The NASA CYGNSS Mission; A Pathfinder for GNSS Scatterometry Remote Sensing Applications

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ABSTRACT

Global Navigation Satellite System (GNSS) based scatterometry offers breakthrough opportunities for wave, wind, ice, and soil moisture remote sensing. Recent developments in electronics and nano-satellite technologies combined with modeling techniques developed over the past 20 years are enabling a new class of remote sensing capabilities that present more cost effective solutions to existing problems while opening new applications of Earth remote sensing. Key information about the ocean and global climate is hidden from existing space borne observatories because of the frequency band in which they operate. Using GNSS-based bi-static scatterometry performed by a constellation of micro-satellites offers remote sensing of ocean wave, wind, and ice data with unprecedented temporal resolution and spatial coverage across the full dynamic range of ocean wind speeds in all precipitating conditions.

The NASA Cyclone Global Navigation Satellite System (CYGNSS) is a space borne mission being developed to study tropical cyclone inner core processes. CYGNSS consists of 8 GPS bi-static radar receivers to be deployed on separate micro-satellites in October 2016. CYGNSS will provide data to address what are thought to be the principle deficiencies with current tropical cyclone intensity forecasts: 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 tropical cyclone life cycle are poorly sampled in time by conventional polar-orbiting, wide-swath surface wind imagers.

It is anticipated that numerous additional Earth science applications can also benefit from the cost effective high spatial and temporal sampling capabilities of GNSS remote sensing. These applications include monitoring of rough and dangerous sea states, global observations of sea ice cover and extent, meso-scale ocean circulation studies, and near surface soil moisture observations. This presentation provides a primer for GNSS based scatterometry, an overview of NASA's CYGNSS mission and its expected performance, as well as a summary of possible other GNSS based remote sensing applications.

1. INTRODUCTION

Electromagnetic radiation scattered by the ocean surface contains information about the sea surface state and its altimetric height. Previous radar based ocean altimetry and wind remote sensing missions rely on this general principle, but they all utilize actively transmitted radar pulses to detect the backscattered reflection. Global Navigation Satellite System reflectometry (GNSS-R) however, utilizes reflections from GNSS signals to sense the ocean altitude and state. This passive approach was demonstrated successfully on-orbit during the 2003 UK-DMC-1 mission(Gleason, 2007). The fundamental measurement made during each quasi-specular reflection contact between a GNSS transmitter and the GNSS-R receiver is the areal increase of scattering due to ocean surface roughness. A perfectly smooth surface reflects a specular point while a rough surface scatters it across a distributed “glistening zone”. The Delay Doppler Map (DDM) created by the GNSS-R instrument is an image of that scattering cross-section in the time and frequency domains across the glistening zone. The DDM is an information-rich data set of surface state statistics. When this measurement is obtained from the ocean's surface, the data is intimately related to the surface wind vector and providing a direct measurement of the wave height statistics.

NASA’s most recently awarded Earth science mission, the NASA EVM-1 Cyclone Global Navigation Satellite System (CYGNSS), uses GNSS-R to provide data that will enable study of the relationship between ocean surface properties, moist atmospheric thermodynamics, radiation and convective dynamics. These relationships are postulated to be intrinsic

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to the genesis and intensification of tropic storms. Key information about the ocean surface under and around a tropic storm is hidden from existing space borne observatories because of the frequency band in which they operate. Using GNSS-based bi-static scatterometry performed by a constellation of micro-satellites offers remote sensing of ocean wave and wind with unprecedented temporal resolution and spatial coverage across the full dynamic range of ocean wind speeds in all precipitating conditions. A better understanding of these relationships and their effects will advance tropical storm intensity and storm surge forecast skill.

Investigation of these properties has not been previously possible due to technology and on-orbit asset cost limitations. Modeling techniques developed over the past 20 years combined with recent developments in nano-satellite technology has enabled the CYGNSS mission. CYGNSS consists of 8 GPS bi-static radar receivers to be deployed on 8 separate micro-satellites in October 2016.

While ocean wind and wave characteristics have been demonstrated using GNSS-R, research as indicated that the technique could be useful in a number of other applications as well. These applications include monitoring of rough and dangerous sea states, global observations of sea ice cover and extent, meso-scale ocean circulation studies, and near surface soil moisture observations.

