology, which supports multiple metal levels and embedded passive components. The dielectric constant is relatively high, thereby reducing the feature size. The filters have been implemented using the substrate integrated waveguide (SIW) technique, allowing high-performance filters to be realized using standard circuit board fabrication techniques to reduce cost. The spectrometer has been extensively tested and yields excellent performance. The packaged, flight-ready subassembly consumes about 370 mW of power with a mass of about 90 g. The electronics feature a low-power mode that will be used in the "off" portion of the mission duty cycle to improve stability and radiometric performance. The six V-band channels span approximately 52.5 to 56.1 GHz in contiguous 600-MHz bands to provide nearly uniform vertical coverage from the surface to approximately 20 km at nadir viewing incidence, which satisfies the PATH requirements [5].

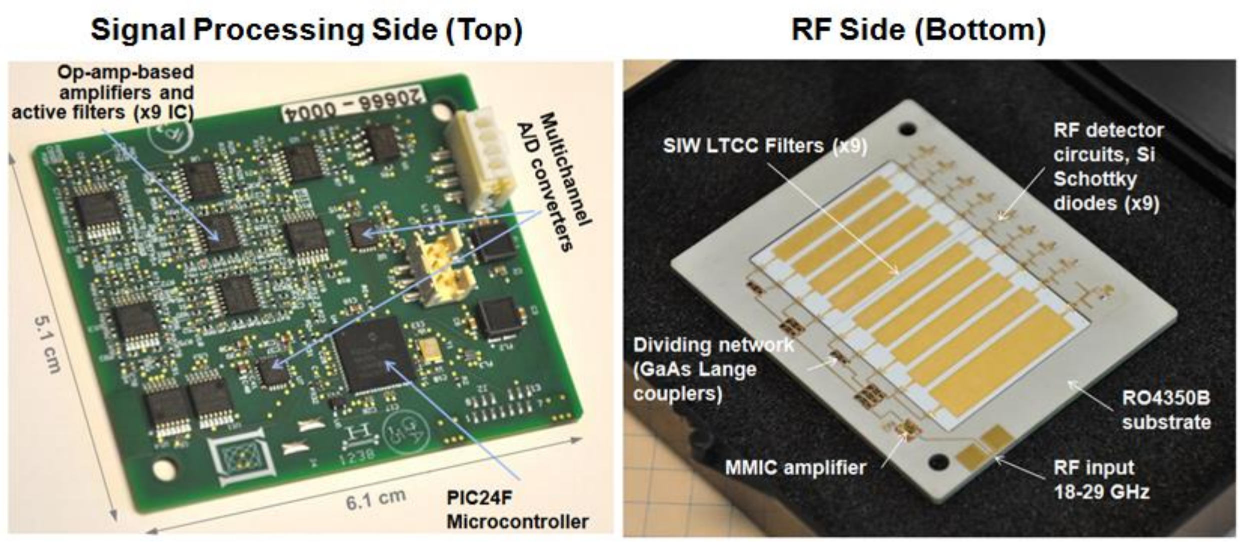

Figure 4: The ultra-compact spectrometer to be used in the MiRaTA V-band radiometer. The top side of the board contains analog and digital signal processing electronics and interfaces to the control and data handling (C&DH) radiometer module. The bottom side of the board contains the microwave components needed for power division, amplification, filtering, and detection. A lightweight, RF-tight enclosure has been fabricated using metal-coated, metal-infused ULTEM.

A recent innovation in millimeterwave receiver development is the construction of broadband mixers that provide useful performance over a wide intermediate frequency range. Virginia Diodes, Inc. (VDI) has recently demonstrated a sub-harmonic mixer at TRL5 (shown in Figure 5) operating near the 183.31-GHz water vapor line that also allows simultaneous observation of a cloud ice channel near 210 GHz without separate downconversion. This simplifies the receiver hardware and enables very compact designs supporting multiple atmospheric bands. The required LO power (2-4 mW) is provided by a compact multiplier chain driven by a dielectric resonator oscillator. This receiver architecture is quite suitable to CubeSat implementation due to the small size and potential for highly integrated packaging (the feed horn will attach directly to the mixer, for example) and has been demonstrated successfully for the MicroMAS CubeSat program at 118 GHz. The G-band radiometer will provide double-sideband measurements centered about the 183.31-GHz water vapor line: ±1 GHz (500-MHz bandwidth), ±3 GHz (1-GHz bandwidth), and ±7 GHz (2-GHz bandwidth). A fourth, single-sideband channel will be observed from 206.4-208.4 GHz. A high-TRL conventional IF back-end filterbank will be used with simple lumped-element and coupled stripline circuits. Power supplies for all needed bias lines will be built into the receiver blocks to minimize size. The radiometer CAD model for both the V- and G-band systems contains connectors and fasteners to ensure mechanical compatibility with the CubeSat structure. Thermal and structural analyses have also been performed to increase design fidelity, and heater provisions are included in the design, mass, and power budget. The MiRaTA radiometer system implementation is highly mature and based heavily on experience with similar flight systems, thereby reducing risk.

