# The CYGNSS Ground Segment; Innovative Mission Operations Concepts to Support a Micro-Satellite Constellation

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*Abstract*—**Hurricane track forecasts have improved in accuracy by ~50% since 1990, while in that same period there has been essentially no improvement in the accuracy of intensity prediction. One of the main problems in addressing intensity occurs because the rapidly evolving stages of the tropical cyclone (TC) life cycle are poorly sampled in time by conventional polar-orbiting, wide-swath surface wind imagers. NASA's most recently awarded Earth science mission, the NASA EV-2 Cyclone Global Navigation Satellite System (CYGNSS) has been designed to address this deficiency by using a constellation of micro-satellite-class Observatories designed to provide improved sampling of the TC during its life cycle.**

**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. Using modern tools and technologies at the Mission Operations Center (MOC) in conjunction with key components implemented in the flight system and an innovative strategy for pass execution coordinated with the ground network operator, the CYGNSS mission reduces the burden of constellation operations to a level commensurate with the low-cost mission concept. This paper focuses on the concept of operations for the CYGNSS constellation as planned for implementation at the CYGNSS MOC in conjunction with the selected ground network operator.**

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## 1. INTRODUCTION

The NASA EV-2 Cyclone Global Navigation Satellite System (CYGNSS) mission has been conceived to develop and operate a constellation of eight Observatories with the goal of enhancing our knowledge of Tropical Cyclone behavior through the use of increased observation samples and the ability to view through the precipitation in the core of the cyclones using GPS technology. Each Observatory in the CYGNSS constellation consists of a microsatellite (commonly referred to as a "microsat") platform hosting a GPS receiver modified to measure surface reflected signals.

Mission implementation uses a simple nadir-pointed Observatory hosting an instrument technically proven on orbit. Required global coverage is provided by 8 Observatories loosely dispersed about a 500 km, 35° circular orbit.

Developing a concept of operations for a constellation of Observatories to fit within a low-cost mission concept is a challenge that has been tackled by the CYGNSS team. This paper outlines these operational concepts and the ground system elements as planned for implementation at the CYGNSS MOC to support a cost effective mission operations effort.

This paper is part of a coordinated series of papers being presented at the 2013 IEEE Aerospace Conference in Big Sky, MT. The full series includes:

- CYGNSS Mission overview, science objectives, and requirement allocation [Session 2.05-2532; Dr. Chris Ruf]
- CYGNSS Mission implementation with specific emphasis on the microsat [Session: 2.05; Randy Rose]
- CYNGSS Science instrument [Session: 6.02-2410; Martin Unwin]
- CYGNSS Avionics [Session: 7.07-2013, John Dickinson]
- CYGNSS Mission operations [Session: 12.02-2559; this paper]

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## 2. CONCEPT OF OPERATIONS

As outlined in the previous section, a CYGNSS Observatory consists of a microsat and its associated Delay Doppler Mapping Instrument (DDMI) package. In developing the design concepts for the CYGNSS Observatories, the Systems Engineering team has kept in mind ensuring the safety of the Observatories without ground intervention. Providing on-board systems which minimize the need to develop time-tagged command sequences for each Observatory for routine operations also supports a simplified operational cadence for maintaining the constellation.

*Launch through Commissioning*

Each Observatory is deployed with solar arrays stowed and the Observatories can remain in this 'stowed' configuration indefinitely. After deployment from the launch vehicle, each Observatory transitions automatically through the initial three states shown in Figure 1 to reach the Standby Mode where it can safely remain indefinitely.

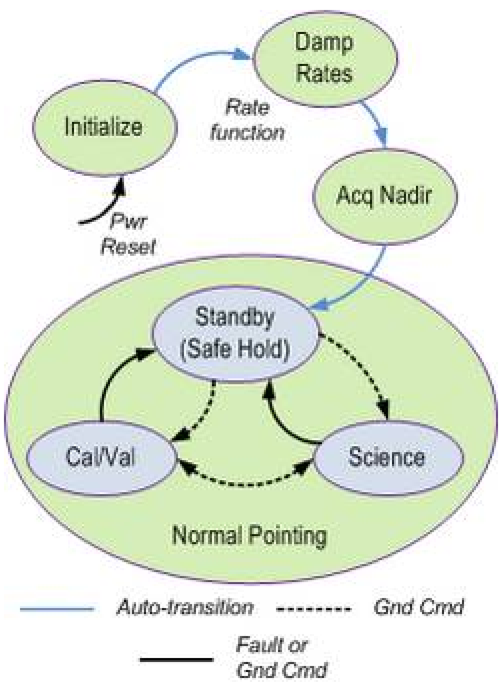


**Figure 1: CYGNSS Modes**

Deployment of the S/As will occur within a communication pass allowing the CYGNSS operations and SC teams to observe the deployment sequence and address any issues that may occur using real-time commanding. Additional commissioning activities for the Observatories will begin once the S/As are deployed on every Observatory in the constellation and will continue for a period of 2 to 4 weeks.

