Avionics of the Cyclone Global Navigation Satellite System (CYGNSS) Microsat Constellation

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Abstract— **The Cyclone Global Navigation Satellite System (CYGNSS), which was recently selected as the Earth Venture-2 investigation by NASA's Earth Science System Pathfinder (ESSP) Program, measures the ocean surface wind field with unprecedented temporal resolution and spatial coverage, under all precipitating conditions, and over the full dynamic range of wind speeds experienced in a tropical cyclone (TC). The CYGNSS flight segment consists of 8 microsatellite-class observatories, which represent SwRI's first spacecraft bus design, installed on a Deployment Module for launch. They are identical in design but provide their own individual contribution to the CYGNSS science data set. Subsystems include the Attitude Determination and Control System (ADCS), the Communication and Data Subsystem (CDS), the Electrical Power Supply (EPS), and the Structure, Mechanisms, and Thermal Subsystem (SMT). This paper will present an overview of the mission and the avionics, including the ADCS, CDS, and EPS, in detail. Specifically, we will detail how off-the-shelf components can be utilized to do ADCS and will highlight how SwRI's existing avionics solutions will be adapted to meet the requirements and cost constraints of microsat applications. Avionics electronics provided by SwRI include a command and data handling computer, a transceiver radio, a low voltage power supply (LVPS), and a peak power tracker (PPT).**

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1. INTRODUCTION

The CYGNSS mission Science Goal is to understand the coupling between ocean surface properties, moist atmospheric thermodynamics, radiation, and convective dynamics in the inner core of a Tropical Cyclone (TC). It achieves this goal by combining the all-weather performance of GPS-based bistatic scatterometry with the sampling properties of a dense microsatellite constellation. Near-surface winds over the ocean are major contributors to and indicators of momentum and energy fluxes at the air/sea interface. CYGNSS' primary objectives are: 1) to measure ocean surface wind speed in all precipitation conditions, including those experienced in the TC eyewall; and 2) to measure ocean surface wind speed in the TC inner core with sufficient frequency to resolve genesis and rapid intensification. A secondary science goal is to support the operational hurricane forecast community by producing and providing ocean surface wind speed data products, and helping them assess the value of these products for use in their retrospective studies of potential new data sources.

The CYGNSS mission is comprised of 8 Observatories that receive both direct and reflected signals from GPS satellites. The direct signals pinpoint CYGNSS Observatory positions, while the reflected signals respond to ocean surface roughness, from which wind speed is retrieved. GPS bi-static scatterometry measures ocean surface winds at all speeds and under all levels of precipitation, including TC conditions.

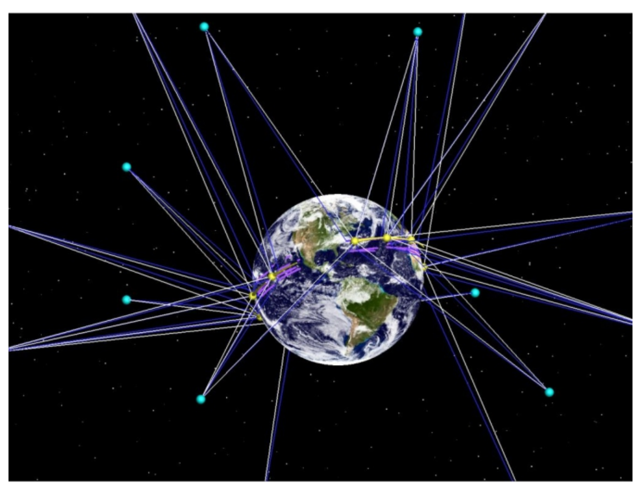

Figure 1. Relative Positions of GPS and CYGNSS satellites.