2. GNSS-R TECHNOLOGY BASIS

When electromagnetic radiation is reflected by the ocean surface, the wave scattering process changes the characteristics of the propagating signal in a way that is dependent on the characteristics of the reflecting surface. These changes contain information on the sea surface waves and indirectly on the near-surface meteorological conditions. Most radar-based ocean remote sensing is founded on this general principle, but generally use actively transmitted radar pulses and then detect the received power of the backscattered radiation. The power and volume accommodations required for these instruments significantly drive costs of these observatories. An alternative signal source using Earth reflected GNSS signals as a means of sensing the ocean surface was proposed in 1988 (Hall, et al., 1988) (Reference Figure 1). Researchers developed this sensing technique during airborne experiments (Katzberg, et al., 2006) and subsequently used data from the GNSS-R experiment on the UK-DMC satellite (Figure 2) to demonstrate that signal retrievals of sufficient signal-to-noise ratio could be used to perform successful ocean wave and wind estimation (Gleason, et al., 2005) (Gleason, et al., 2009) (Clarizia, et al., 2009). Research performed by the CYGNSS mission indicates that it is possible to detect reflected GNSS signals from space across the full range of ocean surface wind and wave conditions using a relatively modest instrument configuration. This enables an alternative to active sensing ocean remote sensing using bi-statically reflected signals transmitted from global navigation satellites.

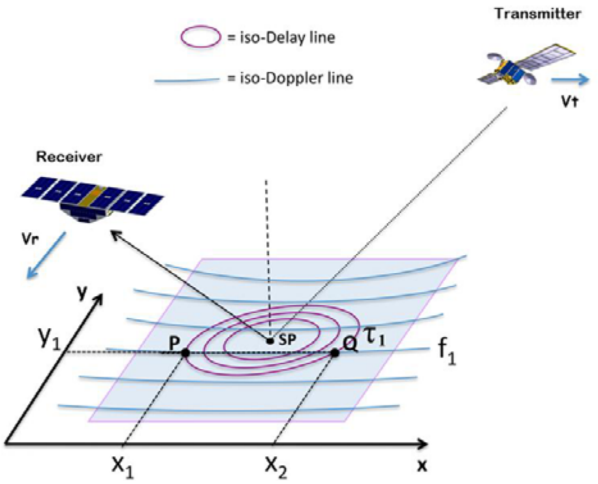

Figure 1 - Geometry of a GNSS-R Measurement of the Delay Doppler Map (DDM)

Figure 1 illustrates the propagation and scattering geometries associated with the GNSS approach to surface scatterometry. The direct GPS signal provides a coherent reference for the coded GPS signal. The quasi-specular forward scattered signal from the Earth surface is received by an antenna on the nadir side of the spacecraft. The scattered signal contains signal lag and frequency shift, the two coordinates of the DDM image, the measurement of which enable the spatial distribution of the scattering cross section to be resolved (Gleason, et al., 2005)(Gleason, 2007). In the case of ocean surface GNSS scatterometry, estimation of the ocean surface roughness and near-surface wind speed is possible from two different properties of the DDM. The maximum scattering cross-section (the dark red region in Fig. 2) and the shape of the scattering arc (the red and yellow regions in Fig. 2). Use of the maximum scattering cross-section requires absolute calibration of the DDM while use of the scattering arc only requires relative calibration of the DDM. The arc approach imposes more relaxed requirements on instrument calibration and stability than does the analysis of the scattering cross-section. However, the arc 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 (Gleason, 2007).

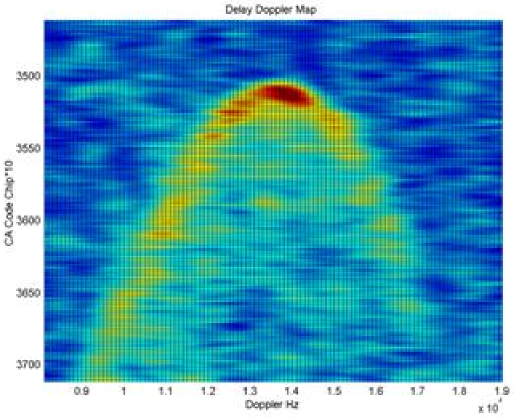

Figure 2 - Spaceborne Empirical Demonstration of Ocean Wind Speed Retrievals by GNSS-R (10m/s)

