Dellingr: NASA Goddard Space Flight Center's First 6U Spacecraft

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ABSTRACT

The Dellingr spacecraft is NASA Goddard Space Flight Center's (GSFC's) first build of a 6U CubeSat. A key driver of the Dellingr project is the recognition that NASA needs to infuse the emergent CubeSat capability into our science missions to support small, focused science objectives while also enabling larger strategic constellation missions in support of Decadal Survey science goals. The primary objective of the Dellingr project was to develop a cost-effective model for CubeSat and SmallSat builds at GSFC with lean end-to-end systems and processes to enable lower-cost, scalable risk, systems. Dellingr is a balance of commercial off the shelf (COTS) and in-house subsystems, leveraging the strengths of both the booming commercial market and existing GSFC infrastructure, capabilities, and experience with similar "Do No Harm" missions, such as sounding rockets. Dellingr carries an advanced gated time-of-flight ion/neutral mass spectrometer (INMS) and three fluxgate magnetometers. Two of these magnetometers are internal to the spacecraft, and will be used to test and validate a new software algorithm that compensates for and removes spacecraft interference; the third magnetometer sits at the end of a 52-cm boom. Together, these instruments will measure the space weather effects of solar wind-magnetosphere coupling on Earth's ion and neutral upper atmosphere.

BACKGROUND & INTRODUCTION

As CubeSat subsystem technologies rapidly improve they have transitioned from educational and/or demonstration platforms to spacecraft capable of delivering compelling science[1,2]. This capability, combined with instrumentation miniaturization efforts, means that in some instances CubeSats or SmallSats can displace larger spacecraft for equivalent or slightly reduced science return, while also enabling affordable constellation missions of many 10s to 100s of satellites.

NASA Goddard Space Flight Center at the Greenbelt campus has many decades of experience designing, building and operating high-reliability spacecraft. Wallops Flight Facility (WFF), a part of GSFC, specializes in "do no harm" sub-orbital platforms, such as sounding rockets and balloons, which are traditionally lower-cost/higher-risk missions. CubeSats occupy a space in between these two areas of expertise. GSFC has in the past implemented missions in this area, in particular Hitchhiker, Get-Away-Specials, and building the first few SMall EXplorer (SMEX) satellites, including SAMPEX and FAST. By combining the extensive spaceflight experience of GSFC/Greenbelt with the "do no harm" culture of GSFC/WFF, GSFC believes it can offer a reliable and scalable CubeSat/SmallSat platform capable of achieving Decadal Survey science objectives at an affordable cost.

It is within this backdrop that GSFC embarked on Dellingr, a 6U CubeSat, in January of 2014. The primary goals of Dellingr were to:

1. Develop a cost-effective Center model for CubeSat development;

2. Develop tailored, lean, and scalable end-to-end systems; and

3. Determine lessons learned, and apply them to the next generation of satellites.

The focus of the Dellingr project was primarily as a pathfinder effort to determine an appropriate level of GSFC processes that should be applied to these types of platforms without burdening the project with excessive requirements or processes while implementing an acceptable level of reliability. The project was also guided by a few defining principles, including:

- Pairing experienced with junior engineers to facilitate training;

- Keeping the core team as small as possible, and reaching out to the Center for focused expertise as needed;

- Smartly applying GSFC knowledge and tailored procedures;

- Minimizing up front component testing and “Test as we fly” to the fullest extent possible;

- Utilizing table-top reviews with subject matter experts, when needed – no confirmation gates.

Dellingr was delivered to NanoRacks on May 31, 2017 and is being processed for a planned August launch aboard the Falcon-9 Commercial Resupply (CRS) SpX-12 as part of ELaNa-22 Mission.

SCIENCE OVERVIEW

Earth’s upper atmosphere changes in response to “space weather”, which is created by the sun’s activity. Much of space weather’s impacts are observed at high latitudes. It is at these regions, such as across Canada, Iceland, and Scandinavia, where space weather has the biggest visible impact in the form of the aurora. Space weather can also affect radio communication, damage sensitive electronics in our satellites, and damage power transmission infrastructure. Space weather causes changes in Earth’s upper atmosphere, and these changes can be measured by scientific satellites in order to better understand these phenomena. To make these measurements, Dellingr carries two instruments:

- A magnetometer is located at the end of the 52-cm boom to avoid magnetic contamination from fluctuating spacecraft-generated fields. Changes in the magnetic field provide clues to space weather effects coming into the atmosphere. The spacecraft also carries two magnetometers internal to the spacecraft. These will use advanced software to ‘clean’ the measurements and compare the results to the better measurements obtained on the boom.

- A ‘spectrometer’ to measure both ion and neutral particles in Earth’s upper atmosphere. These particles respond to space weather effects by getting hotter or moving faster. By measuring these changes, we will learn more about how space weather changes Earth’s upper atmosphere.

Ion Neutral Mass Spectrometer (INMS)

There exists a strong need for in situ measurements of atmospheric neutral and ion composition and density, not only for studies of the dynamic ionosphere-thermosphere-mesosphere system but simply to define the steady state background atmospheric conditions. The INMS (Ion-Neutral Mass Spectrometer) addresses this need by providing simultaneous measurements of both the neutral and ion environment, essentially providing two instruments in one compact model. It can measure H, He, N, O, N2, and O2, among others, with M/dM of approximately 10 at an incoming energy range of 0-50eV. The INMS is based on front end optics, post acceleration, gated time of flight (TOF), an electrostatic analyzer (ESA), and channel electron multiplier (CEM) or microchannel plate (MCP) detectors. The compact sensor has a dual symmetric configuration with the ion and neutral sensor heads on opposite sides, with full electronics in the middle (see Figure 1).