The eight Low Earth Orbit (LEO) S/C orbit at an inclination of 35°, and are each capable of measuring 4 simultaneous

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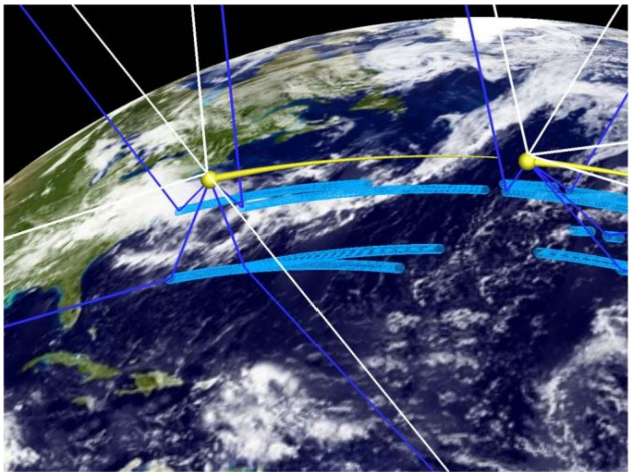

Figure 2. GPS signal geometry for CYGNSS.

reflections, resulting in 32 wind measurements per second across the globe. Ground tracks for 90 minutes and a full day of wind samples are in Figures 3 and 4. Figure 3 shows the geometric configuration of GPS Signals from GPS satellites (in green) received by the CYGNSS constellation (in yellow). Direct GPS signals are shown by white lines and reflected signals by blue lines. Figure 4 shows GPS signal geometry for the CYGNSS constellation satellites. Instantaneous wind samples are indicated by individual blue circles for a five minute period. The number of S/C, their orbit altitudes and inclinations, and the alignment of the antennas are all optimized to provide unprecedented high temporal-resolution wind field imagery of TC genesis, intensification and decay.

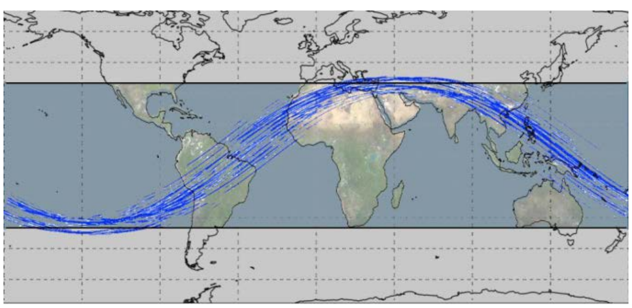

Figure 3. Ground track for a 90 minute sample period.

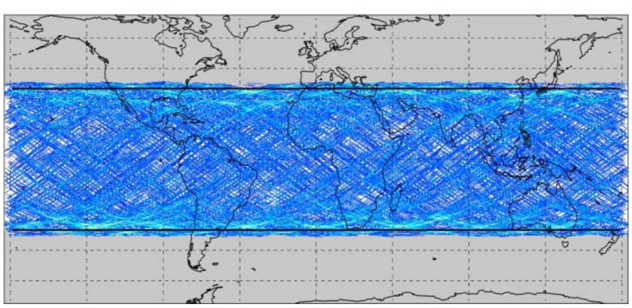

Figure 4. Ground track for a full day sample period.

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) [1]
- CYGNSS Mission implementation with specific emphasis on the microsat (Session: 2.05-0509; Randy Rose) [2]
- CYNGSS Science instrument (Session: 6.02-2410; Marissa Brummitt) [3]
- CYGNSS Avionics and Bus Architecture (This paper, Session: 7.07-2602)
- CYGNSS Mission operations (Session: 12.02-2559; Debi Rose) [4]

2. Science Motivation for a Constellation

Our goal, to understand the coupling between the surface winds and the moist atmosphere within a TC, is key to properly modeling and forecasting its genesis and intensification. CYGNSS provides surface wind fields of the TC inner core, including regions beneath the intense eye wall and rain bands that could not previously be measured from space. Mission simulation studies predict a mean revisit time of 4.0 hrs. The use of a dense constellation of microsatellites results in spatial and temporal sampling properties that are markedly different from conventional wide swath polar imagers. CYGNSS combines the rain penetrating capabilities of GPS-based bistatic ocean scatterometry with the high frequency sampling of a dense microsat constellation. Each CYGNSS Observatory consists of a microsat platform hosting a GPS receiver that has been 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 [5].