3. CYGNSS SCIENCE AND PERFORMANCE

There has been essentially no improvement in the accuracy of Tropical Cyclone (TC) intensity forecasts since 1990 while in that same period TC track forecast skill has improved by ~50%. This fact is widely recognized not only by national research institutions(Foundation, 2007)(Administration, 2008) but by the popular press as well(Borenstein, et al., 2011). TC track forecast skill improvement is thought to be linked to modeling improvements of the mesoscale and synoptic environment facilitated by observations from polar orbiting remote sensing assets. These assets are designed to provide global coverage with temporal resolution on the order of days. They do not though provide adequate observation of the TC inner core. The inadequacy in observations results from two causes: 1) Much of the TC's inner core ocean surface is obscured from conventional remote sensing instruments by the storm's intense precipitation. 2) The rapidly evolving (genesis and intensification) stages of the TC life cycle have temporal features on the order of hours, not days.

3.1 Wind Observations in Precipitating Conditions

Previous spaceborne measurements of ocean surface vector winds made by observatories such as QuikScat have suffered from degradation in highly precipitating regimes. As a result, the accuracy of wind speed estimates in the inner core of the TC is often highly compromised. Figure 3 provides the one-way slant path atmospheric attenuation experienced by a GNSS, ASCAT and QuikScat signal as a function of surface precipitation rate. Precipitation has a negligibly small effect on the GNSS signal, even at the highest rain rates. The ASCAT measurement is attenuated enough at the highest rain rates to severely impact its ability to retrieve surface winds under the TC while QuikScat signals are effectively blocked by heavy rain and cannot sense the surface at all.

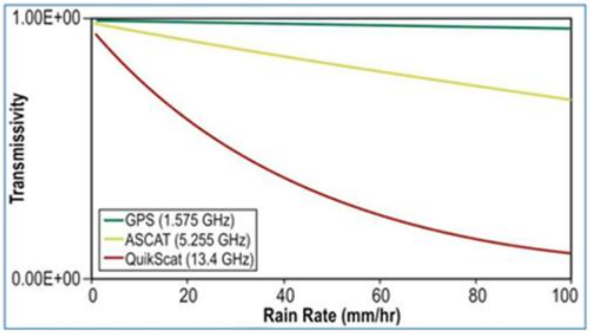

Figure 3 - One-Way Slant Path Atmospheric Attenuation Experienced by a GNSS (green), ASCAT (yellow) and QuikScat (red) Signal

3.2 Temporal Resolution Necessary for TC Wind Observations

Most current spaceborne active and passive microwave instruments are in polar low earth orbits. The orbits maximize global coverage but can result in large tropical coverage gaps(Schlax, et al., 2001). The irregular and infrequent revisit times (ca. 11-35 hrs) of these observatories are likewise not sufficient to resolve synoptic scale temporal variability associated with TCs. Missed TC core imaging events can occur when an organized system passes through a conventional observatory's coverage gap or when its motion is appropriately offset from the motion of the observatory's swath. The much wider and more dispersed effective swath of a micro-satellite GNNS-R 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.

4. CYGNSS FLIGHT SEGMENT IMPLEMENTATION

Implementation of the CYGNSS mission involves eight simple nadir-pointed micro-satellite Observatories, each hosting a GPS scatterometry instrument. Use of GPS L-band frequencies enables measurement in precipitation well beyond that found in the most severe tropic cyclones. The instruments create images representative of the Earth ocean surface roughness and pass this data via digital interfaces to the micro-satellite for compression, data storage, and downlink. The images are processed on the ground to retrieve corresponding wind field information. Required coverage of the historically active tropical cyclone area is provided by 8 Observatories loosely dispersed about a 500km, 35° circular orbit. The full flight segment includes the 8 Observatories and a Deployment Module used to carry the constellation during launch and properly deploy them after orbit insertion is complete.