Commissioning activities for a CYGNSS DDMI commences once its microsat has completed its commissioning sequence. DDMI commissioning begins and lasts an additional 4 weeks. During this time, the DDMI is operated in two Engineering modes, which are used to verify on-orbit performance and tune the on-board Delayed Doppler Map (DDM) generation and subsampling algorithms. At the end of the DDMI commissioning activities, the instrument will be transitioned into its Science mode where it will collect data continuously.

Commissioning activities for the microsats and then the instruments may progress in an interleaved manner. Within a single communication pass activities will be performed on a single Observatory, however it is not necessary to complete all commissioning tasks on one Observatory before progressing to the next Observatory in the constellation. Since all Observatories are independent, it is also unnecessary to ensure each Observatory is at the same 'step' in a commissioning sequence. This independence allows a flexible scheduling approach to be used in setting up commissioning passes and does not delay commissioning activities for all Observatories if a single Observatory requires extra time while an off-nominal issue is being addressed.

*Nominal Operations*

Upon completion of commissioning activities, the Observatories will be transitioned into the 'Science' mode of operation. At this point the DDMI is set to Science mode for the duration of the mission, except for brief returns to Cal/Val mode performed bi-annually. In Science mode, sub-sampled DDMs are generated on-board and downlinked with 100% duty cycle.

The Observatories are designed to implement nominal Observatory operations and science data collection without on-board time-tagged command sequences. With the DDMI in its continuous science mode, and the Observatory set to maintain all nominal operations without additional commanding, the primary 'routine' activity performed on a regular basis is communication with the ground network to downlink the accumulated science and engineering data.

Science and engineering data files are generated, stored on-board, and automatically added into an on-board downlink file list. Retrieval of the science data occurs during communications passes which are planned to occur at the rate of one pass per Observatory every 1.5 to 2 days during the nominal operations period. On-board microsat data storage provides storage for greater than 10 days of science data allowing flexibility in pass scheduling and supporting recovery from loss of communications during a pass.

Downlink pass acquisition operations are automated using an on-board Automated Event Recognition (AER) capability as shown in Figure 2. The mission operations team will schedule passes for each Observatory and when the Observatory is within range of the scheduled ground antenna asset – the antenna will illuminate the microsat with a Clear Channel communication. On board, the AER will be set to switch the microsat transmitter on when the receiver detects the ground network signal. Once the