CYGNSS science requirements for spatial and temporal coverage of storm tracks drive the need for a constellation of space-based Observatories. The cost constraints of the mission, cost capped at $150M including launch vehicle, and the efficiency of dedicated space platforms drives the requirement for microsats. The CYGNSS flight segment leverages the Direct-Doppler Mapping Instrument's (DDMI) capabilities with low-power, low-mass microsat technologies and a straightforward deployment approach to provide fundamental improvements in the observation of TC inner core genesis and intensification. CYGNSS uses a single string hardware architecture with functional and selective redundancy included for critical areas. The microsat consists of an electrical power subsystem (EPS), which supplies, distributes, and regulates power to the other components, a command and data subsystem (CDS), which controls the microsat, responds to ground commands, and formats telemetry, and an attitude determination and control subsystem (ADCS), which controls the orientation of the microsat, all attached to a structural mechanical frame. The microsat has been designed from the beginning for ease of manufacture, integration, and test to provide a low-risk, cost-effective solution across the constellation.

3. Microsatellite Approach

Microsats are colloquially defined as artificial satellites with a wet mass between 10 and 100 kg; they do not conform to a specific specification like CubeSats, and given their infrequent historical use, are an evolving categorization of satellite. The CYGNSS microsat will be about 20 kg and require 50 W of power. Based on a Pegasus launch vehicle, a

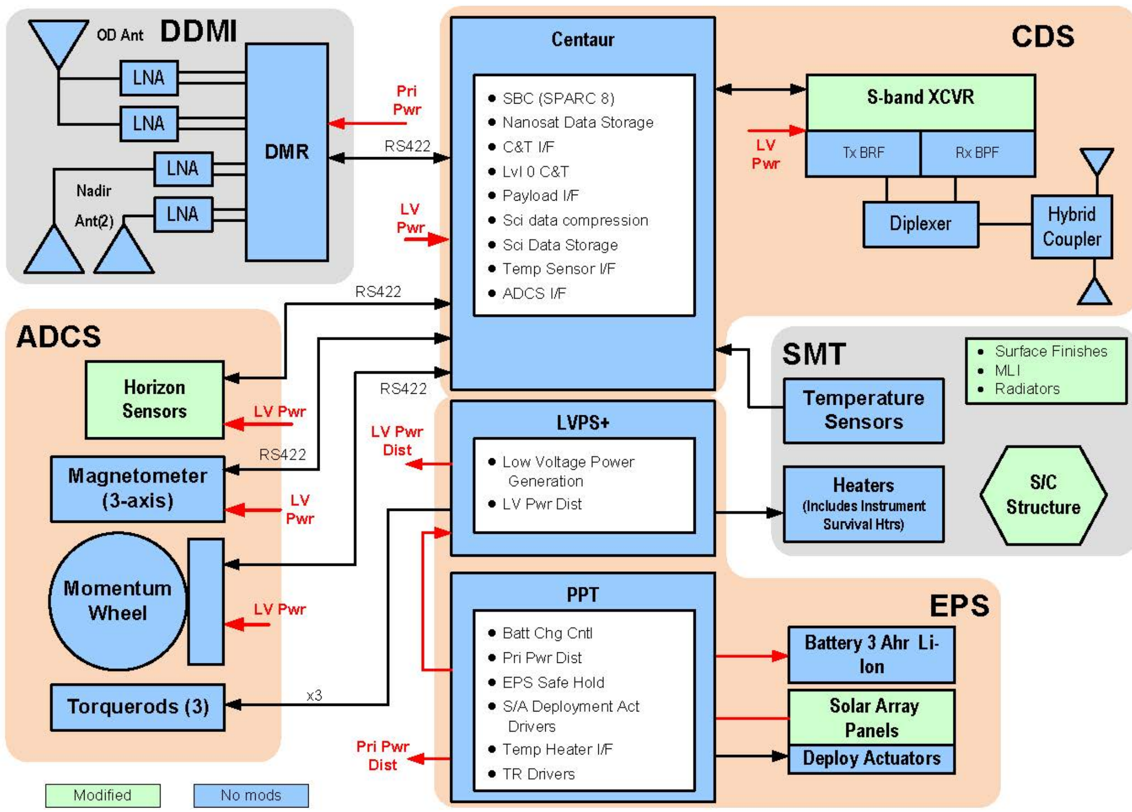

Figure 5. System Level Block Diagram of a CYGNSS observatory.

