CYGNSS Launch and Early Ops: Parenting Octuplets

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ABSTRACT

The eight micro-satellite Cyclone Global Navigation Satellite System (CYGNSS) constellation was launched on December 15, 2016. Each of the observatories carries a 4-channel GNSS-R receiver tuned to receive signals reflected by the Earth's ocean surface from which near-surface wind speed is estimated. The mission is focused on providing high temporal and spatial sensing of the wind conditions under and near developing tropical storms and cyclones. CYGNSS is studying the relationship between ocean surface properties, moist atmospheric thermodynamics, radiation and convective dynamics to determine how a cyclone forms, whether it will strengthen, and how much. A recap of launch and early operations is presented via a somewhat humorous analogy to parenting octuplets, with lessons learned included throughout. Topics include the roller-coaster ride of false labor (launch delays); the excitement of the birth, er, launch; the euphoria of seeing all eight μSats born alive and breathing; the adrenaline rush of saving one μSat born on life support; the total exhaustion that comes with round-the clock care and feeding; and the mixed emotions that come with "sending them out into the world" after a few weeks of doting over them to see them grow up and make their mark in the world.

CYGNSS OVERVIEW

The Cyclone Global Navigation Satellite System (CYGNSS) mission is designed to enhance our understanding of the coupling between ocean surface properties, moist atmospheric thermodynamics, radiation, and convective dynamics in the inner core of tropical cyclones (TCs). Near-surface winds are major contributors to and indicators of momentum and energy fluxes at the air/sea interface. Understanding the coupling between the surface winds and the moist atmosphere within the TC inner core is key to properly modeling and forecasting its genesis and intensification.

Improvements of 50% have been made in TC track forecasting since 1990[1]. Similar improvements have not been made in forecasting intensity with the cause believed to be in large part because:

- Much of the inner core ocean surface is obscured from conventional remote sensing instruments by intense precipitation in the eye wall and inner rain bands.
- The rapidly evolving genesis and intensification stages of the TC life cycle are poorly sampled by conventional polar-orbiting, wide-swath imagers.

CYGNSS addresses these two limitations by combining the all-weather performance of global positioning system (GPS)-based bistatic scatterometry with the spatial and temporal sampling properties of a constellation of observatories. CYGNSS provides surface winds in the TC inner core, including regions beneath the eyewall and rainbands that could not be measured from space previously due to attenuation and scattering by the rain and ice aloft. The CYGNSS wind fields, when combined with precipitation fields sampled as frequently [e.g., as produced by the Global Precipitation Measurement (GPM) core satellite and its constellation of precipitation imagers], will map the evolution of both the precipitation and underlying wind fields throughout complete TC life cycles. Together, they will provide coupled observations of moist atmospheric thermodynamics and ocean surface response, enabling new insights into TC inner-core dynamics and energetics.

The CYGNSS flight segment is composed of eight micro-satellites (µSats) in low-earth orbit (LEO) at an inclination of 35 degrees. Each µSat contains a Delay Doppler Mapping Instrument (DDMI), which receives direct signals from GPS satellites, as well as signals reflected off the ocean surface. The direct signals pinpoint the location of the µSat, while the reflected signals respond to ocean surface roughness, from which wind speed is derived. This signal scattering is analogous to the comparison of the moon reflecting off the surface of a smooth vs. wind-roughed lake. This concept is illustrated in Figure 1.

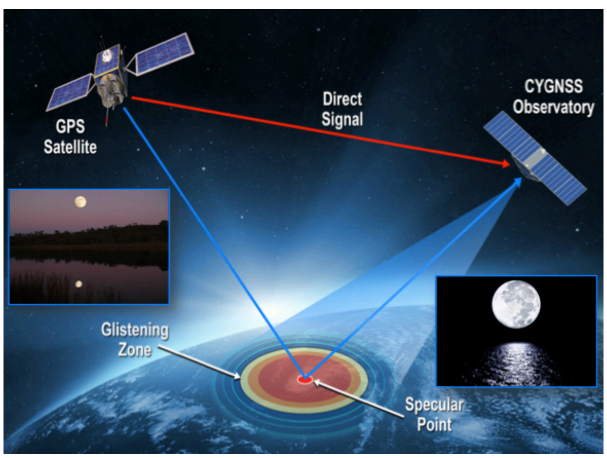

Figure 1: CYGNSS Reflectometry Concept

Signals are measured at 1 Hz, and each of the eight µSats is capable of measuring four simultaneous reflections, resulting in 32 wind measurements per second around the globe. This provides the ability to measure the ocean surface winds with unprecedented temporal resolution (revisit times in hours) and 25 kilometer spatial coverage under all precipitating conditions, up to and including those experienced in the hurricane eyewall.

The primary science product of CYGNSS is the Delay Doppler Map (DDM). Figure 2 shows an early DDM measured by CYGNSS. It is a map of the power in the GNSS signal scattered by the ocean surface after the signals are filtered by time delay (time difference of arrival between the direct and reflected signals) and Doppler shift (difference in frequency between the two signals).

