SSC16-VI-1

CYGNSS MISSION OVERVIEW AND PREFLIGHT UPDATE

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ABSTRACT

The Cyclone Global Navigation Satellite System (CYGNSS) project, NASA's first Earth Venture Mission, is on schedule to launch in late-2016. CYGNSS will implement a spaceborne earth observation system designed to collect measurements of ocean surface winds through measurements of variations in the direct vs. reflected Global Positioning System (GPS) signals. The mission will provide data to enable the study of the relationship between ocean surface properties, moist atmospheric thermodynamics and convective dynamics; factors thought to be fundamental to the genesis and intensification of tropical storms. Key information about the ocean surface under and around a tropical storm is hidden from existing space borne observatories due to signal attenuation in the frequency bands in which they operate by the intense tropical cyclone precipitation, thus obscuring the ocean's surface. This plus poor temporal sampling are driving factors behind the fact that while tropical storm track forecasts have improved in accuracy by ~50% since 1990, there has been essentially no improvement in the accuracy of the storm's intensity prediction [1]. Because L-band signal attenuation is only a minor factor by even the strongest of tropical cyclones, 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 should advance our ability to forecast tropical storm intensity and its closely related 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 the increased risk tolerance allowed by NASA's Earth Venture Program enable CYGNSS to provide science measurements never before available to the tropical cyclone research community. CYGNSS consists of 8 GPS bi-static radar receivers deployed on 8 micro-satellites to be launched in late 2016 aboard an Orbital ATK Pegasus XL launch vehicle. The CYGNSS Observatories are enabled by modern electronic technology; it is an example of how "off the shelf" nanosatellite technology can be applied to replace traditional “old school” solutions at significantly reduced cost while providing an increase in performance. The CYGNSS SmallSat 2016 paper will provide an overview of the mission system and pre-launch status.

INTRODUCTION

The Cyclone Global Navigation Satellite System (CYGNSS), selected as the 1st complete spaceflight mission of NASA's Earth Venture program, is preparing to launch an 8-observatory constellation of micro-satellites to collect data to enhance the understanding of tropical cyclone intensity development. The CYGNSS team is preparing for launch in late-2016 with an implementation of mission flight and ground concepts that will support the deployment and operations of the constellation of observatories in a cost constrained mission environment.

Electromagnetic radiation scattered by the ocean surface contains information about the sea surface state and its altimetric height. Previous radar based ocean altimetry and wind remote sensing missions rely on this general principle, but they all utilize actively transmitted radar pulses to detect the backscattered reflection. Global Navigation Satellite System reflectometry (GNSS-R) however, utilizes reflections from GNSS signals to sense the ocean altitude and state. This passive approach was demonstrated successfully on-orbit during the 2003 UK-DMC-1 mission [1]. The fundamental measurement made during each quasi-specular reflection contact between a GNSS transmitter and the GNSS-R receiver is the areal increase of scattering due to ocean surface roughness. A perfectly smooth surface reflects a specular point while a rough surface scatters it across a distributed "glistening zone". The Delay Doppler Map (DDM) created by the GNSS-R instrument is an image of that scattering cross-section in the time and frequency domains across the glistening zone. The DDM is an information-rich data set of surface state statistics. When this measurement is obtained from the ocean's surface, the data is intimately related to the surface wind vector and providing a direct measurement of the wave height statistics.

The CYGNSS instrument uses GNSS-R to provide data that will enable study of the relationship between ocean surface properties, moist atmospheric thermodynamics, radiation and convective dynamics. These relationships are postulated to be intrinsic to the genesis and intensification of tropic storms [2]. Key information about the ocean surface under and around a tropic storm is hidden from existing space borne observatories because of the frequency band in which they operate. Using GNSS-based bi-static scatterometry performed by a constellation of micro-satellites offers remote sensing of ocean wave 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 tropical storm intensity and storm surge forecast skill. Investigation of these properties has not been previously possible due to technology and on-orbit asset cost limitations. Modeling techniques developed over the past 20 years combined with recent developments in nano-satellite technology and the NASA Earth Venture program's higher risk tolerance to replace existing accepted solutions at significantly reduced cost enable the CYGNSS mission.

MOTIVATIONAL BASIS FOR 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) the rapidly evolving (genesis and intensification) stages of the TC life cycle have temporal features on the order of hours, not days and 2) much of the TC's inner core ocean surface is obscured from conventional remote sensing instruments by the storm's intense precipitation.

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]. 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 that of the observatory's sensor swath. 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 TC development. Early design of CYGNSS focused on constellation formation that would enable monitoring of the TC genesis and intensification by sufficiently closing the coverage gaps. The 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 at least 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 mean revisit time for CYGNSS TC sampling is predicted to be 7.2 hr, and the median revisit time will be 2.8 hr [5], well below the 12 hr revisit requirement.

Wind Observations in Precipitating Conditions

Previous spaceborne measurements of ocean surface vector winds made by observatories such as QuikScat suffered from attenuation 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 [6]. Figure 1 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 and Ku-band (e.g., QuikScat) signals are effectively blocked by heavy rain while precipitation has a negligibly small effect on the L-band signal, even at the highest rain rates. This was a major factor for selection of the CYGNSS instrument.

