MicroNimbus: A CubeSat Mission for Millimeter-Wave Atmospheric Temperature Profiling

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MicroNimbus is a small satellite mission being developed by the Georgia Institute of Technology and Georgia Tech Research Institute that will utilize a frequency-agile mm-wave radiometer to measure and update the temperature profile of the atmosphere from a 3U CubeSat platform. The on-board radiometer instrument will provide atmospheric temperature profile data at an altitude resolution of 10 km, a geographic resolution of 0.5°, and a temperature resolution of 2K RMS. The mission strongly aligns with the goals set forth in NASA's Science Plan and will generate data valuable to researchers in the fields of weather forecasting, LIDAR, and laser communications. MicroNimbus has passed its Preliminary Design Review (PDR) phase and is moving towards the Critical Design Review (CDR) for the mission. If successful, MicroNimbus will serve as a first step towards the creation of a constellation of satellites designed to perform near real-time temperature profiling of the atmosphere.

Nomenclature

ADC	Attitude Determination and Control System
AMSU	Advanced Microwave Sounding Unit
CDH	Command & Data Handling System
COM	Communications System
COTS	Commercial Off-The-Shelf
EPS	Electrical Power System
GPS	Global Positioning System
HDR	High Data Rate
IMU	Inertial Measurement Unit
ISS	International Space Station
K	Kelvin - Temperature Unit
LIDAR	Light Detection and Ranging
LDR	Low Data Rate
MMIC	Monolithic Microwave Integrated Circuit
NAV	Navigation System
PCB	Printed Circuit Board
SCAMS	Scanning Microwave Spectrometer
STR	Structural and Mechanical System
UHF	Ultra High Frequency

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I. Introduction

Atmospheric sounding missions have played a critical role in NASA's and NOAA's ability to monitor, analyze, and predict weather over both short and long time scales. One example of this is the NASA Nimbus 6 satellite − part of the Nimbus series of missions (to which MicroNimbus' name pays homage). One of the many instruments carried by Nimbus 6 was a passive microwave radiometer in the 60 GHz regime that was used to retrieve atmospheric temperature profiles. Another similar, and currently active, mission by NASA is the Aqua (EOS PM-1) satellite. Specifically, the AMSU instrument onboard Aqua is capable of scanning between 10 channels in the ∼60 GHz range where O_2 absorption lines occur[1].

However, the need for global, near real-time weather and temperature measurements has led researchers to look into the use of small satellites, specifically CubeSats, to obtain this data. In recent years, CubeSats have been utilized by the scientific community in the area of remote sensing due to their low cost, fast development schedules, and unique mission architecture configurations (formations, constellations, etc.)[2]. MicroNimbus attempts to do just this; to perform scientific experiments similar to those carried out by Nimbus 6 and Aqua at a fraction of the cost and development time.

Specifically, the MicroNimbus mission attempts to miniaturize the design of a microwave radiometer, such as the Nimbus 6 SCAMS[a] and the AQUA's AMSU instrument, through the use of a silicon-germanium (SiGe) integrated receiver front end and a corrugated horn antenna design. While SCAMS and AMSU focused on scanning three and ten different O_2 absorption bands respectively, MicroNimbus will scan through seven. Furthermore, MicroNimbus will make use of the CubeSat platform in order to reduce the cost and development times required to obtain this type of atmospheric sounding data.

II. Mission Science and Applications

A. Passive Microwave Radiometry

Microwave radiometers are remote sensing instruments that measure the passively emitted electromagnetic radiation by a medium of interest in specific frequency bands in the microwave regime (∼3 to 300 GHz[3]) of the electromagnetic spectrum. Satellite based radiometers have been used for decades by NASA to collect global-scale observations of the Earth which are used by the Earth science community to improve global climate models. These measurements are vital to our understanding of the planet as a system both spatially and temporally and must be collected from satellites orbiting the Earth. Microwave radiometric observations can yield useful information on media ranging from solids (vegetation, ice sheets, snow), liquids (oceans, lakes), and even components of the Earth's atmosphere (water vapor, ozone, oxygen).