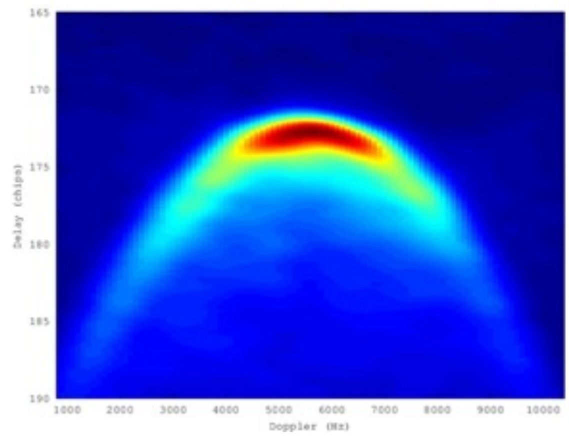

Figure 2: Delay Doppler Map (DDM)

Both delay and Doppler are varied across a range that includes the (delay, Doppler) coordinates of the nominal specular point with respect to mean sea level. Shorter delays generally correspond to locations above the surface; longer delays correspond to iso-delay contours on the surface centered on the specular point. Doppler values above and below that of the specular point correspond to iso-Doppler contours on the surface to either side of it. The DDM is therefore a map of the diffuse surface scattering in the vicinity of the specular point.

CYGNSS DEVELOPMENT

CYGNSS was selected by the National Aeronautics and Space Administration (NASA) as its first Earth Venture mission under NASA's Earth System Science Pathfinder (ESSP) program[2]. CYGNSS is a Category 3 Class D mission, and as such had a limited cost-capped budget and aggressive schedule, particularly for an eight-satellite constellation. The CYGNSS requirements phase kicked off in January 2013 and CYGNSS launched in December 2016.

To design a successful mission meeting these constraints, each CYGNSS µSat employs a simple design and is composed of five subsystems as shown in Figure 3. Each µSat is identical and operates independently of the others.

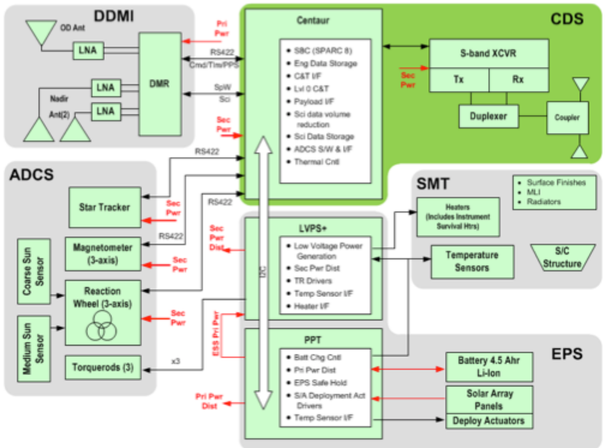

Figure 3: CYGNSS Microsat Architecture

Delay Doppler Mapping Instrument

The Delay Doppler Mapping Instrument (DDMI) is the sole science instrument on each CYGNSS µSat. Each DDMI is composed of a multichannel GNSS-R receiver, a low-gain zenith antenna for reception of the direct signals, and two high-gain nadir antennas to receive the scattered surface signals. Due to the large number of GPS-transmitting satellites, there are typically a number of specular reflections from the surface. Each DDMI selects the four specular reflections located in the highest sensitivity region of its nadir antenna pattern and simultaneously computes DDMs (see Figure 2) at 1 Hz, centered on each specular point over a 25 × 25 km^2 region. [3]

Attitude Determination and Control

The CYGNSS µSats are 3-axis stabilized spacecraft in LEO. Nominal Science Mode pointing is Earth nadir with a requirement of 1.3 degree pointing knowledge and 2.2 degree pointing control. Control authority consists of a 3-axis reaction wheel module, and three magnetic torque rods for momentum dumping. Sensors for attitude determination include a star tracker, magnetometer, medium sun sensor and coarse sun sensor.

In Safe Mode the µSat transitions to a slow-spinning sun-point attitude using only the torque rods for attitude control and the magnetometer and coarse sun sensor for attitude sensing. The ram and wake solar panels are also used as "coarse sun sensors" during sun acquisition.

Structural, Mechanisms and Thermal

The CYGNSS structure is composed of a machined aluminum core that provides the structural interface to the launch system and machined aluminum "spars" that support the remaining subsystems. Solar arrays are mounted on the ram, wake and zenith spacecraft surfaces with one-time-deployment "z-fold" solar array wings attached to and stowed against the zenith surface at launch. The solar arrays are stowed with cup/cone interfaces, and released with a combination of high-output paraffin (HOP) actuators and undamped single-axis spring-loaded hinges.

In the stowed configuration, each CYGNSS µSat measures less than 2 ft^2 and 1 ft tall. On orbit with solar arrays deployed, the length extends to over 5 ft.

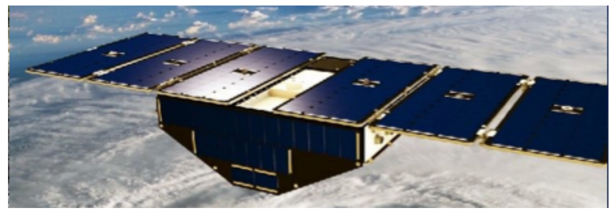

Figure 4: CYGNSS Microsatellite

One advantage of a small simple µSat is the ability to customize the design of the structure around the needs of the instrument, and to employ mass-saving approaches such as leveraging elements of the structure for dual-use. Both of these techniques were exploited on CYGNSS: the satellite core "box beam" also serves as the electronics enclosure; and the angle of the nadir-facing panels (see Figure 4) are at 28 degrees for optimal RF boresight of the DDMI high-gain antennas.

The resulting "wheelbase" of these configuration efforts leaves little room for traditional annular separation systems from the Deployment Module (DM), which is in turn mounted to the launch vehicle avionics. Instead, a segmented nut is utilized with a spring-loaded bolt as a low-shock hold and release mechanism, positioned within a three-point kinematic mount. The spherical posts, release nut and tunable pushoff springs are designed into the DM, with a triangular cone/vee receiving arrangement on the Nadir surface of each µSat.