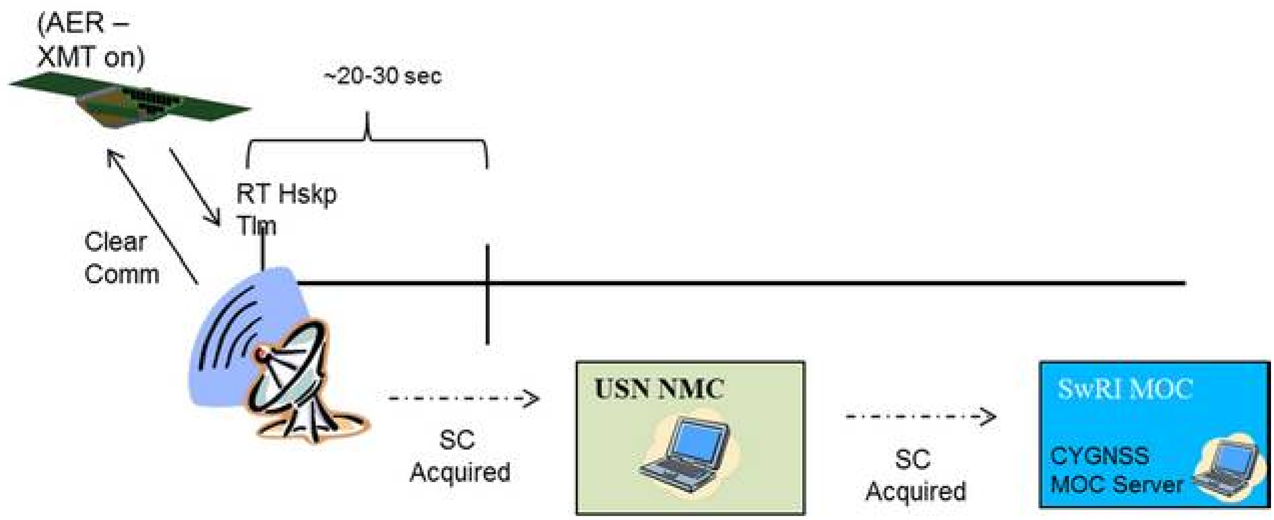


**Figure 2: Establishment of Communication Pass**

transmitter is enabled, housekeeping telemetry will be transmitted allowing the ground antenna to synchronize with the microsat. Once lock has been established, a notification of the acquisition status will be relayed to the CYGNSS Mission Operations Center (MOC).

After establishing contact, the following steps are performed – as shown in Figure 3:

- Housekeeping data is continuously transmitted by the microsat, received on the ground and flowed to the MOC
- MOC sends the command to thaw the CCSDS File Delivery Protocol (CFDP) engine on board the microsat
- MOC sends the CFDP protocol commands associated with the files downlinked during the last pass for this Observatory
- Any incomplete transmissions from the previous pass, based on the protocol messages, will be downlinked by the microsat CFDP engine
- Science and engineering files placed on the downlink list in the microsat since the last pass will be transmitted to the ground and collected at the antenna site
- At the end of the planned pass time, the MOC will send a CFDP freeze command to stop the transmission of files and a transmitter off command
- The AER system on board the microsat will have a backup transmitter off command which will be triggered by a timer that is set when the transmitter is turned on to ensure the transmitter is not inadvertently left on for a long period of time
- Post pass – the collected files will be transferred from the antenna site to the USN (Universal Space Network) Network Management Center (NMC) where they can then be transferred to the CYGNSS MOC for processing and distribution.

As noted in the pass flow, the plan for CYGNSS operations is to flow the CFDP files from the remote USN antenna sites to the USN NMC after the completion of the pass. This flow decouples the file processing from the real-time flow of the pass which simplifies the operations and does not levy any bandwidth requirements on the links form the remote antenna sites to the NMC.

Post pass, the files collected during the pass will be flowed to the CYGNSS MOC where they will be processed through the CFDP engine to create the protocol messages that will be uplinked at the next contact with the Observatory. Complete science files will then be transferred to the Science Operations Center (SOC). Incomplete files will be saved at the MOC until they can be completed during the next pass with the Observatory.

