CYCLONE GLOBAL NAVIGATION SATELLITE SYSTEM (CYGNSS)

CYGNSS Lessons Learned (LL) Report	**UM Doc. No.**	**N/A**
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	Date	**April 2018**
	Contract	**NNL13AQ00C**

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REVISION NOTICE

Document Revision History		
Revision	**Date**	**Changes**
Rev 0 Chg 0	April 2018	Initial Release
Rev 0 Chg 1	April 2018	Addition of unlimited rights legend

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1. Introduction

This report was commissioned by NASA to document lessons learned throughout the mission development, launch, and operations (to date) of the Cyclone Global Navigation Satellite System (CYGNSS) mission. CYGNSS is the first Earth Systems Science Pathfinders (ESSP) Earth Venture Mission (EVM). It is one of the first NASA Class D missions, and is, to date, the only NASA science mission launched comprising a constellation of microsatellite class observatories. It is also led by a Principal Investigator with oversight, but minimum direct involvement, from a NASA Field Center. CYGNSS was launched on December 15, 2016 on schedule and under budget, and is currently operating successfully on orbit. Because of its unique programmatic and technical requirements and its successful implementation, CYGNSS provides an excellent opportunity for NASA and the community to learn from the experience gained during its development and operation. To that end, this report captures and disseminates CYGNSS' lessons learned, including what worked well and what didn't work well (especially in the context of a class D mission), to extend its role as a pathfinder for future low-cost science missions making use of emerging capabilities in the small satellite sector.

After describing the mission to provide context, the main body of this document highlights several major themes that surfaced during the compilation of individual, detailed Lessons Learned. While Appendix A provides the individual lessons in a standardized form (one per page), it is also available as a spreadsheet to facilitate filtering and sorting of individual lessons according to various attributes, such as priority or project phase.

2. Lessons Learned Study Overview

During CYGNSS' development and early operations phases, lessons learned were collected in an online database and presented at CYGNSS reviews and NASA forums. However, due to the unique aspects and success of the CYGNSS project, NASA requested a more in-depth lessons learned product that could be more useful to the community, involving a broader collection of information, formal report generation, and subsequent briefings. The CYGNSS team conducted several brainstorming sessions to identify topic areas that might include lessons not yet captured and encourage team members to add additional lessons after reflecting on their CYGNSS experience. Lessons were then formatted and organized for efficient sorting and filtering by users, and are now documented in this report. Most of these lessons still retain the "voice" of the individual that submitted the lesson. Some lessons may seem contradictory at times, but this was expected and reflects the various perspectives and expertise of the individuals who submitted the lessons. Lastly, the themes that emerged during the LL compilation are discussed in this report to add additional context and highlight big-picture and high-priority lessons.

3. Mission Overview

The CYGNSS constellation was launched December 15, 2016 on a Pegasus XL launch vehicle and comprises eight (8) 3-axis stabilized observatories that each hosts a single Delay Doppler Mapping Instrument (DDMI) as the only science payload. While the constellation is central to meeting science requirements, the individual observatories act independently of each other, with no need to synchronize with the other observatories. The primary mission duration is two years (after commissioning), with potential extended mission operations as warranted by the science data value and Observatory functionality.

3.1 Stakeholders

CYGNSS is sponsored by the Science Mission Directorate (SMD) and is part of the Earth Venture Program managed by the Earth System Science Pathfinder (ESSP) Program Office located at Langley Research Center (LaRC). The Principal Investigator is Dr. Chris Ruf from the University of Michigan (UM). The primary implementing organization responsible for mission/spacecraft development and mission operations is Southwest Research Institute (SwRI). Surrey Satellite Technologies (SSTL) developed the science instrument, and the Science Operations Center (SOC) is at the University of Michigan.

3.2 Mission Objectives

While significant improvement in Tropical Cyclone (TC) track forecasting has been made over the last few decades, improvement in forecast skill for TC intensity has lagged. The often-cited reason for this disparity is the lack of frequent and accurate observations of winds in the inner core of TCs. Existing satellite platforms are unable to make observations through regions of dense precipitation in the core of TCs and provide limited coverage and revisit time over the tropics. Aircraft-based measurements can penetrate dense precipitation, but are also very limited in their temporal and spatial coverage. In contrast, CYGNSS measures the ocean surface wind field with unprecedented temporal resolution and spatial coverage, under all precipitating conditions, and over the full dynamic range of wind speeds experienced in a TC. It does so by combining the all-weather performance of GPS-based bistatic scatterometry with the sampling properties of a microsatellite constellation.

Near-surface winds over the ocean 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 a TC is key to properly modeling and forecasting its genesis and intensification. CYGNSS measurements are yielding a critical data set that will enable science and applications users to better understand processes that link the ocean surface properties, moist atmospheric thermodynamics, radiation and convective dynamics in terrestrial water, energy and carbon cycles.

3.3 Project Milestones

Mission SRR/MDR	Jun 2013
Mission PDR	Jan 2014
Mission CDR	Jan 2015
Mission SMSR	Oct 2016
Launch	Dec 2016
Mission PLAR	Mar 2017

4. Spacecraft Description

4.1 Physical Description of a Single Observatory

Several views of a single CYGNSS Observatory are provided below with outer panels removed (Figure 4-2 and Figure 4-3) to show the internal configuration and layout of components. The only appendages are the deployable solar arrays (SA), and Figure 4-1 shows the transition from stowed to deployed. The final mass of each Observatory was 29.00 +0.00/-0.25 kg, which reflects an early decision to ballast observatories up to a fixed target of 29 kg to ensure a favorable CG location and limit uncertainty in various analyses. The Observatory coordinate system definition (Figure 4-4), the top-level Observatory block diagram (Figure 4-5), and the overall physical dimensions (Figure 4-6) provide additional context.

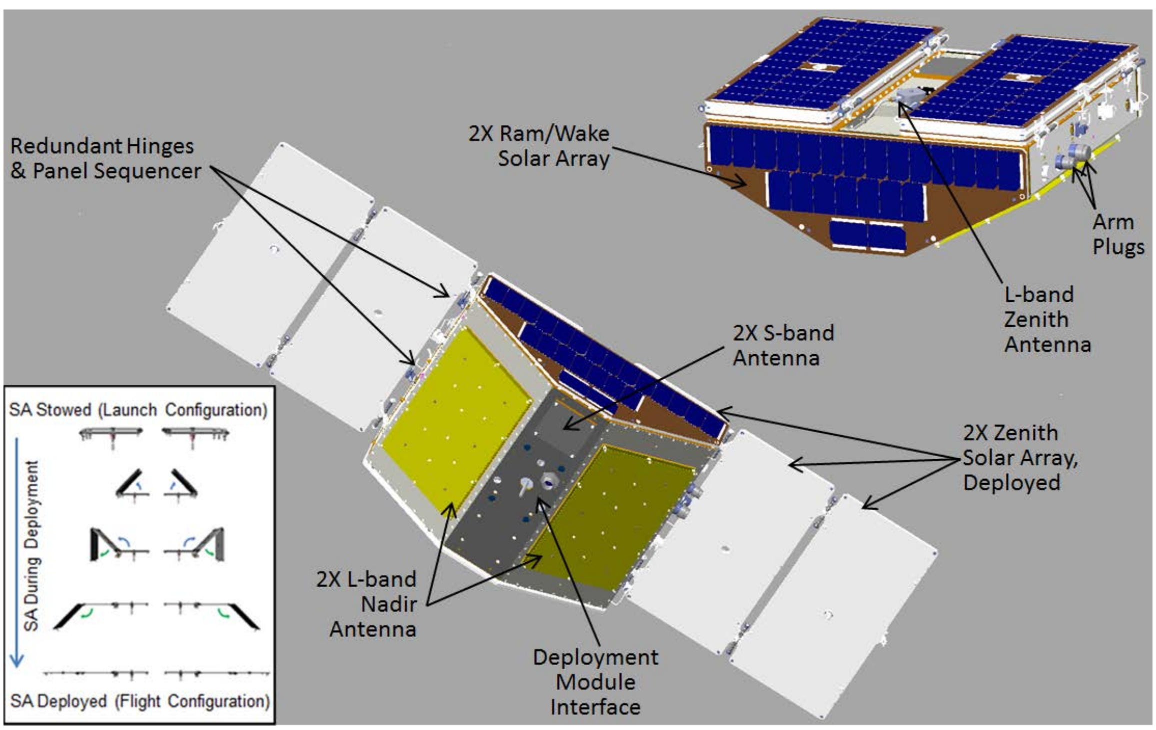

Figure 4-1: Stowed and Deployed Solar Array

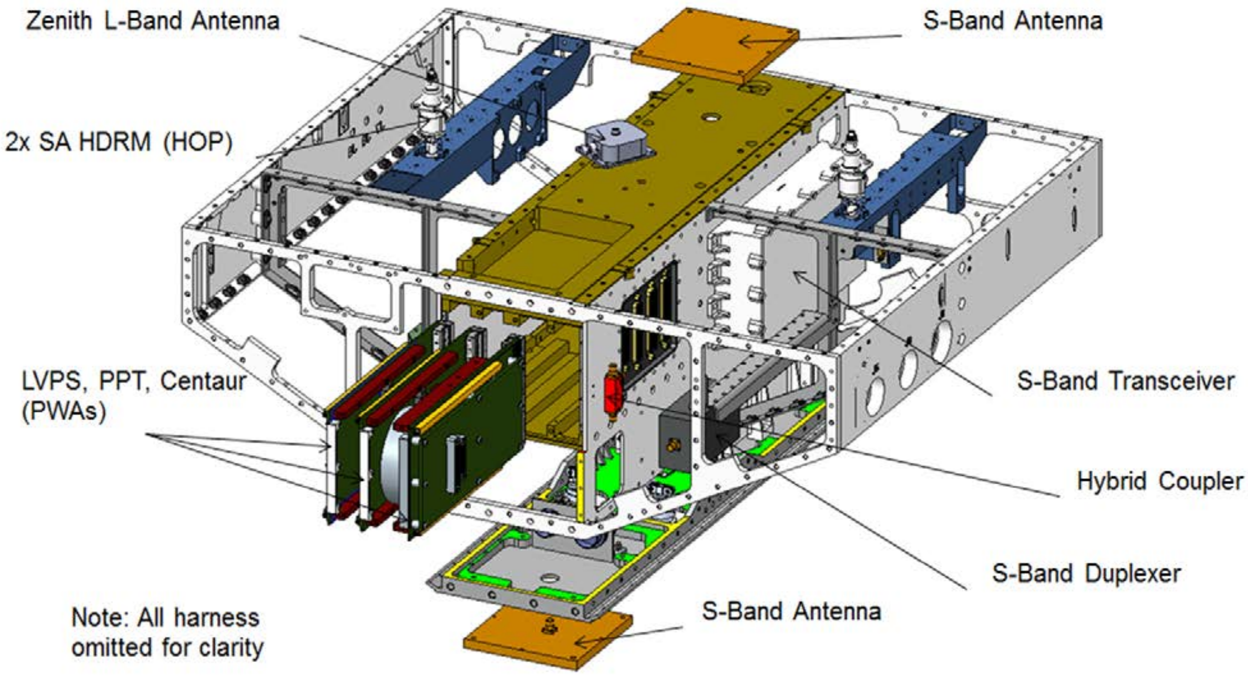

Figure 4-2: Observatory Configuration, Ram (+X) View

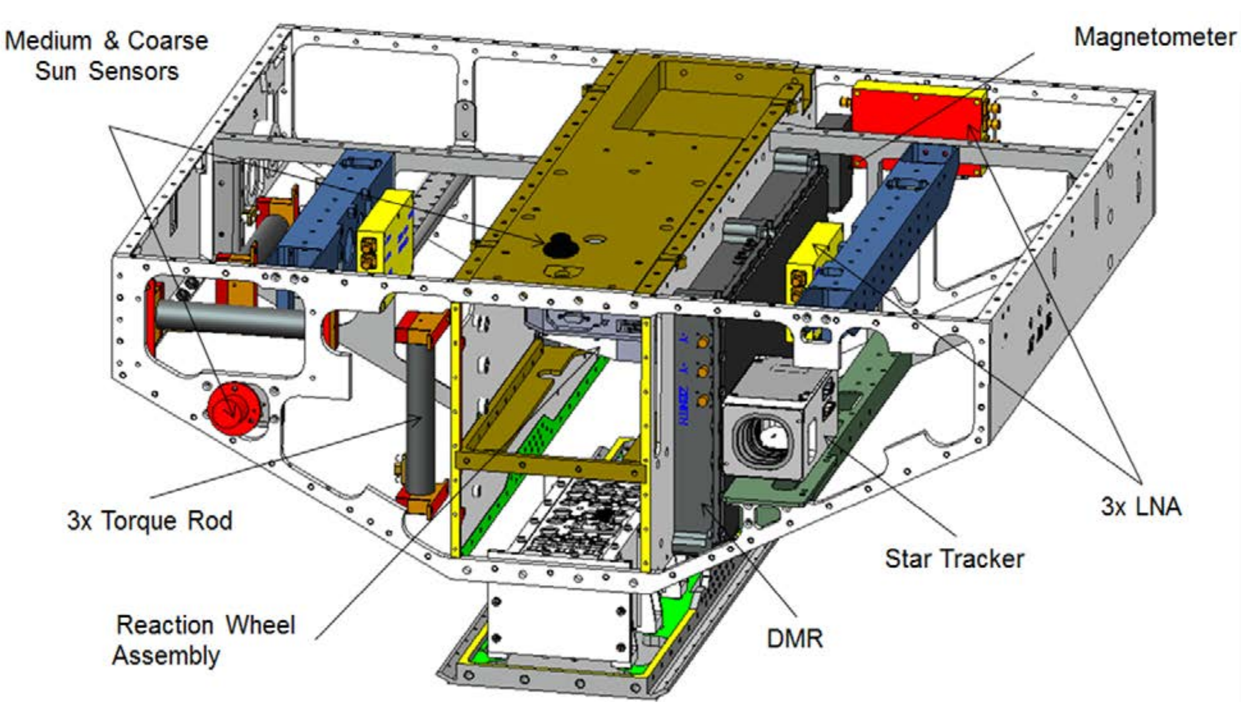

Figure 4-3: Observatory Configuration, Wake (-X) View

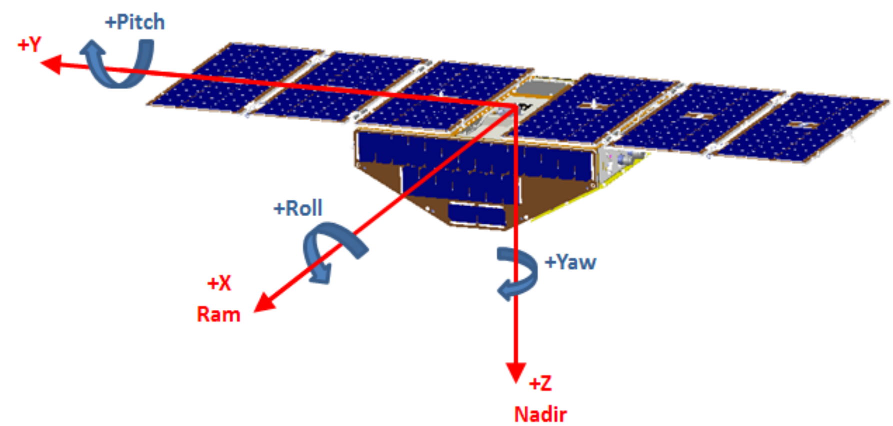

Figure 4-4: Observatory Body Frame Axes

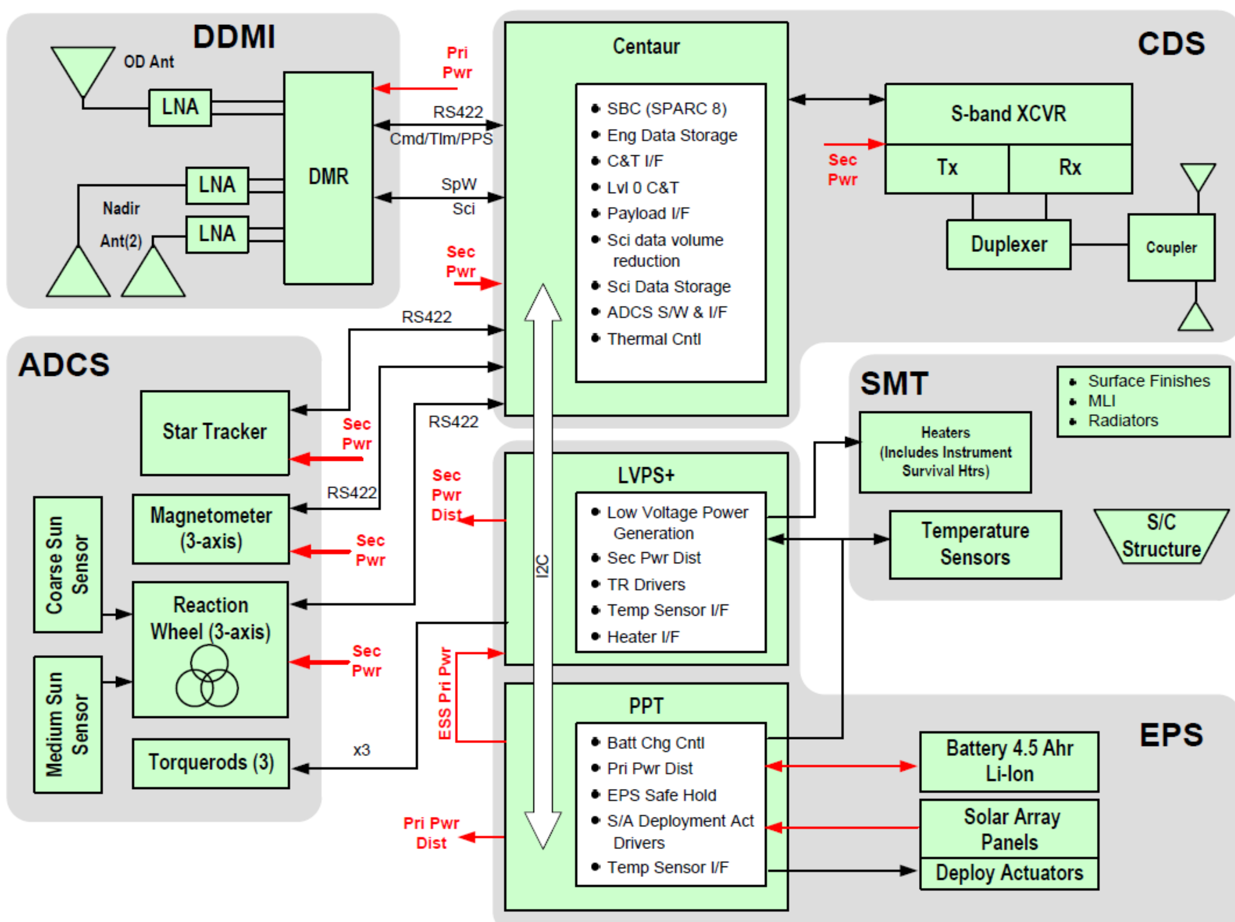

Figure 4-5: Observatory Block Diagram

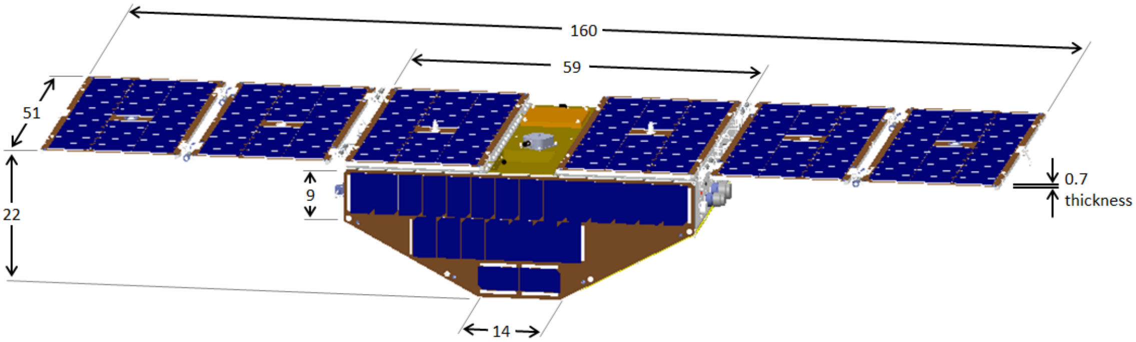

Figure 4-6: Observatory Overall Dimensions (cm)

4.2 Deployment Module and Launch Configuration

The CYGNSS Flight Segment (FS) comprised the 8 observatories attached to a Deployment Module (DM) for launch as shown in Figure 4-7. After insertion into the CYGNSS orbit the LV upper stage reoriented the stack to an attitude suitable for separation of the 8 observatories. The DM, using LV–generated, actuator-drive-electronics separation signals, separated the observatories in a pair-wise fashion with the observatories on opposite sides of the DM released simultaneously. Separating opposing pairs simultaneously limited the net attitude disturbance to the LV+DM stack from each of the four pair-wise separation events, reducing the burden on the LV Reaction Control System (RCS) with respect to recovering the nominal stack orientation between separation events. The DM itself never separated from the LV upper stage and was thus disposed of with the LV upper stage.