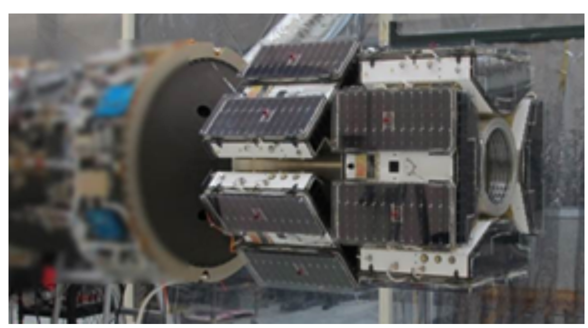

Figure 5: CYGNSS Flight Segment

Passive thermal control is accomplished for all inertial/power modes using a cold-biasing approach, with radiators and heaters sized to maintain hardware limits. Thermal stability is optimized without Multilayer Insulation (MLI), but rather by tuning of radiator surface treatments, to which components are conductively coupled (except the reaction wheel module which has an "inner loop" heater). Primary thermal loads are dissipated through nadir/zenith radiators. Five patch heaters were utilized for critical components, with control switches that feature commandable set points based on feedback from 11 (of 46 total) thermistors. Each Observatory is thermally stable in a stowed/sun-point safe hold configuration, as well as in the deployed/nadir-point science mode of operation.

Electrical Power Subsystem

The Electrical Power Subsystem (EPS) is comprised of solar panels, LiIon battery, a Peak Power Tracker (PPT), and low voltage power supply (LVPS). The main solar panel is deployed on the Z face of the spacecraft (nominally Zenith pointing) and produces at least 220W peak after deployment. There are smaller Ram and Wake panels that produce up to 30W peak each. The battery is a 4.5 A-Hr array of 3 parallel strings of 8 cells in series providing a nominal voltage of 33.6V to the EPS. The PPT keeps the battery charged by operating the solar arrays at their most efficient voltage for maximum power as sensed by a quick scan every 30 seconds whenever the array operating conditions shift. In flight, the team upgraded the flight software to use a Kalman filter to estimate the integrated state of charge of the battery and give controllers a more precise estimate of power available for operations.

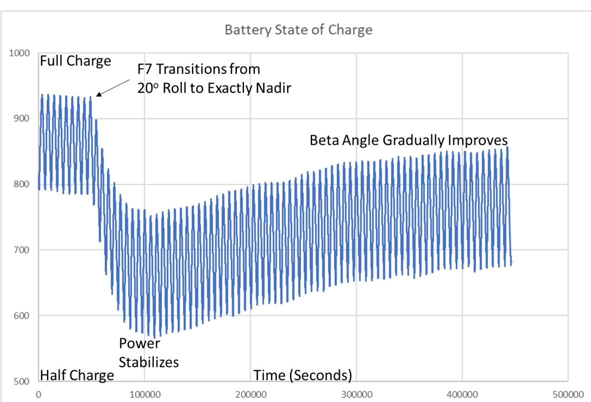

Figure 6: Battery State of Charge Profile

Communication and Data Subsystem

The CYGNSS S-band transceiver (Figure 7) provides a 64 kbps uplink and 4 mbps high-rate downlink and 64 kbps low-rate downlink.

Figure 7: CYGNSS Transceiver

Spacecraft command, data handling, science processing and attitude determination and control algorithms are performed by the Centaur processor board, which is composed of a LEON3FT scalable processor architecture (SPARC) V8 microprocessor, volatile (SRAM) and non-volatile (MRAM, Flash) memories for software and data storage, a field programmable gate array (FPGA) implementing a Consultative Committee for Space Data Systems (CCSDS) uplink/downlink interface to the transceiver, and various input/output interfaces to the science instrument, ADCS sensors and actuators, and the power and thermal subsystems.

The flight software (FSW) was developed in the C language, executes on the RTEMS (Real-Time Executive for Multiprocessor Systems) operating system, and is implemented in a layered and modular architecture as shown in Figure 8.

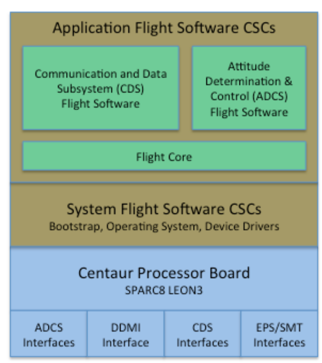

Figure 8: FSW Layered Architecture

Test Environment

Five sets of electrical ground support equipment (EGSE) were constructed to facilitate testing four µSats in parallel, as well as one to operate the engineering model (EM) µSat Test Bench which was used for FSW testing, to verify test scripts, and ground system updates before releasing it for flight model (FM) usage. Apache Subversion software (SVN) was employed to keep each station synched with a released master copy of ground station software and test scripts while maintaining the ability to develop and test updates on EGSE connected to the EM using SVN branches. The EGSE is composed of a Solar Array Simulator (SAS), Spacecraft Dynamics Simulator (SDS) for attitude simulation, a PCI eXtensions for Instrumentation (PXI) platform adapted to enable hardline communication and bypass ground inhibits, ITOS/Galaxy ground system for command and telemetry, NetAcquire for C&T protocol translation, and the GPS Signal Simulator (GSS) to stimulate the DDMI.

Attitude Determination and Control (ADCS) sensors and actuators were simulated via the SDS, in addition to models for dynamics, gravity, and environment effects. Pre-defined scenarios were used to simulate various on-orbit conditions, with the scenarios consisting of initial conditions coupled with scenario-specific fault conditions that could be injected. A unique FSW design approach was employed to enable "Component Mode" testing, in which the actual sensor/actuator component interfaces were exercised, and "Composite Mode" testing, in which all sensor/actuator I/O traffic was re-routed to a single EGSE interface. This latter mode was used once the flight sensors and actuators were installed on the FM µSats, precluding the connection of simulated components to the flight connectors[4]. This approach, coupled with strategically-placed EGSE connectors, proved to be very successful in enabling real-time closed-loop simulations even very late in the I&T program (even after mating with the LV if necessary).