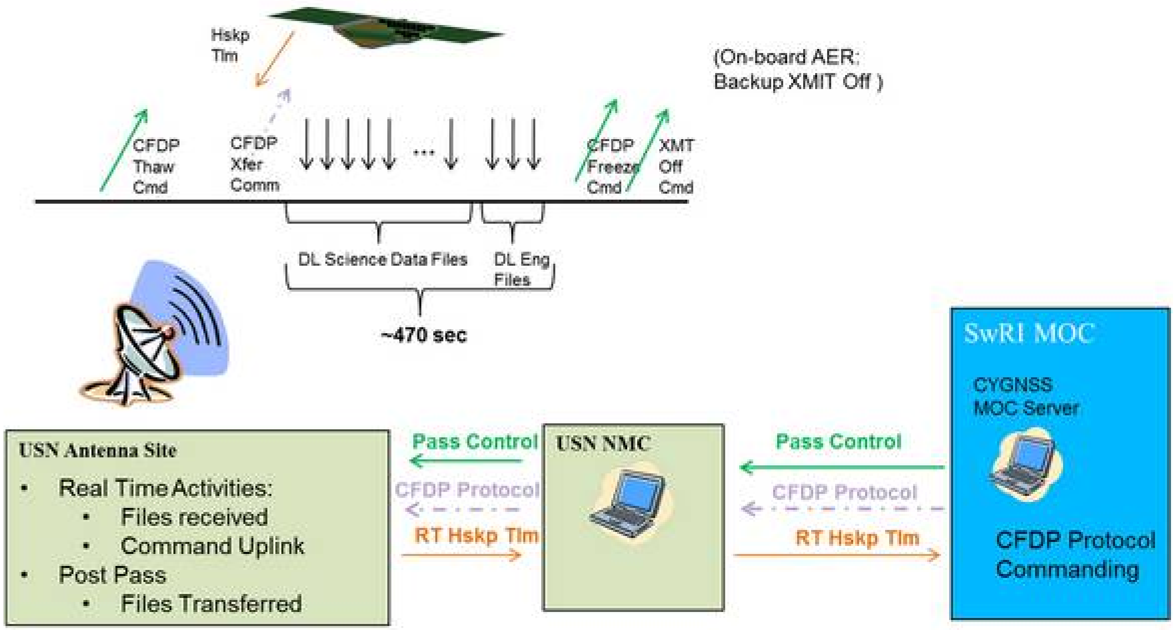


**Figure 3: Communications Pass Flow**

*Routine Maintenance and Calibration*

The majority of post commissioning operations for CYGNSS will occur using the automated features available in the microsat and in the MOC. However, there will also be routine microsat maintenance and DDMI calibration activities that will occur throughout the operational period of the constellation.

Maintenance activities for the microsat do not need to be scheduled on a specific cadence. Review of microsat systems and positioning information will be used to assess the status of each subsystem as well as the location of each Observatory to determine when maintenance activities may be needed. Based on the type of activity, either real-time commanding – or a time-tagged command sequences can be developed to perform the required activities.

Cal/Val of the DDMI is planned to occur two times per year, nominally before and after hurricane season. Cal/Val activities will be performed using on-board time-tagged command sequencing. Part of the Cal/Val process uses cooperative beacons on the ground and the time-tag command sequencing allows the team to coordinate instrument activities with the time periods when the beacons will be observable by the Observatory.

## 3. GROUND SYSTEM OVERVIEW

*Overview*

The CYGNSS ground system, as shown in Figure 4, consists primarily of the MOC; existing USN Prioranet ground stations in Australia, Hawaii, and Santiago, Chile; and the SOC facility. Additional interfaces between the MOC and the microsat engineering team and the DDMI instrument engineering teams are supported. The MOC coordinates operational requests from all facilities and develops long term operations plans.

*Ground Data Network - USN*

CYGNSS selected USN for the ground data network due to their experience in autonomously acquiring S/C per our baselined approach. Co-location of a back-up CYGNSS MOC server at the USN Network Management Center (NMC) can also be supported.

With a 35 degree 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 470-500 seconds visibility per pass. Each Observatory will pass over each of the three ground stations 6-7 times each day, thus providing a large pool of scheduling opportunities for communications passes.

The MOC personnel will schedule passes as necessary to support commissioning and operational activities. High priority passes will be scheduled to support the Observatory S/A deployment for each of the constellation microsats.

For all subsequent stages, the MOC schedules nominal passes for the USN stations for each Observatory in the constellation per the USN scheduling process. As outlined in the previous section, each Observatory can accommodate gaps in contacts with storage capacity for >10 days of data with no interruption of science.