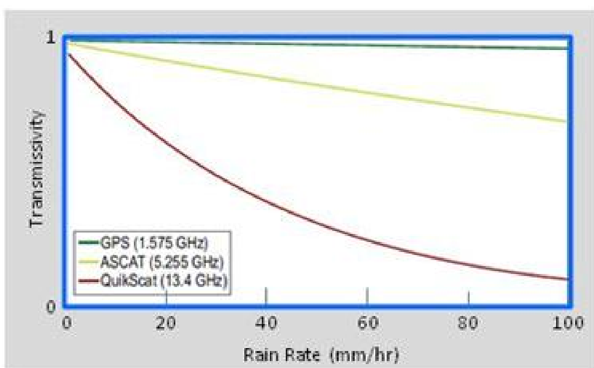

Figure 1 - one-way slant path atmospheric attenuation experienced by an L-band, C-band and Ku-Band signal as a function of surface precipitation rate

The Value of Wind Observations for Tropical Cyclone Forecasting

Sea surface wind measurement is a key factor important factors in both improving our understanding of TCs and predicting them operationally [7], [8]. An example of satellite ocean surface wind observations on TC forecast skill is illustrated by the 60-hr forecast of Hurricane Cindy performed with and without QuikScat scatterometer wind fields [9]. The storm intensity (pressure) forecast error, illustrated in Figure 2 is reduced by ~50% or more with inclusion of surface wind data for all forecast lengths.

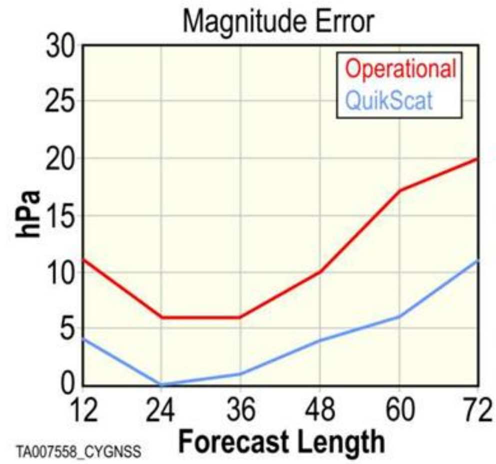

Figure 2 - Intensity forecast error for Hurricane Cindy, with and without wind measurement

CYNGSS MISSION IMPLEMENTATION

Implementation of the CYGNSS mission on-orbit element is achieved using eight simple nadir-pointed µSat-based Observatories, each hosting a GNSS-R instrument. The instruments create images representative of the Earth ocean surface roughness and pass this data via digital interfaces to the µSat for compression, data storage, and downlink. The images are processed on the ground at the Science Operations Center (SOC) to retrieve corresponding wind field information.

Required coverage of the historically active tropical cyclone area, as shown in Figure 3, is provided by the 8 Observatories dispersed about CYGNSS 510km, 35deg circular orbit. Final baseline positioning of the constellation will place the observatories with approximately 45 degrees separation to minimize chances for intra-constellation collisions, provide a more deterministic operational cadence, and maintain science coverage with minimal station keeping required through the course of the 2-year primary mission operational phase.

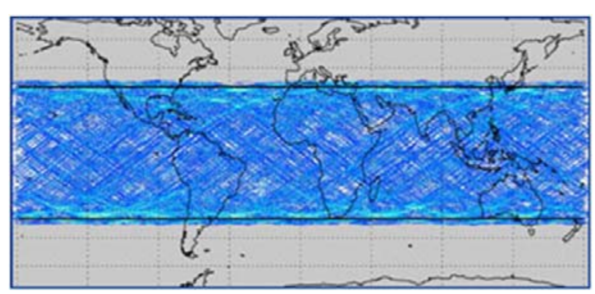

Figure 3 - Historically active TC regions 2000-2009 with CYGNSS coverage area overlaid

Ground system elements completing the CYGNSS mission implementation include: The SwRI Mission Operations Center (MOC) located in Boulder, CO, the Universal Space Network (USN) remote antenna sites in Australia, Hawaii, and Chile connected with the USN Network Management Center (NMC), the University of Michigan Science Operations Center (SOC) in Ann Arbor, the NASA Physical Oceanography Distributed Active Archive Center (PO.DACC) and the NASA Conjunction Assessment Risk Analysis (CARA) team.

Flight Segment Operational Characteristics

CYGNSS uses a NASA-provided Orbital-ATK Pegasus XL launch vehicle (LV) for insertion into orbit. The launch configuration is comprised of 8 Observatories mounted on a Deployment Module (DM) in 2 tiers of 4 Observatories as shown in Figure 4. All activities from LV separation through initial ground communication acquisition is pre-programmed and occurs autonomously without ground intervention. Each uSat will initiate power application at its separation from the DM, initialize uSat subsystems, then sequence through solar-array deployment and establishment of a sun-pointing attitude configuration within the first several orbits after launch.