Being a low-cost Class D mission, closed-loop stimulation of the real sensors and closed-loop verification of actuator response (e.g. via 6DOF platform) was not possible; these components and interfaces were verified individually via test and analysis. In spite of the detailed analyses performed, this deficit did prevent pre-launch detection of one reaction wheel polarity issue that was discovered during initial on-orbit checkout and quickly corrected via a table upload.

The SAS, SDS and GSS were not synchronized. This was an intentional decision driven by a cost/benefit analysis early in the project. In hindsight, however, the additional effort to synchronize those simulators may have been worth the effort. This is an important lessons-learned—make sure and include provisions for synchronizing simulators. Fortunately some "hooks" had been included in the SDS and GSS simulators, and those simulators were eventually synchronized to a limited extent. The lack of synchronization between the SAS and the SDS resulted in excessive reliance on a power supply (with solar array/EPS outputs simulated by the SDS) during otherwise flight-like tests and simulations. This approach allowed two latent issues to remain in the system almost until the moment of launch. One was discovered and corrected at the very end of the I&T campaign and one was discovered and corrected (via table load) just before launch.

Integration and Test

A near-complete EM µSat (Figure 9) was built for use as a risk-reduction pathfinder, and was then used later as the CYGNSS test bench for the FSW, system tests, and ground system development. Integration and initial tests of the EM µSat began in April 2014, and by October 2014 the EM µSat was fully integrated and went on to Electromagnetic Interference/Compatibility testing (EMI/EMC). An early prototype version of the FSW was developed to support this testing, which also included CCSDS commanding and telemetry (C&T). The commands and telemetry were defined in an Excel spreadsheet and used to auto-generate portions of the FSW. This same spreadsheet was then used to auto-generate the ITOS ground system C&T databases. This enabled full operation of the prototype EM observatory very early in the project, using the same ground system planned for flight (ITOS). As such, early I&T scripts were developed in the same STOL language that would later be used for FM I&T as well as on-orbit operations. By late summer of 2014 real-time science data was flowing end-to-end from the GPS signal simulator to the instrument, through the µSat and to the ground system.

The early EM µSat build-up was very beneficial as a mechanical pathfinder but introduced some undesirable decision-making drivers for some subsystems. Due to the very early development of the EM µSat, electronics and FSW, as well as C&T databases, were necessarily very early prototypes and required some non-flight workarounds and usage. There was a strong desire to make minimal effort when transitioning EM I&T scripts into FM scripts to adhere to Class D mission cost and schedule constraints. Inevitably, the approach resulted in an implied agreement to "live" with some of the de facto design decisions made during rapid prototyping that otherwise would have been changed and improved later. From a lessons learned perspective, when pushing hard for early integration milestones be sure to weigh not only the benefits of the effort but also the potential "indirect" risks that it might create and how to mitigate them.

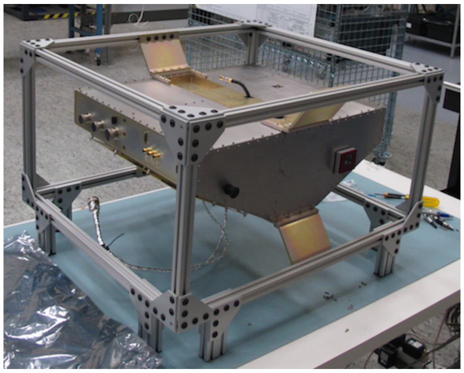

Figure 9: EM µSat (mounted in handling fixture)

Structural assembly of the eight FM µSats began in August 2015, followed by component installation and functional checkout through February 2016. The environmental test campaign was kicked off with EMI/EMC testing that was performed on only one FM due to similarity. Thermal vacuum testing was completed by testing four µSats simultaneously in a newly-developed thermal vacuum chamber (Figure 10). Final solar array installation and testing was completed in June 2016. The eight µSats were then temporarily mated to the Deployment Module for vibration testing (see Figure 11). The µSats were then shipped to Vandenberg AFB for final assembly, post-shipment testing, and mating with the Pegasus XL.

Figure 10: CYGNSS Entering Thermal Vacuum Testing

CYGNSS OPERATIONS APPROACH

The CYGNSS ground segment is composed of a ground data network, a Mission Operations Center, and a Science Operations Center.

Ground Data Network

The CYGNSS ground network is the Universal Space Network (USN), which operates ground stations around the globe and that are manned 24/7.

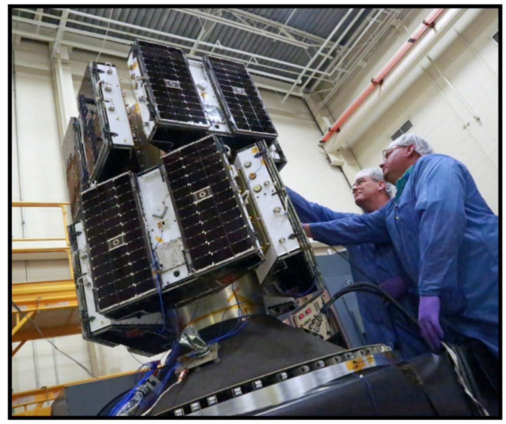

Figure 11: CYGNSS Stack in Vibration Testing

CYGNSS utilizes three of the USN ground stations: Hawaii, Chile, and Australia. During a pass, commands are transmitted from the MOC to the USN in real-time, and the real-time subset of engineering telemetry is also forwarded from the USN to the MOC during the pass. The bulk of the downlinked telemetry (science and engineering) is sent to the MOC after the pass has concluded. CYGNSS contacts last approximately 10 minutes.

