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A Portable Autonomous Ground Station to Support a Constellation of CubeSats

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ABSTRACT

Ground systems have historically been large installations consisting of massive infrastructure and complex software systems requiring significant human effort to construct and operate. In support of the Prometheus project at Los Alamos National Laboratory, which launched a constellation of eight 1.5U CubeSats in November 2013, we developed a portable autonomous ground system. The system consists of a combination of commercial off the shelf components, a custom software defined radio packaged into a small rugged box, and a single custom software application. One of the goals of the project was to make a system that could be deployed in a remote location, setup in a day by two people, and that could autonomously complete the system's data transfer mission. The single software application was designed to provide command and control, mission configuration, situational awareness, real-time monitoring, state of health (SOH) analysis, and mission data transfer. In addition, the software graphical interface was designed to be used by a non-space professional with less than a week of training.

The Prometheus satellites are currently on-orbit and have demonstrated the mission's store and forward capability. Four ground stations were setup as part of the project. Each of the ground stations has been used to automatically; switch between satellites, downlink SOH data, downlink mission data, and uplink operational configuration data. This paper describes the ground system in detail and the hardware and software designs used to keep the system simple while providing significant capability.

INTRODUCTION

The first phase of the Prometheus project at Los Alamos National Laboratory (LANL) consists of four ground stations, eight 1.5U CubeSats, and four field units. Field units are low profile ruggedized satellite modems with small patch antennas that can be connected to a variety of data sources on the ground. The satellites are dual band data relay units that can move files from a field unit to a ground station in real time, or, store and forward full or partial field unit files. The ground stations provide the infrastructure to monitor and configure the constellation, and to analyze satellite data and field unit files.

The satellites were launched into a 40.5 degree inclination 450 km orbit on November 19, 2013. The launch from Wallops Flight Facility was part of an Operationally Responsive Space (ORS) mission using a Minotaur rocket that deployed a total of 28 CubeSats.

The Prometheus ground station was developed and deployed in a low-band and high-band configuration. By design, the low and high band systems are nearly identical except for the antennas and a few RF components. The same software is used to control both types of ground station. To date, four ground stations have been deployed. Initially there were two low band ground stations at Los Alamos, NM, one high band ground station at Los Alamos, and one high band ground station deployed in central Florida. As system operations evolved, one of the low band ground stations at Los Alamos was converted to a high band system. After a year and a half of operations, all aspects of data transfer and command and control have been demonstrated.

The Prometheus project is a follow on to the Perseus project at LANL which launched four 1.5 U CubeSats on a SpaceX Falcon 9 rocket on December 8, 2010. That launch was a 34.5 degree inclination, 300 km orbit. Because of the low orbit, the satellites re-entered after only 16 days, however significant design and operation experience was gained during that demonstration flight. Perseus demonstrated all the major ground station design concepts, including the use of common hardware and software, the ability to communicate with the SV using simple and low cost hardware, the ability to use a simple GUI, the ability to have a non-expert operate the system, and the co-design principles that enable vast simplifications to the ground station hardware and operations.

The current generation Prometheus system pushed these concepts to the next level, first to demonstrate a higher level of hardware integration for simplified deployment, and second to demonstrate fully automated operations and constellation management using multiple ground stations. The goal of the next generation system is to bring these concepts to full fruition, featuring a small tightly integrated ground hardware, for mass production, and a even simpler user interface. This paper is focused on the current incarnation.

Figure 1: Eight Prometheus Flight Units (shown in post-deploy configuration)

CONOPS

The Concept of Operations (CONOPS) and design choices for the Prometheus constellation were focused on keeping both the ground station hardware infrastructure and the software interfaces easy to use. Operating the system involves setting up a ground station anywhere with standard power by two people in a day, using equipment that is easily transportable. Tasking is kept simple by using a software interface that allows an operator to work at the level of configuring the system to retrieve files from a particular field unit, then leaving the system to autonomously do the job.

The idea of configuring the ground station and satellites to do a job, as opposed to strictly tasking based on time, is prevalent throughout the design and operations. The operator selects which field unit to contact, which satellites should contact that field unit, and queues the configuration for uplink. The operator returns later to enjoy the retrieved files. This alleviates the operator from having to repeatedly calculate contact times and generate scripts to perform the desired activities. It also makes the system more robust to non-deterministic communications. If a satellite is unable to contact a field unit, it will automatically try again later. In all cases, the ground stations operate autonomously, and send a page and/or text message to operators with status information.