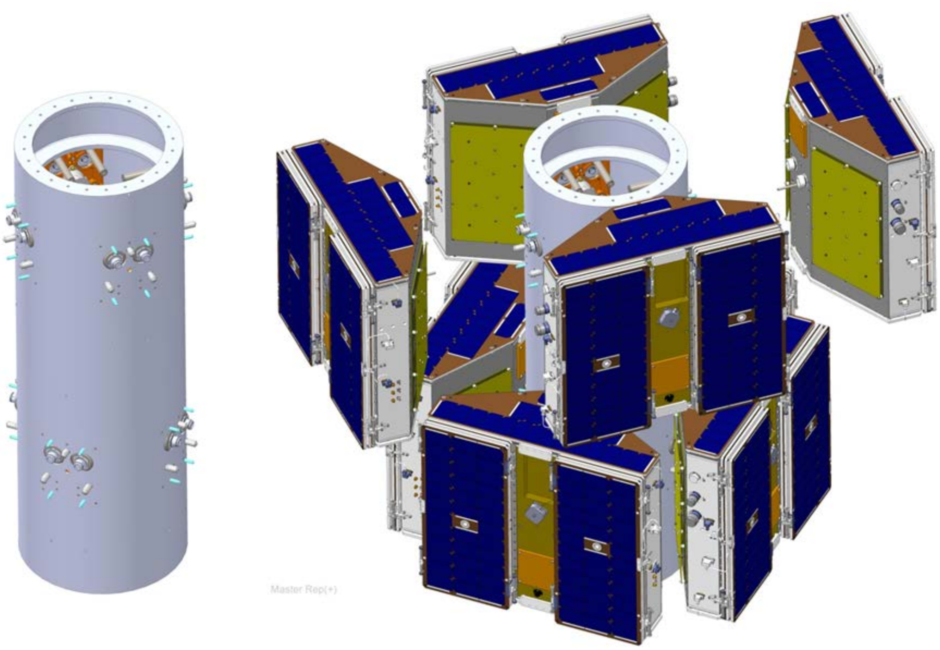
Figure 4-7: Empty DM and Flight Segment Launch Configuration

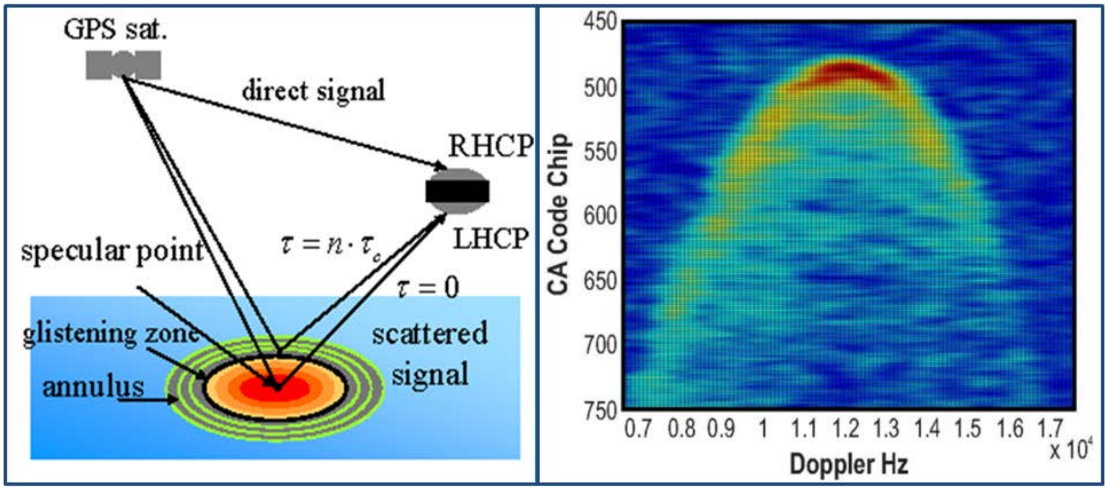

Figure 4-8: Delay Doppler Mapping Concepts

4.3 Science Payload – Delay Doppler Mapping Instrument

The Delay Doppler Mapping Instrument (DDMI) comprises the Delay Mapping Receiver (DMR), a single zenith-facing GPS antenna, two nadir-facing L-band antennas to collect reflected GPS signals, Low-Noise Amplifiers (LNA) for each of the three antennas, and all intra-DDMI RF cables and harnessing.

As shown on the left side of Figure 4-8, the DDMI receives both direct and reflected signals from GPS satellites. The reflected signals respond to ocean surface roughness, with the direct signals serving as a reference for the reflected signals as well as for pinpointing microsat geo-positions. DDMI onboard processing generates maps of the reflected GPS signals scattered from the ocean surface from which wind speeds are derived. These are referred to as Delay Doppler Maps (DDMs), as shown on the right side of Figure 4-8. The coordinates of a DDM are Doppler shift and time delay offset relative to the specular reflection point of the GPS signal. Each DDMI tracks up to four specular points simultaneously, automatically selecting the specular points that lie within the highest gain regions of the nadir-facing antennas. With eight observatories, 32 DDMs (thus 32 wind measurements) are produced every second around the globe.

4.4 Attitude Determination and Control Subsystem

The CYGNSS Attitude Determination and Control Subsystem (ADCS) is based on a standard nadir-pointing, 3-axis stabilized design. It uses a nano star tracker, medium and coarse Sun sensors, and a 3-axis magnetometer for attitude determination, as well as three reaction wheels and three torque rods for attitude control (torque rods also provide momentum management). Attitude maneuvers accommodated by this system include detumbling upon separation from the Deployment Module, high-drag pitch maneuvers for orbit maintenance, a Sun-pointing, safe-hold attitude, and the primary ability to nadir point during nominal science operations. Reaction wheel orientations provide pitch control redundancy to prioritize nadir pointing.

The CYGNSS Observatories spend the majority of their lifetime in the nominal science attitude with the Observatory +Z axis aligned to nadir and the Observatory -Y axis aligned with the orbit normal direction (Observatory +X axis lies in the orbit plane generally aligned with the velocity vector). To facilitate constellation maintenance and reduce the probability of collision with other space objects the Observatories occasionally enter a high-drag attitude by pitching the vehicle at -78° relative to the local horizontal to increase the drag profile of the vehicle by a factor of ~6. The Sun-pointing attitude was assumed for early checkout/commissioning operations and is available as a safe and stable attitude with large power margins in response to on-orbit faults that cannot be corrected without ground intervention.

4.5 Electrical Power Subsystem

The CYGNSS Electrical Power Subsystem (EPS) is responsible for power generation, storage, and distribution onboard the Observatory. The EPS consists of solar arrays (S/A) on three sides of the vehicle, the battery, and control electronics. The EPS uses a peak power tracking (PPT) regulator for battery charging and switching of +28 Vdc to spacecraft components. The PPT board matches S/A conductance to the Observatory load through pulse-width modulation (PWM) using an optimization control circuit that integrates S/A W-sec over a preset period of time. The PPT produces 28 ± 6 Vdc from a S/A voltage of 44 to 133 Vdc. The DC-DC converter output voltage is modulated by the PPT and battery charge regulator to meet Observatory load and battery charging demands. Electrical power storage for eclipse operations is provided by a single 4.5 A-hr Li-ion 8s3p battery connected directly to the primary power bus.

4.6 Communications Subsystem

S-band communication links provide uplink (Earth-to-space) of command sets and downlink (space-to-Earth) of science and engineering data. The S-band RF components include an RF transceiver module, duplexer, coupler, and two S-band antennas (one each located on the nadir/zenith-facing surfaces of the Observatory). The nominal high-speed data downlink rate is 4 Mbps in order to deliver 48 hours of science and engineering data in a single 500–second ground contact. The uplink data rate is 64 Kbps, and a low-speed 64 Kbps downlink rate is also available for times when an Observatory is in a spinning, Sun-pointed attitude. The ground segment uses three Swedish Space Corporation (SSC) (formerly Universal Space Network) ground stations in Hawaii, Western Australia, and Chile.

4.7 Command and Data Handling Subsystem

The command and data handling tasks on CYGNSS are a function of the Centaur board as shown in Figure 4-5. The Centaur receives science data from the DDMI over a high-speed SpaceWire interface; for the nominal "compressed" DDM science product, it performs windowing to achieve a significant reduction in data volume. Full DDMs, as well as raw Intermediate Frequency (I/F) data, can also be collected over targets of interest such as active storms. Four GB of onboard flash memory provides for storage of 10 days' worth of nominal science and engineering data, plus several days of high-cadence diagnostic engineering data (only downlinked when associated with anomalies or calibration activities), and a large allocation for special raw I/F or full DDM data collections.

4.8 Constellation Description

The CYGNSS orbit insertion targets are shown in Table 4-1 below.

LV performance was within tolerances, but resulted in a higher-than-target average altitude of ~530 km. The higher-than-nominal altitude combined with lower-than-predicted solar activity (thus lower atmospheric density at the CYGNSS altitude) has impacted the effectiveness of the aforementioned high-drag pitch maneuvers used to space the constellation. Therefore, it is taking longer than planned for all Observatories to match the lowest vehicle's altitude and establish fixed, equal spacing in true anomaly.

The goal is to establish equal spacing around the orbit at 45 ± 10° between adjacent Observatories. Thereafter, infrequent orbital adjustment maneuvers will be performed to keep the relative satellite spacing fixed. As of this report's release, four Observatories are located in their desired "slot" at the same altitude, with the other four still performing high-drag maneuvers (two Observatories at a time max) to lower their altitude and arrive at their optimal position in the constellation. Even without the optimal spacing, as long as adjacent Observatories are separated by more than ~10° in true anomaly, they are able to make fully unique observations.

Periodic maneuvers are also performed in response to conjunction assessment results from JSpOC that indicate a collision probability greater than the threshold defined by CYGNSS MOC requirements. Maneuvers occur as needed to decrease the probability of a conjunction below the minimum safety threshold (4.4E-4). After ~15 months on-orbit, the probability threshold has been crossed twice across the entire constellation. However, CYGNSS has taken action 5 times since a short maneuver performed early can sometimes completely eliminate a threat that has an increasing probability.

Table 4-1: CYGNSS Orbit Target/Tolerance Requirements

Orbit Target/Tolerance Requirements		
Parameter	***Target Value***	***3-Sigma Tolerance***
Insertion Apse (km)	510	+10/-15 km
Non-Insertion Apse[2] (km)	510	
Semimajor Axis (km)	6888.137	± 35 km
Inclination (deg)	35	± 0.25°

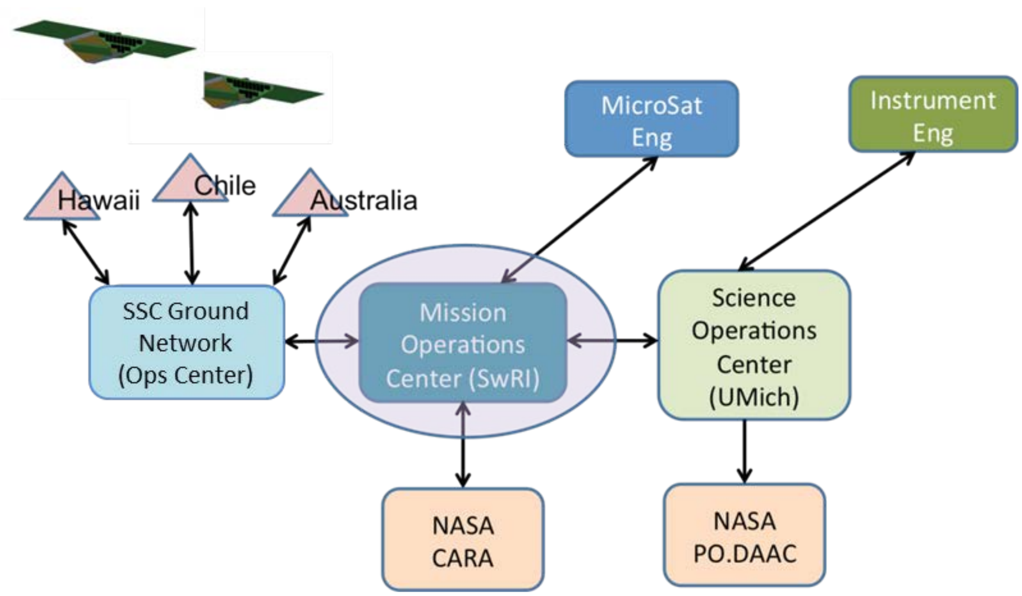

Figure 4-9: CYGNSS Ground Segment Overview

4.9 Ground Segment Description

Figure 4-9 shows the elements and interfaces of the CYGNSS Ground Segment. The SSC Space U.S. Network Management Center in Pennsylvania facilitates the command and telemetry links between the three remote antenna stations (Hawaii, Chile, and Australia) and the CYGNSS Mission Operations Center (MOC) located in Boulder, CO.

The MOC is responsible for the mission planning, flight dynamics, and command and control tasks for the constellation. SSC Space U.S. flows Observatory engineering data to the MOC in Real Time (RT) for use by flight controllers during ground contacts then delivers files containing back-orbit engineering and science data to the MOC shortly after each pass. The MOC processes, archives, and sends the data to the Science Operations Center (SOC). When gaps in the data are identified, the MOC generates replay requests to retransmit any missing data on a subsequent pass. The MOC also processes requests from the SOC to perform special raw I/F and full DDM collections over targets of interest. Thrice-daily reports from NASA's Conjunction Assessment Risk Analysis (CARA) group informs the CYGNNS team of potential conjunctions with other space objects. The MOC executes a high-drag maneuver (or exits high-drag attitude if already performing a constellation-spacing maneuver) when the risk of a collision for a CYGNSS Observatory exceeds the established safety threshold, and a maneuver is predicted to reduce risk.

The SOC generates instrument command sets for nominal and special science data collections and trends instrument performance based on the science data at a level beyond the MOC capabilities. The Level 0 science data and ancillary data are processed at the SOC to create all higher-level science data products. The SOC also archives all Level 0 – 3 data products, DDMI commands, code, algorithms, and ancillary data at NASA's Physical Oceanography Distributed Active Archive Center (PO.DAAC).

5. Description of the Individual Lessons Learned Fields

The CYGNSS team used the following definitions when generating the individual lessons learned.

Project Phase: Project phase(s) where the lesson learned should be applied/implemented. This is not necessarily the project phase where the lesson learned impacts the project.

WBS: Primary WBS that the lesson learned impacts.

Components: Primary component and secondary component that the lesson learned impacts. Note that some lessons learned will not impact any component directly (e.g., Earned Value Management) so no component will be checked.

Priority: Qualitative assessment of the importance of the lesson learned (Low, Medium or High). In general, High means "absolutely critical to the mission"; Low is "a good idea that would be nice to implement."

Big Picture Lesson Learned: Yes or No as to whether the lesson is a "big-picture" overarching lesson learned.

Lesson vs. Description of Driving Event: While there is no strict rule applied to these terms, "Lesson" is usually the lesson learned and "Description of Driving Event" is a longer explanation of that lesson learned. "Lesson" is typically a succinct description of the lesson learned. "Description of Driving Event" is a longer description of the reason behind the lesson learned and may include some driving event (e.g., Lesson Learned: we should have more closely studied the strength margin on the DM; Driving Event: failure during sine burst test). There may be no specific driving event, in which case the rationale for the lesson learned is included in the Description of Driving Event.

6. Big Picture Themes

6.1 Risks associated with Cubesat Vendors/Suppliers

Aside from its scientific successes, CYGNSS demonstrated the feasibility of developing, launching, and operating a constellation of at least eight microsatellites (microsats) even on a SMEX budget. The growth of the small-satellite ecosystem is not generally centered on microsats, but rather is most exemplified by the explosion in the cubesat market. As a result, most small-satellite component vendors are focusing their product development and marketing efforts on cubesats. Cubesats differ from other classes of small satellites in a number of areas, including expected performance and reliability. Since cubesats are on the least expensive side of the cost spectrum, it is not only accepted but expected that a cubesat can launch with components of little or no heritage, containing parts with little or no screening, with lower overall reliability than traditional satellite components.

This places other small satellite programs, particularly Class D microsat missions, in a sort of programmatic "No Man's Land": 1) budgets are probably too small to purchase higher-reliability components, if those components exist at all in a mass and form factor appropriate for a microsat; and 2) cubesat-class components probably will not meet parts, reliability and radiation requirements associated with NASA AOs and GOLD rules. If cubesat components are nevertheless selected for use via requirement waivers and/or referencing flight heritage, the components are still far more likely to exhibit undocumented and/or unexpected on-orbit behaviors than traditional components (LL-037). Including redundancy in the microsat design to compensate (where applicable) for these shortcomings is often not feasible due to conservative reserve-release policies (LL-004). (Note that in some cases, the use of mass or power margin to provide redundant components does not equate to "loss" of that margin – the mass or power could be recovered by removing the redundant part if a more critical need arose.) For certain types of on-orbit faults, using "higher-level" fault detection and correction logic in the spacecraft flight software can help mitigate problems encountered on-orbit[1].

[1] Killough, Ronnie, "Is On-Board Fault Management the Anti-Dote to Low-Cost/Low-Heritage Components in Small Satellites?", presentation at the Flight Software Workshop 2017, held at The Johns Hopkins University Applied Physics Laboratory, December 5-7, 2017.

Many cubesat components are produced by start-up companies that (from necessity) focus their efforts on their core technology, getting product to market, and simply reaching escape velocity—that is, surviving long enough for product sales and revenues to catch up with their investment. It is important to face the reality that some of these vendors may not be around when the microsat launches (LL-067) and address that possibility in risk management plans. Because these companies have small staffs, they may also lack the bandwidth to communicate adequately with their customers (LL-087). Engineering disciplines outside their core competency, such as software and firmware development, and support practices such as clear and correct documentation (LL-021) and sound configuration management, are often inadequate throughout the company's formative years. Similarly, design techniques common at larger companies (such as use of TMR in FPGAs for improved radiation tolerance, use of sync words and checksums in commands and messages, and inclusion of alignment cubes in designs (LL-090), etc.), may not yet be considered standard practice for these smaller vendors. Finally, engineering analyses may not be as thorough as might be reasonably assumed from a larger more established vendor, and/or those analyses may not be fully validated (LL-042).

Cubesat missions rely on very rapid assembly and production, therefore some cubesat products are more aptly described as a "subsystem in a box" rather than a "component," especially in regard to ADCS. This can introduce challenges in meeting at least the intent of some GOLD rules, such as using a minimum set of components in the implementation of Safe Mode (LL-036, LL-103). Additional challenges may also be encountered if a project desires to incorporate a subset of company's standard product — for example, individual ADCS sensors or effectors. When incorporated into the vendor's own flagship product, these components may be tested within that system and perform as expected — but adapting those components to a project-managed flight system can lead to more complexity and more engineering risk than would be expected from a traditional spaceflight component vendor.

A key lessons–learned theme from CYGNSS is the importance of creating a "vendor vetting plan" (LL-015). The vendor vetting plan should consider vendor "tenure" (i.e., how long the company has been in business), processes, and product maturity. Outputs from the plan would include the level of quality oversight, review, acceptance and post-delivery testing (e.g. LL-015, LL-021, LL-100) needed for each vendor. Updates to the project risk list and mitigations should also be performed following this assessment, including an evaluation of the vendor's "staying power" and plans for what to do if the vendor goes out of business. This may include ensuring that adequate spares are procured; non-disclosures signed providing access to (what would otherwise be) internal company documentation; and perhaps plans to hire the company's former employees as consultants if the company does not succeed.

6.2 Even larger, established vendors/suppliers may have issues

While "dealing with cubesat vendors and the uncertainty associated with them" is one major theme from CYGNSS' lessons learned effort, another theme is "don't just trust the vendor because they are large or have been doing this forever." This theme is not unique to Class D missions or constellations, but rather to all NASA missions. Of this type of challenge, CYGNSS faced: 1) a large institution increasing its cost of a critical subsystem by a factor of three; 2) another organization moving their fabrication facilities (but not personnel) from Europe to the U.S.; and 3) a manufacturer changing their materials in an off-the-shelf heritage component without notification.

When the institution tripled its cost, we quickly created an RFP and approached two other potential suppliers for the critical subsystem. The original institution was kept apprised of our plans and informed that the cost increase was unacceptable. ESSP and the CYGNSS PI were updated regularly as the process unfolded. In the end, the original institution lowered their cost but was still the most expensive of the three proposals we received so we informed ESSP of our intention to drop the original institution and use one of the new proposers instead. This overall process took about 2 months, but was necessary to maintain the budget of a cost-capped mission. For a project to stay within cost constraints, the PI/PM will need to make hard decisions that may involve kicking an established institution off the team if it is not performing. This applies to not only small, fledgling cubesat startups, but also to large, established vendors. The lesson learned is to do what is best for the project, even if it requires dropping an institution. (See LL-006)

The second issue CYGNSS faced with a large, established organization involved a foreign vendor trying to establish a presence in the U.S. using CYGNSS as its test case. The foreign institution, part of the CYGNSS team from the initial proposal, informed us that they were going to move the fabrication and test of the CYGNSS electronics to a new facility in the U.S. This immediately raised concerns, but with no leverage to prevent the move, we could only attempt to monitor the fabrication as much as possible. Ultimately, they skipped a key step in the fabrication process that left the flight boards suspect to potential damage to the parts installed due to moisture. The vendor admitted to violating their own fabrication procedures but refused to take any corrective action. Instead of bringing legal action to the supplier, we used project reserves (dollars and schedule) to have the vendor fabricate new flight boards. The lesson learned is that it is sometimes more important to use project reserves to ensure project success than it is to force a supplier to take responsibility for their errors. (See LL-038 and LL-027).

The third issue involves CYGNSS' coarse Sun sensors. The sensors were a COTS item from an established vendor with proven on-orbit performance. Soon after launch, we learned that the manufacturer had used a different material in the sensors, which degraded with exposure to UV light. We have seen degradation during CYGNSS operations but fortunately the rate has greatly slowed, suggesting that the sensors will likely be adequate for the life of the mission. It is difficult to summarize this experience as a lesson learned. We went with a proven component and vendor, received a materials list from the vendor that had the old material listed, and the delivered sensors were fully verified. There was no way that we could have known that the vendor's material list was incorrect. (See also Test Theme; though incoming tests would not have detected this).

In all three of these cases, the institutions involved were experienced with good reputations. The overall lesson learned is that issues occur with large, established institutions as well as small startup companies. Vigilance regarding EEE parts and processes and strict application of receiving test and inspections need to be applied to all component vendors (see also Test theme).

6.3 Constellations

The global coverage and sampling frequency that makes CYGNSS science so valuable is made possible only with a constellation of satellites. The earliest CYGNSS concept proposed to build and fly more than the eight observatories that eventually fit within the cost and schedule of an Earth Venture Mission. The feasibility for applications of small-sat constellations is rapidly increasing with more options for low-cost, low-mass/power, high-performance spacecraft components. While constellations offer many advantages (redundancy, temporal/spatial resolution, etc.) they present additional challenges and deviations from long-standing norms associated with large, single spacecraft builds.

Configuration management is an obvious challenge in building multiple spacecraft. In fact, just distinguishing any particular spacecraft from its brethren can become non-trivial (LL-068). The CYGNSS observatories accumulated a number of identifiers over the course of the project due to strong and varying opinions for naming conventions, with each group holding to its preference. It's easy to confuse FM-7 with 0xF7 (which is actually FM-1). Unfortunately, spacecraft numbering standards themselves require multiple S/C identifiers, but the choice of identifiers could have been better to avoid potential confusion if due consideration would have been given earlier in the project.