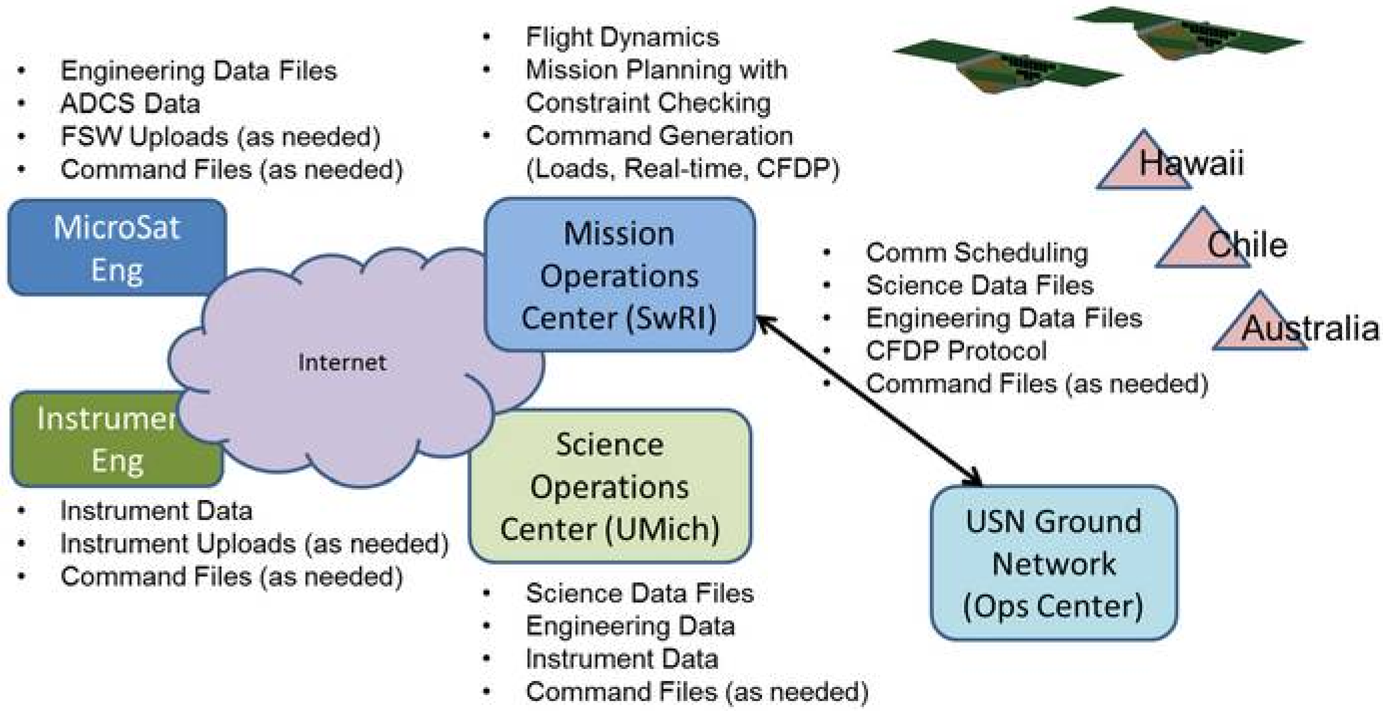


**Figure 4: CYGNSS Ground System Overview**

*Mission Operations Center (MOC)*

During the mission, the CYGNSS MOC, located at the SwRI Boulder location, is responsible for the mission planning, flight dynamics, and command and control tasks for each of the Observatories in the constellation. A summary of the primary MOC tasks includes:

- Coordinating activity requests,
- Scheduling ground network passes,
- Maintaining the CFDP ground processing engine,
- Collecting and distributing engineering and science data,
- Tracking and adjusting the orbit location of each Observatory in the constellation,
- Trending microsat data,
- Creating real-time command procedures or command loads required to perform maintenance and calibration activities, and
- Maintaining configuration of on-board and ground parameters for each Observatory.

Tools to support these tasks have been selected and are discussed in more detail in Section 4.

*Science Operations Center (SOC)*

The CYGNSS SOC, located at the University of Michigan, will be responsible for the following items:

- Support DDMI testing and validation both pre-launch and on-orbit,
- Provide science operations planning tools,
- Generate instrument command requests for the MOC,
- Process science data Levels 0 – 3, and
- Archive Level 0 – 3 data products, DDMI commands, code, algorithms and ancillary data at a NASA Distributed Active Archive Center (DAAC).

Figure 5 shows the flow of data processing in the SOC as well as the flow of data between the SOC and its two primary interfaces – the MOC and the DAAC.