Achieving this level of automation was twofold. First, the satellite and ground station were co-designed from the beginning to work with each other, and enable automated operations. Second, intelligence and flexibility was put into both the ground station and the satellite. For example, each satellite's attitude determination and control system (ADCS) continually propagates its orbit. Based on the operator's uplinked configuration, it autonomously contacts the desired field units. The ground station, based on the operator's chosen configuration, also propagates the orbits of the satellites, automatically switch between them, and downlinks the desired files spanning multiple contacts if necessary. This in turn removes the need for time-based commanding, allowing the user to task the system with jobs.

The basic mission operations described are intended to make the system easy to use by a minimally trained operator. However, there is still a need by the system's designers to monitor, command, control, update, and troubleshoot the satellites without operations becoming too onerous. Supporting both the basic end user and the designer was a difficult development effort. The current system was initially designed for administrator and on-orbit testing needs, while demonstrating and validating the concepts and software needed for a much simpler interface for a more casual user. The ground station's software was designed to override the basic operations and allow for specialized yet still automated commanding. This includes automated; downlink of satellite state of health, monitoring and alarms, and uplink of test configurations and new flight software.

GROUND STATION HARDWARE

The hardware was designed to be portable, field deployable, and easy to use. Instead of racks of specialized equipment, the user system consists of a single Windows 7 laptop computer connected to a custom 18"' x 16" x 8" 'GS Box' that houses the LANL designed software defined radio boards and the commercial off the shelf (COTS) rotor controller. The connections between the laptop and the GS box are two standard serial over USB cables. One connection provides communication with the radio transceiver and the other provides communications with the rotor controller.

Figure 2: Prometheus Ground Station – Laptop and Indoor GS Box

In addition to the laptop and indoor GS box, the ground station hardware consists of the antennas, rotors, outdoor RF box, and lightning protection. The separation of the components was driven by various design considerations including:

- Low cost
- Quick setup using easily transportable and connectorized components
- Antennas located far from the laptop require long cable runs
- Protecting GS encryption keys by keeping them inside
- Ease of troubleshooting and resetting of the antenna system
- Need for lightning protection of indoor components

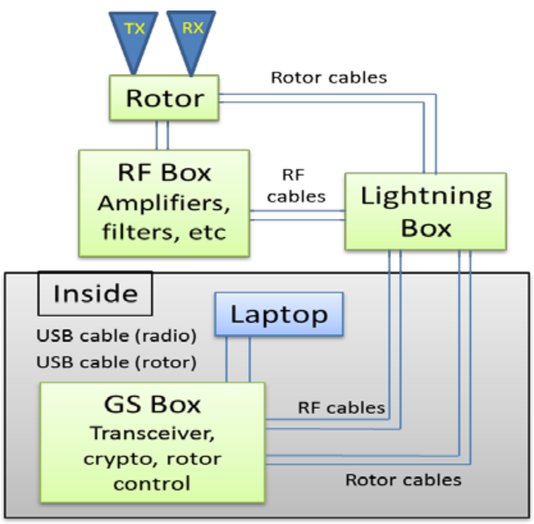

Figure 3: Prometheus Ground Station Hardware Block Diagram

The hardware and software is fully Government Off the Shelf (GOTS) and hence available to other government users. LANL is also commercializing the technology to make it available to non-government users.

The need to keep the transceiver secure, and transmit the RF signals a fairly long distance, 100's of feet, drove the design of the RF Box components. An appropriately sized power amplifier and low noise amplifier are housed in this box along with other analog RF components like band pass filters.

One important co-design choice that carried over from Perseus is the re-use of the same radio on-board the satellites and in the ground stations. The GS box houses the exact same 4" x 4" digital radio, and, analog radio boards that are in each CubeSat. In addition, the digital radio board consisting of a microcontroller and a reprogrammable FPGA, is the exact same for both the low band radio and the high band radio. This allowed for significant software re-use. The same embedded code used for communications protocols, encoding, and cryptography is shared between the satellite and the ground station, thus the two systems are inherently designed to communicate with each other.

These design choices makes it easy to convert a ground station from a low band GS to a high band GS. The only changes required are; swap out the antennas, swap out the RF box, and make one jumper change to the transceiver in the GS box. All other components, including software, remain the same.

Figure 4: Prometheus High Band Antenna with Outdoor RF Box

GROUND STATION SOFTWARE

There are two main software components to the ground station; the embedded software running on the radio, and the user interface running on the laptop. The embedded radio software provides the details associated with the communication link such as packetization, forward error correction and encryption, while the user application provides higher level functions like orbit propagation, automation, and a graphical user interface (GUI).

