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CYGNSS: Enabling the Future of Hurricane Prediction

1. INTRODUCTION

Hurricane track forecasts have improved in accuracy by about 50% since 1990, largely as a result of improved mesoscale and synoptic modeling and data assimilation of the remotely sensed background environment. In that same period, there has been essentially no improvement in the accuracy of intensity forecasts due to inadequate modeling and observing capabilities in the hurricane inner core. The inadequacy in observations results from two causes: 1) much of the inner core ocean surface is obscured from conventional remote sensing instruments by intense precipitation in the eye wall and inner rain bands, 2) The rapidly evolving (genesis and intensification) stages of the tropical cyclone (TC) life cycle are poorly sampled in time by conventional polar-orbiting imagers.

CYGNSS (Cyclone Global Navigation Satellite System) is specifically designed to address these two limitations by combining the all-weather performance of GNSS bistatic ocean surface scatterometry with the sampling properties of a constellation of satellites [1], [2].

This article will describe the motivation for using a micro-satellite constellation, the mission design and deployment module. To view a short video about CYGNSS, click here: http://www.youtube.com/watch?v=iruxa6F4OJ8&feature=player_embedded.

2. THE SCIENCE MOTIVATION FOR THE CYGNSS APPROACH

2.1. THE VALUE OF WIND OBSERVATIONS IN PRECIPITATING CONDITIONS

Previous spaceborne measurements of ocean surface vector winds have suffered from degradation in highly precipitating regimes, as was the case for QuikScat. As a result, in the absence of reconnaissance aircraft, the accuracy of wind speed estimates in the inner core of the hurricane is often highly compromised. The added quality and quantity of surface wind data provided by CYGNSS in precipitating conditions significantly improves estimates of intensity.

Mesoscale Convective Systems (MCSs) contribute more than half of the total rainfall in the tropics and serve as the precursors to TCs. Over the ocean, the organization of the fluxes depends on a complex interaction between surface level winds and storm dynamics. Their development and characteristics depend critically on the interaction between ocean surface properties, moist atmospheric thermodynamics, radiation, and convective dynamics.

2.2. THE VALUE OF FREQUENT WIND OBSERVATIONS

Most current spaceborne active and passive microwave instruments are in polar low earth orbit (LEO). LEO maximizes global coverage but can result in large gaps in the tropics. Schlax et al. (2001) [17] present a comprehensive analysis of the sampling characteristics of conventional polar-orbiting, swath-based imaging systems, including consideration of so-called tandem missions. The study demonstrates that a single, wide-swath, high-resolution scatterometer system cannot resolve synoptic scale spatial detail everywhere on the globe, and in particular not in the tropics. The irregular and infrequent revisit times (ca. 11–35 hrs) are likewise not sufficient to resolve synoptic scale temporal variability. As a striking example, Figure 1 shows the percentage of time that the core of every tropical depression, storm and cyclone from the 2007 Atlantic and Pacific seasons was successfully imaged by QuikScat or ASCAT. Missed core imaging events can occur when an organized system

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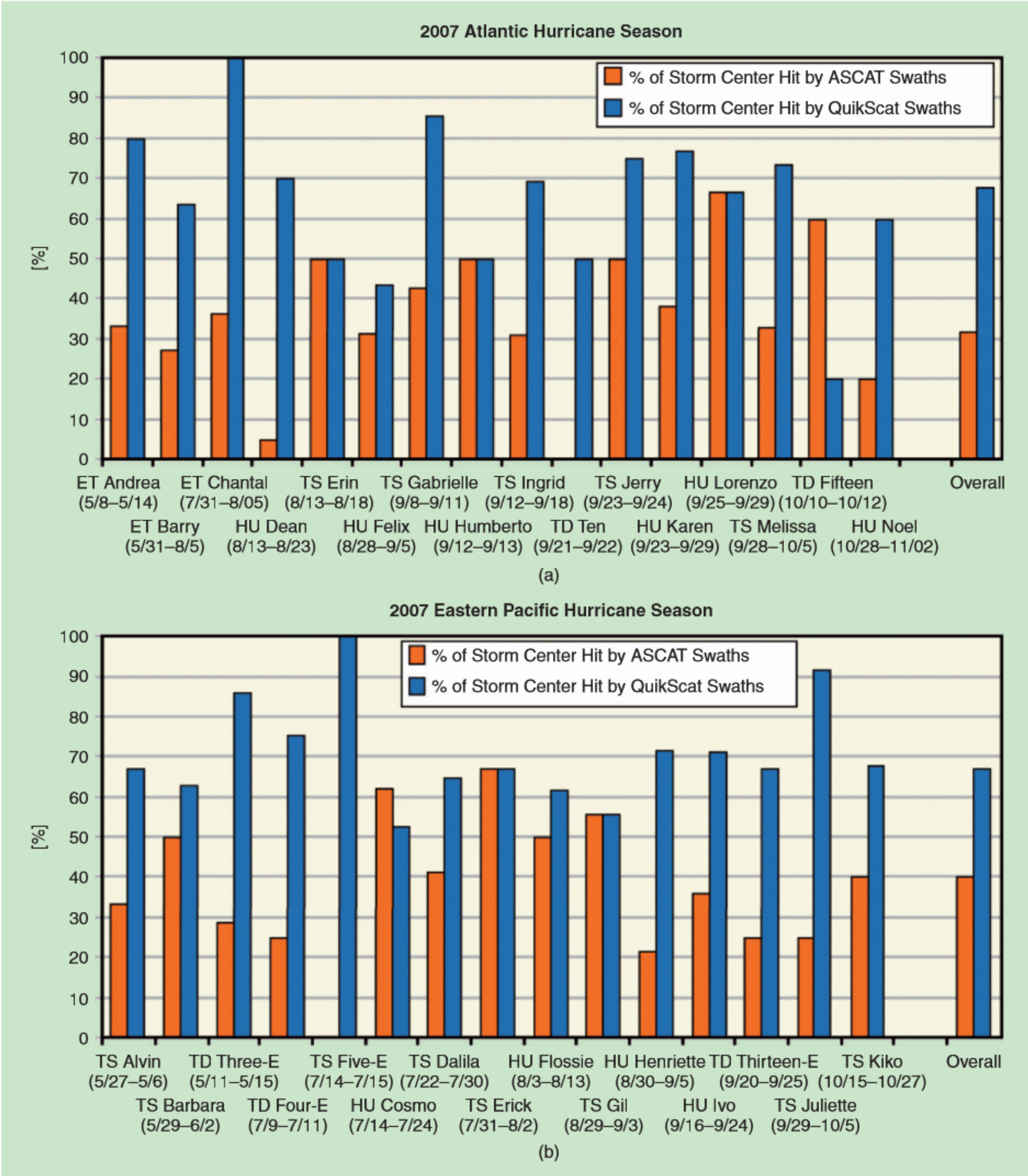

FIGURE 1. Percentage of time the center of named storms was observed with either QuikScat (blue) or ASCAT (orange) polar-orbiting scatterometers during the 2007 Atlantic (a) and Pacific (b) hurricane season. Poor performance results from the coverage gaps and infrequent revisit times that are characteristic of polar-orbiting wide-swath imagers.

passes through an imager's coverage gap or when its motion is appropriately offset from the motion of the imager's swath. The figure highlights the many cases in which TCs are resolved much less than half the time. One particularly egregious case is Hurricane Dean, which was sampled less than 5% of the time possible by ASCAT.

