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SCIENCE IMPACTS OF THE NASA CYGNSS MISSION

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ABSTRACT

NASA's Cyclone Global Navigation Satellite System (CYGNSS) constellation of 8 small satellites was launched into low Earth orbit in 2016. The objectives of its initial two year mission were to study how well GPS signals that are reflected from the ocean surface can measure the winds in hurricanes and how well those measurements can improve our ability to forecast them. In the 5+ years it has been in orbit, CYGNSS has accomplished those objectives. It has also significantly expanded the scope of its scientific investigations. GPS signals reflected from the storm-free parts of the ocean as well as the signals reflected from land have also been found to contain valuable information about surface conditions. An overview of the scientific impacts of CYGNSS observations, for hurricane prediction studies and many other applications, are presented.

Index Terms— CYGNSS, GNSS-R

1. INTRODUCTION

The CYGNSS constellation of eight satellites was successfully launched on December 15, 2016 into a low inclination (tropical) Earth orbit. Each satellite carries a four-channel bistatic radar receiver that measures GPS signals scattered by the Earth surface. Over ocean, near-surface wind speed is retrieved. GPS signals operate at 19 cm wavelength and are largely unaffected by even the heaviest precipitation. As a result, wind speed retrievals are possible in the inner core of tropical cyclones. The satellites are always between 35N and 35S latitude due to the low orbit inclination. That fact, plus the fact that there are eight of them, results in a low revisit time everywhere in the tropics, with most storms sampled 2-3 times per day depending on their exact latitude. This allows CYGNSS to reliably capture a storm's rapid intensification phase plus other short time-scale dynamics [1].

Over the land, estimates of near-surface soil moisture and images of inland water bodies and flood inundation are derived from the surface reflections. The measurements are able to penetrate through all levels of precipitation and through most vegetation canopies due to the long radio wavelength. The number of satellites in the constellation and their continuous data-taking operation produces high spatial sampling density and low temporal revisit times. As a result, diurnal soil moisture variability can be resolved and rapidly changing flood inundation events can be imaged.

Science data products are regularly produced over ocean for wind speed, surface roughness, and sensible and latent heat fluxes and over land for near surface volumetric soil moisture. Data products currently in development over ocean include tropical cyclone intensity (peak sustained winds) size (radius of maximum winds), extent (34, 50 and 64 knot wind radii), storm center location, and integrated kinetic energy. Over land, data products in development include refined versions of volumetric soil moisture content, flood inundation extent, time-varying inland water body maps, riverine streamflow rate, and freeze/thaw land surface state.

An illustration of the spatial coverage provided by the full constellation of 8 spacecraft is shown in Fig. 1. The top panel depicts all samples taken after one 95 min orbit. Individual tracks of the GPS reflected signal are typically between 200 and 1200 km in length as the specular point of reflection passes through a CYGNSS science antenna beam. The bottom panel shows samples taken over 24 hrs.

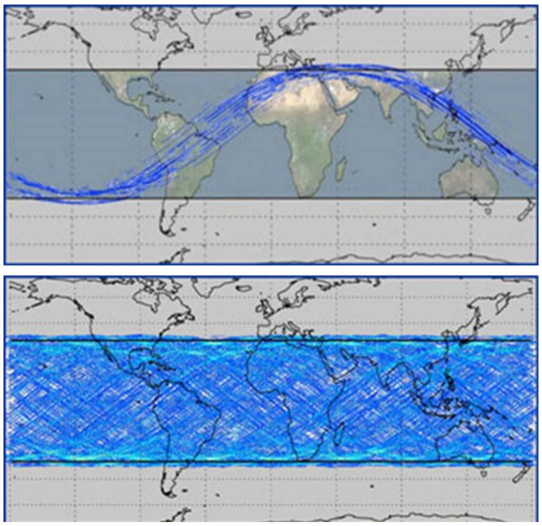

Fig. 1. Spatial coverage by the full CYGNSS constellation of 8 spacecraft after one orbit, or 95 min, (top) and after 24 hours (bottom).

2. OCEAN APPLICATIONS

2.1 Tropical Cyclone Observations and Prediction

Frequent sampling of ocean surface wind speed in the hurricane environment facilitates hurricane weather research. An example of CYGNSS wind speed measurements of Hurricane Dorian are shown in Fig. 2. CYGNSS wind products have been assimilated into research and operational hurricane weather prediction models to demonstrate their ability to improve forecasting [2-4]. Using the NOAA National Center for Environmental Prediction (NCEP) Hurricane Weather Research and Forecasting (HWRF) regional model and a 3-dimensional hybrid ensemble-variational data assimilation system, studies suggest that assimilation of the CYGNSS data results in improved hurricane track and intensity simulations of 2017 Hurricanes Harvey and Irma through the improved representation of surface wind fields, hurricane inner-core structures, and surface fluxes.