Many of these media emit radiation in a specific frequency regime that can be detected by radiometers sensitive to those frequencies. Specifically, for this mission, radiometric measurements of Earth's atmosphere will be considered as the focal point of the research. In the ∼60 GHz frequency range, multiple frequency bands exist in which atmospheric oxygen (O_2) absorbs the radiation emitted by the Earth's surface and produces absorption lines that a microwave radiometer is sensitive to. Some of these frequency bands correspond to different optical depths in the atmosphere, as seen in Figure 1. Measuring these frequency bands can be used to derive temperature profiles of the atmosphere, an example of which can be seen in Figure 2.

B. Traceability to NASA's Objectives

One of the high level goals presented in the NASA 2014 Strategic Plan is to "Advance knowledge of the Earth as a system to meet the challenges of environmental change, and to improve life on our planet"[6]. This high level goal flows down into two sub-goals; scientific understanding of the climate system and technology development of Earth based remote sensing instruments. More specifically, the NASA 2014 Science Plan calls for researchers to "improve the ability to predict climate changes by better understanding the roles and interactions of the ocean, atmosphere, land, and ice in the climate system"[7] and the NASA 2015 Technology Roadmap calls for researchers to "improve remote sensing capabilities and performance" through "investments in microwave, millimeter-. . . receiver component technology include low-noise receivers. . . and field demonstration of active and passive instruments from mm to sub-mm wavelengths" [8]. The MicroNimbus mission directly addresses both of these sub-goals by creating a single integrated mm-wave radiometer

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[a] http://nssdc.gsfc.nasa.gov/nmc/experimentDisplay.do?id=1975-052A-10

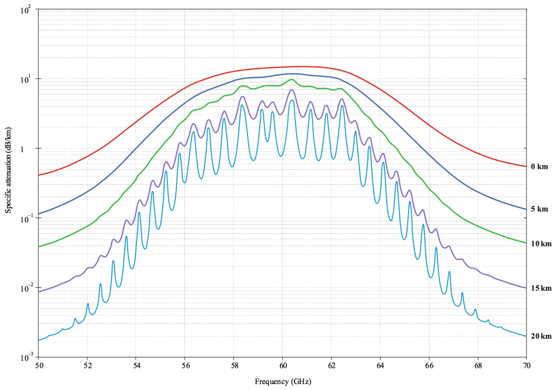


Figure 1. Specific Attenuation in the Range 50-70 GHz [4]

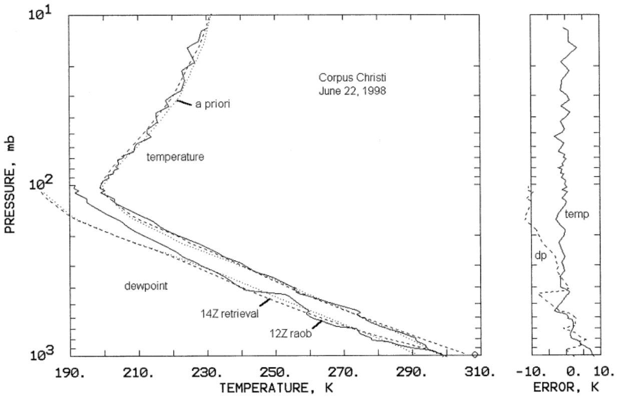


Figure 2. Atmospheric Temperature Retrieval at Corpus Christi, TX [5]

front end and using this device in space to provide near real-time atmospheric temperature profile data to researchers for verification and improvement of current weather models over daily and monthly time scales.

C. Applications

Researchers can use the data generated by MicroNimbus to understand a variety of climate and weather related phenomenon. For example, the data generated by the AMSU instrument has been used to observe tropical storms because the measurements are not significantly affected by cloud cover that typically resides over these storm systems. Thus, these passive measurements can penetrate through the layers of cloud cover, allowing researchers to determine how temperature anomalies affect wind speeds, pressure, and rainfall near the storm system[9].

III. Mission Description

A. Mission Design

1. Orbit Options

Currently, the mission baseline design is that the satellite will be deployed from the ISS and will perform nominal operations until orbital decay due to atmospheric drag causes the satellite to be destroyed in the atmosphere. Because MicroNimbus has no on-board propulsion system for station-keeping, it will optimistically remain in orbit for approximately 6 to 9 months. Even at this orbit, nominal operations should yield data for at least one season. The concept of operations of the nominal mission can be seen in Figure 3.

Other orbit options have been considered and will be addressed should the launch opportunity provide it. The most likely of these options is a polar orbit at higher altitudes than the ISS. Polar orbits would be ideal for a remote sensing mission such as this due to the fact that global coverage can be achieved. Furthermore, power requirements would be relaxed if the orbit is constrained to be sun-synchronous. However, higher altitude orbits would cause a lower spatial resolution for the instrument.