2.3. MEASUREMENT METHODOLOGY

Figure 2 illustrates the propagation and scattering geometries associated with the GNSS approach to ocean surface scatterometry. The direct GPS signal provides a coherent reference for the coded GPS transmit signal. It is received by an RHCP receive antenna on the zenith side of the spacecraft. The quasi-specular forward scattered signal from the ocean

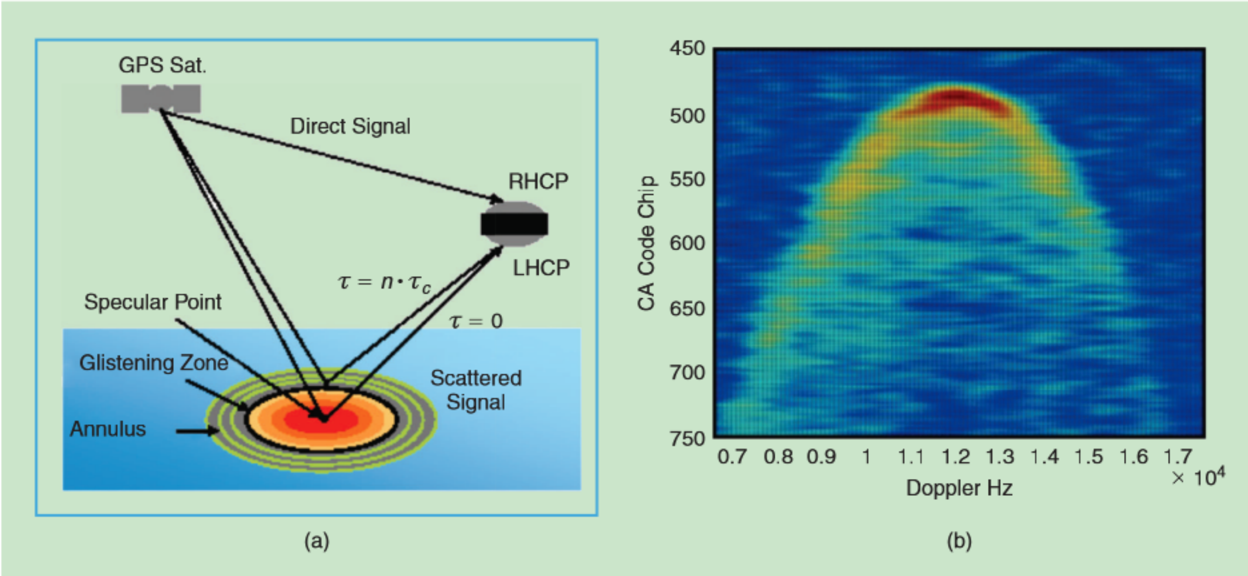

FIGURE 2. GPS signal propagation and scattering geometries for ocean surface bistatic quasi-specular scatterometry. (b) Spatial distribution of the ocean surface scattering measured by the UK-DMC-1 demonstration spaceborne mission—referred to as the Delay Doppler Map (DDM) [5].

surface is received by a downward looking, LHCP antenna on the nadir side of the spacecraft. The scattered signal contains detailed information about its roughness statistics, from which local wind speed can be derived [3]. The scattering cross-section image produced by the UK-DMC-1 demonstration spaceborne mission is shown in Fig. 2. Variable lag correlation and Doppler shift, the two coordinates of the image, enable the spatial distribution of the scattering cross section to be resolved [4], [5]. This type of scattering image is referred to as a Delay Doppler Map (DDM). Estimation of the ocean surface roughness and near-surface wind speed is possible from two properties of the DDM. The maximum scattering cross-section (the dark red region in Fig. 2) can be related to roughness and wind speed. This requires absolute calibration of the DDM. Wind speed can also be estimated from a relatively calibrated DDM by the shape of the scattering arc (the red and yellow regions in Fig. 2). The arc represents the departure of the actual bistatic scattering from the purely specular case that would correspond to a perfectly flat ocean surface, which appear in the DDM as a single point scatterer. The latter approach imposes more relaxed requirements on instrument calibration and stability than does the former. However, it 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 is an active area of research [5].

2.4. EXAMPLE OF SCIENCE COVERAGE

A time-lapse simulation comparing CYGNSS and ASCAT coverage of Hurricane Frances just before its U.S. landfall is shown in Fig. 3. The simulation was created by projecting satellite coverage predictions for each mission onto the archival storm track record for Frances. Each frame represents all samples taken within a 3-hour interval. The TC inner core is shown as a large blue dot in each frame. ASCAT, with its relatively narrow swath width, only infrequently samples the inner core, whereas the much wider and more dispersed effective swath of the CYGNSS constellation allows for much more frequent sampling. The average revisit time for TC sampling is predicted to be 4.0 hour, and the median revisit time will be 1.5 hour.

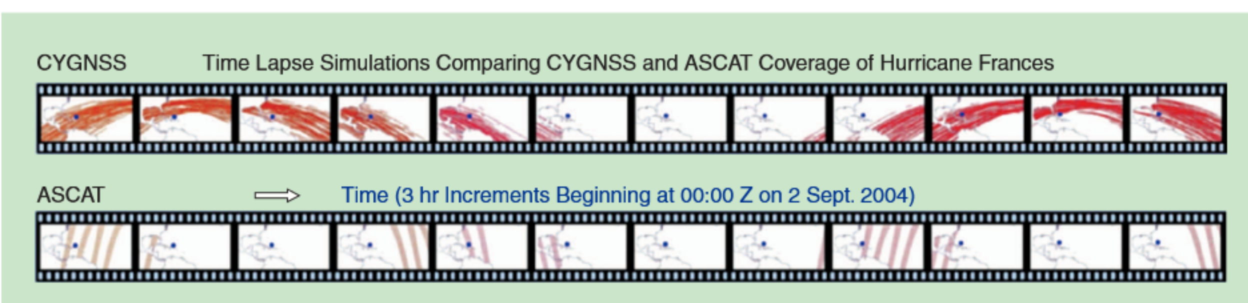

FIGURE 3. Time lapse simulation comparing the spatial and temporal sampling properties of CYGNSS and ASCAT, if they had both been in orbit during the Hurricane Frances U.S. landfall on 2 Sept. 2004.

3. MISSION DESIGN

3.1. MICROSATELLITE OBSERVATORIES

Each CYGNSS Observatory consists of a microsatellite (microsat) platform hosting a GPS receiver modified to measure surface reflected signals. Similar GPS-based instruments have been demonstrated on both airborne and spaceborne platforms to retrieve wind speeds as high as 60 m/s (a Category 4 hurricane) through all levels of precipitation, including the intense levels experienced in a TC eyewall [1].

Each Observatory simultaneously tracks scattered signals from up to four independent transmitters in the operational GPS network. The number of Observatories and orbit inclination are chosen to optimize the TC sampling properties. The result is a dense cross-hatch of sample points on the ground that cover the critical latitude band between ±35°.

The Observatory is based on a single-string hardware architecture (Fig. 4) with functional and selective redundancy included in critical areas. The microsatellite has been designed for ease of manufacture, integration, and test to provide a low-risk, cost-effective solution across the constellation.

3.2. GPS REFLECTOMETRY AND UK-DMC

For some years, GPS receivers have been used to provide position, velocity and time knowledge to satellite platforms in low Earth orbit in a similar way to ground-based satellite navigation receivers.

In addition to navigation, GPS signals have also been increasingly used for remote sensing. Signals at L-band with a 2–20 MHz bandwidth are being broadcast globally from a 20,000 km altitude and can be used to measure, amongst other things, tectonic plate motion and ionospheric and tropospheric parameters. Furthermore, signals from other GNSS are becoming available, and there will soon be more than 120 signal sources in space.