Mission Operations Center

The Mission Operations Center (MOC) (Figure 12), located at the Southwest Research Institute in Boulder, Colorado operates the eight-spacecraft constellation. The core of the MOC is the Integrated Test and Operations System (ITOS) providing command uplink and telemetry downlink, real-time display, limits checking, and procedure scripting. Additional MOC functions include mission planning, orbit analysis, data processing and management, and a paging/alert system.

Figure 12: Mission Operations Center at Southwest Research Institute/Boulder

The MOC is designed to support contact with up to three µSats simultaneously, and is also designed to switch between µSats very rapidly. This latter capability was utilized early in the mission when the constellation was closely clustered together, as contacts would sometimes occur back-to-back. At one point during LEOps, two contacts in a row had been missed. Concerned that there might be a systemic problem with the constellation, the MOC successfully contacted five µSats in under 10 minutes on a single ground station.

During nominal mission operations, contacts with the µSats are conducted 'lights-out'; meaning contacts with the µSats are performed autonomously without a human operator in the loop. Without autonomous contacts, the MOC would have to be staffed continuously in order to take advantage of available pass times and downlink accumulated science data from all eight µSats. The automated passes are enabled via a program called Schedule Executor (SE) that runs ground-based absolute time command sequences (ATSs) known as SEATS files. These are analagous to the ATSs that are uplinked to the µSats and that define the onboard science observing sequences. The µSats are designed to playback telemetry stored in the on-board recorder autonomously during a ground contact. Playback and record pointers are maintained by onboard flight software, and telemetry can be retransmitted on request without affecting nominal playback cadence.

The MOC employs a Data Management System (DMS) that moves files automatically as they arrive in the MOC, and manages the movement of data through the various processing steps. DMS can also start processes automatically, so once the data is transferred to the MOC all steps in the process can proceed autonomously up to the point of data transfer to the SOC.

The level of autonomy implemented in the MOC is key to operating the eight µSats within the limited budgets available in this class of mission, and frees the MOC staff to concentrate on planning activities.

Science Operations Center

The Science Operations Center (SOC) (Figure 13) located at the University of Michigan in Ann Arbor receives Level 0 (L0) uncalibrated DDM data packets from the MOC and processes them into science data products. The processing includes L1 calibration of the surface radar scattering cross section, L2 estimation of the ocean surface wind speed and roughness, L3 gridding of the L2 products into wind field maps, and L4 determination of the size, structure and intensity of tropical cyclones. The SOC also performs comprehensive quality control and flagging of the science data products before posting them for public distribution by the NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC).

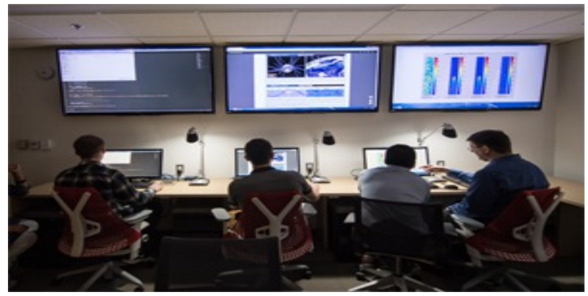

Figure 13: Science Operations Center at the University of Michigan

REARING CHILDREN: LAUNCH & EARLY OPS

The experience of launching and commissioning a constellation of eight µSats proved to have many parallels with raising children. Joy, excitement, anxiety, worry, exhaustion, and pride were all experienced by the CYGNSS LEOps team. And like children, the same eight µSats built and "raised" by the same "parents" somehow wound up with their own distinct personalities. In spite of their obvious similarities each µSat has to be dealt with, at some level, individually and uniquely. Further, it was hard not to play favorites. Some µSats were "loved" more than others—those that were trouble-free vs. those that misbehaved—and some, for whatever reason, seemed to get neglected from time to time, such as in the planning and allocation of ground contacts.

The next few sections recap the launch and early operations (LEOps) phase of CYGNSS, along the way providing additional analogies to parenting as well as more lessons learned for the benefit of those brave enough to have octuplets or more.

False Labor (Launch Delays)

Launch vehicle schedule issues and weather impacts contributed to the delay of the original launch date of October 17, 2016, first to November and then into December. Following a ferry flight from the Orbital ATK integration facilities at VAFB to the launch site at Kennedy Space Center, CYGNSS was scheduled for launch on Monday, December 12, 2016.

The Launch and Early Operations (LEOps) team began arriving at the CYGNSS MOC at SwRI's facilities in Boulder, Colorado on Saturday, December 10. The LEOps team was divided into two teams—Blue and Green—with the Blue team working the day shift and the Green team working the night shift. The early arrival at the MOC was scheduled to provide for final pre-launch MOC checks and to allow the Green team to begin adjusting to a night work schedule.

Adrenaline was running high early Monday morning as the Lockheed L-1011 Stargazer lifted off with the Pegasus XL carrying the eight CYGNSS µSats. The launch was aborted—more false labor—as failures onboard the L-1011 forced a return to the runway and an initially unknown launch delay as the anomalies were investigated and resolved.

As the issues with the L-1011 were worked at Kennedy, back at the MOC in Boulder the LEOps team determined to turn disappointment into additional preparations for the "arrival" of our eight living, breathing, orbiting cygnets. The team met and discussed what additional testing and analyses could be done with the additional two days we had been given, as a new launch date of Wednesday, December 14 had been announced. Tasks were handed out and work commenced. As evening approached, the Blue team handed the work off to the night-shift Green team.