2. Scientific Data Collection Requirements

Two types of temperature sounding data must be obtained for this mission in order to satisfy science requirements, a short-term (day to day) variation and a long-term (weekly to monthly) variation. Because of constraints on attitude knowledge in the eclipse phase of the orbit, the payload will only collect data during the sunlight side of the orbit.

The Level 1 System Requirements call for the mission to be operational for up to 6 months to obtain seasonal variations in atmospheric sounding data. However, due to the power limitations of the mission, this data will not be continuous. Nominally, the mission is designed to perform ten consecutive orbits worth of science data collection followed by one orbit for recharging the on-board batteries. This includes time dedicated for scientific and spacecraft health data downlink, regardless of being in a science orbit or a

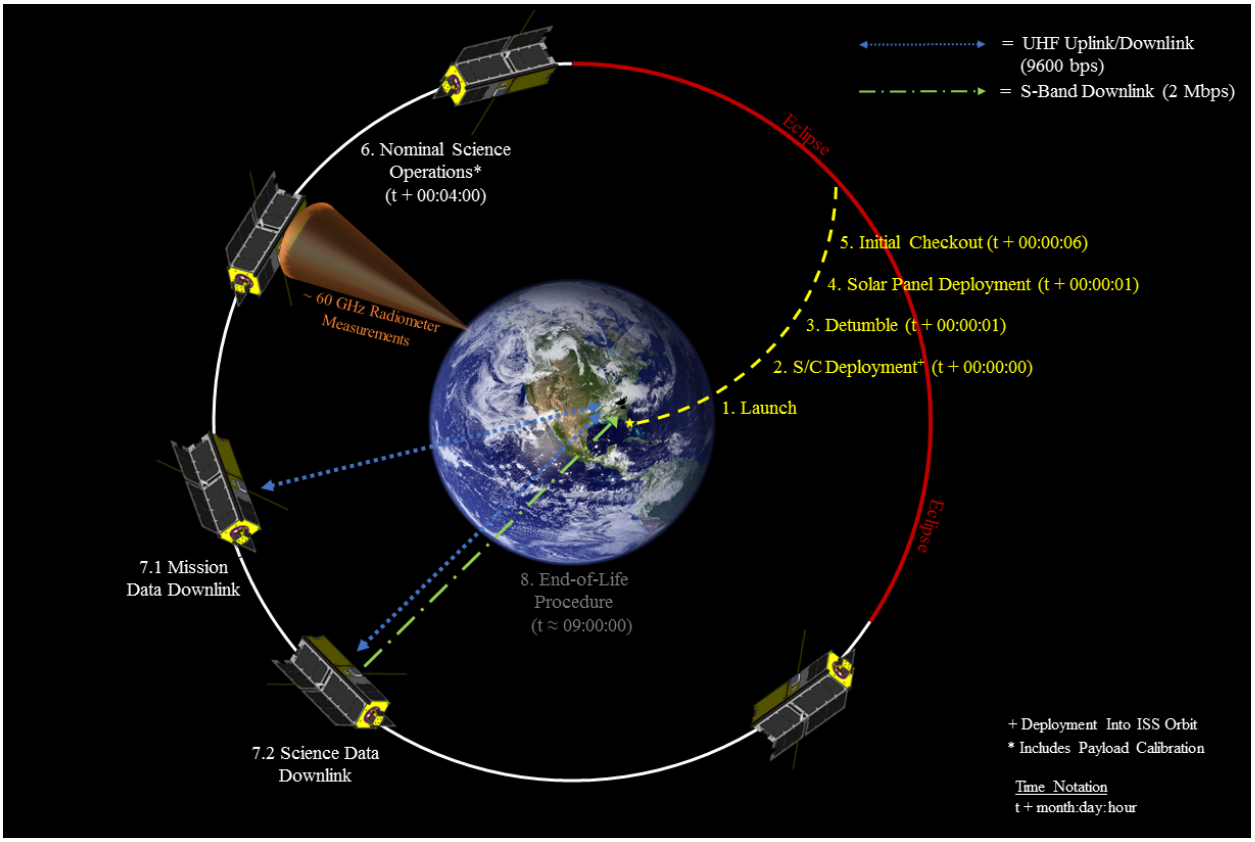


Figure 3. MicroNimbus Concept of Operations

charging orbit, as seen in Figure 4. Although this will create gaps in the data obtained, for the purposes of observing changes on weekly or monthly time scales, the overall trends in the measurements will still provide valuable scientific insight.