Spaceborne GNSS Reflectometry uses GNSS signals that have been scattered by the Earth surface to measure geophysical parameters. The potential for GNSS Reflectometry was demonstrated by the UK-DMC (British National Space Centre Satellite) mission in 2003. The mission included a GNSS-R sensor with a nadir-pointing antenna (gain just under 12 dBiC, 3 dB field of view approximately 20° × 70°) permitting collection of as many as three reflected signals simultaneously. The primary mode of operation on the first experiment was the collection of sampled IF data into a data-recorder, typically 20 seconds, and downloading for

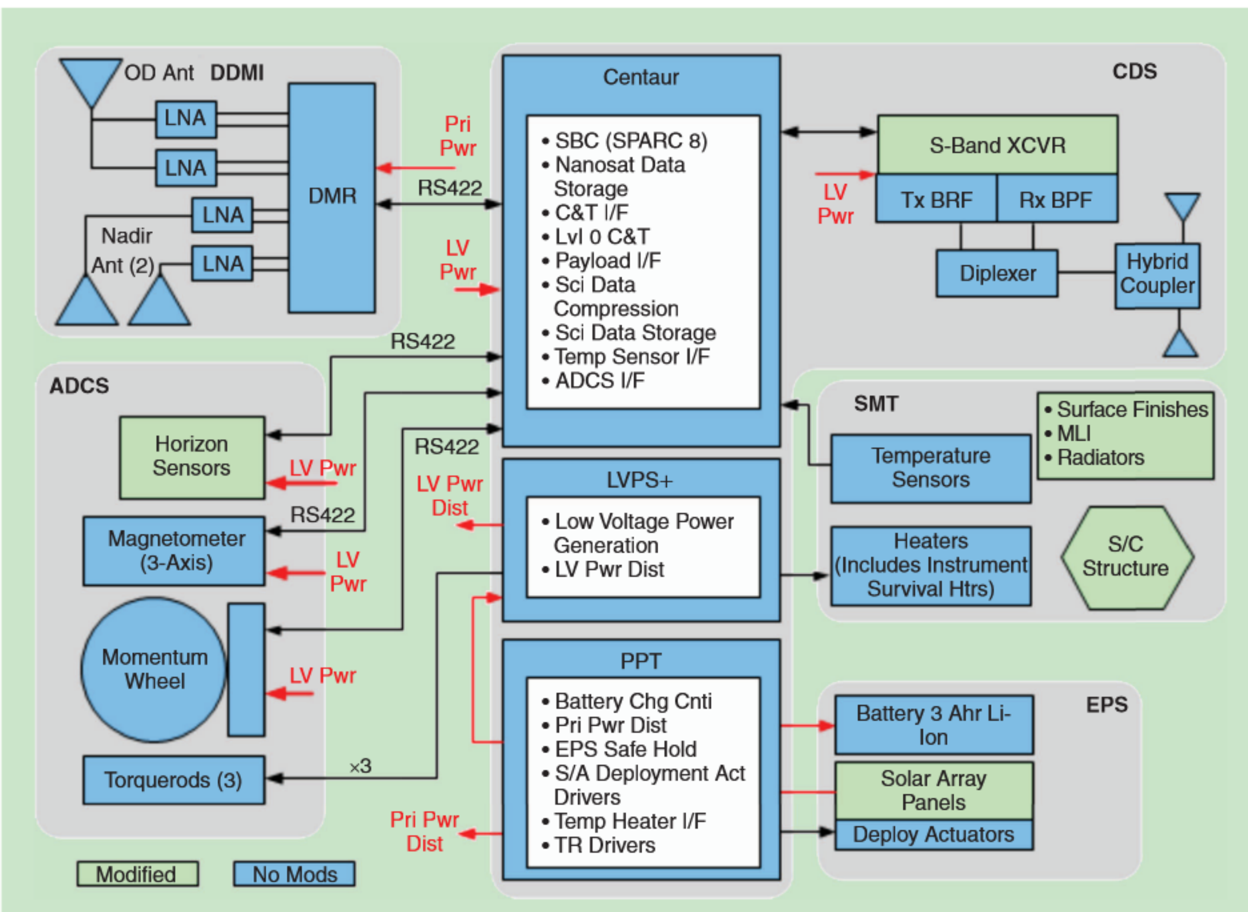

FIGURE 4. CYGNSS single-string architecture.

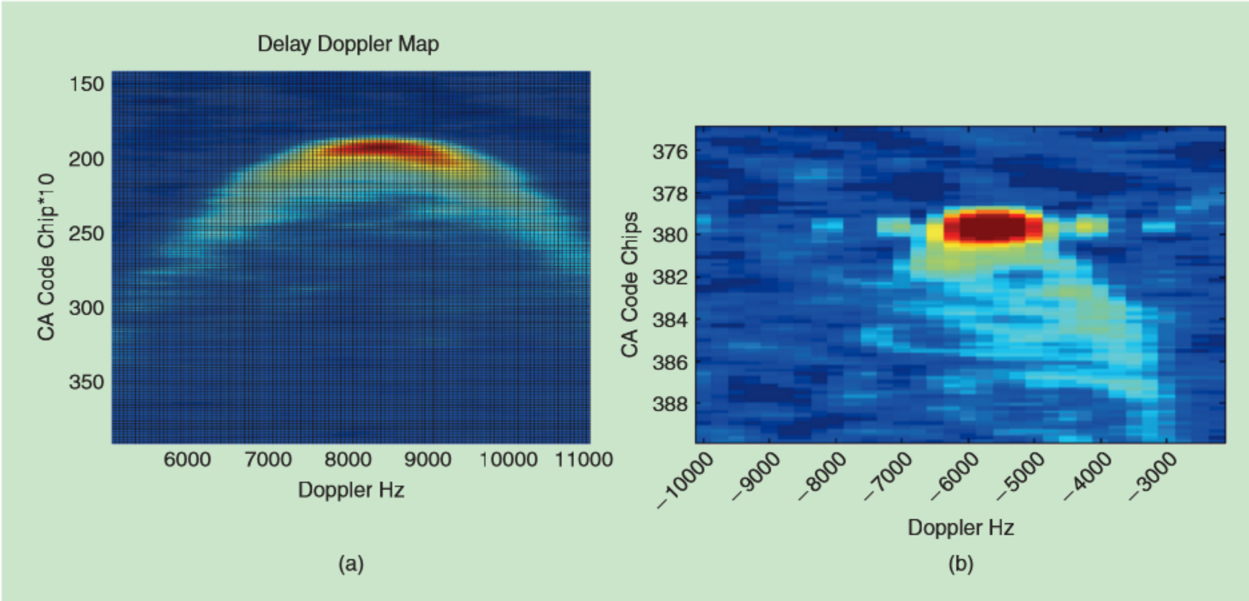

FIGURE 5. Example delay-Doppler maps from UK-DMC GPS-R experiment. (a) Ocean reflection, (b) sea ice/water reflection.

post processing on the ground. The raw data were processed on the ground into DDMs using software receiver techniques to allow analysis of signal returns off ocean, land and ice. Two example DDMs are shown in Fig. 5; they measure the spread in energy away from the specular point, and the spread grows as the surface becomes rougher.