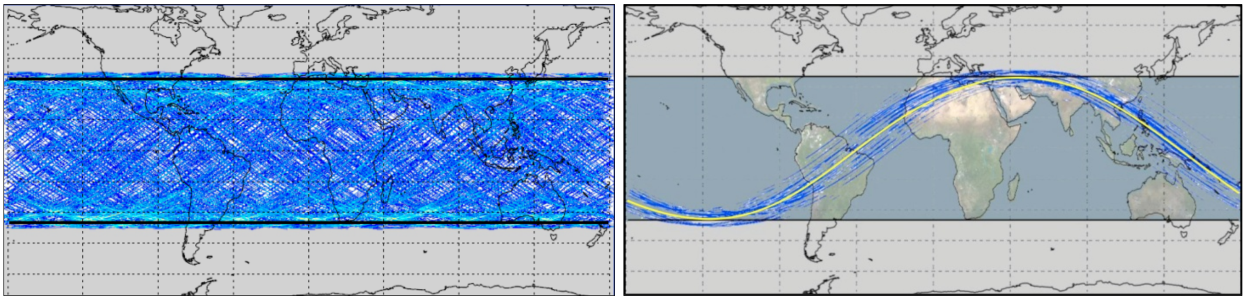

Figure 4 - CYGNSS Constellation Coverage, Left 24hr, Right 1.5hr

4.1 Delay Doppler Mapping Instrument

CYGNSS accomplishes its science goal using a Delay Doppler Mapping Instrument (DDMI) on each Observatory. The CYGNSS DDMI uses Surrey's GNSS Receiver-Remote Sensing Instrument (SGR-ReSI), an upgraded version of the UK-DMC-1 instrument that flew in 2003. The upgrades leverage recent advances in microelectronics that include a new GPS front end MMIC receiver and the addition of a digital signal processing back end. The new front end improves noise performance, adds internal calibration, and raises the digital sample rate. The new back end adds more on-board processing capacity in order to raise the duty cycle of science operations.

In total, the DDMI consists of the Delay Mapping Receiver (DMR) electronics unit, two nadir-pointing antennas for collecting reflected GNSS signals, and a zenith-facing antenna to provide a coherent reference for the coded GPS signal plus space-geolocation capability (Reference Figure 5).

DDMI onboard processing generates the GPS DDMs. Each pixel of the DDM is obtained by cross-correlation of the received signal with a locally generated replica time delay and Doppler shift. An open-loop tracking algorithm allows each DDM to be processed by predicting the position of the specular reflection point from the known positions of the receiver (i.e. the CYGNSS Observatory) and GPS transmitter (i.e. the GPS spacecraft). Each DDM has 128 delay pixels with resolution of 61 ns. The Doppler resolution is 250 Hz over a ±6.5 kHz range, resulting in 52 Doppler pixels.

Available hardware resources allow generation of four simultaneous DDMs. The output data rate is determined by onboard coherent and incoherent integration. The coherent (complex signal) integration time is limited to 1 ms by the rate of change of the propagation geometry due to receiver motion. Individual complex DDMs are then incoherently integrated (magnitude only) for 1 s to form the final DDM. Incoherent integration reduces noise due to speckle and improves the signal-to-noise ratio (SNR). The incoherent integration time is limited to 1 s due to the degradation in spatial resolution caused by along-track smearing.