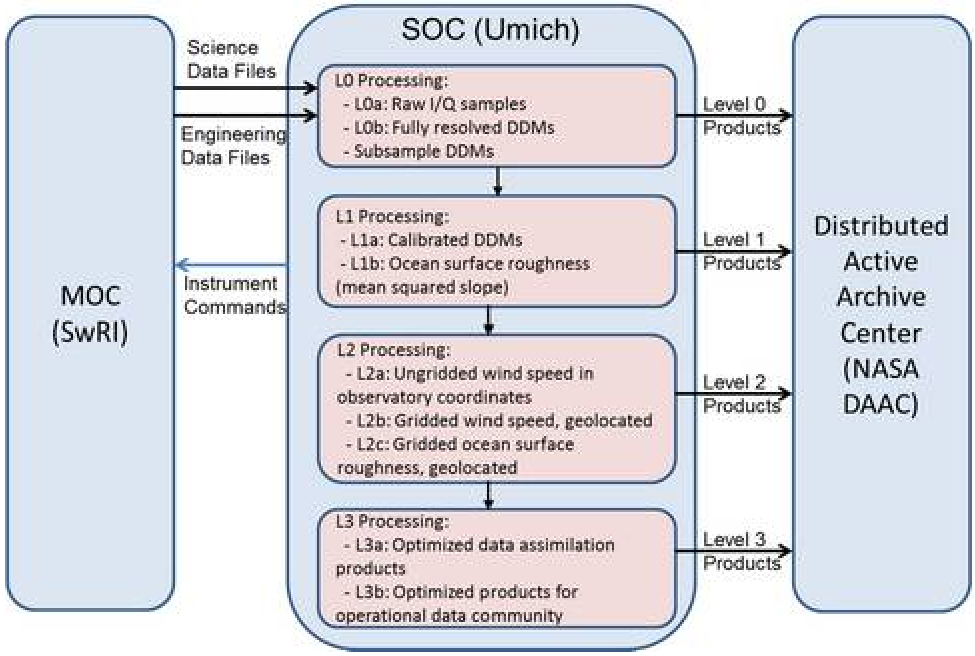


**Figure 5: CYGNSS SOC Overview**

## 4. MISSION OPERATIONS CENTER - TOOLS

Another key aspect to providing cost effective support for a constellation, is to have a set of tools supporting the mission operations team that allow the team to see issues with any single Observatory as well as supporting a view of the potential issues or interactions between Observatories. The CYGNSS mission operations team has selected a set of tools with the feature sets available to address this issue as outlined in the following paragraphs.

*Command and Control System*

The requirements for the Mission Operations Center are to implement a command and control system that can handle all unique aspects of the CYNGSS mission. An overview of the command and control system is shown in Figure 6. For uplink, it must support real-time commanding at 2000 bps, including memory load-dump-compare operations. On downlink, it must support ingesting CFDP data, Reed-Solomon decoding, derandomization and include real-time telemetry display, and long-term archival and analysis tools. For the ground segment, the tools need to be able to interface, configure and monitor the ground network. It is also important that the system is easily deployed, low cost and facilitates use by a team distributed across the country.

The CYGNSS mission chose the Integrated Test and Operations System (ITOS) for its command and control system. ITOS is a suite of software developed by the Real-Time Software Engineering Branch at the Goddard Space Flight Center, and is supported by the Hammers Company. This Government Off-the-Shelf (GOTS) solution also has zero license costs for NASA missions and runs on inexpensive Linux hardware [1].

ITOS itself is not uniquely customized from mission to mission, instead mission customization is through database driven command and telemetry specifications and a small set of configuration files. This obviates the need for additional software development and training. The database includes limit checking and engineering unit configurations as well as highly customizable display pages for monitoring spacecraft data. The ITOS telemetry server can interface across a firewall to a public server which can display telemetry and events remotely via a web browser which facilitates simple, real-time monitoring of the spacecraft from a geographically diverse mission team.

For the CYGNSS mission, it is critical for the command and control system to be able to define eight unique and concurrent spacecraft, and be able to manage and display data unique to each. Though the spacecraft will be identical by design, they will all likely have unique aspects that the ground system must take into account, including unique command constraints, telemetry conversions and limit checking. The ITOS tools provide the database elements necessary to support and maintain a constellation configuration.

The CYGNSS team will be using ITOS throughout the spacecraft development including as the main control system during system integration and environmental testing. This bench-to-flight approach allows for heavy reuse of existing STOL (Spacecraft Test and Operations Language) procedures that will be baselined into the Mission Operations configuration management system as the standard scripts and processes the team will use to fly the mission, implementing a true end-to-end, test-like-you-fly, fly-like-you-test approach.