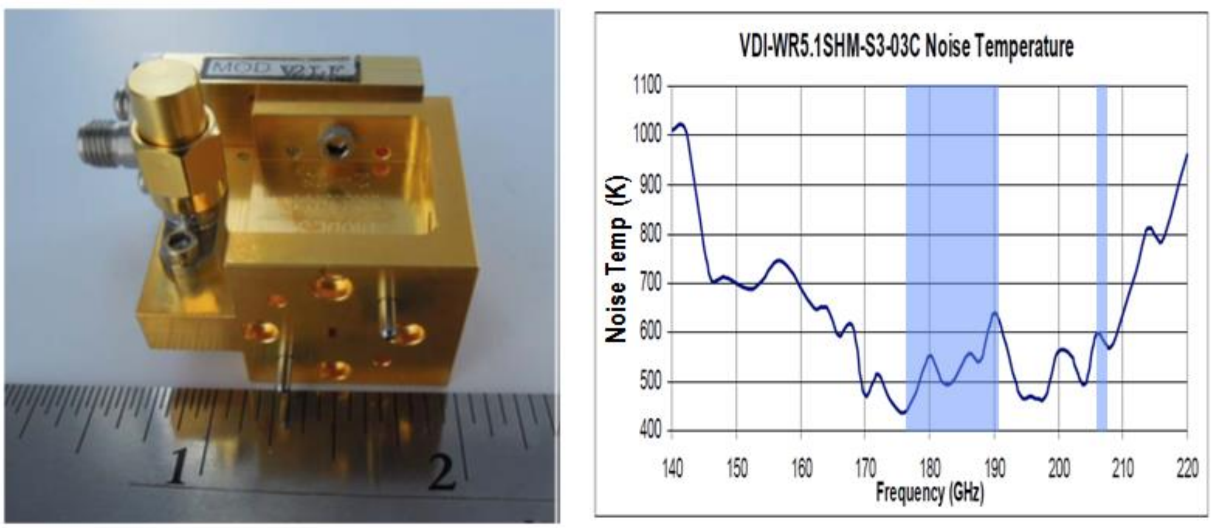

Figure 5: The Virginia Diodes, Inc. (VDI) wideband mixer front end will provide double-sideband measurements in three channels near the water vapor absorption band (183.31 ±1, ±3, and ±7 GHz), and a single-sideband measurement of a 206.4 to 208.4 GHz cloud ice band.

The V- and G-band radiometer systems are integrated in a payload assembly, shown in Figure 6. The V-band front end comprises a high-excess-noise-ratio weakly-coupled noise diode for calibration, followed by a low-noise RF MMIC preamplifier. Two scalar feed horns illuminate an offset parabolic reflector yielding FWHM beamwidths (aligned in the pitch plane) of approximately 1.25 and 5 degrees for the G and V-band systems, respectively, with >95 beam efficiency. These beamwidths meet PATH requirements [4] from an ISS orbit, and the design can easily be scaled to use a larger aperture that could be accommodated on a 6U CubeSat operating at higher orbit altitudes. The DRO is fully redundant and shared among the two receivers.