deployment module, and eight microsatellites, almost 60% margin is carried on the mass. Power margin is carried individually per satellite based on the solar array design and is currently 30%. While smaller satellites are often associated with lower reliability, the CYGNSS microsat is executed with a rigorous safety and mission assurance program, structured to provide proactive guidance and oversight necessary to ensure CYGNSS mission success within program cost and schedule constraints. The tenets are compliant with Category 3 missions (per NM 7120-81) [6] with Class D payloads (per NPR 8705.4) [7]. The mission assurance plan includes a comprehensive Electrical, Electronic, and Electromechanical (EEE) parts plan; a materials and processes plan; workmanship, procurement, and inspection requirements; a mission-wide, on-line failure and nonconformance management toolset; and a comprehensive test philosophy.

CYGNSS uses a "single-string" H/W architecture with functional and selective redundancy included for critical areas (e.g., a 2-stage cmd, single-fault-tolerant driver design for all deployment mechanisms, Level 0 command and telemetry hardware for communication without FSW). This architecture, combined with correct selection of parts reliability, fault management, and a rigorous test campaign promotes low risk and cost effectiveness. The CYGNSS team implements proactive reliability engineering early in Phase B that includes Failure Modes Effects Analysis and parts stress analysis for all Observatory components. Fault Tree Analysis and Probabilistic Risk Assessment are performed for all safety critical items.

The orbit chosen for the CYGNSS mission provides radiation constraints that are almost entirely driven by the trapped proton environment in LEO. CYGNSS uses a radiation design margin of 5 (i.e. the the spacecraft could withstand five times the mission duration in the radiation environment). Mature semiconductor manufacturing processes typically produce highly reliable electrical piece parts with a relatively low likelihood of failure. CYGNSS combines traditional parts assurance techniques and assembly level screening and qualification to achieve a reliable design. Our parts program uses a modified EEE-INST-002 Level 3 approach enhanced by a significant amount of unit level stress testing. This program selects Level 3 parts when resources allow, and when they do not, they are procured to the highest quality standards available with a preference for parts from QML-certified manufacturers. Stress screening and life testing of the flight design is conducted on a single assembly to assure that the design meets the mission requirements. Each flight unit also undergoes a screening burn-in prior to the normal test flow to expose infant mortality issues.

4. AVIONICS

The CYGNSS Avionics consists of four boards, portions of the EPS and CDS, as discussed below. 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 6. The avionics unit does not include a box; instead, the microsat structure itself provides mechanical mounting and electrical interconnects over a backplane and cables.

Electrical Power Subsystem

The EPS design performance provides robust margins on all requirements. The EPS is designed to perform battery