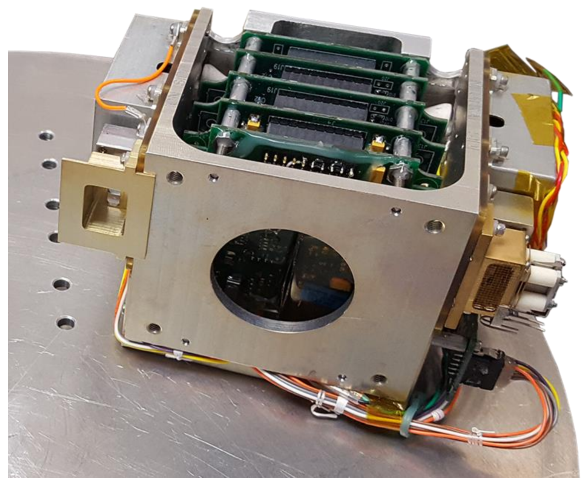

Figure 1: Ion-Neutral Mass Spectrometer.

The neutral front end optics includes thermionic emission ionization and ion blocking grids, and the ion front end optics includes spacecraft potential compensation grids. The electronics include front end, fast gating, high voltage power supply, ionizer, TOF binning and full bi directional C&DH digital electronics. The data package includes 400 mass bins each for ions and neutrals and key housekeeping data for instrument health and calibration. The data sampling can be commanded as fast as 10 msec per frame (corresponding to ~80 m spatial separation) in burst mode, and has significant onboard storage capability and data compression scheme. The 1.3U volume, 570 grams, 1.8W nominal power INMS instrument makes implementation into CubeSat designs (3U and above) practical and feasible. With high dynamic range (0.1-500eV), mass dynamic range of 1-40amu, sharp time resolution (0.1s), and mass resolution M/dM of 16, the INMS instrument addresses the atmospheric science needs that otherwise would have required larger more expensive instrumentation. INMS-v1 (version 1) launched on Exocube (CalPoly 3U CubeSat) in 2015 and INMS-v2 is used for Dellingr.

Distributed Acquisition for Geomagnetic Research (DAGR)

DAGR instrument includes three science-grade fluxgate magnetometers. The two internal magnetometers are designed to test new software 'scrubbing' algorithms that remove interference created by the electronics of the spacecraft. The traditional approach for magnetic field measurements is to place the magnetometer at the end of a long boom, away from magnetic contamination. But through software, it is possible to remove spacecraft interference from magnetometers embedded within the spacecraft, thereby reducing cost and complexity by eliminating the need for a magnetometer boom. By flying both a boom-mounted magnetometer and two internal magnetometers, we will be able to test the capability of the software scrubbing algorithms against 'pristine' magnetic field data collected by the boom magnetometer.

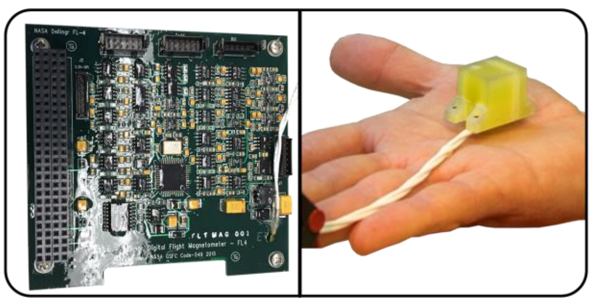

Figure 2: DAGR in-house electronics board and magnetometer head.

Two of Dellingr magnetometers are miniature fluxgate magnetometer developed by GSFC over the last several years (see Figure 2). The sensor weights 19 grams, has 24-bit A/D, consumes 750 mW, and has 12 pT/√Hz sensitivity at 1Hz. One of the magnetometer sits on a 52-cm extendable double-hinged boom, and sample at a minimum of least 10 Hz. Measurements in the GSFC coil facility show it has a noise level of <0.1 nT.

MISSION DESIGN

Dellingr is a 3-axis stabilized spacecraft consisting of fine and coarse sun sensors, MEMs gyro, magnetometer, torque coils and three reaction wheels (see Figure 3). The communication system is UHF uplink and downlink with a deployable dipole antenna. In addition, the spacecraft includes six body mounted solar panels with a maximum power point tracking (MPPT) electrical power system and lithium polymer batteries. A passive thermal system maintains temperature of components within limits. The on-board computer utilizes the in-house core Flight Software (cFS) and handles the command and data handling in addition to the guidance, navigation and control processing.

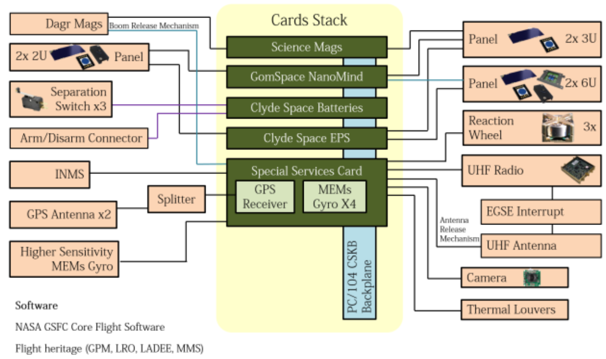

Figure 3: Spacecraft architecture.

The instruments were selected based on their level of maturity and achievable compelling science. The Spacecraft bus and orbit operations were architected based on the instruments and science requirements. Requirements were periodically reevaluated as the system matured in an effort to reduce cost and schedule without compromising or significantly affecting the science products. The pointing requirement is one example of such a trade. Initially the INMS instrument required pointing knowledge of less than 0.5 degree. Such requirement would leverage a more expensive solution while compelling science could still be achieved at a relaxed pointing knowledge enabling a cheaper solution with sun sensor and MEMs gyro instead of star trackers. This is a common theme across the project up until delivery and operations. A combined science-bus team effort is paramount for trades between science requirements and bus capability decisions, compromising at both ends to reach science goals and a feasible technical solution within budget.

A second example of a trade between science and bus is the decision to use only body mounted solar panels. Deployed arrays were not implemented in an effort to minimize technical complexity. Instead, science operations were modified to allow for charging orbits in between science orbits. This adaptation enabled science goals to be met with reduced programmatic and development costs.