Most project tools/systems used for CYGNSS (configuration management, work orders, travelers, etc.) easily accommodated the constellation, but early decisions on how such tools are used can impact whether tracking configuration, build/test status, verification, etc. over the course of the project is intuitive or painful. The pros/cons of a particular approach may be different for the engineer, manager, or quality assurance inspector (LL-149). Considering the implications to all parties, and defining the approach early is important, especially when the spacecraft AI&T process starts to look more like an assembly line compared to a one-off build.

Automation also becomes more important as the number of space vehicles increases. This is true during AI&T on the ground and during on-orbit operations. The level of automation is often driven by comparing the net difference between time to develop the automation vs. repeated manual efforts. It usually doesn't take many repetitions before the automation stands out as the clear winner, and it often comes with the inherent benefit of reduced typos, omissions, and other human errors (LL-065). The level of automation can range from full-up, self-test certification of EGSE (LL-119) to simply modularizing test scripts for use across multiple tests. Even very small improvements can lead to significant savings in the long run (LL-030), and those are best implemented as early as possible to reap maximum rewards. It's easy to get stuck using an inefficient, repetitive process, assuming it's too much trouble to improve it. However, you may be underestimating how many more cycles you have. If it seems like a wash it's probably better to automate or improve efficiency; and sooner is better since changes maybe more disruptive once production is at its peak.

Simultaneous production of several spacecraft comes with inherent advantages and challenges. If a serial process gets stalled on one Observatory, it's possible to divert resources to the next Observatory in the queue to stay productive. Similarly, the flexibility to swap hardware between Observatories may allow an Observatory to move forward to the next level of testing quicker when an issue with a low-level component requires re-work. This flexibility makes for a very dynamic environment requiring rigorous configuration control and quick (re)planning. Careful consideration of GSE and personnel resources, both in number and capabilities, is needed (LL-041), and balancing the number of serial vs. parallel efforts is key to avoiding "log-jams" in the AI&T flow. Finally, keeping AI&T on-track is obviously important, but it shouldn't be at the expense of the quality of work, adequate review of test data, and timely paper work closeout (LL-113).

The constellation presents a whole new set of operational challenges after launch. By the time you talk to each spacecraft just once, you could have made significant progress checking out multiple systems on a single spacecraft. How to allocate ground contacts across the constellation requires careful planning, and the ability of each spacecraft to autonomously assume a safe, power-positive attitude is paramount (LL-061). It's likely that the entire constellation will be initially clustered together such that there are fewer possible ground contacts over a given duration compared to later in the mission after the constellation has spread out. Since every contact opportunity during LEOps is critical, there is little room for error (LL-096). Even with great planning and practice, LEOps will undoubtedly stress the team (LL-010, LL-018). If staffing operations 24/7 is required initially, it is better to limit the duration of 24/7 operations to the minimum required to ensure all spacecraft are safe and stable.

The MOC is likely to be quite crowded during LEOps with the operations team, subsystems leads, subject-matter experts, management, customers, etc. Many data displays are needed to provide real-time telemetry to all parties who need (and some who want) to see it. Different users need to view different subsets of the telemetry from the spacecraft, and the transition between viewing telemetry from one spacecraft to the next must be smooth to support the fast pace of contacts during LEOps (LL-063). These capabilities are also important later in the mission when there may be a desire to contact multiple observatories simultaneously. CYGNSS' use of fleet context in ITOS (aka Galaxy) worked well for this purpose, with the MOC hosting at least 10 virtual machines (VMs) running ITOS (for telemetry monitoring only, no commanding). As of this report's release, they are still in use, allowing support staff to establish a remote desktop connection to the VMs and view real-time telemetry during ground contacts even when they are not on-site at the CYGNSS MOC (LL-062).

After LEOps and commissioning, operating the constellation should settle into a more reasonable schedule. There are still challenges associated with maintaining many spacecraft, and there are no breaks. The theme of automation and efficiency applies to day-to-day operations at the MOC and SOC (LL-094). There is always pass scheduling (or re-scheduling) to work, science data to process, engineering data to trend, data gaps to identify, SOC requests to implement, all multiplied by the number of spacecraft in the constellation. The number of staff supporting operations is typically small, so automating the regular tasks to the maximum extent allows more time for investigating/resolving anomalies and other off-nominal tasks.

The theme of configuration management also persists during nominal operations. While all spacecraft in the constellation might, ideally, be identical, they will not be (LL-078). Accommodating the unique characteristics of each individual spacecraft is necessary, and mechanisms to do so should be set up early. ITOS fleet context in combination with unique spacecraft identifiers embedded in commands works well to ensure that uplinked commands are executed only on the intended spacecraft, but this in itself won't protect against sending the wrong parameter value. Careful tracking of all spacecraft-unique parameters and configuration settings is an ongoing task. Designing the ground system, spacecraft FSW, and operational procedures to inherently prevent confusing parameters, table loads, etc. between spacecraft is recommended (LL-059). Designing out the capacity for human errors to cause major problems is the best approach for avoiding mistakes that can and will occur, especially when less experienced staff may become operators later in the mission.

6.4 Systems Engineering Challenges and Successes

The most prevalent lessons learned in the area of Systems Engineering (SE) revolve around staffing levels, experience, and team communication/technical coordination (LL-026, LL-081, LL-087, LL-098). Consistent with a Class D mission budget, CYGNSS had a very lean systems engineering team that consisted of one Project System Engineer (PSE) plus discipline-specific SEs that served double-duty as subsystem leads with minimal additional SE support staff. It was thought that this arrangement would be advantageous from a communications perspective (fewer staff = fewer lines of communication). However, the CYGNSS SE team turned out to be too lean—both the PSE and subsystem leads were simply too over-tasked to consistently operate as an effective SE team (LL-005). This problem was exacerbated by two other factors: (1) the PSE is regularly pulled away for meetings with outside stakeholders and NASA mandated reviews (LL-069, LL-126), limiting availability for hands-on SE work and team communications, and (2) CYGNSS subsystem leads had limited experience (LL-003). This latter issue was partially intentional—it was thought that a Class D mission would provide a great training ground for up-and-coming engineering staff. However, a low-budget, small-team arrangement does not provide enough mentoring support for inexperienced staff (LL-011). While reducing the number of meetings and reviews the PSE must support will help, maintaining contact and relationships with program stakeholders is also important (LL-001). With no Spacecraft SE to look inward to the project, the PSE can become over taxed. In addition to avoiding an excessively lean SE team, it is also important to cross-train staff that can step in when key staff members are unavailable (LL-029, LL-151). Finally, participation of the PI in technical interchange meetings is vital. The PI must be able to provide real-time guidance in risk-related technical decisions, since decisions must be made and acted upon quickly on these quick-turnaround missions (LL-033). See also the "Project Relationships and PI Engagement" theme.

All missions must balance technical risk with technical reserves. However, small Class D missions require the PSE to design an Observatory subject to a higher level of risk than higher-class missions (and with a commensurately lower budget), while maintaining the same margin requirements of higher-class missions (LL-028, LL-118). This can force less-than-ideal technical decisions early in the program that actually increase risk, and many of those decisions are ones that can't be easily changed later in the development when reserves are allowed to be released. See also the "NASA 'standard processes' don't always reduce risk" theme.

Several technical lessons were learned during CYGNSS development. On the positive side, CYGNSS chose to build an early engineering model (EM) spacecraft that provided significant risk reduction (LL-060). However, it is important to clearly define, communicate, and stick to objectives to avoid "expectations creep" that can result in the introduction of new problems (LL-016). Another positive lesson was that good SE practices can and did result in smooth integration with minimal rework, despite the SE staffing challenges (LL-108). Areas needing improvement were either not intuitively obvious, or were unique to small satellites and/or constellations. For example, CYGNSS faced a number of unexpected challenges with separation connectors and tipoff rates (LL-086, LL-085, LL-115). Other lessons learned were agnostic of small vs. large spacecraft and constellations, such as the importance of a sound grounding design (LL-043), the need for thorough test planning (for completeness/validity and also for efficiency), and the requirements of the test system itself (LL-014, LL-020, LL-047, LL-097, LL-117, LL-136).

CYGNSS worked to optimize the design so that subsystems could be used to meet multiple requirements. This was successful in some areas (e.g., having the microsat bus structure serve double-duty as the avionics chassis to save mass); and less successful in others (e.g., use of S/A panels as additional coarse Sun sensors). When looking for these types of optimizations, it is important to assess the potential impact to requirements levied on the "double-duty" subsystem (LL-104).

In addition to these more significant technical lessons learned, a number of "motherhood and apple pie" lessons manifested themselves during the course of the CYGNSS program. These lessons include items such as being more thorough in configuration management planning (LL-124), the importance of early and consistent naming conventions (LL-031, LL-068, LL-099), lessons in requirements management and verification (LL-121, LL-046), and discipline in the peer review process (LL-025).

6.5 NASA "standard processes" don't always reduce risk

Over the decades, NASA has developed proven processes and procedures that enhance the likelihood of success. These are captured in NPRs (7120.5, 8000.4, 7123.1, 7150.2B, etc.), design principles (GOLD Rules, etc.), and in Announcements of Opportunity (AO). These documents specify items such as the required amount of margin and reserves, Earned Value Management (EVM) requirements, and the required mission reviews. The NPRs and design principles are largely agnostic to mission class: a class D mission has the same requirements as a class B mission for reserves, EVM, reviews etc. In principle some of this can be tailored, but tailoring takes time, and even when tailoring is complete, getting all of the various stakeholders on board takes even more time and can have an uncertain outcome. For small, fast-paced missions like Earth Ventures, some of these processes and procedures may, in fact, add risk rather than reduce risk. Some examples of this include:

1. Margin and Reserves requirements: Mass margin is a good example of a requirement that is potentially over conservative. With today's accurate 3-D modeling software, mass is much better known than it was just 10 years ago. Rather than have a standing requirement of XX% mass margin at Key Decision Points (KDPs), it might make more sense to base the requirement on the maturity of the system at that point in time. CYGNSS, like many missions, ended up flying a significant amount of ballast due to having to meet the conservative mass margin requirements. This mass potentially could have been used for other risk-reduction activities, particularly those that could only be implemented early in the design phase. Adding redundant components, for example, should be strongly considered early in the program even if this reduces mass or power margins below a traditional threshold. If a significant power or mass issue develops later, the redundant component can then be deleted to resolve the late-breaking issue, but the risk associated with the single-string component would be retired pending that development. Funding reserve requirements as specified in the AO likewise drove some early technical decisions away from a direction that could have reduced risk. If money had been spent earlier, a more robust technical solution may have been attained. (Note that spending reserves earlier is not a slam dunk on reducing risk. Reserves WILL be needed late in the project during integration and test). (See LL-118, LL-004, LL-028, and LL-105)

2. Earned Value Management (EVM) is a great tool that provides the project management team with early warning signs of potential schedule or cost issues. The process is valuable whether it is a Class B project or a Class D project. In particular, SwRI has been using some form of EVM on missions going all the way back to IMAGE and then IBEX. That said, the EVM process on those missions was much, much less cumbersome than what was required for was used on CYGNSS (and CYGNSS was not even completely ANSI compliant). While ANSI-compliant EVM is maybe slightly more accurate and better documented than "EVM-lite," it comes at a very large cost to the project. That extra cost is significantly more than the benefit. The use of EVM-lite is a much more cost-efficient process that provides all the benefits of the EVM as a management tool. (See LL-009 and LL-013)
3. An Earth Venture Mission (by definition) has a small team with little "redundancy." Per 7120.5, NASA now requires five specific Standing Review Board (SRB) reviews (this assumes that SRR and MDR are combined) with subsequent Key Decision Point (KDP) reviews. Between CYGNSS' SRB and KDP reviews, there was also typically a LaRC Center Management Council (CMC) review, a review and update of the Independent Cost Estimate (ICE), and most KDP reviews required several chart walkthroughs leading up to the KDP. The period from SRB to KDP was 6 to 8 weeks. While the post-SRB activities only impacted a small part of the mission team, all of these activities pulled, at a minimum, some percentage of the PI, PM and PSE away from project work for more than 2 months, including the lead-up to the SRB review (i.e., for CYGNSS, this amounted to ~10 months out of a ~41-month schedule). The lesson learned is that when establishing your project team, until NASA reduces the burden of all of these reviews, management team backfill will be required to keep the project moving forward. (See LL-126 and LL-069).

The above "NASA standard practices" do reduce risks on large NASA missions with big teams and long schedules. On small, fast-paced Class D missions, however, the impact of these "standard process" can be detrimental.

6.6 LV interface may be the toughest

At a recent Explorers Forum where PI's and PM's presented lessons learned from past missions, virtually every project commented that dealing with the Launch Vehicle interface took considerable effort. On CYGNSS, even with the project's great relationships with KSC and the launch vehicle provider, it took significant effort, which was grossly underestimated by the project even though the CYGNSS PM had relevant experience from a past project of similar scope. (See LL-024). The following are some likely complications to this interface:

1. Contractual reporting chain: Since the LV is contracted by KSC and (in the case of CYGNSS) the project was contracted by LaRC, official communication from the project to the LV goes from the project to LaRC, LaRC to KSC, and then KSC to the LV. This made communication difficult at best. It required the involvement of too many individuals, slowing the process of communication.

2. LV schedule and project schedule conflict: On EVMs, the LV is typically placed under contract after PDR, when the preliminary design is complete and approved. While the project tries to maintain compatibility to all of the candidate LVs, each LV is unique (i.e., fairing size, loads, integration requirements, etc.). If the LV team was involved earlier, the project and LV could work together to optimize the overall design. Similarly, the LV requires a test-verified finite element model (FEM) earlier than it is typically available. For the project to obtain a test-verified FEM, the flight segment must be subjected to vibration, which is usually after all flight hardware has been delivered and integrated. On fast-paced EVMs there is typically little time between the flight segment vibration test and launch, compressing the LV and KSC's time for coupled loads analysis. This issue is exacerbated as project schedules are shortened. (See LL-007 and LL-066).
3. There is currently no such thing as a Class D LV: While the spacecraft community has moved to various levels of risk and reliability, from cubesats (less than Class D) to Class A missions, the LV community has only recently developed low-cost LVs. This different risk posture can put the project at odds with the LV provider and KSC.

The complexity of the LV/project interface requires significant attention from a mission's engineering team and its project management, which will likely remain unchanged until contracting/scheduling differences are resolved.

6.7 Thorough Testing is Even More Important for Class D Missions

The new generation of microsatellites (microsats), and the growing popularity of using microsatellite constellations, faces strongly competing forces affecting the design and implementation of a mission's test program. First, cost and schedule are tightly constrained as the project attempts to put multiple copies of a new spacecraft design into operation on a funding profile originally intended to support only one copy of a derivative design. Second, narrow resource margins mean the microsats must be designed with a minimum of redundancy or excess capacity, which inevitably leads to innovative repurposing of systems and to the use of single systems to serve multiple functions (LL-104). The result is that the requirements on various subsystems can be very unique to the mission, may vary over the course of operations (LL-136), and time and money to develop verifications reflecting the unique requirements will be in short supply.

An additional set of complicating factors arises from the fact that solutions supplying the high ratio of performance to resources used are often new, high-technology developments provided by companies that are new to the spaceflight-supplier arena. To keep their component costs low, these companies may not apply the same level of rigor to their development, test, and documentation as traditional companies (LL-042). In an effort to compete on price, these vendors may also be over-streamlining their test and development processes. The microsat developer may be surprised to find that delivered components need a much more involved level of acceptance testing than they are accustomed to vs. what traditional Class C or better off-the-shelf components would require. This drives the test program in sometimes unexpected, but often important ways.

A large class of CYGNSS's lessons-learned stems from these factors. In a program environment like CYGNSS, it becomes absolutely essential that the end-to-end test strategy be planned, from program inception, as an integral part of the development process (LL-014 and LL-041). The CYGNSS team planned effective early steps, including prototype/EM spacecraft and a Structural Thermal Model (STM) to validate interfaces and mechanical/thermal design (LL-060 and LL-083). However the long-term functional requirements of these models were not initially appreciated (LL-016), and were therefore repeatedly extended and modified. Particularly in the ADCS test environment, there were some great successes (LL-097 and LL-091) and some serious shortcomings in the original planning (LL-047), which led to re-design and stop-gap measures late in the program (LL-079), and to some issues being overlooked entirely (LL-084). A particularly thorny area was the means of "closing the loop" so that ADCS effector outputs fed back to sensor inputs in a way realistic enough to thoroughly test the flight hardware, software, and algorithms (LL-137). In addition, nearly all of the planned tests were short-term in nature, testing isolated events but not persisting through multiple orbits (LL-020). A long-term test would have exposed at least two flaws in the system that later led to the need for FSW modifications on-orbit (LL-117). Although accuracy and fidelity of test environments can be a cost driver, the critical importance of those factors has been repeatedly demonstrated (LL-023), and a careful assessment of cost vs. risk must be performed in this area.

One option for mitigating cost impact is that test design may be separated into tiers. At the highest tier are flight-critical functions: ADCS safe-mode pointing (LL-036); EPS operation; thermal subsystem operation; and basic C&DH functions including communication and flight software updates. By making those functions as simple as possible, involving the minimum number of components (LL-036) and shortest duration feasible, system engineers can make it easier to design high-fidelity tests validating the functions. A second tier of testing includes system performance testing that crosses multiple system boundaries. Test shortcomings in this area are generally correctible on orbit via software uploads or changes in operating procedure, therefore some relaxation of fidelity is permissible; however interactions between and among subsystems must be driven out in these tests. To the maximum degree possible, these tests should reflect actual mission operation sequences and commanding, which drives early development of operations scripts (LL-064). Finally, there is a tier of acceptance and workmanship testing, which is repeated for each Observatory (LL-065 and LL-114). These tests should be automated to the highest degree possible to conserve subsystem engineer and AI&T engineer time during the integration process.

Implicit in the above lessons on test strategy and criticality is that every phase of the development and test process must involve each of the various teams contributing to the mission, from subsystem engineers to AI&T to the Operations team (LL-026). Each team should contribute valuable insight into the test design and to point out gaps in test validity. A painful set of lessons from CYGNSS arose from our naming conventions for spacecraft (LL-068), command and telemetry mnemonics (LL-099), and files (formats as well as names) (LL-031). Related to this are lessons learned on GSE requirements (LL-098) and on data sources to generate command and telemetry databases (LL-110). It is particularly worth emphasizing that the Operations team brings invaluable perspective to the test process (LL-039), and their input on selecting test scenarios (LL-096) and methods of execution form a vital part of test definition. As many tests as possible should be executed through the flight operations consoles and data handling system, and in later phases of the testing program using actual flight instead of test versions of microsat tables and parameters (LL-023). To this end, not only must the flight system provide adequate consoles to accommodate the subsystem engineers (LL-095), but there also needs to be accommodation in alarm and trending processing for any differences between the test and flight environments (LL-093). As a corollary, the subsystem engineers must be present at mission simulations as well as integrated system tests, particularly thermal-vacuum testing (LL-122).

A final category of lessons learned from CYGNSS concerns the most nearly lethal set of mistakes made. In multiple cases, tests were conducted that produced results indicating potentially mission-ending flaws in the system. In each case these results, because they were not the subject of the test that produced them, were not reviewed and the flaw went undetected until a later test or in-flight experience revealed it. Despite the schedule and budget pressure, which always mount steadily as the launch date approaches, it is absolutely imperative that engineers for each subsystem review in detail the data collected during each test (LL-022). This is most effectively done in real-time, with subsystem engineers participating in the tests, but can also be done via offline analysis during requirement verification (LL-113). This is not to denigrate the need for automated telemetry checks (LL-037) and highly fault-tolerant data handling schemes (LL-075), but CYGNSS' experience clearly shows that the value of running a test is not fully realized until all of the data from that test have been thoroughly examined, not only for what is expected from the test, but for what is not expected in the test.

6.8 Project Relationships

On fast–paced, cost-capped projects like Earth Venture Missions, personal relationships are important. It is imperative for the project to not only have good internal relationships within the team, but to also have good relationships with the external stakeholders including the program office, KSC, HQ, Launch Vehicle team, range, etc. Good working relationships help the project get over any bumps in the process. Conversely, a bad relationship can become a major hindrance to progress. (LL-001).

One of the most important lessons learned is “the team matters”. When setting up the project organization, it cannot be stressed enough to have good self-starting personnel. An Earth Venture Mission, by definition, does not have any fat. You have to have a very lean organization where everyone not only pulls their weight but is willing and able to step in and fill roles and work issues beyond their defined roles. Having over-achievers is probably more important than their experience. That said, contrary to some thoughts, an Earth Venture Mission is a bad training ground for key personnel such as subsystem leads. With a very fast-paced project and small team, experienced key personnel with requisite technical, managerial, leadership and communication skills are even more important for successful project completion than on large Class C or B projects. (LL-019).

6.9 PI Engagement

Earth Venture Missions require the PI to be fully engaged with the project team. There is neither the time nor money to let issues go unresolved. An “engaged PI” is aware of an issue when it is small and solvable versus having to be brought up to speed later when the issue becomes larger. Close communication with the team expedites closure and resolution. The PI is ultimately responsible for all aspects of mission execution, not just the science, so success requires active participation in mission engineering and programmatics. (LL-017, LL-033)

There were three significant instances when quick action and decisions avoided major potential impacts to CYGNSS’ cost and schedule. 1) In the first days of Phase A, one of the major engineering subcontractors declared a need for a large increase in their cost. An immediate decision was made by the PI and project management team to re-compete the contract and a new partner was selected at a favorable cost (LL-006). 2) One month after CDR, the supplier of a critical flight subsystem went out of business. An immediate decision was made by the PI and project management team to award two new contracts in parallel for the same subsystem. This was done because the required delivery schedule was extremely tight. In the end, both suppliers delivered on time and there were many flight spares. (LL-067) 3) During fabrication of the primary science payloads, the vendor admitted to making a major processing mistake but refused to take corrective action. They verbally claimed the error would not compromise the hardware integrity but refused to provide experimental evidence or written confirmation. This was a clear instance where legal action could have been taken, but at significant risk to project schedule. The PI and project management team decided instead to spend project reserves and have all science payloads rebuilt. (LL-027)

The PI is responsible for the management and coordination of the science team. This is helped by the delegation of science team management tasks, e.g. appointment of several deputy PI team managers responsible for different team activities such as algorithm development, end-to-end mission simulators, and end-user science applications (LL-053). The establishment of contracts supporting the individual science team members also provides an opportunity for constructive management, including the delivery of regular progress reports and scheduled inputs to support major mission design reviews and science team meetings (LL-054).

