The NASA EV-2 Cyclone Global Navigation Satellite System (CYGNSS) Mission

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Abstract— **The NASA EV-2 Cyclone Global Navigation Satellite System (CYGNSS) is a spaceborne mission focused on tropical cyclone (TC) inner core process studies. CYGNSS attempts to resolve the principle deficiencies with current TC intensity forecasts, which lies in inadequate observations and modeling of the 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 TC life cycle are poorly sampled in time by conventional polar-orbiting, wide-swath surface wind imagers. 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.**

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1. Overview

Tropical cycle track forecasts have improved in accuracy by ~50% since 1990, largely as a result of improved mesoscale and synoptic modeling and data assimilation. In that same period, there has been essentially no improvement in the accuracy of intensity forecasts. 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 TC life cycle are poorly sampled in time by conventional polar-orbiting, wide-swath surface wind imagers. 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 [1, 2]. The use of a dense constellation of micro-satellites results in spatial and temporal sampling properties which are markedly different from conventional imagers. A candidate low-cost spacecraft and GNSS receiver design are considered which could practically be used in an affordable constellation mission. Compromises in some aspects of the design are necessary (e.g. limiting the downward looking antenna gain) in order to keep the system small and affordable. The signal-to-noise ratio of the measured scattered signal, and the resulting uncertainty in retrieved surface wind speed, are also examined.

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 [this paper; Session 2.05-2532]

• CYGNSS Mission implementation with specific emphasis on the microsat [Session: 2.05-2540; Randy Rose]

• CYGNSS Science Instrument [Session: 6.02-2410; Martin Unwin]

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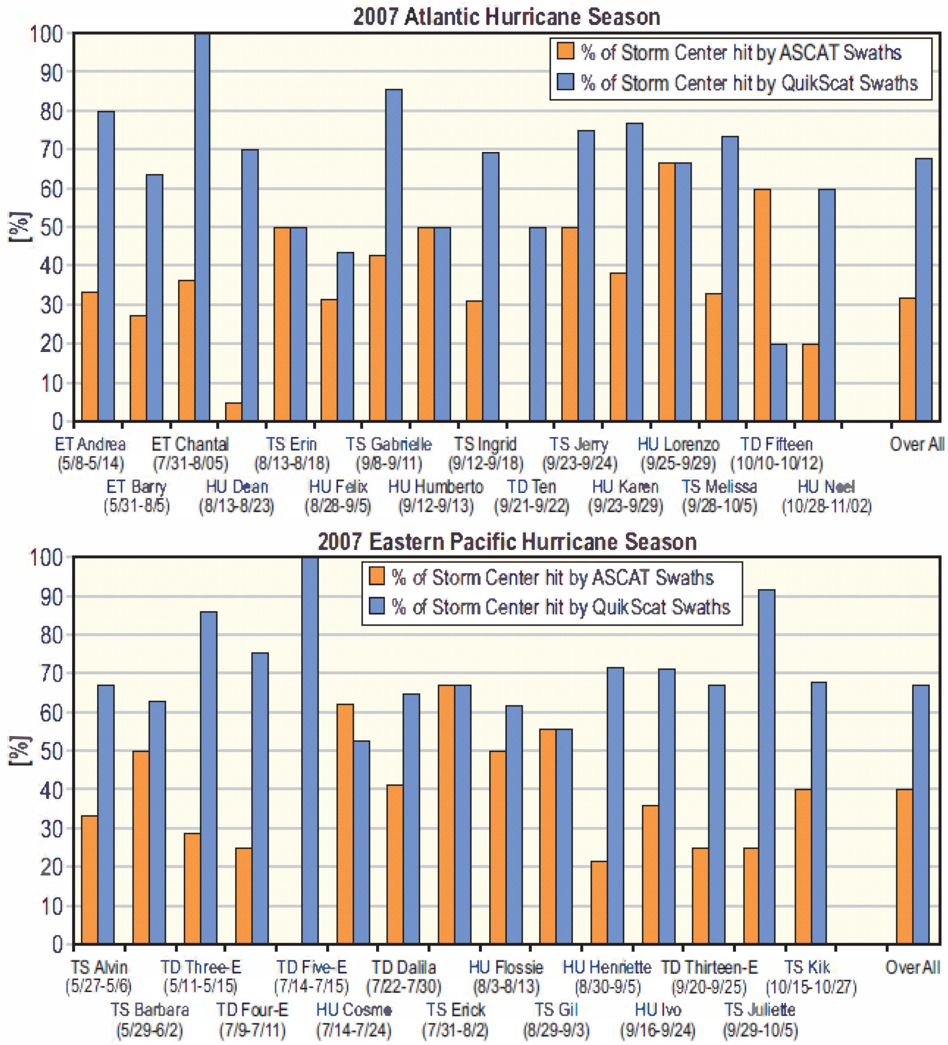

