Developing Mission Operations Tools and Procedures for the Microwave Radiometer Technology Acceleration (MiRaTA) CubeSat Mission

by

Erin Lynn Main

Submitted to the Department of Electrical Engineering and Computer Science
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Abstract

Small satellites (CubeSats) provide platforms for science payloads in space. A previous Earth weather observing CubeSat mission, the Micro-sized Microwave Atmospheric Satellite-1 (MicroMAS-1), used a manual approach to both testing and commanding. This approach did not work well when it came to mission operations, as it was error-prone, stressful, and non-repeatable. In this thesis work, we designed and implemented an automated testing framework for the Microwave Radiometer Technology Acceleration (MiRaTA) CubeSat, which was used during testing and mission operations; we also prepared tools and procedures for mission operations. The MiRaTA system presented large improvements in usability and repeatability as compared to the MicroMAS-1 system; for instance, an automated functional test could be run 38x faster as compared to a manual functional test.

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I am grateful to all of the MIT Lincoln Lab staff that I have worked with since I started in 2015. All of you have been so supportive and helpful at every turn; it has been a great pleasure working with you all. I would like to especially thank Dr. William Blackwell for advising my thesis, Dr. Daniel Cousins for his professional guidance, leadership, and support, and Michael DiLiberto for lending his considerable technical expertise, advice, and guidance to the MiRaTA team.

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Last but not least I'd like to thank my family and friends for helping me get to/through MIT. None of this would have been possible without your support.

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Chapter 1

Introduction

The purpose of this thesis is to demonstrate process improvement for testing and mission operations for CubeSats. Although this work was created specifically for the MiRaTA mission, the general concepts can be applied to other CubeSats as well.

1.1 CubeSats and Weather Sensing

Remote sensing enables scientists to measure properties of the Earth, such as surface temperature and atmosphere composition, from afar. One important type of Earth observing remote sensor is the microwave radiometer; radiometers currently in orbit around the planet capture important observational data as input for weather forecasting models, which generate our day-to-day weather forecasts. Therefore, improving the quality, global coverage, and frequency of microwave radiometer data is of direct interest to scientific organizations such as the National Oceanic and Atmospheric Administration, NASA, and society at large. One way to accomplish this goal is to improve the development process and on-orbit operations of spacecraft used to carry and operate radiometers.

Currently operating weather satellites are typically monolithic structures that host many different types of sensors.[6] These satellites are very large in size (thousands of kg), with high development costs in time (over ten years) and money (hundreds of millions to billions of dollars). Due to their expensive and monolithic nature, these satellites also have a high impact of failure. In addition, their revisit period is too long (from a minimum of 4-6 hours to up to 2 weeks over the same ground site) for what would be necessary to improve severe weather tracking (15-30 minutes).[6]

Instead of using large satellites to hold many sensors, an alternative solution is to build many small satellites (also known as CubeSats or nanosatellites), each holding their own remote sensing payload.[6] Each satellite would have costs in the million-dollar range, with a development time of 2-3 years. Since each satellite is relatively cheap and has only one payload, if several are built, the failure impact is low. To achieve a low revisit period (15-30 min), a constellation of small satellites could be flown. This alternative satellite development paradigm is currently being undertaken at MIT Lincoln Laboratory (MIT LL) in collaboration with the MIT Space Systems Lab (MIT SSL); many other universities are developing and flying CubeSats as well.

Several CubeSat programs from MIT LL/MIT SSL have already flown. The Micro-sized Microwave Atmospheric Satellite-1 (MicroMAS-1) was the first CubeSat launched by MITLL/MIT SSL, in March 2015. MicroMAS-1 was able to perform a successful checkout of its spacecraft systems; however, its transmitter eventually failed a week into the mission, and no payload data was successfully received.[6] The Microwave Radiometer Technology Acceleration spacecraft (MiRaTA) All of these radiometer spacecraft have similar size (3U, 30 cm x 10 cm x 10 cm) and power specifications (10 watts); each has a different radiometric payload, however.[6] The MiRaTA spacecraft is of interest to this work, and will be discussed further.

1.2 MiRaTA and MicroMAS-1

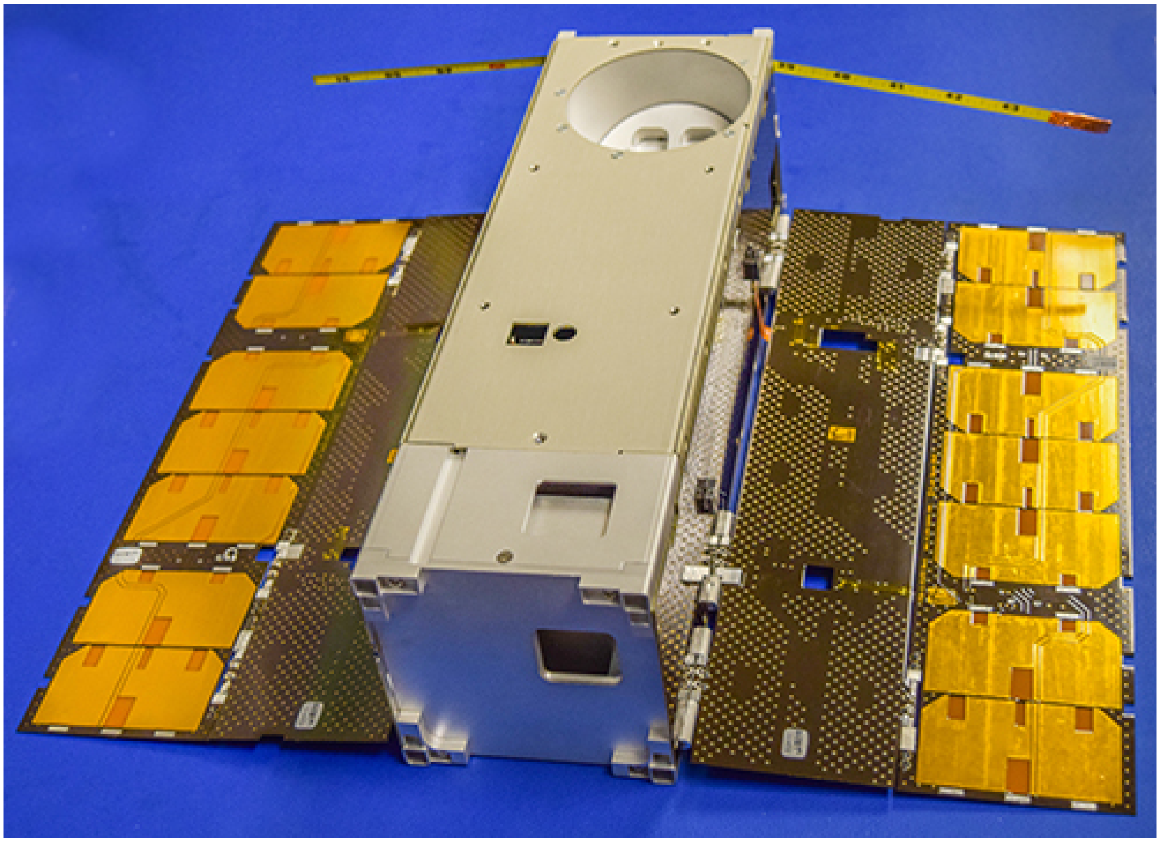

Figure 1-1: MiRaTA spacecraft.[26]

The MiRaTA spacecraft is comprised of several printed circuitboards (PCBs) connected through a common header; on each circuitboard there are several types of sensors (such as temperature and voltage sensors) as well as connections to devices (such as reaction wheels and radios). MiRaTA also has a main microcontroller that coordinates interactions with each device; the microcontroller runs a lightweight real-time operating system which uses a cooperative scheduler to make sure tasks are executed properly. External input to MiRaTA comes in the form of packets; these packets can be sent via radio or via serial. MiRaTA has two types of radios, the Micron radio (used for live commanding) and the L3 Cadet radio (used for rapid data downlink); both radios operate in the ultra-high frequency (UHF) range.

MiRaTA utilized a good deal of code from MicroMAS-1. One software tool that was used on MicroMAS-1 and adapted for MiRaTA is Dashboard[19], an application that can interface with ground station hardware to talk to the satellite. Dashboard was used to both test the spacecraft on the ground and communicate with the spacecraft while it was orbiting Earth. Its user interface provided a simple command form for issuing packets to the satellite, as well as a few different displays of telemetry from the latest packets received from the spacecraft. Dashboard also saves data it receives from the satellite, for later processing. Dashboard played a crucial role in testing the MicroMAS-1 satellite, as it is the primary way of commanding the satellite and viewing its state.

In order to ensure that a satellite will operate when it is launched into space, a satellite must undergo a gamut of electrical, software, and environmental testing on the ground. The bare minimum for the electrical and software testing is manual verification of each parameter under test, which was the strategy used for the MicroMAS-1 mission. Most manual tests involved looking at a piece of data from a particular sensor and seeing if it made sense given the current spacecraft environmental conditions.

These manual tests have several flaws, stemming from their very human-intensive nature. Since each test needed to be run by an engineer, tests were subject to variability such as timing between commands, errors in command sequence or parameters, or failure to properly document the command sequence used. The tests were also very repetitive, which can be boring for the test engineers, and also led to a disinclination to run tests more often than the minimum necessary to ensure the spacecraft was functioning at a basic level. Since the spacecraftâĂŹs state was constantly in flux (due to changing software, hardware, and environments), ideally testing would be done frequently to ensure operation of both new and old features.

During the MicroMAS-1 mission, Dashboard was also used as the primary way of interfacing with the satellite. Dashboard did not have capabilities beyond the bare minimum (command and view of telemetry), which led to some operational difficulties while using Dashboard during the mission. For example, often, ground station engineers would need to issue a sequence of predetermined commands. Unfortunately, Dashboard at the time offered no way to define and verify these commands prior to sending them, which resulted in engineers having to manually fill in the command form each time, in a specified order, every time they wanted to command the spacecraft to do something. This introduces a great risk of human error. The difficulty of issuing these commands was compounded by the short time that the satellite was in communication at a given time with a ground station, creating a source of stress for the ground station engineers. Eventually software workarounds were made, but they were ad-hoc.

Automated testing and commanding provides another alternative to manual testing, and addresses concerns related to the manual testing approach. An automated test is comprised of the same command sequences and telemetry checkpoints as described for the manual test, but would be issued/checked by software rather than by human operators. Automated testing would allow for a test to be run many times over, reducing human error and cognitive load during testing. The repeatability of an automated test would also ensure that any changes in the results of a test were due to either environmental changes, hardware changes, or software changes (rather than variance in how the test was administered). Finally, mission operations would benefit from an automated approach, as operators would not need to worry about accidentally missing a command, or entering in a wrong command. Automated commanding gives mission operators a way to carefully plan out what command sequences would be issued while the spacecraft is reachable from the ground station.

In Chapter 2, we discuss testing and mission operations of a spacecraft, the MiRaTA mission, and the MicroMAS-1 mission. In Chapter 3, we present the basic capabilities of Dashboard. In Chapter 4, we cover our approach to building testing / automated commanding systems for MiRaTA. In Chapter 5, we discuss the performance of the MiRaTA systems as compared to the MicroMAS-1 systems and suggest avenues for future work.

Chapter 2

The MiRaTA and MicroMAS CubeSat Missions

As background for this thesis, we provide a brief overview of general concepts relating to the testing and operations of satellite missions. We then describe the MiRaTA mission, with a focus on its hardware and software components. Finally, we briefly discuss the MicroMAS mission.

2.1 Testing and Mission Operations

2.1.1 Qualification and Acceptance Testing

All spacecraft must go through a battery of tests before they are approved for launch by the company that coordinates launches of spacecraft (a launch service provider). These tests (also known as acceptance tests) emulate the conditions the spacecraft will be subjected to during launch and after deployment in space.[5] They help verify spacecraft build quality, integrity, and ensure that the spacecraft will be able to be launched properly. In addition to the LSP's tests, teams also conduct their own tests to check spacecraft workmanship and functionality; tests to check if the spacecraft will meet design parameters are called qualification tests.[5]

For testing, multiple versions of the spacecraft design are built. The spacecraft

Table 2.1: Types of environmental tests conducted on MiRaTA.

Test	**Conditions**	**Component lvl**	**Subassembly lvl**	**SV lvl**
TC	Vacuum or oven		X	X
TB	Vacuum			X
Vibration	Room temp/pressure		X	X
EMC	Room temp/pressure		X	X
Functional	Vacuum or room	X	X	X

An X indicates that at least one of that type of test was performed on MiRaTA. Component/subassembly/space vehicle examples: A component would be something like a battery, subassembly means the entire power system, and space vehicle means the entire spacecraft.

which will be launched is called the flight model (FM); usually the FM is subjected to the bare minimum of tests needed to verify that the spacecraft is operational, in order to avoid causing harm to the spacecraft while doing testing. A structural/thermal model (STM) replicates the physical structure and thermal properties of the spacecraft but without functional components; building an STM is much cheaper and easier than building a full spacecraft and allows the team to do rigorous physical testing without risk of harming the FM. The engineering model (EM) is a replica of the FM, but is used on the ground for development and functional testing much more than the flight model; for instance, on MiRaTA, the EM was used for virtually all of software development. During mission operations, the EM can be used as a way to verify expected spacecraft behavior, before sending commands to the actual FM in space.

Figure 2-1: MicroMAS-1 spacecraft in a thermal vacuum chamber.[9]

Types of tests that a spacecraft undergoes include, but are not limited to:

- **Thermal cycling (TC)**: Repeatedly expose the spacecraft to a cycle of cold temperatures, then hot temperatures.[3] Thermal cycling causes expansion and contraction of components, another potential source of stress for the spacecraft. Workmanship issues (how well components are assembled) can be exposed in this test.

- **Thermal balance (TB)**: Makes sure that the spacecraft does not heat up or cool down too much while in vacuum; the spacecraft temperatures are compared to the thermal model for verification.[3] This test is necessary because heat transfer is different in space versus on Earth.

- **Thermal vacuum (TV or TVAC)**: Expose the spacecraft to high vacuum and extreme temperatures, to emulate flight conditions.[5]

- **Vibration**: Vibration tests vibrate the spacecraft in a way that emulates the type of vibrations that may arise during launch.[5] Different types of vibration profiles are used, such as sinusoidal vibrations and random vibrations.[1]

- **Shock**: Shock tests subject the spacecraft to sudden motion.[1]
- **Electromagnetic compatibility (EMC)**: EMC tests check for excessive electromagnetic (EM) emissions created by the spacecraft, and also determine if the spacecraft is susceptible to external EM interference.[2]
- **Functional**: Functional tests check if the spacecraft can execute all of the functions required of it to complete the mission. These are defined by the team developing the spacecraft.

2.1.2 Mission Operations

After satisfactory qualification/assurance testing, the spacecraft is integrated into the launch vehicle by the LSP. Some time after that, the spacecraft is launched into orbit, at which point mission operations begins. Mission operations is the point at which the spacecraft is remotely controlled by operators. There are two main phases to mission operations: in-orbit testing (also called early orbit checkout) and nominal operations. The purpose of in-orbit testing is to verify that the spacecraft is operating as expected in space; this includes telemetry/radio communications verification, payload checkout, calibration, and some other functional tests.[27] Once in-orbit testing has been completed, the mission enters nominal operations; for MiRaTA, this involves collecting science data.

In order to communicate with the satellite, the spacecraft operators must utilize a ground station. A ground station contains the radio frequency (RF) equipment and software to be able to encode and decode information to/from the spacecraft, in addition to any networking/software needed for the operators to connect to the ground station hardware (if the operators are remote).[27] Communications with the satellite can only occur when the satellite is visible from the ground station; the period of time the satellite is overhead is called an overpass. For MiRaTA, the overpass durations are no longer than 10-12 minutes.

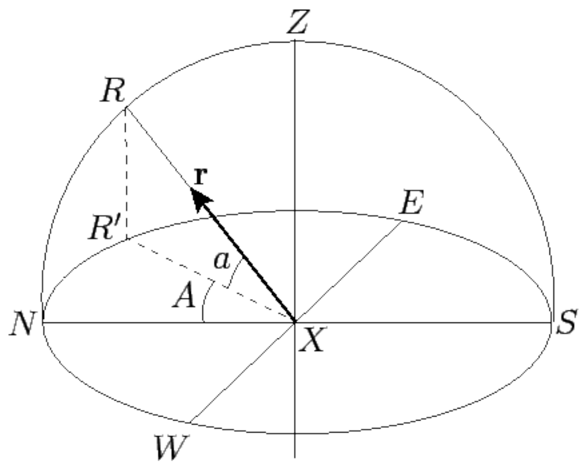

Figure 2-2: The horizontal coordinate system.[13]

The satellite's position relative to the ground station is typically specified in the horizontal coordinate system (as shown in Figure 2-2).[13] In Figure 2-2,

- $NESW$ are the cardinal directions (north, east, south, west), which defines the horizontal plane.
- X is the observer (the ground station in our case).
- R is the satellite.
- R' is the projection of R onto the horizontal plane (also called the local horizon).
- a is the altitude of R, or the angle between XR and XR'.
- A is the azimuth of R, or the angle between XN and XR'; it increases from north to east.

Information about the satellite's orbit is stored in the two-line element (TLE) format.[17] TLEs describe the orbit of a satellite, and are generated periodically by NORAD (North American Aerospace Defense Command).[17] To use TLEs, an operator feeds them into an orbit propagator, which calculates the path of a satellite (also called the ground track) and when the satellite will pass over the ground station; the propagator then displays the results via a graphical user interface. GPredict[1] is

[1] http://gpredict.oz9aec.net/

an open-source piece of software that is commonly used for this purpose; there is also a website called `n2yo.com` that will also display satellite ground tracks.