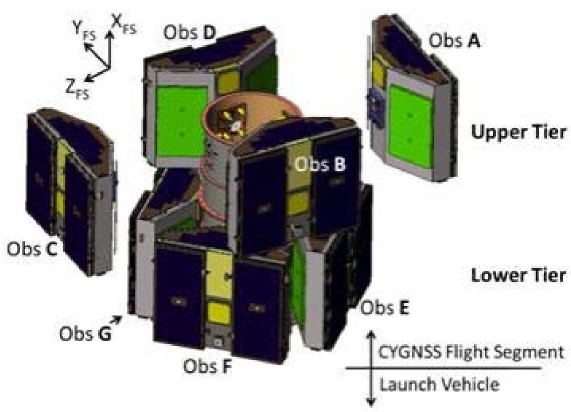

Figure 4 - CYGNSS launch configuration is comprised of 8 Observatories mounted on the Deployment Module (DM) in 2 tiers of 4 Observatories

Observatory Mode Flow

The CYGNSS Observatory operational modes are streamlined with provisions for initial Observatory operations, nominal science operations, and fault recovery. Figure 5 provides an overview of the Observatory mode flow. The Observatory initializes into a 'Startup' transitory mode from which it transitions into one of the three primary operational modes: 1) Safe Mode, 2) Engineering Mode, or 3) Science Mode.

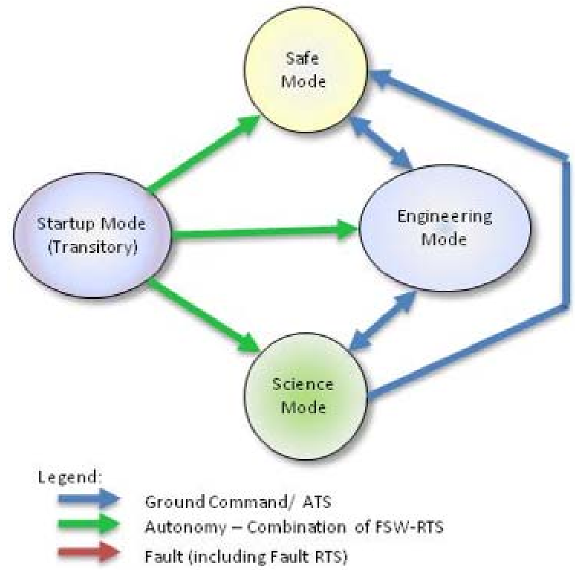

Figure 5 - CYGNSS Observatory mode flow diagram

Included as part of the 'Startup Mode', the µSat Attitude Determination and Control Subsystem (ADCS) is designed to damp Observatory attitude rates allowing capture of the Observatory's attitude after initial separation and to address any potential attitude control problems after the initial separation.

The initial Observatory entry into 'Startup Mode' after separation from the launch vehicle deployment module will result in a transition into the 'Safe Mode'. 'Safe Mode' is designed as an indefinitely stable configuration for all uSat subsystems. It employs a coning maneuver about the uSat's major axis with the large zenith solar array oriented towards the Sun.

From 'Safe Mode' the Observatory will typically be transitioned into 'Engineering Mode' via either real-time ground or Absolute Time Sequence (ATS) commands. 'Engineering Mode' is used to perform calibrations, engineering checkout activities of uSat subsystems or instrument capabilities, or to put an Observatory into a high-drag configuration for a differential drag maneuver. 'Science Mode' configures the Observatory for a precision nadir-point attitude and science data collection. The CYGNSS mission is designed for the Observatory to spend the majority of its operational time in this mode.

Fault recovery capabilities have been built into the mode-flow logic to facilitate keeping the Observatory in 'Science Mode' for the maximum possible periods. Faults that do not require ground intervention for diagnosis and recovery will result in the Observatory transitioning through 'Startup Mode' directly back into

‘Science Mode’. This recovery capability will help to minimize the loss of science data collection by keeping the uSat in a nadir point configuration through a brief recovery period and by not requiring the vehicle to wait until the next ground contact for recovery, potentially more than 48-hours away.

CYGNSS Science Instrument and Science Data

The CYGNSS science instrument is a Delay Doppler Mapping Instrument (DDMI). 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 monolithic microwave integrated circuit 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. The upgraded SGR-ReSI has been flight qualified aboard the UK TechDemoSat-1 *(url: https://directory.eoportal.org/web/eoportal/satellite-missions/t/techdemosat-1)*.

In total, the DDMI consists of the Delay Mapping Receiver (DMR) electronics unit, two nadir- pointing antennas for collecting reflected GNSS signals, a zenith-facing antenna to provide a coherent reference for the coded GPS signal plus space-geolocation capability, and a Low Noise Amplifier for each DDMI antenna (Figure 6).

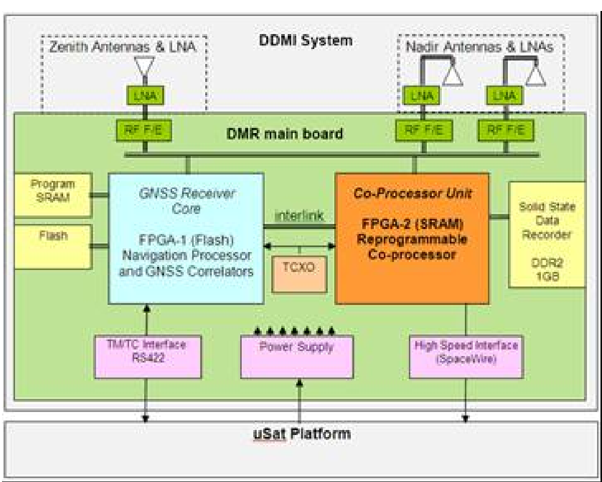

Figure 6 - DDMI functional block diagram

DDMI onboard processing generates the DDM images. Each pixel of the DDM is obtained by cross-correlation of the received signal with a locally generated replica time delay and Doppler shift. The direct GPS signal provides a coherent reference for the coded GPS signal while the quasi-specular forward scattered signal from the Earth surface is received by antennas on the nadir side of the spacecraft. The scattered signal contains signal lag and frequency shift, the two coordinates of the DDM image (Figure 7), the measurement of which enables the spatial distribution of the scattering cross section to be resolved as described by Scott Gleason, et al. [10] [11]. Each CYGNSS DDM has 128 delay pixels with resolution of 61 ns. The Doppler resolution is 250 Hz over a ±6.5 kHz range, resulting in 52 Doppler pixels.