Figure 1. Percentage of 3 hr time intervals in which the center of named storms was observed with either QuikScat (blue) or ASCAT (orange) polar-orbiting scatterometers during the 2007 Atlantic (top) and Pacific (bottom) hurricane season. Poor performance results from the coverage gaps and infrequent revisit times that are characteristic of polar-orbiting wide-swath imagers.

• CYGNSS Avionics [Session: 7.07-2013; John Dickinson]

• CYGNSS Mission operations [Session: 12.02-2559; Debi Rose]

2. Wind Observation Forecast Value

The fact that forecast improvements in TC intensity have lagged so far behind those of TC track suggests that the deficiency lies somewhere other than proper observations and modeling of the mesoscale and synoptic environment. CYGNSS will attempt to resolve the principle deficiency with current TC intensity forecasts, which lies in inadequate observations and modeling of the storm's 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 TC life cycle are poorly sampled in time by conventional polar orbiting, wide-swath imagers. CYGNSS is specifically designed to address these two limitations.

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.

Mesoscale Convective Systems (MCSs) contribute more than half of the total rainfall in the tropics and serve as

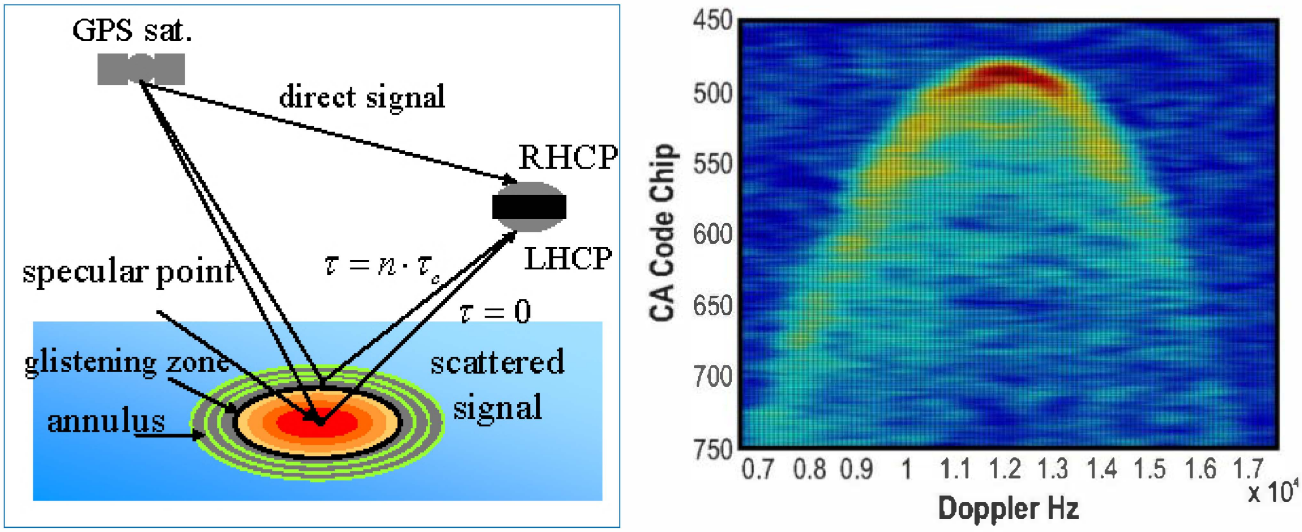

Figure 2. (left) GPS signal propagation and scattering geometries for ocean surface bistatic quasi-specular scatterometry. (right) Spatial distribution of the ocean surface scattering measured by the UK-DMC-1 demonstration spaceborne mission – referred to as the Delay Doppler Map [5].

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.

The Value of Frequent Wind Observations. Most current spaceborne active and passive microwave instruments are in polar low earth orbits (LEOs). The orbits maximize global coverage but can result in large gaps in the tropics. Schlax et al. (2001) present a comprehensive analysis of the sampling characteristics of conventional polar-orbiting, swath-based imaging systems, including consideration of so-called tandem missions [6]. The study demonstrates that a single, broad-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, Fig. 1 shows the percentage of times 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.

