# The CYGNSS Flight Segment; Mainstream Science on a Micro-Budget

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*Abstract*— **NASA's first Earth Venture mission, the NASA EVM-1 Cyclone Global Navigation Satellite System (CYGNSS), is designed to provide data that will enable the study of the relationship between ocean surface properties, moist atmospheric thermodynamics and convective dynamics. These relationships are postulated to be intrinsic to the genesis and intensification of tropic storms. Key information about the ocean surface under and around a tropical storm is hidden from existing space borne observatories because the intense precipitation degrades the frequency bands in which they operate, obscuring the ocean's surface. GNSS-based bi-static scatterometry performed by a constellation of micro-satellites offers remote sensing of ocean waves and wind with unprecedented temporal resolution and spatial coverage across the full dynamic range of ocean wind speeds in all precipitating conditions. A better understanding of these relationships and their effects will advance our ability to forecast tropical storm intensity and storm surge.**

**Achieving the required temporal and spatial resolution for tropical cyclone remote sensing has not been possible previously due to technology and cost limitations. Modeling techniques developed over the past 20 years combined with recent developments in nano-satellite technology and an increased risk tolerance by NASA have enabled the CYGNSS mission. CYGNSS consists of 8 GPS bi-static radar receivers deployed on 8 separate micro-satellites to be launched in October 2016. The mission is cost capped at $102M exclusive of launch vehicle. It is being developed as a Category 3 mission (per NPR 7120.5D NID) with Class D payloads (per NPR 8705.4). This paper will present an overview of the CYGNSS flight segment implementation and how our Class D approach allows the development to meet cost constraints.**

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## 1. INTRODUCTION

Budgetary pressure in all sectors of the economy continues to drive the need for innovative methods of implementing cost effective science and research, allowing the concurrent development of only a few traditional large observatory missions. The investment necessary for these platforms dictates low risk development approaches to ensure operability and return on investment. Funding opportunities for research and development not related to these missions has been limited, enticing mission stakeholders looking for lower cost alternatives to accept higher risk associated with non-traditional forms of development and technology.

In parallel to the push for low cost mainstream science investigations, there has been significant technical and infrastructure development to serve the growing nano-satellite market. Acceptance of nano-satellite-based missions within the science mainstream requires mission performance at existing mission levels, bolstered by potential cost savings and increased reliability. As the market for nano-satellites increases, it attracts developers capable of cost effectively combining lessons learned from the traditional spacecraft development with new technology to produce reliable components to support nano-satellite missions. The success of CubeSats at price points and schedules far below what have become standard development norms has resulted in mission designers and component developers taking the necessary steps to move Cubesats from educational curiosities to reliable mainstream science applications [1]. The CYclone Global Navigation Satellite System (CYGNSS) mission, NASA's first Earth Venture mission, is an example of combining nano-satellite technology with higher risk tolerance to replace existing accepted solutions at significantly reduced cost while providing an increase in performance.

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## 2. WHY CYGNSS?

There has been essentially no improvement in the accuracy of Tropical Cyclone (TC) intensity forecasts since 1990 while in that same period TC track forecast skill has improved by ~50% [2] [3]. TC track forecast skill improvement is thought to be linked to modeling improvements of the mesoscale and synoptic environment facilitated by observations from polar orbiting remote sensing assets. These assets are designed to provide global coverage with temporal resolution on the order of days. However, they do not provide adequate observation of the TC inner core. This inadequacy is the result of two causes: 1) Much of the TC's inner core ocean surface is obscured from conventional remote sensing instruments by the storm's intense precipitation. 2) The rapidly evolving (genesis and intensification) stages of the TC life cycle have temporal features on the order of hours, not days.