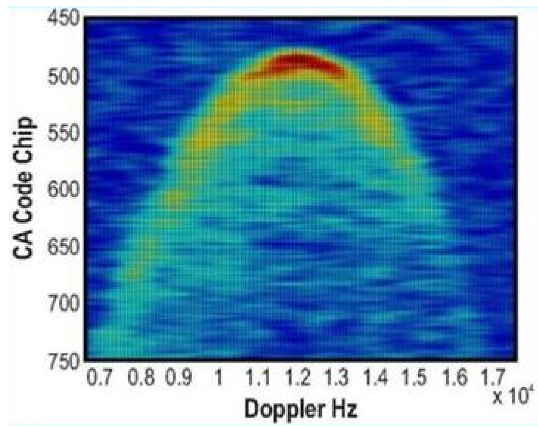

Figure 7 - Delay Doppler Map image

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). There are typically many specular reflections from the surface available at any given time due to the large number of GPS transmitting satellites. Available DDMI resources allow generation of up to four simultaneous DDMs each second, selection of the specific reflection being based on location within the highest sensitivity region of the DDMI nadir antenna pattern. Individual DDM integration times last one second and wind speeds are derived from measurements over a 25x25 km^2 region centered 234 on the specular point. This results in a total of 32 wind measurements per second by the full constellation. CYGNSS spatial sampling consists of 32 simultaneous single pixel “swaths” that are 25 km wide and, typically, 100s of km long, as the specular points move across the surface due to orbital motion by CYGNSS and the GPS satellites.

The baseline wind speed retrieval algorithm planned for CYGNSS is an extension of one previously developed for the UK-DMC spaceborne mission, as described in Clarizia et al. [12]. The algorithm uses an empirically-derived geophysical model function to estimate the 10 m referenced wind speed from the measured DDM within a 25x25 km2 region centered on the specular reflection point. The UK-DMC algorithm has been extended to higher wind speeds by applying a detailed end-to-end simulator of the CYGNSS measurements to a realistic Nature Run simulation of the full life cycle of a Category 4 hurricane [12]. The end-to-end simulator models the complete bistatic radar measurement process, including electromagnetic propagation down from the GPS satellite to the ocean surface, rough surface scattering by the ocean, propagation back up to the CYGNSS satellite, and the engineering design of the CYGNSS GNSS-R receiver [14]. A large population of simulated DDMs, covering a wide dynamic range of wind speeds, is generated and used to extend the geophysical model function from the lower wind speed regime experienced by UK-DMC to the much higher winds of interest to CYGNSS. The RMS wind speed retrieval error is expected to meet or exceed the mission requirement of 2 m/s or 10% of the wind speed, whichever is greater [5].

MicroSatellite On-Board Systems

A uSat platform hosts the DDMI on each CYGNSS Observatory. The CYGNSS Observatory is based on a single-string hardware architecture with functional and selective redundancy included for critical areas (

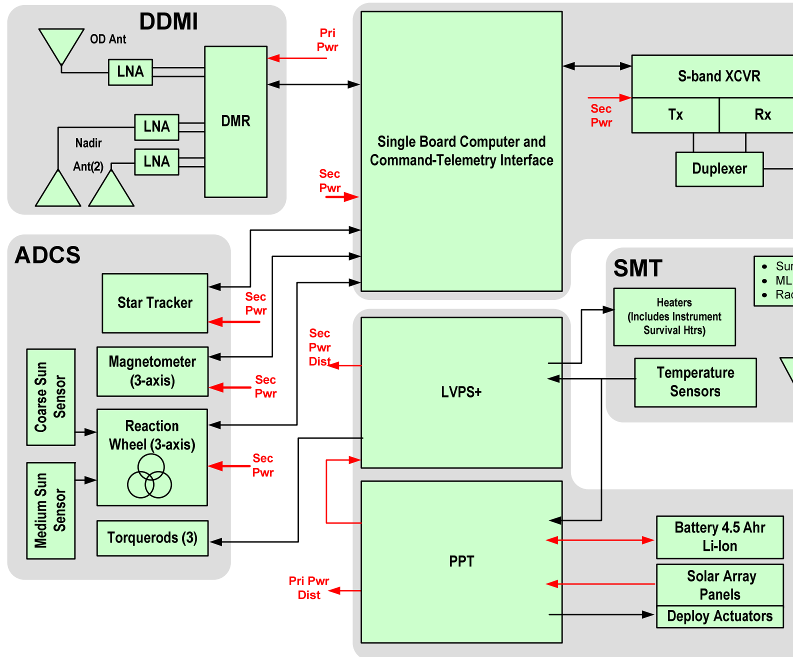

Figure 8). Due to the limited planned contact schedule as well as the limited time per contact, each uSat platform is designed and implemented to maintain the safety of the Observatory without ground intervention. The design philosophy of the CYGNSS flight segment is to maximize fault tolerance by eliminating unnecessary functionality and failure points. The CYGNSS Observatories employ a simple architecture and a simple operational schema. Redundancy is