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Appendix A. Individual LL

CYGNSS – LL-001: Project relationships with stakeholders	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 1.0 Project Management
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	1. Yes
Lesson:	It is imperative to develop good working relationships. This IS after all rocket science which is hard enough without relationship issues.
Description of Driving Event :	1. Most importantly work with the Program office. They want the project to succeed as much as the project team. 2. It was important to develop relationships with key stakeholders (KSC, LV, Range, HQ, etc.). NASAs willingness to answer questions contributed greatly to financial success. 3. High ethical integrity was critical to fostering the necessary relationships and for NASA trust in CYGNSS.

CYGNSS – LL-002: Funding reserves release plan	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	2. No
I&T Phase:	2. No
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 1.0 Project Management
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	1. Yes
Lesson:	It is strongly suggested to limit the release of funding reserves until Phase C.
Description of Driving Event:	Yes, this says that you are limited in the risk reduction activities that you can do before PDR. The issue is you are guaranteed to need reserves in Phase C/D.

CYGNSS – LL-003: SE staff levels vs experience	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	2. No
WBS Element:	WBS 2.0 Systems Engineering
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	1. Yes
Lesson:	The only S/C subsystem staffed by experienced engineers was the SMT subsystem. Future project need to have mostly experienced subsystem engineers as lead with less (no) experienced engineers brought on for training.
Description of Driving Event :	Multiple examples: 1. ADCS: SwRI ADCS Lead (junior engineer) was assigned to coordinate with the ADCS subcontractor for algorithm and FSW development in parallel with managing subcontracts for ST, MSS, CSS, RW, and TR 2. CDS: CDS engineer was expected to be able to perform analyses for telecomm, data systems, and avionics subcontractor in parallel with performing as the EPS engineer. The CDS had only limited experience with Telecomm and data systems so those areas suffered neglect and other SE had to perform the necessary tasks 3. EPS: EPS engineer had no previous experience. Bringing on an experienced consultant proved critical to mission success.

CYGNSS – LL-004: Reserve release policy sometimes adds risk	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 2.0 Systems Engineering
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	1. Yes

Lesson:

Conservative management of programmatic and technical reserves drives technical risks dependent on maturity of technology. See also LL-028, LL-105, LL-118.

Description of Driving Event :

There are several examples of this on CYGNSS:

1. 1 Star Tracker vs 2 Star Trackers: A key operational issue is the fact that the Star Trackers lose lock due to Sun incursion in their field of view (FOV) on a near orbital basis. This was fully expected during early ADCS development. The accepted solution is to find a Star Tracker orientation that doesn't experience Sun incursion or fly multiple units so that attitude knowledge is not interrupted. Unfortunately, no combination of location and orientation could provide a FOV absent of Sun incursion. Given tight control of funding during early phases of CYGNSS, the ADCS team was not allowed to consider use of multiple Star Trackers so a novel solution to use Sun Sensor data during Sun induced Star Tracker outages was developed. The long term analyses necessary to prove the performance far outweighed the initial costs of using 2 Star Trackers, plus the Sun Sensors ultimately did not meet specifications.
2. Ground Segment Development: Early ground segment development was held back due to funding constraints and the (naive) perception it could be delayed to later phases of the project. The level of effort necessary for the MOC development was not clearly understood initially and then when it was, development was delayed due to funding profiles.
3. Using Solar Arrays as Sun Sensors: Lack of interface resources in the CDS avionics forced ADCS design decisions to minimize the number of Sun Sensors and ADCS was encouraged to find alternative sensor information such as using the Solar Array output as a Sun Sensor. This is a novel approach, but due to the EPS architecture it was ultimately not feasible (at least without on-orbit calibration) though significant funding was expending to arrive at this conclusion. A much more cost effective solution would have been to develop a Sun Sensor interface unit to expand the number of possible Sun Sensor interfaces within the avionics. Note: Sun Sensors are now on the market that minimize the number of sensor interfaces while providing much improved accuracies.

CYGNSS – LL-005: Don't short change the need for SE staffing levels	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	2. No
WBS Element:	WBS 2.0 Systems Engineering
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	1. Yes
Lesson:	While a small team of qualified systems engineers works well for a class D project, not having sufficient staff causes staff overload and subsequent effects such as missing critical task completion dates (requirement develop, ICD definition, etc.), insufficient analysis and review of test data (see LL-022), delayed close-out of requirement verification
Description of Driving Event:	The CYGNSS systems engineering team was designed from the start to be small with PSE, Obs SE, and S/C SE all being filled by 1 person with only a part time mid-level engineer for support. All subsystems were staffed with only 1 SE/subsystem with the exception of ADCS where we had a junior engineer trying to manage the subcontractor responsible for ADCS algorithm and FSW development

CYGNSS – LL-006: Don't be afraid to kick an institution off the team to stay within the cost cap	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	2. No
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 1.0 Project Management
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	1. Yes
Lesson:	In a cost capped mission, every institution must stick to their original cost estimates. If an institution greatly increases their cost estimate or technical risk, that should open the door to other institutions to propose.
Description of Driving Event:	One of the CYGNSS institutions after selection, informed management that their costs were going to increase 3X. We then put together a RFP to the original institution and several outside institutions keeping NASA informed all along the way. We ended up going with a new institution and dropped the original institution. These are tough trades that the PI and PM must make to stay within the cost cap.

CYGNSS – LL-007: LV definition after PDR is very late	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 1.0 Project Management
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	1. Yes
Lesson:	The current practice for a GFE launch is for KSC to not put the LV provider under contract until after mission PDR. The lesson learned is this means that the project has to carry lots of unknowns all the way through preliminary design thus potentially impacting the mission design, schedule and cost.
Description of Driving Event:	Because of the late LV selection, and thus the late development of launch loads, we elected to have the Deployment Module (DM) go on hold until the loads were developed. In the end this caused the DM to become the critical path of the mission.

CYGNSS – LL-008: Cubesat vendors may not have the rigor of typical aerospace companies	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 1.0 Project Management
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	1. Yes
Lesson:	Cubesat vendors typically produce products that do not even meet Class D standards and will often have Configuration Management (CM) difficulties. Lesson learned is more oversight/insight/mentoring is needed.
Description of Driving Event:	CYGNSS used Cubesat ADCS components and while not universal, one particular vendor had many issues with lack of CM, product not meeting the ICD or spec, and lack of good design practices. These issues manifested soon after the company was put under contract and are still issues now that CYGNSS is on orbit.

CYGNSS – LL-009: ANSI compliant EVM as required by the contractual FAR clause is a huge effort	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 1.0 Project Management
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	1. Yes
Lesson:	Current NASA projects are contractually bound by a NASA FAR clause to perform ANSI compliant Earned Value Management (EVM) if the project life cycle cost is greater than $20M and certified EVM if the project life cycle cost is greater than $100M. This includes Class D missions. To perform ANSI compliant / certified EVM requires dedicated personnel, additional paperwork and adds requirements on subsystem engineers. Lesson learned is either a) get rid of the FAR clause or b) plan on a substantial effort across the team for EVM.
Description of Driving Event:	CYGNSS performed EVM while SwRI was working on its certification. Even this less onerous EVM that was used required ~1FTE solely focused on EVM. True compliant / certified EVM requires probably twice the effort and adds additional work for subsystem engineers.

CYGNSS – LL-010: Commissioning 8 S/C in LEO with small team is tough	
Project Phase (where LL needs to be implemented) -	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	2. No
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	2. No
WBS Element:	WBS 7.0 Mission Operations
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	1. Yes
Lesson:	Commissioning 8 S/C in LEO means that you will have many (~10 to 40) contacts a day. This provides the team very little time to solve any problems. The goals and schedule for commissioning needs to take this into account (i.e. commissioning will take longer than the equivalent for a single spacecraft mission). See also LL-018.
Description of Driving Event:	By definition, a class D mission will have a small team which makes it very difficult to 1) staff 24-7 for any extended period and 2) to have an on console team(s) and a troubleshooting team. In retrospect, we should have limited the goal of early LEOps to strictly observatory safety and health and limited the contacts with the healthy spacecraft so that we could focus on the problem children. Once a spacecraft is deemed healthy, the schedule could be relaxed and the team could go back to more normal working hours.

CYGNSS – LL-011: Class D projects are not a good training ground for key project personnel	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 1.0 Project Management
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	1. Yes
Lesson:	With a very fast paced project with a small team, experienced key personnel with requisite technical, managerial, leadership and communication skills are even more important for successful project completion than large Class C or B projects.
Description of Driving Event:	Class D projects with typically short durations and a small team are not the best place for training of key personnel. You typically don't have the time or money for this and it just makes success more difficult.

CYGNSS – LL-012: Contract details such as reserves, CLINS, and funding	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 1.0 Project Management
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	1. Yes
Lesson :	1. Putting reserves on the PI contract allowed the project team to more easily manage/navigate the cost cap. The PI institution rightfully carried all of the reserves as they carried the mission financial risk. 2. CLINs should not be used due to additional operational and funding issues. 3. Project funding allocations from NASA should be based on planned and actual spending (from the 533 or CPR) and not invoicing. This is particularly important with a distributed PM project structure where invoicing by the subcontractors to the PI institution can be delayed. 4. Having a clear and unambiguous contract important.
Description of Driving Event :	1. It is imperative for the prime contract to have the reserves on contract from the very beginning. This eliminates the issues with contract office lag time. 2. Likewise, CLINs represent an added complication (i.e. tracking, invoicing etc.) that adds no value to the project. They should be highly discouraged. 3. Project funding should be tied to actual spending not invoicing. Otherwise the project is serving as "the bank" for NASA.

CYGNSS – LL-013: Cost, EVM, and status reporting	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 1.0 Project Management
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	1. Yes
Lesson:	Financial reporting should be tailored to what adds value to the particular phase of the project. The "ones size fits all" NASA financial reporting requirements are a larger percentage burden on Small Class D projects than large Class B or C missions.
Description of Driving Event :	1. All reporting was forthcoming, accurate, consistent, inclusive and open. Facts were stated and spin was limited. Reports were developed that provided NASA with necessary insight and that kept them informed (per the CPARs). 2. Financial Non-Disclosure Agreements (NDAs) with subcontractors should have been signed to obtain proprietary or confidential rate information to limit administrative burden and provide openness with reporting. (see LL-035) 3. NASA reporting templates were used but were changed to make them better! 4. Reporting should be streamlined to only include necessary reports and information. The MPSR was consistently important. The CPR was important during Phases C/D. The 533 was important during Phases A/B, but was ineffective (and did not provide accurate financial performance information) during Phases C/D. Variance reporting was important at the cumulative level but was unnecessary at the monthly level. 5. EVM reporting predicted potential cost issues, schedule delays, and EAC problems at critical times during the project. However, an EVM-lite would have provided the same quality of information at a much lower cost.

CYGNSS – LL-014: Perform holistic test planning	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 10.0 System AI&T
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	1. Yes
Lesson:	Efficiencies can be gained by assessing the various types and levels of testing that are being planned (e.g. FSW ATP, S/C Verif, Obs FFTs, MSTs, etc.) and looking for areas where testing levels can be combined.
Description of Driving Event:	While some duplication in testing is helpful, on lower budget missions such as CYGNSS, sometimes there can be significant duplication of effort across the FSW AI&T, and SE/Ops testing. Holistic test planning should be performed on these smaller missions to specifically define which test activities can be combined and which should be separate.

CYGNSS – LL-015: Create a vendor/component vetting plan	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	2. No
I&T Phase:	2. No
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 2.0 Systems Engineering
Components - Primary (if applicable):	ADCS - Reaction Wheel
Components - Secondary (if applicable):	ADCS - Star Tracker
Priority:	1. High
Big Picture LL:	1. Yes
Lesson:	Create a vendor/component "vetting plan" that identifies all components/vendors and defines the level of vetting that will be applied based on vendor longevity and component heritage.
Description of Driving Event:	The small satellite market is still new and growing rapidly. As such, components are often selected that have little or no heritage, and may be procured from upstart companies. Because of the budget of these programs, significant $ can be saved by leveraging vendor testing of the components vs. duplicating tests by the S/C developer. However, an assessment of the vendor and the component needs to be made to determine whether that approach is viable in each case. Particularly for components with little or no heritage and components from new vendors, EM, and in some cases FM, models of the components should be brought into the lab and tested/characterized in a standalone mode, and perhaps some other specific/special tests, before attempting to integrate them even on the EM S/C.

CYGNSS – LL-016: Clearly define objectives when building early EM spacecraft	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 10.0 System AI&T
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	1. Yes
Lesson:	Clearly define and document objectives for any early AI&T tasks to avoid unrealistic growth in expectations that may drive costs and/or result in "de facto design decisions" that you later have to live with.
Description of Driving Event:	The project plan included production of an EM microsat very early in the schedule. This was initially intended to be primarily a mechanical, interfaces, and limited electrical pathfinder. However, expectations quickly escalated such that by the time it was done we were flowing science data end-to-end from the S/C through the FSW to the ITOS ground system and to an early MOC. The result was an initial version of the FSW that was best described as a rapid prototype, and the early ground system was put together in similar haste. The result was the FSW was almost written twice which was costly. Additionally, a number of "decisions" had to be made in haste, especially in nomenclatures and conventions, that the project wound up having to live with throughout the project that were less than ideal.

CYGNSS – LL-017: PI engagement is vital for success	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 1.0 Project Management
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	1. Yes
Lesson:	For tightly coupled small satellite projects, having a PI that is actively engaged in the development and execution details is critical. On CYGNSS, there was close communication and feedback between the PI, PM, and SE, which expedited the resolution of many issues. The PI had full control of the cost reserves and was given regular updates by the Business Manager. The PI also oversaw the Science Team and was able to rapidly adjudicate cost/schedule/performance trade-offs on the spacecraft with impacts on the PLRA defined science requirements. For lean projects to succeed, the PI needs to be an active participant and not a "sage on the stage".
Description of Driving Event:	Allocation of technical margins and cost and schedule reserves.

CYGNSS – LL-018: 24/7 LEOps with only 2 shifts was brutal	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	2. No
I&T Phase:	2. No
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 7.0 Mission Operations
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	1. Yes
Lesson:	24/7 LEOps with only 2 shifts was brutal. Either have enough qualified/trained staff for 3 shifts, or probably better, find a way to avoid 24/7 operations. See also LL-010.
Description of Driving Event:	Team was already exhausted after several days of launch delays/scrubs. Carrying on with 24/7 operations for over a week put enormous stress on the team. It's surprising we didn't make more mistakes. Best case scenario the 24/7 2-shift approach requires something like 14-hour shifts in order to have enough overlap to share info during the handover. In reality it became more like 18-hour shifts since the "off-shift" team would need to work anomalies/issues while the other team was on-shift running passes. Several folks worked more than 24 hours straight, and many were sleeping only a few hours here and there.

CYGNSS – LL-019: Of all things that are important, the team may be first	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 10.0 System AI&T
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	1. Yes
Lesson:	Form a team of excellent performers.
Description of Driving Event:	A large contributor to CYGNSS I&T cost and schedule success was the outstanding team put together. With a combination of talented I&T Engineers and dedicated Engineering Technologist and Technicians, I&T team hit every target. Across the project there were extremely talented, dedicated professionals who made great personal sacrifices for CYGNSS' success. A great team is probably the most important ingredient in the secret sauce.

CYGNSS – LL-020: Assess simulator synchronization requirements	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.9 Microsat GSE
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	1. Yes
Lesson:	Specifically assess what synchronization is needed among I&T simulators.
Description of Driving Event:	On CYGNSS, the various simulators (e.g. Spacecraft Dynamics Simulator, GPS Signal Simulator, Solar Array Simulator) were not designed to be synchronized with one another. Initially this was not deemed necessary but later this proved to be a barrier to test-as-you- fly. On low-cost missions it may not be possible to synchronize all simulators but a more careful assessment of cost vs. risk should be performed.

CYGNSS – LL-021: Requirements verification matrix and ICD verification reports for subcomponents and subcontractors	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	2. No
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 2.0 Systems Engineering
Components - Primary (if applicable):	ADCS - Reaction Wheel
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	1. Yes
Lesson:	Ensure that at the time of delivery of lower level components and subcontracted assemblies a thorough review of the acceptance data package, V&V matrix and ICD verification is performed (and thorough). Even after this review, it is better to test rather than trust the documentation.
Description of Driving Event:	Discrepancy and unexpected behavior of RWAM during Commissioning phase (first LVLH transition).

CYGNSS – LL-022: Analyze all of your test data carefully	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 10.0 System AI&T
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	1. Yes
Lesson:	Any time a test is run, dedicate all of the required resources to carefully examine all of the collected data (each parameter) comparing against expected values and explaining any discrepancy. It is better to use test data as predictive diagnostics than as forensics.
Description of Driving Event:	Before the ferry flight from VAFB to KSC, one of the flight batteries showed a change in its charging profile though the change was within limits. This was not caught until much later at KSC. Ideally, the pre-ferry data would have been trended (somehow) to catch the change earlier. On a Class D cost capped mission, it is always a trade on spending resources to make something better. Tests on FSW including RTS's and internal error causing mis-configuration of the PPT did in fact generate telemetry months in advance of launch showing that the PPT GPD settings were dangerously mis-configured. However because of the test configuration, the PPT never used those particular settings and continued to operate normally. Had *all* the telemetry (settings as well as output current and voltage) been carefully examined at the time, the mis-configuration should have been detected then instead of the day after launch was scheduled. See (PFR-17790-427-OP) "FSW branch structure causes PPT load-shed commands to mis-set GPD parameters".

CYGNSS – LL-023: Fly like you test and test like you'll fly	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	2. No
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 10.0 System AI&T
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	1. Yes

Lesson:

In designing test environments and hardware, make every effort to simulate the operational environment in *all* feasible details; include human-driven elements if necessary, or actual software links if possible, but combining every element of the active environment simultaneously is crucial in driving out subtle system-wide and cross-system errors and problems. Step back and examine all TLYF exceptions.

To ensure that spacecraft power system functions accurately in flight like conditions, include ground testing of a spacecraft that is fully electrically isolated from facility ground so that the spacecraft ground can float as it would in orbit. The spacecraft should be communicating using its radio connection only ensuring that there is a small air gap to maintain isolation. Testing should cover at least 3-4 orbits to allow the power system to settle to equilibrium values. All spacecraft systems should cycle in a flight like manner so that transitions and disturbances to the power system are present, including reaction wheels, torque rods, heaters, transmitters, and payload modes. Special attention should be paid to review battery voltage and current measurements and all measurements where spacecraft grounding could perturb accuracy. This “plugs out” test is also typically an excellent opportunity to assess functionality of critical items such as deployments and EMI/EMC self-compatibility across the key receiver frequencies.

Make every effort to load, enable, and run the full FSW complement including all fault detection and correction algorithms; where this is not easy because faults are tripping that "would not happen on orbit", it is an indication that the test environment is not adequate and should be improved.

Description of Driving Event:

An unappreciated TLYF exception was created by not linking Solar Array Simulator to either the dynamics simulator or an orbit period eclipse profile. As a consequence, Mission Simulation Tests (which included flight RTS's which exposed a serious configuration issue in the PPT GPD settings) did not in fact point out the faulty behavior whereby the FSW branch structure caused PPT load-shed commands to mis-set GPD parameters. More realism in the MST would have exposed the problem months before launch; even so simple a remedy as having an engineer turn the SAS down and back upon a 90-minute (orbital) cycle would have prompted the potentially mission-ending behavior to display itself.

CYGNSS – LL-024: LV interface takes considerable effort	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	2. No
WBS Element:	WBS 2.0 Systems Engineering
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	1. Yes
Lesson:	The launch vehicle interface is possibly the most difficult external interface that the project has to deal with. This is largely due to the LV provider not reporting to the PI or the program office. It makes communication difficult at best. Also, the LV schedule is frequently at odds with the project schedule. At a recent Explorers PI/PM forum, this interface was discussed by every project. Dealing with this interface will take considerable time and project funds. See also LL-007 and LL-066.
Description of Driving Event:	Project needed design loads earlier than available.

CYGNSS – LL-025: Maintain engineering table-top design review robustness	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 2.0 Systems Engineering
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	1. Yes
Lesson:	Protect the robust implementation of the peer review process. More smaller peer reviews with only SMEs and minimize (eliminate?) use of PowerPoint is highly recommended to avoid a detailed down-in-the-weeds review from turning into a high level formal summary review
Description of Driving Event:	• EMI issues encountered with the cover on the NSTs • Fastener issue encountered during sine burst testing of the DM • PPT issues • XCVR connector issue • Reaction wheel direction cosine matrix

CYGNSS – LL-026: Cross element coordination is vital	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	2. No
WBS Element:	WBS 1.0 Project Management
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	1. Yes
Lesson:	If you are expecting some type of support from other groups - you need to make sure all groups are clear on what you are expecting from them and by when - and if it is not in their budget, the team needs to figure out where best to put it and establish the resources to make it happen
Description of Driving Event:	Cross-segment, cross-element, and cross-subsystem developments in general

CYGNSS – LL-027: Project success and keeping schedule is more important than sticking it to your vendors	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 1.0 Project Management
Components - Primary (if applicable):	DDMI - DMR
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	1. Yes
Lesson:	Project success and keeping schedule can be more important than forcing a supplier to take responsibility for manufacturing mistakes.
Description of Driving Event :	The DMR supplier refused to fund rework of the flight unit DMRs that were potentially damaged as a result of process errors during manufacturing. 1. The supplier readily admitted that they had violated their own flight fabrication processes and that all flight unit DMRs were impacted. 2. The supplier refused to take any corrective action on their own. 3. The supplier refused to provide any documentation indicating that the damaged hardware was OK to fly. Instead of bringing a legal challenge to the supplier, project reserves were released to fund a major rework of the flight boards (pay for the same hardware twice) in order to hold project schedule.

CYGNSS – LL-028: Balancing technical risks with holding recommended amount of reserves	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 1.0 Project Management
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	1. Yes
Lesson:	Holding onto large (perhaps unnecessarily large) reserves/margins may impose a higher level of technical risk that could end up costing more in the long run than releasing reserves earlier to mitigate the risk. See also LL-118.
Description of Driving Event:	Early decision to have only one star tracker to maintain recommended cost and mass reserves is an example.