### *Temporal Resolution Necessary for TC Wind Observations*

Most current spaceborne active and passive microwave instruments are in polar low earth orbits. The orbits maximize global coverage but because of the instrument's size, power, and cost, usually only one Observatory is flown thus resulting in large tropical coverage gaps [4]. The irregular and infrequent revisit times (ca. 11-35 hrs) of these observatories are likewise not sufficient to resolve synoptic scale temporal variability associated with TCs. Missed TC core imaging events can occur when an organized system passes through a conventional observatory's coverage gap or when its motion is appropriately offset from the motion of the observatory's swath. Early design of CYGNSS focused on constellation formation to close the coverage gaps sufficiently to enable monitoring of the TC genesis and intensification. It was determined early in the CYGNSS concept development that, given cost constraints of the NASA Earth Venture program, global coverage would need to be sacrificed for TC core imaging. The much wider and more dispersed effective swath of a micro-satellite (μSat) constellation allows for a much higher sampling rate. Required coverage of the historically active tropical cyclone area is provided by 6 Observatories loosely dispersed about a 510 km-altitude, 35°-inclination circular orbit. The cost-effectiveness of the CYGNSS Observatory allows the mission to fly 8 Observatories thus providing redundancy at the vehicle level. The average revisit time for CYGNSS TC sampling is predicted to be 6 hr, and the median revisit time will be 3 hr, well below the 12 hr revisit requirement. Figure 1.

### *Wind Observations in Precipitating Conditions*

Previous spaceborne measurements of ocean surface vector winds made by observatories such as QuikScat have suffered from degradation in highly precipitating regimes because of the signal frequency they use. As a result, the accuracy of wind speed estimates in the inner core of the TC is often highly compromised if not eliminated altogether. Figure 2 provides the one-way slant path atmospheric attenuation experienced by an L-band, C-band and Ku-Band signal as a function of surface precipitation rate. The C-band (e.g. ASCAT) measurement is attenuated enough at the highest rain rates to severely impact its ability to retrieve surface winds under the TC while Ku-band (e.g., QuikScat) signals are effectively blocked by heavy rain and cannot sense the surface at all. Precipitation has a negligibly small

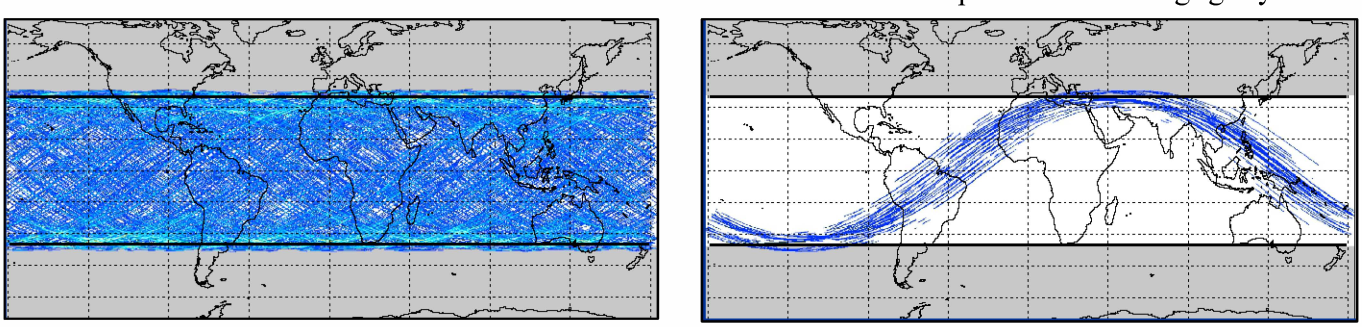

**Figure 1 -- CYGNSS Constellation Coverage, Left 24hr, Right 1.5hr**

effect on the L-band signal, even at the highest rain rates. This was a major factor for selection of the CYGNSS instrument. We needed a signal band that could penetrate heavy precipitation, this suggested use of the L-band signal, but use of standard active scatterometer techniques in the L-band are of course limited by GPS. Concept development for CYGNSS revealed GNSS Reflectometry (GNSS-R) as an excellent candidate but while it has extensive heritage for airborne sensing, it had only been flown in space once and then only demonstrated for winds less than 16m/s [5] [6], nowhere close to the CYGNSS requirement to measure the highest sustained winds of a TC (70m/s). In the end, the L-band signal's low attenuation in heavy precipitation combined with a small GNSS-R instrument that requires little power as described in Sec 3 are major enablers of the CYGNSS mission, but to do so the project has invested significant effort to develop high fidelity models to demonstrate that GNSS-R can be extended to meet the CYGNSS wind speed requirements.

