CYGNSS: NASA Earth Venture Tropical Cyclone Mission

Christopher Ruf*[a], Paul Chang[b], Maria Paola Clarizia[a], Zorana Jelenak[b], Aaron Ridley[a], Randall Rose[c]
[a]AOSS/University of Michigan, Ann Arbor, MI USA; [b]NOAA/NESDIS/StAR, Silver Spring, MD USA; [c]Southwest Research Institute, San Antonio, TX USA

ABSTRACT

The NASA Earth Venture Cyclone Global Navigation Satellite System (CYGNSS) is a spaceborne mission scheduled to launch in October 2016 that is focused on tropical cyclone (TC) inner core process studies. CYGNSS attempts to resolve one of the principle deficiencies with current TC intensity forecasts, which lies in inadequate observations and modeling of the inner core. CYGNSS 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. CYGNSS measurements of bistatic radar cross section of the ocean can be directly related to the near surface wind speed, in a manner roughly analogous to that of conventional ocean wind scatterometers. The technique has been demonstrated previously from space by the UK-DMC mission in 2005-6.

Keywords: Small satellites, remote sensing, bistatic radar, hurricanes, GNSS-R

1. INTRODUCTION

The CYGNSS constellation is comprised of 8 observatories in 500 km circular orbits at a common inclination angle of 35°. Each observatory contains a Delay Doppler Mapping Instrument (DDMI) which consists of a multi-channel GPS receiver, a low gain zenith antenna and two high gain nadir antennas. Each DDMI measures simultaneous specular scattered signals from the 4 GPS transmitters with the highest probable signal-to-noise ratio. This results in 32 wind measurements per second. An exploded view of one of the eight observatories is shown in Fig. 1.

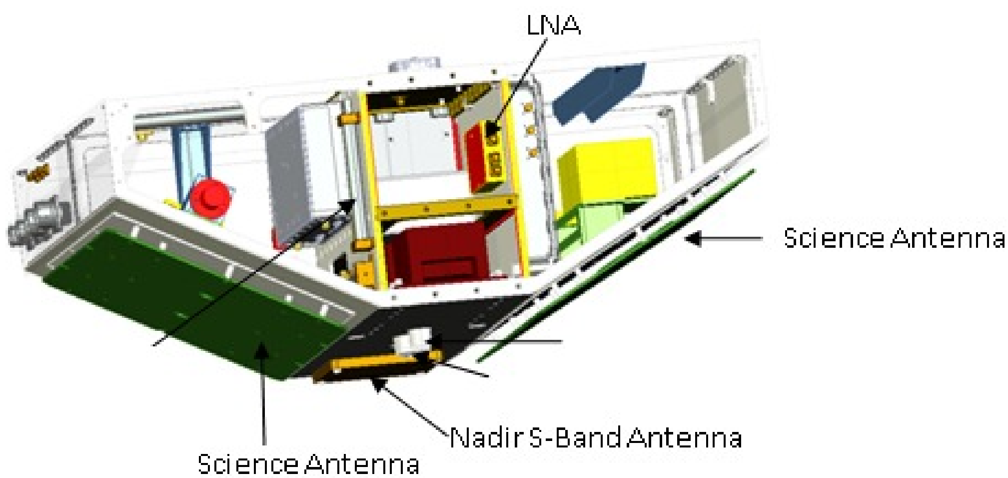

Figure 1. Exploded view of one of the eight CYGNSS observatories.

CYGNSS spatial sampling is marked by 32 simultaneous single pixel "swaths" that are 25 km wide and, typically, 100s of km long. The temporal sampling is best described by a probability distribution of the revisit time at each location within the +/- 35o latitude coverage area. The median value of the revisit time is ~2 hours and the mean revisit time is ~6 hours.

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The bistatic radar cross section of the ocean surface at the specular reflection point between a GPS transmitter and a CYGNSS receiver is measured in the form of Delay-Doppler Maps (DDMs). Wind speed is estimated from the DDMs using a minimum variance (MV) estimator. The MV estimator is a composite of wind estimates obtained from different observables that can be derived from the DDMs. Regression-based wind retrievals are developed for each observable using geophysical model functions that relate an observable to the surface wind speed.