Testing and analysis performed overnight on the EM µSat Test Bench revealed a previously-undiscovered issue that was determined to be potentially serious enough to warrant another launch delay. The issue fortunately had a straightforward solution via a table modification. The new table was immediately sent to the launch site, and a long day and night of more testing, another thorough scrub of every step in the power and boot-up sequence, and root-cause analysis were performed to obtain a green light for a Thursday launch.

Early Wednesday morning a telecon was held with NASA and the launch team at Kennedy, and the results of the 36-hour marathon test and analysis activities were presented. Satisfied with the report, the launch was again scheduled for Thursday, December 15.

After extensive testing and analysis, the issue that resulted in this last delay would almost certainly not have occurred at launch. Two lessons learned emerged from this experience. First, while some risk trades and sacrifices must be made in lower-cost missions, never stop testing and analyzing data; use every minute of every hour and look at every piece of data available—you never know what you might discover. Second, be willing to "make the call"—calling Kennedy where all the pre-launch celebrations were in full swing was a very hard call to make, but even in hindsight it was the right thing to do.

The Birth, Er, Launch and Deployment

The L-1011 once again lifted off on December 15, 2016, for a flawless launch and successful deployment of all eight µSats. After what seemed an interminable two hours, the first µSat passed over the USN-Hawaii ground station and lit up the screens in the MOC right on schedule: the first µSat reported in sun-pointing and power-positive! One down and seven to go.

Figure 14: CYGNSS Launch - December 15, 2016

Approximately 90 minutes later the second µSat followed her sister's lead and reported in on schedule and healthy. Now feeling confident, the LEOps team settled in for what was now hoped to be an "easy" day. Unfortunately the third µSat contacted (FM06) wasn't so cooperative; contact with FM06 revealed that it had not achieved the safe sun-pointing attitude, and its battery state of charge (SoC) was dangerously low and declining—one of our children was born on life support. Lesson learned: don't get cocky. The LEOps team spent the next 14 hours largely neglecting the other seven µSats (other than verifying that, fortunately, the remaining five were healthy) and working feverishly to save the one. "What do you think? If a man owns a hundred sheep, and one of them wanders away, will he not leave the ninety-nine on the hills and go to look for the one that wandered off?"[5] Fortunately, not long after the Green Team arrived for the overnight shift, CYGNSS FM06 came up in sun point with an improving battery SoC. Just like a parent, it is unlikely anyone on the Blue team would have gotten any sleep anyway without knowing their sick child had recovered!

As in other areas, the final analysis revealed some valuable lessons learned. The µSat born on life support had somehow wound up in a flat spin 90 degrees to the sun, resulting in a power-negative situation that the µSat seemed to be struggling to emerge from. The LEOps team worked diligently to analyze the very limited data available between ground contacts, and devise a set of commands to the µSat that we believed would force the µSat to acquire the sun. It was a race against time and power; the irony of this situation is that contacting the µSat results in additional power consumption (and so reduced SoC) due to the additional load of the transmitter, but not contacting it precludes attempts at saving it or checking its status. The first lesson learned is to trust your design. After all the analyses were in, indications are that the µSat may have found the sun a few orbits sooner on its own had no ground intervention been taken. Hindsight is 20/20, but it is important not to jump too quickly to the conclusion that intervention is required.

Interestingly, a similar lesson learned of "trust your design" showed up again later during commissioning. As the µSats began their transition from a safe sun-pointing attitude to the nadir-pointing science attitude, some on-board fault rules fired due to a combination of excessive conservatism in thresholds as well as unexpected on-orbit behaviors in some ADCS components that had little or no flight heritage (recall CYGNSS is Class D). Because the specific sequence of fault responses was different than what had been tested and observed pre-launch, it was initially believed that there could be flaws in the fault detection or responses. However, in every case, once all the data were downlinked and analyzed, the fault detection system responded correctly to the conditions.

The second lesson learned relates to statistics and preparedness. Most are familiar with the anecdotal definition of statistics.[6] Monte Carlo simulations conducted pre-launch revealed that the sort of scenario seen in FM06 occurred in roughly 1 in 3000 simulations. Nothing in the actual deployment data of FM06 revealed any reason that this particular µSat fell into the "trough"—no out of family deployment forces, no sensor failure—FM06 appears to have presumably been the "one in a million", so to speak. The lesson learned is to realize that statistics are just statistics—be prepared in case Murphy shows up.

Sleepless Nights

As any parent knows, caring for newborns is hard work and sleep is hard to come by—even more so when there are eight of them! The LEOps team was divided into a day-shift "Blue" team and a night-shift "Green" team. However the planned 12-hour shift (plus a 1-hour team handoff overlap) often turned into 14-18 hour shifts. This was due to a couple of factors:

- the excitement as well as the sense of responsibility the entire team felt made it difficult to walk away and get needed rest, and

- the same staff who were operating the constellation on-console were the same staff who were trying to analyze downlinked data between passes, develop and test any new command sequences needed, and investigate any anomalies that may have occurred.