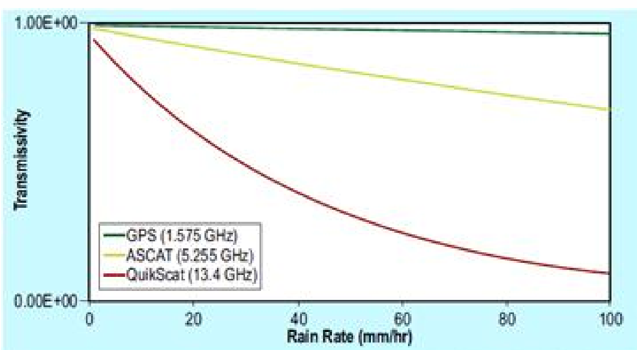


**Figure 2 -- One-Way Slant Path Atmospheric Attenuation Experienced by a GNSS (green), ASCAT (yellow) and QuikScat (red) Signal**

## 3. What is CYGNSS?

CYGNSS is an innovative 8 satellite constellation that leverages recent developments in remote sensting and nano-satellite technology to overcome limitations of traditional space-based ocean remote sensing. The following sections describe the CYGNSS instrumentation and the observatory design and operations.

### 3.1 CYGNSS Instrumentation

GNSS-R is used by the Delay Doppler Mapping Instrument (DDMI) to obtain data about the ocean surface and near-surface wind speed and is one of the major enablers of the CYGNSS mission.

***How GNSS-R Works.*** When electromagnetic radiation is reflected by the ocean surface, the wave scattering process changes the characteristics of the propagating signal in a way that is dependent on the characteristics of the reflecting surface. In the case of GNSS-R, these changes contain information on the sea surface waves and indirectly on the near-surface meteorological conditions. Most radar-based ocean remote sensing is founded on this general principle, but it generally uses actively transmitted radar pulses and then detects the received power of the backscattered radiation. The payload power and volume accommodations required for these instruments significantly drive costs of the observatory. An alternative signal source using Earth reflected GNSS signals as a means of sensing the ocean surface was proposed in 1988 [7] (Reference Figure 3). Researchers developed this sensing technique during airborne experiments [8] and subsequently used data from the GNSS-R experiment on the UK-DMC satellite (Figure 4) to demonstrate that signal retrievals of sufficient signal-to-noise ratio could be used to perform successful ocean wave and wind estimation [9] [10] [11]. Research performed by the CYGNSS mission indicates that the signal-to-noise ratio was not near saturation and in fact is sufficient to allow measurement of maximum TC winds, thus making it is possible to detect reflected GNSS signals from space across the full range of ocean surface wind and wave conditions using a relatively modest instrument configuration. GNSS thus provides an alternative to active sensing ocean remote sensing using bi-statically reflected signals transmitted from global navigation satellites.

Figure 3 illustrates the propagation and scattering geometries associated with the GNSS approach to surface scatterometry. The direct GPS signal provides a coherent reference for the coded GPS signal. The quasi-specular forward scattered signal from the Earth surface is received by an antenna on the nadir side of the spacecraft. The scattered signal contains signal lag and frequency shift information, the two coordinates of the DDM image, the measurement of which enable the spatial distribution of the scattering cross section to be resolved [9]. In the case of ocean surface GNSS scatterometry, estimation of the ocean surface roughness and near-surface wind speed is possible from two different properties of the DDM. The maximum scattering cross-section (the dark red region in Figure 4) and the shape of the scattering arc (the red and yellow regions in Figure 4). Use of the maximum scattering cross-section requires absolute calibration of the DDM while use of the scattering arc only requires relative calibration of the DDM. The arc approach imposes more relaxed requirements on instrument calibration and stability than does the analysis of the scattering cross-section. However, the arc derives its wind speed estimate from a wider region of the ocean surface and so necessarily has poorer spatial resolution. Development of wind speed retrieval algorithms from DDMs continues to be an active area of research (Gleason, 2007) that will .be further enabled by the CYGNSS flight science data set.