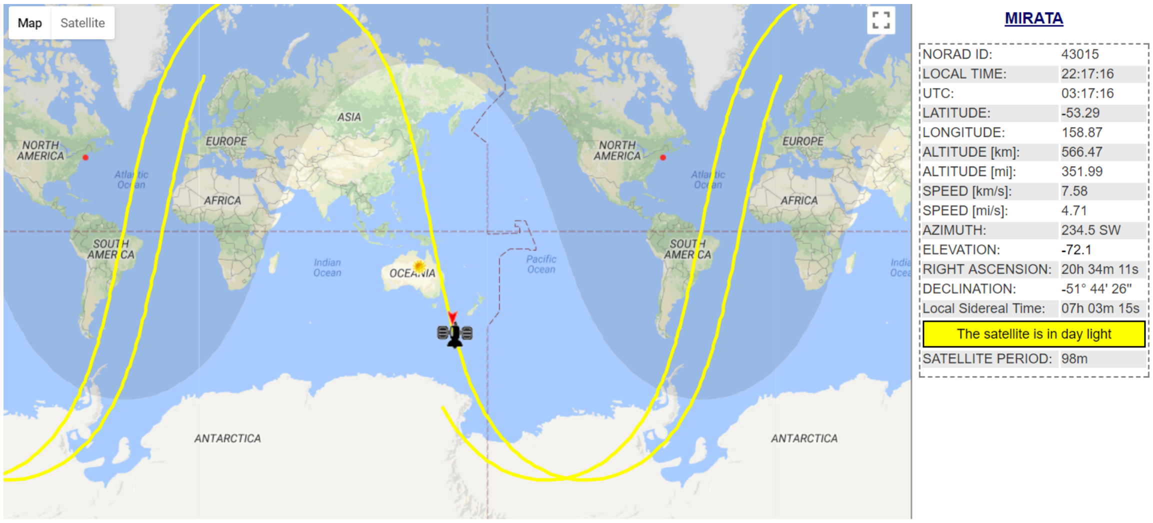

Figure 2-3: MiRaTA's ground track shown in n2yo.com.[28] Imagery from Google Maps.[15]

Another important variable for the operator to keep in mind during mission operations is the effect of Doppler shift on satellite communications. Doppler shift is the phenomena where a receiver (e.g. a ground station) of a signal generated by a moving source (e.g. a satellite) will observe a change in frequency of the signal; this change depends on the relative velocity of the source and the receiver.[14] If the source is moving towards the receiver, then the receiver will perceive a higher-frequency signal than what the source is actually emitting; if the source is moving away from the receiver, then the receiver will perceive a lower-frequency signal. Depending on the bandwidth (the understandable frequency range) of the receiver, Doppler shift can make communications useless. Ground stations often implement Doppler correction measures to account for Doppler shift; for instance, if a satellite is traveling towards a ground station, the ground station will emit signals which are lower than the expected receiver frequency of the satellite so that, when the signals arrive at the satellite, they are at about the proper frequency. The appropriate Doppler correction is calculated using the spacecraft TLE and the ground station location latitude/longitude/elevation.

2.2 MicroMAS-1

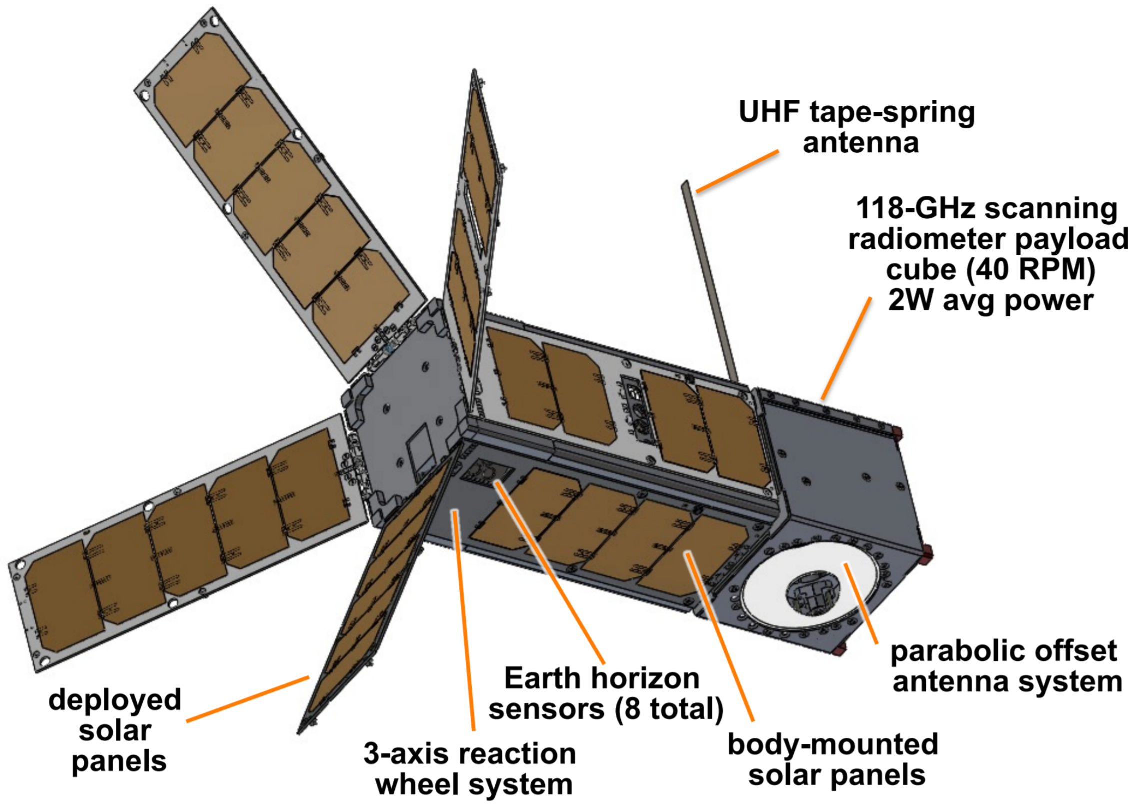

Figure 2-4: MicroMAS-1 model.[9]

The MicroMAS-1 mission was the first joint CubeSat mission between the MIT Space Systems Laboratory (SSL), MIT Lincoln Laboratory, and the University of Massachusetts at Amherst.[11] The payload of MicroMAS-1 was a passive scanning microwave radiometer; it had a scanner assembly that rotated the payload at about 0.8 Hz.[11] MicroMAS-1 was delivered to the International Space Station in 2014 and was deployed in March 2015; unfortunately, after one week, the spacecraft suffered a transmitter fault.[9]

The small MicroMAS-1 team had to design many procedures, build avionics boards, and write flight/ground software code all from scratch. This understandably led to some sub-optimality in MicroMAS-1 testing and mission operations procedures, as the team was stretched thin and simply did not have enough time to complete the necessary work. MiRaTA, which has the advantage of relying upon the vast body of work done by the MicroMAS-1 team, was able to improve upon some of the issues, as described in Chapter 5.

2.2.1 Mission Operations

Some background on the specific configuration for MicroMAS-1 mission operations is useful for understanding MiRaTA's set-up, as several aspects remained the same through both programs. The high-level block diagram is shown in Figure 5-2.

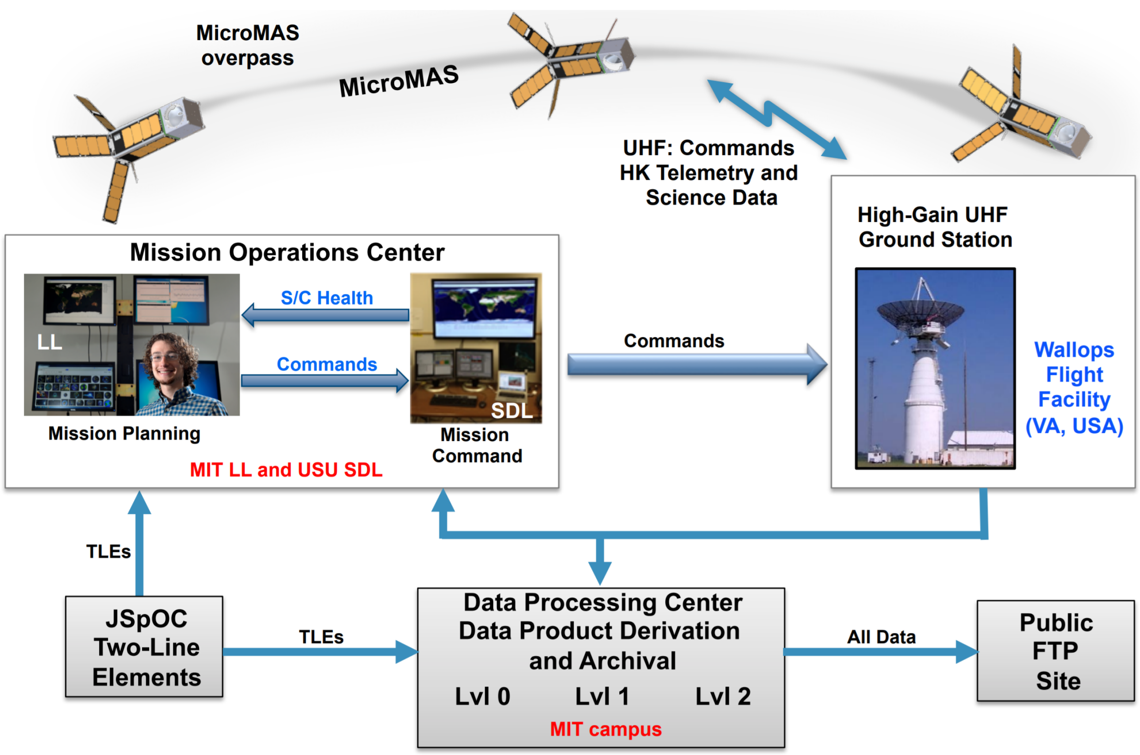

Figure 2-5: MicroMAS-1 ground station diagram.[9]

The process of communicating with the satellite during MicroMAS-1 operations went as follows:

1. The mission planning team at LL (in Massachusetts) would figure out what the goal of the next overpass was. For instance, confirm that a particular subsystem is working.

2. The mission planning team would come up with a sequence of commands to

send during the overpass, and notify the mission command team at SDL (in Utah).

3. The mission command team would issue commands and receive telemetry remotely through the dish at the Wallops Flight Facility (in Virginia).

4. Any data would also arrive at MIT campus, where it would be processed by the data analysts.

As a result of data analysis, multiple data products are produced. These data products are described by the NOAA processing levels:[24]

- **Level 0**: Unprocessed spacecraft telemetry.
- **Level 1**: Instrument-specific datasets that have been timestamped and include raw unprocessed science data, with other information like data quality measurements and calibration coefficients.
- **Level 2**: Contains geophysical variables derived from the Level 1 data, with the same resolution and locations.

2.3 MiRaTA

The MiRaTA spacecraft, the primary focus of this thesis, is the result of a collaboration between the MIT STAR (Space Telecommunications, Astronomy, and Radiation) Laboratory, MIT Lincoln Laboratory, The Aerospace Corporation, the University of Massachusetts, and Utah State University.[7] The goal of the MiRaTA mission is to validate a passive microwave radiometer (MWR) and a GPS radio occultation (GPSRO) instrument, and also use a new approach to CubeSat radiometer calibration using GPSRO measurements.[7] The planned mission duration is 90 days long.[12]

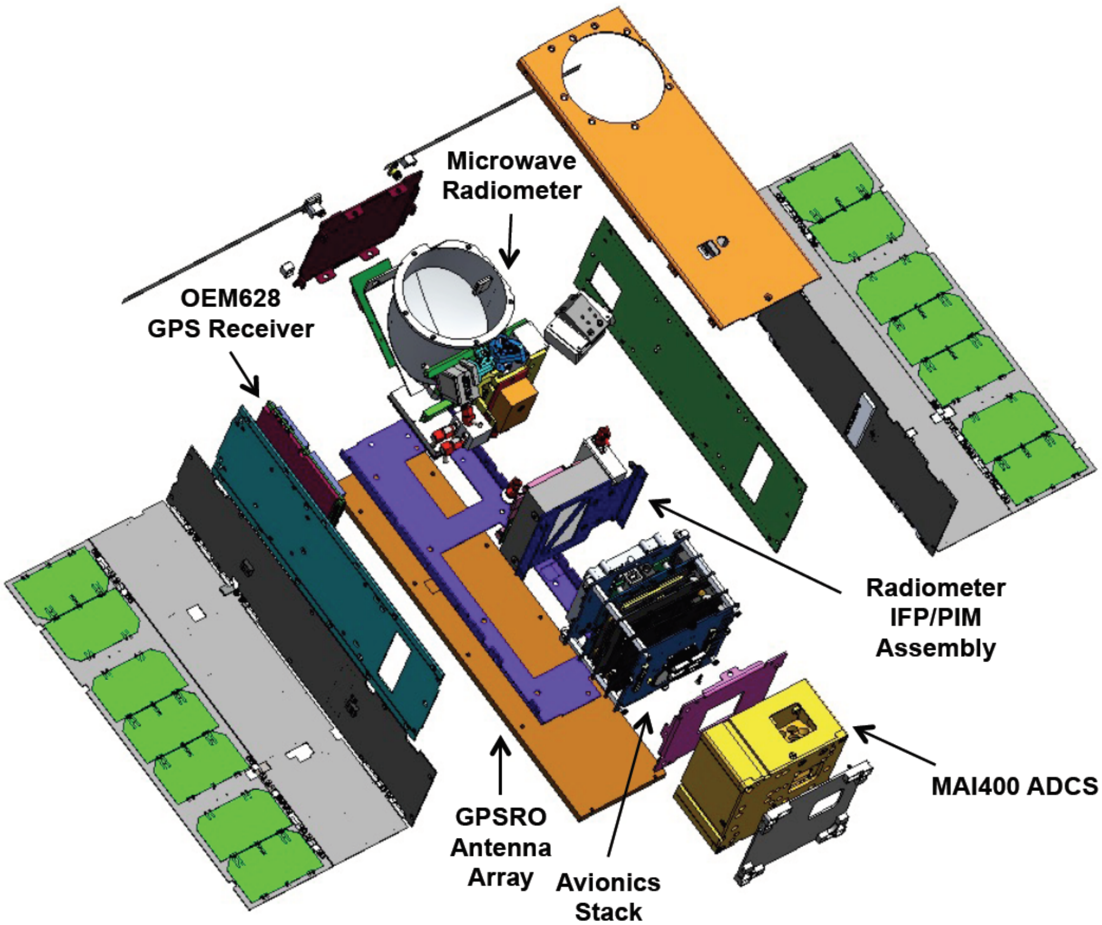

Figure 2-6: MiRaTA spacecraft, expanded so some components are visible.[8]

2.3.1 Payload

The microwave radiometer is a tri-band, 10-channel sensor that provides temperature, humidity, and cloud ice measurements; its three frequency bands are 52-58, 175-191, and 206-208 GHz.[7] [2] A microwave radiometer works by measuring the thermal radiation (brightness temperature) emitted by objects of interest (e.g. clouds, the Earth's surface, vegetation) over various frequencies; the response received by the radiometer versus the frequency of the response is used to create an absorption profile.[23] This absorption profile can then be compared to known absorption profile characteristics to figure out various aspects of climate data (such as the temperature profiles MiRaTA

[2]The radiometer was developed by MIT LL and UMass Amherst.

hopes to obtain). Microwave radiometers report brightness in raw digital numbers (also called DNs or counts); it is thus important to calibrate the radiometer so that one knows what counts correspond to what temperature. Calibration is typically done by repeatedly pointing the radiometer at a hot target, then a cold target; these targets are usually blackbodies, which means they have a known relationship between their temperature and the amount of microwave energy they emit. On orbit, calibration must be done frequently in order to correct sensor drift. Using bulky blackbodies is unfortunately not an option for small CubeSats, which means alternative calibration methods (such as the one being pioneered by MiRaTA) must be used.

The GPSRO instrument is called the Compact TEC (Total Electron Count) / Atmosphere GPS Sensor (CTAGS), and is based on a GPS receiver (OEM628) plus a patch antenna array.[8] [3] GPSRO measurements have been demonstrated to have the capability to create temperature profiles in the upper troposphere / lower stratosphere that approach 0.1K accuracy.[7] MiRaTA's radiometer calibration approach will leverage GPSRO measurements of the Earth's limb, which is the atmosphere at the visual edge of the Earth. The calibration approach will also use a noise diode, which serves as a source of calibration signal; it itself will be calibrated using GPSRO measurements. Together, using the noise diode and GPSRO, MiRaTA is able to avoid the use of the aforementioned bulky blackbody targets for calibration.[7] Because MiRaTA does not do the typical calibration via external targets, MiRATA has no active scanning mechanisms, simplifying the spacecraft structure.[26]

The final components of the payload are the Intermediate Frequency Processor (IFP) and Payload Interface Module (PIM). The IFP does digitization and signal processing on the incoming radio frequency (RF) signal. The PIM coordinates the actions of the payload sensors, and serves as an interface between the bus and the payload.

[3] CTAGS was developed by the Aerospace Corporation.

2.3.2 Bus

The operation of the MiRaTA payload is supported by the spacecraft bus, which is a collection of boards and components that make up the rest of the spacecraft; it includes, among other components, two radios, a microcontroller, a power subsystem, and an attitude determination and control system (ADCS). The design of the bus carries over many lessons learned from MicroMAS-1 and uses many of the same commercial off-the-shelf (COTS) components.[26] The COTS components are integrated together using several custom-designed boards. Together, the bus and the payload fit in a standard 3U CubeSat configuration, which is 10 cm x 10 cm x 34 cm with a mass of around 4.5 kg.[12] [4]

Power

MiRaTA's power[5] is provided by the Clyde Space[6] Electronic Power System (EPS), a Clyde Space battery, and Clyde Space double-deployed solar panels.[7] The EPS provides the spacecraft bus regulated sources of 3.3V and 5V power, as well as a connection to the battery (7-8V depending on charge). All lines also contain overcurrent protection; when the EPS's microcontroller detects an overcurrent condition, the output lines are disconnected from the rest of the spacecraft bus.[10] The solar panels connect to the EPS through a battery charge regulator (BCR), which then connects to the battery for charging.

External to the EPS are a handful of power switches (called power distribution units or PDUs). These PDUs control power to each individual sensor/subsystem and can be toggled with the microcontroller.