CYGNSS – LL-029: Staff Cross-training with small teams is vital	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 2.0 Systems Engineering
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	1. Yes
Lesson:	The small team approach of CYGNSS offered many opportunities for the staff to cross train between subsystems, engineering vs AI&T, and development vs operations. The cross training that occurred was invaluable, more would have been better but cross-training results in loss of time spent on primary responsibilities
Description of Driving Event:	Staffing levels meant that when SE's were used in AI&T and FSW development, they were not available to work primary SE tasks. Prioritization of the cross-training resulted in key SE tasks not being accomplished or being late. This significantly increased end risks.

CYGNSS – LL-030: Small improvements in efficiency lead to real gains for constellations	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 10.0 System AI&T
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	1. Yes
Lesson:	Many activities will be repeated when building and testing a constellation. Small improvements in efficiency can really add up to significant time savings. Improvements in process efficiency and adding automation where possible can reap large rewards when building 4, 8, or more spacecraft.
Description of Driving Event:	Example: In a test procedure, only require recording date/time on steps for which it is valuable. It makes sense to record the time for starting test scripts, sending commands, or other time sensitive activities, but it does not add value for every step. The date need not be recorded 20 times on the same page when all steps happened in the same hour. When there are literally hundreds of as-runs to be performed, small time savings add up. Example: On a Manufacturing Planning Sheet (MPS), as-runs could be added directly to the operation where they are performed and rows in the As-run Tab of the MPS could be populated automatically (manually entering as-runs to the as-run tab already requires matching the as-run with an operation). As a manual process it is subject to errors/typos and often gets deferred until the MPS is in the closeout cycle, when it is more difficult to map as-runs to operations. Similarly, Test Readiness Review (TRR) form numbers assignments and association with MPSs could be improved/automated.

CYGNSS – LL-031: Define consistent file format and naming conventions early	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	2. No
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 9.0 Ground Segment
Components - Primary (if applicable):	MOC Systems
Components - Secondary (if applicable):	SOC Systems
Priority:	2. Medium
Big Picture LL:	1. Yes
Lesson:	Early in the project, identify the various types of data files that will be produced and document a consistent file naming and file formatting convention. Communicate that convention across the team (e.g. FSW, AI&T, MOC, SOC, and SSC Space US). Get MOC involved early to lead this, with FSW team input. See also LL-068, LL-081, LL-099.
Description of Driving Event:	Currently FSW, AI&T, various MOC subsystems, the SOC and SSC Space US all name their data files and archives in a different format. Some are named by VCID and some by buffer type. This causes a lot of hand editing of filenames prior to running data processing at the MOC. If we followed a similar naming scheme, then less editing would be needed. Creating files for the SOC becomes an exercise in renaming files to match what data processing is expecting.

CYGNSS – LL-032: SOW requirement flowdown: COTS vs. custom	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	2. No
I&T Phase:	2. No
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 1.0 Project Management
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	1. Yes
Lesson:	Flowdown of SOW requirements to subcontractors can easily drive costs and schedule if ramification of requirements are not carefully considered. This is part of the COTS vs. custom philosophies.
Description of Driving Event:	Vendor FFP cost/schedule responses are being driven due to literal interpretation of SOW requirements (including MAIP and other ref plans) rather than desired response for subcontractors to use their inhouse procedures and processes if compliant with requirements

CYGNSS – LL-033: PI engagement with engineering team is vital	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 4.0 Science
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	2. No
Lesson:	The PI should attend and actively participate in engineering TIMs throughout Phases B/C/D. Similarly, participating in a variety of weekly telecons/tag-ups helps the PI stay abreast of engineering activities, hot topics and problems that might otherwise not be reported up to the PI level.
Description of Driving Event:	Since on PI-led missions, the PI is the ultimate authority and overall responsible for the mission, he has to stay very involved throughout development.

CYGNSS – LL-034: Small allotment of reserves held at non-PI institution	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 1.0 Project Management
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	2. No
Lesson:	While it is vitally important for the PI to own and to be in control of the cost reserves on a PI-led cost capped mission, some small allotment of reserves should be put on the implementing organizations contract to mitigate the long duration (~6 months) in getting a contract mod in place. The size of the allotment should be determined by the Project Phase and reserves release plan.
Description of Driving Event:	With the added government audit scrutiny, it takes on average 6 months to get a contract mod in place. To not stop work, the implementing organizations contract should have a small reserve allocation from day 1 so they are not working in the hole from the first submitted contract mod proposal. Use of this funding should still only be allowed with PI consent. Having this small bucket of reserves would have saved considerable non-value added effort each month with the SwRI project having to deal with SwRI administration for Authorized Unpriced Work not yet on contract.

CYGNSS – LL-035: BCR review and audits	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 1.0 Project Management
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	2. No
Lesson:	Federal audits and requirements continue to increase making it very difficult to get a contract mod in place in any reasonable amount of time. Every university, private and public institutions that does business with the government has had to adjust to this greatly increased overhead of doing business with the government. Lesson learned; don't underestimate the effort and time it takes for the contractual process and try to implement workarounds. See LL-070. Also, make sure that there is funding in place to carry the project until the BCR is approved. One positive outcome of the BCR process, however, was the improved visibility it afforded the PI and supporting project management at UM with regard to SwRI costs, schedules and general project execution.
Description of Driving Event:	A BCR from SwRI to UM at the start of the project took almost nine months to get through the full system for approval. SwRI (like most institutions) will not give out proprietary rates to clients that are potential competitions. This plus the great detail and backup required by government auditors and enforced by UM (for an estimate on a cost capped project) , greatly increased the time to generate the proposal, for UM to review it, and for the government to approve the (already government approved) SwRI rates. After a couple dozen of these mods, we got the turnaround time down to about 6 months - still way too long if mitigation were not in place.

CYGNSS – LL-036: Spacecraft safe mode should use minimum suite of components	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	2. No
I&T Phase:	2. No
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.2 Microsat Sys. Eng.
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	2. No
Distribution:	2. External
Lesson:	Spacecraft Safe Mode needs to be robust. Designing the safe mode to use the minimum suite of components means less things that could go wrong to jeopardize safety of the spacecraft and simplifies testing and analysis. Components that are highly reliable and have simple interfaces are preferred. See also LL-103.
Description of Driving Event:	See LL-103 describing use of the RWA as the interface for the CSS. While a component hardware failure could occur at any time during the mission, undiscovered interface issues (reversed polarity, incorrect signal level thresholds, etc.) are most likely to be exposed during LEOps. Keeping the required set of components to a minimum addresses both scenarios.

CYGNSS – LL-037: Telemetry validity checks beyond simple sanity-check may be needed	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	2. No
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 6.4 Comm. & Data Subsystem
Components - Primary (if applicable):	FSW - Flight Software
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	2. No
Lesson:	Telemetry delivered from any subsystem to FSW should have both first-order checks applied (such as checksum/EDAC provisions and range-of-value checks) but also sometimes derivative checks such as provisions to reject sudden jumps in temperature, attitude quaternion oscillations when no RW/TR levels have been changed, sudden unanticipated changes in battery voltage, current, or SOC, etc. Single-reading errors should be rejected and persistent errors channeled to Fault Detection/Correction responses (e.g. reset offending subsystem). See presentation by Killough at FSW Workshop 2017, "Is On-Board Fault Management the Anti-Dote to Low-Cost/Low-Heritage Components in Small Satellites?" and paper by Killough et al, CYGNSS Launch and Early Ops: Parenting Octuplets; SmallSat 2017.
Description of Driving Event:	Small/micro-satellites often use less robust components vs. those used on higher-class missions. These components may not have internal provisions for ensuring telemetry integrity, and may be more susceptible to SEUs than more expensive components. CYGNSS has experienced multiple cases in which telemetry would pass first-order checks but were, in fact, incorrect, resulting in unnecessary Safe Mode transitions (e.g. RW temperatures or wheel speeds, star tracker quaternions, GPS position determinations, etc.)

CYGNSS – LL-038: Vendor manufacturing changes can add risk	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	2. No
WBS Element:	WBS 5.0 DDMI
Components - Primary (if applicable):	DDMI - DMR
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	2. No
Lesson:	"Heritage" also applies to people and processes. Need to develop multi-prong strategies for handling COTS-ish components while not weighing down the project.
Description of Driving Event:	An important, high-heritage, CYGNSS subsystem had been built by the same team for many years. Early in the project, the company made a unilateral decision to move the manufacturing of this component to a new facility with a new team. While there was a training period for the new team, CYGNSS encountered major issues due to the inexperience of the new team. While this was immediately flagged as a project risk when the change was announced, there were few good courses of action to mitigate the change. With more integration of "COTS" components, this could become a more common problem. Frequent mergers and acquisitions within the SmallSat community could further exacerbate this issue.

CYGNSS – LL-039: Ops personnel should participate in I&T	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 7.0 Mission Operations
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	2. No
Lesson:	Operations personnel should participate in I&T for on the job training to learn how the observatory and FSW function.
Description of Driving Event:	Because ops personnel did not participate in I&T, there was a large learning curve that had to be accounted for and additional I&T members had to be brought on line. In addition, additional mission sims were also then needed to train the ops personnel. Lastly, the I&T team had to remain on the project longer to support commissioning. Likewise, the I&T team should be at the MOC for mission sims and rehearsals.

CYGNSS – LL-040: In anomaly resolution, taking no action may be the best course	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	2. No
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 7.0 Mission Operations
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	2. No
Lesson:	While no design is perfect, it is easy to jump to incorrect conclusions when a S/C behaves in a way not observed during ground testing, as it is not possible to anticipate and test every scenario that will occur on-orbit. However, it is important to consider that the design may be working as intended.
Description of Driving Event:	There are a number of times during LEOps where we were concerned the S/C was "broken" or had some design flaw, that turned out not to be true - that is, that the S/C was responding correctly. Most of those incidents were minor or short-lived conclusions, but one example is when FM06 came up in a flat spin to the sun and in a low and declining SoC. While it is difficult to know for sure, data analysis suggests that the S/C would have found the sun on its own had we not taken intervening steps.

CYGNSS – LL-041: Clearly define EGSE sets, and responsibilities among FSW, EGSE, AI&T, and Ops teams	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.9 Microsat GSE
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	2. No
Lesson:	Clearly define the EGSE and simulators that will be produced, use cases, and roles & responsibilities related to EGSE/simulators/test equipment.
Description of Driving Event:	Development and maintenance of EGSE can easily fall to FSW, AI&T, EGSE and Ops teams. Without clear lines of responsibility, each of these teams will likely make different assumptions about who is responsible for various aspects of the EGSE and its capabilities are resulting in gaps that can result in cost and/or schedule impacts and frustration among the team.

CYGNSS – LL-042: Reaction wheel thermal response not correctly validated by vendor	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 6.6 Struct., Mech. & Therm.
Components - Primary (if applicable):	ADCS - Reaction Wheel
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	2. No
Lesson:	Changes in reaction wheels did not have adequate engineering attention to capture thermal impact of the mechanical interface changes. Vendor did not appear to have the resources to evaluate this in a timely manner. They relied on a contractor to provide thermal assessment, but didn't seem to include them when results were being compiled from relevant tests. A thermal balance test on the component should have been performed by the vendor.
Description of Driving Event:	The wheels operated at excessive temperatures which limited their operation in flight. A thermal model was developed by a contractor but was never validated. The actual power dissipated by the wheels was higher and the thermal conduction to the wheels was less than the preliminary model. Since insufficient attention was given to the change, the impact didn't show up until thermal balance testing and limited options were available to mitigate.

CYGNSS – LL-043: EPS: uSat grounding review and control	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.7 EPS Subsystem
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	2. No
Lesson:	Design and maintain grounding scheme. Include review at all levels of component development for all components (in-house and external subcontractors)
Description of Driving Event:	A single point "star ground" was designed originally for the CYGNSS spacecraft. Requirements were developed and flowed to all components for Primary/Chassis conductivity and Primary/Secondary isolation. All externally sourced components included review of ground configuration. When the SwRI transceiver was redesigned to be external from the avionics core, it's grounding system ultimately unilaterally violated the grounding design without notification to systems engineering. A work around was developed due to schedule impacts to change the transceiver. The redesign failed to meet noise performance requirements resulting in many issues with noise on various signals during I&T and in flight. Signals such as current monitoring were especially effected due to "sneak paths" in the grounding system "work around".

CYGNSS – LL-044: Establish clear FSW module boundaries even in early prototype efforts	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.5 Microsat Flight Software
Components - Primary (if applicable):	FSW - Flight Software
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	2. No
Lesson:	Initial prototyping of FSW during early AI&T resulted in software with strong coupling, allowing minor changes in code to have moderate negative impacts. Due to schedule pressure and staffing constraints, not enough time was spent on ensuring the software designed in a modular way. After the prototyping stage, the FSW effort spent time on re- work, and emerged with much more modular (and much better) design, allowing for (1) less risk in making a minor code change, (2) better unit testing capability, (3) easier review of software, and (4) more maintainable software.
Description of Driving Event:	Due to schedule pressure and staffing constraints, early AI&T FSW efforts resulted in non- modular prototype FSW. Re-work resulted in much cleaner, and more modular, software.

CYGNSS – LL-045: FSW - continually manage scope in scrupulous detail	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 6.5 Microsat Flight Software
Components - Primary (if applicable):	FSW - Flight Software
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	2. No
Lesson:	Managing FSW schedule, cost, and scope creep can be done, but must be meticulously documented through a good Problem Report / Change Request (PR/CR) tracking system. Every new FSW-related request should have a CR opened for it, and even the most minor problem should have a PR opened for it. Note that this is especially relevant for FSW since it is often the most complicated on board system and suffers the latest requirements changes even through operations.
Description of Driving Event:	From early AI&T through Operations, staffing constraints, initial prototyping/re-work, and expanded scope drove periodic schedule and cost-renegotiation.

CYGNSS – LL-046: Commit to implementing 2- stage process for verification closeout	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 2.0 Systems Engineering
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	2. No
Lesson:	At least two persons should review verification closeout for all requirements. Typically this should be 1) the CogE who marks the requirement complete and enters all relevant info regarding the verification results and references to verification artifacts and 2) another (typically higher level) SE that actually looks at the data entered, agrees that it is accurate and sufficient, and marks it approved/closed. The level of scrutiny from the 2nd person necessarily varies, but at the bare minimum the 2nd person should confirm that the data entered is complete and reasonable, devoid of obvious omissions, typos, placeholders, copy/paste errors, etc.
Description of Driving Event:	Some errors in verification closeout information in the database were discovered and fixed very late. The cause of most of the errors was simply a result of bypassing the 2-stage review process.

CYGNSS – LL-047: Implement simulator models completely independent of ADCS team	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.9 Microsat GSE
Components - Primary (if applicable):	EGSE - SDS
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	2. No
Lesson:	Development of the simulators/models used during I&T for simulating spacecraft dynamics and input/output of ADCS sensors/actuators should be completely independent of ADCS FSW development, and the ADCS team in general, to the greatest extent possible. See also LL-097.
Description of Driving Event:	CYGNSS employed the Spacecraft Dynamics Simulator (SDS) in the integrated uSat environment. Because models used in the SDS were provided by the same group that was developing the ADCS FSW, there was no independent verification of said models. In fact, there was a problem with how the orientation of the RWA was modeled that went unnoticed until flight. For sun-point safe-mode, arguably the most critical aspect of the ADCS design, a completely independent model was developed outside of the ADCS team. It uncovered issues that were able to be fixed prior to launch.

CYGNSS – LL-048: Requirement document ownership	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 2.0 Systems Engineering
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	2. No
Lesson:	Upon creation of any new requirements document, identify a single owner. Establish clear expectations for document upkeep over the course of the project including timely updates and completion of verification planning/closeout efforts. The owner must understand and commit to the process. If the owner leaves the project, a new owner must be identified.
Description of Driving Event:	Requirements documents co-authored by multiple persons, followed by confusion/debate over who is responsible for updates, leads to delays in updates and sub-par verification planning.

CYGNSS – LL-049: Contract initiation	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	2. No
Fab Phase:	2. No
I&T Phase:	2. No
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 1.0 Project Management
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	2. No
Lesson:	New projects: Don't be in a rush to get the Formulation agreement out and the SOW and deliverables agreed to in order to be put under contract. Before the contract is in place, is the time that you can tailor requirements. This is especially important for Class D missions. And yes, getting the requirement stake holders to agree to any tailoring is very difficult.
Description of Driving Event:	SOW negotiation at LaRC and subsequent tailoring of the FAD with NASA HQ

CYGNSS – LL-050: Battery safety: train, document, inspect	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	2. No
WBS Element:	WBS 3.0 Safety and Mission Assurance
Components - Primary (if applicable):	EPS - Battery
Components - Secondary (if applicable):	-
Priority:	1. High
Big Picture LL:	2. No
Lesson:	Develop and implement training program for Battery safety, both with respect to human safety and product safety
Description of Driving Event:	See battery related NCR's. Special attention needs to be taken when dealing with a live battery. Processes, procedures, GSE, personnel, etc. all must take this into account.

CYGNSS – LL-051: PI Management of implementing institution: detailed baseline change requests	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 1.0 Project Management
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Using detailed Baseline Change Requests to document changes to the project provides the PI increased visibility into the prime's costs, schedules, and project execution.
Description of Driving Event:	BCR's provide a good way to keep the PI in the loop for any scope changes.

CYGNSS – LL-052: PI management of implementing institution: hold project reserves at PI institution	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 1.0 Project Management
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Holding project reserves at the PI institution increases the PI's visibility into project execution in general, and budget details in particular.
Description of Driving Event:	PI is ultimately responsible thus PI institution should hold the reserves.

CYGNSS – LL-053: PI science team management: delegation of PI duties	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 4.0 Science
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	The PI should consider appointing several deputy PI's as science team managers who can lead and manage science team activities in different areas such as algorithm development, simulations, applications, etc.
Description of Driving Event:	PI has so much on his plate that he needs to delegate to be an effective project leader.

CYGNSS – LL-054: PI science team management: set up of science team contracts	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 4.0 Science
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Science team contracts should be set up with specific deliverables and for conditional renewal at regular intervals with provisions for adjustment of statement of work.
Description of Driving Event:	Definition of specific deliverables such as regular progress reports, inputs to support of major reviews, inputs to science team meetings, etc. is important. While it may be more obvious for contracts calling for delivery of hardware, science team contracts should include such specifics as well to ensure you get what you really need by the date you really need it. Setting up science team contracts for conditional renewal at regular intervals (e.g., bi- annual) accommodates changes in project needs. Statements of work can be modified or PI can elect not to renew contracts.

CYGNSS – LL-055: Define and communicate parts requirements across the project	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	2. No
I&T Phase:	2. No
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 3.0 Safety and Mission Assurance
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Ensure design engineers understand the kinds of parts available for use and the limitations.
Description of Driving Event:	On CYGNSS, not all commercial parts were acceptable and most actives had to be evaluated by a SME on a case by case basis, which was a challenge during design

CYGNSS – LL-056: Challenges of using part types different than vendor is used to	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	2. No
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 3.0 Safety and Mission Assurance
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	SwRI's design and fab process was built around hermetic standard space parts. Getting away from this generated hurdles in several places
Description of Driving Event:	• Use of commercial parts generally results in pure tin. Mitigation approach must be determined and accepted • PEDs (plastic encapsulated devices) are the rule, rather than exception • Use of commercial and PEDs led to Complications to thermal design and analysis at the circuit board level • Introduces unique manufacturing considerations at the circuit board level. Component packages often different from traditional space parts. Introduction of plastic packages to a manufacturing process designed for ceramic packages.

CYGNSS – LL-057: Early radiation evaluation is paramount for proper parts selection	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	2. No
I&T Phase:	2. No
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 3.0 Safety and Mission Assurance
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Radiation evaluation is paramount
Description of Driving Event:	Radiation evaluation has to come early and before parts are assessed from a parts quality perspective. If data is not available, project must decide between changing parts and testing the part (or assembly (for TID only)

CYGNSS – LL-058: Issues with modern software source control systems	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.5 Microsat Flight Software
Components - Primary (if applicable):	FSW - Flight Software
Components - Secondary (if applicable):	MOC Systems
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Carefully select, configure and implement FSW and GSW source code control systems, processes and procedures. Determine how best to use the system to meet needs in spite of less-than-desirable feature sets. Document how the tools will be used and train the staff.
Description of Driving Event:	All modern software CM systems (e.g. SVN, Mercurial, Git) were developed by and for the distributed, open-source community. The way these tools work is advantageous for that community, but lack many of the features that are important and very helpful in more critical s/w development efforts (like FSW) and that have smaller development teams. Some of these missing features include: lack of file checkout feature/requirement, baseline tags affect the entire repository instead of only the module/CSCI you are baselining, some tools lack the ability to automatically insert the file version # into the file when it is checked in, some tools don't even have file-, module-, or even system-level revision #s (e.g. Git only has long hash codes that are cumbersome to use in place of a revision #).

CYGNSS – LL-059: Include the SCID in S/C- specific uploadable tables	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 6.4 Comm. & Data Subsystem
Components - Primary (if applicable):	FSW - Flight Software
Components - Secondary (if applicable):	MOC Systems
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Include a field that contains the spacecraft ID (SCID) in any uploadable table containing spacecraft-specific parameters in constellations.
Description of Driving Event:	The CCSDS protocol is such that any command received by one spacecraft that is intended for a different spacecraft will be rejected based on the SCID. However, if that command (or series of commands) contains a table upload, the command(s) will be accepted even if the table is wrong (i.e. contains parameter values for a different spacecraft in the constellation). This occurred in one case on CYGNSS, and the issue was resolved via an improvement in ground ops procedures. However, this could be further improved by adding the SCID to the tables themselves.