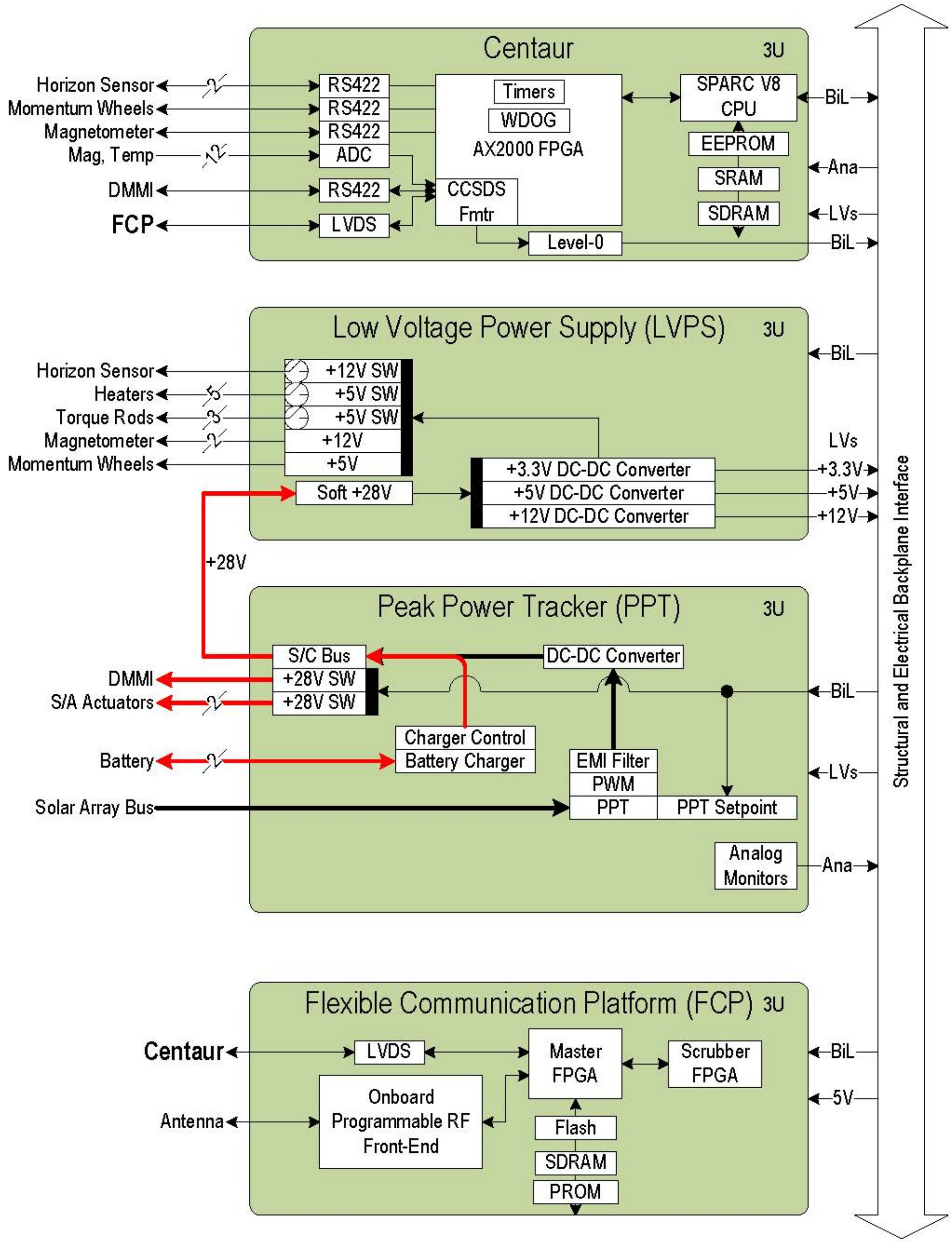

Figure 6. Block diagram of the Avionics Unit.

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 a 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 $1.2 \times I_{dis} \times T_{eclipse}$ (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.

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.

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.