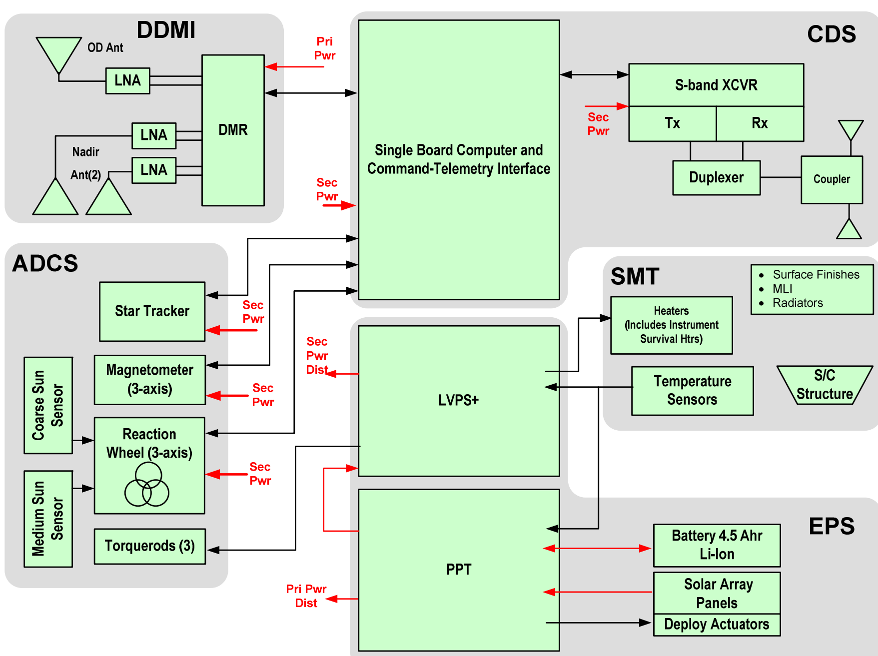

Figure 8 - CYGNSS Observatory functional block diagram

achieved at the constellation level since 6 of the 8 Observatories are required to meet baseline science requirements.

Communication and Data Subsystem (CDS)– CYGNSS Observatory on-board data handling and command and telemetry (C&T) S-band communication link are implemented in the CDS providing the operational interfaces to the Observatory. The CDS also contains the Microsat control processor with the associated Flight Software (FSW) necessary to manage operations of each of the uSat subsystems and the data interface with the DDMI.

Two downlink data rates (64kbps and 4Mbps) and one uplink data rate (64kbps) have been established for the CYGNSS Observatories. All CYGNSS uSats share the same downlink frequency. The constellation relies on coded fill patterns and the CCSDS Spacecraft ID field in ground commands to initiate data downlink operations and to avoid intra-constellation interference.

Attitude Determination and Control Subsystem (ADCS)– The CYGNSS ADCS is a star tracker based, 3-axis reaction wheel design with torque rods for wheel momentum desaturation. Maneuverability is limited to recovering from the Deployment Module separation tip-off rates, performance of a Sun referenced Safe mode, and local vertical/local horizontal pointing that includes nadir or roll offset for Science operations and a High Drag, Torque Equilibrium Attitude (HD-TEA) for orbit maintenance.

Electrical Power Subsystem (EPS) – The EPS is designed to perform battery charging without interrupting science data acquisition. It is based on a 28±4 Vdc primary power bus with electrical power generated by an 8-panel rigid S/A. When stowed, the z-fold design of the S/A allows the solar cells to face outward, to power the micro-satellite in Safe mode before S/A deployment.

Structures, Mechanical, Thermal Subsystem (SMT) – Observatory mechanisms are limited to heritage solar array (S/A) deployment devices and 3-axis reaction wheels. The two “z-fold” Solar Array (S/A) wings are held in place for launch using a cup/cone interface and deployed by a combination of actuators and single-axis spring-loaded hinges into a permanently held position planar along the zenith side of the Observatory. The solar arrays will be deployed by a FSW controlled Relative Time Sequence (RTS) shortly after launch. Backup commands that can be issued from the ground to deploy the solar arrays have been implemented to allow the Operations team to command a S/A deployment if the automated sequence fails.

The thermal control design provides thermal stability and minimizes thermal gradients through an integrated design including surface treatments and localized radiators. The arrangement of internal equipment is used to aid thermal control and minimize the need for supplemental heaters except for Safe Mode operations. Heater control is implemented via hardware control with parameters that are modifiable on-orbit.

GROUND SEGMENT

CYGNSS Ground Segment operations are streamlined and straight-forward, thus allowing for a high degree of automation at the MOC. Both the CYGNSS MOC and the SOC will be staffed 9 hours a day, 5 days a week in the science operations phase of the mission. The USN Network Management Center (NMC) is staffed 24/7.

Ground Data Network - USN

USN provides the ground data network services for the CYGNSS mission. With a 35deg inclination, the observatories within the CYGNSS constellation will be visible to three ground stations within the Universal Space Network (USN) – located in Hawaii, Australia, and Santiago, Chile - for periods which average 500+ seconds visibility per pass when the observatory is nadir pointed. A communication analysis has been performed and confirms there are an adequate number of pass options available to support the CYGNSS operations concept. In the normal operations phase, CYGNSS is projected to require ~ 4 passes per day as the plan is to communicate with each of the 8 observatories every ~ 48 hours.