As LEOps activities progressed into the second week, the physical and mental toll on the operations staff began to manifest itself in interesting ways. An entire room outside the MOC had been dedicated to the storage of provisions to keep the LEOps team fed and watered. A whiteboard was available where the staff could record special requests or make note of food or drink items that needed to be replenished. Initially the items listed on the whiteboard would include things such as dried fruit, crackers, Dr. Pepper, diet soda, etc. Later, however, the requests became markedly different. The first sign of possible distress was the appearance of Red Bull on the list, but a couple of days later someone put in a request for Kahlua, but then apparently changed their mind, marked through it and instead wrote "Everclear".[7]

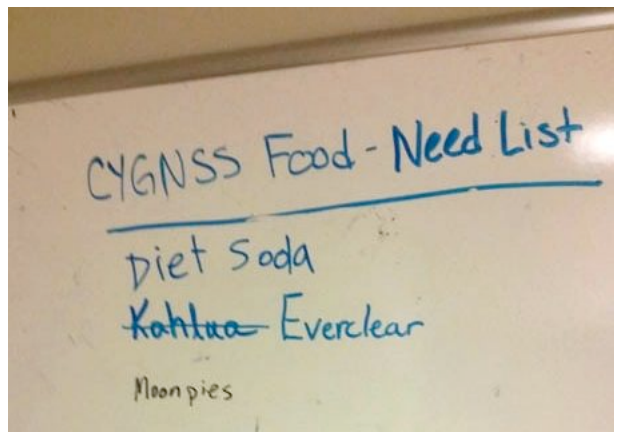

Figure 15: The Result of Long Hours

Other staff reported having difficulty doing simple math due to exhaustion, and one of the flight directors reported putting both contacts in one eye and attempting to put his shirt on his feet one morning—and that was after a landmark 6 hours sleep.

Wisely the team recognized the symptoms and, given that the Christmas holidays were at hand, put the µSats into safe mode and (other than periodic health and status checks) allowed the constellation to "coast" into the new year to provide time for the operations staff to rest and recover before proceeding with commissioning. It was with mixed emotions that the LEOps team departed the MOC—all were looking forward to getting some rest, but after doting over the constellation around the clock it somehow felt like abandoning your own children.

Implementable lessons learned in this area are somewhat hard to come by. Obviously a larger operations staff would have been beneficial. That is something that we (and our review board) could clearly see in advance, but issues of practicality presented difficult barriers. The primary impact is not really the costs that would have been incurred to have a third shift during LEOps: after all, the LEOps phase lasts only for a short period of time. Rather, the barriers include both the costs that would be incurred in training the extra team, and the need to find time in the schedule to give a third-shift team the on-console experience needed to ensure their confidence and competence in operating the constellation. That is a significant investment to make for a post-launch staffing commitment that will be needed for only a few weeks at most. Further, this in itself may increase mission risk as time given to a third-shift team would necessarily reduce the amount of on-console time available to the primary operations teams.

In hindsight the best approach would probably have been to terminate the 24x7 contacts much earlier. This lesson learned couples with another lesson learned stated earlier—trust your design. After a few days it was clear that aside from the initial post-deployment issue with FM06, all of the µSats were very stable, were operating completely as designed, and really did not require round-the-clock care and feeding. That is, the constellation was working very well and we could have taken advantage of that. Eliminating the 24x7 support would then have allowed one team to sit on-console, while the other team could respond to command uplink requests, analyze downlinked data and investigate possible anomalies. Additionally, as described previously the MOC was designed with the capability to operate passes autonomously. This capability was put into effect with great success over the holidays, but probably could have been activated up to a week earlier and used for the overnight status checks.

Sending Them Out To Make Their Mark in the World

Commissioning of the constellation commenced with the arrival of 2017. As in LEOps, the µSats performed very well overall as each on-orbit subsystem checkout and on-orbit functional test proceeded. The exhausting days and long nights began paying off as instrument "first light" data were downlinked from CYGNSS spacecraft FM03 on January 4, 2017.[8]

A number of lessons learned surfaced during the commissioning period. First, "identical" subsystems and µSats will have their own personalities—just like children do. During development it is easy to think (or hope!) that your mission or subsystem or component will be the exception; it won't be, so plan for it in processes, procedures, on-board table structures, etc. Think carefully about what will be personality-agnostic and what will or could be affected by variances among µSats. The CYGNSS team had already considered this during design; however personality-specific issues can sneak into unexpected places. For example, by design µSat-specific parameters were limited to and just two on-board tables, while relative time sequences (RTSs, or command macros) were intended to be the same across the constellation. During commissioning, the parameters to some commands unexpectedly wound up being µSat-specific. When that command is used in an on-board RTS, that RTS then becomes µSat-specific. As such, a thorough review of all command parameters should be performed for their *potential* to become µSat-specific, and in those cases consider redefining the command such that the parameter selects one of several table values (e.g. nominal value, safe mode value) rather than having the parameter value specified in the command itself. In the case of CYGNSS, the configuration management and compilation processes were readily updated to accommodate µSat-specific RTSs, and additional µSat-specific table values were added to a later FSW load.

An additional set of lessons learned relate to the use of limited-heritage components and fault management. As CYGNSS was a Class D mission, some cubesat/nanosat class ADCS components were included in the design that had little or no flight heritage. These components were also not radiation hardened, which was acceptable for the CYGNSS LEO orbit. However CYGNSS does pass through the South Atlantic Anomaly (SAA); as such both preventative operational considerations and on-board fault response rules had been put in place to handle radiation-induced faults. As CYGNSS proceeded through LEOps and commissioning, however, several on-orbit behaviors began to manifest themselves in these components that caused a number of fault rules to fire across the constellation, including a number of transitions to safe mode. It took a few weeks to determine the right mix of fault threshold tweaks and new autonomy fault rules that would effectively deal with these ADCS component "features" and behaviors, and then to get those changes deployed across the constellation.