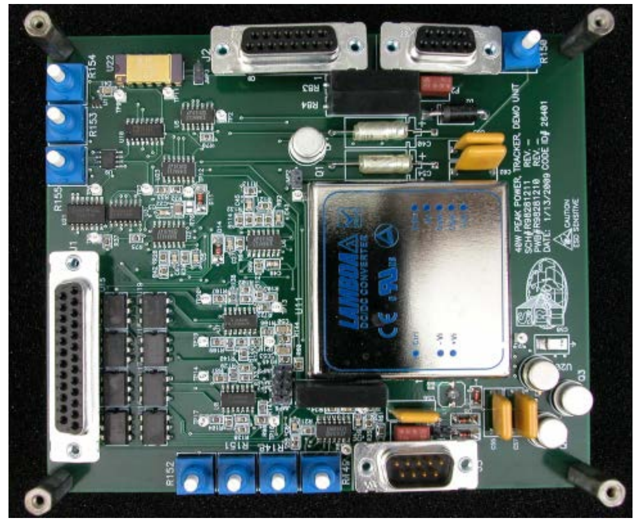

Figure 7. Peak Power Tracker (PPT) board

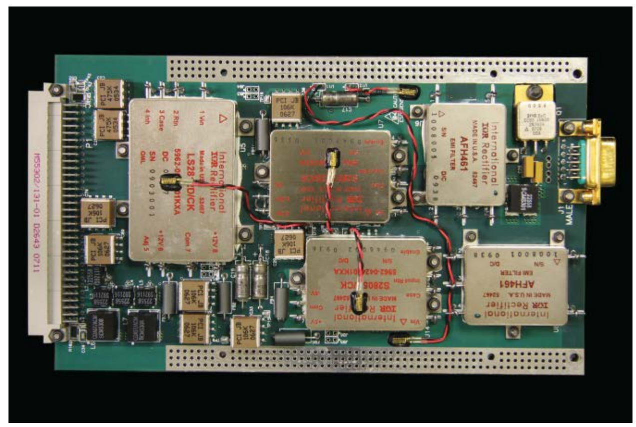

Figure 8. Low Voltage Power Supply (LVPS) board

Centaur—All on-board microsat processing is performed on SwRIs 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 relayout 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 software processing. The LEON3 dual-core processor, successor to the LEON2 core, utilizes a 7-stage pipeline, 8 reigster windows, a 4x4 kByte i-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.

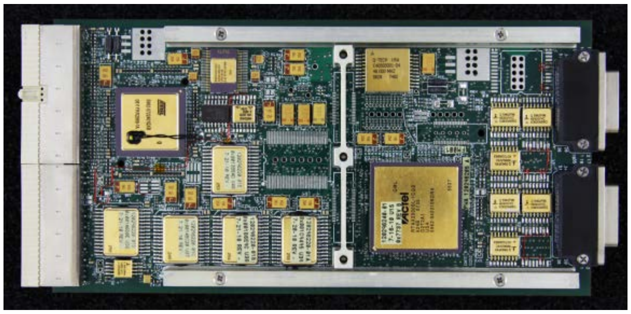

Figure 9. Instrument Processor Board (Centaur prototype)

• Processor Support Circuitry: The processor requires additional parts, including memories, clock, reset, and power management, and interface drivers. The processor support circuitry is identical to that on the Juno JADE Instrument Processor Board. 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.

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.

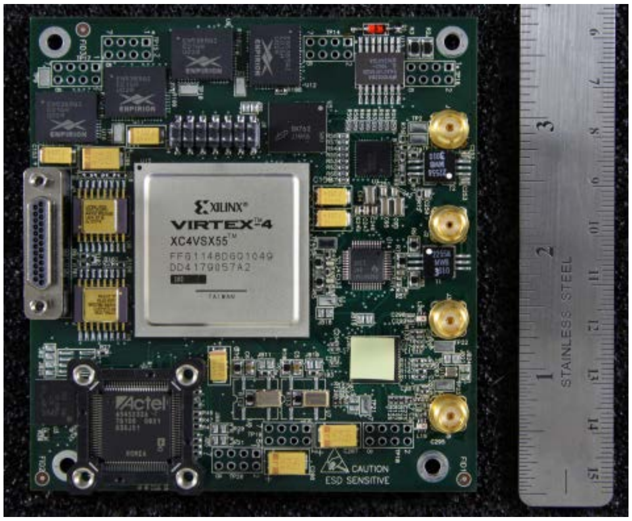

Figure 10. Flexible Communication Platform (FCP) radio

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 Am^2 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 ($\pm 5°$). 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 compares 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. MICROSAT FLIGHT SOFTWARE

The CYGNSS microsat flight software, which handles all station keeping and is a superset of the CDS flight software, 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 provides 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.

We evaluated the CYGNSS computing requirements to define required computer resources and identify changes necessary for the heritage code. 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. CONCLUSION

The CYGNSS avionics take advantage of SwRI's tremendous experience in radiation hardened electronics for space missions. The SwRI-designed avionics electronics are coupled with heritage small satellite components to provide the power, communications, and attitude determination and control systems of the CYGNSS microsat. All elements are adapted to a microsat mission enabling an innovative parts program and profuse use of off-the-shelf components. Further, the fault tolerance of a constellation mission and selective functional redundancy within the avionics helps to improve mission. Consequently, the avionics package provides a high reliability microsat bus, able to meet the mission requirements while fitting neatly within the missions constraints.