A substantial effort into the modeling of signal returns has been undertaken using data from the first UK-DMC experiment with the intention to assess inversion of sea state parameters [4], [5] and the retrieval of directional roughness information [7], [8]. Although severely bandlimited, the collection of reflected Galileo signals (from GIOVE-A) was also demonstrated. Moreover, the collection of signals over mixed sea and ice indicates the potential of GNSS reflectometry for ice edge mapping [9]. The UK-DMC experiment demonstrated the feasibility for many remote sensing applications but limited space-based data is available for robust assessment of the geophysical retrieval accuracy of GNSS-R.

3.3. THE SPACE GNSS RECEIVER—REMOTE SENSING INSTRUMENT (SGR-ReSI) AND DELAY DOPPLER MAPS

The UK-DMC experiment demonstrated that a microsatellite-compatible passive instrument was able to make scientifically relevant geophysical measurements using GPS reflectometry.

Satellite Technology Ltd. (SSTL) teamed with the National Oceanographic Centre in Southampton and other partners to develop a new GNSS-R instrument for this purpose, the *Space GNSS Receiver—Remote Sensing Instrument (SGR-ReSI)*.

A schematic of the SGR-ReSI [10] is shown in Fig. 6. The SGR-ReSI in effect fulfils in one module what might be handled by three separate units on previous spacecraft.

a) It performs all the core functions of a space GNSS receiver, with front-ends supporting up to 8 single or 4 dual frequency antenna ports.
b) It is able to store a quantity of raw sampled data from multiple front-ends or processed data in its 1 GByte solid state data recorder
c) It has a dedicated reprogrammable FPGA co-processor (Virtex 4).

The co-processor was specifically included for the real-time processing of the raw reflected GNSS data into DDMs. However, it has flexibility to be programmed in orbit as required for different purposes, for example to track new GNSS signals, or to apply spectral analysis to received signals.

For the co-processor to generate DDMs of the sampled reflected data, it needs to be primed with the PRN (pseudo-random noise) code of the transmitting GPS satellite, and the estimated time delay and Doppler of the reflection as seen from the satellite. These are calculated by the processor in conjunction with the main navigation solution—the data flow for this is shown in Fig. 7. Direct signals (received by the zenith antenna) are used to acquire and track GNSS signals. From the broadcast ephemerides, the GNSS satellite positions are known. Then, from the geometry of the position of the transmit and receive satellites, the reflectometion geometry can be calculated.

The processing of the Delay Doppler Map is performed on the coprocessor using data directly sampled from the nadir antenna. In common with a standard GNSS receiver, the local PRN is generated on-board the co-processor. As an alternative to synchronizing and decoding the reflected signal in a standalone manner, the direct signals can be used to feed the navigation data sense, and assist the synchronization. The sampled data is multiplied by a replica carrier and fed into a matrix that performs an FFT on a row-by-row basis to form the DDM, to achieve in effect a 7000 channel correlator, integrating over 1 millisecond. Each point is then accumulated incoherently over hundreds of milliseconds to bring the weak signals out of the noise.

This processing is performed in real-time on-board the satellite, which greatly reduces the quantity of data required to be stored and for the satellite's downlink. CYGNSS plans to use the SGR-ReSI primarily in an autonomous manner generating DDMs at a low data rate continuously, which will provide gap-free measurements of the ocean roughness throughout the tropical oceans.

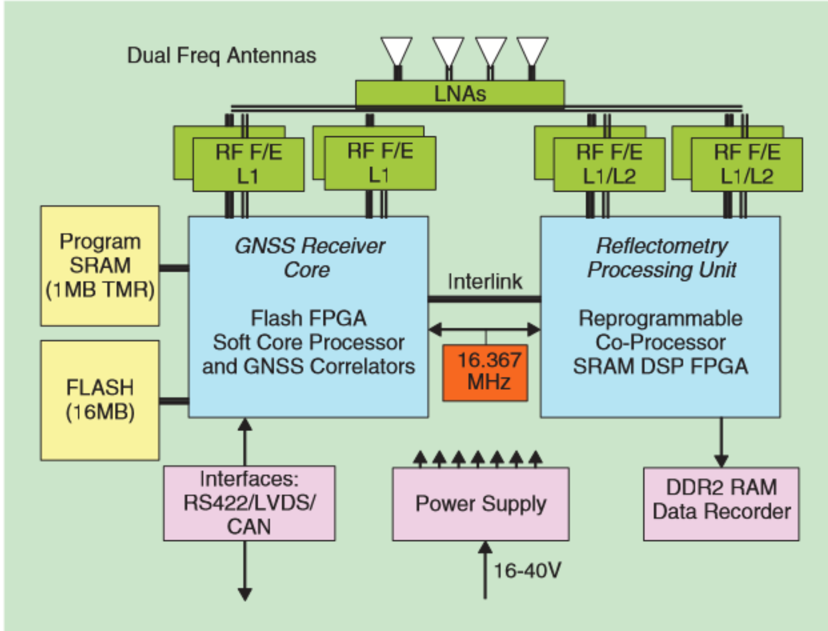

FIGURE 6. GNSS reflectometry instrument configuration.

3.5. MICROSATELLITE STRUCTURE

The microsat structure requirements are driven by physical accommodation of the DDMI antennas, the S/As, and launch configuration constraints. Our design uses the same principles as our heritage avionics chassis, using milled Al piece parts bolted together to provide an integrated, mass efficient solution for CYGNSS. Close tolerance pins/holes ensure repeatability of structural alignment. The microsat's shape is specifically configured to allow clear nadir and zenith FOV for the DDMI antennas, while its structure integrates the microsat and instrument electronic boards directly by creating avionics and Delay Mapping Receiver (DMR) "bays." The avionics and DMR bays form the core of the microsat; all other components are mounted to this backbone with structural extensions included to accommodate the Al honeycomb-based S/As and DDMI nadir antenna assemblies. The structural configuration allows easy access to all Observatory components when the nadir DDMI antenna panel assemblies and microsat endplates are removed for Observatory AI&T.

The microsat primary structure's nadir baseplate is the DM mechanical interface for launch. Primary shear and axial loads are carried by the microsat primary structure, providing full compliance with the dynamic launch vehicle envelope. Preliminary FEA of the Observatory results predict launch loads are well within allowable material stress levels with a first mode natural frequency of 211 Hz in the launch configuration, avoiding harmonic coupling with the LV natural frequency of 75 Hz during launch.

3.6. MICROSATELLITE MECHANISMS

Observatory mechanisms are limited to heritage S/A deployment devices. The four "z-fold" S/A panels perform a one-time deployment into a permanently locked position planar with the fixed center panels. The S/As are held in place for launch using a cup/cone interface and deployed by a combination of flight-proven TiNi Aerospace Frangibolt actuators and Sierra Nevada Corp. S/A single-axis, locking, spring-loaded hinges.

3.7. MICROSATELLITE THERMAL

The CYGNSS Observatory thermal design meets requirements to maintain all components within their temperature limits during all operational modes by using Southwest

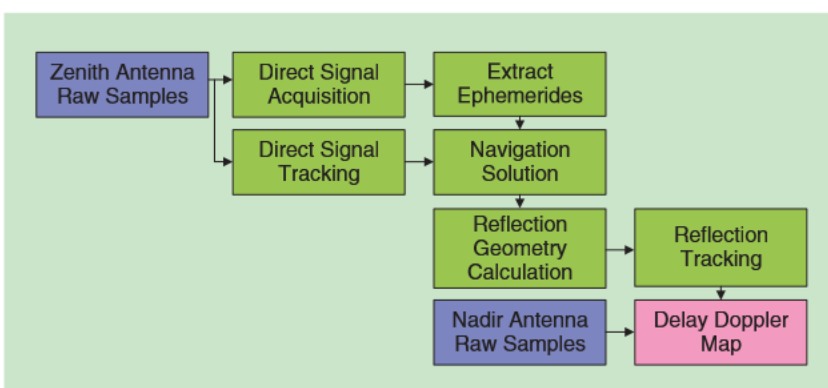

FIGURE 7. GNSS reflectometry dataflow.