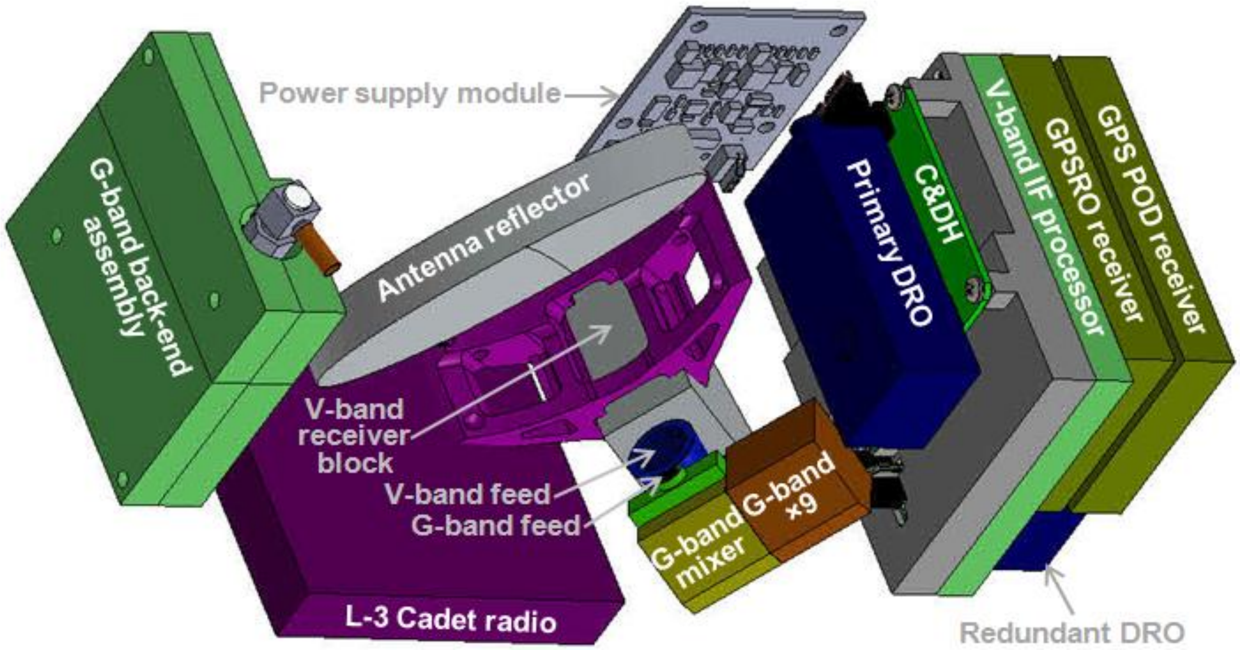
Power supply module
G-band back-end assembly
Antenna reflector
Primary DRO
C&DH
V-band IF processor
GPSRO receiver
GPS POD receiver
V-band receiver block
V-band feed
G-band feed
G-band x9
G-band mixer
L-3 Cadet radio
Redundant DRO

Figure 6: MiRaTA tri-band sounder (antenna shroud not shown) and GPS receiver notional layout. Total radiometer mass is 907g and power consumption is 5.5W. Assembly size is 10 x10 x18 cm.

GPS Radio Occultation with the Compact TEC/Atmosphere GPS Sensor

Spaceborne GPS radio occultation (GPSRO) sensors provide all-weather atmospheric temperature measurements with high accuracy and precision [23]. To date, size, power, and antenna gain requirements for GPSRO atmospheric sensors (as opposed to ionospheric sensing, where GPSRO has been demonstrated on nanosatellite platforms) have precluded their use on CubeSats. A new GPS receiver, the NovAtel OEM628 currently at TRL5, together with a multi-element antenna array (3 or 5 patch antennas), enables atmospheric GPSRO from CubeSats. With MiRaTA, a 3U CubeSat-compatible atmospheric GPSRO sensor will be validated at TRL7. The Compact TEC (Total Electron Content)/Atmosphere GPS Sensor (CTAGS) to be flown on MiRaTA is a GPSRO sensor based on the successful CTECS (Compact Total Electron Content Sensor) that will obtain atmospheric temperature profiles down to at least 20 km altitude in addition to ionospheric measurements. CTAGS extends the capability of CTECS by using a more compact and capable GPS receiver and a relatively high-gain patch antenna array that will allow measurements into the lower atmosphere. The CTAGS sensor consists of four components (see Figure 7): 1) multi-element antenna array, 2) single patch antenna for precision orbit determination, 3) Low-Noise-Amplifier (LNA), and 4) NovaTel GPS receiver.

Modifications are needed in order to adapt a GPSRO sensor for tropospheric sounding onto a CubeSat..First, a higher gain antenna is required to retain lock on the GPS signals as the satellite sets behind the Earth from the perspective of MiRaTA and the signals pass through the denser lower atmosphere. The gain improvement is achieved by an array of patch antennas. Each individual patch antenna will use the heritage CTECS antenna design. The antenna array improves the gain to over 10 dBi and also creates a directional pattern. The antenna boresight will be directed toward the limb by maneuvering the spacecraft (see Figure 3). Figure 8 illustrates the CTAGS antenna array on the MiRaTA spacecraft as embedded in the deployed solar panels. CTAGS utilizes the NovAtel OEM628 receiver. This receiver is smaller in size and power than the CTECS receiver and has improved capabilities. The OEM628 receiver has not flown in space before, but is now commercially available at TRL5. The receiver can track up to 120 signals (60 dual frequency satellites) at any time, thereby permitting both atmospheric and navigation observations.

