ABSTRACT

Advancements in electronics and nano-satellite technologies combined with recent modeling development 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. Increased temporal sampling on both a global and macroscale is one such example of capability increase enabled by nano- and micro-satellites. NASA's CYclone Global Navigation Satellite System (CYGNSS), recently launched and commissioned, uses passive GNSS-based bi-static scatterometry and a 8-spacecraft constellation to provide breakthrough remote sensing of ocean wave and wind data with unprecedented temporal resolution across the full dynamic range of ocean wind speeds in all precipitating conditions. 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.

Numerous additional Earth remote sensing 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 paper provides a summary of early CYGNSS performance and a primer of other GNSS scatterometry based remote sensing applications.

INTRODUCTION

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%. [1] [2] 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 observatories. These assets are designed to provide global coverage with temporal resolution on the order of days. However, they do not provide adequate observation of the TC inner core due to two causes: 1) the rapidly evolving (genesis and intensification) stages of the TC life cycle have temporal features on the order of hours, not days and 2) much of the TC's inner core ocean surface is obscured from conventional remote sensing instruments by the storm's intense precipitation. Key information about the ocean surface under and around a tropic storm is hidden from existing space borne observatories because of the frequency bands in which their sensors operate. Performance requirements and available technology of existing space-based ocean surface wind observatories use active C and Ku-band radar-based instruments. There are many disadvantages of this technique, including:

- These types of instruments require large aperture antennas and significant power resources for pulse transmission;
- The rapidly evolving (genesis and intensification) stages of the TC life cycle are poorly sampled in time by conventional polar orbiting, wide-swath observatories; and
- Costs for these observatories, both for development and launch, are prohibitive for the multi-vehicle constellations necessary to fill the temporal coverage gaps;
Much of the inner core ocean surface is obscured from conventional wind remote sensing observatories by intense precipitation in the eye wall and inner rain bands due to significant signal attenuation of the C and Ku-band signals.

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. This is known as a monostatic backscatter radar system and can only provide measurements along a single ground track. Global Navigation Satellite System reflectometry (GNSS-R) however, utilizes reflections from GNSS signals to create a non-cooperative bistatic radar of opportunity providing measurements along multiple widely spaced ground tracks by acquiring multiple signals simultaneously from different GNSS satellites. Since the GNSS-R does not transmit the source signal, it requires much less volume and power than traditional monostatic radar instruments and thereby enables its use in micro-satellite applications.

Measuring the temporal delay between the direct GNSS signal and the reflected one from the Earth’s surface allows the GNSS bistatic radar to function as an altimeter. Adding the measurement of the scattered GNSS signal peak power and widening its waveform enables the retrieval from these parameters the surface roughness and dielectric properties of the probed media thus making the GNSS bistatic radar a multi-beam scatterometer. When operating as a scatterometer, 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 (Reference Figure 1) providing an information-rich data set of surface state statistics. Similar to traditional radar remote sensing, the GNSS-R technique can be applied to remote sensing of various types of natural covers, such as ocean, land, ice, snow, vegetation. The GNSS signals reside at frequencies in the L-band. Not only is L-band wavelength capable of penetrating cloud cover and heavy precipitation, it is particularly sensitive to soil moisture, sea-ice salinity and snow water content. 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.

![Figure 1 -- GNSS-based bi-static scatterometry geometries depicting measurement of signal time delay and frequency shift](image)

NASA's CYclone Global Navigation Satellite System (CYGNSS) mission exploits the all-weather performance of GNSS bi-static ocean surface scatterometry combined with the sampling properties of a multi-satellite constellation to provide science measurements never before available to the tropical cyclone operational and research communities. CYGNSS, NASA's 1st Earth Venture mission, was launched 15-Dec-2017, successfully completed commissioning activities 23-Mar-2017, and is presently in Science operations. It is an 8-observatory constellation of micro-satellites designed to measure the ocean surface wind field with spatial coverage comparable to conventional scatterometers and unprecedented temporal resolution, under all precipitating conditions, and over the full dynamic range of wind speeds experienced in a TC. This data will serve to improve study of the relationship between ocean surface properties, moist atmospheric thermodynamics, radiation and convective dynamics as these relationships are postulated to be intrinsic to the genesis and intensification of tropic storms. [2]

**CYGNSS MISSION OVERVIEW**

Tropical cyclone (TC) track forecasts have improved in accuracy by ~50% since 1990 as illustrated in Figure 2, largely as a result of improved mesoscale and synoptic modeling and data assimilation. [2] This improvement has been made possible largely through the availability of space borne ocean altimetry and wind observatories operating in near-polar low-Earth orbit. These observatories are designed to provide maximized global coverage and high precision altimetry data for large-
scale topographic studies which have demonstrated a close relationship between measurement of large-scale Earth phenomena and TC track forecast skills.