An International Space Station (ISS) deployment was selected because that represented the quickest pathway to launch for a 6U satellite. This orbit presents challenges from the power and thermal standpoints because of the beta angle changes. At the same time, the orbit offers a benign radiation environment.

Dellingr operations start when the spacecraft is ejected from ISS utilizing one of the ISS robotic arms and a NanoRacks deployer. The satellite turns on immediately after ejection and enters a timer stage after boot up. The timer stage does not have active attitude control plus deployments and radio transmissions are prohibited. After the timer period, the satellite deploys the science magnetometer boom, the UHF antenna, and points the largest solar panel towards the Sun.

Commissioning phase consists of verifying proper functionality of the bus subsystems and science instruments. Science operations starts immediately upon completion of the commissioning phase.

Science operations alternate between a full INMS science orbit, a full DAGR science orbit, and a number of charging orbits in between. These operations are performed as relative time sequence commands with a final command to restart the system after roughly 24 hours. The restart ensures bit flip errors get cleared at a rate that minimizes adverse effects to the bus.

Mechanical structure and mechanisms

Since the mission lacked a manifest throughout the development, the project had to assume interface requirements. As such, the structure was designed to the Planetary Systems Corporation (PSC) standard. Overall volume allocation is 366 mm x 239 mm x 113 mm with 2 tabs along the base edge which serves as the interface with the deployer (see Figure 4). The NanoRacks 6U deployer, used to jettison Dellingr from the ISS, is compatible with the PSC standard.

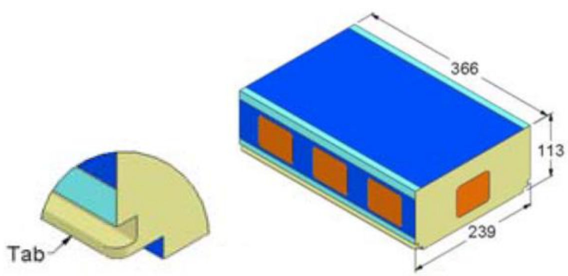

Figure 4: PSC 6U volume allocation.

The majority of the bus components are mounted to a baseplate, while the remaining sides of the structure are solar closeout panels joined by structural bars (see Figure 5). The baseplate is the primary load path since it contains the deployer mounting edge and it also houses the majority of the mass.

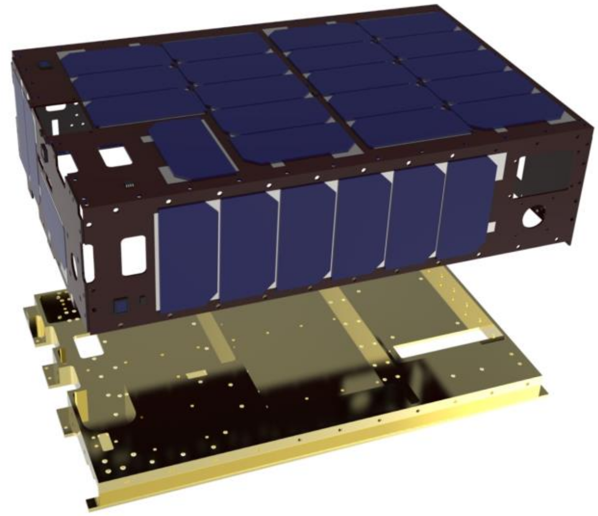

Figure 5: Baseplate and closeout solar panels.

Dellingr contains two deployables, the UHF antenna and a magnetometer boom, each utilizing the same type of release mechanism developed during the mission (see Figure 6).

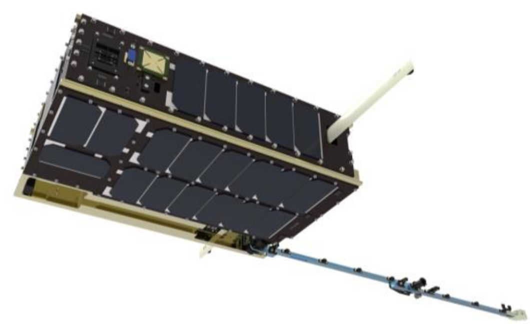

Figure 6: Fully deployed spacecraft.

The two UHF antennae are modified stainless steel retractable tape measure strips. Each strip was cut to length, the original coating removed, and a white paint coating added. The UHF antenna strips protrude from an opening in each of the 3U panels and fold into a single point at the adjoining 2U panel while held by the release mechanism (see Figure 7). The strips immediately retake their linear shape upon release.

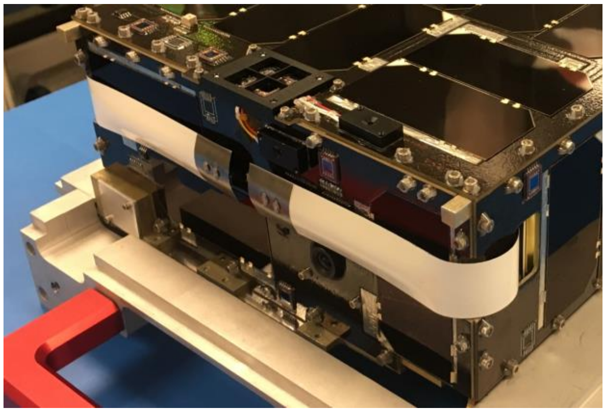

Figure 7: Stowed UHF antenna.

The magnetometer boom consists of an upper and lower arm, with elbow and shoulder hinges (see Figure 8). The boom is stowed in a pocket on the underside of the spacecraft baseplate, and is restrained for launch near the shoulder hinge, with passive restraint at the elbow hinge. The magnetometer mounts to the end of the 52-cm, 0.2 kg, boom assembly.