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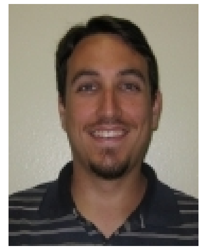
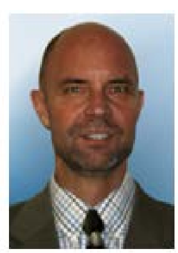
BIOGRAPHY

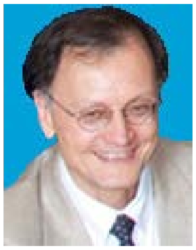


John Dickinson is a Senior Research Engineer at Southwest Research Institute. Having studied Electrical Engineering at Johns Hopkins University with a focus on control systems and signals, he began work at SwRI in the Avionics Systems Group of the Space Science and Engineering Division. He is currently the Command, Data, and Power Subsystem (CDP) lead for NASA's CYGNSS microsat constellation mission, Systems Engineer for the ISIS suite of energetic particle instruments on NASAs Solar Probe Plus mission, and the lead engineer on the Command and Data Handling board for ESA's Solar Orbiter HIS instrument. He was the lead test engineer for the WISE and Kepler Mission Unique Boards (MUB) and the lead design engineer for the Juno JADE Instrument Processor Board. He has assisted with systems engineering tasks on multiple projects, including NASAs MMS, RBSP, and IBEX missions and DoDs Tracker and Wiper programs, as well as on proposal activities. He is currently pursuing a Master's Degree in Electrical and Computer Engineering from Georgia Institute of Technology.

Jennifer L. Alvarez has significant experience in designing small, low-power digital electronics with microcontrollers, digital signal processors, and field programmable gate arrays. She has extensive system engineering and project management experience for U.S. Government, commercial and foreign government clients. As the manager of the Tracking Systems Section, she provides clients with systems for covert surveillance, tracking, sensor data communication using low probability of intercept/low probability of detection signals, and Global Positioning System threat detection and mitigation.



Randy Rose received a B.S. in Engineering from the South Dakota School of Mines and Technology in 1980. Mr. Rose is a staff engineer for SwRI Space Systems Division where he serves as a lead for spacecraft systems development. He has more than 30 years of experience in the spacecraft development community with experience in all aspects of spacecraft development including project management, systems engineering, computer architecture, ADCS, hardware and software design, I&T, and operations. His experience includes hands-on hardware development experience with all spacecraft subsystems. Mr. Rose is the CYGNSS Project Systems Engineer responsible for the development of the overall CYGNSS system and microsat designs.



Chris Ruf received the B.A. degree in physics from Reed College, Portland, OR, and the Ph.D. degree in electrical and computer engineering from the University of Massachusetts, Amherst. He is currently Professor of Atmospheric, Oceanic, and Space Sciences and Director of the Space Physics Research Laboratory at the University of Michigan and Principal Investigator of the NASA EV-2 CYGNSS Mission. He has worked previously at Intel Corporation, Hughes Space and Communication, the NASA Jet Propulsion Laboratory, and Penn State University. In 2000, he was a Guest Professor with the Technical University of Denmark. He has published in the areas of satellite microwave radiometry and atmospheric, oceanic, land surface and cryosphere retrieval algorithms. Dr. Ruf is a Fellow of the IEEE, and a member of the American Geophysical Union (AGU), the American Meteorological Society (AMS), and Commission F of the Union Radio Scientifique Internationale. He has served on the editorial boards of AGU Radio Science, the IEEE Transactions on Geoscience and Remote Sensing (TGRS), and the AMS Journal of Atmospheric and Oceanic Technology. He is currently the Editor-in-Chief of TGRS.

Buddy J. Walls has served as the systems engineer on multiple programs, most recently the NASA-JPL Deep Impact Spacecraft Control Unit (SCU). The SCU is a complete cPCI based command and data handling system incorporating CCSDS command / telemetry processing, high-speed instrument data collection and DMA, as well as radiation hardened processor and memory modules. Mr. Walls program management experience includes technical and cost management at both the module and avionics box level. He has served as the program manager for SwRIs Command and Telemetry Formatter (AES version) modules for the Commercial WorldView I and II spacecraft, as well as the program manager for avionics boxes on the NASA-JPL Kepler Spacecraft, the NASA-JPL WISE spacecraft. Most recently, Mr. Walls has served as the program manager on a redundant avionics box for a US Government, non-NASA program and is currently the program manager on SwRIs System F6 Wireless Information Communication System for DARPA.