Research Institute's flight-proven, well-characterized, thermal design techniques. The thermal control design provides thermal stability and minimizes thermal gradients through an integrated design of multilayer insulation blankets (MLI), surface treatments, and localized radiators. The arrangement of internal equipment is used to aid thermal control and eliminate the need for supplemental heaters except for Standby/Safe Hold operations.

Results from our thermal analysis were used to size the thermal radiators (EOL). The primary radiator is located on zenith surface in the S/A gap along the Observatory center line, with a second radiator on the nadir baseplate. These locations are chosen to provide a direct, cohesive thermal conductive path to the primary observatory dissipative loads. The radiators are coated with 5 mil ITO/Tef/Ag, while MLI is used on non-radiating external surfaces.

4. AVIONICS

The CYGNSS Avionics consists of four boards, portions of the EPS and CDS. The boards include the Peak Power Tracker, the Low Voltage Power Supply, the Centaur single board computer, and the Flexible Communication Platform radio. A block diagram of the avionics unit is shown in Figure 9. The avionics unit does not include a box; instead, the microsat structure itself provides mechanical mounting and electrical interconnects over a backplane and cables.

4.1. ELECTRICAL POWER SUBSYSTEM

The EPS design performance provides robust margins on all requirements. The EPS is designed to perform battery charging without interrupting science data acquisition.

SOLAR ARRAY

The EPS is based on a 28±4 Vdc primary power bus with electrical power generated by an 8-panel rigid solar array (S/A). The S/A design is composed of solar panels, hinges, and deployment actuators. Four of the eight panels are "z-folded" for launch. Flight-qualified, triple-junction solar cells are arranged with an 84% packing density on the solar panel substrates, including cover glass to improve their thermal performance and ground handling robustness. The 0.71 m^2 total area S/A provides a 30.3% margin during max eclipse periods (35.8 min). Full mission duration simulations were performed to analyze worse case solar Beta cases (58). The design provides 43.4% margin during these periods. When stowed, the z-fold design of the S/A allows the solar cells to face outward, combining with the two supplemental ram/wake S/As to power the microsat indefinitely in Standby mode before S/A deployment (22% margin).

BATTERIES

Electrical power storage for eclipse operations is provided by two 1.5 A-hr Li-ion 8s1p batteries connected directly to the primary power bus. The batteries are configured for 3 A-hr (EOL) at 28.8 Vdc nominal. Temperature sensors, and bypass diodes (to withstand a failed cell) are included in the battery assembly. Battery performance models were used to analyze the CYGNSS mission with predicted EOL nominal battery state-of-charge being 87.6%. Battery charging uses a constant current, voltage-temperature limited charge scheme based on four stored profiles matched to the CYGNSS battery. Charging is also Coulomb limited to 120% of discharge level. The primary power bus voltage is modulated to maintain charge current and termination voltage. The Coulombic charge limit is tracked with an A-min integrator and when the level exceeds $1.2 \times I_{dis}T_{eclipse}$ (Amin), battery charging levels are reduced to C/100.

PEAK POWER TRACKER

Battery charge regulation for the CYGNSS EPS is a peak power tracking (PPT) type regulator. The PPT board, developed using SwRI internal funds, 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 includes a ground support equipment (GSE) interface that serves as the connection point for ground power and battery maintenance, conditioning, and pre-launch trickle charging.

The PPT unit is based on a 40W DC-DC converter, which produces 28±4 Vdc from a solar array voltage of 36 to 72 Vdc. The design was produced with multiple missions in mind, from a long-duration, intense radiation environment to a short, LEO mission, CYGNSS being toward the latter of these two extremes. The DC-DC converter output voltage is modulated by the PPT and battery charge regulator to meet load power and battery charging demands. Power from the solar array flows into the PPT through an over current protection fuse, current sense resistor and EMI filter. S/A current and voltage are sensed and conditioned before connection to an analog multiplier within the PPT circuit. The analog multiplier converts these signals into instantaneous S/A power, which is processed by the PPT watt-second integrator to track the power peak. The PPT circuit generates an error signal (PPT Error), which is used to provide supervisory control of the DC-DC converter in conjunction with the battery charge regulator.

Housekeeping power is provided by a high input voltage linear regulator, which provides +16 Vdc for control circuit power and midpoint bias of +8 Vdc to operate single supply operational amplifiers.

Battery charge regulation consists of programmable charge current and end-of-charge voltage settings, which are each controlled via opto-isolated 4-bit interfaces. The opto-isolators are set up for 3.3 Vdc CMOS drive levels from the Centaur interface. No flight software is required for the control electronics, except for configuration control.

The PPT is also used to switch +28 Vdc bus voltage to spacecraft components, including the S/A deployment actuators, the DMMI, heaters, and momentum wheels.