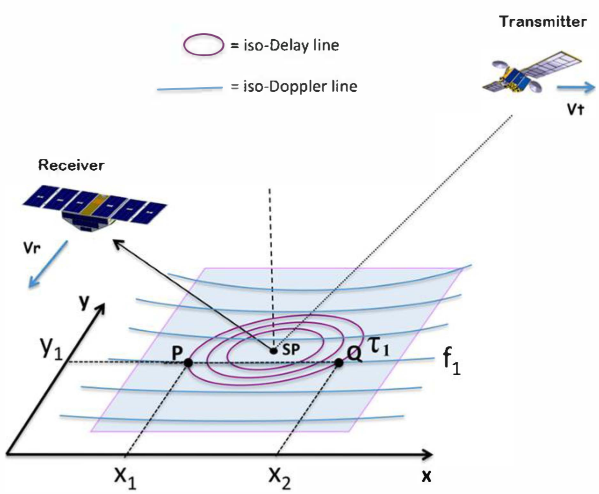


**Figure 3 -- Geometry of a GNSS-R Measurement of the Delay Doppler Map (DDM)**

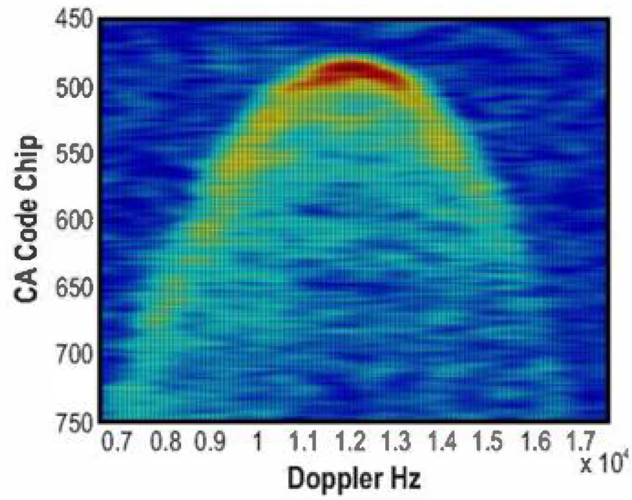


**Figure 4 -- Spaceborne Empirical Demonstration of Ocean Wind Speed Retrievals by GNSS-R (10m/s)**

***Delay Doppler Mapping Instrument (DDMI).*** CYGNSS carries a DDMI on each Observatory. The CYGNSS DDMI uses Surrey's GNSS Receiver-Remote Sensing Instrument (SGR-ReSI), an upgraded version of the UK-DMC-1 instrument that flew in 2003. The upgrades leverage recent advances in microelectronics that include a new GPS front end MMIC receiver and the addition of a digital signal processing back end. The new front end improves noise performance, adds internal calibration, and raises the digital sample rate. The new back end adds more on-board processing capacity in order to raise the duty cycle of science operations.

In total, the DDMI consists of the Delay Mapping Receiver (DMR) electronics unit, two nadir-pointing antennas for collecting reflected GNSS signals, and a zenith-facing antenna to provide a coherent reference for the coded GPS signal plus space-geolocation capability.

DDMI onboard processing generates the GPS DDMs. Each pixel of the DDM is obtained by cross-correlation of the received signal with a locally generated replica with the proper time delay and Doppler shift. An open-loop tracking algorithm allows each DDM to be processed by predicting the position of the specular reflection point from the known positions of the receiver (i.e., the CYGNSS Observatory) and GPS transmitter (i.e., the GPS spacecraft).

Available onboard firmware resources allow generation of four simultaneous DDMs. The output data rate is determined by onboard coherent and incoherent integration. The coherent (complex signal) integration time is limited to 1 ms by the rate of change of the propagation geometry due to receiver motion. Individual complex DDMs are then incoherently integrated (magnitude only) for 1 s to form the final DDM.

### 3.2 CYGNSS Flight System Design and Development

***Observatory Configuration.*** Accommodation of the DDMI antennas and the solar arrays (S/As), together with launch configuration constraints, drives the μSat physical configuration. The μSat's shape is specifically configured to allow clear nadir and zenith FOVs for the DDMI antennas, while its structure integrates the micro-sat and instrument electronic boards by creating an avionics bay and accommodating the Delay Mapping Receiver (DMR) housing. The avionics bay forms the core of the micro-sat; all other components are mounted to this backbone with structural extensions included to accommodate the S/As and DDMI nadir antenna assemblies. See Figure 5 for an exploded view of the CYGNSS Observatory.