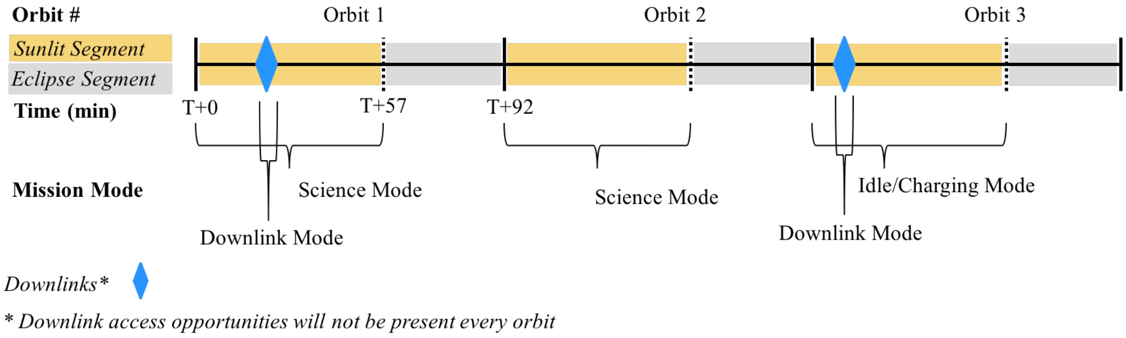


Figure 4. MicroNimbus Example Operations Schedule

3. TECHBus

This mission will be the first to make use of The Evolved Common Hardware Bus (TECHBus), a generic 3U or 6U CubeSat bus under development at Georgia Tech. Arising from the need of having a satellite bus that can be used to fly a variety of scientific payloads without having to be redesigned for each mission, the TECHBus is an in-house, versatile, reusable, and reliable approach to solving this problem[10]. Although older iterations of the final design have been used on previous missions, MicroNimbus will be the first mission to make use of this iteration of the bus design. Because almost every mission requires some level of customization, the payload section of the TECHBus can be customized to incorporate the payload and any required sensors or actuators that are not already present on the standard bus.

B. Radiometer Payload

The microwave radiometer onboard MicroNimbus will be capable of scanning through seven frequencies, allowing the instrument to sound the atmosphere from an altitude range of 10-80 km[11], as summarized in Table 1. Since CubeSats are inherently volume, mass, and power constrained, these limitations also translate into constraints on the radiometer itself. For MicroNimbus, the radiometer payload (including all additional required sensors, boards, etc.) was designed to take up no more than 1.5U of volume with a mass limit of 0.5 kg and power consumption of less than 1 W. To accomplish this, the 60 GHz receiver front-end will be integrated on a single SiGe integrated circuit, a level of integration not yet achieved at 60 GHz[12].

Table 1. Radiometer Frequencies and Corresponding Altitude Windows

Frequency (GHz)	Bandwidth (MHz)	Altitude Window (km)	Window Width (km)
64.47	200	12	11
60.82	200	18	7
58.388	30	27	9
60.4409	2.5	40	12
60.4365	1	50	20
60.5685	1.5	60 (equator), 54 (pole)	21 (equator), 26 (pole)
60.4348	1.5	73 (equator), 66 (pole)	20 (equator), 26 (pole)

1. *SiGe Integrated Receiver Front End*

The main reason why an integrated receiver front end was selected for the payload was due to the large reduction in size, weight, and power consumption that comes as a result of creating one integrated circuit. While typical radiometers make use of multiple chips from multiple material technologies, the approach for this design was to use a single semiconductor material for the entire chip – an approach that SiGe technologies are capable of. Although this approach does have some drawbacks in performance, it does however offer major advantages in the areas of manufacturing, radiation tolerance, and thermal management[13].