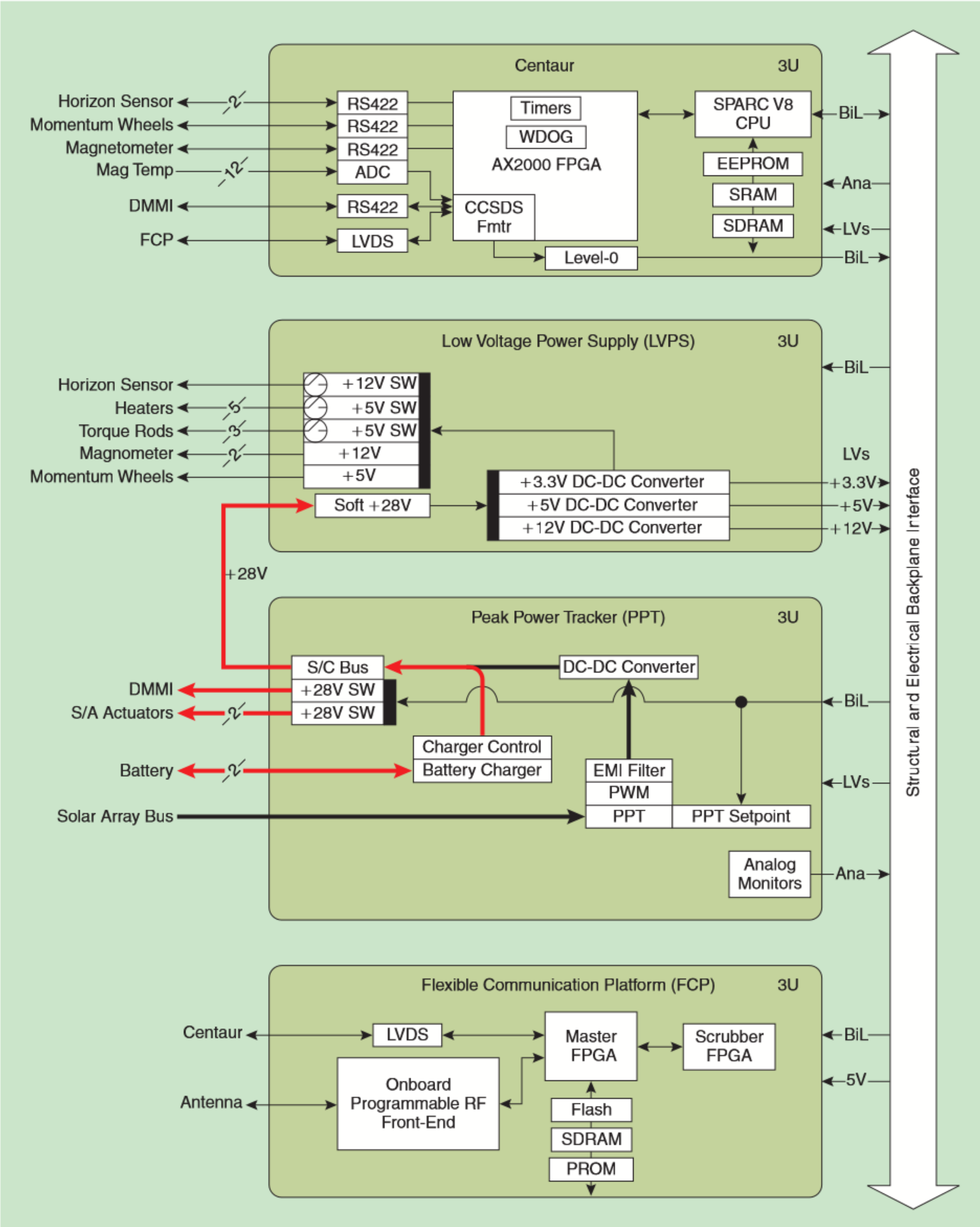

FIGURE 9. Block diagram of the Avionics Unit.

LOW VOLTAGE POWER SUPPLY

Low voltages required by the avionics boards as well as switched low voltages for several ADCS components are generated by the Low Voltage Power Supply (LVPS). The CYGNSS design is based heavily on the Juno JADE LVPS, which was tailored specifically to lower power, embedded use, making it ideal for microsatellite missions. SwRI has produced LVPSs for Orbital Express, Deep Impact, Kepler, WISE, and DoD flight missions. The board receives +28 Vdc from the PPT and regulates low voltages, including +/−12 Vdc, +5 Vdc, and +3.3 Vdc, for use by the Centaur, FCP, and PPT control circuitry. Further, the board includes low voltage switches (+5 Vdc) to power ADCS components, including the magnetometer, momentum wheel, and horizon sensor.

4.2. COMMUNICATIONS AND DATA SUBSYSTEM

Most of the hardware to implement the CDS resides within the CYGNSS avionics bay, with the exceptions of the S-band antennas, diplexer, and hybrid.

CENTAUR

All on-board microsat processing is performed on SwRI's Centaur board. The Centaur consists of our space-qualified heritage Atmel SPARC8 processor with heritage CCSDS compliant command and telemetry interface, instrument data interface, and ADCS interface designs. The board architecture is based on the Juno JADE IPB (launched Aug 2011) and extensively reuses the command and telemetry circuitry from Deep Impact, Orbital Express, Kepler, and WISE only requiring a board relay out for CYGNSS. This board was designed to be a very low power embedded microcontroller and was also designed with multiple mission requirements in mind. The CYGNSS version of the board will be tailored to a LEO radiation environment, providing a dense non-volatile memory, and ample interfaces to ADCS, CDS, DDMI, and thermal components throughout the observatory.

The Centaur provides the following functionality:

- Processor: The LEON3 ASIC is the spacecraft computer, which provides all resources for on-board microsat flight soft-ware processing. The LEON3 dual-core processor, successor to the LEON2 core, utilizes a 7-stage pipeline, 8 register windows, a 4×4 kBytei-cache and d-cache, branch prediction, hardware multiply/divide, and hardware watchdogs. It interfaces to EDAC-protected memories, including MRAM, SDRAM, and Flash. External interfaces include multiple SpaceWire, 1553, CAN, Ethernet, and UART ports.
- Processor Support Circuitry: The processor requires additional parts, including memories, clock, reset, and power management, and interface drivers. Memories include MRAM for code storage, SDRAM for code execution, and Flash memory for data storage. The radiation tested Flash parts are being used on MMS.
- CCSDS Command and Telemetry Core (CTC) (Heritage HDL in FPGA): Resident in the Centaur FPGA, the CTC autonomously receives and routes ground commands from the transceiver, assembles and packetizes science data, and autonomously collects and formats housekeeping telemetry for transmission to the transceiver, significantly reducing flight software processing loads. The telemetry algorithms to perform the CCSDS packetization are identical to those used on the WISE Mission Unique Board, which produced CCSDS Telemetry TM Source Packets and Transfer Frames with Reed-Solomon Codeblocks (E-16, I=5). The command algorithms are identical to those used on Deep Impact, Orbital Express, Kepler, and WISE, which produce CCSDS TC Transfer Frames with Viterbi (rate 1=2) encoding. The CCSDS File Delivery Proocol (CFDP) File Protocol for hardware acceleration of CFDP Protocol Data Units (PDUs) is used, leveraging designs from MMS. Further, Level 0 telemetry and commanded resets are generated by the CTC without required intervention from the processor. In this manner, the ground station can reset the spacecraft even with the processor in a non-responsive state.
- CCSDS Command and Telemetry Circuitry: The CCSDS command and telemetry circuitry includes ADCs (Analog to Digital Converters), RS422 command interfaces, and power switches, controlled by the Centaur but housed on the Peak Power Tracker. All components utilize the same circuitry as the Command and Telemetry Boards on Deep Impact, Orbital Express, Kepler, and WISE.
- General Purpose Interfaces: The Centaur design includes LVDS, RS422, analog, and discrete (low-level) interfaces. The CYGNSS ADCS and DDMI are compatible with these interfaces and do not require Centaur modification to accommodate.

4.3. CDS FLIGHT SOFTWARE

The simple operational nature of the DDMI and science profile allows the CDS flight software to be designed for autonomous control during all normal science and communication operation using only on-board Level 0 command capabilities of the Centaur, stored command sequences, and CCSDS File Delivery Protocol (CFDP) processes. CDS flight software refers specifically to the portion of software dealing with data upload and downlink, including command upload, parsing, telemetry generation, and transmission. Engineering operations require standard command services provided by our hardware-based heritage designs located on the Centaur. Command services include COP-0 uplink command processing with BCH error detect and correction. The Centaur also provides FSW-independent execution of a Level-0 command set used for ground-based fault management. All other commands are passed to the FSW Command Manager for execution or to the Stored Command Sequence Manager as onboard absolute and relative time sequences.

The FSW Telemetry Manager provides collection and high-level formatting of housekeeping data. These data are either downlinked in real-time or passed to the FSW Storage Manager to be stored for later downlink. The Storage Manager software controls data acquisition, recording, and playback of housekeeping and science data using the 4 GB on-board memory for data storage. The heritage 4 GB Flash memory data store allows for >10 days of continuous science operations without downlink, providing significant margin for contingency operations. A heritage hardware formatter from Orbital Express and WISE forms CCSDS source packets into transfer frames and supports four separate Virtual Channel (VC) buffers to enable optimized data routing and processing within the CYGNSS Ground Data System. These channels have been designated as real-time housekeeping, stored science data, stored housekeeping data, and Level 0 housekeeping data. CFDP is used for reliable delivery of stored data across the spacelink.

FLEXIBLE COMMUNICATION PLATFORM

S-band communication links are provided to uplink command sets and downlink science and housekeeping data. These links use two fixed omnidirectional micro-strip patch antennas, one on the nadir baseplate and one on the zenith panel, to provide near 4π steradian communications without interrupting science operations. Normal communications use the nadir antenna, while the zenith antenna is provided for anomalous pointing.