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.

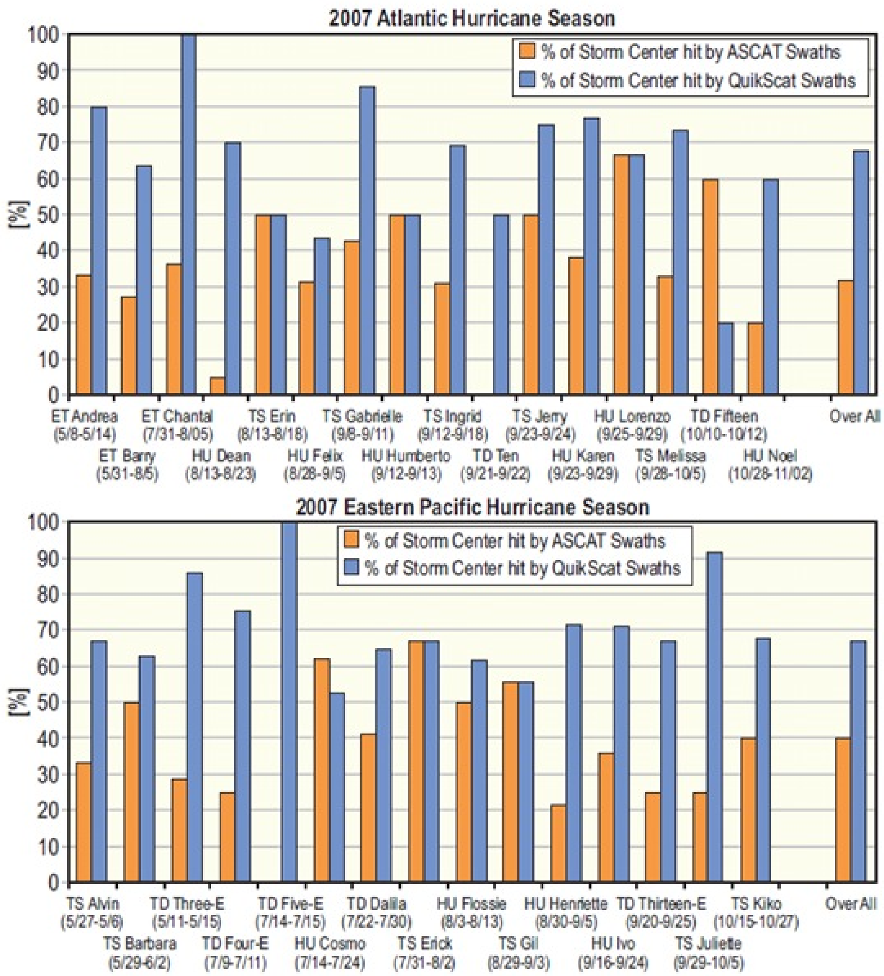

Figure 2. Percentage of time the center of named storms was observed with either QuikScat (blue) or ASCAT (orange) polar-orbiting scatterometers during the 2007 Atlantic (top) and Pacific (bottom) hurricane season. Poor performance results from the coverage gaps and infrequent revisit times that are characteristic of polar-orbiting wide-swath imagers.

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 2 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 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