The user application performs the following functions:

- Automated operations
- Automated constellation management
- Orbit propagation
- Doppler correction
- TLE retrieval
- Configuration file creation and uplink
- Antenna rotor control
- Alarms distribution
- SOH logging and display
- Status display
- Scripting

In an effort to limit the complexity of operating the system, it was decided to put all the user functionality into a single custom LANL developed application as opposed to having the user manage multiple applications. Having a single application also simplifies installation and setup of a new computer for ground station operations.

Figure 5: Prometheus Command and Control Software Main Window

Figure 5 is a screenshot of the main operator window. At the top of the window, basic information like contact start and stop time, if a satellite is currently in view, radio signal strength, and the state of the connection process are displayed. Tabs on the main window provide the interface to task the field units and ground station, perform manual commanding, and display status and SOH data.

Autonomous operations are configured and monitored using a separate dialog. However this is only needed by an expert user, a basic user will not need much more than the main window.

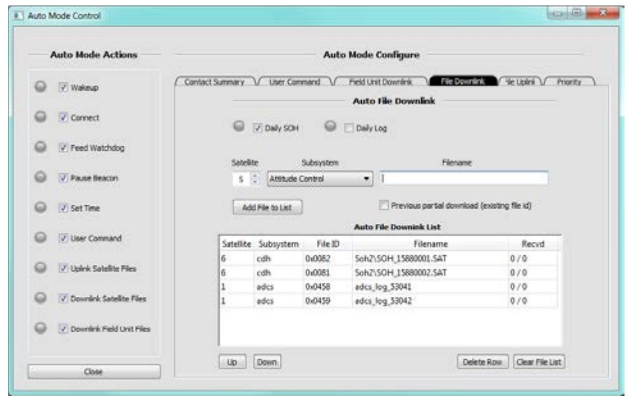

Figure 6: Auto Mode Configuration and Monitoring

If a network connection is available, the software will automatically contact Space-Track daily and download the latest Two Line Element (TLE) set for all active satellites. Orbit data, like contact start and stop times for the ground station, range, and range rate information for each satellite is calculated and stored. To keep transmit and receive frequencies within the bandwidth of the system, the automated process uses the range rate information to update the frequencies for Doppler correction. The updated frequency information is communicated to the ground station radio once per second during a satellite pass.

The operator can configure the ground station to automatically conduct maintenance, like setting the current time on each satellite, along with automated file uplink and downlink actions. The queues of files are accessible to the operator if needed, and can be manually modified to support troubleshooting, testing, or, changing priorities.

The decision of which satellite in the constellation a particular ground station will contact was an issue especially early in the mission before their orbits spread out. The ground station must decide which satellite to contact when two or more overlap. A fairly simple approach was taken whereby the operator creates a sequence of satellites. The automatic processing attempts to contact each satellite in the order specified. While this takes some effort and knowledge on the part of the operator, it provides the flexibility to focus on particular satellites in the constellation while ensuring others do not starve for attention.

State of Health (SOH) data about the satellites comes in two forms; a small amount relayed during a ground station ping request, and, files stored on-board that are continuously updated every five minutes. Ping responses are used for immediate status information when a satellite is in contact with the ground station. The long term data files, which can be automatically downlinked and converted into engineering units by the ground station, are used for monitoring of satellite conditions over time. The SOH data is stored in a standard file format and can be displayed by plotting tools also built into the ground station software.

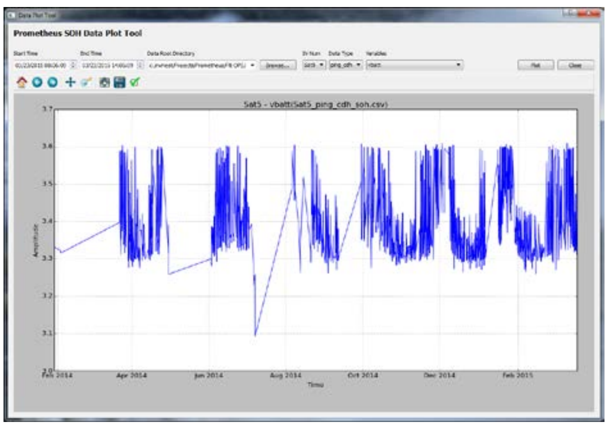

Figure 7: Integrated SOH Plotting Tool

Because the ground station can run unattended for many days, there needs to be a method to inform operators of alarm conditions and status. If connected to a network, the main application can make use of a mail server to send email, text, and pager messages.