The S-band transceiver, or Flexible Communication Platform (FCP), is a single card communication solution developed by SwRI to provide a low-cost, radiation-tolerant, software defined radio system. The FCP was designed with flexibility in mind, compatible with either an on-board analog front end or a highly radiation tolerant front end, and is configured to provide S-band (2 GHz) communications. The FCP provides O-QPSK encoded transmit data at 1.25 Mbps (up to 5 Mbps) with an FSK uplink receiver supporting data rates to 64 kbps. The FCP was developed in 2010 with internal research funds to support small spacecraft platforms and forms the basis of SwRIs recent System F6 wireless communication system for DARPA. F6 utilizes a variant of the FCP as an intra-constellation satellite communication link. Functions of the FCP are listed below.

SOFTWARE DEFINED RADIO CORE (FPGA)

The SDR FPGA on the FCP is responsible for the modulation, demodulation, and functional control of the transceiver. It receives and transmits raw telemetry and command data (respectively) from the Centaur. Telemetry data is up-converted to an intermediate frequency and modulated using FSK. This data is sent directly to the on-board RF front-end which modulates to S-Band frequencies. Ground command data is received and down-sampled in the RF front-end and demodulated by the FPGA. Commands are interpreted by the Centaur.

SUPPORT CIRCUITRY

The FCP includes support circuitry, including FPGA configuration PROM, buffer memories, and housekeeping components, with which SwRI has extensive experience. Keeping the entire observatory command and telemetry chain in house allows SwRI to respond quickly to issues and effectively tailor the hardware to the required application, being sensitive to resource constraints such as on-board FSW processing, mass, and power.

ANTENNAS

The S-Band Microstrip Patch Antenna has a hemispherical gain pattern, with a 0 dBiC gain drop out to 60 off the boresight. These characteristics make it ideally suited to the design of the CYGNSS Observatories. The CYGNSS observatories will use 2 of these antennas, one on the nadir surface of the vehicle and one on the zenith surface to provide near 4π steradian coverage to allow communications from all attitudes.

5. ATTITUDE DETERMINATION AND CONTROL SUBSYSTEM

The CYGNSS ADCS enables a standard nadir-pointing, 3-axis, momentum-bias design derived from the Heat Capacity Mapping Mission. CYGNSS is able to take advantage of entirely off-the-shelf ADCS components, using pitch/roll horizon sensors and a 3-axis magnetometer for attitude determination; a pitch momentum wheel and 3-axis torque rods provide attitude control (torque rods also provide momentum wheel desaturation). The only attitude "maneuver" required by CYGNSS is to recover from deployment modulation separation tipoff rates and establish a nadir-pointing configuration, allowing an extremely simple mode flow.

All CYGNSS ADCS components are COTS units with high technology readiness level (TRL), helping to minimize non-recurring engineering (NRE) costs while providing reliability and functionality assurance. The 30 mNm-sec nominal momentum wheel was flown on CanX-2, launched in April 2008, and AISSAT-1, launched in July 2010. The momentum wheels are still fully operation on both missions. The torque rods are 1 *Am2* units, which have successfully flown on the JAXA led FedSat and Micro-LabSat missions. The magnetometer is a three-axis smart digital magnetometer to detect the strength and direction of an incident magnetic field. The three magneto-resistive sensors are oriented in orthogonal directions to measure the X, Y and Z vector components of a magnetic field. These sensor outputs are converted to 16-bit digital values using an internal delta-sigma A/D converter. An onboard EEPROM stores the magnetometers configuration for consistent operation. The data output is serial full-duplex RS-232 or half-duplex RS-485 with 9600 or 19,200 data rates. It has flown on several missions, including CanX-1. CYGNSS uses two Earth Horizon Sensors to measure pitch and roll angles of the spacecraft. Each sensor has two thermopile detectors which view the Earth limb and measure the dip angle with respect to the horizon.

The ADCS has three primary states of operation: rate damping, nadir acquisition, and normal pointing. The rate damping state is used initially after separation from the launch vehicle and for anomaly recovery if rates exceed normal state capabilities. Rate damping uses a "B-dot" algorithm to command magnetic dipole moments opposed to the rate of change of the magnetic vector, both measured in body coordinates. It only uses the sensed magnetic field, and does not rely on a correct orbital ephemeris or magnetic field model. Wheel speed is off for launch and initial tip-off recovery, or set to its nominal value during anomaly recovery.

After the body rates are damped, the system transitions into nadir acquisition, which monitors the pitch/roll horizon sensors to determine a rough Earth vector. The sensors are not assumed to be in their linear range; simple "on Earth" and "off Earth" measurements are used to establish slow roll and pitch rates to bring the sensors into their linear range (± 5°). The momentum wheel is also maintained relatively close to its commanded nominal speed, with a desaturation gain much lower than normal.

When the ADCS brings the sensors within their linear ranges, it transitions to normal operations. The normal state uses pitch and roll measurements from the horizon sensors to calculate pitch, roll, and filtered roll rate information. It com-pares the measured magnetic field with a calculated model to determine yaw and filtered yaw rate information. These measurements are used to control momentum wheel torques for pitch and the electromagnets for roll and yaw angle, and pitch wheel desaturation.

Normal control is capable of degraded operation (used in Standby mode) if the ephemeris and magnetic field model are temporarily unavailable. Pitch and wheel desaturation are controlled as before, but roll and B-dot (y axis) information (as in HCMM) are used to control roll and yaw with slightly degraded accuracy. The torque rod commanding is synchronized to permit accurate measurement of the local geomagnetic field. A Kalman filter is used to estimate body rates and improve yaw attitude estimation. Orbit position is provided via GPS determination from the DDMI.

6. MICROSATELLITE FLIGHT SOFTWARE

The CYGNSS microsat flight software, which handles all station keeping, is based on a cost-effective, component architecture, enabling significant software reuse. It is developed in the C Language, executing on the Centaur computer in the RTEMS real-time operating system environment. The modular architecture and components enable efficient development and verification while directly supporting on-orbit modification. The flight software is table-driven and includes provisions for memory, table, and program image uploads. Application components interface through a software bus implementation (part of the Flight Core) to exchange CCSDS packets. Standard CCSDS protocols simplify the integration of application components and provide a reliable mechanism to install component stubs and simulations during software testing. During flight software development, the software bus is bridged to an Ethernet network via TCP/IP to permit the use of external simulators to test the ADCS.

RTEMS provides a small memory footprint and deterministic timing. Software development tools include the GCC compiler, the debug monitor, and the Software Verification Environment. The flight software team has significant flight development experience with this environment from the Fermi, Juno, and MMS missions.

7. GROUND SEGMENT AND MISSION OPERATIONS

7.1. CONCEPT OF OPERATIONS

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 to reach the Standby Mode where it can safely remain indefinitely.

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, subsampled 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. 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 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:

- 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.

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.