Initial design goals were to base the Observatory on a 6U CubeSat configuration. Two key analyses resulted in the evolution to the configuration depicted in Figure 5:

- A wide range of antenna configurations were analyzed to meet the science requirements for 70% 24 hr storm coverage with a <12 hr mean revisit tempo. This effort identified the need for dual side viewing science antennas, tilted from nadir to provide a broad field of view.

- Use of CubeSat avionics, to allow the core to comply with CubeSat standards, posed risks of identifying a avionics solution that meets mission lifetime requirements. The alternative was to use heritage SwRI avionics

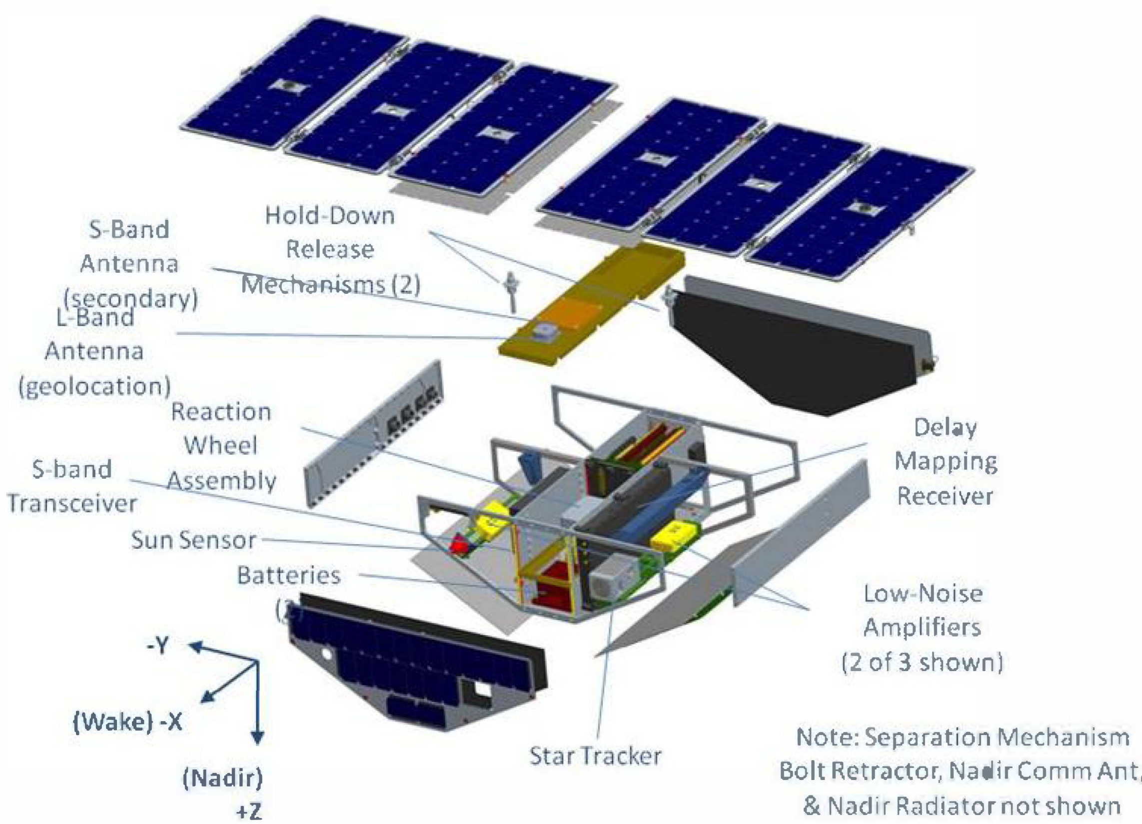


**Figure 5 -- CYGNS Observatory Mechanical Configuration (Exploded)**

but costs exceeded the CYGNSS budget. The solution was to develop a EEE parts control plan to allow the use of commercial parts that meet CYGNSS radiation, reliability, and quality requirements. This development enabled the use of heritage SwRI 3U avionic circuit designs, thus saving significant non-recurring engineering costs.

The resultant Observatory design is robust with wide margins for easy manufacturing tolerances and launch vehicle (LV) envelope constraints.