The components that exhibited the unexpected behaviors are typically delivered by the vendor in an integrated solution, rather than as individual components as they were used on CYGNSS. One important lesson-learned is that subtle differences in application and use, and the potential implications, must be recognized and dealt with during development. In such cases, additional laboratory testing of these components should be scheduled, to include both nominal and off-nominal conditions, to characterize the devices and reveal behaviors that may not be included in component documentation and ICDs.

With regard to fault management, the combination of a Class D mission and an 8-µSat constellation presents some challenges in striking the right balance between simplicity, development cost, risk and constellation manageability. The CYGNSS design team spent considerable time analyzing potential faults and defining, in the form of a Fault Detection and Correction (FDC) Subsystem Description Document, which faults would have on-board autonomy responses and which would be deferred to ground intervention. In the end the CYGNSS FDC design demonstrated a conservative balance in that regard, once the issues related to the ADCS component behaviors were addressed, and some excessive conservatism in the at-launch fault thresholds was removed.

The first of the CYGNSS µSats began to emerge from planned commissioning activities in March. The ability of the CYGNSS constellation to track the development of surface winds in a major storm is demonstrated by preliminary measurements made during its flyover of Tropical Cyclone Enawo as the storm approached Madagascar with surface winds in excess of 100 mph.[9] Observations by the constellation on March 6, 2017, are shown in Figure 16. During the flyover, four of the eight spacecraft were operating in science mode and captured important elements of the size and structure of the storm. The other four spacecraft were completing engineering commissioning activities at the time. Those activities are now complete and all eight spacecraft are available for science operations.

CONCLUSION

CYGNSS is a mission of firsts: NASA's first Earth Venture mission, arguably the first Class D constellation mission, and the first mission and constellation fully devoted to GNSS-R. CYGNSS was launched on schedule and within budget, and all eight µSats are healthy and fully operational. CYGNSS began regular delivery of science data products to NASA's public data distribution web site (PO.DAAC) on May 22, 2017.[9] The CYGNSS development program presented significant challenges and required many risk trades to be made along the way, and produced a number of lessons learned that will benefit future similar missions. The CYGNSS mission proved that it is possible to successfully develop, launch and operate a constellation of µSats on a limited Class D budget. As the 2017 hurricane season begins, CYGNSS is now on course to prove out a new technique for saving lives in the measurement and prediction of the strength of tropical cyclones.

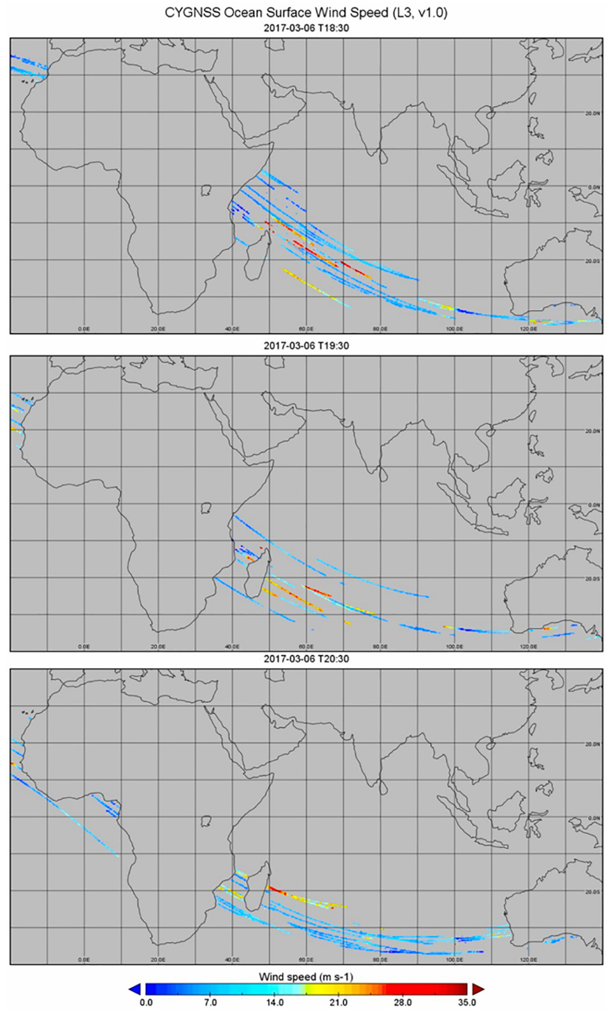

Figure 16: Hourly gridded measurements of ocean surface wind speed made by four of the eight CYGNSS spacecraft on March 6, 2017, as Tropical Cyclone Enawo approaches landfall on Madagascar. The times of the measurements, from top to bottom, are centered at 1830, 1930, and 2030 UTC.

Acknowledgments

The authors would like to thank our NASA sponsors who were so supportive and encouraging throughout CYGNSS development, integration and launch. Additionally, the extraordinary dedication and the very long hours contributed by the entire LEOps team is gratefully acknowledged. The CYGNSS LEOps team included the following (with sincere apologies to any that may have been inadvertently left off this list):

Jennifer Alvarez	Tonya Brody	Rich Cassell
Jed Diller	Zach Dischner	Anthony Egan
Steven Escobedo	Matt Fritz	Marissa Intellisano
Scott Gleason	Omar Granados	Alan Henry
Ronnie Killough	Robert Klar	Chris Mangels
Jacob McGee	Richard Medina	Scott Miller
Kyle Nave	John Noonan	Jon Van Noord
Susan Pope	Jillian Redfern	Debi Rose
Randy Rose	Chris Ruf	John Scherrer
Michael Shoffner	Keith Smith	Peter Tamblyn
Mark Tapley	Dirk Terrell	Steve Torno
Michael Vincent	Kerry Wahl	William Wells
Martin Wasiewicz	Terrance Yee	Kevin Zajicek

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