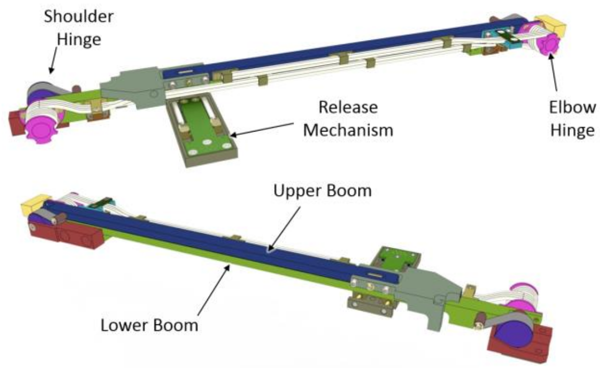

Figure 8: The magnetometer boom in the stowed position.

The UHF antenna and magnetometer boom utilize the same Diminutive Assembly for Nanosatellite deploYables (DANY) release mechanism developed internally in 2013 (U.S. PTO Number 9,546,008). Each release mechanism consists of two spring-loaded plungers held in place by a plastic retaining bar of ABS Plus material (see Figure 9). The plungers will retract under the spring force once the plastic piece is heated by redundant heating elements. Each mechanism also contains redundant separation switches to confirm proper functionality of the release action.

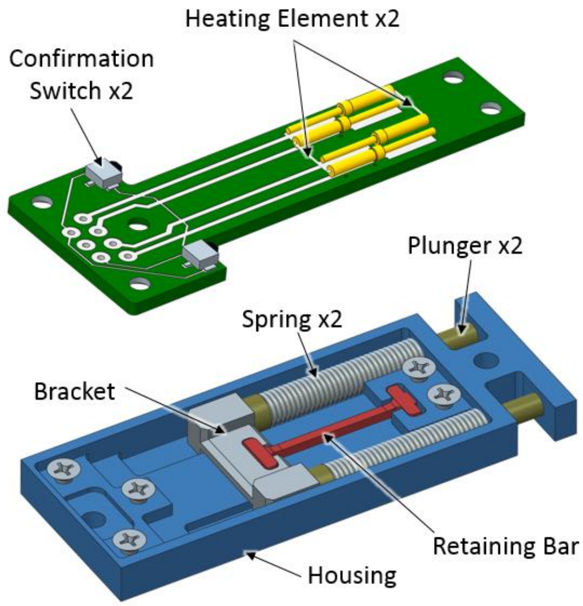

Figure 9: DANY release mechanism utilized to restrain and release the UHF antennae and magnetometer boom.

Power System

The final flight power subsystem consists of a Clyde Space 3rd generation Electrical Power System (EPS), two Clyde Space 40 watt-hour standalone batteries, and fixed solar panels produced in-house. The original design used a similar EPS and three 30 watt-hour batteries (90W total) from Clyde Space. These components were used throughout a large part of Dellingr's development but, ultimately, had to be replaced by the newer battery components for a variety of reasons, including ISS safety compliance. Such compliance also forced a reduction of the battery capacity to 80 Watt-hour maximum and required that inhibits entirely isolate the battery. Clyde Space was able to provide 40 watt-hour batteries that met the inhibit specifications and underwent the extra testing required. This reduction in battery capacity, along with higher than expected power requirements for other subsystems, required a modification to the mission profile to allow for more charging orbits (sun-pointing) for each science orbit.

A design compromise was reached to account for the number of switched power buses available on the EPS. Even with ten available, additional switches were added to a special services card and some components share a single switched bus (e.g., all three reaction wheels are on the same bus).

Several mishandling incidents during spacecraft integration occurred. One serious incident resulted in damage to the 30 watt-hour batteries when two PC-104 connectors were misaligned resulting in the batteries being drained to an unacceptable low voltage. The inhibit configuration of the 40 watt-hour batteries and new EPS may have prevented this incident as the batteries can be isolated from the PC-104 bus. The original EPS was also stressed when a mounting screw on a solar panel contacted a solar cell, shorting the strand. As a precaution this EPS was replaced with a new one.

Dellingr solar panels were designed and assembled in-house using spare SolAero ZTJ Triple Junction CIC cells with integrated bypass diode leftover from the Global Precipitation Measurement mission. These cells were mounted to a PCB substrate with double-sided kapton tape. There are 6 unique panels ranging from 2U (3 cells) to 6U (20 cells). Each panel is custom designed to incorporate features needed for mechanical mounting, experiments, GSE, antennas, and sensors.

The solar panels incorporate torquers as a PCB trace routed around the perimeter creating an air coil though all inner layers of the PCB. A pulse width modulator driver per axis produces a current which generates a magnetic dipole. The solar panels are connected in axis pairs to produce a single magnetic torquer per axis.

The solar panels are fabricated with 2 oz./ft copper for thermal dissipation and torquer performance. The solar panel exterior is protected with a Kapton overlay.

Attitude Control System

The Attitude Control System (ACS) is comprised of a complement of sensors and actuators comparable to larger satellites. The main premise of the attitude determination scheme is to combine information from sun sensors, magnetometers, and inertial rate sensors in whatever combination is best at any given position in orbit. Once the attitude is determined, three reaction wheels are commanded to null errors relative to a selected target attitude and rate. System angular momentum tends to increase in the chosen mission attitudes, so magnetic torque coils in the body face solar panels are employed to remove that momentum over time.

The ACS algorithms were developed in a Matlab/Simulink simulation based on a heritage simulation and ACS design from the Solar Dynamics Observatory (SDO) mission[3]. The simulation includes translational and rotational dynamics, multibody gravitational models, an up-to-date magnetic field model, and a set of representative sensor and actuator models. Selected functionality, such as ACS Failure Detection and Correction, was omitted from the simulation to meet Dellingr's low-cost and fast turnaround requirements. The ACS team used the simulation to develop an algorithm document, upon which the actual C-based ACS Flight Software (FSW) was developed. The ACS includes two main wheel-based Proportional–Integral–Derivative controllers — Sun Pointing and Local-Vertical, Local Horizontal (LVLH) — and simple magnetic momentum management algorithms. An extended Kalman filter, representing essentially a stripped-down version of the heritage filter from SDO, was implemented to achieve desired onboard attitude knowledge.