Figure 2 – National Hurricane Center Annual Average Track Errors; Atlantic Basin Tropical Cyclones [3]

In that same period since 1990, there has been essentially no improvement in the accuracy of TC intensity forecasts (Reference Figure 3). This is widely recognized not only by national research institutions [1] [2] but also by the general public as recently demonstrated during Hurricanes Katrina, Irene, and Sandy. 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. Review of dataset gaps lead researchers to conclude TC intensity forecasts are tied to local conditions in and around the TC as it develops.

Near-surface winds over the ocean are major contributors to and indicators of momentum and energy fluxes at the air/sea interface. The coupling between the surface winds and the moist atmosphere within a TC are thought to be key in its genesis and intensification.

**CYGNSS Mission Implementation**

Implementation of the CYGNSS mission involves eight nadir-pointed microsatellite Observatories, each hosting a GPS scatterometry instrument. Use of GPS L-band frequencies enables measurement through precipitation found in the most severe tropic cyclones. The instruments create images representative of the ocean surface roughness and pass this data to the microsatellite 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 global regions 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 completion of orbit insertion. Interfaces were provided between the Observatories and Deployment Module to enable pre-launch maintenance and verification as well as to properly implement deployment of the Observatories on-orbit. Communication links between each Observatory and the ground segment during flight operations is via S-band CCSDS spacelinks. Ground segment components for CYGNSS consist of the Universal Space Network (USN) remote antenna sites in Australia, Hawaii, and Chile connected with the USN Network Management Center, the SwRI Mission Operations Center (MOC) located in Boulder, CO, the University of Michigan Science Operations Center (SOC) in Ann Arbor, the NASA Physical Oceanography Distributed Active Archive Center (PO.DACC) and the NASA Robotic Systems Protection Program (RSPP).

**OPERATIONAL OVERVIEW**

Each CYGNSS Observatory collects, processes, and downlinks science and engineering data with no commanding required. Flowing data from each Observatory to the ground segment is the predominant operational activity during the science acquisition mission phase. To streamline operations, the CYGNSS microsatellites are designed to support initiation and completion of ground contacts without any Absolute Time Sequence (ATS) or ground commands. This design supports adding or rescheduling a ground contact by simply coordinating the appropriate ground segment resources.
ATS command loads are generated and uplinked as required to support calibration activities, instrument mode changes, maneuver commanding, and other special case microsatellite or instrument maintenance commanding. As noted previously, there are no ATS commands required to support routine science data collection or ground contacts.

**Flight Segment Element Description**

*Delay Doppler Mapping Instrument – CYGNSS* accomplishes its science goal using a Delay Doppler Mapping Instrument (DDMI) on each Observatory. The CYGNSS DDMI, a block diagram of which is provided in Figure 4, uses Surrey’s off-the-shelf GNSS Receiver-Remote Sensing Instrument (SGR-ReSI), an upgraded version of the original UK-DMC-1 instrument that flew in 2003 used to demonstrate the space-based GNSS-R concept. Instrument 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 electronics improve noise performance, adds internal calibration, and raises the digital sample rate. The new back end processing adds more on-board processing capacity 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 providing space-geolocation capability.

DDMI onboard processing generates maps of GPS signals scattered from the Earth's surface. These are referred to as Delay Doppler Maps (DDMs, reference Figure 5). The coordinates of a DDM are Doppler shift and time delay offset relative to the specular reflection point of the GPS signal. Each pixel of the DDM is obtained by cross-correlation of the received reflected signal with the received direct signal in 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 and velocities of the GPS transmitter (i.e. the GPS spacecraft) and receiver (i.e. the CYGNSS Observatory).

*Microsatellite – The CYGNSS Observatory* is based on a single-string hardware architecture with functional and selective redundancy included for critical areas. It consists of the DDMI and a highly integrated microsatellite. The simple operational nature of the DDMI and science profile allows the microsatellite to be designed for autonomous control during all normal science and communication operations without need of daily on-board command sequences.

![Figure 4 -- CYGNSS Delay Doppler Map Instrument Architecture](image)
The microsatellite is a 3-axis stabilized, nadir pointed vehicle using a star tracker for primary attitude knowledge and a reaction wheel triad for control. Fixed solar arrays, stowed for launch and then deployed soon thereafter provide power to the on-board peak power tracking electronics for battery charging. Communication is provided by an S-band transceiver and low-gain patch antennas to provide near 4π steradian communications without interrupting science operations. The vehicle's structure and thermal design is driven by physical accommodation of the DDMI antennas, the Solar Arrays, and launch configuration constraints.