[4]MiRaTA structures were worked on by Tim Cordeiro and Dave Toher.
[5]MiRaTA's power subsystem was worked on by Annie Marinan and Ayesha Hein.
[6]https://www.clyde.space/products

Communications

MiRaTA sports two ultra-high frequency (UHF) radios, one for data downlink and one for commanding.[7]

The first is called the Cadet-U radio, developed by L-3 Communications and the Space Dynamics Laboratory (SDL). It is the way payload and spacecraft data is downlinked from the spacecraft, due to its high downlinked data rate (3.0 Mbps) and large amount of internal storage.[20] It operates in the UHF range at around 450-460 MHz; in order to communicate with it, we use the NASA Wallops ground station coupled with SDL's SATRN and Titan software.[20, 8] The Cadet has a "store-and-forward" architecture, which means that the radio collects data from the spacecraft in its first-in-first-out buffer (which we call the FIFO), and the operators on the ground must request particular subsets of the data in the FIFO; the Cadet cannot respond with real-time data.[20]

The second radio on board MiRaTA is called the Micron radio, and is based on a Planet UHF design which uses the CC1110 radio transceiver.[21] Since it can respond in real time (unlike the Cadet), it is used as the primary commanding radio. Its ground station is based on MIT's campus.[8]

[7] MiRaTA's communication systems were worked on by Greg Allan, Mic Byrne, Myron Lee, Julian Mendoza, Joey Murphy, Stephen Shea, and Michael Shields.

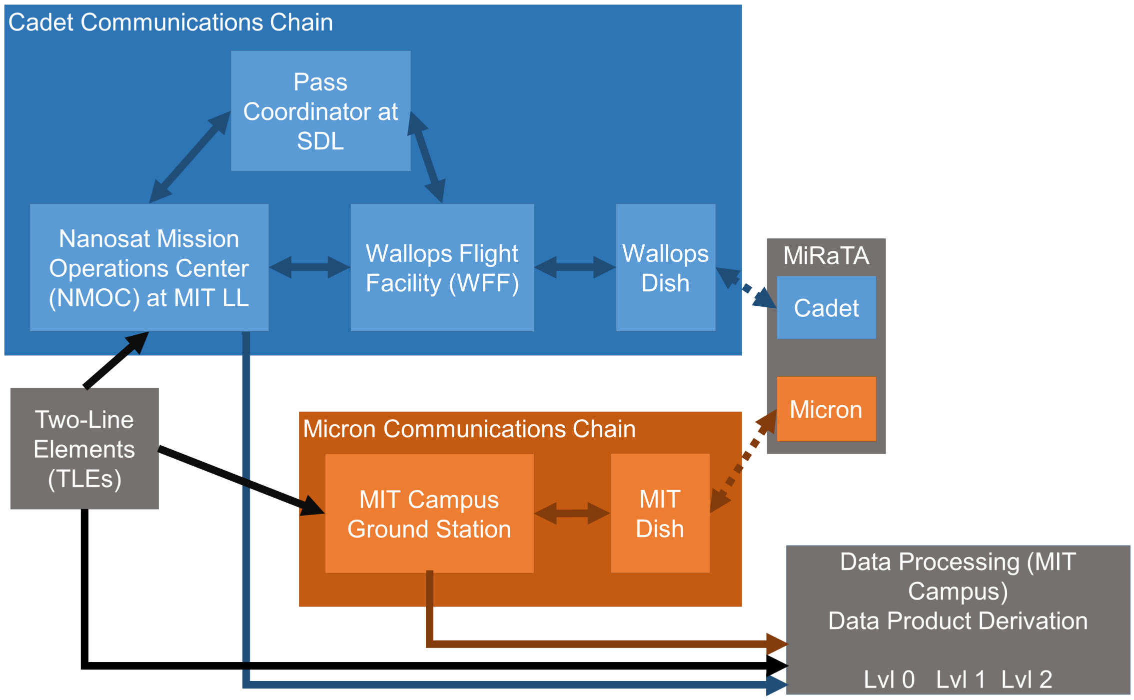

Figure 2-7: MiRaTA ground station diagram. The Cadet communications chain in MiRaTA is similar to the MicroMAS-1 one. For MiRaTA, we have added the Micron communications chain.

ADCS

The ADCS is made of a complement of sensors and actuators.[8] The bulk of the ADCS consists of the MAI-400 from Adcole Maryland Aerospace[4]. It contains a 3-axis magnetometer, two IR Earth Horizon Sensors (IREHS), three electromagnets (also called torque rods), three reaction wheels, and an ADACS computer.[4] In addition to the MAI-400, MiRaTA also has an inertial measurement unit (IMU) and another EHS.[7]

[8]The ADCS subsystem for MiRaTA was worked on by Zack Lee, Weston Marlow, and Adam Milstein.

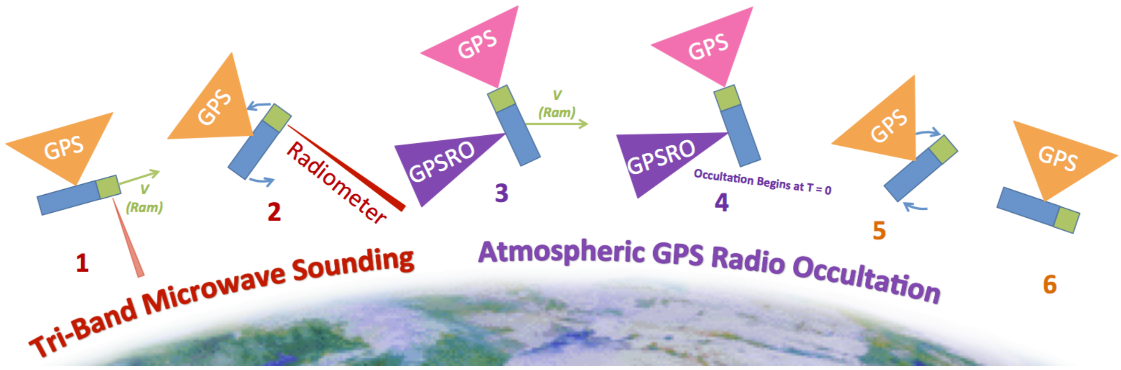

Figure 2-8: MiRaTA spacecraft science maneuver. The green is the payload and the blue is the spacecraft bus. The triangles indicate relative fields-of-view and direction of the payload instruments (GPS, GPSRO antenna, and radiometer).[8]

All of these sensors and actuators are used to perform several spacecraft movements, critical to mission success. The first ADCS mode to run is detumble, which stabilizes the spacecraft from tumbling after deployment. In nominal operations, the ADCS will also execute pitch-up and pitch-down moves, which moves the bus in such a way that the payload can scan the Earth's limb. These pitch-up and pitch-down moves are a part of the spacecraft's calibration maneuver (also called maneuver mode), depicted in Figure 2-8; it lasts about 10 minutes.[8]

Other Components

Other components of note include:

- A set of resistive temperature detectors (RTDs) for monitoring the temperature of various components.
- An oscillator to serve as the spacecraft's sense of time/clock (also called avionics elapsed time or AET).
- A flash chip for storage of multiple flight software images.
- A set of thermal knife drivers (TKDs) which, when fired, deploy the solar panels.

The spacecraft motherboard is a Pumpkin CubeSat motherboard.[7] Custom-built boards interface with the COTS components, and form the backbone of the avionics stack. These boards are called the Top Interface Board (TIB), which interfaces with the Cadet radio; the Bottom Interface Board (BIB), which interfaces with the MAI-400; and the Micron Motherboard (MMB). The format of the boards follows the CubeSat Kit PCB Specification.[9]

Microcontroller and Flight Software (FSW)

MiRaTA's onboard microcontroller is a PIC24 running the Salvo Real Time Operating System (RTOS).[25] Salvo was chosen for its extremely low memory requirement, and was previously used on MicroMAS-1.[25, 11] The flight software (FSW) is written in C.[10]

Salvo is a purely event-driven, stack-less cooperative multitasking RTOS[11].[25] A Salvo program is broken into a main program and various tasks. The main program typically runs setup code (running initialization code for subsystems, for instance), then runs the Salvo scheduler forever in a while loop. The scheduler then runs tasks according to priority (there are 16 levels of priority available in Salvo); tasks that share the same priority run in round-robin fashion.[25] Since Salvo is cooperative, each task must manage task switching; this means that when a task is waiting or done, the task must explicitly yield control to the scheduler, otherwise the operating system can become stuck. Because each task controls when it switches, Salvo does not need to keep a per-task stack; it merely needs to save registers on a task switch. Another important part of the OS are interrupt service routines (ISRs), which are pieces of code that handle external events (such as data becoming available from a sensor). An ISR can interrupt any task; once the ISR is finished running, control is returned back to the task that was interrupted.

[9] Available at `http://www.cubesatkit.com/docs/CSK_PCB_Spec-A5.pdf`

[10] Some code was taken from MicroMAS-1's FSW, which was primarily written by Ryan Kingsbury; other contributors include Kris Frey and the author. The FSW for MiRaTA was primarily written by Kit Kennedy, with contributions by Julian Mendoza, Joe Kusters and Patrick Kage.

[11] Salvo is very different in concept from Linux, MacOS, or Windows, all which are pre-emptive multitasking operating systems. In a pre-emptive OS, tasks can interrupt each other, with the assumption that an interrupted task will resume later.

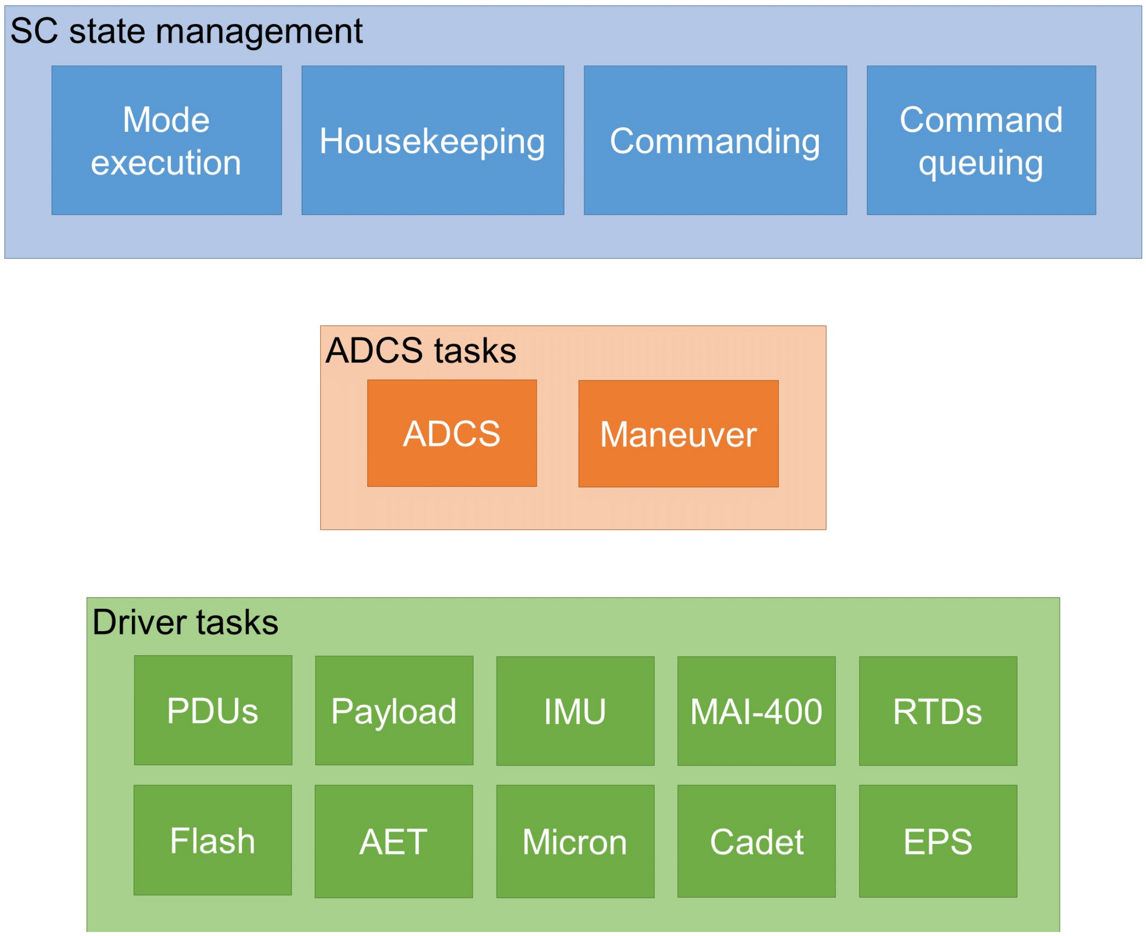

Figure 2-9: Collection of the tasks that run in the FSW.

The FSW consists of all the tasks listed in Figure 2-9.

- **Device drivers**: At the lowest level, all subsystems/sensors have their own driver, which is code that handles communication with the subsystem/sensor. Drivers issue commands to their respective subsystems, collect data, and monitor their subsystems for faults/errors. Each driver is structured in a loop which executes forever while the processor is running. Most drivers also contain ISRs to handle the many communication interfaces used on the spacecraft; examples include SPI (Serial Peripheral Interface Bus), I2C (Inter-Integrated Circuit), and UART (Universal Asynchronous Receiver-Transmitter). Device functionality can be enabled or disabled by either the special function tasks or the high level tasks.

- **ADCS tasks**: These tasks control the execution of complicated routines. The ADCS task manages the algorithmic aspects of moving the spacecraft in certain ways; it executes spacecraft detumbling and pitch-up/down motions. The maneuver task is in charge of managing the ADCS task state so that the payload can take radiometer and GPSRO measurements, as shown in Figure 2-8.

- **Spacecraft state tasks**: The mode execution task keeps track of what mode the spacecraft is in, and handles both autonomous and manual state transitions; nominal modes are shown in figure 2-10. The housekeeping task keeps track of all of the faults that accumulate from the different subsystems on the spacecraft, and also keeps track of the frequency of code execution and the last time the spacecraft heard from a ground station. The commanding task handles the interpretation of commands from the ground, and can command a transition to a modes or turning devices on and off. The command queuing task keeps track of commands to be executed in the future; when it comes time to execute queued commands, the command queuing task issues them to the commanding task.

Spacecraft Modes

There are a few special modes that the spacecraft enters; nominal operational modes are discussed below. When the microcontroller boots up (either through deployment or through a spacecraft reset), the spacecraft is in "not initialized" mode. It then autonomously and immediately moves to "inhibit mode" where the spacecraft waits for some time. After "inhibit mode", the spacecraft autonomously moves to "deploy mode", which fires the TKDs, thereby deploying the solar panels. After that, the spacecraft autonomously enters "safe mode", which indicates that the spacecraft is ready to begin mission operations. The spacecraft can then be manually commanded into the modes listed in Figure 2-10 below. The only one of the previously-described modes that the spacecraft can return to (without a spacecraft reset) is "safe mode", which the spacecraft can autonomously transition to if there are too many faults; in transitioning to safe mode, all non-essential devices are turned off.

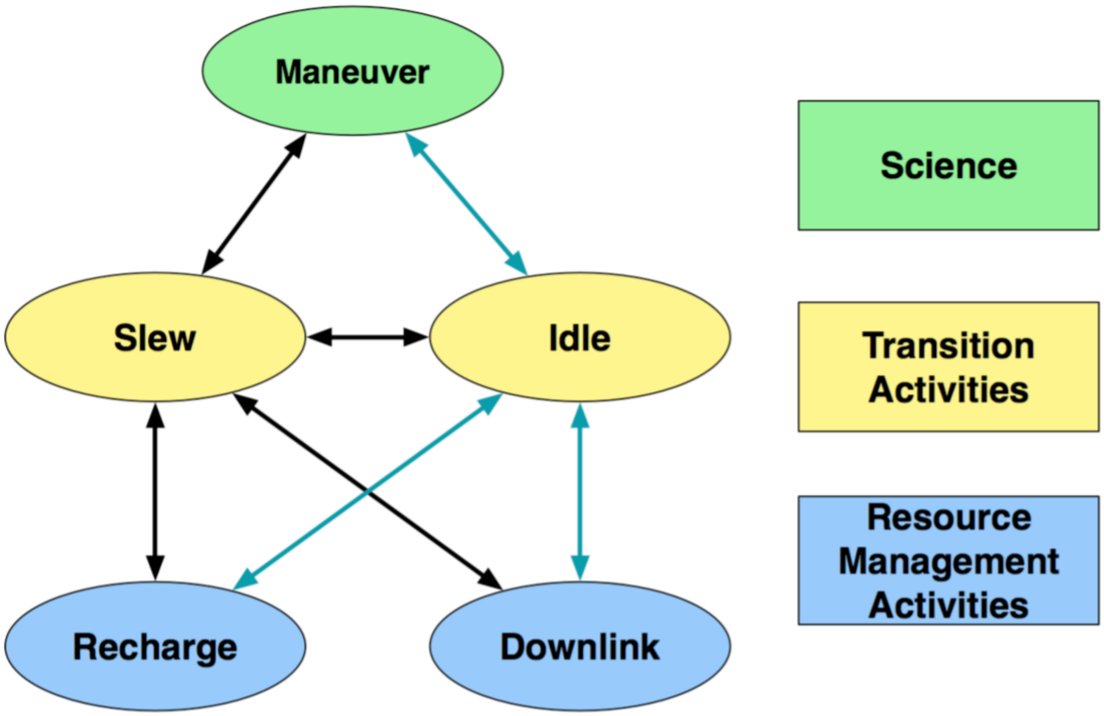

Figure 2-10: Nominal spacecraft modes.[18]

The five listed modes are the nominal operational activities for MiRaTA, and are mutually exclusive.[18] Maneuver mode is as described in Figure 2-8. The slew mode involves moving the spacecraft from one attitude (orientation) to another. Recharge mode corresponds to the ADCS suntracking mode, which charges the batteries with solar energy. Downlink mode corresponds to when the spacecraft is commanded to downlink data through the Cadet radio. Idle mode is the mode where the spacecraft is doing nothing but maintaining a radiometer nadir pointing attitude, Local Vertical Local Horizontal (LVLH); this means that the spacecraft is oriented parallel to Earth's surface.