The ACS mode application was one of several applications that run on the cFS architecture. Important ACS hardware processes such as GPS data ingest, reaction wheel tachometer processing, and gyro readouts, are organized into their own applications or sub-applications for priority processing in advance of the ACS mode execution, or in some cases, more frequent execution than the baseline 1Hz ACS sample rate.

Table 1: The Dellingr ACS has 5 modes of operation.

Mode	Attitude	Momentum Management	Attitude Determination	Quaternion Target
SAFE	Sun Pointing	RWA Momentum All the Time	N/A	N/A
CHARGING	Sun Pointing	RWA Momentum All the Time	N/A	N/A
TRIAD	Sun Pointing	System Momentum All the Time	TRIAD	N/A
DAGR	Sun Pointing	System Momentum |Latitude| < 20°	Attitude Kalman Filter (AKF)	N/A
INMS	LVLH Control (Low) Beta < -36° +Z Ram; +X Zenith	N/A	Attitude Kalman Filter (AKF)	[0; 0.7071; 0; 0.7071]
	LVLH Control (Mid) |Beta| < 36° +Z Ram; +Y Zenith	N/A	Attitude Kalman Filter (AKF)	[-0.5; 0.5 ; -0.5; 0.5]
	LVLH Control (High) Beta > +36° +Z Ram; -X Zenith	N/A	Attitude Kalman Filter (AKF)	[0.7071; 0; 0.7071; 0];

In order to verify the ACS FSW implementation on the ground, the Dellingr Hardware Library (DHL) was developed to support two distinct hardware/software interfaces/ports: the GomSpace NanoMind version for the actual flight computer and the Linux version for when Dellingr uses the independent, software-only spacecraft dynamics simulator, 42[4], to verify ACS FSW functionalities. The 42 system simulates all 6 degrees-of-freedom of the spacecraft, all sensors (coarse and fine sun sensors, gyro, and magnetometers) and all actuators including the reaction wheels and the torquers. All ACS Modes (Table 1) were verified by using the independent, software-only spacecraft simulator. The use of a software-only simulation as opposed to a flatsat to validate the FSW was also a deliberate deviation from how GSFC typically develops FSW, in order to reduce cost. In addition, because of Dellingr's size, end-to-end verifications were performed for all sensor/actuator pair (see Figure 10), something usually done in piecemeal for larger spacecraft.

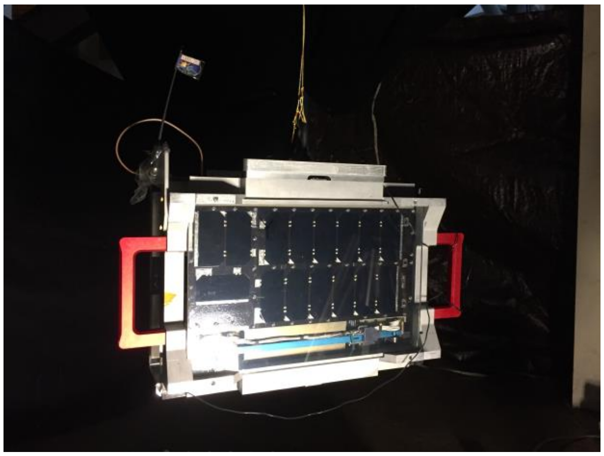

Figure 10: Dellingr underwent a hang and spin test, where the Sun sensor-to-reaction wheel implementation was verified and validated on the ground; something we are not be able to do on larger spacecraft.

The Fine Sun Sensor (FSS) was developed at GSFC and designed to provide high-accuracy Sun orientation readings for a CubeSat with minimal resource impact (15 g, 54.5x32.3x6.4 mm, 0.25 W peak). The FSS is mounted directly to the solar panels, meaning the only required internal space is for harnessing, and has a field-of-view of ±60° relative to normal. The sensor features an onboard microcontroller to reduce the calculations required by the flight processor. Use of custom components was minimized in the design to keep the cost of production low. The FSS uses a four-quadrant photodiode to measure shadows cast by a cruciform shade running between the quadrants (see Figure 11). The relative proportion of each quadrant that is illuminated is unique for a given orientation relative to the Sun. Using the ratio of the difference between solar flux on two halves over the total sum of the fluxes on all four quadrants, a two-axis orientation relative to the Sun is computed. Testing shows the 3-σ uncertainty ranges from about 3 to 30 arcminutes over the field of view of the four sensors, better at larger solar angles, with an average just under 11 arcminutes.

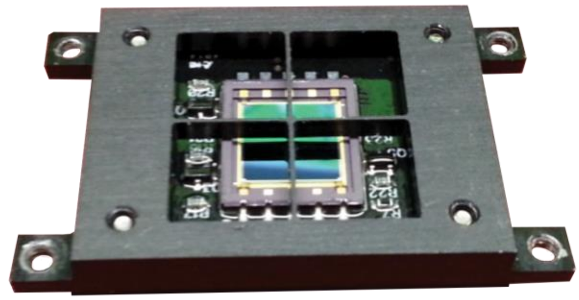

Figure 11: FSS has a thin form factor allowing direct mount to the solar panels.

Communication

Dellingr uses an L3 Cadet-U radio for RF communication and primary storage for Satellite telemetry and science data. The Cadet-U radio is a half-duplex UHF transceiver with downlink speed of 3 Mbps. The radio interfaces with the Nanomind through a 57600 baud serial port. Its storage area is divided into HIGH-FIFO (smaller size) and LOW-FIFO (larger size). Dellingr used this feature to store the most recent housekeeping data in the HIGH-FIFO memory while saving the rest of telemetry and science data in LOW-FIFO.

Command and Data Handling (C&DH)

Dellingr uses a GomSpace NanoMind A712D as the flight computer. The GomSpace NanoMind consists of an Amtel ARM microcontroller that runs at 40 MHz, 2 Megabytes of SRAM, and 8 Megabytes of flash memory. The NanoMind interfaces with each subsystem, sending commands and collecting telemetry that the NanoMind then processes and sends to the radio as needed. The ACS algorithms are also run on the NanoMind.