Microsatellite performance is enabled by key nanosatellite technology, specifically the star tracker and reaction wheels, both provided by Blue Canyon Technologies of Boulder Colorado. The form-factor, mass, and power requirements of these components are well suited for the highly integrated nature of the CYGNSS Observatory. The SwRI avionics, including the flight computer, S-band transceiver, PPT, and low voltage power supply, are based on heritage solutions that have been used on more than 20 previous missions. The avionics leverage recent development in high density microelectronics to achieve a packaging volume of a 3U CubeSat; a 4:1 volume reduction.

Integration of the 8 flight observatories occurred between Aug-2015 and Jan-2016. Environmental testing of the observatories was performed Feb-2016 through Jun-2016 (reference Figure 6 and Figure 7). Integrated flight segment testing (launch configuration) was performed Jul-2016 through Aug-2016 (reference Figure 8) with launch vehicle integration, staging, and launch occurring between Sept-2016 and Dec-2016 (reference Figure 9 and Figure 10).
EARLY CYGNSS SCIENCE RESULTS

"First Light"…

NASA’s Cyclone Global Navigation Satellite System (CYGNSS) constellation of 8 spacecraft made its “first light” measurements of the ocean surface on 04-Jan-2017. The ocean DDM (reference Figure 11) was acquired by constellation spacecraft FM03 at 15:48:31 UTC in the South Atlantic Ocean, east of Brazil. This "first light" DDM provided direct confirmation that the design of the CYGNSS science instrument would perform as projected and that the instrument on FM03 was operational. Of particular note were (1) the fact that the instrument was tracking the GPS "specular point" perfectly as indicated by it being centered in the DDM, and (2) the system background noise was excellent as indicated by the dark blue regions above the specular point.

CYGNSS Satellite Constellation Enters Science Operations Phase…

CYGNSS successfully completed the development and on-orbit commissioning phases of its mission on 23-Mar-2017 and moved into its science operations phase. The observatories were transitioned into science instrument calibration and validation operations. Figure 12 provides a 4 orbit (~6hrs) map of wind speed measurements acquired the CYGNSS FM02 observatory on 14-Feb-2017. The blue values indicate relatively low wind speeds, while the yellow, orange, and red values indicate increasingly higher wind speeds. The highest wind speeds in this image (orange and red) are associated with a powerful extra-tropical cyclone that moved off the East Coast of North America.
CYGNSS Satellite Constellation Begins Public Data Release...

On 22-May-2017, CYGNSS began regular production of its science data products – measurements of ocean surface wind speed and roughness – with public release of these data facilitated by the NASA Physical Oceanography Distributed Active Archive Center (PO.DAAC). The production and distribution was timed to coincide with the beginning of the Atlantic hurricane season on 01-Jun-2017.

Data acquired prior to the public release and subsequently part of the initial public release (reference Figure 13) demonstrated the ability of the CYGNSS constellation to track the development of surface winds in a major storm as demonstrated by measurements made during its flyover of Tropical Cyclone Enawo on 06-Mar-2017, just hours before the storm made landfall over Madagascar. Enawo had maximum sustained winds estimated at 56m/s (125 mph or Cat3) by the Joint Typhoon Warning Center around the time of the CYGNSS overpass, well within the CYGNSS instrument design maximum wind speed sensitivity of beyond 70m/s (Cat5). The satellites’ measurements responded as expected to changes in the wind speed as they approached and passed over the storm center, showing strong and reliable sensitivity throughout. Successive spacecraft in the constellation observed Enawo over a period of several hours just before the TC made landfall on Madagascar, capturing important elements of the size and structure of the storm. [6]

BEYOND TROPICAL CYCLONES

With the successful transition of CYGNSS into science operations, measurement of ocean winds using GNSS-R techniques are becoming a proven commodity. The CYGNSS database is already being exploited by scientists in studies of the inherent coupling of ocean sea surface conditions and winds to monitor maritime surface conditions within the CYGNSS coverage area, convective dynamics in the Madden-Julian Oscillation, as well as the understanding of general air/sea momentum, heat, and moisture flux transfer. While using GNSS-R for ocean surface related science is being well established by CYGNSS, GNSS-R has potential applications well beyond the tropical ocean surface, most of which have only been developed in the last ten years. They include soil moisture and vegetation sensing, snow depth monitoring, sea ice mapping, and when fused with other data sources, the potential for tsunami detection/warning, avalanche monitoring, and landslide prediction.

Altimetry

The first application foreseen for GNSS-R was determination of the sea-surface height using ocean surface altimetry. Given that altimetric measurement principles are general in nature, GNSS-R based altimetry is also valid over any other surface that can reflect enough power to enable precise observables. For GNSS-R, this is typically ocean and ice.