***Observatory Pointing.*** Pointing knowledge uncertainty directly translates into an uncertainty in the antenna pattern gain in the direction of the specular reflection point, producing an uncertainty in calibration of the scattering cross-section needed to estimate wind speed. Decomposition of the wind speed error science requirement of <2 m/s or 10% of the wind speed (whichever is greater) results in a pointing knowledge uncertainty requirement of 2.7° (3σ). The pointing knowledge requirement posed an interesting challenge because analysis revealed that (1) the pointing knowledge requirement cannot be met using sun sensors or magnetometers alone, (2) horizon sensor technology is not yet sufficiently developed for flight, and (3) the level of performance provided by traditional costly star-trackers is not required. Investigation of the nano-satellite market identified several companies that have developed, or are developing, very low cost CubeSat-class star trackers. We therefore developed an attitude determination and control subsystem (ADCS) that uses a CubeSat-class star tracker and magnetometer based ADCS configuration with a 3-axis reaction wheel attitude control design and torque rods for wheel momentum desaturation. Maneuverability requirements are limited to recovering from the launch vehicle separation tip-off rates, performance of a sun referenced safe mode, and local vertical/local horizontal pointing that includes nadir for science operations and a high drag, torque equilibrium attitude for differential drag orbit maintenance.

***Observatory Data Handling.*** The DDMI illustrates how recent technology development helped to enable the CYGNSS mission. Using GNSS-R to determine ocean surface features was originally demonstrated on the UK DMC-2 mission in 2003. This experiment captured raw I/Q data which was transmitted to the ground for post processing. The quantity of data required for this implementation to operate anywhere near the duty cycle necessary to meet mission coverage requirements far exceeds existing downlink capabilities. The ability to use recent FPGA and DSP technology allows necessary post-processing to convert raw I/Q data to DDMs on-board thus greatly reducing the telemetry demands, downlinking of which is within existing high speed downlink bandwidths. Early evaluation of the operational scheme revealed that the DDM processing requires even further on-board data volume reduction to limit downlink costs to within budget. The CYGNSS Systems Engineering and Science Teams worked early definition of candidate ground processing algorithms to determine the amount of compression/decimation that could be tolerated and still meet mission requirements. The teams then focused on on-board algorithms that would provide the data necessary for the ground processing. The resulting on-board algorithms provide 56:1 effective compression. They were prototyped and demonstrated to meet mission performance requirements before PDR. The implementation of the onboard algorithms alone saved CYGNSS over $3M in downlink costs.

***Constellation Operations.*** Managing a constellation of observatories has classically resulted in an increased load on the ground operations team as they work to create and maintain schedules and command loads for multiple observatories. CYGNSS uses modern tools and technologies at the mission operations center (MOC) in conjunction with key functional aspects implemented in the observatories and an innovative strategy for pass execution coordinated with the ground network operator. The CYGNSS mission thus reduces the burden of constellation operations to a level commensurate with the low-cost mission concept.

The observatories are designed to implement nominal operations and science data collection without schedule-driven on-board command sequences. Science and engineering data files are generated, stored on board, and automatically added into an on-board downlink buffer. Downlink operations with one communication pass per 2 days for each observatory are automated using a data transfer engine located on a CYGNSS MOC server. The Observatory and ground network systems allow the ground station to automatically establish the communication link. During routine communication passes, the ground station establishes contact with the CYGNSS Observatory and then initiates the data downlink. Passes for each observatory execute autonomously and can be rescheduled to address emergencies or science opportunities without having to develop and deploy command sequences to the constellation.

## 4. SYSTEM DEVELOPMENT

CYGNSS is classified as Category 3 Class D mission per NPR 8704.5 Risk Classification for NASA Payloads. Class D missions are defined as "Low Priority and High Risk.," implying that their implementation may involve a risk not acceptable for a Class B or C mission, but tolerated for a Class D mission.

### 4.1 Risk Management

The CYGNSS project uses standard processes to identify, capture, and rank risks as part of continuous risk management throughout the development of the mission. This approach follows a general project theme of "Risk Tolerance, not Risk Ignorance". Risks are assessed on a regular basis to maintain threat levels within acceptable risk levels that are commensurate with a Class D approach and available project resources. As an example, we recognized that early development margins afforded significant mass resources that were used instead of investing in high cost development options. This approach occasionally drove mass margins below classically accepted margin levels but allowed the development team to identify long-term cost-effective solutions.