Several communication buses are provided by the NanoMind, including I2C, SPI and three UARTs. These are further supplemented by the Special Services Card (SSC). The SSC provides additional Analog-to-Digital (A2D) inputs, General Purpose Input/Output (GPIO) pins, and additional UARTS.

The NanoMind was delivered with firmware that included the FreeRTOS real time operating system, a complete set of device drivers for the communications buses, and a diagnostic shell. The GomSpace Diagnostic shell was utilized as a framework for diagnostic tests, allowing hardware checkout and aliveness tests to be run without reloading the software.

The devices on the spacecraft implement a wide variety of command / telemetry formats and communication protocols of varying levels of complexity and robustness. A team member would "own" all tasks related to each device including testing the component, resolving issues, writing the software library, aiding in its integration, and working on related ground software such as telemetry pages.

The I2C and SPI buses are shared between multiple devices which caused some issues during integration and design changes. Some of these were expected, such as I2C bus capacitance changing with the addition of more devices and bus contention. Others were unexpected such as an I2C device that would disable the entire bus when turned off and another device which would in certain circumstances take 10x the expected amount of time to return telemetry. In general, sufficient time was allocated in the schedule to deal with these issues during integration.

Flight Software

Dellingr makes use of NASA's cFS[5] as the basis for the flight software. CFS is an open source framework and set of applications designed for and used on flight projects, including the Lunar Reconnaissance Orbiter, Global Precipitation Measurement Mission, and the Magnetospheric MultiScale mission. For use on Dellingr, cFS was ported to FreeRTOS and the NanoMind flight computer. Using cFS provided a base of flight-tested functionality including a publish / subscribe message passing framework, spacecraft event reporting, relative and absolute time sequence commands, modifiable tables, a robust failure detection and correction framework, and fine grained control over scheduling. The portable nature of the cFS framework allows for the creation of portable flight software libraries and applications.

In addition to the reusable cFS framework and applications, Dellingr has several mission specific applications such as the ACS, Spacecraft Housekeeping (SHK), instrument interface applications, and radio control applications. To facilitate portability and simulation, low level hardware interfaces are segregated into a library. By using the cFS and the hardware interface library, developers were able to run the Dellingr Flight Software on a Linux workstation for rapid development and testing. The hardware interface library also served as the interface to the "42" dynamic simulator, allowing the ACS software to be debugged and validated.

Failure Detection and Correction

Dellingr is a low-cost single string CubeSat, therefore, failure detection and correction (FDC) has a limited ability to correct faults. All FDC testing was done on the flight unit as there was no other test platform available. The lack of a flatsat precluded the injection of potentially hardware damaging errors in order to test the FDC. Therefore, the Dellingr FDC focused on monitoring for faults that could be corrected, and these faults would be tested on the flight unit. The Dellingr FDCs that passed this philosophy fall into four broad categories.

1. Category 1 is things that should have happened but didn't. FDC monitored for the antenna and boom deployments, and if not successful, command the deployment sequence to start again.

2. Category 2 is invalid configurations. FDC monitored for proper configuration of radio authentication. Also FDC monitored for proper battery heater control setting.

3. Category 3 is critical errors that should not happen. FDC will reset the radio or reset the spacecraft if no communication with the cadet radio from the NanoMind occurs. Also FDC will reset the spacecraft if unsuccessful communication with the reaction wheels occurs.

4. Category 4 is invalid state information. FDC will command the spacecraft to safe mode, the lowest power mode, if a low battery voltage threshold is reached.

The FDC were all implemented in the Limit Checker (LC) application and Stored Command (SC) application. The LC and SC applications are reusable with mission defined configuration tables. The LC and SC apps have a four step process to detect and correct faults.

1. The LC watch point table defines which telemetry points to compare to a limit which results in a true or false result, neither of which is necessarily good or bad.

2. The LC action point table then combines one or more action points together using logical "or", "and", and "not" operations to determine if a fault is happening. In this case true defines a fault.

3. The LC action point table also defines a persistence which is how long the fault must be happening prior to starting a SC Relative Time Sequence (RTS).

4. Implementation of the SC RTS is a canned command sequence to try and recover from the fault or simply safe the spacecraft.

All FDCs were tested on the flight hardware and most were tested with the flight software. A few FDCs had to be tested with a modified version of the flight software to report the erroneous telemetry values.

Thermal

The thermal control system is a passive design relying on heat conduction from powered components into the common aluminum baseplate which radiates to space. The solar cells are body mounted on all of the sides, which means that the sides of Dellingr that view direct sun can get hot and not make for a good radiator. The interior surfaces were coated with low emissivity material to better protect Dellingr from getting too hot when the solar cells were pointed to the sun. The nadir pointing side was used as the baseplate and radiator since it doesn't get direct sun. The solar cells on the baseplate side are high emissivity, and the exposed metal was coated with high emissivity Teflon impregnated anodize. The baseplate was designed to be higher in mass than required by structural analysis in order to dampen the transient temperature swing during low beta angles when Dellingr is going from full sun into eclipse behind Earth.

The thermal limiting component was the batteries, with flight allowable temperature limits of 0°C and +45°C. Radiator area was adequate to keep them from reaching the 45°C hot limit. The internal battery heaters have sufficient power to overcome the rapid cooling that occurs when going into eclipse.

The L3 Cadet radio produces a hot temperature concern since it dissipates a total of 10W when it transmits during a 10-minute pass. To mitigate this problem, the radio was mounted on the housing with the use of NuSil thermal interface material to enhance the thermal path and dampen the temperature spike when the radio transmits. In addition, FDC will preclude Lo-FIFO transmissions if the cadet radio temperature exceeds a certain value.

The magnetometer boom was anodized for high emissivity to avoid overheating during sun exposure. The magnetometer at the boom tip is lightweight and changes rapidly in temperature as the environment changes from full sun to eclipse. A tailorable emittance coating was manufactured with a low enough emissivity to slow down the temperature drop during eclipse and an even lower solar absorptance to slow down the temperature spike during sun exposure.