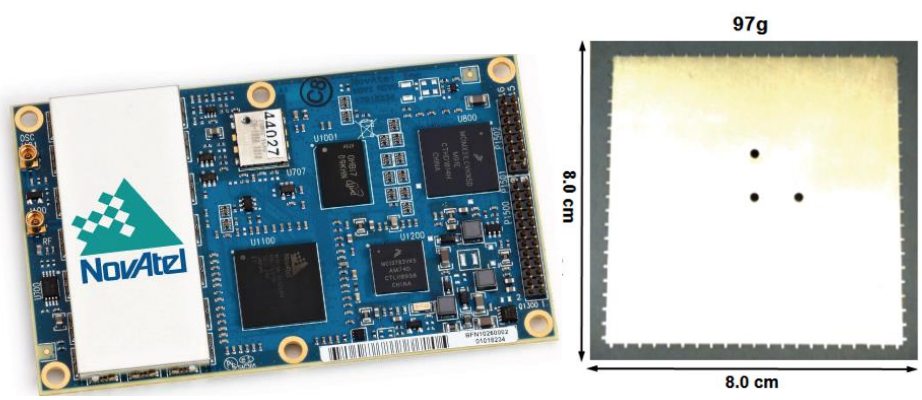

Figure 7: The NovAtel OEM628 GPS receiver is shown on the left, and one of the dual-band GPS patch antenna/LNAs is shown on the right. The GPSRO element of CTAGS (nominally zenith facing) consumes < 2W and the precision orbit determination element of CTAGS (nominally ram facing) consumes ~1.3W.

BUS DESCRIPTION

Structural Layout

A notional CAD model of the MiRaTA spacecraft is shown in Figure 8. The flight design is not yet finalized and will be based on this model. The MiRaTA bus design is simpler in many respects than its predecessor, MicroMAS, which had scanning mechanism [10]. There are no active mechanisms on MiRaTA, and the only deployable structures are two solar panels and a simple tape-spring antenna for UHF communications with the NASA Wallops Flight Facility ground station. The radiometer views the Earth through the nadir deck of the spacecraft, and in this frame, the GPSRO patch antennas have a field of view in the zenith direction. During a GPSRO sounding, the antenna array is oriented to the limb during GPSRO sounding via a simple pitch maneuver (see Figure 3). The radiometer and GPSRO fields of view are used to probe the same volume of atmosphere by using the control authority of the reaction wheel assembly to pitch the spacecraft up approximately once per orbit. The radiometer will be sampled at 10 Hz (i.e., every 0.05° in pitch) yielding an NEdT of ~0.1/0.2/0.25 K at 55/183/207 GHz, which meets PATH requirements (Lambrigtsen, Brown, Tanner, Gaier, Herrell, & Kangaslathi, 2010) and is sufficiently sensitive to meet MiRaTA mission objectives. The current estimate of the total spacecraft mass is about 4 kg, of which about 2 kg is bus structure, and the spacecraft average and peak power is about 6 W and 14 W, respectively. These mass and power requirements can be supported by existing 3U CubeSat subsystem components.