Another example of risk tolerance was to eliminate non-recurring development costs through the use of Commercial Off The Shelf (COTS) spaceflight components, some of which exist with only TRL-6 heritage. The risk of this approach is mitigated by working with the vendor to understand the environment for which the component was designed, accommodating the component accordingly, and making selected upgrades to match CYGNSS reliability requirements.

This risk tolerance theme was carried down to even the documentation level where the use of existing data sheets and/or user manuals as Interface Control Documents (ICD's) for COTS components rather than "rewriting" them into a more traditional ICD. The ICD's are placed under configuration management and included as interface requirements in the DOORs database to ensure proper verification.

### 4.2 Requirements Development

Instead of using the traditional spacecraft “top down” approach for requirements development, a hybrid approach was developed that combined the top down allocation and synthesis of key science requirements merged with a “bottoms up” approach based on available COTS equipment that met the key science requirements. The resulting hierarchically oriented requirements database was enveloped with a functional flow exercise to identify a detailed operational concept that accommodated the science requirements and the component requirements. Use of COTS equipment provided the special benefit of having known mechanical and electrical interfaces, software, environmental qualification, and performance capability, thus simplifying the early design effort timeline.

### 4.3 Reliability

Reliability is achieved through design at both the component and mission levels. CYGNSS requires a design lifetime of 2 yrs. Such a reliability requirement can be met through a strategy of parts engineering, selective on-board redundancy (typically for moving parts), and mission fault tolerance afforded by the constellation itself.

Mature semiconductor manufacturing processes typically produce highly reliable electrical piece parts with a relatively low likelihood of failure. A properly tailored combination of traditional parts assurance techniques, selection of parts that meet environmental requirements, and assembly level screening with qualification testing can be used to achieve a reliable design. This type of a parts program uses a modified EEE-INST- 002 Level 3 approach enhanced by unit level stress testing. The parts program uses Level 3 parts when resources allow, and when they do not, the parts are procured to the highest quality standards available with a preference for parts from QML-certified manufacturers. Each flight unit undergoes a screening burn-in prior to the normal test flow to expose infant mortality issues.

Use of constellations allows mission fault tolerance to be improved by including entirely redundant flight assets on-orbit such that the loss of a given number of observatories does not impact mission success. The redundancy inherent in a constellation is a significant strength over single, monolithic spacecraft applications as it serves to improve the performance of the constellation during the early stages of the mission because 8 observatories are launched while only 6 are required for end of life performance). The design process requires specific modeling and analyses not performed during standard mission design efforts. This effort involves the statistical evaluation of spatial and temporal considerations to determine the minimum number of vehicles required to meet mission requirements. The issue then becomes a program trade between the number of on-orbit assets the program can afford versus what fault tolerance the mission is able to accept.

CYGNSS science requirements for spatial and temporal coverage are met with six Observatories while we fly eight. Given redundancy carried at the constellation level, the CYGNSS Observatories were able to be designed with very cost effective "single string" architectures. CYGNSS chose to perform "functional" fault tree analyses and probability analyses to identify high probability single point failures even though NASA's Class D classification require reliability analyses only on safety critical functionality. These analyses were limited to "functional" aspects of the system, typically involving interfaces and binning large functional elements into failure categories, then using high level historical failure probabilities rather than traditional part count types of analyses.

## 5. Conclusion

CYGNSS not only serves as a pathfinder in GNSS-R technology application at the mission level, but also in the use of nanosatellite technology for a mainstream science investigation. The CYGNSS project is cost-capped at $100M exclusive of the launch vehicle. This compares to other wind measuring observatories that have estimated budgets >5x as large.

The CYGNSS project has worked to infuse cost effective nanosatellite technology and eliminate non-value added tasks while ensuring good engineering practices are employed. This often time takes the form of performing the traditional analyses with a reduced requirement for documentation. "Class D" and "risk tolerance" does not mean elimination of all traditional processes and procedures associated with Class B and Class C developments. The overall cost effectiveness of the GNSS-R instrument and its μSat platform combined with a risk tolerant system engineering and project management approach enables a mainstream science on a micro-budget.

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## BIOGRAPHY

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