Neither component nor subsystem level TVAC testing was done except for release mechanism, boom and solar panel engineering units. A total of 8 thermal cycles were done at the system level. A variety of problems were found, and some components had to be repaired or replaced. A lack of component level testing precluded driving them to the qualification temperature levels since the batteries were limiting the temperature range at the system level.

Four thermal balance points were done. Since each side of Dellingr saw different sink temperatures for a particular orbit and no sides were insulated, the most appropriate way to run a thermal balance would've been to have different GSE test thermal zones looking at each side. Due to cost limitations, it was decided to use a two-zone approach where the baseplate saw one temperature, and the other 5 sides of the spacecraft saw a different one. Settings were tweaked to match both temperature predictions and heat flows. Thermal balance test results demonstrated that the system is safely running cooler than predicted, which is a more desirable and manageable situation than running warmer.

Additional experiment

For future CubeSat missions, thermal louvers could be a passive means of thermal control to stabilize internal temperatures. The Thermal Louver Experiment is intended to raise the TRL of an in-house GSFC development for this class of thermal louvers. As shown in Figure 12, the Thermal Louver Experiment consists of a single flap and bimetal spring combination thermally isolated from the spacecraft and monitored with both an infrared motion sensor for flap movement and a pair of thermocouples for temperature detection. At discrete times during the mission, ground commands will be sent to power on the heater. Experiment success relies on the spring heating up, resulting in the flap opening and triggering the proximity sensor.

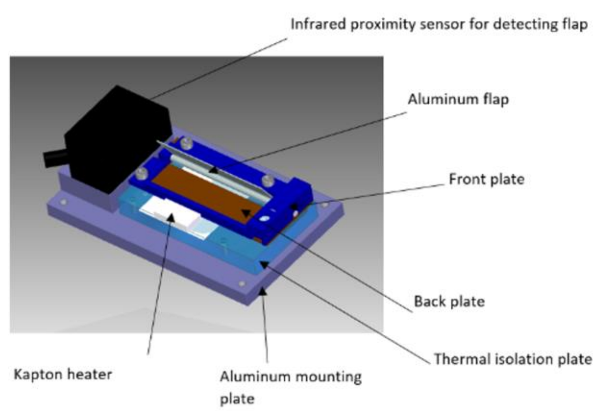

Figure 12: Thermal louver experiment.

Ground segment

Dellingr uses the Wallops Flight Facility UHF ground station and Goddard Space Flight Center mission operation center (MOC) for the entire mission (see Figure 13). The Integrated Test and Operation System (ITOS), originally developed for the SMall EXplorer (SMEX) program, is used for mission operation and ground control. All commands are initiated in ITOS from the MOC and then delivered to the Space Dynamics Laboratory TITAN ground system at Wallops to modulate and transfer to satellite. The satellite return signals are demodulated and, after a Forward Error Correction (FEC) decoding process, data is transferred to ITOS in a packet format. ITOS displays the latest housekeeping telemetry and stored science data for later processing and analysis by the science team.

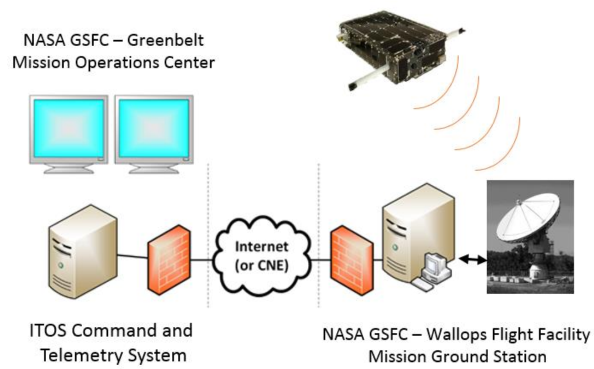

Figure 13: Dellingr ground system.

Integration and environmental testing

The Dellingr Integration and Test (I&T) process was loosely captured in five phases: Integration, Initial Testing, Initial Environmental Testing, Rework, and Regression Testing. This approach followed the “build, test and repair” philosophy in which many upfront analyses were sacrificed for good design practices with verification and debugging occurring on the back end. Component level testing was performed on only a few higher risk items. Prior to integration we tested the magnetometer boom (functional lab and TVAC), the release mechanism (vibe, functional lab and TVAC), solar panels (vibe, bend test, flash and thermal cycles) and UHF antenna (characterization test). Note that rework and regression testing were planned since inherently the testing was intended to uncover issues and reveal system behavior.

The first two phases, integration and initial testing, occurred simultaneously since verifications were needed at different levels of assembly. ACS component phasing, solar panel flash, harness continuity, battery heater checkout, EPS receiving inspection, and deployment mechanism tests were performed before these components were installed to the spacecraft. Lacking a flatsat for software developments, perhaps the largest I&T management hurdle during this phase was coordinating efforts among technicians while managing the configurations needed for the software developments. Additionally, a handling fixture was fabricated and implemented to reduce the risk of damaging a solar cell during normal lab activities and during transport.

Initial Environmental Testing consisted of magnetic checkout, vacuum deployment, end to end communication, vibration, and thermal vacuum testing. Magnetic checkout, performed in GSFCs magnetic calibration facility (see Figure 14), provided some confirmation of torquer phasing and also verified the spacecraft does not generate strong enough magnetic fields to affect the boom magnetometer. Due to chamber spatial limitations for the planned thermal vacuum test, a separate vacuum deployments test was performed in a chamber at WFF which confirmed the boom and antenna deployments at cold. End-to-End Communication Testing and subsequent tests verified the full path from the Greenbelt MOC through the WFF dish and ultimately to the spacecraft. A functional test was performed as a baseline prior to the 3-axis random (9.47 GRMS) and sine-bust (14.5g) vibration testing. A post-vibration functional test was performed successfully along with a visual inspection of the spacecraft with sine sweep verifications, confirming no structural changes occurred. Thermal vacuum testing was performed for 8 cycles, and, while largely successful, revealed hardware and software issues needing correction before flight.