Software Development

MiRaTA uses the Git[12] version control system. All code resides in the same monolithic repository, so that the team knows that a particular version of the flight software will

[12] `https://git-scm.com/`

work with the ground software (which was a concern on MicroMAS-1).

Chapter 3

Dashboard: Software for Command and Data Handling

3.1 Introduction

Dashboard[1] serves as a way for human operators to communicate with the satellite, and also observe the state of the satellite. Dashboard has the capability to interface with several types of ground stations, up to the operator's choosing. Using Dashboard's web interface, operators can send commands to the spacecraft, and observe telemetry in real-time. In this chapter, we cover the basic functionality of Dashboard: its software architecture, as well as some screen shots. The automated testing/commanding features will be discussed in the next chapter. Note that all screen shots used here and in the next chapter use randomly generated data.

Originally, Dashboard was created for the MicroMAS-1 mission, to assist in commanding and debugging the spacecraft telemetry. It was also used as a part of MicroMAS-1 mission operations, which will be discussed in Chapter 5.

Dashboard's functional requirements are as follows[2]:

1. Dashboard must support real-time (live) communications with the spacecraft

[1] Dashboard was originally written by Ryan Kingsbury, with many modifications from Kit Kennedy, the author, Patrick Kage, and Erik Thompson.

[2] Many of these are the result of MicroMAS-1 experiences; specific suggestions were made by Michael DiLiberto and Kit Kennedy.

via the Micron radio, the Cadet radio, and a USB-serial link.

2. For each link, Dashboard must allow for commanding on that link, and interpreting telemetry packets from that link.

3. Dashboard must be able to display real-time telemetry from the spacecraft.

4. Dashboard must be able to facilitate live-debugging of the spacecraft and its constituent components.

5. Dashboard must provide a time-tagged command log file, to record the commands sent during a session.

6. Dashboard must provide a time-tagged telemetry log file, to record the telemetry sent during a session.

7. Dashboard must be operator friendly: minimize operator error; provide easy-to-use tools.

8. Dashboard must provide a method for Doppler effect compensation.

As context for this chapter and the next, Figure 3-1 shows the specific Dashboard functionality that will be discussed.

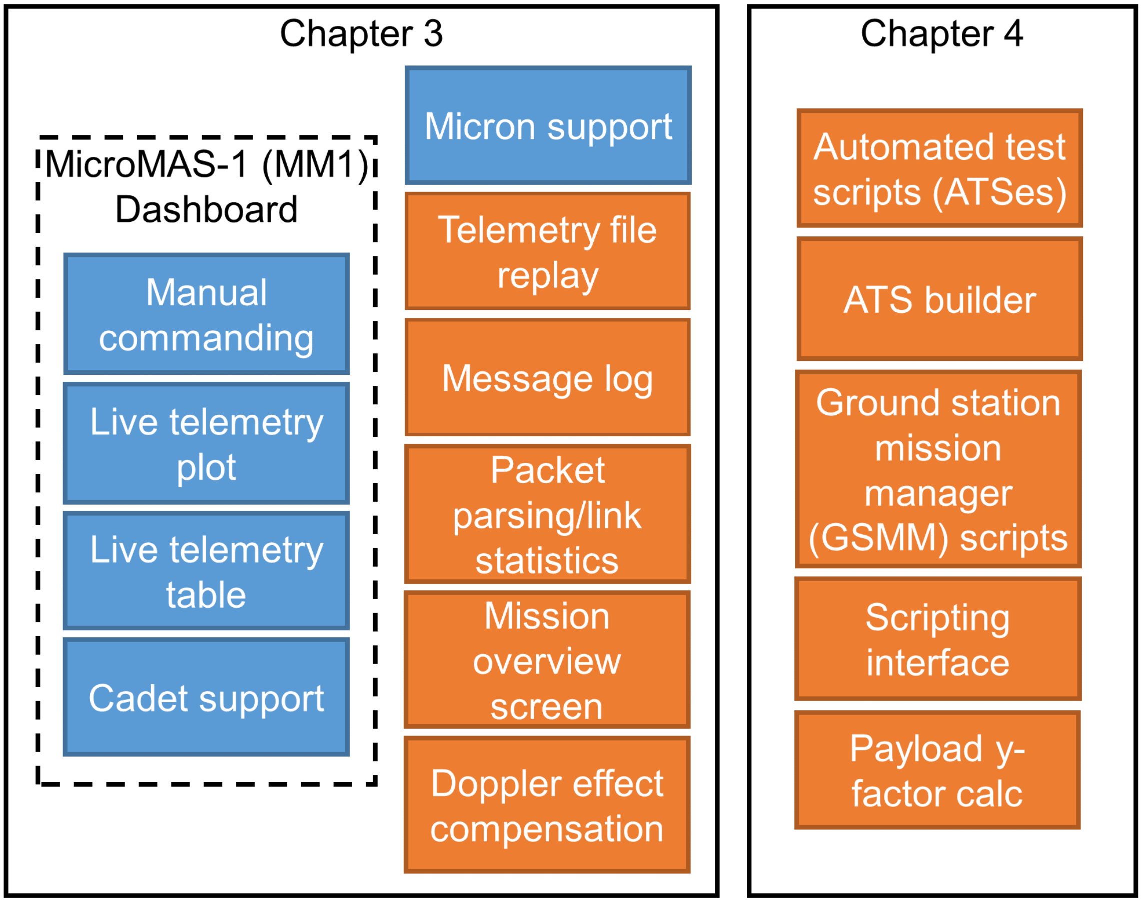

Figure 3-1: An overview of the functionality of Dashboard. All functionality shown is present in MiRaTA's Dashboard. Orange boxes show where the author made significant contributions.

3.2 Dashboard User Interface

Dashboard is started in one of many modes depending on what the operator would like to do. The most frequently-used options are as follows:

- **Serial**: Command the spacecraft over USB-serial.
- **Micron**: Command the spacecraft via Micron radio.
- **Cadet**: Command the spacecraft via Cadet radio.
- **File**: A special mode where Dashboard reads in a telemetry file and displays the telemetry to the operator; not used for commanding.

- **Doppler**: Prior to Dashboard sending a spacecraft command, Dashboard will calculate the proper uplink frequency to transmit the command at to compensate for the Doppler effect.

3.2.1 Commanding

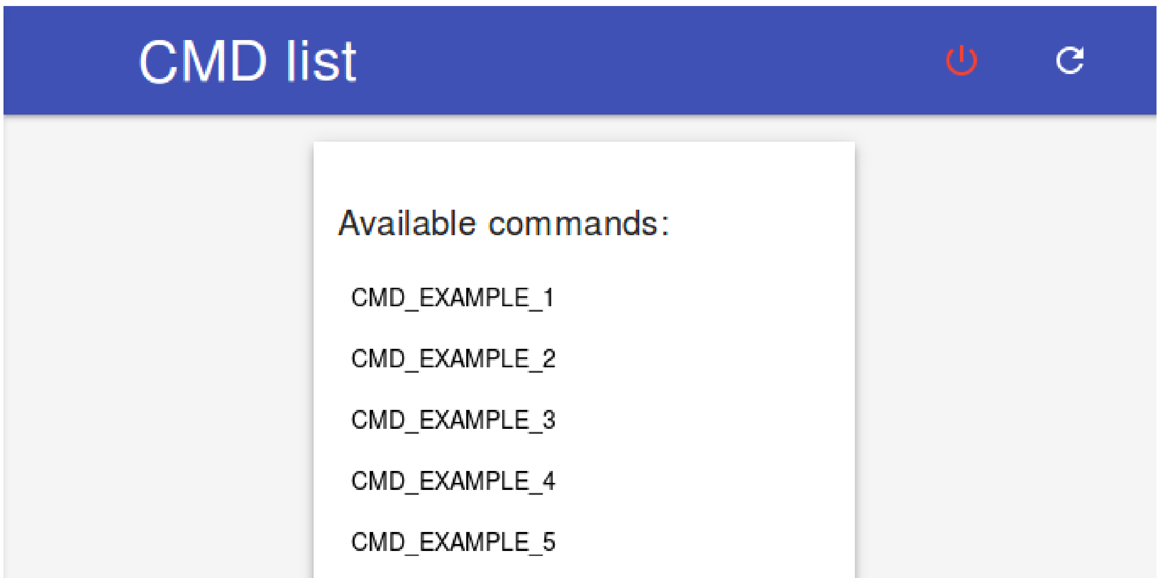

Figure 3-2: List of sample commands.

In order to command the spacecraft, an operator will visit the command page and can click on a command under the "Available commands" heading. CMD_EXAMPLE_1 in Figure 3-2 is an example of such a command.

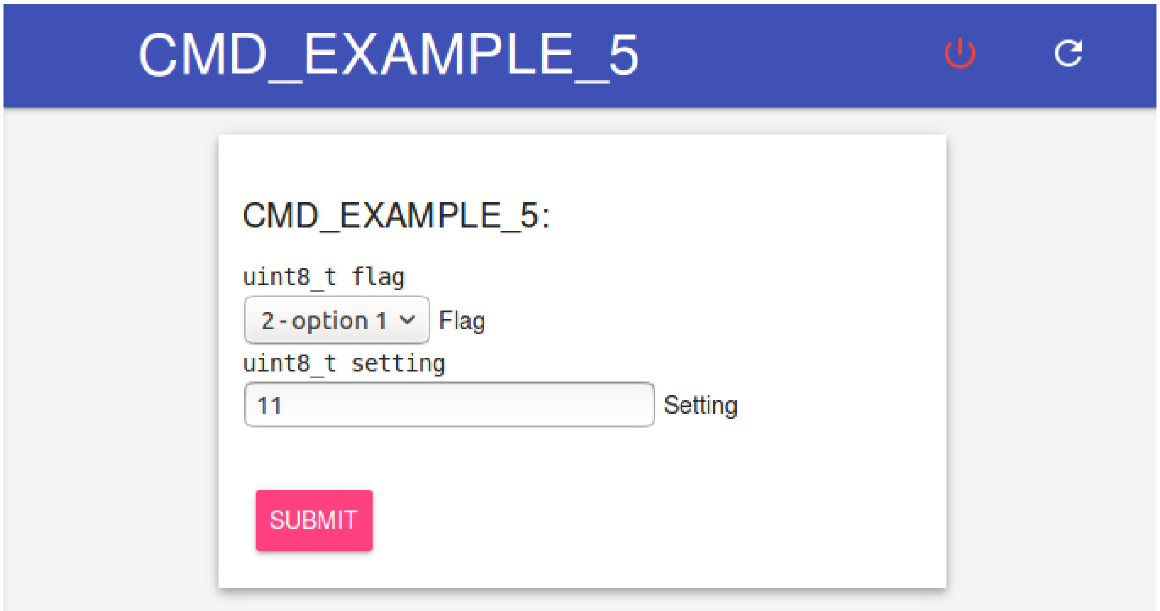

Figure 3-3: Sample command form.

When clicking on one of the commands in the command list, a form will appear with fields corresponding to the packet's schema. On clicking submit, a packet will be generated and sent to the spacecraft.

3.2.2 Telemetry

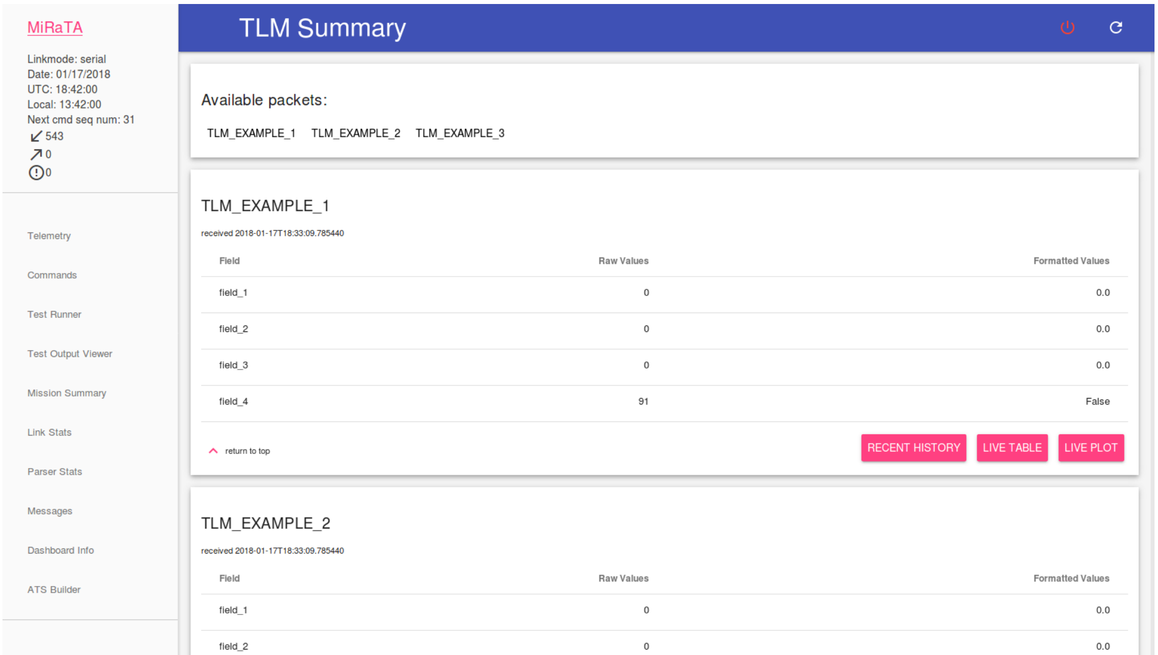

Figure 3-4: Dashboard's main screen. This is also the telemetry overview page.

When first opening Dashboard in the browser, the operator is shown a summary of the telemetry packets received so far. The left pane of all pages (including this one) is a collapsible navigation bar, shared between all Dashboard pages. The top-left is a live updating section that shows useful information such as the type of link-mode (serial, Micron radio, or Cadet radio), the time, the current command sequence number, number of packets received, number of packets sent, and number of packet errors.

The operator can click one of the buttons at the top of the page under "Available packets" to take them to the telemetry packet that they are interested in. For each packet, the operator can choose to either view the recent history of packets (the last 10, 50, or 100 packets received); see a live-updating table containing the packet data; or do a live plot of the fields in the packet.

Live Plotting

In order to do a live plot of a packet, the operator should click the "live plot" button and select how many data points and what fields to plot.

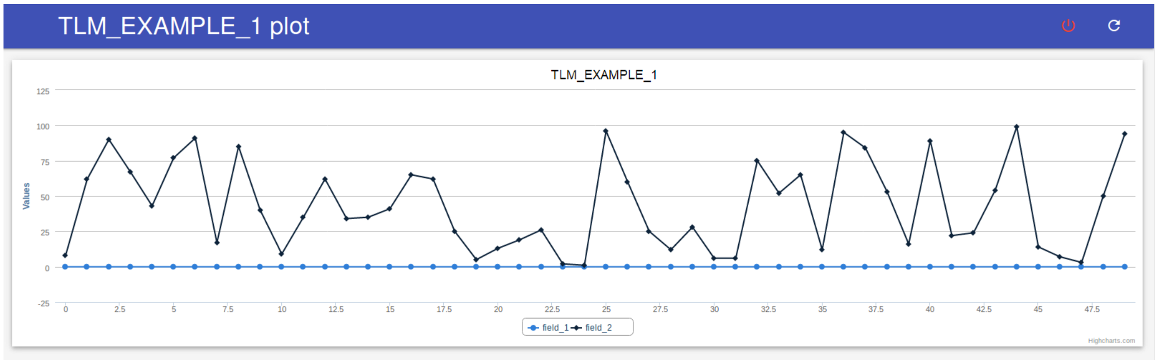

Figure 3-5: Sample telemetry plot.

Figure 3-5 shows an example of a live plot; it uses the Highcharts Javascript library.[3] The live plot feature is useful during testing and debugging, for observing transient effects in telemetry.

[3] Available at `https://www.highcharts.com/`

Message Log

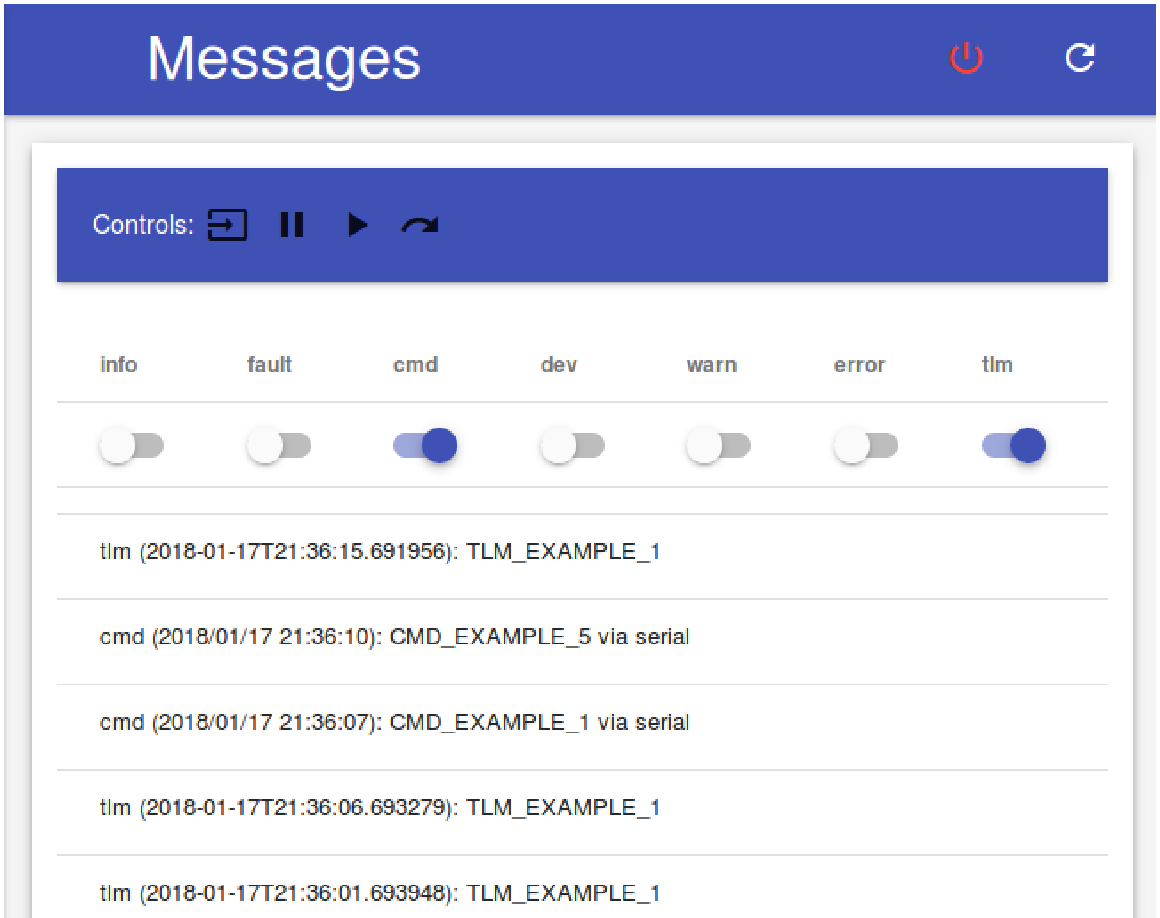

Figure 3-6: Message log, with two of the message options selected.