3. Measurement Methodology

Fig. 2 (left) 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 a RHCP polarized 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 polarized 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 (right). 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-right) 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-right). 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].

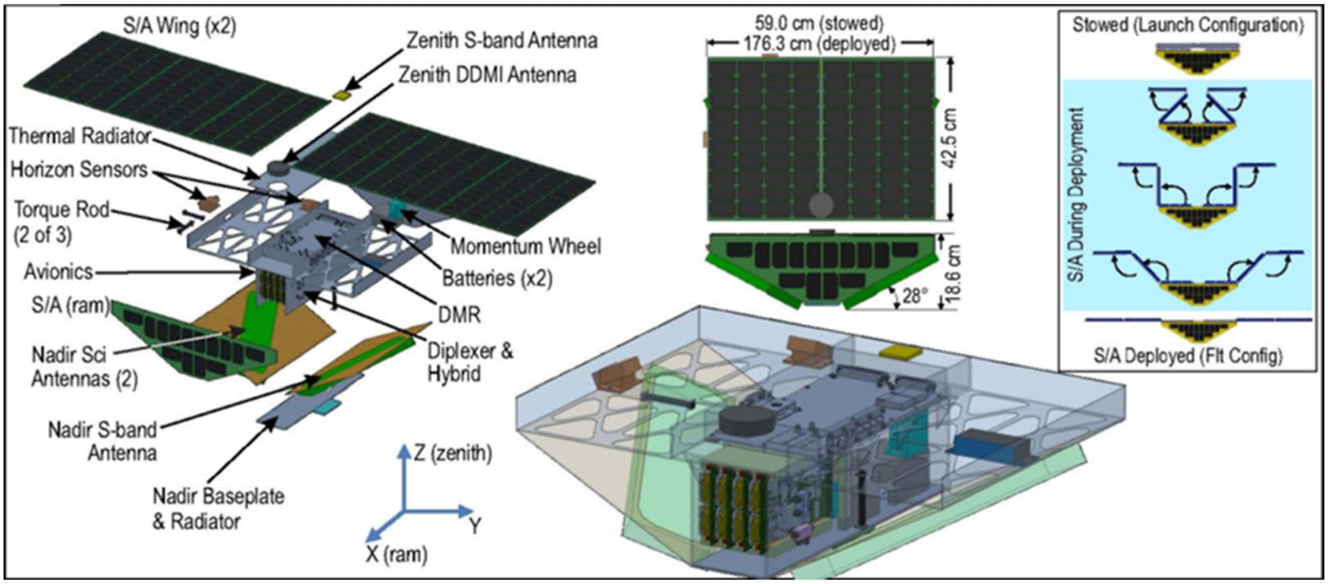

Figure 3. The CYGNSS Observatory. The exploded view shows individual subsystems, including the science payload's Delay Doppler Mapping Imager (DDMI) antennas and receiver electronics (DMR). Solar Array deployment, performed after ejection from the launch deployment module, is illustrated in the insert. .

4. SPACECRAFT CONSTELLATION

Fig. 3 shows details for one of the eight CYGNSS observatories. Included are all of the spacecraft support subsystems (e.g. avionics, power and communication) as well as the science payload. Fig. 4 illustrates the CYGNSS constellation concept. Eight observatories are positioned in low inclination (35^o) low earth (500 km altitude) orbit. Each of them simultaneously samples quasi-specular scattered signals from up to four available GPS transmitters. The resulting spatial and temporal sampling properties can provide excellent sampling of evolving TCs. This is illustrated by the following example.