Figure 13 -- These maps show measurements of ocean surface wind speeds made by four of the eight CYGNSS spacecraft on 06-Mar-2017, as Tropical Cyclone Enawo approaches landfall on Madagascar. The times of the measurements are, from top to bottom: 1830, 1930, and 2030 UTC [6]

The product of interest in altimetric applications is the vertical height of the reflecting surface, either in absolute terms (e.g., with respect to the center of the Earth) or in relative terms (e.g., with respect to a given reference surface such as the ellipsoid, geoid, or a well-established spatiotemporal average of the elevation...
surface). Since a GNSS-R observation is representative of a certain area over the surface, the GNSS-R measured surface height is an averaged value across this area. The resulting expected precision corresponding to observations at nadir and integrated for 100 km along orbit track are approximately 15 cm at GPS L1 band[8][9] and 30 cm at GPS L5. [9]

**Soil Moisture and Vegetation**

Permittivity of the reflecting surface in a radar measurement has direct impact on the received power, through the Fresnel reflection coefficient. [10] Furthermore, the permittivity of the soil depends on its moisture content and vegetation cover. [11] Attenuation of the L-band signals limits GNSS-R soil moisture measurements to the upper 1–2 cm layer of the soil. [12] This depth decreases when the soil is covered with dense vegetation due to the reflection power attenuation associated with increasing plant biomass. [14]

Over bare soil, and if the reflection process were perfectly coherent, the ratio between the reflected and the line-of-sight electromagnetic fields would be directly proportional to the Fresnel reflection coefficient, together with a geometric factor due to the longer path trajectory of the reflected signal, and the instrument antenna pattern. Due to incoherent scattering from surface features, the scattered peak power is also a function of the surface roughness and any vegetation canopy. This then requires careful separation of the vegetation, the surface roughness, and the soil moisture effects on the total power received. An implementation of the one such complete processing model that accounts for both coherent and incoherent components of the scattering, soil roughness, and vegetation canopy has been demonstrated with robust results. [13] Furthermore, recent studies using ground-based stations have demonstrated that multi-path reflectometry and interferometric pattern techniques have excellent potential to derive soil moisture measurement [16][13][17][18][19] and vegetation. [20][21] The retrieval error of the bare soil moisture due to surface roughness in these interferometric techniques has been reported in the 3–4% range. [18]

**Snow**

Continental snow is currently being monitored with GNSS-R measurements as it occurs in geodetic GNSS stations. The multi-path reflectometry technique analyzes the interferometric pattern to infer the depth of the snow. The measurement principle is based on the frequency of the interference to measure snow depth variations, [22][23] or on both its frequency and amplitude to solve for snow thickness and equivalent water content. [24][25] The estimated precision of these measurements is at the few cm level.

**Sea Ice**

Because the sea-ice surface can be relatively smooth, especially at its earlier stages of development, L-band signals reflect coherently using phase-delay altimetry. [26][27] Such measurements can be related to the ice thickness or free-board level. The fact that dry snow is essentially transparent for L-band signals makes measurements of sea ice thickness using this technique less contaminated by snow accumulation.

Besides altimetric measurements, GNSS-R has been used to characterize Arctic sea ice permittivity (temperature and brine) and sea-ice surface roughness by analyzing the shape of GPS waveforms and performing model-based comparisons. [28][29] A correlation between the peak power of the GPS returns and RADARSAT backscattered measurements over such surfaces was demonstrated from an aircraft platform [30] with technical feasibility of obtaining sea-ice information from space proven using UK-DMC data. [31]

**Data Fusion**

As discussed above, recent research demonstrates GNSS-R based altimetry and scatterometry measurements have strong potential to provide cost effective monitoring of the ocean and land surfaces. The application of the resultant data sets hold further potential for expansion when fusion with other data sources is considered. Several researchers have proposed the use of GNSS altimetry for tsunami detection. [32] Given the height profile of tsunami in deep open ocean is approximately 20 cm 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-R altimetry and scatterometry data set might be exploited for predicting these events as well.

**CONCLUSION**

Research has indicated that GNSS remote sensing has the potential to provide environmental scientists a cost effective, 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 with additional GNSS-R based missions in various planning stages. While applications beyond sea surface and wind monitoring require further research, it is clear that if research such as that enabled by the CYGNSS mission is applied, GNSS altimetry and scatterometry hold excellent potential for providing cost effective monitoring techniques by themselves and as complemented by other data sources where some cases represent unique opportunities and capabilities that cannot be achieved by existing traditional remote sensing tools.

REFERENCES