A helpful debugging tool is the message log, which keeps track of interesting events as they occur. It is most often used with the "cmd" and "tlm" options enabled, which tracks the interleaving of commands as they are sent and telemetry received in response. Other especially useful messages include "dev", which prints when devices on the spacecraft are turned on and off, as well as "fault", which prints when the spacecraft generates a fault message.

Mission Summary

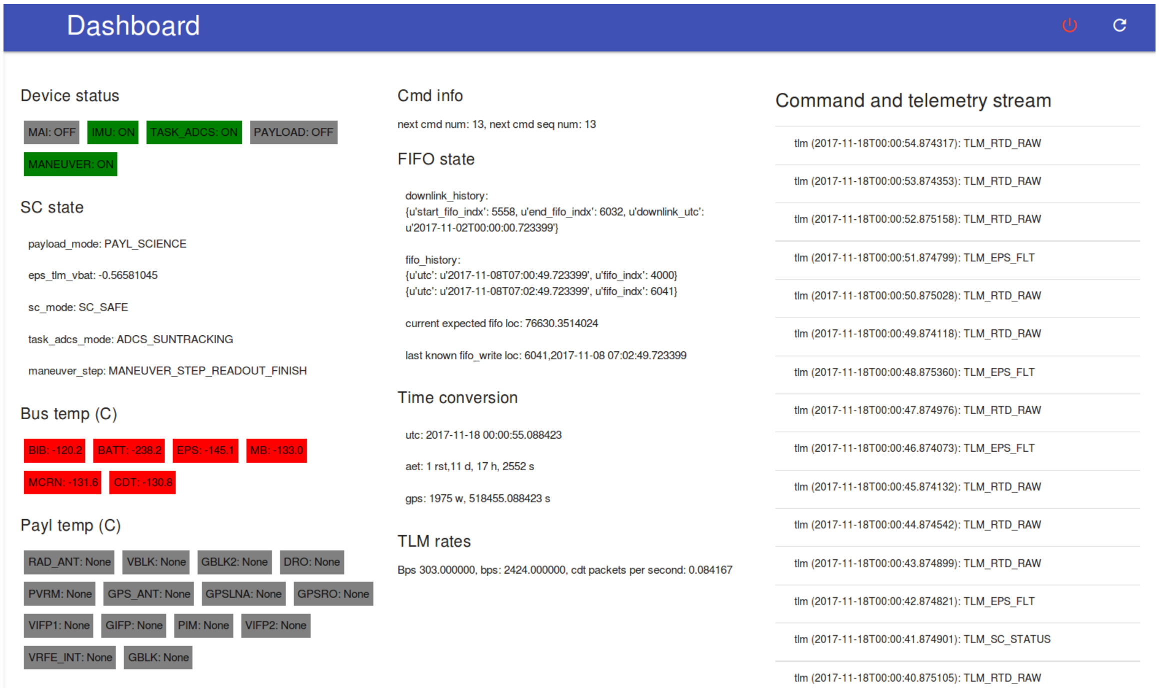

Figure 3-7: Mission summary page (showing random data).

Unlike the other telemetry views, this page was created with mission operations in mind. It contains the spacecraft state tracked by Dashboard's backend. By looking at the leftmost column, the operator can tell at a glance what devices are on, what state the spacecraft is in, and what temperatures all the components are at currently. In the middle column, we track the command numbers, the FIFO state (the Cadet radio's internal storage), the conversion between three onboard time systems, and the spacecraft telemetry generation rate. In the right column, we see a message log consisting of the incoming telemetry packets and outgoing commands.

Other Telemetry Views

In addition to the above views, Dashboard offers several other debugging tools:

- **Link stats**: Shows bytes received and bytes sent, as well as other statistics corresponding to packet framing and deframing.

- **Parser stats**: Keeps track of how many packets of each type have been parsed, in addition to parsing errors.

- **Telemetry file replay**: Allows a telemetry file to be loaded into Dashboard. An operator can then select specific portions of the file to inspect, for quick sanity checking of a previous logfile.

3.3 Dashboard Architecture

Dashboard consists of two main parts: the data-processing backend, and the operator-facing frontend. It is written in Python 2.7.[4] The library used to establish connections is Twisted[5], a networking engine. Flask[6] is used to serve pages to the browser, and templates were created using Jinja2[7].

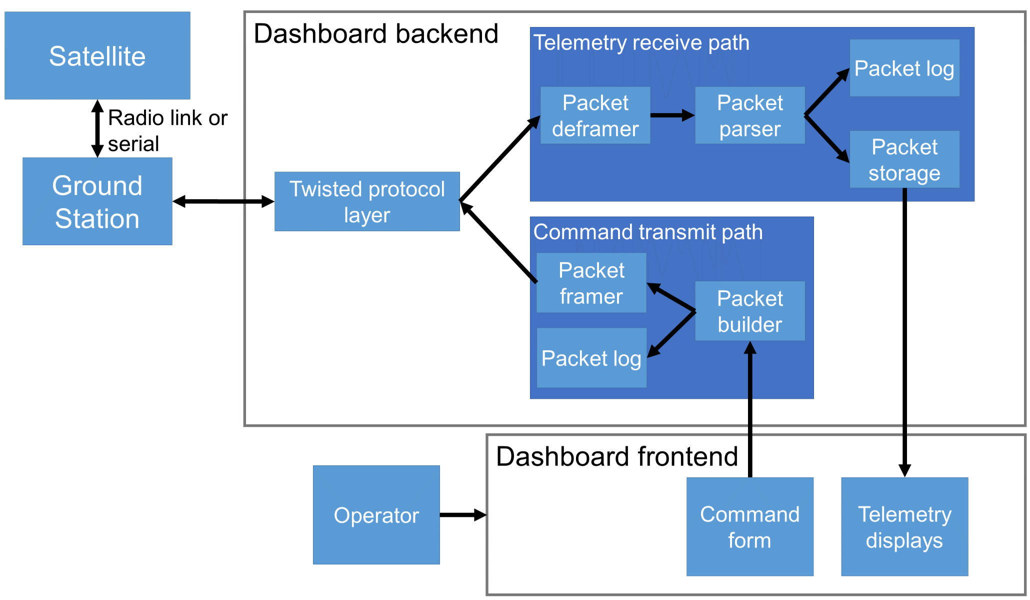

Figure 3-8: Dashboard architecture.

[4]https://www.python.org/
[5]https://twistedmatrix.com/trac/
[6]http://flask.pocoo.org/
[7]http://jinja.pocoo.org/docs/2.10/

3.3.1 Command Transmit Path

In order to transmit a command, a user goes to the command form page in the Dashboard GUI and fills out the fields. On form submission, the packet builder is called, generating a serialized form of the packet. This serialized form is then passed on to the logger and the packet framer; the logger saves the packet to disk, and the packet framer adds on additional bytes to the beginning of the packet (a packet header) depending on what type of link we are using (Cadet radio, Micron radio, or serial). After packet framing, the packet is passed to the Twisted protocol layer, which sends the packet to the ground station. Finally, the ground station transmits the packet to the satellite.

3.3.2 Telemetry Receive Path

The telemetry receive path is the inverse of the command transmit path. The spacecraft transmits RF energy, which is received by the ground station. The ground station then demodulates the signal and digitizes it before sending it to Dashboard via the Twisted protocol layer. The bytes are then sent to a deframer, which searches for sentinel bytes signaling the start of a packet frame. After a frame is found, the header is stripped off and the packet is sent to the packet parser. The packet parser checks the deframed data against the packet specifications, and if it matches one of the packet specifications, sends the packet to Dashboard's internal storage and also logs the packet to disk. After parsing, the packet data is then available in any of the telemetry views.

Chapter 4

Software Development for Spacecraft Testing and Mission Operations

In this chapter we discuss some of the work involved in testing and operating MiRaTA. We briefly cover interfaces for testing of the payload. The bulk of the chapter covers the development of the automated testing system for Dashboard.

4.1 MiRaTA Payload Testing Software

As covered in Chapter 2, it is important to make sure that a microwave radiometer (MWR) is properly calibrated to ensure correct correspondence between reported digital numbers and temperature. Before our MWR is flown, we measure its performance in a known testing environment that replicates space conditions (a thermal vacuum chamber, or TVAC chamber). Running the calibration within the TVAC chamber requires assembling special ground support equipment (GSE).[22]

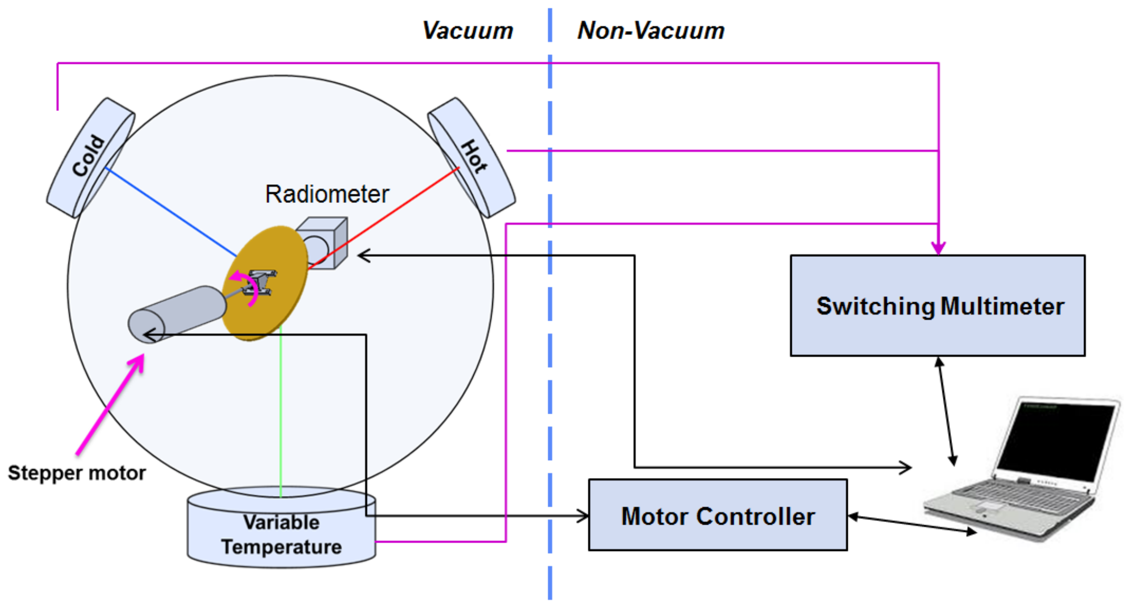

Figure 4-1: Radiometer TVAC GSE equipment diagram.[22]

On the ground, we are able to use conventional blackbody targets for calibrating our MWR; this technique is called periodic absolute calibration, or PAC.[22] As shown in Figure 4-1, a box frame was constructed to hold three blackbody targets: one hot, one cold, and one variable. The frame also held a reflector that could rotate to point at each target in turn, reflecting the radiation of each blackbody target onto the MWR in sequence. A computer was connected to the reflector motor driver (to control the motor) and a Keithley switching multimeter (for temperature sensing of the blackbody targets and motor); the computer provided a GUI (see Figure 4-2) to control and observe the state of the system.[1] The GUI is written in Python, and uses the PyQt framework.[2]

[1] The TVAC GSE GUI was originally written by Michael DiLiberto, with rewriting by the author.
[2] `https://riverbankcomputing.com/software/pyqt/intro`

Figure 4-2: Radiometer TVAC GSE GUI for controlling the reflector's motor.[22]

The TVAC GSE GUI features buttons to move the reflector for testing, control radiometer data collection, and view temperature plots and statistics. In order to head off some amount of operator error, the buttons on the GUI would grey-out if clicking them would cause strange motor controller behavior.

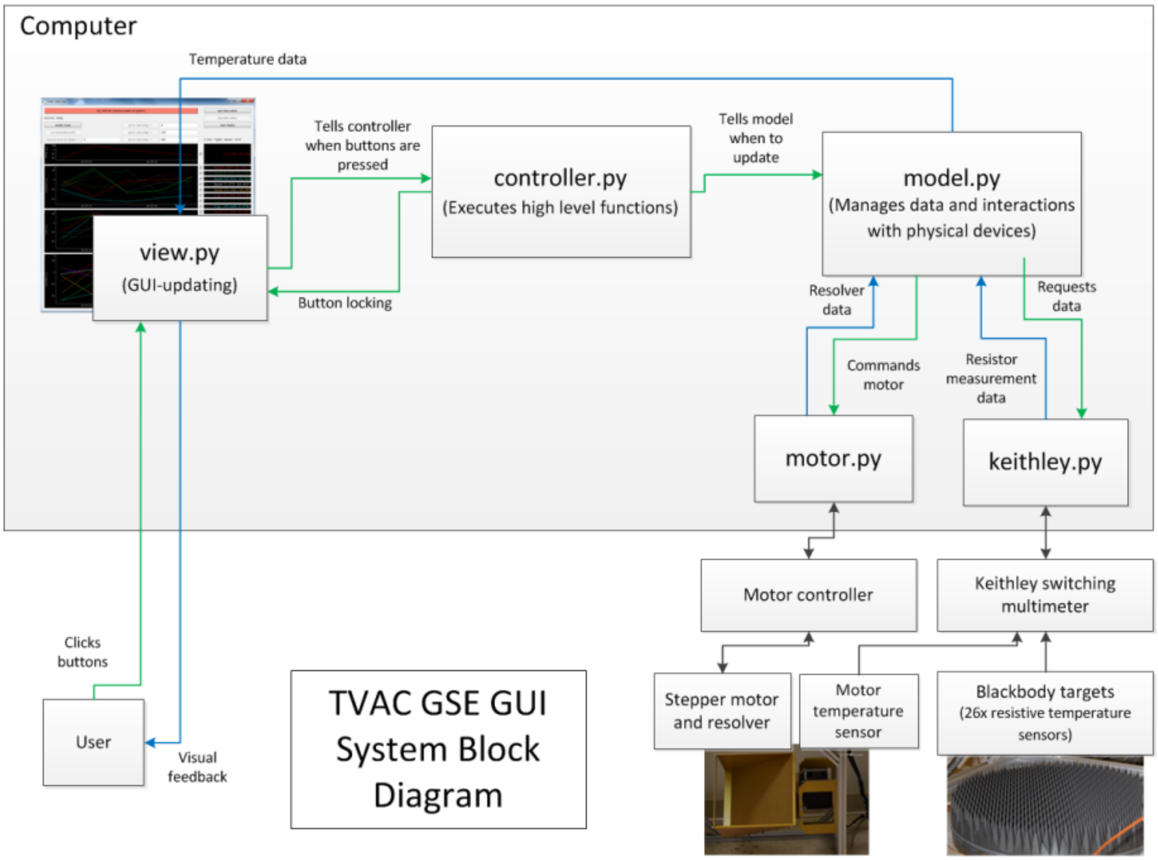

Figure 4-3: Code layout of the TVAC GSE GUI.[22]

The first prototype of the GUI was able to plot temperature, but could be slow to update. In order to support concurrent data updating and motor control, the GUI's backend was rewritten into several parts that did not block on each other (see Figure 4-3).

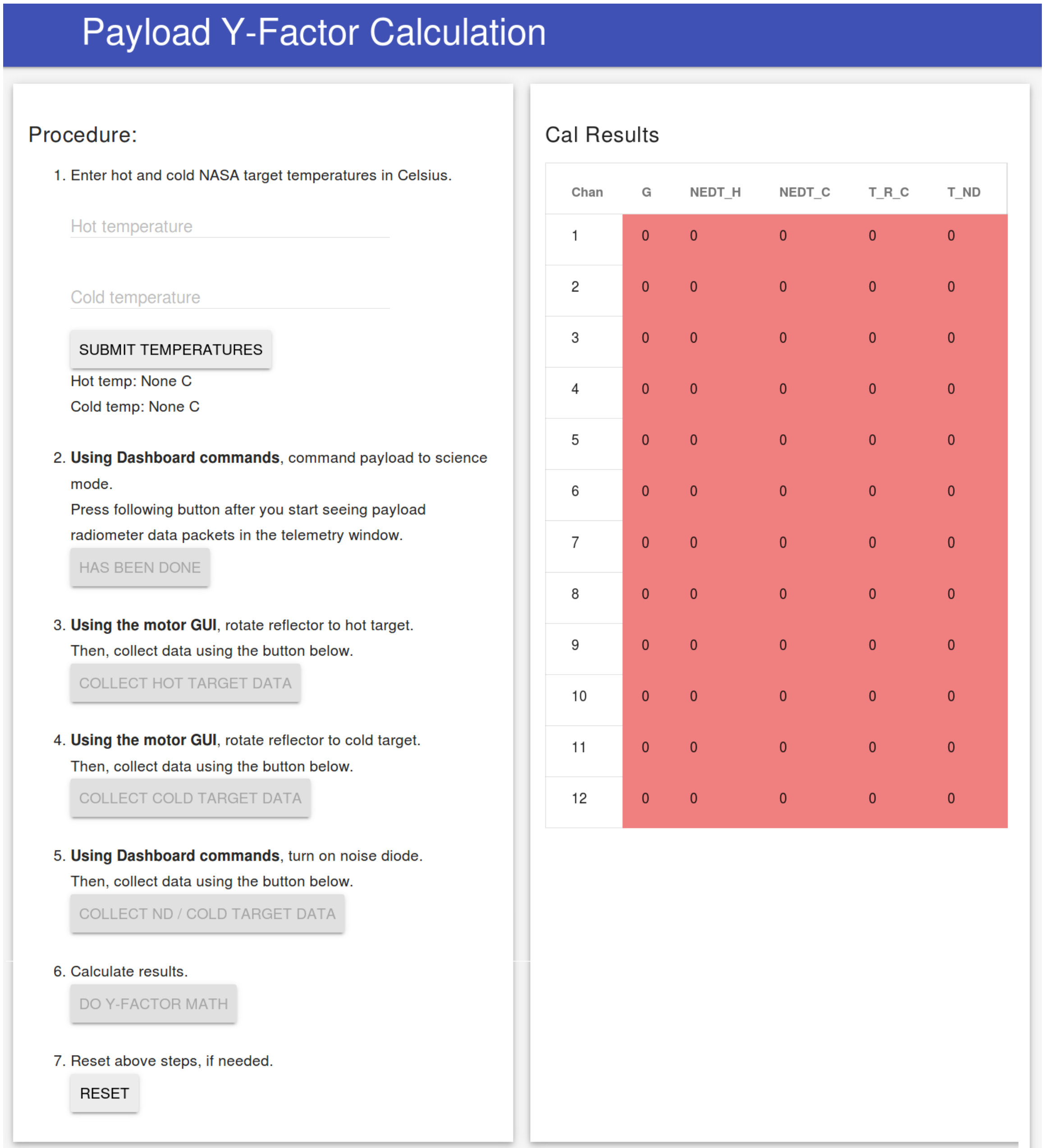

Figure 4-4: Payload y-factor calibration page in Dashboard.