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

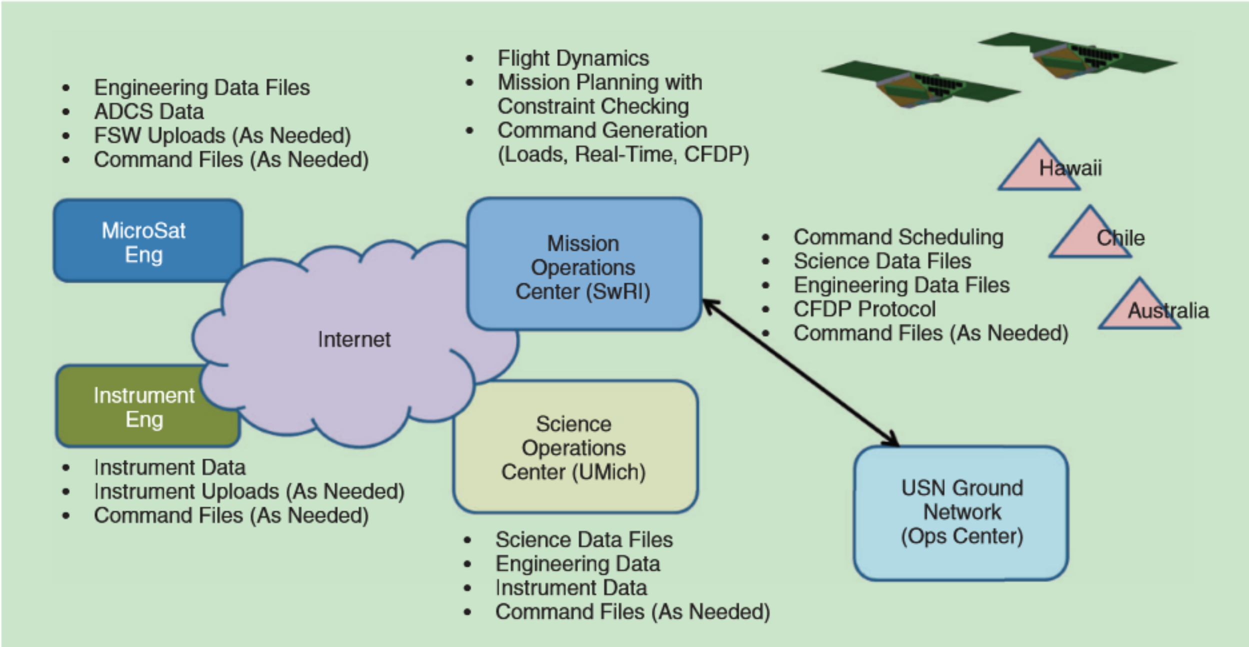

FIGURE 10. CYGNSS ground system overview.

command sequencing allows the team to coordinate instrument activities with the time periods when the beacons will be observable by the Observatory.

7.2. GROUND SYSTEM OVERVIEW

The CYGNSS ground system, as shown in Figure 10, 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.

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. Each Observatory can accommodate gaps in contacts with storage capacity for >10 days of data with no interruption of science.

7.3. 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
- maintaining configuration of on-board and ground parameters for each Observatory.

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
- archive Level 0–3 data products, DDMI commands, code, algorithms and ancillary data at a NASA Distributed Active Archive Center (DAAC).

MISSION OPERATIONS CENTER

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. 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.

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 [16]. 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.

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.

8. DEPLOYMENT MODULE

8.1. DEPLOYMENT MODULE STRUCTURE

The deployment module (DM) serves as the constellation carrier during launch and then deploys the Observatories into their proper orbital configuration once on orbit.

The DM consists of 2 AL cylindrical sections or tiers, each with 4 mounting/separation assemblies (Fig. 10). The tier design approach simplifies Observatory-DM integration by enabling easy access of GSE while minimizing potential for damage inherent in a single core structure. The mounting/separation assemblies are positioned 90° apart to release the Observatories in pairs opposite each other, balancing deployment forces and keeping disturbance torques well within LV capabilities. Tier 2 is clocked 45° from Tier 1 to provide proper orbital dispersal vectoring.

Deployment is initiated using flight-proven, high-reliability Qwknuts. Observatory separation tip-off errors are minimized by averaging 4 push springs (Fig. 11) to reduce microsat cg location criticality and minimize the effects of spring tolerances. Screening the springs during DM assembly further reduces tip off errors. Each Observatory is secured to the DM by torquing the Qwknut actuator into the microsat nadir baseplate, compressing the separation springs to achieve desired spring load for Observatory ejection. Tapered alignment pins, combined with the Qwknut actuator, rigidly constrain each Observatory to the DM for launch. Preliminary FEM quasi-static load analysis of the fully integrated FS indicates that launch loads have a 2.17 safety factor against ultimate loads. The FEA also indicates the first natural frequency of the structure is a radial mode (Lobar) at 47.6 Hz in the launch configuration, avoiding harmonic coupling with the LV during launch.

8.2. DEPLOYMENT MODULE AVIONICS

The DM uses a heritage electronic sequencer to release the Observatories in a pre-determined sequence stored within the sequencer memory. The sequence is initiated via a standard LV discrete signal when the LV arrives at the required orbit. The sequencer then performs the deployment sequence by actuating the Qwknut actuators. Sequence timing incorporates constellation separation requirements and deployment actuation tolerances. Hardware safety is ensured through the use of a 2-stage command, single-fault tolerant actuator driver design that includes a pre-flight Safe/Arm connector to fully disarm the system.

A 28 Vdc DC 140 W-hr Li-Ion battery is used to power the DM avionics and activates the deployment Qwknut actuators. The battery is fully charged at launch with <5% of capacity required to complete the orbit insertion and deployment sequence.

In support of pre-launch operations, the DM avionics route Observatory battery trickle charge power from the GSE to the Observatory via separation connectors, with battery temperature signals acquired by the DM avionics and routed to the GSE for monitoring. Pre-launch Observatory command and telemetry handling is also provided by the DM avionics. The GSE command data stream is routed to each Observatory command hardline interface with only buffering provided by the DM. Specific command targeting is a function of S/C ID; the Observatory ignores the command if the S/C ID is not applicable. The DM enables Observatory pre-launch health and status monitoring by multiplexing the Observatory hardline telemetry.

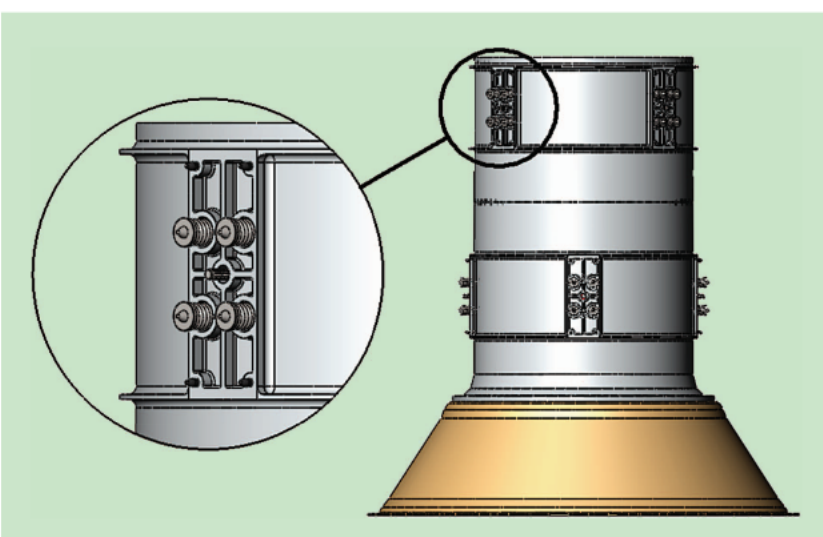

FIGURE 11. 2-tier deployment module provides balanced separation forces by using a matched spring deployment mechanism.

9. CONCLUDING REMARKS

The CYGNSS mission introduces a new paradigm in low-cost Earth science missions that employs a constellation of science-based microsats to fill a gap in capabilities of existing large systems at a fraction of the cost.

The CYGNSS observatories will make frequent wind observations, and wind observations in precipitating conditions, using GPS reflectometry to observe the TC inner core ocean surface. These efforts will result in unprecedented coverage of winds within a TC throughout its life cycle and thus provide critical data necessary for advancing the forecast of TC intensification.

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