Standard USN processes for scheduling contacts and communicating between MOC and USN during each contact are followed with minor modifications. CYGNSS will be using a unique idle pattern for each Observatory to aid in establishing communication with a select Observatory during each planned contact. The unique idle pattern also facilitates adding or moving contacts without updating on-board sequences when necessary.

Using the ‘unique idle pattern’ concept, communication with each CYGNSS Observatory is simplified by having the µSat initiate the nominal stored engineering and stored science data playback activities. A typical communication sequence using the unique idle pattern is shown in Figure 10.

Mission Operations Center (MOC) – Southwest Research Institute (SwRI) Boulder, CO

The CYGNSS MOC is responsible for mission planning, flight dynamics, and command and control tasks for each of the Observatories in the constellation.

The MOC architecture and top level data flow is illustrated in Figure 9. Responsibilities allocated to each area in the MOC include:

- Mission Planning: identifying and scheduling ground contacts, receiving requests for activities on the observatories, assessing requests checking against rules and constraints, tracking memory resources, and creating the command loads and ground contact control procedures necessary to implement received requests and execute each ground contact,
- Flight Dynamics (FD): provides predictive and definitive position information for each Observatory. This information is used to facilitate constellation Observatory communication, as well as constellation configuration management for both nominal operations and in response to Collision Avoidance data,
- Command and Control (C2): establishing, controlling, and monitoring Observatory communication contacts. C2 is responsible for receiving all telemetry data; generating, testing, and executing real-time commanding and procedures when necessary, and
- Mission Monitoring and Offline Processing: processing and archiving received telemetry data, creating and distributing data sets, providing remote access to real-time and archived data, performing monitoring of systems (flight and ground) for general health and status, trending engineering data, and issuing pages and alarms as required.

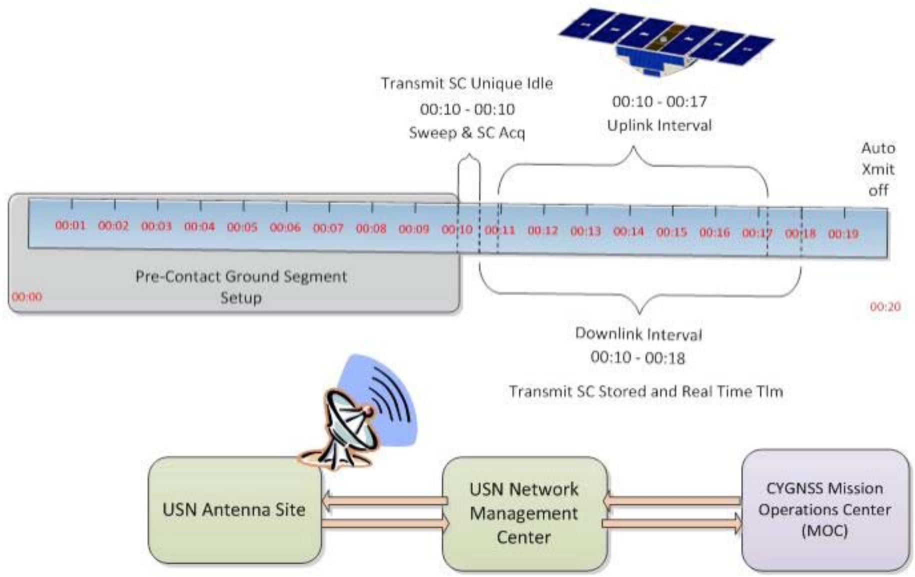

Figure 10 - Typical CYGNSS communication pass timeline

Data flows between ground segment elements to support routine operations are straight forward.