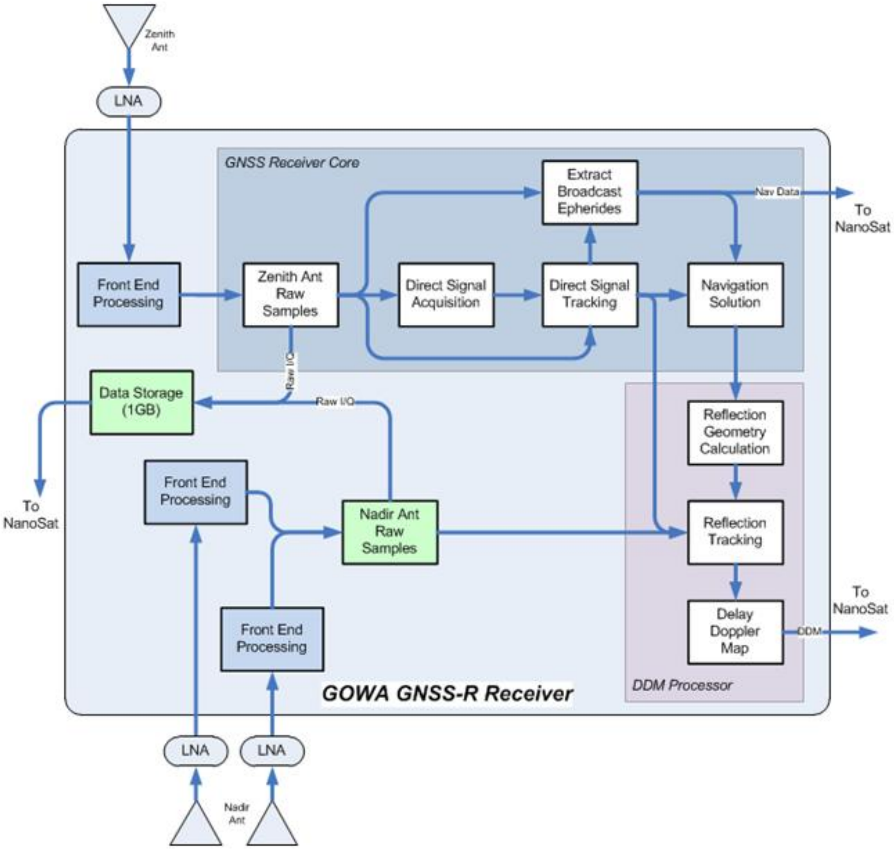

Figure 5 - CYGNSS Delay Doppler Map Instrument Architecture

4.2 Micro-satellite

The CYGNSS Observatory is based on a single-string hardware architecture with functional and selective redundancy included for critical areas (Reference Figure 6).

Structure—The micro-satellite structure requirements are driven by physical accommodation of the DDMI antennas, the Solar Arrays (S/As), and launch configuration constraints. The micro-satellite's shape is specifically configured to allow clear nadir and zenith FOV for the DDMI antennas, while its structure integrates the micro-satellite and instrument electronic boards by creating an avionics bay and accommodating the Delay Mapping Receiver (DMR) housing. The avionics bay forms the core of the micro-satellite; 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 micro-satellite primary structure's nadir baseplate is the DM mechanical interface for launch. See Figure 7 for an exploded view of the CYGNSS Observatory.

Mechanisms—Observatory mechanisms are limited to heritage solar array (S/A) deployment devices and 3-axis reaction wheels. The four "z-fold" S/A panels perform a one-time deployment into a permanently locked position planar along the zenith side of the Observatory. The S/As are held in place for launch using a cup/cone interface and deployed by a combination of actuators and single-axis spring-loaded hinges.

Thermal—The CYGNSS Observatory thermal design meets requirements to maintain all components within their temperature limits during all operational modes. 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 minimize the need for supplemental heaters except for Standby/Safe Hold operations. 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.