The first of these advantages is manufacturing; SiGe technologies have better manufacturing tolerances than other semiconductor materials (GaAs, InP, etc.) allowing for low chip-to-chip and circuit-to-circuit variation. Another advantage is that SiGe heterojunction bipolar transistors (HBTs) have the best low-frequency noise characteristics of all high-frequency semiconductor technologies – a critical consideration for minimizing the out of band sensitivity in radiometers. Additionally, they are far more resistant to degradation due to total dose radiation, suffering almost no performance change up to multi-Mrad doses[13]. Because CubeSats are weight and volume constrained, there is often little radiation shielding available and thus radiation tolerant components are of high value for these types of missions. Finally, silicon integrated circuits have high thermal conductivity, leading to more stable thermal properties on orbit and requiring less active thermal management – once again reducing overall size, weight, and power consumption.

The SiGe integrated receiver comprises most of the major components of the radiometer[12] as seen in Figure 5. Specifically, all components within the red box in Figure 5 are integrated onto the single SiGe MMIC.

2. *Radiometer Horn and Structure*

The volume constraint of 1.5U was the driving factor in the selection and design of the radiometer horn antenna design. For this mission, a corrugated horn was selected because it has similar performance (low loss and good match) to that of a larger antenna but fits within a smaller form factor, thus allowing the antenna to fit inside the payload volume[14]. Although this antenna is more difficult to manufacture than traditional

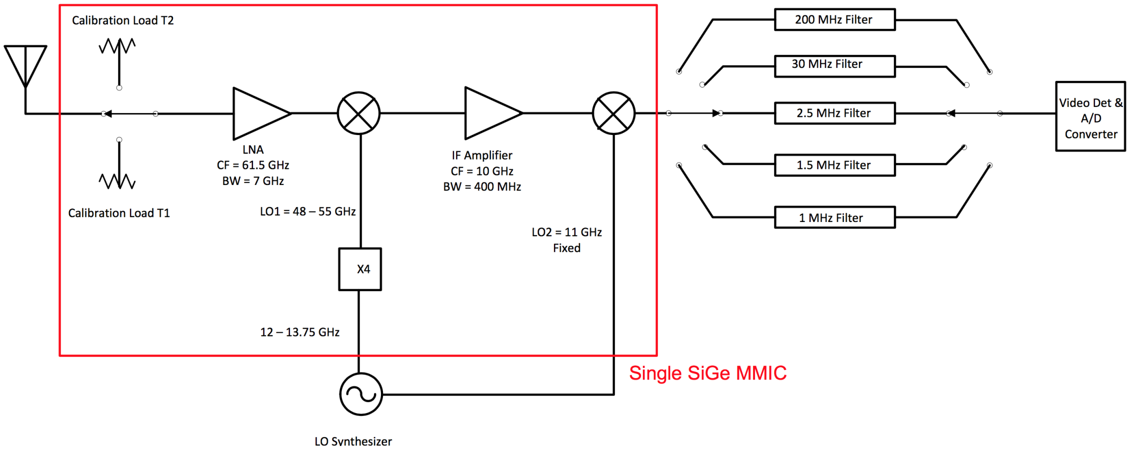


Figure 5. 60 GHz Profilometer Radiometer - Preliminary Block Diagram

horn antennas, the performance combined with compactness of the design outweighs the additional schedule and cost increases required for manufacturing. The final integrated payload module can be seen in Figure 6.

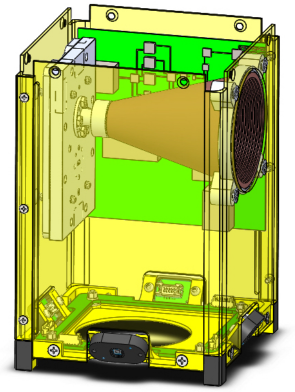


Figure 6. MicroNimbus Payload Module - Integrated

C. Subsystems

1. *Attitude Determination and Control - ADC*

The ADC subsystem consists of a variety of sensors, actuators, and interface boards. The attitude is determined primarily through the use of eight sun sensors, which are photodiode arrays that provide a sun vector to the spacecraft. The attitude is mainly actuated with reaction wheels, which are desaturated using magnetic torque rods. The eight sun sensors present on the spacecraft allow for full-sky coverage to be achieved in daylight and the reaction wheels allow for enough fine pointing to meet both the payload and COM subsystem requirements. The main requirements enforced onto the ADC subsystem stem from the payload and the COM subsystem. The radiometer payload requires nadir attitude pointing to within 1° while the COM subsystem requires a maximum slew rate of up to 1.5° per second for downlinking to the ground station.