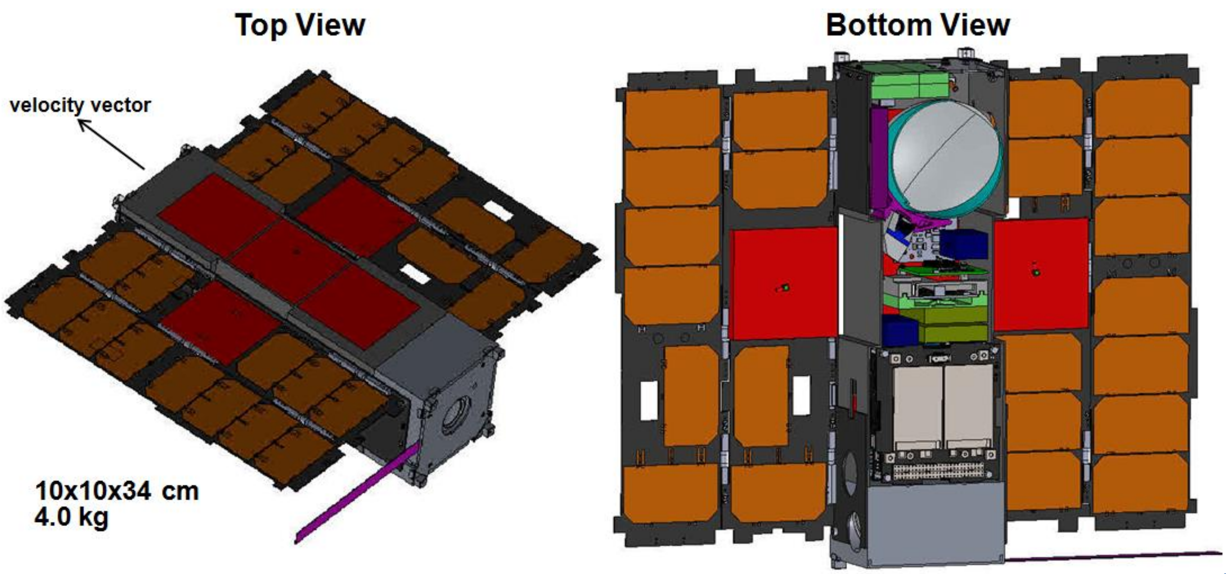

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Figure 8: The MiRaTA 3U spacecraft. Left: top view. Right: looking at the nadir-facing "bottom" of the spacecraft (with the bottom body panel removed for illustration. The multi-element antenna patch array on the zenith deck of the spacecraft is used for the atmospheric GPSRO measurements. Three elements run along the top body panel. If necessary (detailed analysis underway), two additional side patches can be integrated onto deployable solar panels (mounted beneath the substrate)..The primary spacecraft components, whose flight configuration is still being finalized are visible in the image on the right, including (from the bottom up): MAI-400 reaction wheel assembly, avionics and power stack (batteries visible), GPS receivers, and radiometer components. The side patch antennas fold inwards and occupy a fraction of space along the body panels of the spacecraft prior to deployment. The holes in the deployed solar panels allow access to spacecraft electronics. A representative UHF tape-spring antenna is shown for illustration purposes - the flight version will likely be positioned on the lower deck of the spacecraft to permit the use of a larger ground plane.

Subsystem Summaries

Power: To meet the MiRaTA mission goals, the average energy required per orbit is about 8.25 W-hr, and the power and lifetime requirements are met with > 20% margin using a 20 W-hr Clyde Space Lithium Ion battery, electrical power system (EPS), and double-deployed solar panels. The 20W-hr battery meets power and lifetime requirements if discharged less than 30% to maintain 80% of its initial capacity by the end of the 90-day validation period [1]. The current estimate of the power system mass is about 1.0 kg and power consumption about 0.3 W.

ADCS: The pointing requirements are met with sensor and actuator systems that are similar to those used on MicroMAS, including the MAI-400 reaction wheel assembly, three earth horizon sensors (two integrated in the MAI-400 and one additional to support the pitch-up maneuver), tri-axial magnetometer, sun sensors, and magnetorquers for detumbling and reaction wheel desaturation. The current estimate of the ADCS mass is about 0.75 kg. with power consumption during nominal use of about 4 W.

Communications: MiRaTA will use the same L3 Cadet nanosatellite UHF radio as MicroMAS, and plans to also use the Wallops 18.3 m dish for the ground station. Link budget analyses indicate >10 dB margin from the ISS orbit. The current estimate of the communications system mass is about 0.15 kg and average power of 0.5 W although power increases to several watts during transmission intervals (communications passes are generally less than ten minutes long).

C&DH: MiRaTA will use a Pumpkin CubeSat motherboard with a PIC24 microcontroller running the Salvo Real Time Operating System. This is the same general approach used on the previous MicroMAS CubeSat, Custom interface boards will supply power and data connections to the other subsystem components. The current estimate of mass is about 0.2 kg and power consumption is 0.4 W.

SUMMARY AND CONCLUSIONS

The MiRaTA mission will demonstrate advanced atmospheric remote sensing capabilities from a 3U CubeSat platform which will improve radiometric observations of the earth's weather. The miniaturized three-band microwave radiometer and GPSRO experiments to be demonstrated on MiRaTA will provide all-weather measurements of temperature, humidity, and cloud ice, as well as profiles of electron density, and temperature in the upper troposphere. The co-located radiometer and GPSRO measurements will investigate using GPSRO temperature profiles for calibrating the radiometer. The payload and platform development for the MicroMAS and MiRaTA missions are the first steps along a pathway to a new observing architecture comprising (at least in part) very small satellites hosting radiometers to provide all-weather sounding capabilities. Constellations of such satellites would profoundly improve the performance and reduce the cost of modern environmental monitoring satellite systems. MicroMAS will launch in Summer 2014, and MiRaTA is expected to launch in 2016.

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