Alarm and status messages:

- Low battery alarm
- No ping reply received on 4 or more consecutive passes
- No successful watchdog monitor command on 7 consecutive passes
- Power configuration (which satellite components are powered) does not match what was expected
- Information message that a pass will start in 5 minutes
- Information message after a pass indicating contact activity e.g. how many commands were sent and how many data frames were transferred

The messages proved to be very useful not only to inform the operator of problems with the satellites, but also problems with the ground station itself.

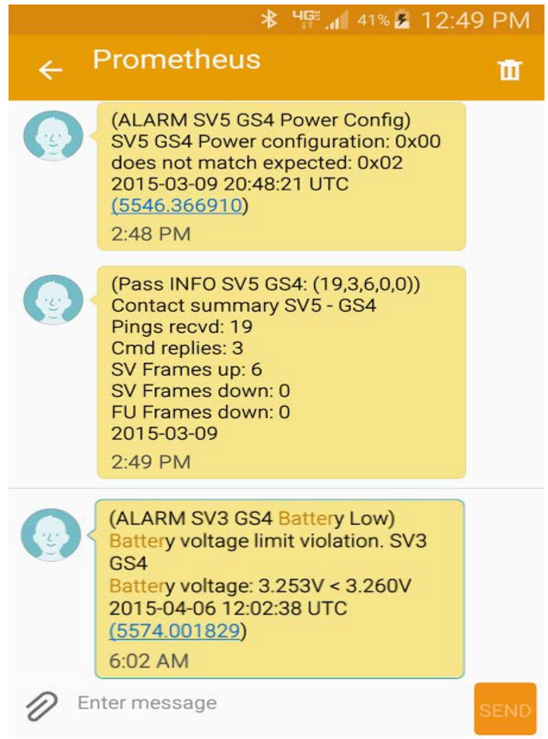

Figure 8: Text Messages Showing Alarm and Status sent from Prometheus Ground Station

While scripting is not used for nominal operations, it did become useful for troubleshooting and for executing commands that would be tedious to perform by an operator. An example is overcoming the inadequate default camera exposure settings. Numerous time-tagged commands were queued in a script file and uplinked. This allowed the operator to try multiple exposure settings, compress, and downlink the photos with minimal interaction.

PERFORMANCE

The Prometheus ground stations have been operational for over 18 months. During that time:

- The satellites were successfully contacted on over 7,200 ground station passes
- Over 16,300 commands were sent and a successful execution reply received

- 20 Mbytes of data were uplinked
- 16 Mbytes of data were downlinked

The majority of the contacts, commands, and data transfers were simply configured by an operator and then autonomously executed by the ground stations.

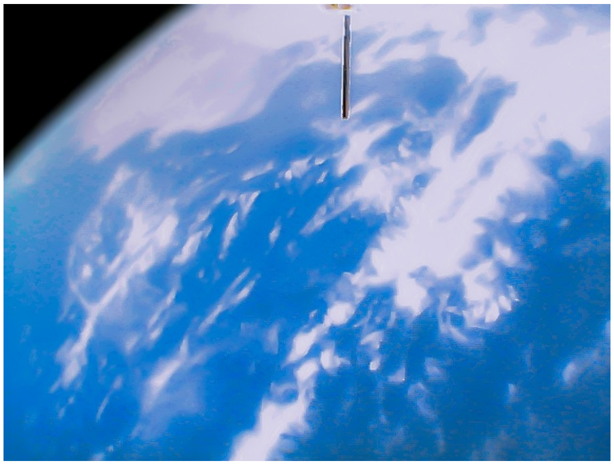

Figure 9: Prometheus Photo of Oman and the Arabian Sea (satellite low band antenna element in top center of photo)

CONCLUSION

A co-design approach was used to make the Prometheus satellite, field unit, and ground station an effective system. By keeping the operator experience simple while still providing powerful tools where needed, the ground station made huge strides in making the operations of a constellation manageable.

Improvements in-work for the next generation autonomous ground station:

- More compact and mass-producible hardware
- Cleaner and simpler user interface
- Expanded rotor compatibility (user able to choose rotor based on cost and requirements)
- Automated remote network operations
- More sophisticated constellation management

Another important note: we are in the process of commercializing this technology, to make it available for other users.