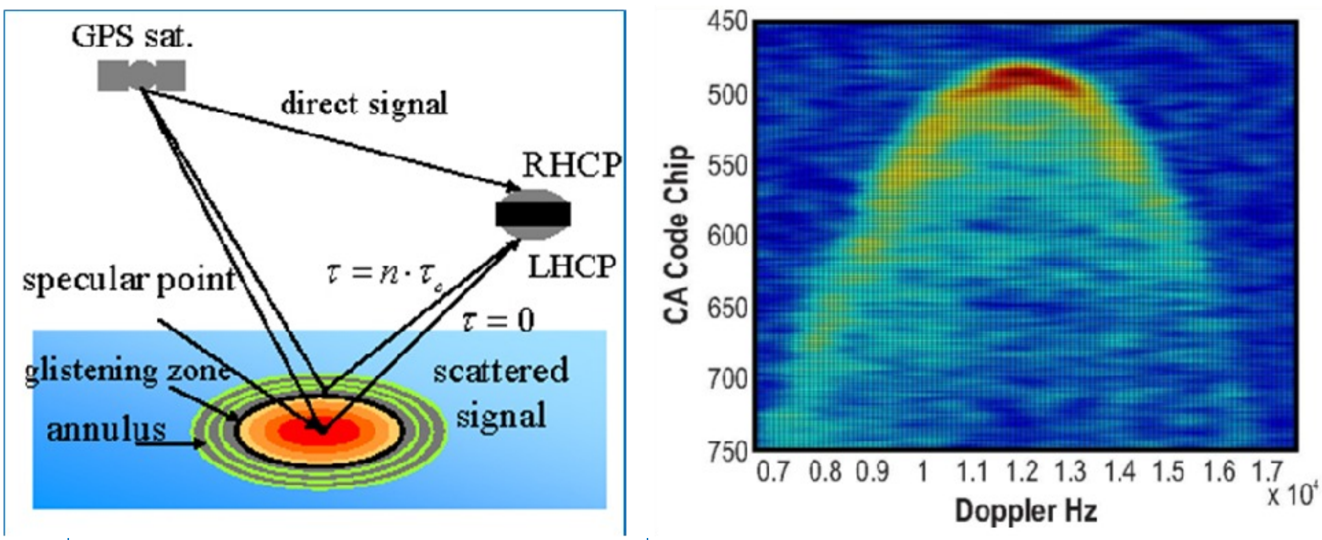

Figure 3. GPS signal propagation and scattering geometries for ocean surface bistatic quasi-specular scatterometry. (right) Spatial distribution of the ocean surface scattering measured by the UK-DMC-1 demonstration spaceborne mission – referred to as the Delay Doppler Map (DDM) [5].

Figure 3 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 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. 3. 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. 3) 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. 3). The arc represents the departure of the actual bi-static 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. 4. 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.

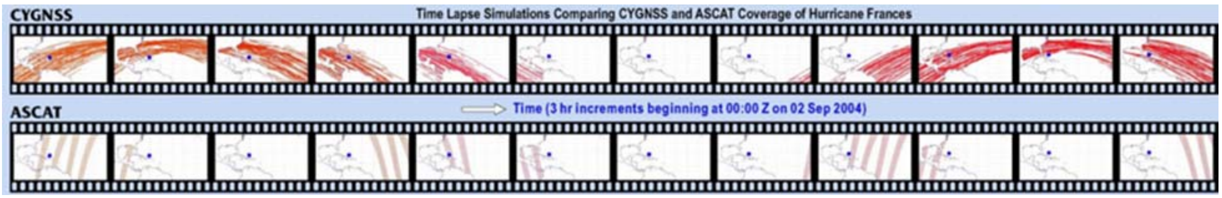

Figure 4. Time lapse simulation comparing the spatial and temporal sampling properties of CYGNSS and ASCAT, if they had both been in orbit during the Hurricane Frances U.S. landfall on 2 Sep 2004.

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 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.