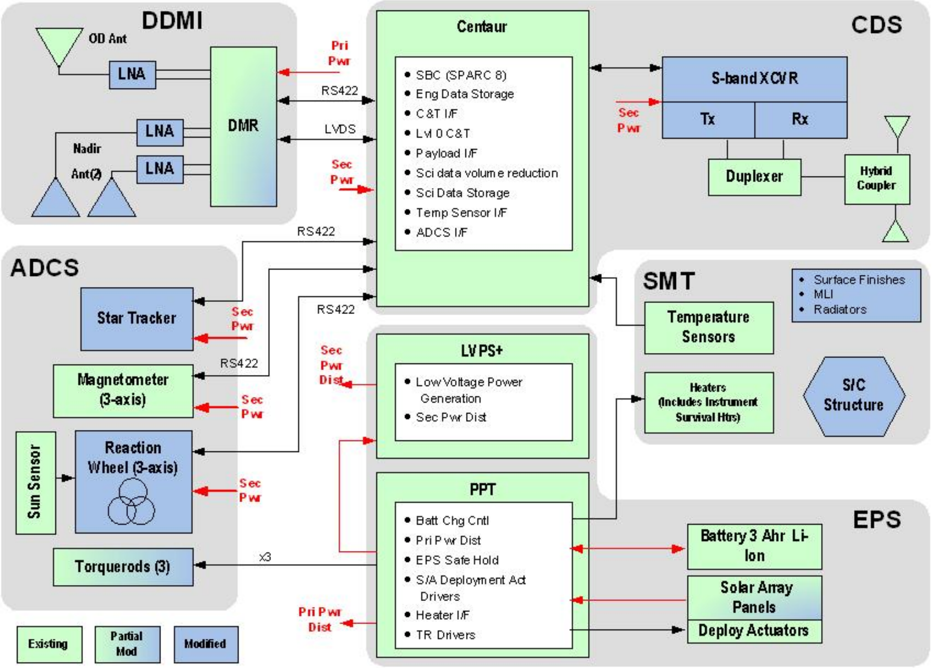

Figure 6 - CYGNSS Observatory Functional Block Diagram

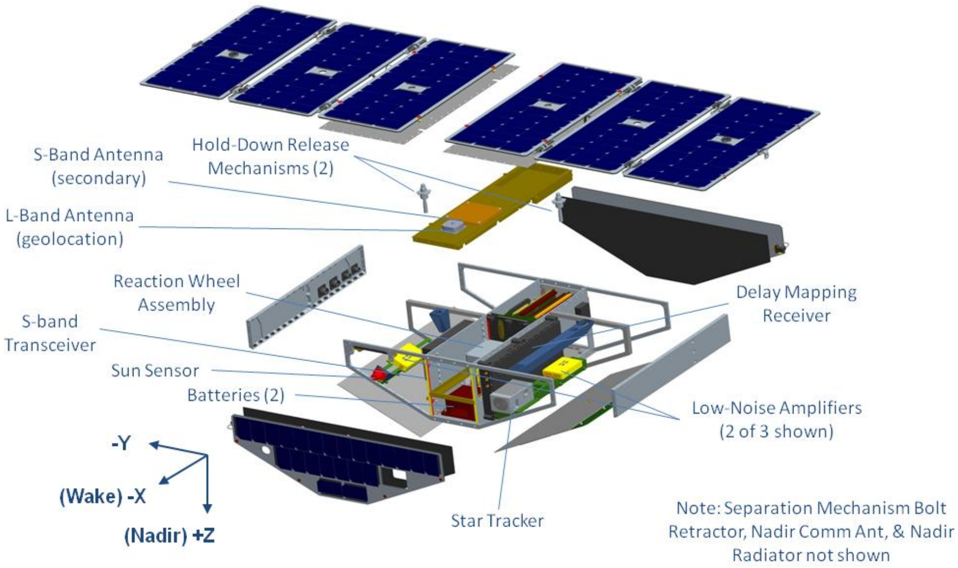

Figure 7 - CYGNS Observatory Mechanical Configuration (Exploded)

Electrical Power Subsystem (EPS)—The EPS is designed to perform battery charging without interrupting science data acquisition. It is based on a 28±4 Vdc primary power bus with electrical power generated by an 8-panel rigid S/A. When stowed, the z-fold design of the S/A allows the solar cells to face outward, to power the micro-satellite indefinitely in Safe mode before S/A deployment.

Electrical power storage for eclipse operations is provided by a 4.5 A-hr Li-ion battery connected directly to the primary power bus. Battery charging uses a constant current, voltage-temperature limited charge scheme. The primary power bus voltage is modulated to maintain charge current and termination voltage. Battery charge regulation for the CYGNSS EPS is a peak power tracking (PPT) type regulator. The PPT 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 EPS battery charging and power distribution hardware operates independent of flight software (FSW) except for configuration commanding and status reporting.

Communications and Data Subsystem (CDS)—The CDS meets the requirements of the CYGNSS Observatory on-board data handling and command and telemetry (C&T) communication link. All on-board micro-satellite processing is performed by the CDS computer. The computer includes the necessary functionality for the CCSDS compliant C&T interface, instrument data interface, and ADCS interface. The simple operational nature of the DDMI and science profile allows the CDS to be designed for autonomous control during all normal science and communication operation.

The flight software Telemetry Manager provides collection and high-level formatting of the science and housekeeping data. These data are either downlinked in real-time or passed to the flight software based 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 on-board memory is capable of holding >10 days of CYGNSS science and housekeeping telemetry.

S-band communication links are provided to uplink command sets and downlink science and housekeeping data. These links use two fixed omni-directional micro-strip patch antennas, one on the nadir baseplate and one on the zenith panel, to provide near 4π sr communications without interrupting science operations.

Attitude Determination and Control Subsystem (ADCS)—The CYGNSS ADCS is a star tracker and magnetometer based, 3-axis reaction wheel design with torque rods for wheel momentum desaturation). Maneuverability is limited to recovering from the Deployment Module separation tip-off rates, performance of a sun referenced Safe mode, and local vertical/local horizontal pointing that includes nadir for Science operations and a high drag, torque equilibrium attitude for orbit maintenance.