The final piece of the radiometer calibration is Dashboard, which is the primary way of controlling the radiometer through testing. One of the ways the radiometer's performance was calculated (in addition to PAC) is called the y-factor method, which allows one to calculate the noise figure and gain of a sensor.[16] For TVAC testing, a special y-factor calculation page (Figure 4-4) was written for Dashboard. It stepped the operators through the process of commanding the radiometer, moving the motor, and collecting data. It also calculated the final y-factor results, so that the test operator could see at a glance if the radiometer was operating within parameters.

4.1.1 Results

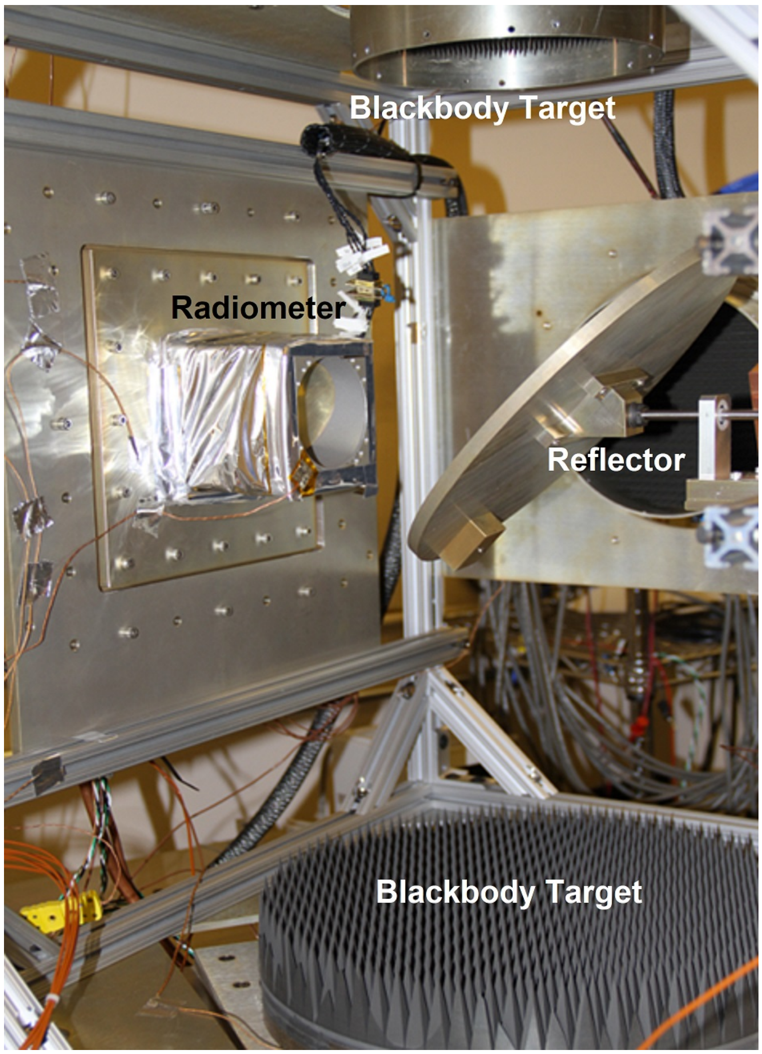

Figure 4-5: MicroMAS-1 payload calibration set up.[9]

The TVAC GSE/GUI and Dashboard were used in September/October 2016 to run MiRaTA's MWR TVAC testing.[8] Preliminary results from the data analysis of testing showed that MWR values were well within acceptable ranges for gain (accuracy) and noise equivalent differential temperature (NeDT, or precision).[8] The TVAC GSE/GUI and Dashboard commands developed for MiRaTA worked well enough for it to be used as the basis for MWR TVAC calibration for MicroMAS-2a and MicroMAS-2b (follow-on missions for MicroMAS-1).

4.2 Automated Testing Capability for Dashboard

As a result of the team's stressful experiences from MicroMAS-1 operations, it was decided that automated testing and commanding would be a great addition to Dashboard's capabilities. Automated testing was developed for use in space vehicle (SV) TVAC testing during late 2016.[3] Like in the previous chapter, all packets and scripts shown are dummy versions for demonstration.

4.2.1 Scripts

There are two types of scripts that an operator can run from Dashboard. The first type is called an Automatic Test Script (ATS), and the second is called a Ground Station Mission Manager script (GSMM script). Both types of scripts are executed by the GSMM subsystem in Dashboard.

An ATS consists of a timeline of commands and telemetry check points, as in Figure 4-6.

- 0.0s: Start device A in mode 2.
- 1.0s: Check device A telemetry packet: verify that device A is on and mode is set to 2.
- 2.0s: Turn off device A.
- 3.0s: Check device A telemetry packet: verify that device A is off.

Figure 4-6: ATS concept.

When an ATS is run, the script manager within Dashboard steps through the timeline specified in the ATS and issues commands to the spacecraft and/or checks

[3]The automated testing system was developed by the author and Kit Kennedy, with advice from Nicholas Zorn and Michael DiLiberto.

telemetry from the spacecraft. In order to keep the system simple, the timeline specified in the ATS is relative to the beginning of when the script is executed (instead of specifying the timeline in absolute time). As an ATS executes, it keeps track of what telemetry checkpoints succeeded or failed. After an ATS is finished executing, the results are written to a log file and displayed to the user. The ATS format was intentionally kept simple, as it is intended to serve as a way to execute small device-level tests, and as a building block for more complicated behavior.

The second type of script that an operator can run is a GSMM script. Figure 4-7 shows an example of possible GSMM script behavior.

1. Execute sampleATS.
2. Wait 2 seconds.
3. Check success result of sampleATS. If it did not succeed, and the test has been running for less than one minute, go back to step 1.

Figure 4-7: GSMM script concept.

This type of script allows for more complicated control of Dashboard, as it allows the script writer to use Python to specify commanding/telemetry reading behavior. Several building blocks are built into the GSMM execution framework to enable the script writer to access Dashboard interfaces; these include the ability to execute ATSes, send single commands/read telemetry packets, and display data in the Dashboard GUI. A GSMM script can be as simple as a sequence of ATSes ("a script of scripts"). On the other end of the complexity spectrum, a GSMM script can also be used to issue all ground commands needed to run the spacecraft's maneuver mode.

4.2.2 Scripting Related User Interfaces

ATS Building

ATSes are conceptually fairly simple, but their constituent commands and telemetry packet fields can be quite complex. Thus, Dashboard provides a basic ATS creation tool that allows the script writer to fill in fields using a GUI that looks the same as the command forms used in commanding.

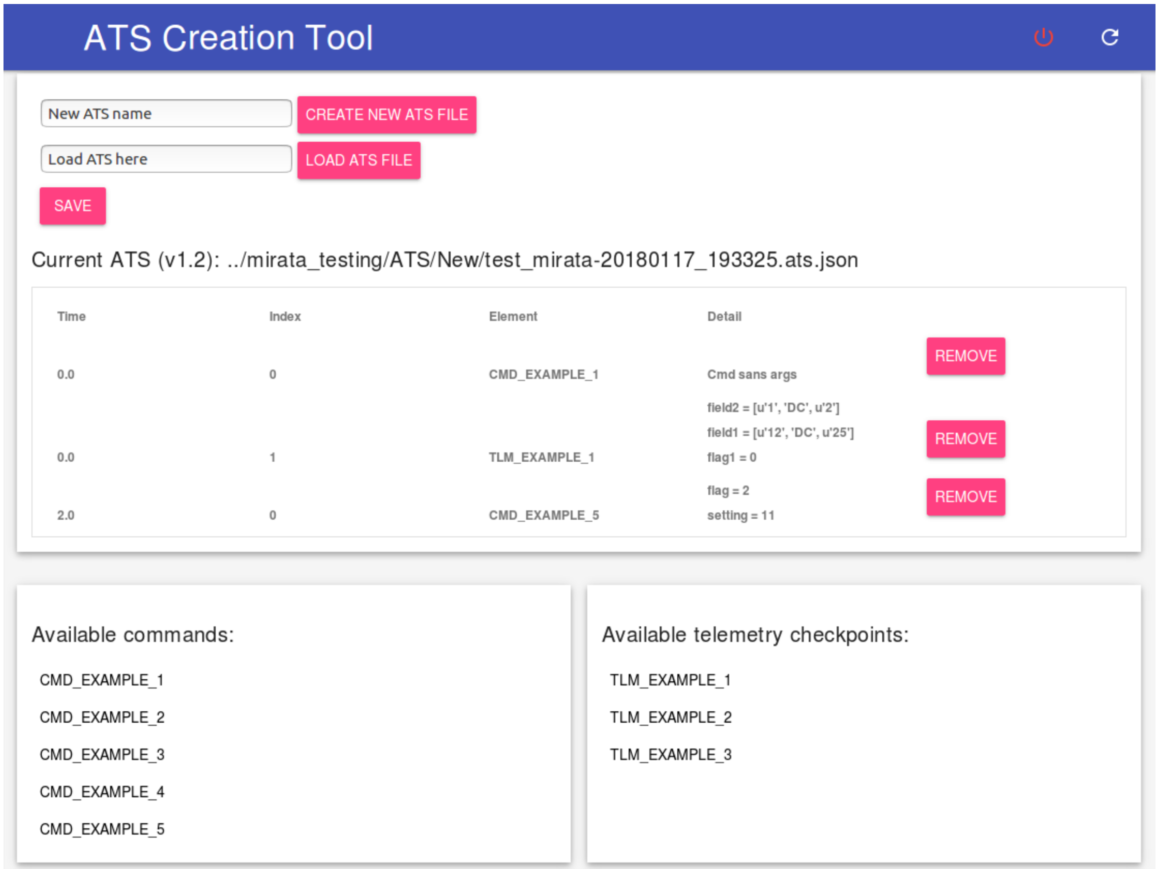

Figure 4-8: ATS creation tool main page.

The field "New ATS name" allows you to specify a new name for an ATS file. The field "Load ATS here" allows you to open an existing ATS for editing. If a name is not specified at file creation, the date and time is used (as shown in the line Current ATS). If the script writer wishes to save their script, they can hit the SAVE button at any point.

The table right under "Current ATS" shows a brief summary of the contents of the ATS. It lists the times, type of command or telemetry packet, and important fields that are being issued. An ATS element can also be removed via this table.

To add a command or telemetry checkpoint to the loaded script, the operator clicks one of the listed commands under "Available commands" or "Available telemetry checkpoints".

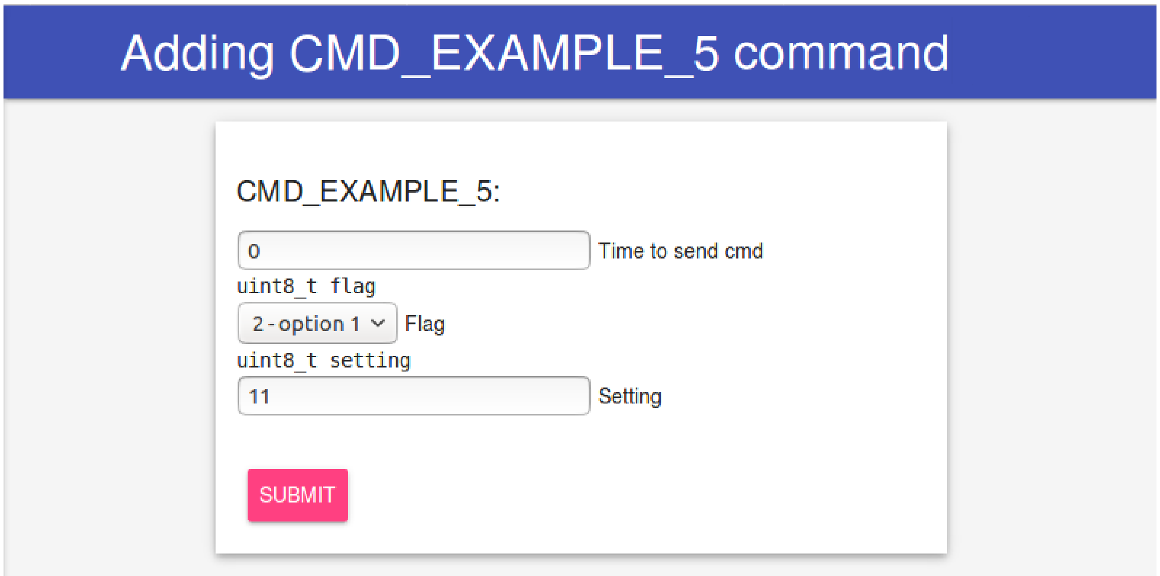

Figure 4-9: Form to add a command to an ATS. A similar form is used to add a telemetry checkpoint to an ATS.

Figure 4-9 shows the interface to add a command to an ATS. It is entirely identical to the manual command form, with the exception of the page title at the top. After hitting the submit button, the script writer is redirected back to the main ATS creation page.

The corresponding ATS file on disk to Figure 4-8 is Figure 4-10.

```
{
    "0.0": [{
                "description": "Command example 1.",
                "id": 1,
                "name": "CMD_EXAMPLE_1",
                "values": {}
            },
                {
                "description": "Telemetry packet example 1.",
                "id": 101,
                "name": "TLM_EXAMPLE_1",
                "values": {
                    "field1": [
                        "12",
                        "DC",
                        "25"
                    ],
                    "field2": [
                        "1",
                        "DC",
                        "2"
                    ],
                    "flag1": "0"
                }
            }],
    "2.0": [{
                "description": "Command example 5.",
                "id": 5,
                "name": "CMD_EXAMPLE_5",
                "values": {
                    "flag": "2",
                    "setting": "11"
                }
            }],
    "metadata": {"description": "ATS sample.", "version":"1.2"}
}
```


Figure 4-10: Simple raw ATS file sample. ATSes are formatted as Javascript Object Notation (JSON).

The raw file reflects the same amount of information visible in the ATS builder. The JSON format was chosen since it is a common data representation and, if needed, can be directly modified.

GSMM Script Building

Since GSMM scripts are just Python scripts, there is no built-in editor in Dashboard for them. However, Dashboard's source contains a sample GSMM script for reference.

The following features are available for use in a GSMM script:

1. Requesting telemetry from Dashboard packet storage.
2. Sending a command to Dashboard.
3. Custom user-input at script execution time.
4. Execution of ATS and checking of ATS success/fail results.
5. Printing status messages to Dashboard script output page.
6. Interruptible waiting function, that allows Dashboard to gracefully kill the script if needed.

Running Scripts

The process of running an ATS and the process of running a GSMM script are virtually identical.

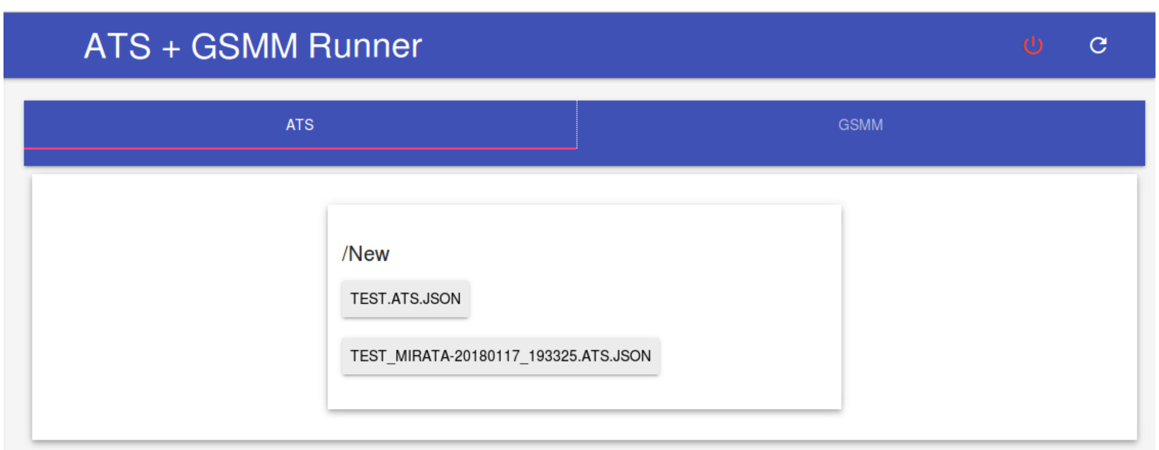

Figure 4-11: An operator can choose an ATS to run from the ATS tab.