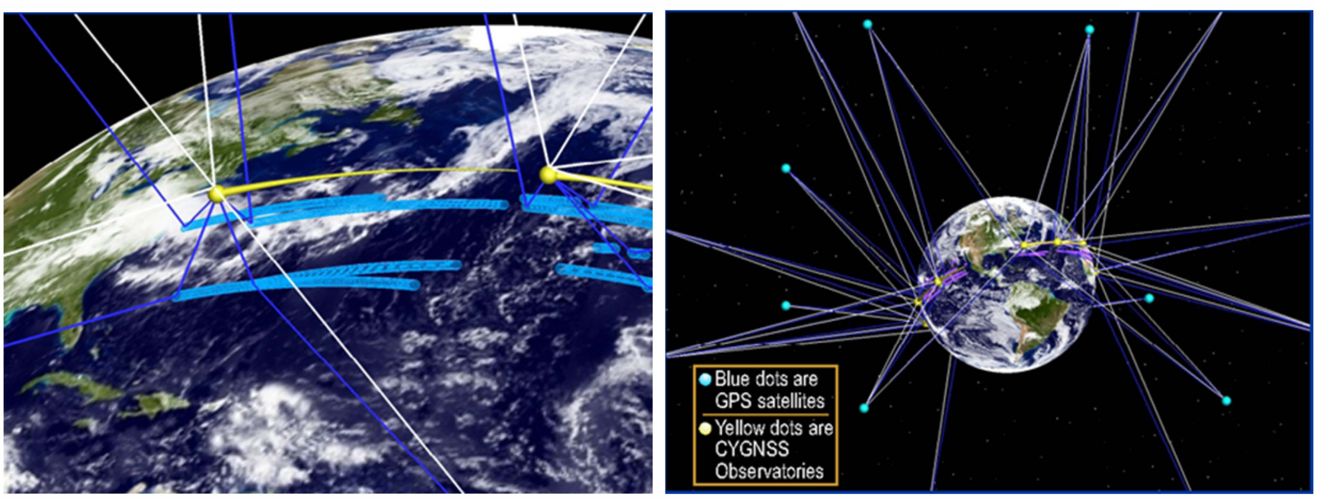

Figure 4. The CYGNSS Constellation. (top) The CYGNSS observatories are shown as yellow spheres. The white lines represent direct GPS signals and the blue ocean surface scattered signals. The lighter blue circles on the earth surface represent individual samples of the Delay Doppler Map. (bottom) The full constellation of GPS transmitters and CYGNSS receivers in the bistatic radar constellation are shown. .

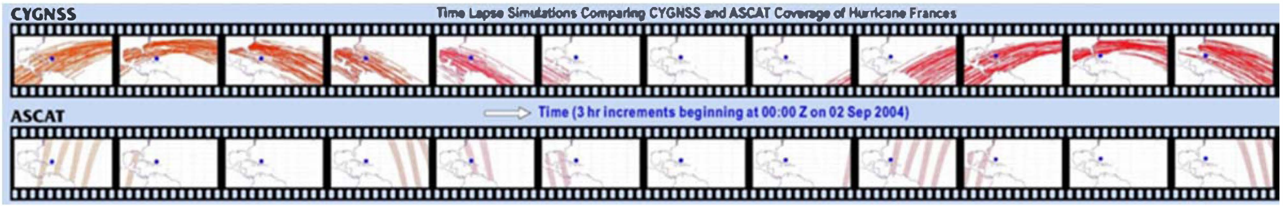

Figure 5. Time lapse simulation comparing the spatial and temporal sampling properties of CYGNSS and ASCAT, if they had both been in orbit during the Hurricane Frances U.S. landfall on 2 Sep 2004

5. 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. 5. The simulation was created by projecting satellite coverage models for each mission onto the archival storm track record for Frances. Each frame represents all samples taken within a 3 hour intervals. 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 hr, and the mean revisit time will be 1.5 hr.

6. Summary

The Cyclone Global Navigation Satellite System (CYGNSS) goal is to understand the coupling between ocean surface properties, moist atmospheric thermodynamics, radiation, and convective dynamics in the inner core of Tropical Cyclones (TCs). Our goal directly supports the NASA strategic objective to enable improved predictive capability for weather and extreme weather events. Near-surface winds are major contributors to and indicators of momentum and energy fluxes at the air/sea interface. Understanding the coupling between the surface winds and the moist atmosphere within the TC inner core is key to properly modeling and forecasting its genesis and intensification. Of particular interest is the lack of significant improvement in storm intensity forecasts over the past two decades, relative to forecasts of storm track.

Advances in track forecast have resulted in large part from the improvements that have been made in observations and modeling of the mesoscale and synoptic environment surrounding a TC. We hypothesize that the lack of an accompanying improvement in intensity forecast is largely due to a lack of observations and proper modeling of the TC 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 TC life cycle are poorly sampled by conventional polar-orbiting, wide-swath imagers. CYGNSS addresses these two limitations by combining the all-weather performance of GPS-based bistatic scatterometry with the spatial and temporal sampling properties of a constellation of observatories. The constellation consists of individual GPS surface reflection receivers flown on 8 micro-satellites. This provides the ability to measure the ocean surface winds with unprecedented temporal resolution and spatial coverage under all precipitating conditions, up to and including those experienced in the hurricane eyewall.

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BIOGRAPHIES

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.*

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