5. BEYOND TROPICAL CYCLONES

In addition to sensing ocean surface winds, it is also possible to use GNSS R in other applications. One such application is to exploit the inherent coupling of ocean sea surface conditions and winds to monitor maritime surface conditions in general. This data can be used locally for small craft advisories and regionally to direct shipping lanes in the most efficient manner. Other applications of GNSS altimetry and scatterometry include the investigation of convective dynamics in the Madden-Julian Oscillation, the understanding of air/sea momentum, heat, and moisture fluxes, ice edge sensing (Komjathy, et al., 2000)(Zavorotny, 2005)(Belmonte, et al., 2005), soil moisture (Masters, 2004)(Katzberg, et al., 2005), vegetation sensing (Long, et al., 2000), and when fused with other data sources, the potential for tsunami detection/warning (Stosius, 2010), avalanche monitoring, and landslide prediction.

***Sea Surface Height and Ocean Currents*—**Recent altimetry observatories such as Jason and GFO provide 100-300 km spatial resolution of topographic features with temporal resolution measured in days. These spatial and temporal measurement scales are not sufficient to study mesoscale ocean eddies. Mesoscale eddies represent one of the largest global climate modeling errors and also play an important role in the transport of momentum, heat, salt, nutrients, and other chemical properties of the ocean. A constellation using GNSS based altimetry could directly addresses this need with spatial resolution of 25 km, temporal resolution of <12 hours, and measurement accuracies comparable to previous missions, thus enabling measurement of mesoscale eddy processes.

***Ice monitoring*—**It has been demonstrated that scatterometers, such as the SeaWinds instrument, can be used to remotely sense ice, including tracking icebergs and monitoring ice shelve structures (Long, 2000). Using the UK-DMC GPS experiment, reflected signals have been detected off sea ice (Gleason, 2007) and from ice shelves. Using the reflected signal's carrier phase coherency combined with its variation in received magnitude, delay, and frequency spreading, it has been shown that it is possible to measure ice surface characteristics such as the total ice concentration, ice cover and possibly the ice thickness (Zavorotny, 2005)(Belmonte, et al., 2005).

***Land Surface Measurements*—**The UK-DMC data set includes land data collections that demonstrate reflections from land surfaces provide a relatively clear signal that is suspected to be related to surface characteristics including; the small scale roughness (ground coverage such as fields or forests), medium size features (such as buildings), large gradual changes in terrain (rolling hills for example) and the surface cover (such as rain or snow)(Gleason, 2007). Existing space-based scatterometers have had some success in separating these effects and identifying surface vegetation (Long, et al., 2000). While present levels of research are not conclusive what the signals detected from land are dependent on, it has been demonstrated that the signals do vary significantly from different terrain and that the signals are obviously responding to visible surface features. Given the signal attenuation characteristics of GNSS signal, it is clear that further research of data sets made available by CYGNSS should yield several useful remote sensing capabilities for land monitoring.

***Data Fusion*—**Recent research indicates that GNSS altimetry and scatterometry has strong potential to provide low cost monitoring of the ocean and land surfaces. The application of the resultant data sets hold further potential for expansion when fusion with other date sources is considered. Several researchers have proposed the use of GNSS altimetry for tsunami detection. Given the height profile of tsunami in deep open ocean is approximately 20cm swells, use of GNSS altimetry alone is unlikely to be able to warn of impending danger. When this data is combined with the knowledge of geologic events likely to create tsunami, focused data processing is much more likely to identify the phenomena associated with the tsunami, thus allowing much more accurate warnings. This same principle of data fusion can also be applied for ice and soil moisture monitoring. When combined with a priori knowledge of geographic structures prone to avalanche and mud slides, the GNSS altimetry and scatterometry data set might be exploited for predicting these events as well.

6. CONCLUSION

Research has indicated that GNSS remote sensing has the potential to give environmental scientists a low-cost, wide-coverage measurement network that will greatly increase our knowledge of the Earth's environmental processes. NASA's CYGNSS mission represents the pathfinder in this technology regime. While applications beyond sea surface and wind monitoring require further research, it is clear that GNSS altimetry and scatterometry hold excellent potential for providing cost effective monitoring techniques if research such as that enabled by the CYGNSS mission is applied.

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