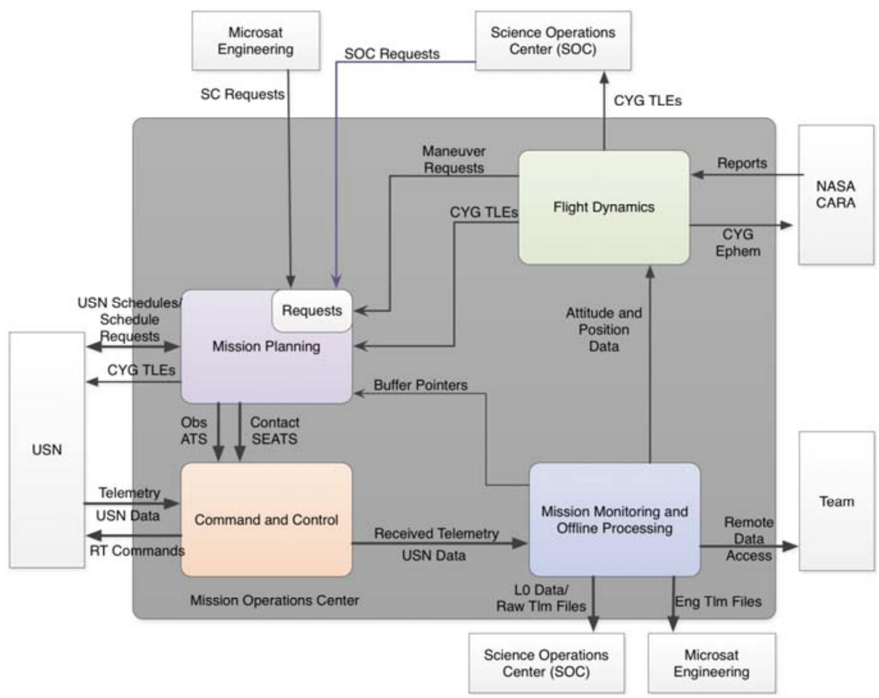

Figure 9 - CYGNSS Mission Operations Center functional block diagram

Planning flows consist of emails between the CYNGSS MOC and the USN Network Management Center (NMC) to select and confirm contacts for all CYGNSS Observatories and to communicate the CYGNSS Observatory location Two Line Elements (TLEs) for upcoming contacts. Email communication is also used between the NASA CARA team and MOC as necessary to provide warning of any impending potential conjunctions with a CYGNSS Observatory, transfer of ephemeris data from the MOC to the CARA team for screening.

During a ground contact with an Observatory, the data flows from USN to the MOC consist of engineering telemetry extracted from Virtual Channel (VC) 0 and VC1. At the MOC, this data is limit checked, routed to a real-time archive, and pushed to a location where authorized remote users can access the real-time engineering data for analysis. Due to limited bandwidth availability between the USN remote antenna sites and the USN NMC, it is not feasible to route stored science and engineering telemetry data to the MOC in real-time during the pass. All CYGNSS telemetry data received at the remote antenna site is stored at the antenna site and transferred to the CYGNSS MOC post pass. Once the full data for each contact is received at the MOC, it is processed and distributed to the SOC.

Science Operations Center (SOC) – University of Michigan Ann Arbor, MI

The Science Operations Center (SOC) team is the operational interface with the CYGNSS science and instrument teams. The CYGNSS SOC is responsible for:

- Support of DDMI testing and validation both pre-launch and on-orbit,
- Generate instrument command requests for the MOC,
- Processing Level 0 science data and ancillary data to produce Level 1, 2, 3 and 4 science data products, and
- Science data archival products, DDMI commands, code, algorithms and ancillary data at the NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC).

During the science phase of the mission, SOC requests for instrument operations will occur infrequently and will typically be sent when the science team wants to collect enhanced science data sampling of special interest events.

CONSTELLATION DESIGN AND CONTROL

Science coverage requirements, avoiding intra-constellation collisions, and providing the ability to achieve a defined operations tempo are the driving factors in establishing a stable constellation configuration with defined spacing between the CYGNSS observatories. Mission analyses of spatial coverage have determined that any fixed configuration with phase angles of at least 15 degrees between any two satellites will achieve coverage requirements; however by maximizing the phase angle between satellites we can maximize the time between station keeping maneuvers due to residual drift between satellites. This drives a desired constellation configuration of eight, evenly spaced observatories separated by 45deg (Figure 11).

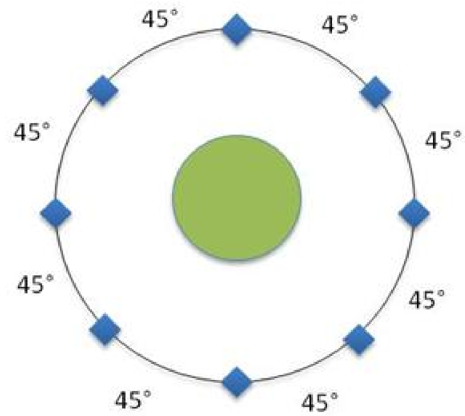

Figure 11 - Nominal CYGNSS constellation orbital phasing

Establishing the desired spacing between observatories is accomplished by using differential drag maneuvers during the initial operational phases of the mission. A differential drag approach has been adopted to leverage the Observatory inherent geometry of a low drag profile during science operations with the potential of high drag when the solar array normal is oriented with the velocity vector. This approach was chosen to avoid the costs associated with adding propulsive capability. It is also relatively simple to execute from an operations stand point ensuring the cost savings in hardware are not just translated into operational costs to maintain a complex operation schedule.

MISSION STATUS

The CYGNSS flight and ground segments are on schedule for a late-2016 launch as of the submittal of this paper (May 2016). All 8 observatories are fully integrated and have completed a suite of environmental tests designed to ensure successful launch, operational compatibility, and science performance.

CYGNSS system testing was designed to verify and validate all elements against their requirements, ensure system interoperability, and provide training for the Flight Operations team. A full form, fit, and functional engineering model of the Observatory was completed prior to CDR allowing design requirement compliance to be assessed, acting as a pathfinder for fabrication and test procedures, and to assure the program we were ready to proceed to full production.

Flight hardware verification testing was performed at multiple levels using our heritage test and verification environment. Early flight software development was performed on software development platforms using COTS processors and then transitioned to engineering models of the flight computer external interface simulators. Testing then transitioned to the System Test Bench (STB) where the EM Observatory supports full dynamic simulations including pointing models for the Observatory and GNSS Signal Stimulator (GSS). The pointing simulation is a 6-DOF dynamic simulation developed for CYGNSS while the GSS provides simulated on-orbit signal input to the DDMI. The combination of these simulators fully exercise the on-board ADCS and science data processing algorithms while also supporting high fidelity Mission Simulation Tests.