Due to the need for high reliability and flight heritage, most of the sensors and actuators are COTS components except for the magnetic torque rods, and certain printed circuit boards. The magnetic torque rods are manufactured in-house using a stainless steel core with magnet wire wrappings and are designed to provide enough magnetic moment to desaturate the reaction wheels and detumble the spacecraft. Due to the variety of communication protocols used by the ADC components, a customized ADC interface board has been made in order to connect all sensors and actuators to the flight computer.

Furthermore, a full ADC simulation is being developed within NASA Goddard Space Flight Center's 42 software. This simulation imports spacecraft parameters (e.g. overall CAD, moments of inertia, actuator/sensor models, ADC software, etc.) and performs high-fidelity orbit and attitude propagation with controller in the loop.

A summary of all components present in the ADC subsystem are shown in Table 2. Readers should note that the VectorNav contains both an IMU and magnetometer in one package and two are used for redundancy. However, the potential to switch to an individual magnetometer and IMU combination has been considered due to higher achievable accuracy and lower drift rates. The individual sensors can still fit within the volume, mass, and power requirements and will be finalized as more testing is performed.

Table 2. ADC Subsystem Components

Type	Component	Quantity	Manufacturer
Sensor	Sun Sensor	8	Solar MEMS
Sensor	IMU/Magnetometer	2	VectorNAV
Actuator	Magnetorquer	3	In-house
Actuator	Reaction Wheel	3	Sinclair Interplanetary
PCB	ADC Interface Board	1	In-house
PCB	Sun Sensor Interface	2	In-house

2. Command & Data Handling - CDH

Because the bus is designed to be robust and have redundant components, one of the biggest challenges in designing the CDH subsystem was finding a flight computer with the required peripherals to be able to interface with all components. This led to eventually selecting the Phytec phyCORE Vybrid, an embedded system used for industrial robots and machines. A predecessor to the Vybrid (LPC3250) has been used on previous iterations of the TECHBus. Additionally, this flight computer brings the added benefits of having large operating temperature ranges (-40°C to $+85$°C), low power consumption (< 1W), error correcting memory, and long manufacturing runs (thus reducing the risk of the product being discontinued and having major software bugs worked out $-$ downsides that most COTS CubeSat flight computers face).

3. Communications - COM

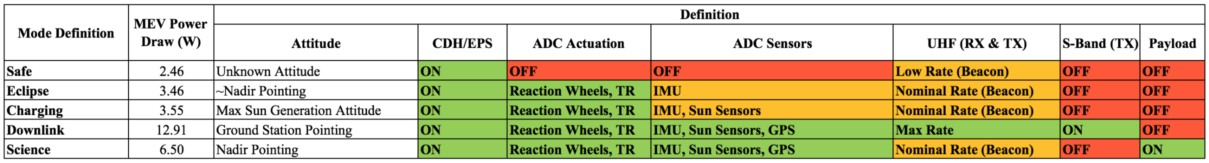
The COM subsystem is designed to satisfy two major driving requirements. The first, and most important requirement, is to be able to communicate command and telemetry data regardless of attitude control ability. This drove the selection of a LDR communication system that uses UHF (430 to 440 MHz) with an omni-directional dipole antenna. The second driving requirement is to be able to communicate the large amount of scientific data to existing Georgia Tech ground stations. This requirement drove the selection of a HDR communication system that uses S-band frequencies (2200 to 2250 MHz) with a patch antenna ($\pm 60°$ beamwidth).

Both UHF and S-band communications will take place through Georgia Tech run ground stations located in or around campus. There are two ground stations on campus which can communicate via UHF/VHF frequencies (for command, health, and telemetry) and on off campus which communicates via S-band frequencies (for science data downlink)[15].

4. Electrical Power System - EPS

The EPS subsystem is designed to be able to operate for at least the six month mission lifetime and be capable of operating continuously throughout all phases of orbit (sunlight, eclipse, etc.). These two requirements led to the selection of the GOMSpace BP4 battery pack and the GOMSpace P31us power distribution board. Figure 8 shows the power generation and battery energy simulations for the worst case power draw/generation scenarios that were created to determine the number of solar panels required close power budgets for all operational modes. For the worst case power draw and generation, the spacecraft requires two orbits of science followed by one orbit of power generation. However, if nominal power draw and generation is assumed, the spacecraft requires ten orbits of science operations followed by one orbit of power generation.