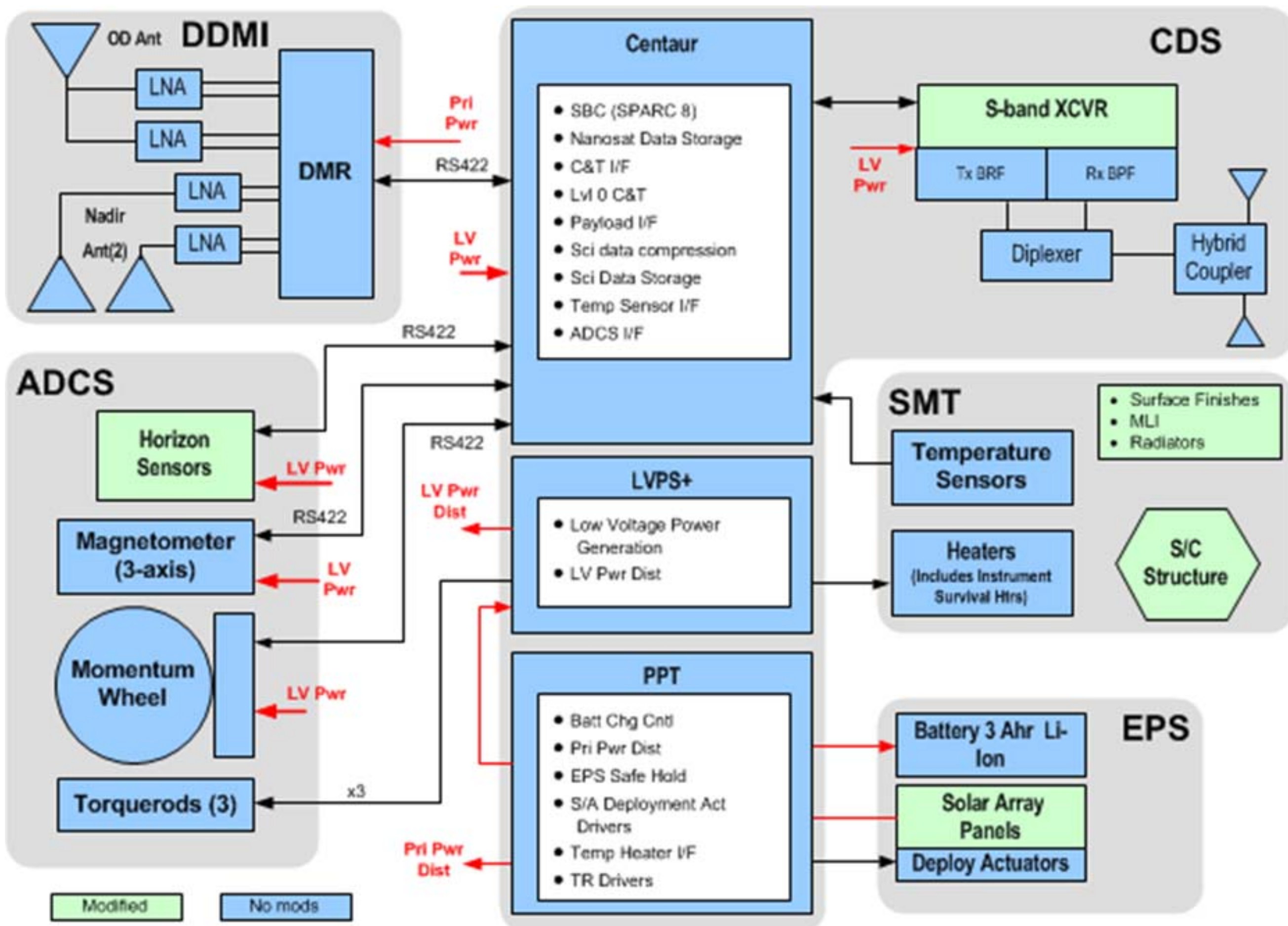

Figure 5. CYGNSS single-string architecture.

3.3 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.

3.4 Microsatellite Thermal

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

The data returned from CYGNSS are expected to expand our knowledge of the rapidly changing environment in the core of a developing tropical cyclone. The Science Operation Center (SOC) is responsible for data product development and dissemination. After science commissioning is complete and the mission enters its nominal science operations stage, the L2 data will be made available for public release. The CYGNSS science team members will use the fully calibrated L2 data for their own research and make it available to the external user science community and eventually to operational users. Calibration/validation assessment of L2 data quality continues for the life of the mission using an updated version of the same wind field intercomparison database used during science commissioning. Twice a year, nominally at the beginning and end of the Atlantic hurricane season, engineering performance will be verified by a brief (approximately two-week) repeat of the instrument calibration activities performed during engineering commissioning.

5. 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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