Figure 14: NASA GSFC Magnetic Calibration Facility.

The rework phase addressed the issues uncovered during Initial Environmental Testing. Due to battery telemetry drop out and the solar panel short, the batteries and EPS card were removed and sent back to the vendor. Upon receiving the new EPS and using spare flight batteries, thermal vacuum screening tests were performed to verify component-level functionality. SPI & I2C signal integrity tests were performed to confirm bus implementations. Code updates corrected observed software issues. Upon reintegration of the spacecraft, another functional test was performed as the new baseline.

The final part of I&T consisted of the soft-stowed NanoRacks random vibration test (5.76 GRMS) and a two-cycle thermal vacuum test. The regression vibration test was performed in a spare flight deployer supplied by the launch provider, confirming the flight interface. Day-in-the-Life tests were performed during the regression thermal vacuum test which simulated on-orbit operations from initial ejection off the ISS to nominal science collection and potential failure modes. At the magnetic facility, final magnetometer calibrations were performed. Additionally, ACS sun-pointing was verified by suspending the satellite by a tether and observing the spacecraft orient itself toward the light.

The spacecraft was integrated to the NanoRacks flight deployer (see Figure 15) on May 31, 2017.

Figure 15: Dellingr in NanoRacks deployer during integration.

Cost and risk approach

Dellingr is classified as a sub Class D (NPR 8705.4) "do no harm" mission, with no formal quality assurance support. Consistent with this approach there was no adherence to typical Key Decision Points (KDP) or review gates. Instead, mission assurance was accomplished with "table top" peer reviews and selected analyses and simulations with acceptable fidelity as determined by the Project Manager (PM) and Mission System Engineer (MSE). Requirements were negotiated with the subsystems and instruments to achieve a feasible solution with a low resources environment; i.e., the project traded 'soft requirements' against capability and resource utilization, taking a 'design to cost' rather than 'design to requirement' approach. Peer reviews at the subsystem level were recommended but not mandated, dependent on the subsystem lead comfort level and expertise.

The project used COTS hardware whenever possible and appropriate, with extensive software reuse from previous GSFC flight projects. Limited spare flight hardware was available due to cost constraints. Component parts were of reduced quality/reliability compared to typical GSFC flight hardware, and commercial unscreened parts were acceptable. The project relied heavily on selective testing and minimized analyses in favor of a "build, test and fix" approach including environmental testing primarily at the system level only.

Lessons Learned

Dellingr delivered a wealth of knowledge and experience to the center. Some of the most notable are the need for a flatsat, harness mockup, baseline test of component hardware from vendors, I&T procedures and cubesat complexity.

1. FlatSat - Software effort could not continue to system integration until the flight system was assembled. This issue pushed the development risk later in the delivery schedule. This approach also put the flight hardware at risk while debugging hardware issues and disassembling the system. The PC104 card stack does not disassemble easily and, with repeated removal, can damage or wear out pin retention forces. Highly recommended are two sets of hardware of the critical avionic components where practical and saving one for final flight assembly.

2. Harness Mockup – A 3D printed or similar physical model is needed for wire harness development. Trying to produce the harness on the flight hardware adds risk of more handling issues. In addition, this harness development approach can be done in parallel to other activities to reduce the development schedule.

3. Baseline Component Testing – Component level performance tests should be completed before integration. A part of Dellingr's approach to reduce cost and schedule included only basic component testing/checks in favor of comprehensive system level testing. This decision was made with the assumptions that purchased hardware is tested by the vendor and is flight proven with sufficient documentation to proceed with minimal risk. System integration and system level testing revealed that such hardware did not operate as expected or as described in the manuals. In addition, performance numbers for the hardware

can be obtain that may be useful during I&T to diagnose problems.

4. I&T Procedures – Dellingr invested in detailed I&T procedures and documentation as part of the pathfinder approach. Documentation of test setup and results was useful as problems were encountered, recreating hardware performance timelines to identify when a system started malfunctioning.

5. CubeSat Complexity – Efforts between large and small spacecraft are analogous in regards to software, communications, ground system, and ACS, which is still fundamentally needed to perform the same functions with comparable analysis and testing.

Many of the lessons learned are old lessons relearned because basic best practices are universal in application regardless of the size of mission.

SUMMARY

Dellingr is already a successful project based on the original pathfinder goals. The Dellingr bus has evolved into a baseline for GSFC CubeSat developments by providing a customizable generic platform for near term CubeSat proposals as well as a starting point for the next generation of CubeSat buses. Additionally, the wealth of lessons learned will be applied to improve future CubeSat developments and extend into SmallSat missions. The Dellingr investment has expanded GSFC's expertise in CubeSats and is expected to enable high science returns for low cost.

REFERENCES

1. Li, X., et al. (2013), First results from CSSWE CubeSat: Characteristics of relativistic electrons in the near-Earth environment during the October 2012 magnetic storms, J. Geophys. Res. Space Physics, 118, 6489–6499, doi:10.1002/2013JA019342.

2. National Academies of Sciences, Engineering, and Medicine. 2016. *Achieving Science with CubeSats: Thinking Inside the Box*. Washington, DC: The National Academies Press. doi:https://doi.org/10.17226/23503

3. Solar Dynamics Observatory Guidance, Navigation, and Control System Overview, Wendy Morgenstern, Kristin Bourkland, Oscar Hsu, Alice Liu, Paul Mason, James O'Donnell, Angela Russo, Scott Starin, and Melissa Vess, AIAA Guidance, Navigation, and Control Conference. Portland, Oregon. 2011.

4. Stoneking, E., "42, Simulation for spacecraft attitude control system analysis and design," SourceForge [online database], URL: https://sourceforge.net/projects/fortytwospacecraftsimulation/

5. https://cfs.gsfc.nasa.gov/