It was determined that the 3U structure with a total of 49 solar cells (requiring two single deployed solar panels off the 3U face of the CubeSat), would be able to sufficiently close the power budget. Furthermore, the battery depth-of-discharge (DoD) was set at 30% so that enough battery cycles can be achieved for the predicted 6-9 months of nominal operations. Based on this, operational modes for the mission were developed and can be seen in Figure 7.



Mode Definition	MEV Power Draw (W)	Definition						
		Attitude	CDH/EPS	ADC Actuation	ADC Sensors	UHF (RX & TX)	S-Band (TX)	Payload
Safe	2.46	Unknown Attitude	**ON**	**OFF**	**OFF**	**Low Rate (Beacon)**	**OFF**	**OFF**
Eclipse	3.46	~Nadir Pointing	**ON**	**Reaction Wheels, TR**	**IMU**	**Nominal Rate (Beacon)**	**OFF**	**OFF**
Charging	3.55	Max Sun Generation Attitude	**ON**	**Reaction Wheels, TR**	**IMU, Sun Sensors**	**Nominal Rate (Beacon)**	**OFF**	**OFF**
Downlink	12.91	Ground Station Pointing	**ON**	**Reaction Wheels, TR**	**IMU, Sun Sensors, GPS**	**Max Rate**	**ON**	**OFF**
Science	6.50	Nadir Pointing	**ON**	**Reaction Wheels, TR**	**IMU, Sun Sensors, GPS**	**Nominal Rate (Beacon)**	**OFF**	**ON**

Figure 7. MicroNimbus Operational Modes (Red, Yellow, and Green Correspond to Low, Medium, and High Duty Cycles)

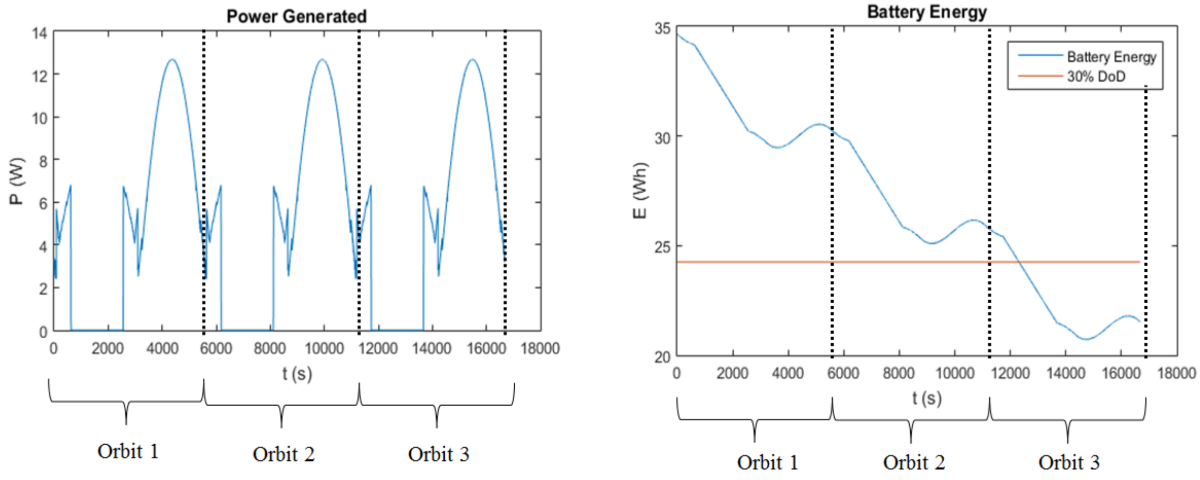


Figure 8. Power Generation (left) and Battery Energy Simulations (right) Over Three Orbits

5. *Structures - STR*

The overall structure of the spacecraft is designed specifically such that it not only meets the structural requirements set forth by most major CubeSat specifications (Cal Poly, NanoRacks, etc.), but also that it is easy to machine and integrate. For example, each module (ADC, service, payload) of the CubeSat is comprised of L-shells, each of which is created from individual blocks of aluminum. Then each module is joined together through the use of section connectors. This allows for schedule margin within the machining process to be smaller and poses less risk of large schedule delays for overall delivery of the structure[10]. Furthermore, because the satellite is inherently modular (seen in Figure 9) each module can be tested, during integration, and integrated individually without interfering with other modules. This once again helps alleviate schedule risks during integration. Fully integrated views of the spacecraft (including solar panels) can be seen in Figure 10 and Figure 11.