CYGNSS – LL-060: Development of a prototype spacecraft provides risk reduction	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	2. No
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 2.0 Systems Engineering
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	The early development of the Engineering Model spacecraft was a huge success for CYGNSS. It proved extremely valuable in many ways. While the fidelity of the EM proved very useful, future projects should consider an even earlier prototype spacecraft with less rigorous fidelity in addition to the later high fidelity model. This will allow and enable early design development and critical design decisions.
Description of Driving Event:	None, mainly hindsight. Not all development efforts need the fidelity offered by the EM based test bench. The development of an early prototype would allow potential future implementation of a lower fidelity test bench to offload critical testing later in the project

CYGNSS – LL-061:Autonomous solar array deployment via RTS worked well	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	2. No
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	2. No
WBS Element:	WBS 6.5 Microsat Flight Software
Components - Primary (if applicable):	FSW - Flight Software
Components - Secondary (if applicable):	SMT - Solar Array
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Autonomous deployment of Solar Arrays via Relative Time Sequence (RTS) 10 minutes after separation worked well to ensure that solar arrays were deployed on all 8 S/C ASAP.
Description of Driving Event:	Solar array deployment is considered a critical event that requires real-time TLM coverage per NASA GOLD rules (1.14), but allowing autonomous deployment greatly simplifies operations during LEOps and is equally, if not more, reliable than real-time commanding during a ground contact. After a year of on-orbit operations, RTSs have proven to be the most reliable method of ensuring that a sequence of commands is executed as intended. Real-time CMD & TLM can be impeded for a variety of reasons and there is no additional TLM available in real- time that is not also stored on the S/C for purposes of verifying deployment. Further, there are only so many possible ground passes that must be shared across the 8 S/C. With autonomous solar array deployment prior to the first contact of each S/C, verification can commence immediately upon acquisition of signal and the step of commanding the deployment is only needed as a contingency.

CYGNSS – LL-062: Remote desktop, telemetry broadcast, and ITOS-mons	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 7.0 Mission Operations
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Ensure enough resources are available for LEOps period. We ended up scaling up the number of machines we had for remote viewing.
Description of Driving Event:	Being able to see telemetry from remote is essential to operations. Our system broadcasts to over 10+ machines to allow engineers to view telemetry.

CYGNSS – LL-063: Fleet context in ITOS proved beneficial	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	2. No
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 7.0 Mission Operations
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	The fleet/context features of ITOS proved extremely valuable.
Description of Driving Event:	These features of ITOS allow the Ops team to use the same database which simplifies configuration management, allows multiple S/C to be seen at once, and allows the LEOps and Ops teams to rapidly switch between spacecraft contexts when performing back-to- back passes on separate spacecraft which occurs frequently during LEOps.

CYGNSS – LL-064: Utilize AI&T and FSW scripts for Ops as much as possible	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	2. No
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 7.0 Mission Operations
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	The entire end-to-end command and telemetry flow, C&T database, scripts, trending, data processing should be instituted at the beginning of I&T and carried through with minimal changes to the end of mission. This both reduces work and increases confidence in and familiarity with the operational system.
Description of Driving Event:	On CYGNSS we did try to utilize previously created STOL procs and procedures. In data processing we didn't utilize previously written code; instead we re-wrote data processing in a different language all together.

CYGNSS – LL-065: When building and testing more than one item, automate as much as possible	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 10.0 System AI&T
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	One of the key advantages of constellations is they afford the possibility of automation to minimize test time and test labor. With single spacecraft builds, it is usually not beneficial to spend funds on automation.
Description of Driving Event:	One of the key pieces of automation we employed was a test set for the avionics that was computer controlled and allowed automated testing of the multiple sets of avionics while minimizing labor and mistakes.

CYGNSS – LL-066: LV will want test verified analytical model typically before it is available	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	2. No
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.6 Struct., Mech. & Therm.
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	LV/KSC Coupled Loads Analysis (CLA) is a catch-22. LV/KSC wants the analytical model to be as accurate as possible and verified by test. The catch is to be able to meet this requirement puts the delivery later than the LV/KSC would like.
Description of Driving Event:	In almost all NASA missions, CYGNSS included, vibration testing of the flight segment is one of the last tests before delivery to the launch site and this test is required by LV/KSC to have a test verified analytical model. This forces the CLA to always be a schedule driver. There really is no option here for the project other than to maximize the time between flight segment vibe and delivery, and to have LV/KSC speed up the CLA process.

CYGNSS – LL-067: Cubesat vendors may not be here in 3 years	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	2. No
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 1.0 Project Management
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Cubesat vendors are often new, small entrepreneurial companies that may not exist in the future. If possible, it is great to have backups available.
Description of Driving Event:	Our Torque Rod (TR) vendor went out of business about 6 months before the 27 flight rods were scheduled to be delivered. We ended up scrambling and came up with two different alternate suppliers as risk reduction. Both vendors ended up coming through meeting the schedule demands. Our criteria for the backups were flight experience with TRs and ability to quickly get them under contract for the TRs. Using institutions that were already under contract for other activities and then only having to do a contract mod greatly expedited the contractual process.

CYGNSS – LL-068: Come up with simple naming convention and stick to it	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 1.0 Project Management
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	When dealing with constellations, a simple naming convention should be established early and applied project-wide. Different names by different groups or for different phases of the project creates confusion, creates more work, and potentially creates mistakes.
Description of Driving Event:	The names for each observatory should be established early in the project and the simpler is better.

CYGNSS – LL-069: CMC and KDP reviews pull team leads away from project work	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 1.0 Project Management
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Per 7120.5E, there are several different types of reviews. Peer reviews and life cycle reviews (i.e. SRR, PDR, CDR, etc.) impact the whole team and are addressed in another lesson learned. CMC and KDP reviews while not impacting the whole team do pull team leads away from day-to-day project activities for 6 to 8 weeks at every life cycle review
Description of Driving Event:	First, CMC and KDP reviews should be minimized. This should be addressed in the very early project formulation (or before). Second, if the reviews are not eliminated, they should at least be combined.

CYGNSS – LL-070: BCR and invoice review	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 1.0 Project Management
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	1. The review process for BCR's took lots of effort and time, more than planned. (See LL-035) 2. Likewise the stringent review of invoices for correct charges was a larger than planned effort.
Description of Driving Event:	1. Much time was spent developing a BCR process and the necessary forms. Required sign-offs were important as they limited unnecessary scope changes. Administrative burden and time was added to the review process due to proprietary nature of a subcontractor's rates, as ONR or NASA was needed to review the budgets. This process could have been streamlined with an NDA. 2. Stringent guidelines were followed for review of all expenses. All invoices were reviewed and questioned/revised if there were discrepancies.

CYGNSS – LL-071: Cost estimating/budgeting	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 1.0 Project Management
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	The cost estimating and budgeting process is something that starts with the proposal and lives though the life of the project. Lesson Learned: Don't underestimate the required effort. Any kind of standardization or automation will likely pay for itself.
Description of Driving Event:	1. Mandatory budget templates were used to make baselining and reporting easier. NASA B.3 table was used for budget summary and the implementing institution budget template was used for detailed budgets at lower WBSs. 2. Reserve allocations were reviewed after major milestones (KDPs, baselining) and updated as necessary to reflect risk. Previous industry studies were utilized to determine best practices. 3. Budgets were developed using a bottoms up methodology, and detailed Basis of Estimates (BOEs) were used to document the budget justification. 4. The ICE models need to be updated to allow for a distributed PM approach without penalty. (UM needed to provide ~$2M in cost sharing support to support the need for PM expenses at both the PI and the implementing institution.)

CYGNSS – LL-072: Don't automate SOC systems too early	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	2. No
WBS Element:	WBS 4.0 Science
Components - Primary (if applicable):	SOC Systems
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Develop a set of focused applications first. Automate after they are stable.
Description of Driving Event:	At the beginning of the project, processing automation was designed into the SOC software. As the design evolved, we realized that we didn't understand the low-level processes well enough to automate them. So, we concentrated on developing a set of focused command-line applications that could be executed manually or by scripts. During testing and early operations, we processed science data by manually executing the applications. After the applications were stable, we automated the process using scripts and time-based automatic execution (Linux cron jobs).

CYGNSS – LL-073: SOC should always get all engineering telemetry	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 4.0 Science
Components - Primary (if applicable):	SOC Systems
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Even if you have no immediate need for it, get all the telemetry from the MOC.
Description of Driving Event:	The MOC-SOC ICD originally called for the MOC to send only science telemetry packets to the SOC. Later we requested that the MOC also send all the engineering telemetry to the SOC. The engineering telemetry proved useful for anomaly resolution and other unanticipated situations.

CYGNSS – LL-074: SOC should process telemetry at the lowest possible level	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 4.0 Science
Components - Primary (if applicable):	SOC Systems
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	If possible, keep the MOC out of the science telemetry processing business. Accept science telemetry at the lowest possible level. Expect malformed, out-of-order and duplicate packets.
Description of Driving Event:	The MOC-SOC ICD originally called for the MOC to perform telemetry packet-level filtering, sorting and duplicate deletion before transmission to the SOC. During early operations, the MOC was extremely busy commissioning the spacecraft. Processing telemetry packets for the SOC became a low priority. Shortly after launch, we modified the SOC software to accept malformed, out-of-order and duplicate telemetry packets from the MOC. This system continues to work well.

CYGNSS – LL-075: The SOC should expect telemetry surprises	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 4.0 Science
Components - Primary (if applicable):	SOC Systems
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Since FSW is much more difficult to modify than ground software, it's usually up to the SOC to process the science telemetry any way it comes. SOC software should be designed for flexibility and maintainability.
Description of Driving Event:	The bulk of the SOC processing software was developed before receiving any FSW- generated telemetry. We expected that FSW-generated telemetry would differ somewhat from the interface document description, but it was impossible to anticipate what those differences would be. So, we programmed defensively, making the software as modular and flexible as possible. This effort paid off during early operations when we were able to program around unexpected telemetry features without significant design modifications.

CYGNSS – LL-076: Flag and deal with questionable packet timestamps	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 7.0 Mission Operations
Components - Primary (if applicable):	SOC Systems
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Ensure that all packet time stamps are valid or that unreliable time stamps are flagged by flight software. In addition, design ground processing fallback methods to deal with bad time stamp packets.
Description of Driving Event:	The SOC processes telemetry packets contained in files received from the Mission Operations Center (MOC). The packets themselves are produced on-orbit by the flight software (FSW) and are unaltered by the MOC. Early in the project, the telemetry packets contained a time-quality field which indicated the reliability of the packet time stamp. Later, during FSW development, the time-quality field was replaced by another field that was deemed more important at the time. The SOC software was developed assuming reliable time stamps, but we were surprised to receive malformed, invalid and out of order time stamps. Sorting this out on the ground cost a significant amount of SOC development time and led to some early loss of data.

CYGNSS – LL-077: Maintain a functional description of the ground processing software	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 4.0 Science
Components - Primary (if applicable):	SOC Systems
Components - Secondary (if applicable):	MOC Systems
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Write and maintain a software functional description based on the requirements, and update it as the requirements and design evolve. The science team then has a readable, detailed, up-to-date description of the SOC software and can request changes in that context. SOC developers can verify the software against the functional description.
Description of Driving Event:	The CYGNSS SOC received science data processing requirements in the form of Algorithm Theoretical Basis Documents (ATBD), example Matlab code and email feature requests from various science team members. The SOC then used those requirements to develop the science processing software. During software development and after launch, the science team requested many processing changes, but the original requirements documents fell out of date. The only up-to-date description of the processing software was the source code itself. When a science team member had a question about the processing software, a SOC software engineer needed to review the source code to answer the question. This process worked, but was time-consuming and sometimes led to misunderstandings and confusion.

CYGNSS – LL-078: For constellations thoroughly assess S/C-unique parameters	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	2. No
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 2.0 Systems Engineering
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Very carefully assess and discuss with each subsystem lead, what parameters may wind up being S/C-specific.
Description of Driving Event:	While an assessment of S/C-specific parameters was made, throughout most of Phase C most subsystem leads were anticipating very little in terms of S/C-specific parameters and settings. This turned out to be naive, resulting in a number of parameters having to be added to the settings table even post-launch, which also forced RTSs to be S/C-specific for some period of time which was not planned for by the MOC.

CYGNSS – LL-079: Use of "intentional malware" to interface with dynamics simulator worked well	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.5 Microsat Flight Software
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	The CYGNSS FSW used an innovative approach, borrowing techniques from malware, to allow the exact same FSW image to be used during closed-loop model-based ADCS simulation tests on the observatories even though the small size of the microsats precluded attaching the dynamics simulator in place of the actual ADCS components. For more detail, see Killough, et al, Simulators, Software and Small Satellites: Testing in Tight Space, IEEE Aerospace Conference 2016.
Description of Driving Event:	Microsats are so small that once buttoned up, it is difficult or impossible to connect model simulators in place of components to conduct closed-loop ADCS tests and algorithm verification. Using a test version of the FSW introduces risk since you are testing with a different version of the FSW than you fly with. The approach taken on CYGNSS alleviated this issue.

CYGNSS – LL-080: Include hi/low watermarks for key telemetry in per-pass packet	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	2. No
I&T Phase:	2. No
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.5 Microsat Flight Software
Components - Primary (if applicable):	FSW - Flight Software
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Include high/low watermarks for key telemetry in the once-per-pass engineering TLM packet.
Description of Driving Event:	Including watermark telemetry helps to quickly identify whether a given key parameter has gone out of limits without having to wait for all the telemetry to be downlinked and processed.

CYGNSS – LL-081: Include C&DH/FSW teams in all data-related ICDs	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	2. No
I&T Phase:	2. No
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 9.0 Ground Segment
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Include the H/W and S/W C&DH/FSW teams in all data-related ICDs.
Description of Driving Event:	Some agreements, CONOPS and ICDs were established by the MOC and between the MOC and SOC that did not take into consideration the implementation of the on-board data system. Including the C&DH/FSW teams in those CONOPS and ICDs would help prevent designs and agreements from being established that are not particularly compatible with on-board designs. Once agreements are made some may resist changing them resulting in ground processing designs that may be more complicated than necessary in order to avoid changing those agreements.

CYGNSS – LL-082: Thermal design of small S/C is challenging due to small area for radiators	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.6 Struct., Mech. & Therm.
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Smaller spacecraft push for "racier" thermal design due to limited power and real estate for radiators. It is more important that the design "threads the needle". In the design process, allocate area for radiators and power for heaters. This may require more expensive coatings or thermal control devices.
Description of Driving Event:	CYGNSS design resulted in premium radiator coatings that had additional handling concerns.

CYGNSS – LL-083: Benefits and limitations of a structural thermal model (STM)	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.6 Struct., Mech. & Therm.
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	The use of an STM was valuable to calibrate the thermal mode early of the spacecraft. However, STM was not useful to capture any discrepancies related to electrical dissipation of components. See also LL-060.
Description of Driving Event:	The spacecraft thermal model had very little modifications needed on the flight thermal balance since STM testing provided valuable information. However, it is a worthwhile question pondering if a more expensive qual unit would have been more useful since it may have uncovered component irregularities earlier.

CYGNSS – LL-084: Disturbance torques from magnetic moment	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.2 Microsat Sys. Eng.
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Even if the science payload doesn't impose magnetic cleanliness requirements, an unintended magnetic dipole on the spacecraft may cause attitude control issues (i.e. implement a magnetic control plan).
Description of Driving Event:	A pitch oscillation behavior on the CYGNSS S/C has been attributed to a large magnetic dipole likely existing on all of the S/C. Analysis suggests that the dipole is fairly constant in magnitude (constant on any 1 S/C, but significantly different across the 8 CYGNSS S/C) and fixed in direction relative to the S/C body coordinate frame. The source of the dipole is still under investigation. The behavior has largely been curbed via increasing various controller gain settings in the ADCS flight software, but with the negative consequence of reduced stability margins.

CYGNSS – LL-085: Small separation system footprint can cause high stresses and high tip off angular rates	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.6 Struct., Mech. & Therm.
Components - Primary (if applicable):	ADCS - Torque Rod
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	A small footprint drives mechanical stresses and release shock levels to high values and can increase tip off angular rates.
Description of Driving Event:	Early evaluation of couple loads analysis would have allowed for a better trade of options to deal with issues. See also LL-115.

CYGNSS – LL-086: Don't underestimate the challenges of separation connectors	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.6 Struct., Mech. & Therm.
Components - Primary (if applicable):	Harness
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Separation connectors, especially on small satellites, can present various challenges, so don't underestimate the level of attention that will be needed. And different types of separation connectors present different challenges.
Description of Driving Event:	CYGNSS started with a large number of conductors, as requested by systems engineering, in the separation connector. This led to a connector so large that it couldn't be accommodated in high stress area). The structure was redesigned to accommodate two connectors, but that broke the separation kinematics (difficult to deal with tolerances/uncertainties). We also had significant problems with the supplier literature not matching the hardware availability and performance. Simply put, it was not a zero-force connector - so it had to be characterized (repeatability was not great) and included in the separation analysis.

CYGNSS – LL-087: Communication across team is paramount	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 2.0 Systems Engineering
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Communication across the team on what are the requirements is very important. Also make sure that everyone clearly understands the requirements especially for outside institutions or for folks that have a specific niche discipline (thus more isolated from the team).
Description of Driving Event:	Initial thermal modeling of safe mode wrongly did not include a spinning spacecraft. The impact turned out to be minimal, but it was a weakness to not be included.

CYGNSS – LL-088: L-band antenna optical surface properties inaccurate from vendor	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.6 Struct., Mech. & Therm.
Components - Primary (if applicable):	DDMI - Antenna
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	It is important to have documented surface optical properties on all external items to ensure a good thermal model and that the components are sufficiently validated.
Description of Driving Event:	The initial alpha and emissivity for the L-band antennas was provided by the vendor to be emiss=0.8 and alpha=0.25. This was a suspicious value that it turns out the vendor did not have documentation for. Subsequent testing indicated values of emiss=0.76 and alpha=0.918. This meant that the antennas absorbed much more sunlight than initially modeled. This affected the spacecraft model to some extent, but the temperatures of the antennas were affected even more. The antennas had to be delta qual'ed to new temperatures late in the mission to ensure they could handle the expected environment.

CYGNSS – LL-089: PPT inefficiencies determined late in design and limited ability to thermally accommodate	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.6 Struct., Mech. & Therm.
Components - Primary (if applicable):	EPS - Peak Performance Tracker
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	A roughly 8 W increase (23% increase) of heat had to be accommodated for late in the design. Should have held an additional 15-30% of margin (thermally) on the power early in the design instead of basing design on MEV.
Description of Driving Event:	Once tested, the PPT design proved to be much less efficient than the MEV predicted early in the design. Since the size of the radiators were basically fixed and would have required substantial redesigns to accommodate, the result was using high performance paints that were more difficult to handle and also the batteries were pushed higher in temperatures. This resulted in further work to document that the lifetimes of the batteries would still be sufficient.

CYGNSS – LL-090: Star tracker accuracy limited without alignment cube.	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.6 Struct., Mech. & Therm.
Components - Primary (if applicable):	ADCS - Torque Rod
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	While the Star Tracker detector used by CYGNSS may have attitude knowledge to arc seconds, the star tracker did not include any alignment cube so one cannot deconvolve the reported pointing of the star tracker (quaternions) to its mounting on the spacecraft. Basically the star tracker detector can resolve quaternions very accurately but the uncertainty in how detector is mounted relative to the star tracker and the tracker relative to the spacecraft is best case several degrees. Lesson learned: generic-don't believe what the vendor says; specific-plan for an alignment test that does not depend on vendor fiducials.
Description of Driving Event:	On CYGNSS, we had to develop special test software to use the star tracker as a “camera” and then set up a pre and post laser alignment test before and after environmental test. Not only was all of this extra testing and software expensive (on the order of what a star tracker costs) and a schedule driver but as with many star tracker issues, it was a change in what they delivered. Originally they said that the star tracker had an inner baffle that was mirrored pointing outward that could be used for at pitch and yaw calibration. In the end, the star tracker vendor did not do any pointing calibration between the star tracker detector and the mirror so we had to develop and perform our own test.

CYGNSS – LL-091: Hardware in the loop testing sounds good but can be difficult to implement	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	2. No
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.8 ADCS Subsystem
Components - Primary (if applicable):	ADCS - Star Tracker
Components - Secondary (if applicable):	ADCS - Reaction Wheel
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Lack of hardware in the loop testing can lead to operational issues / surprises
Description of Driving Event:	While it is very easy to say that more testing is always better, on a class D cost capped mission it is impossible to perform all the testing that is desired. On CYGNSS, early on for cost reasons we consciously elected to not do ADCS hardware in the loop testing but rather rely on simulation. In hindsight, almost all of our on orbit ADCS issues would have not been uncovered by hardware in the loop testing. The only issue that might have been discovered was the reaction wheel direction not matching the ICD.

CYGNSS – LL-092: Battery state-of-charge measurement needs to be unambiguous	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.7 EPS Subsystem
Components - Primary (if applicable):	EPS - Battery
Components - Secondary (if applicable):	EPS - Peak Performance Tracker
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Battery voltage measurement alone may not be adequate for battery State-of-Charge determination due to very high sensitivity to measurement errors. May need
Description of Driving Event:	Battery voltage measurement was not reliable as originally designed to unambiguously indicate battery SoC. Large discrepancy in reported battery voltage under different loading/charging conditions. The measurement point may also be to blame. Had to implement a battery state-of-charge estimation algorithm (integrating current in/out of battery, etc.) in FSW after launch because the bus voltage TLM did not provide an unambiguous indication of battery SoC. Loadshed FDC needed a more reliable measure of battery SoC.

CYGNSS – LL-093: Use more derived TLM for limit checking	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	2. No
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 7.0 Mission Operations
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Consider differences between I&T and on-orbit telemetry limits and use derived/pseudo telemetry as needed to define limits that will work for both I&T and flight. See also LL-123.
Description of Driving Event:	Limits defined at launch were mostly carried over from AI&T resulting in many changes being needed post launch. Limit checking against individual telemetry points cannot always meet intent, but often some sort of "derived" or "pseudo" TLM can be defined that will. This effectively allows definition of mode-specific limits and early creation of limits that will work for both I&T and flight. Note: ITOS TLM database re-compile is needed when creating new derived TLM, so another thing to do sooner than later.

CYGNSS – LL-094: Implementing automated flow of data and products is worth the investment	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 9.0 Ground Segment
Components - Primary (if applicable):	MOC Systems
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Implementing the data management system to flow products and data between various end points was extremely beneficial in dealing with all the flows necessary to support a constellation.
Description of Driving Event:	It is easy to make mistakes when typing lots of information as occurs when staging files to various locations throughout operations. Implementing the automated data management system was a big help.

CYGNSS – LL-095: Staffing for command and control system setup and maintenance	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 7.0 Mission Operations
Components - Primary (if applicable):	MOC Systems
Components - Secondary (if applicable):	FSW - Flight Software
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Using the same command/TLM system throughout AI&T and Ops is beneficial - but, it is necessary to create the proper organization (staff) to get the system (ITOS in our case) configured in a manner that takes the needs and requirements of the different groups into consideration.
Description of Driving Event:	FSW, AI&T, and MOC were all using ITOS - but with all groups having small teams and focused on their core requirements, many times configurations were developed by a specific team to meet their needs - and then things often had to be redone as requirements from other teams were not being met. Establishing a more centralized team - perhaps within the GSE group - that could gather requirements from all the various stake holders and work to develop a configuration to best meet them can likely save having to rework things at different phases of the project.