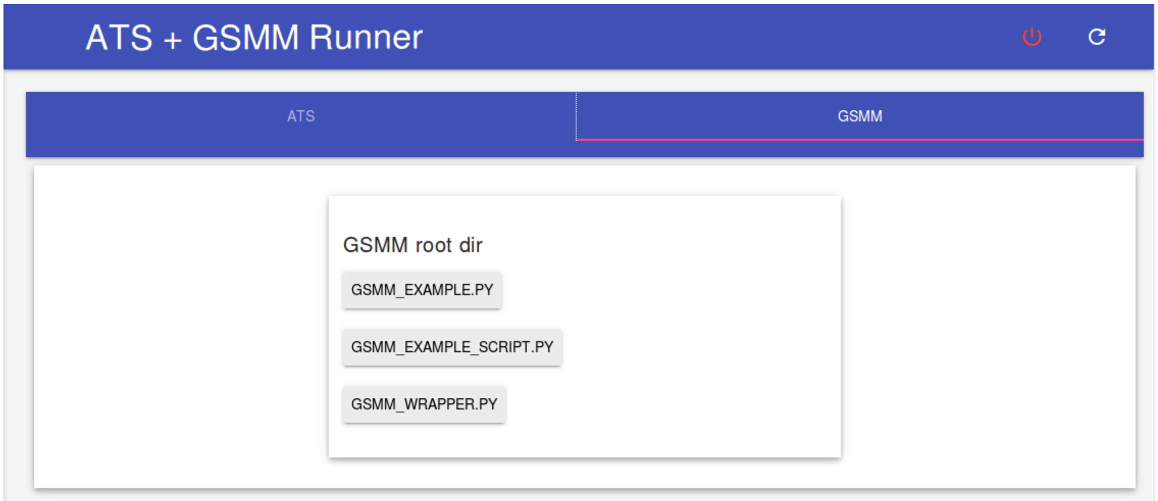

Figure 4-12: An operator can choose a GSMM script to run from the GSMM tab.

From the "ATS + GSMM Runner" screen, an operator can choose the script that they want to run. The entries of the ATS/GSMM tabs are auto-populated by the scripts available in the `mirata_testing` directory.

Figure 4-13: ATS summary before execution.

Figure 4-13 shows what happens when the operator clicks on an ATS name under the ATS tab. The operator is directed to an overview of the script to be run, and an execute button.

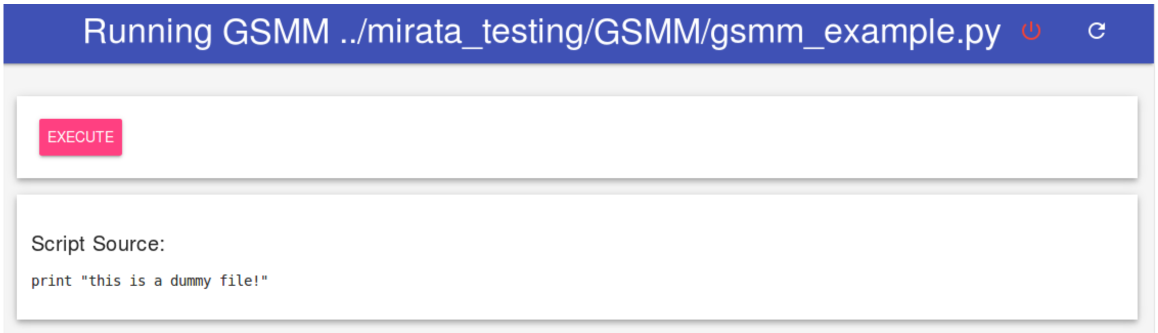

Figure 4-14: GSMM script summary before execution.

Like what happens when an ATS is clicked from the ATS tab, Figure 4-14 shows the screen that appears when a GSMM script is clicked from the GSMM tab. Instead of a script summary, the GSMM script source is just directly printed to the screen.

To actually execute the ATS or GSMM script, the operator must hit the execute button.

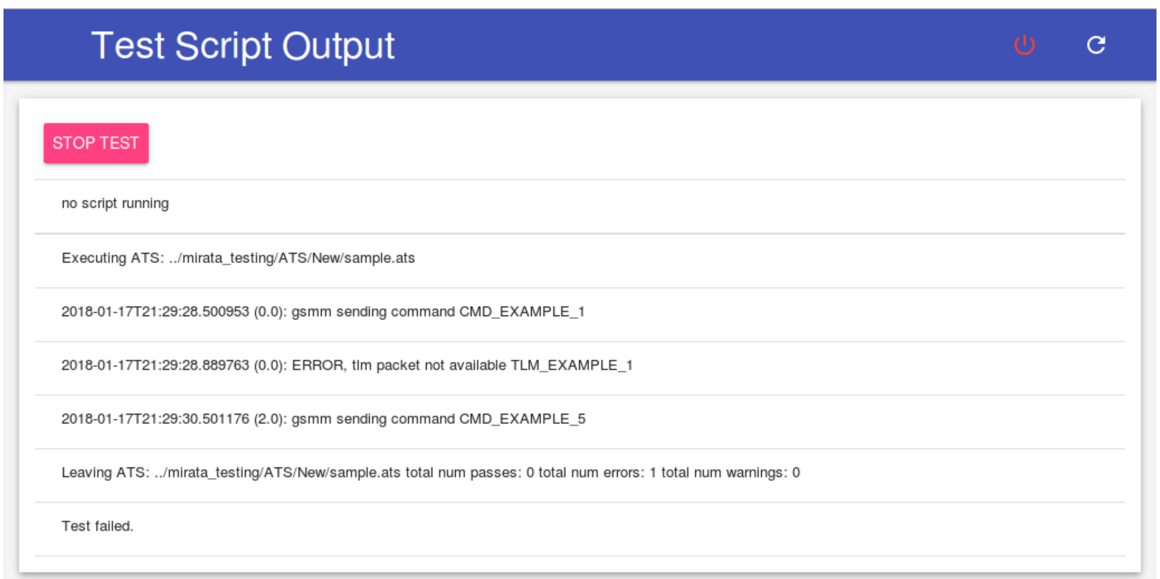

Figure 4-15: ATS output.

After a script (either ATS or GSMM) is executed by the operator, Dashboard automatically redirects to the script output page. Figure 4-15 depicts an example of what happens when executing the example ATS from Figure 4-13.

4.2.3 Architecture

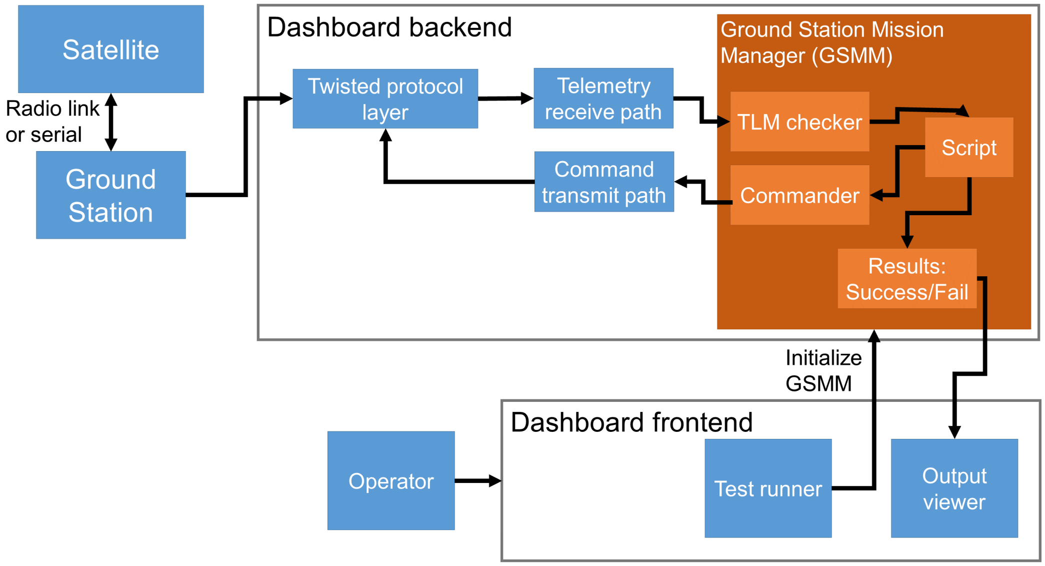

Figure 4-16: Dashboard block diagram with the addition of the GSMM subsystem.

The code that enables the automated commanding/testing is called the Ground Station Mission Manager (GSMM), so named because this testing system would ultimately be used to run the MiRaTA overpasses. The orange block in Figure 4-16 represents the new code that implements the GSMM functionality. The GSMM submodule runs in a separate process from the main Dashboard backend process, to protect the main Dashboard event loop in the case of a script programmer error. As a result, the GSMM submodule and Dashboard communicate through interprocess pipes.

When the operator accesses the test runner and clicks execute, any options (such as the name of the script) are sent to the GSMM submodule. The GSMM then executes the specified script. Any telemetry points that need to be checked go through the telemetry checker, which asks Dashboard for a telemetry packet from its packet storage; upon getting a packet, the fields are verified against the script-writer's input. Any commands that need to be issued go through the commander, which sends a command to Dashboard for sending via the normal command transmit path.

Chapter 5

Discussion and Future Work

In this chapter, we compare MicroMAS-1 testing and mission operations procedures to MiRaTA procedures, focusing on how the work for MiRaTA in Chapter 4 helped the development process. We also discuss avenues for future work.

5.1 Comparing MicroMAS-1 and MiRaTA Procedures

As mentioned in Chapter 2, MiRaTA was able to take advantage of all of the work the MicroMAS-1 team did to help create testing and mission operations procedures. The lessons learned from the MicroMAS-1 mission informed many of the design decisions made for the MiRaTA mission. The version of Dashboard used by MicroMAS-1 only had manual commanding, the live telemetry tables, and live telemetry plotting, as described in chapter 3; we will refer to MicroMAS-1's Dashboard as MM1-Dashboard, and the term Dashboard will refer to MiRaTA's Dashboard.

5.2 Testing

5.2.1 Manual vs Automated Testing Comparison

As described in chapter 2, there are many assurance tests that are required to confirm spacecraft functionality in the face of extreme environmental conditions. To determine whether or not an assurance test damaged the spacecraft, it is advisable to do a functional test before and after any assurance test that the team would like to undertake.

On MicroMAS-1, the approach to determine whether or not a component was operational was for an operator to watch individual telemetry values and ascertain whether or not they were acceptable. For instance, an engineer, if they wanted to confirm the function of a temperature sensor, would inspect values reported by the spacecraft for current ambient temperatures, and making sure that they are within reasonable bounds (e.g. about equal to what an external room thermometer was reporting). In practice, this required an engineer to start MM1-Dashboard and view the live value of each temperature sensor on board the spacecraft. The engineer would then record a single value in a logbook and whether or not the value was within allowable bounds. This manual testing would be done on the lab bench and also within environmental test chambers, and be done for each system on the satellite. Because of this manual nature of testing, it was difficult and extremely-time consuming for the team to do thorough and repeatable functional tests. As a result, the satellite did not get as much testing as it needed.

For MiRaTA, the team started out doing manual functional tests, and transitioned to automated functional tests after the system in Chapter 5.2 was completed.

We can numerically compare the manual vs automatic approaches by estimating how much time it takes for an engineer to complete a manual test of a component versus an automated test, and then multiply by the amount of components that are on the spacecraft.

For both MicroMAS-1 and MiRaTA, the set-up work is going to be of similar length, since the test development engineer needs, in both cases, to establish the list of components under test, and determine how each component's performance will be verified. There is additional work required of the MiRaTA test engineer to write ATSes for each component, but the additional work is minimal since it is just a formalization of the procedure established to test each component.

Here is what a component test would look like, using the inertial measurement unit (IMU) as a simple example:

1. Verify the initial state of the component by checking telemetry: Make sure that the IMU is OFF.

2. Change one aspect of the state of the component: Turn on the IMU.

3. Check to make sure the state of the component is as expected: Make sure the IMU is on and that it reports an acceleration vector consistent with the spacecraft in an upright position.

4. Finish the test: Turn off the IMU.

To manually execute the test, the operator would do the following:

1. Click on the live view of telemetry for the spacecraft status packet.

2. Check that the IMU is OFF.

3. Click on the command form page and issue a command to turn the IMU on.

4. Return to the live view of telemetry for the spacecraft status, and make sure that the IMU actually turned on.

5. Click on the live view of telemetry for the IMU packet.

6. Make sure that the acceleration values are what is expected.

7. Click on the command form page and issue a command to turn the IMU off.

8. Return to the live view of telemetry for the spacecraft status, and make sure that the IMU actually turned off.

To automatically execute this test, the operator would do the following (after the test engineer has defined the test ATS):

1. Click on the script runner page.

2. Click on the ATS corresponding to the IMU test.

3. Click execute.

4. Wait for results.

Comparing the two methods, we can see improvements using the automated version over the manual version. The second procedure will take at most half the time of the first procedure; likely there is even a greater time savings for using the second procedure, as the operator only has to check one result at the end (success/failure). In addition, the second procedure will be identical for each component under test; the first procedure will change, causing more complexity for operators.

The time and complexity savings are more apparent if we compare the amount of time it takes to run many component-level tests in a row. For the manual procedure, the operator has to check every single component as per procedure 1: this procedure suffers from clear scalability issues. For the automated procedure, if there is a GSMM script defined that can run all of the ATSes in sequence, then the active operator time (how much time is spent clicking buttons and checking results) it takes to run all of the ATSes in sequence is the same as the active operator time for executing one ATS. To estimate the factor of automated testing improvement, let t represent the time that it takes to navigate to a Dashboard page and click something. The manual procedure for our single IMU test is thus $4t$ long; the automated procedure is $2t$ long. For MiRaTA, there were 19 different tests that were run for functional testing. The time it takes to run the functional test manually is then $4t * 19 = 76t$; the time to execute the functional test automatically remains at $2t$. Thus we should naively see a 38x speedup of test execution. This is partially corroborated by a comparison of the time taken completing a MiRaTA manual functional test versus an automatic functional test: an automatic functional test takes 30 mins $- 30 * 38/60 = 19$ hrs for an equivalent manual test, and the first MiRaTA manual functional test was spread out over three work days according to test logs.

The ease of execution for the automated tests versus the manual tests meant that team members with minimal training and/or familiarity with the spacecraft could execute system functional tests. The automated testing system played a key role in

MiRaTA's environmental testing, most notably in space vehicle thermal vacuum (SV TVAC) testing Thermal vacuum (TVAC) testing occurs continuously for 3-4 days, and the spacecraft must be attended the entire time by operators; this means that any testing procedure must be able to be executed by sleep-deprived staff. The simplicity of the automated procedure meant that the MiRaTA team could execute a spacecraft-wide functional test even while sleep-deprived. Also, because it is relatively simple to build an ATS, it was easy to create new, repeatable tests on the fly. For instance, the team decided to build a test that downlinked data repeatedly from the Cadet; the ATS build system meant that the script was created with little hassle.

5.2.2 MiRaTA Test Scripts

Spacecraft Functional Test

Where possible, each subsystem specified in Chapter 2 had an ATS script defined for it. After each ATS was defined, the ATSes were strung together in two testing configurations: the functional test via serial (called the "serial functional test") and the functional test via radio (called the "radio functional test"). "Serial" and "Radio" indicate the different modes that the spacecraft was in for each test: serial mode corresponds to when the spacecraft communicates via USB, streaming live data; radio mode corresponds to when the spacecraft communicates via the two radios. Each functional test was its own GSMM script.[1]

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[1] The author wrote the ATSes and GSMM scripts used for functional testing, with spacecraft knowledge assistance from Ayesha Hein, Kit Kennedy, Myron Lee, Zack Lee, Weston Marlow, and Erik Thompson.

Table 5.1: Types of functional tests conducted on MiRaTA.

Test name	What the test checks	Serial	Radio
Battery telemetry	Battery status nominal	X	X
EPS telemetry	EPS voltages and currents as expected	X	X
AET timestamps	AET is valid	X	X
IMU on	IMU turns on	X	X
IMU telemetry	IMU acceleration matches the orientation of the spacecraft	X	X
MAI on	MAI turns on	X	X
Reaction wheels	Spin the reaction wheels and check the telemetry to see if the wheels are indeed spinning	X	X
Torque rod telemetry	Turn on the torque rods and make sure the torques are reported correctly	X	X
Earth horizon sensor aliveness	EHS readings are within bounds	X	X
Magnetometer aliveness	Magnetometer readings are within bounds	X	X
PIC reset via reset command	Spacecraft reset command resets the spacecraft	X	X
Payload on	The payload turns on	X	X
Payload GPS time check	The payload GPS time monotonically increases	X	X
Payload GPS lock	The payload acquires GPS lock	X	X
Payload science mode	Payload enters science mode (produces radiometer data)	X	X
Payload GPSRO	Payload enters GPSRO mode (produces GPSRO data)	X	X
PIC reset via Cadet	The Cadet can reset the PIC		X
PIC reset via Micron	The Micron can reset the PIC		X
Micron reset	The Micron can reset itself		X

During a thermal vacuum test, the TVAC chamber is cycled through hot and cold temperatures, pausing at each extreme (called a "hot soak"/"cold soak"). After each hot soak and cold soak a pair of serial and radio functional tests was run. In total, during SV TVAC testing, there were 21 functional tests run (counting serial and radio together). In addition to running the functional tests during TVAC, the functional tests were run before and after each thermal cycling (oven) test, and before and after each vibe test.

Other Tests/Scripts

Other engineers on the team besides the author were able to design and make tests using the automated testing system. Examples of various tests created by the team include:

- An ATS to spin up the reaction wheels deterministically for performance checking.[2]
- A GSMM script to run the spacecraft's maneuver mode.[3]
- An ATS to test Cadet downlinks.[4]
- A GSMM script to test the reaction wheels and torque rods on an air bearing (which allows the spacecraft to rotate freely).[5]

[2] By Weston Marlow.
[3] By Kit Kennedy.
[4] By Kit Kennedy.
[5] by the author, Weston Marlow, and Zack Lee.