Custom hinges have been developed for the deployment of the solar panels. The hinges deploy to 120°(rather than 90°) so that the UHF antenna gain pattern is minimally affected. These hinges use a burn-wire to keep the panels folded in. Once commanded, the spacecraft sends current through a resistor, which burns the burn-wire, and a torsion spring forces open the panels. This design has been tested in both air and vacuum and has been shown to successfully operate.

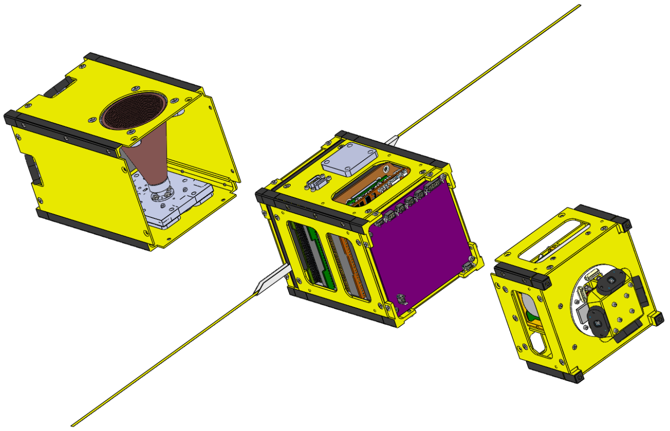


Figure 9. MicroNimbus Modules - Payload (Left), Service (Middle), and ADC (Right)

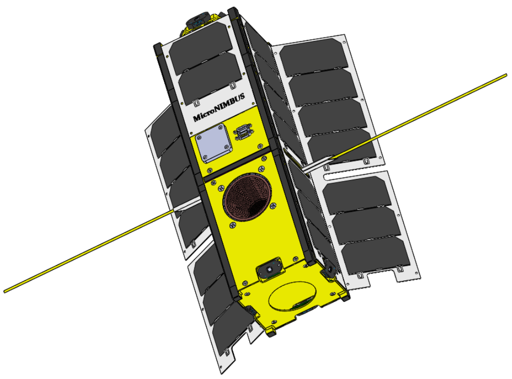


Figure 10. MicroNimbus - Integrated View 1

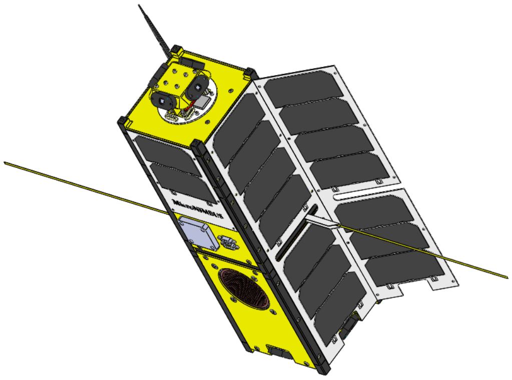


Figure 11. MicroNimbus - Integrated View 2

6. Navigation - NAV

The NAV subsystems plays a critical role for the payload. First, for the overall science mission, the position of the spacecraft relative to the Earth (in addition to the attitude) is critical in determining which part of the atmosphere the instrument is sounding. Secondly, the GPS receiver plays a critical role for the radiometer payload itself. The radiometer requires a well-disciplined 10 MHz signal for both the SiGe integrated receiver front end and the down-mixer. However, since the GPS receiver used on the satellite (NovAtel OEM615) only provides a 1 Pulse-Per-Second (PPS) disciplined signal, the payload interface board will be used to convert this signal into the required 10 MHz signal. The payload interface board sits in-between the service module and the payload module, and will be used to place any communication interfaces between the payload and the flight computer.

IV. Conclusion

This paper presents the design of a remote sensing CubeSat mission known as MicroNimbus. The purpose of this mission is to use a frequency tunable mm-wave radiometer in order to measure and update the temperature profile of the atmosphere. The 3U satellite is composed of a standardized bus design known as TECHBus which houses the payload. The radiometer payload itself is composed of an integrated SiGe radiometer receiver and a corrugated horn antenna that will allow for the observation of the atmosphere in the 60 GHz regime where O_2 absorption bands exist. Data gathered from this mission can help with weather forecasting and serves as a step towards the creation of a constellation of remote sensing CubeSats dedicated to near real-time global atmospheric temperature profiling.

Acknowledgments

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