CYGNSS – LL-096: Practice LEOps as soon as possible	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	2. No
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 9.0 Ground Segment
Components - Primary (if applicable):	MOC Systems
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Practice LEOps as soon as possible to determine if the tools available can support the different environment presented in early orbit operations.
Description of Driving Event:	MOC planning tools were geared towards the 'nominal operations' environment and in some cases were too rigid to meet the requirements of the highly dynamic early operations environment. Work arounds had to be quickly developed to deal with the early orbit communication planning. LEOps rehearsals were very helpful in bringing out potential issues that may not be as apparent until actually running through the paces.

CYGNSS – LL-097: Spacecraft dynamic simulator was useful as a mission simulation and software validation tool, but had no independent verification value	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.8 ADCS Subsystem
Components - Primary (if applicable):	FSW - Flight Software
Components - Secondary (if applicable):	EGSE - SDS
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	The Spacecraft Dynamic Simulator was valuable in its applications to MSTs, rehearsals, MOC testing, and other applications. However the internal models were developed by the same outside institution that developed the ADCS FSW. This meant that it would always operate optimally compared to what ADCS was designed to handle. More value could have been gained by plugging the ADCS into an independent set of simulations and models. This was done to a limited extent using Satellite Dynamic Toolkit for sun point mode, which proved very valuable. See also LL-047.
Description of Driving Event:	Independent verification of sun point proved very valuable. It would be good to plan to do this more comprehensively in the future.

CYGNSS – LL-098: Have all stakeholders involved in setting GSE definition and requirements	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.9 Microsat GSE
Components - Primary (if applicable):	EGSE - GSS
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Make sure that all stakeholders are involved in setting GSE / simulator requirements and expectations. See also LL-041.
Description of Driving Event:	Even if the proposed spacecraft / payload is "simple" on paper, developing the required GSE to verify / validate the system can be challenging. As the CYGNSS project matured, the capabilities required of the GPS Satellite Simulator (GSS) evolved (e.g. need for a longer duration simulation). While modifications were made to accommodate, the changes required substantial effort. Additionally, the constellation aspect of multiple satellites present opportunities and challenges in determining the number of GSE required. Spares should be carefully considered.

CYGNSS – LL-099: Implement mnemonics naming convention asap	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 10.0 System AI&T
Components - Primary (if applicable):	MOC Systems
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Implement naming convention for telemetry and script mnemonics as soon as possible. Ensure MOC and I&T team agree on implemented scheme
Description of Driving Event:	There was a substantial change to mnemonic names in database during transition from EM to FM. That in turn forced undesirable updates to prior developed scripts. Such enormous task can be avoided if planned accordingly. It is also problematic for trending if the same TLM has different names.

CYGNSS – LL-100: Inrush requirements are important even for COTS	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 2.0 Systems Engineering
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Ensure the power supply is capable to support COTS unswitched components during initialization by implementing inrush requirements that can be used to select COTS components or design power supply accordingly. See also LL-008.
Description of Driving Event:	I&T and FSW team could not communicate to COTS ADCS components during initial testing and blamed software. However, it was discovered that COTS components remained in reset (therefore did not respond to FSW poling) because the inrush exceeded power supply capabilities at start up.

CYGNSS – LL-101: PLRA definition: No time to be a hero	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	2. No
I&T Phase:	2. No
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 1.0 Project Management
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Define achievable baseline and threshold requirements (when in doubt, err on the side of under promising). Early in the project (Pre-Phase A), there was close coordination between CYGNSS and the NASA LARC / HQ team to define achievable baseline and threshold requirements. The majority were based off either the AO or CYGNSS proposal but the CYGNSS team did spend considerable amount of time reviewing and updating language. These remained relatively constant over the lifetime of the project and that stability made the milestone reviews much less painful than on other projects.
Description of Driving Event:	Milestone Reviews

CYGNSS – LL-102: Project schedule and EVM fully integrated with team	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 1.0 Project Management
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Project Schedule and EVM Planner should be co-located with team and knowledgeable about mission development.
Description of Driving Event:	Project Schedule and EVM Planner was fully integrated with team. Planner was knowledgeable in engineering and fabrication processes to offer and implement work around solutions to meet schedule milestones and project efficiency. Planner was able to monitor and provide bi-weekly support to CAMs of performance metrics and variances to take action on. Planner was and should be Co-located with PM, MSE, DPM, and AI&T leading to good communication and quick response to changes.

CYGNSS – LL-103: Sun sensors connected to RWAM violated minimum hardware set requirement	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	2. No
I&T Phase:	2. No
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.8 ADCS Subsystem
Components - Primary (if applicable):	ADCS - Reaction Wheel
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Due to limited interfaces on the CYGNSS centaur the RWAM module was ordered to include an interface for several sun sensors. While this was convenient and driven by the board design, it violated the minimum hardware set requirement on the ADCS system by forcing the CSS through the RWAM. This shouldn't have been allowed if the requirement had been properly enforced. See also LL-036.
Description of Driving Event:	Lack of interfaces in heritage CDH board design drove sun sensor interface to RWAM.

CYGNSS – LL-104: Additional requirements on other subsystems if used for ADCS purposes	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	2. No
WBS Element:	WBS 6.8 ADCS Subsystem
Components - Primary (if applicable):	EPS - Peak Performance Tracker
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	If subsystem A is relying on data from subsystem B, subsystem A must set the requirements for subsystem B. And subsystem B must be aware of those requirements to be able to meet those requirements.
Description of Driving Event:	The decision to use the solar arrays as sensors on CYGNSS never went as intended and led to several issues during the project, ultimately culminating in a limited redesign of the Safe Mode/ Sun Point logic. While ADCS used the SA telemetry as sensors, the EPS had no requirement to produce telemetry at some defined standard of quality or documentation. This lead to poorer quality than expected in the telemetry available and disconnection between the ADCS and EPS subsystems. Additional requirements would have influenced the testing procedures of the PPT at a minimum and possibly the design of the solar arrays themselves. Reassessment of PPT/SA signal traits late in project demonstrated weaknesses in ADCS sun point logic and simulation as well as very poor quality in SA related telemetry.

CYGNSS – LL-105: ADCS financial budget contributed to weaknesses in ADCS design	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	2. No
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.8 ADCS Subsystem
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Early versions of the CYGNSS ADCS design were oriented around defining the minimum hardware set that could meet requirements. This evaluation did not take into account situations, like sun outages, the ADCS would encounter (at least not accurately). The early budget for the system made sense for the original hardware set, but as issues with the architecture became apparent the budgetary constraints drove (in part) the selection of new hardware. While not solely responsible for the performance issues with the FM systems it did influence decisions that left in design weaknesses/vulnerabilities. Budget and cost are important and ADCS can't have infinite funds, but early cost constraints may have contributed to the increase of other costs in later project phases. See also LL-004.
Description of Driving Event:	Analyses in design reviews showed the knowledge and control impacts of sun outages to be greater than anticipated. Subsequent changes to the ADCS system we driven by cost primarily, with performance improvements oriented towards being adequate instead of eliminating the scenario.

CYGNSS – LL-106: Key unique external connectors	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 10.0 System AI&T
Components - Primary (if applicable):	Harness
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Follow Gold rule 2.13 for uniquely keyed connectors.
Description of Driving Event:	The side panel EGSE connector and RF Safe/Arm connector were similar connectors but were not uniquely keyed. There was a preliminary plan to "jam" one of the pin locations to make them keyed but we didn't follow through. There was at least one incident where an EGSE connector was installed in the Safe/Arm connector locations. No damage came out of this, but it did require several hours of unplanned investigation to make sure there was not a fault condition.

CYGNSS – LL-107: Hazardous operations to test procedures	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	2. No
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 10.0 System AI&T
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Hazardous operations identified in the SHA or hazard reports should be better identified within test procedures.
Description of Driving Event:	High current event with battery

CYGNSS – LL-108: Good SE practices led to smooth DMAU-ASE-Harness development	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	2. No
WBS Element:	WBS 6.9 Microsat GSE
Components - Primary (if applicable):	Harness
Components - Secondary (if applicable):	DM - DMAU
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	If you follow good SE practices, you will have less problems.
Description of Driving Event:	Early engagement by the DMAU/ASE/Flight harnessing team with the greater CYGNSS systems engineering and launch vehicle (LV) staff allowed for efficient development of that subsystem with minimal rework. Concept of operations were discussed with lead engineers of the other affected subsystems to understand all the use cases from ground integration, ground testing, ferry flight and launch-day operations; including as-needed diagnostic operations such as CYGNSS observatory software and table uploads. Early interviews and intermediate demos were performed with the Pegasus lead engineer to help develop the DMAU and ASE user interfaces. Deployment Module (DM) staff provided valuable insight for the requirements that drove the flight harnessing design which connected LV interfaces through the DM/DMAU to the CYGNSS observatories. Testing during flight segment I&T was thorough; first as separate components (i.e., DMAU, ASE and harnessing separately), then assembled for end-to-end testing prior to integrating with the observatories. The above systems engineering practices helped reduce the risk in this subsystem, and provided reliable functions to support the flight segment.

CYGNSS – LL-109: DMAU - Measure current in the power leg rather than return leg	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.9 Microsat GSE
Components - Primary (if applicable):	DM - DMAU
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	The DMAU measured the charging current for each of the eight S/C in the return leg. Current data was ambiguous when more than one S/C was being charged. This was decided due to the sense resistor derating requirements, and the incorrect assumption that the returns would be independent of each other in the flight segment configuration.
Description of Driving Event:	It was discovered that all the returns were tied together in the flight segment, and that there would be ambiguity as to the current measurement to each S/C if more than one S/C were being charged. The flight segment tied all the returns associated with charging together.

CYGNSS – LL-110: Use common info sources and auto-generation for flight and ground software	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 6.5 Microsat Flight Software
Components - Primary (if applicable):	FSW - Flight Software
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Creation of tools that auto-generated tables, header files and databases for multiple teams was incredibly useful. As an example: Python scripts were written that pulled in the Command and Telemetry spreadsheets, and output two products: (1.) an auto-generated .h file for inclusion of the FSW, defining the CMD/TLM packet definitions, and (2.) an auto- generated set of .rec files for ITOS, also defining the CMD/TLM packet structures. Other Python scripts were used for similar purposes. This approach, although it requires more time up front, was incredibly useful: 1. it minimized mistakes in hand-editing ground/FSW packet definitions, 2. it allowed the FSW team to know *exactly* where a particular telemetry point was assigned in the FSW source, and 3. minimized the risk in making a telemetry packet change.
Description of Driving Event:	Early AI&T and tight integration of ground and FSW databases drove the decision to do this, and it proved useful throughout the project.

CYGNSS – LL-111: Tag FSW baselines often, and keep all development on a source tree "trunk"	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 6.5 Microsat Flight Software
Components - Primary (if applicable):	FSW - Flight Software
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Throughout the project, almost all FSW development was done on one main trunk (as opposed to each developer creating branches). While this method has the possibility of leading to "hey you broke my code with that check-in", this result is mostly good, because it usually showed deficiencies in a modular design and testing when it did happen. In addition to minimizing branches, tagging of baselines was used often, with good results. Tagging often had several advantages: 1. baselines were well communicated between all subsystems (e.g. FSW, AI&T, SE, etc..) 2. it provided a target for the team to work for (i.e. v2.4 shall contain [X], [Y]), and 3. it allowed for quick identification of issues between builds (via comparison tools of full source tree deltas).
Description of Driving Event:	Defining a proper CM / tagging / baseline process is crucial to any good process (not just software).

CYGNSS – LL-112: FSW - templates, templates, templates!	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	2. No
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.5 Microsat Flight Software
Components - Primary (if applicable):	FSW - Flight Software
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Throughout the software development process, templates were invaluable. In particular, the following templates were found to be very useful: 1. Software Development Plan template (as modeled after previous well-run project plans) 2. Peer Review defect/issue spreadsheet template (used for requirement/design/code/test reviews) 3. Coding standard sample .c file template (used for defining a well-understood coding standard) 4. Design PowerPoint template (used for defining a FSW CSC design) 5. Unit Test template (used for defining the detailed contents of a unit test plan)
Description of Driving Event:	Templates are part of any good software development process.

CYGNSS – LL-113: Implement mandatory as-run closeout meetings	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 10.0 System AI&T
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Implement periodic, mandatory as-run closeout meetings or otherwise prevent old as-runs from getting ignored for too long. It's very difficult to disposition anomalies and otherwise close out paperwork when the testing occurred too long ago for anyone to remember details of what/why/who/when. This is not a new issue, but needs a new solution.
Description of Driving Event:	Paperwork closeout pre-ship is always a nightmare. Meeting schedule should not preclude doing this the right way.

CYGNSS – LL-114: Electronic test procedures work well for component integration tests	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 10.0 System AI&T
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Electronic test procedures (in DOORS for CYGNSS) can work well, particularly for component integration tests. Allows easy side-by-side comparison of measured values and/or scope shots across all as-runs instead of flipping through lots of paper.
Description of Driving Event:	Side-by-side compare of in-rush scope shots was useful in determining problem on a particular LVPS S/Ns. Additional advantages include the fact that anyone can easily pull up any as-run to view details without having to ask Document Control for a copy. And in DOORS, all changes are automatically tracked in the history including timestamp and user who made the change. This could also be taken a step further by linking the electronic test procedure step(s) to the particular requirement(s) being verified.

CYGNSS – LL-115: Low tip-off rate requirements are difficult to meet for SmallSats	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 2.0 Systems Engineering
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Small satellites will naturally have low rotational inertia. Very low tip-off rate requirements that can be met for larger more massive satellites using traditional separation systems will likely be much more difficult to meet for SmallSats. Designing EPS and ADCS to accommodate higher tip-off rates on SmallSats is recommended. This is exacerbated if you use the push off springs to establish constellation spacing (higher spring force is required).
Description of Driving Event:	SmallSats will be more sensitive to push-off force being offset from S/C CG as well as uncertainty in the push-off force due to phenomenon that is difficult to model accurately like friction/stiction in push-off spring assemblies and separation connectors. Tip-off performance is also not easy to test on the ground. It was discovered late in the project that the tip-off rate requirement carried since the proposal could not be verified and separation testing was not very repeatable (large scatter in results). Additional iterations of power and ADCS analyses were needed to relax the tip- off requirement and much more time and effort was spent on sep testing/analysis than was originally planned for.

CYGNSS – LL-116: Visual Inspection of components with directional installation requirements	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	2. No
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 3.0 Safety and Mission Assurance
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Ensure that components that have to be installed in a certain direction are positively inspected (with photographic evidence) to ensure proper orientation is achieved before component is covered up (in AI&T flow). A dedicated step in the relevant MPS is recommended.
Description of Driving Event:	Torque rods, magnetometer, RWAM, CSS, MSS, Coupler

CYGNSS – LL-117: Carry out extended duration testing and testing at all parts of mission calendar	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	2. No
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 2.0 Systems Engineering
Components - Primary (if applicable):	FSW - Flight Software
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Pay special attention to long duration time outs, end of year transitions, and leap year with additional inspections and long duration tests (if possible). Special corner cases and especially mission critical events if they are triggered by elapsed/relative time or UTC fall into this category.
Description of Driving Event:	SE and ATP/CPT/MST engineers need to institute process and procedure to ensure that tests simulating both long durations during the mission and all relevant dates during the mission are exercised. Both the 7-day timeout bug and the end-of-year bug would have been detected by such testing.

CYGNSS – LL-118: GOLD Rules required mass margin may be too high	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	2. No
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 2.0 Systems Engineering
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	With today's accurate 3D modeling of satellite structure, harnesses, solar arrays and avionics, the required GOLD margins are frequently too high causing the project to carry too much margin that in the end has to be handled as useless ballast. This is especially a problem if Engineering Models are built which further nails down the expected flight mass
Description of Driving Event:	CDR and PGAA

CYGNSS – LL-119: Automated self-test is efficient	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	2. No
WBS Element:	WBS 6.9 Microsat GSE
Components - Primary (if applicable):	EGSE and uSat EM Backplane
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Automated self-testing for certification more than pays for itself when you have multiple items (EGSE) used in many locations and certification is a frequent activity. See also LL-030.
Description of Driving Event:	With six complete complex EGSE test sets, having our Automated Self-Test unit allowed quick and efficient certifications when moving/connecting/disconnecting equipment and microsats

CYGNSS – LL-120: Government can change I/F with no recourse	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 7.0 Mission Operations
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	The government can change ICD interface requirements with no recourse. Example was CARA changing the IF with no say from CYGNSS flight dynamics. LL is don't be surprised if this happens and make sure that you have $ and schedule reserve to accommodate their changes.
Description of Driving Event:	CARA ICD changes

CYGNSS – LL-121: Avoid duplication of requirements	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 2.0 Systems Engineering
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Avoid having the same requirement repeated in more than one place. Any benefit is outweighed by the potential complications and additional overhead associated with maintaining the same requirement in more than one place.
Description of Driving Event:	Having experienced the pros/cons of different approaches for requirement flowdown, any benefits of flowing down a requirement, verbatim, through multiple levels (often justified as providing a "one-stop-shop" experience for a person/component/subsystem/organization) is outweighed by the potential complications and additional overhead. The advantages are less tangible than the additional burden, especially for a small SE team.

CYGNSS – LL-122: On-site support during AI&T	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	2. No
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 10.0 System AI&T
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	During time-critical AI&T activities, all subsystem cogE and SEs should be on site for quick response and decision making.
Description of Driving Event:	Geographically distributed team meant that key team members were sometimes not available. Hard to get timely decisions or issue resolution.

CYGNSS – LL-123: Separate static vs. dynamic items in C&T database spreadsheets	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 7.0 Mission Operations
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	CYGNSS used spreadsheets to define the commands & telemetry packets. Scripts were used to convert the spreadsheets into FSW C&T data structures and into ITOS DB files. This proved effective, but some improvements should be made on the next mission: 1. Separate static C&T definitions from more dynamic attributes such as conversions & limits. Having static attributes in the same file with attributes that can change during I&T made CM of the spreadsheets more difficult than otherwise necessary. 2. Define enumerations for all discrete command parameters and telemetry fields from the start to avoid numbers/hex values that are hard to interpret from appearing in PROCs. 3. Some telemetry fields are really bit fields where each bit indicates some status (enabled/disabled, fault/no fault, etc.). These fields started out being defined as single 16- or 32-bit integers, but as time went on they would be broken out into single-bit mnemonics. This caused issues when using the s/s to generate FSW structures, and also sometimes existing scripts assumed the integer mnemonic existed, which later disappeared when the bits were broken out. In the future, the s/s should use the integer representation and derived telemetry defined separately should be used for the bit breakouts. See also LL-093.
Description of Driving Event:	Progression through I&T revealed issues in the CYGNSS approach that could be improved on in future missions.

CYGNSS – LL-124: Perform more comprehensive CM planning & tool selection	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 7.0 Mission Operations
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Up-front CM planning and tool selection should be performed to include FSW, EGSE, I&T, and Ops systems.
Description of Driving Event:	The MOC chose to use a different version control system (Git) vs. what was used by FSW and AI&T (SVN). This resulted in having to modify scripts and version identification schemes (for things like observatory table loads) that had been used throughout FSW development and AI&T, once things began transitioning to operation. This made the transition from FSW development/AI&T to mission operations much less seamless than it could have been otherwise.

CYGNSS – LL-125: Complicated harness fabrication aid	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 10.0 System AI&T
Components - Primary (if applicable):	Harness
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	When complicated cable runs are outsourced (like semi-rigid cable runs), provide the vendor with a fabrication jig rather on relying them to model the run correctly
Description of Driving Event:	Multiple iterations on semi-rigid cable build presented potential schedule risk.

CYGNSS – LL-126: Project support of reviews	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 1.0 Project Management
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	2. Medium
Big Picture LL:	2. No
Lesson:	Don't under estimate the time and disruption of supporting mission reviews. With a small team, basically work stops for a couple of weeks around each review. This is really exaggerated if there are peer reviews leading up to the review or follow on CMC or KDP reviews. On the flip side, reviews do force closure.
Description of Driving Event:	Mission PDR, CMC and KDP-C support.

CYGNSS – LL-127: Explore something like a CAN bus to make use of more sensors	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	2. No
I&T Phase:	2. No
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.2 Microsat Sys. Eng.
Components - Primary (if applicable):	CDS - Centaur Board
Components - Secondary (if applicable):	FSW - Flight Software
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	Future missions should explore the feasibility of using something like a CAN bus to increase the number of sensors when using dedicated I/O would otherwise limit the number of sensors in the design. There may be other potential advantages such as reducing harness mass or ability for devices on the network to share information in a way that allows novel FDC/autonomy implementations.
Description of Driving Event:	Sometimes the sensors themselves are cheap, but accommodating the extra I/O is expensive/difficult. Example would be adding extra coarse sun sensors so that spacecraft safe mode can quickly/easily find the sun. See also LL-036.

CYGNSS – LL-128: Commercial parts obsolescence and die revision	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 3.0 Safety and Mission Assurance
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	The life cycle of commercial parts is very different from the space parts world.
Description of Driving Event:	Likely need a different system to manage obsolescence if systems need to be maintained or rebuilt over a period of years. Die rev is particularly a concern from a radiation perspective.

CYGNSS – LL-129: Commercial parts cost and schedule awareness	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	2. No
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 3.0 Safety and Mission Assurance
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	Even with nontraditional parts programs, cost and lead-time can still be an issue.
Description of Driving Event:	While the occurrence on long lead and expensive parts is greatly reduced with a non-INST-002 type parts program, they can still be a challenge. Given the tighter development schedule, a 12 week lead time could be a killer. Awareness of what the commercial parts market is doing may not be ingrained in system. For example, some automotive resistors and capacitors are very difficult to get currently. Not knowing this would have a serious impact

CYGNSS – LL-130: If code seems slow, don't automatically blame the server	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	2. No
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 7.0 Mission Operations
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	If code execution time is sub-optimal, investigate why vs. automatically assuming that the server needs more resources.
Description of Driving Event:	The numpy (Python) installation at the MOC was found to have a bug in it such that data processing takes ~1.5 hours instead of ~10-20 minutes. It was a bug that existed in the numpy release for 3 weeks and the MOC was unlucky enough to have used this particular one. In testing, the data processing programmers all stated that it was super slow, but didn't investigate the cause, they simply blamed the server the code ran on.