Our verification approach tested flight hardware and software at the lowest level practical. All components were subjected to functional and performance testing to demonstrate requirement compliance then vibration and thermal cycle tested to screen for workmanship and infant mortality issues. After component testing was completed, the observatories were integrated during a multi-unit AI&T campaign using a "waterfall" schedule approach for the full constellation of observatories where the 1st completed Observatory was subjected to special “one-time-only” tests to verify key performance aspects. The "one-time-only" tests included:

- Full electromagnetic interference and compatibility tests
- Thermal balance and low level vibration tests (Figure 12) to correlate thermal and structural models
- Instrument - µSat L-band compatibility tests to assure the DDMI measurements will not be corrupted by the µSat subsystem operation (Figure 13)

Finally, after all observatories were integrated and functionally tested, they were subjected to thermal vacuum tests (Figure 14) with S/A deployment tests afterward (Figure 15). Vibration and shock testing of the observatories is planned to occur after flight segment integration with the Deployment Module. This will allow a "test as you fly" approach and results in a much higher fidelity test.

In parallel with the flight segment, the CYGNSS ground segment has been developed and integrated with the MOC and SOC (Figure 16 and Figure 17 respectively) recently completing comprehensive functional tests and the Flight Operations Review.

Approximately 2mos prior to launch, the CYGNSS flight segment and GSE will be shipped to the launch site for inspection, final functional tests, compatibility tests, launch MSTs, LV encapsulation, and launch.

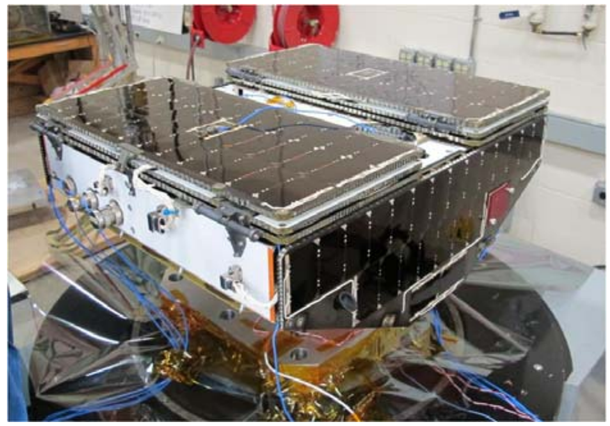

Figure 12 - CYGNSS Observatory during vibration testing

Figure 13 - CYGNSS Observatory during L-band noise floor testing

Figure 14 - CYGNSS observatory level thermal vacuum testing

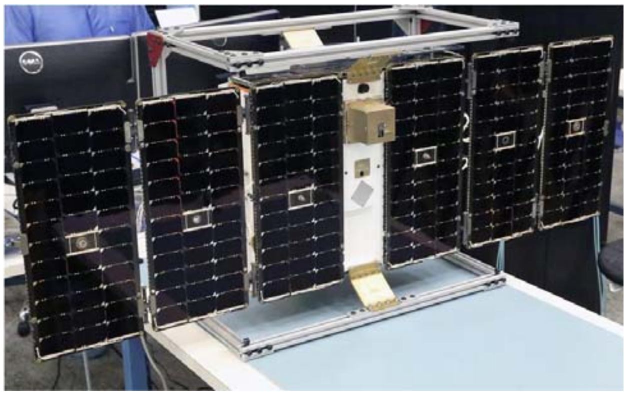

Figure 15 -- CYGNSS Observatory Solar Array Deployment Test

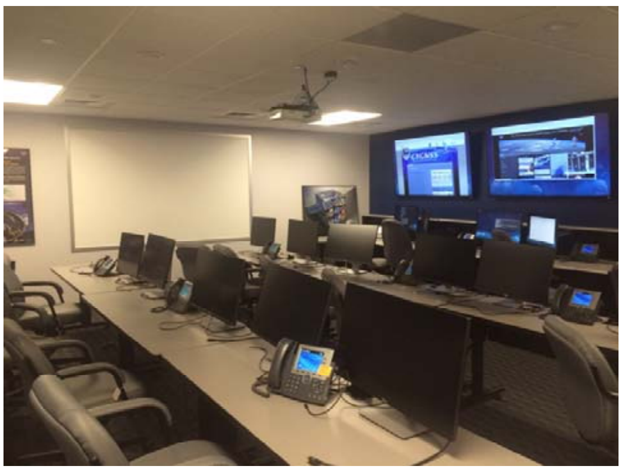

Figure 16 -- CYGNSS Mission Operations Center

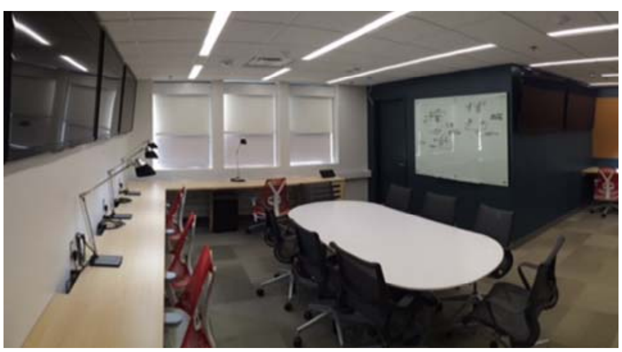

Figure 17 -- CYGNSS Science Operations Center

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