5.3 Mission Operations

5.3.1 MicroMAS-1

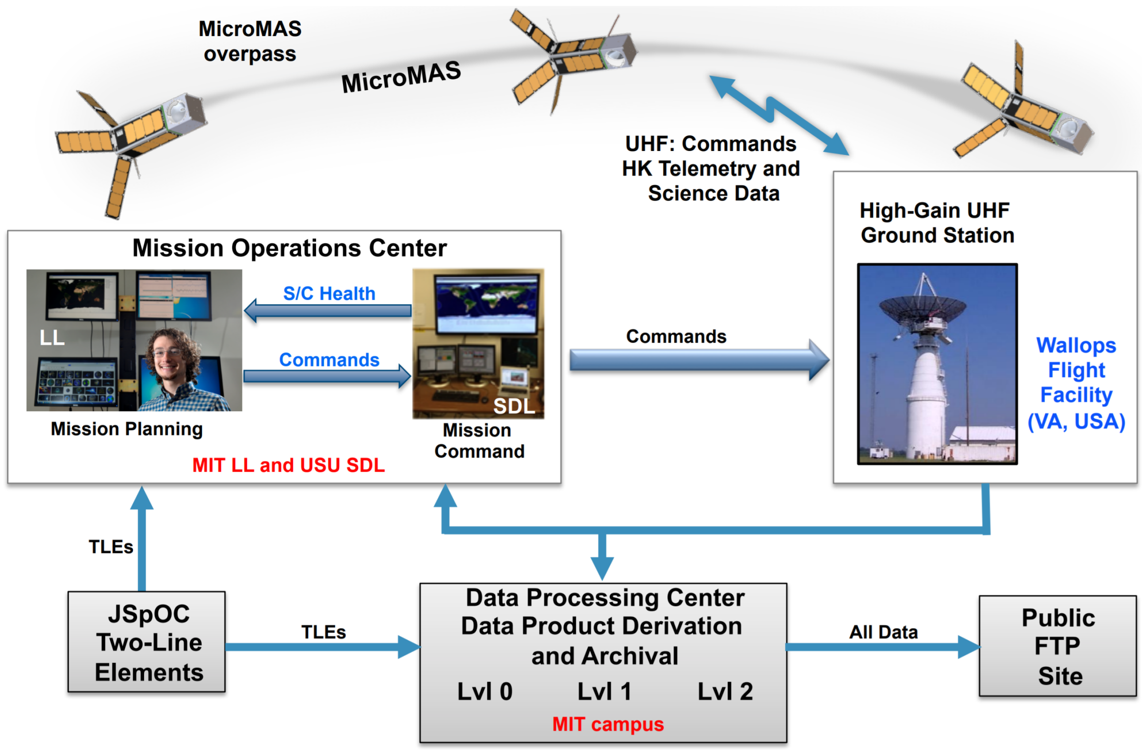
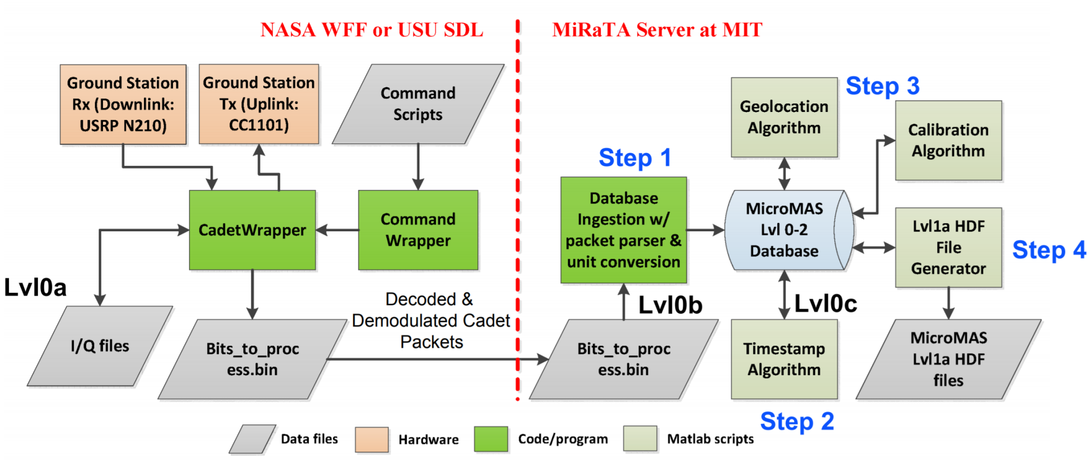


Figure 5-1: MicroMAS-1 ground station diagram, repeated from Chapter 2 for reference.[9]

MM1-Dashboard was used at SDL for MicroMAS-1 mission operations. Unlike MiRaTA, the team did not have time/manpower to do additional development between testing and mission operations, which resulted in some suboptimal operational conditions. Since there initially was no way for operators to send an automated sequence of commands in MM1-Dashboard, it was stressful for operators to command the spacecraft. Operators had to make sure that they did not send an incorrect command, make sure that they executed the commands in the right sequence, and confirm that they executed properly, all in a ten-minute overpass. This process was error-prone, stressful, and was not tolerant to deviations in the overpass plan. As a result, during mission operations, the team implemented "command scripts" that were similar in concept to the MiRaTA ATSes, although implemented quite differently. The architecture of the final MicroMAS-1 software and data processing pipeline is shown in Figure 5-2.



Data Product	Description
Level 0a	Raw I/Q samples from USRP N210 containing L-3 Cadet packets
Level 0b	Decoded & demodulated L-3 Cadet packets
Level 0c	Ingested MicroMAS packets with units converted and timestamped
Level 1a	Calibrated & geolocated antenna temperatures at native resolution

Figure 5-2: MicroMAS-1 software and data processing pipeline.[9]

To generate a command script, an operator would open MM1-Dashboard and issue a sequence of manual commands; MM1-Dashboard would log those raw bytes to a file. Thus, a script would consist of a sequence of raw bytes. This sequence of bytes would then be sent by the command wrapper to the CadetWrapper (which encapsulates spacecraft data in a format that the Cadet can understand). This is better than issuing the command sequences manually, but also introduced a few problems of their own. The scripts were not human-readable, as they were just raw bytes. Thus an error or corruption of the bytes to be sent would be very difficult to catch; an error in the bytes of one of the playbook sequences was only discovered late in the mission operations process. In addition, the interface for sending scripts was not clear; the operator would run the command wrapper with a numerical argument specifying the number of the command script to be run. The number would come from an Excel spreadsheet (the playbook) documenting the command script names.

If the operator had command scripts that were out-of-date, or a playbook that was out-of-date, then the operator could send wrong commands without knowing it.

Difficulties also arose in the data processing step for MicroMAS-1. The CadetWrapper in Figure 5-2 was used to send commands via the ground station hardware. However, the CadetWrapper was being developed frequently and thus its logfiles were not consistent from pass to pass, causing the team much consternation in attempting to recreate a definitive sequence of commands that were sent to the spacecraft. The conversion process (Step 1) was cumbersome as it required running a few scripts, including MM1-Dashboard. It also took many pieces of software to get spacecraft data to a manipulatable state by data analysts.

5.3.2 MiRaTA

The MiRaTA software pipeline is shown in Figure 5-4 and Figure 5-3. To reduce operational complexity, the team decided to treat the two ground stations as independent entities, only commanding through one ground station at one time.

Cadet Downlink/Uplink Chain

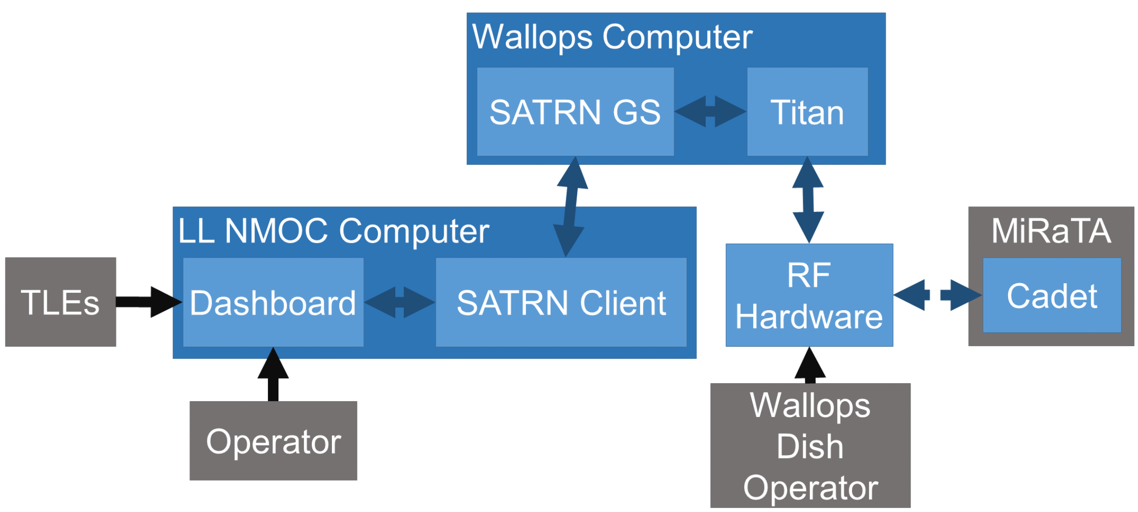


Figure 5-3: Cadet downlink/uplink chain.

The Cadet downlink chain contains some new elements from MicroMAS-1. The SATRN software developed by SDL allows for commanding from a remote computer; this meant that SDL engineers did not have to command the spacecraft themselves, reducing some complexity. Another piece of software developed by SDL (Titan) handles the demodulation step (and controlling some aspects of the RF receiver/transmitter), reducing the amount of work needed to be done by MiRaTA team. Finally, Dashboard was improved to contain the functionality previously implemented by the CadetWrapper, so that the CadetWrapper no longer needed to be used. These software advances helped make using the Cadet radio for communications easier than in MicroMAS-1.

The process of an overpass[6] is as follows:

- The operator gets the latest Dashboard code from the Git repository to get the newest GSMM scripts/ATSes.
- Operator schedules an overpass using the SATRN client software. The operator also makes sure the spacecraft TLE is up-to-date so that Dashboard does Doppler compensation properly.
- When the overpass begins, SATRN client establishes a connection to the SATRN GS software. The Wallops dish begins tracking the spacecraft.
- The operator then starts Dashboard with the SATRN + Doppler compensation settings enabled.
- The operator issues a GSMM script for commanding. Dashboard sends spacecraft command packets to the SATRN Client, which relays them to the Wallops GS for transmission. Since Dashboard is started in Doppler compensation mode, it also automatically handles changing the uplink frequency of commands.
- At the end of the overpass, the SATRN Client closes the connection with the SATRN GS.

[6] The author developed the SATRN-specific part of Dashboard and implemented Doppler compensation; Mark Tolman set up the NMOC computer; Cameron Weston and Chad Buttars helped with SATRN and Titan interfacing; Dan Cousins drove overpass procedure formalization.

- Dashboard produces command and parsed telemetry logs; SATRN produces the bytes demodulated by Titan. The operator moves these files to the MiRaTA server by running a script which is automatically generated by Dashboard.

Micron Downlink/Uplink Chain

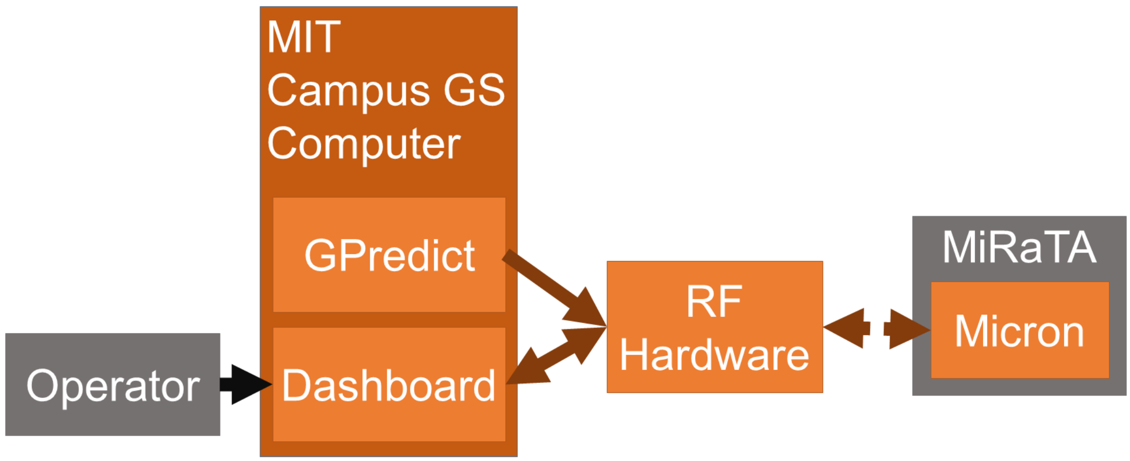


Figure 5-4: Micron downlink/uplink chain.

The Micron downlink/uplink chain is new for MiRaTA; as discussed in Chapter 2 it is the real-time responding radio onboard the spacecraft. Since everything is located on the MIT campus, the set-up is much simpler than the Cadet chain, and also allows for the team to take overpasses whenever they happen (rather than having to schedule them in advance with SDL and Wallops).

The process of an overpass[7] is as follows:

- The operator gets the latest Dashboard code from the Git repository to get the newest GSMM scripts/ATSes.
- The operator uses GPredict to see when an overpass is.
- Before the overpass, the operator turns on the RF hardware, sets up GPredict to control the antenna, and sets up Dashboard in Micron mode.

[7]The campus GS was developed by Greg Allan and Joey Murphy.

- During the overpass, the operator issues a GSMM script for commanding. Dashboard sends spacecraft command packets to the Micron GS board, which handles modulation/demodulation. (No Doppler compensation is needed for the Micron GS.)

- The operator stops commanding when they decide to.

- Dashboard produces command and parsed telemetry logs, and also saves the raw demodulated bytes from the Micron GS board. The operator moves these files to the MiRaTA server by running a script which is automatically generated by Dashboard.

MiRaTA Mission Operations Scripts

Lessons learned from the MicroMAS-1 mission operations process drove the development of MiRaTA's mission operations procedures and software. Mission operations is an even more hectic period than SV TVAC, as spacecraft operators have less than ten minutes to actually contact and command the satellite. Before launch, the MiRaTA team predefined aspects of spacecraft functionality to verify on orbit. Each bit of functionality could be verified in one overpass; for instance, the first overpass was "verify that the spacecraft can respond to Micron-issued commands". From these overpass definitions, the team built several early orbit checkout (EOC) ATSes and GSMM script templates.[8]

Some examples of ATSes include:

- get_tlm_pkts: Request all interesting spacecraft telemetry.

- sc_cadet_status: Request the spacecraft status packet and the cadet status packet.

- set_operational_fault_thresholds: Set the thresholds at which the spacecraft will do something about fault packets.

[8] Early orbit checkout script development was done by Greg Allan and the author.

- rad_orbit_turnon: Turn on the radiometer.

At time of writing, the MiRaTA team is in the middle of mission operations. Because the time between overpasses is so low (12 hours), the team often issues simple GSMM scripts/ATSes. The main GSMM script type used by the team is the "repeat GSMM" script; this script will repeat an ATS over and over.

The repeat GSMM functions as follows:

1. In the Dashboard test runner interface, the operator specifies an ATS to repeat, a duration to repeat the ATS, and a time delay. The operator then hits execute.

2. The GSMM script executes the specified ATS.

3. The GSMM script waits for the specified time delay.

4. The GSMM script checks how long it has been executing; if it has been executing less than the specified duration, return to step 2.

Having the repeat GSMM script on hand during overpasses helps to streamline the overpass process. Since the spacecraft (in early orbit, before detumble) occasionally tumbles to point its antenna away from the ground station, commands get missed by the spacecraft; thus, it was important to have the repeat GSMM functionality to ensure that commands would reach the spacecraft. Because the GSMM script automatically handled repeating the ATS, it made things much easier on the spacecraft operator.

Comparing the ATS/GSMM/Dashboard system of MiRaTA mission operations with the command script system of MicroMAS-1 mission operations:

- ATSes and GSMMs were designed to be human-readable; command scripts were bytestrings and thus not human-readable.

- Sending an ATS or GSMM script from the Dashboard user interface gives the operator several notices on what the script does; the command script interface for MicroMAS-1 did not.

- It is about as easy to create an ATS from scratch as to create a command script, as both require Dashboard to be started. However, an operator can modify a raw ATS file (since it is JSON); an operator cannot modify a command script.
- The ability to automatically repeat a string of commands was missing from the MicroMAS-1 command wrapper.
- Since the MiRaTA team was able to use version control, the ATS/GSMM scripts were easier to keep up to date as compared to the command scripts.
- Dashboard logs commands in a singular log; the command scripts presented difficulties in post-overpass command parsing.

Thus, the MiRaTA system offers many improvements over the previous system. In the end, 142 ATSes and 120 GSMM scripts were written collectively by the MiRaTA team, which demonstrates that the system was key to the MiRaTA testing and mission operations process.

5.4 Future Work

The system did conclusively help with testing and mission operations. However, there are many ways to improve the current system and Dashboard.

1. Improve the usability of the ATS creator.
2. Enable non-coders to build GSMM scripts.
3. Allow the GSMM to run completely independently of Dashboard. (Right now it needs to be launched by Dashboard.)
4. Add more flexibility to the Dashboard system so that it can accommodate arbitrary spacecraft.
5. Add awareness of spacecraft limits to the Dashboard commanding system, so that Dashboard cannot command the spacecraft to do something that will harm it.

6. Add more tests for the Dashboard code itself.

Chapter 6

Conclusion

In this thesis, we cover the MiRaTA mission and the testing systems used to validate its payload and bus. The Dashboard software, heritage from MicroMAS-1, has been augmented with an automated testing system which allows for an operator to predefine Automated Test Scripts (ATSes) – sequences of commands and telemetry checkpoints, and Ground Station Mission Manager scripts (GSMM scripts) – scripts that enable the execution of complicated spacecraft operations for the mission. Both ATS and GSMM scripts played a crucial role in testing and mission operations, streamlining the process for operators, improving usability while being much faster than previous testing procedures.

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