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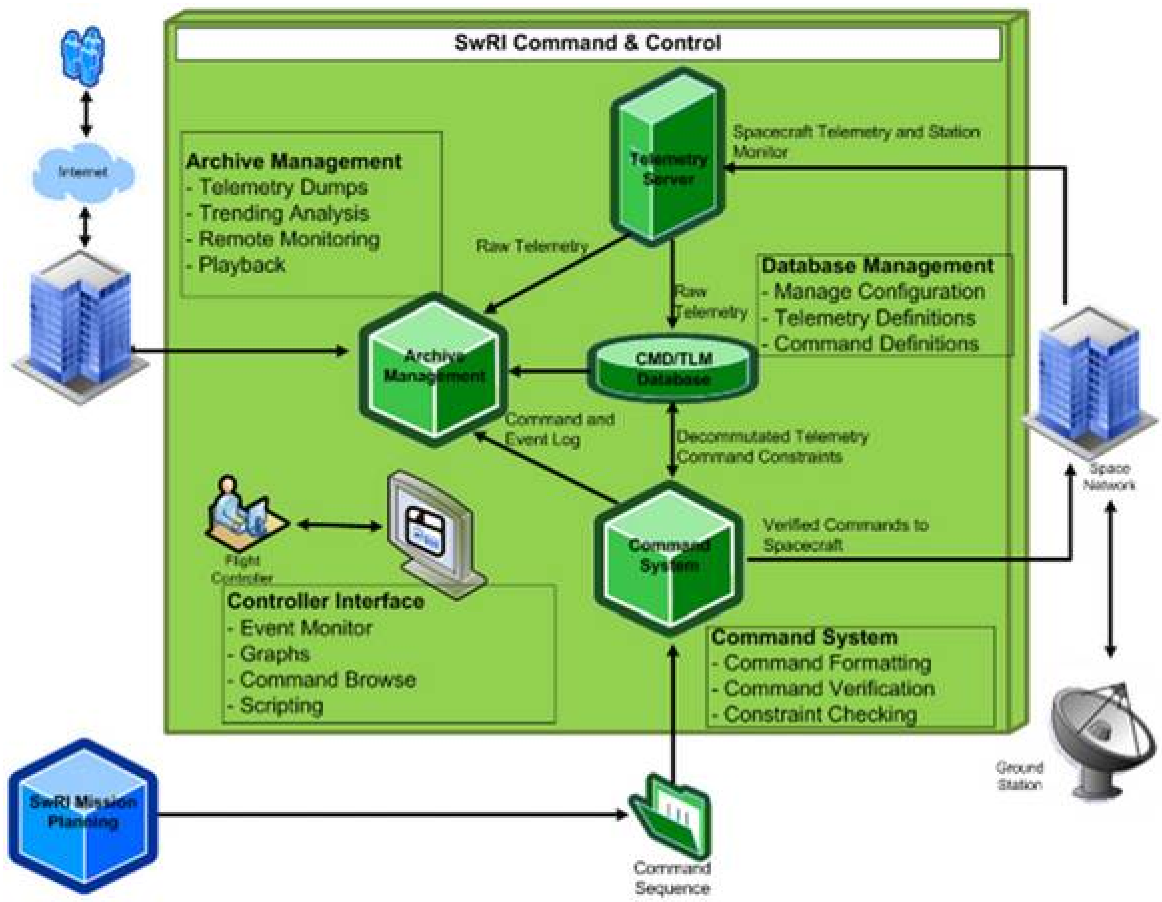


**Figure 6: CYGNSS Command and Control System**

*Mission Planning System – FlexPlan*

The CYNGSS Mission Planning System takes inputs from flight dynamics, and science activities from the science operations center (SOC), as well as event files, such as eclipse periods and ground tracks. In addition, it must resolve resource conflicts, such as power load, recorder usage, or over subscription of a ground antenna resource. The system must also check that planned events do not result in violation of flight constraints – either for a single Observatory or for the constellation. Resolving the conflicts, the system can then generate a command load, when required, that is handed off to the command and control system for uplink to the spacecraft.

The CYGNSS mission chose FlexPlan as the basis for its mission planning system. FlexPlan, is specifically designed to manage multi-elements such as a spacecraft constellation and is a highly configurable tool, implemented with customization in mind [2]. It contains five major architectural components, Mission Environment Preparation (MEP), Planning Input Customization (PIC), Schedule Generator (SG), Conflict Resolution (CR) and External Interfaces (EI).

The MEP is an offline tool that is used to define the flight rules and mission rules, as well as event and resource availability for standard operations segments of the mission. It will be defined early in the mission cycle, and only redefined on an as-needed basis if there are large changes to the concept of operations of the mission.

The PIC module takes event triggers from external inputs (for instance, Flight Dynamics, SOC or ground network events) and interfaces to the SG. The SG then takes the MEP and the PIC inputs to generate a first revision of a mission schedule. At this stage, the mission schedule still may not be conflict free, so the user must execute the CR module. This module detects conflicts due to timeline or resource constraints, and resolves them with the user-in-the-loop. The required external data products are then created using the EI module, which uses an XML interface schema to easily adapt to different external interface requirements.

Figure 7 shows a screenshot of FlexPlan's typical Gantt chart GUI. This example shows conflicts in the resource profile across a multi-satellite system. All tasks associated with a particular satellite are in the same color. Commands are built up into activities. Many activities are combined into mini-sequences, which are then combined to create the overall sequence.