CYGNSS – LL-131: Use of 80-20 roll cage for S/C handling	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	2. No
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 10.0 System AI&T
Components - Primary (if applicable):	ADCS - Magnetometer
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	The use of 80-20 T-slot aluminum extrusions for GSE was a highly valuable contribution to I&T.
Description of Driving Event:	Because of the large amount of no touch surfaces on each observatory and the many different orientations that the observatories had to be in during AI&T, the use of a 80-20 slotted aluminum “roll cage” made handling much easier and reduced risk. While 80-20 is not cheap, it is much less expensive than delaying schedule and the cost is more than offset in reduced I&T personnel time.

CYGNSS – LL-132: Use a NASA DAAC to distribute data products	
Project Phase (where LL needs to be implemented)	
Pre Contract:	1. Yes
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	2. No
Launch & Commissioning:	2. No
Operations:	1. Yes
WBS Element:	WBS 4.0 Science
Components - Primary (if applicable):	SOC Systems
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	The requirement to use a NASA DAAC and established formatting standards (for CYGNSS this was netCDF) is beneficial.
Description of Driving Event:	We were required by NASA to use the NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC) for science data product distribution and netCDF for formatting. Absent this requirement, we probably would have distributed science data products through a custom web site and that would have been a mistake. The PO.DAAC relieved us of the burden of the developing and maintaining our own web site. It provides long-term archiving and many online tools that we could not duplicate. The PO.DAAC staff gave us guidance to ensure that our netCDF files conformed to earth science data standards.

CYGNSS – LL-133: Avoid separate I2C interfaces to torque rods	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	2. No
I&T Phase:	2. No
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.8 ADCS Subsystem
Components - Primary (if applicable):	ADCS - Torque Rod
Components - Secondary (if applicable):	CDS - Centaur Board
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	Avoid implementing individual I2C interfaces to each torque rod as it results in excessive I2C transactions. Additionally, the FSW had to deconflict TR from Mag readings which was made even more difficult with the I2C interface to the TRs. It would have been better to have some semi-autonomous device to handle the torque rod and magnetometer commands.
Description of Driving Event:	On CYGNSS, each of 3 torque rods needs 2 transactions each cycle, for a total of 6 transactions. This requires ~3 msec/transaction for a total of 18+ msecs which is very high just to command torque rods.

CYGNSS – LL-134: Have defined dump commands and packets for all tables	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	2. No
I&T Phase:	2. No
Launch & Commissioning:	2. No
Operations:	1. Yes
WBS Element:	WBS 6.5 Microsat Flight Software
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	Define specific commands and dump packets for all tables.
Description of Driving Event:	It is tempting to just use the generic memory dump capability to download tables. However, CYGNSS experience shows that you wind up dumping these tables to verify things more often than you think you will, so having specific commands and packets (i.e. APIDs) for each helps decode and display them in the MOC.

CYGNSS – LL-135: Additional thermistors to solar arrays would have aided evaluation of deployment	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	2. No
WBS Element:	WBS 6.6 Struct., Mech. & Therm.
Components - Primary (if applicable):	SMT - Solar Array
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	When evaluating whether the solar arrays had deployed, thermistors are good proxies to evaluate the condition of the solar arrays and aid in determination of spacecraft attitude.
Description of Driving Event:	During commissioning, one of the observatories was initially thought to not have deployed a set of arrays. These arrays did not have thermistors on them since there were thermistors on the other arrays. This is sufficient since in nominal conditions those temperatures represent the arrays without thermistors. However, if we had had thermistors on the array we had thought didn't deployed, we would have had convincing information that would have indicated they did deploy.

CYGNSS – LL-136: Account for unique knowledge and control scenarios when assessing requirements and Monte Carlo statistics	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.8 ADCS Subsystem
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	Lesson learned is that if a period of reduced knowledge is nominal and significant in length, like NST sun outages are for CYGNSS, then it should be assessed independently from when the NST is tracking and requirements should be written against it.
Description of Driving Event:	Early in the project, for example during PDR, ADCS performance was presented in terms of combinations of sensors and actuators. In effect Sun Outage performance was assessed independently at this phase. Later statistics were presented in terms of average performance or max error over entire orbits or scenarios. While the latter was driven by Sun Outages, the former was used to verify requirements. This lead to Sun Outage performance not being considered independently against any requirement (it was reviewed independently by engineering team members at multiple institutions, however). If the statistics had been broken down below the Design Reference Mission level in LVLH cases to look specifically at averages and maxes over sun outages, or if requirements had been written specifically against sun outage performance and not just overall performance, different design decisions might have been made. This gives better insight into performance for the engineering team and would better expose vulnerabilities in the system. Final V&V packages, and their comparison against the requirement, do not clearly show what the average errors and 3-sigma distributions are during sun outages or how much sun outage performance drives the overall statistics.

CYGNSS – LL-137: Use of static telemetry in simulators	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 6.9 Microsat GSE
Components - Primary (if applicable):	EGSE - SDS
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	Several parameters in the engineering telemetry from the canned ADCS components were set to static values rather than behaving "realistically", such as internal monitor voltages and temperatures. Telemetry parameters that directly related to ADCS were prioritized and simulated rather than all parameters. While simulators are good to have, they often have an effect in areas beyond their intended use, and these effects should be considered. See also LL-041.
Description of Driving Event:	During simulation of operations, some static settings of simulated ADCS component parameters inadvertently tripped CYGNSS fault management software.

CYGNSS – LL-138: Cloud tools worked well for Ops but are less secure, and required excessive emailing	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	2. No
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 7.0 Mission Operations
Components - Primary (if applicable):	MOC Systems
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	Use of Google documents that allow multiple users to access and modify the document worked very well but is likely not the best method from a security standpoint. Also, too many files are exchanged via emails, so a more integrated solution would be more optimal. An internal system that provides the same flexibility and is affordable would be preferred.
Description of Driving Event:	Workload and money.

CYGNSS – LL-139: Segmentation in project management database makes operations difficult at times	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 1.0 Project Management
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	If a project uses more than one instance of a project management database, the strategy for cross connecting or amalgamating needs to be planned in the very beginning of the project (i.e. the proposal stage). The plan should be included in the SEMP.
Description of Driving Event:	Currently the Ops team has to go multiple different projects to find FRCs, CCRs, URs, NCRs. It would be nice if everything could coalesce into 1 single project once we are in operations. FRC belongs in the MOC more than elsewhere. We also should have moved the NCRs for Operations into the MOC project (assuming they are staying all separate) as originally intended.

CYGNSS – LL-140: Load testing not required by ASME B30 standards	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	2. No
WBS Element:	WBS 3.0 Safety and Mission Assurance
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	Load testing is required by NASA-STD-8719.24 but not by ASME B30 standards for lifting devices.
Description of Driving Event:	Lifting devices with CofCs showing compliance to an ASME B30 standard may still have to be load tested after receipt.

CYGNSS – LL-141: Early coordination with launch site personnel on hazards	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	2. No
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 3.0 Safety and Mission Assurance
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	Early communication with launch site personnel on spacecraft level hazards can help to close them prior to spacecraft delivery.
Description of Driving Event:	Early communication with LV and range about Li-ion batteries and S-band antennas prevented hold ups due to lack of planning.

CYGNSS – LL-142: Identification of manufacturing planning sheets (MPSs) with no traveler	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 3.0 Safety and Mission Assurance
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	Electronic MPSs should identify whether a paper traveler is created.
Description of Driving Event:	During documentation close-out, some MPSs remained open while their traveler was searched for, though it wasn't clear if a traveler was actually issued.

CYGNSS – LL-143: Visible proof of last EGSE cert on racks	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	2. No
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.9 Microsat GSE
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	A log sheet should be affixed to each EGSE rack to show a date and location of the last cert.
Description of Driving Event:	Identifying date and location of last cert for an EGSE rack is not otherwise easily identifiable.

CYGNSS – LL-144: Create drawings of critical MGSE	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.9 Microsat GSE
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	Create a drawing for safety critical MGSE configurations that includes torque value for fasteners.
Description of Driving Event:	Different flight segment lifting fixtures, assembled in different configurations, used different fasteners requiring different torque values.

CYGNSS – LL-145: Add something to prevent inadvertent human machine interface "button" activation	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	2. No
WBS Element:	WBS 6.9 Microsat GSE
Components - Primary (if applicable):	EGSE - ASE
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	Human machine interface (HMI) on ASE rack did not have a means to prevent a human from inadvertently touching the screen and initiating functions. Possible solutions include: a clear barrier (such as plexiglass) that can be lowered over the screen so that it can be viewed but not activated, or a screen lock button requiring key strokes to activate and deactivate the screen. Use cases should consider what we don't want to happen as well as what we want to happen.
Description of Driving Event:	Suggested by OATK.

CYGNSS – LL-146: Connector choices - don't forget locking mechanism	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 8.0 Launch Vehicle/ Services & DM
Components - Primary (if applicable):	DM - DMAU
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	A connector that uses a bayonet-style locking mechanism would have been an easier choice than relying on a threaded connector. There was some ambiguity about the amount of torque that could be applied. Also, since the connectors were thread-staked, more work is required to remove the connector. Once installed, the DMAU was difficult to access and complicated any rework.
Description of Driving Event:	What-if scenario if DMAU needed to be removed.

CYGNSS – LL-147: Battery power switching circuitry for DMAU	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 8.0 Launch Vehicle/ Services & DM
Components - Primary (if applicable):	DM - DMAU
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	Power FETs were used for the DMAU, when solid state relays would likely have been a simpler and more robust solution, especially since the DMAU is not being used during flight operations. The FETs added complexity, and their smaller operating range ended up limiting the battery charging voltage to around 60V, when the S/C power system input is capable of higher voltages. Higher voltages would have allowed for quicker charging. An earlier investigation/trade study of alternative means to perform this function should have been conducted.
Description of Driving Event:	Circuit complexity and constraints were discussed during a design review, but the design had already matured too far with accommodations for the FETs.

CYGNSS – LL-148: HMI user interface parameters for DMAU	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.9 Microsat GSE
Components - Primary (if applicable):	DM - DMAU
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	Make all parameters in the user interface runtime configurable. Operator use cases, operability and flexibility should be documented and vetted for consideration during the early design of the system.
Description of Driving Event:	The warning limits in the Human Machine Interface (HMI) were originally hard-coded since they weren't expected to be changed. During integration, however, the limits had to be tweaked several times, and there were scenarios where the limits needed to be changed temporarily. Initially every limits change required building and loading a new HMI image. Eventually an interface was added to allow the operator to tweak the limits in the field. Essentially any constant value (limits, scale factors, time bases) should be configurable through the user interface.

CYGNSS – LL-149: Multiple assemblies on one traveler	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	1. Yes
I&T Phase:	2. No
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 3.0 Safety and Mission Assurance
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	Consider the implications of combining multiple assemblies on one traveler or Manufacturing Planning sheet (MPS). It might make sense for simple assemblies to be combined on one traveler. More complicated assemblies with lots of steps and inspections should be put on separate travelers.
Description of Driving Event:	Mix records were not being updated correctly due to the fact that we had 1 Manufacturing Planning Sheet (MPS) issued to cover 8 mechanical parts/assemblies. The boards were processed at different times and final sign off was hard to track. In the future we should only use 1 MPS for each assembly. This was an issue for most mechanical assemblies. Performing close out inspections on MPS packages presented a very time consuming process with multiple re-inspections preformed to verify all of the parts/assemblies were complete.

CYGNSS – LL-150: Stop playback before FSW reboot or reboot/change image	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	2. No
I&T Phase:	2. No
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 7.0 Mission Operations
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	When performing a FSW reboot, either to same or a different OP image, it is cleaner to halt playback (issue stop playback command) prior to issuing the reboot.
Description of Driving Event:	SC 2C transition from FSW 4.1 to FSW 4.2 via reboot with restore. Begin-of-pass RTS kicked off a playback which was still in effect when the reboot command was issued. MOC did issue stop playback command during reboot, and no ill effects were observed, but cleaner process would be to precede the reboot with the stop playback.

CYGNSS – LL-151: With small team, knowing when Joe is going on vacation is important	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	1. Yes
WBS Element:	WBS 6.1 Microsat Mgmt.
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	Be vigilant about asking staff if they have any upcoming planned leave.
Description of Driving Event:	We got caught a couple of times with some staff being unavailable due to medical (surgery) issues. We worked around it, however, with a little more insight we could have coped easier by getting work done sooner, or cross-assigning work, etc.

CYGNSS – LL-152: Check equipment calibration well before long duration tests	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	1. Yes
Operations:	2. No
WBS Element:	WBS 10.0 System AI&T
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	Check equipment calibration especially well before long duration tests.
Description of Driving Event:	It goes without saying that calibration is important, however, when running long duration tests or large volumes of tests, you don't (ideally) want to replace active equipment while something gets calibrated, so, check the calibration date and make sure it covers the target test time. we had to re-cal in the middle of some testing, which turned out fine, but would best have been avoided by pre-calibrating before starting the testing.

CYGNSS – LL-153: Don't assume someone is certified for the particular activity	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	2. No
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 10.0 System AI&T
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	Don’t assume someone has been trained/certified properly for a task, check and record training/certifications
Description of Driving Event:	When we became short-handed and borrowed staff from other divisions, and asked about their certifications, they responded 'yes', but then we discovered, by the time we utilized them, their certifications had expired! We were forced to re-certify/train them ASAP.

CYGNSS – LL-154: Label everything	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 10.0 System AI&T
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	Label everything
Description of Driving Event:	Even though we attempt to use unique connectors to avoid mis-connections, sometimes the cables themselves are confusing. We needed to label cables so that when troubleshooting over the phone, it was clear which end of the cable was being talked about, to which connector, etc.

CYGNSS – LL-155: Make high-level assembly drawings of EGSE	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 6.9 Microsat GSE
Components - Primary (if applicable):	EGSE and uSat EM Backplane
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	Make drawings for all GSE assemblies, with high-level block diagrams the interface count is too high to remember all the details over many months
Description of Driving Event:	When confronted with assembling and disassembling multiple racks, having the detailed assembly drawings is critical to reliable systems

CYGNSS – LL-156: Check lead times early; even simple parts can have long lead times	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 10.0 System AI&T
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	Check lead times early. Sometimes even simple parts have long lead times.
Description of Driving Event:	Even simple connector parts can have a significant lead time, buy extras and plan accordingly. TVAC heater cabling required simple connectors, but stock was on backorder, so we needed to re-purpose used connectors

CYGNSS – LL-157: All cables should have drawings	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 10.0 System AI&T
Components - Primary (if applicable):	-
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	No cable is too simple to have a drawing
Description of Driving Event:	Misunderstanding of LVDS wiring

CYGNSS – LL-158: Threaded connector locking mechanisms	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	1. Yes
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 8.0 Launch Vehicle/ Services & DM
Components - Primary (if applicable):	DM - DMAU
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	Twist type connectors (vs bayonet type) should be treated like any other threaded joint; preload to spec then use some locking mechanism. Locking mechanism options would normally involve staking or safety wire the connectors, where safety wiring is my preference. See also LL-146
Description of Driving Event:	DMAU connector came loose during vibration testing.

CYGNSS – LL-159: Standardize flight hardware label format, content, material and placement definitions	
Project Phase (where LL needs to be implemented)	
Pre Contract:	2. No
Design Phase:	1. Yes
Fab Phase:	1. Yes
I&T Phase:	2. No
Launch & Commissioning:	2. No
Operations:	2. No
WBS Element:	WBS 3.0 Safety and Mission Assurance
Components - Primary (if applicable):	DDMI - DMR
Components - Secondary (if applicable):	-
Priority:	3. Low
Big Picture LL:	2. No
Lesson:	Consider providing subcontractors detailed guidance (standardized by the Division based on best practices and NASA/customer expectations and requirements): • location on hardware to avoid interference and enable access during AI&T • size (legibility, avoiding interference) • font (legibility) • content (CM traceability) • material (Contam Control) This should all be agreed to on the MICD or materials list. See also LL-154.
Description of Driving Event:	During the inspection of DMRs it was noted, that SSTL provided labels did not meet material requirements and were poorly placed on the units.

Appendix B. Acronyms

Abbreviation/Acronym	***Definition***
ADCS	Attitude Determination & Control System
AI&T	Assembly, Integration and Test
AO	Announcement of Opportunity
APID	Application Identifier
ASE	Airborne Support Equipment
ASME	American Society of Mechanical Engineers
ATBD	Algorithm Theoretical Basis Document
ATP	Acceptance Test Procedure
BCR	Baseline Change Request
BCT	Blue Canyon Technologies
BOE	Basis of Estimate
C&DH	Command and Data Handling
C&T	Command and Telemetry
CAM	Control Account Manager
CARA	Conjunction Assessment Risk Analysis
CCR	Configuration Change Request
CCSDS	Consultative Committee for Space Data Systems
CDH	Command and Data Handling
CDR	Critical Design Review
CDS	Communications and Data Subsystem
CG	Center of Gravity
CLA	Coupled Loads Analysis
CLIN	Contract Line Item Number
CM	Configuration Management
CMC	Center Management Council
CMD	Command
CofC	Certificate of Conformance
CogE	Cognizant Engineer
CONOPS	Concept of Operations
COTS	Commercial off the Shelf
CPAR	Contractor Performance Assessment Report
CPR	Cost Performance Report
CPT	Comprehensive Performance Test
CR	Change Request
CSC	Computer Software Component
CSCI	Computer Software Configuration Item
CSS	Coarse Sun Sensor

Abbreviation/Acronym	***Definition***
CYGNSS	Cyclone Global Navigation Satellite System
DAAC	NASA Distributed Active Archive Center
DB	Database
DDM	Delay Doppler Map
DDMI	Delay Doppler Mapping Instrument
DM	Deployment Module
DMAU	Deployment Module Avionics Unit
DMR	Delay Mapping Receiver
DOORS	Dynamic Object Oriented Requirements System
DPM	Deputy Project Manager
EDAC	Error Detection and Correction
EGSE	Electrical Ground Support Equipment
EM	Engineering Model
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EPS	Electrical Power Subsystem
ESD	Electrostatic Discharge
ESSP	Earth System Science Pathfinder
EVM	Earned Value Management
FAD	Formulation Authorization Document
FDC	Fault Detection and Correction
FEM	Finite Element Model
FET	Field Effect Transistor
FFP	Firm Fixed Price
FFT	Full Functional Test
FM	Flight Model
FRC	Flight Rule/Constraint
FS	Flight Segment
FSW	Flight Software
FTE	Full-Time Equivalent
GFE	Government Furnished Equipment
GPD	Global Peak Detect
GPS	Global Positioning System
GSE	Ground Support Equipment
GSS	GPS Signal Simulator
HMI	Human Machine Interface
HQ	Headquarters
I&T	Integration and Test

Abbreviation/Acronym	***Definition***
ICD	Interface Control Document
ICE	Independent Cost Estimate
IEEE	Institute of Electrical and Electronics Engineers
I/F	Intermediate Frequency
IMAGE	Imager for Magnetopause-to-Aurora Global Exploration
ITOS	Integrated Test and Operations System
KDP	Key Decision Point
KSC	Kennedy Space Center
LaRC	NASA Langley Research Center
LEO	Low Earth Orbit
LEOps	Launch and Early Operations
LL	Lesson Learned
LNA	Low-Noise Amplifier
LV	Launch Vehicle
LVLH	Local Vertical Local Horizontal
LVPS	Low Voltage Power Supply
MAIP	Mission Assurance Implementation Plan
MDR	Mission Definition Review
MEV	Maximum Expected Value
MICD	Mechanical Interface Control Drawing
MOC	Mission Operations Center
MPS	Manufacturing Planning Sheet
MPSR	Monthly Project Status Report
MSE	Mission Systems Engineer
MSS	Medium Sun Sensor
MST	Mission Simulation Test
NASA	National Aeronautics and Space Administration
NCR	Nonconformance Report
NDA	Nondisclosure Agreement
NetCDF	Network Common Data Form
NST	Nano Star Tracker
OATK	Orbital ATK
Obs.	Observatory
ONR	Office of Naval Research
Ops	Operations
PDR	Preliminary Design Review
PEDs	Plastic Encapsulated Devices
PGAA	Performance and Guidance Accuracy Analysis

Abbreviation/Acronym	***Definition***
PI	Principal Investigator
PLAR	Post Launch Assessment Review
PLRA	Project Level Requirements Agreement
PM	Project Manager
PO.DAAC	Physical Oceanography Distributed Active Archive Center
PPT	Peak Power Tracker
PR	Problem Report
PSE	Project Systems Engineer
PWM	Pulse-width Modulation
RCS	Reaction Control System
RF	Radio Frequency
RFP	Request for Proposal
RT	Real-time
RTS	Relative Time Sequences
RW	Reaction Wheel
RWA	Reaction Wheel Assembly
RWAM	Reaction Wheel Assembly Module
S/C	Spacecraft
SA	Solar Array
SCID	Spacecraft Identifier
SDS	Spacecraft Dynamics Simulator
SE	Systems Engineering
SE	Systems Engineer
SEMP	Systems Engineering Management Plan
SEU	Single Event Upset
SHA	Safety Hazard Analysis
SMD	Science Mission Directorate
SME	Subject Matter Expert
SMEX	Small Explorer
SMSR	Safety and Mission Success Review
SMT	Structure, Mechanisms, and Thermal
SNC	Sierra Nevada Corporation
SOC	Science Operations Center
SoC	State-of-Charge
SOW	Statement of Work
SRB	Standing Review Board
SSC	Swedish Space Corporation (formerly Universal Space Network)
SSR	System Requirements Review

Abbreviation/Acronym	***Definition***
SSTL	Surrey Satellite Technologies, Limited
ST	Star Tracker
STM	Structural/Thermal Model
STOL	Satellite Test and Operations Language
SVN	Subversion
SwRI	Southwest Research Institute
TC	Tropical Cyclone
TIM	Technical Interchange Meeting
TLM	Telemetry
TLYF	Test Like You Fly
TR	Torque Rod
TRR	Test Readiness Review
TVAC	Thermal Vacuum
UM	University of Michigan
UR	Uplink Request
USN	Universal Space Network
UTC	Coordinated Universal Time
V&V	Verification and Validation
VAFB	Vandenberg Air Force Base
VCID	Virtual Channel Identifier
WBS	Work Breakdown Structure
XCVR	Transceiver