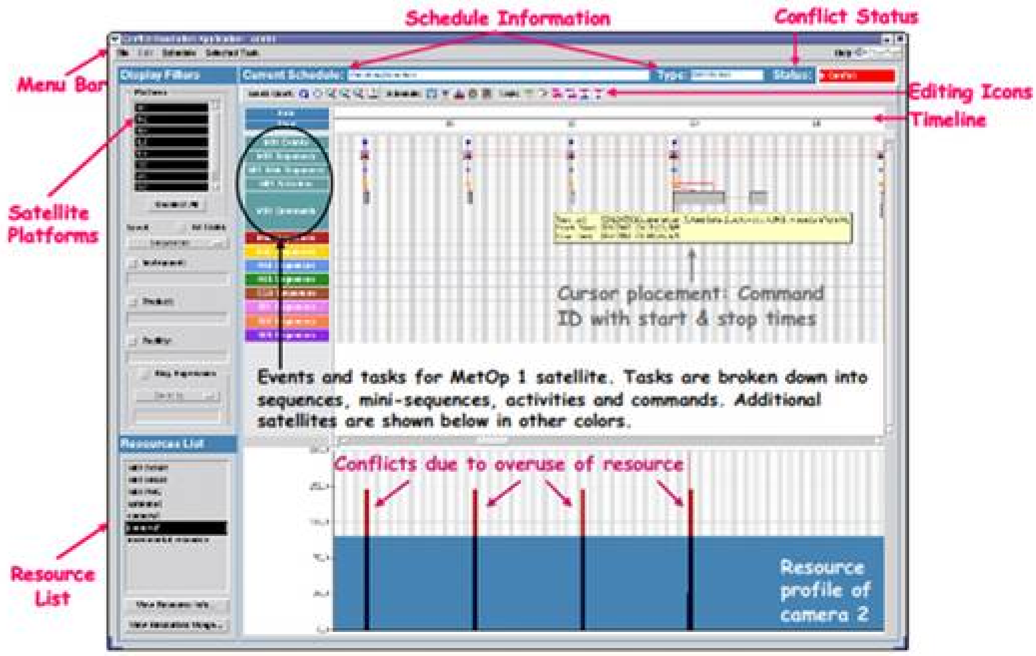


**Figure 7: CYGNSS Mission Planning Schedule [2]**

*Flight Dynamics – STK®*

Satellite Tool Kit (STK®) has been selected by the CYGNSS team for the flight dynamics tool. During mission development, STK® will be used by the science and systems teams to evaluate the science coverage of the constellation as well as the dispersion of Observatories through various mission phases. The mission operations team will pick up the scenarios developed and maintain and use these scenarios to support the mission operations Flight Dynamics tasks.

CYGNSS Flight Dynamics tasks are straight forward and include assessing satellite locations in support of ground station scheduling and working with the systems team to assess, plan, and execute drag maneuvers as required to maintain constellation coverage and positioning. STK® is an industry recognized tool with a mature tool set fully capable of supporting satellite constellation analysis.

## 5. CONCLUSIONS

CYGNSS mission operations and ground element requirements focus on effectively managing the CYNGSS flight constellation and processing its science dataset. Dealing with a constellation of Observatories introduces a number of unique challenges to the operations team compared with operating a single vehicle. Requirements related to operational tempo (8 contacts per 1.5-2 days), configuration control, and reaction to potential systemic issues in both Flight and Ground Segments are some of the primary concerns.

In response to these issues, the CYGNSS systems engineering team has developed specific requirements and capabilities to support the CYGNSS constellation in a low-cost, low-risk manner. For example, the ability of the Observatory to operate without standard daily on-board time-tagged command sequences provides mission operators significant flexibility in scheduling Observatory communications; this allows operators to completely reschedule the entire constellation communication profile without having to reload any command sets to the Observatories.

Combining the operational concepts implemented via the flight and ground element capabilities with the use of cost effective GOTS/ COTS tools built with constellation support capabilities, the CYGNSS mission operations team is well situated to manage the CYGNSS constellation.

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## BIOGRAPHIES

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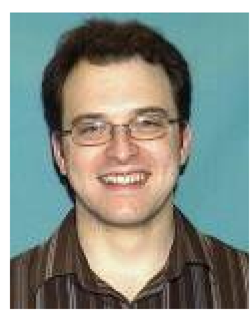

***Michael Vincent*** *received a B.S. and an M.S. in Electrical Engineering from the University of Colorado, Boulder CO in 2001, and is a principle engineer at the Southwest Research Institute. He has been with the Institute for 5 years. Prior to working at the Institute, he worked at the Johns Hopkins Applied Physics Laboratory. He has been involved in many aspects across spacecraft and instrument development, including payload system engineering, instrument engineering, I&T, operations and hands-on hardware development and test. Mr. Vincent is the CYGNSS Lead Mission Operations Analyst.*