2.2 Ocean Surface Heat Fluxes

Ocean surface heat flux plays a significant role in the formation and development of many weather systems. Latent (LHF) and sensible (SHF) heat fluxes over the open oceans are measured by polar orbiting spaceborne instruments, with decreased reliability during significant weather events. CYGNSS wind speed measurements are used to develop a surface heat flux products for the CYGNSS mission [5]. They provide LHF and SHF estimates at every CYGNSS specular point over the oceans using its Level-2 winds together with MERRA-2 reanalysis data for the thermodynamic variables (temperature, humidity, air density). The CYGNSS LHF and SHF products have been the focal used in recent Madden-Julian Oscillation (MJO) convection [6] and extratropical cyclone [7-8] analyses.

2.3 Tropical Meteorology

The low inclination CYGNSS orbit is well suited to observe tropical convective systems. In addition to tropical cyclones, this includes convection that is a part of the formation and evolution of large-scale tropical circulation features such as the MJO. CYGNSS observations have provided substantial insight into its dynamics. [6] use CYGNSS wind speed fields and associated surface fluxes to demonstrate that enhanced wind-induced surface fluxes in regions of MJO precipitation are an important ingredient for maintaining the MJO.

2.4 Extratropical Cyclones

CYGNSS was designed to study tropical processes. However, observations up to ~40 deg north and south latitude have resulted in observations of a large number of low-latitude extratropical cyclones (ETCs). The CYGNSS science team has been investigating what we may learn about ETCs from those ocean surface wind and heat flux measurements. In particular, they have examined how surface heat flux changes as ETCs age to, better understand their energy exchanges with the ocean.

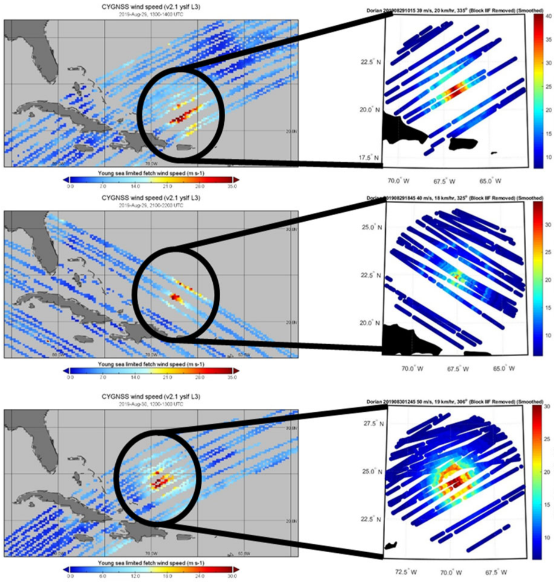

Fig. 2. CYGNSS measurements of wind speed during constellation overpasses of 2019 Hurricane Dorian centered on 29 Aug at 1015 UT (top), 29 Aug at 1815 UT (center), and 30 Aug at 1245 UT (bottom). The left panels are standard 1 hr gridded products and the right panels are 3 hr composites after storm centric re-gridding.

3. LAND APPLICATIONS

GPS reflections over land have been the focus of increasing study since the launch of the mission. Potential land applications of CYGNSS include surface- and root-zone soil moisture retrieval, freeze-thaw monitoring, and wetlands and inland water mapping. These products have traditionally been generated imaging microwave instruments. CYGNSS is not a traditional imager, but the large number of reflections tracked by each satellite combined with the large number of satellites in the constellation allow it to produce roughly comparable maps.

3.1 Soil Moisture

CYGNSS land reflectivity observations contain information about the dielectric properties of the surface, which is directly affected by soil moisture content. The CYGNSS science team are developing several different methods and associated products for surface (upper 5 cm) soil moisture. The first product was released by UCAR [9] and is available on a 36 km grid at 6-hour intervals within the CYGNSS latitude coverage of +/- 38 deg. The product has been validated using networks of in situ soil moisture probes and has an overall unbiased root mean square error of 0.047 cm^3cm^{-3}. Several other products are currently undergoing performance evaluation by the CYGNSS Soil Moisture Assessment Working group. These include products using a time-series method [10], a machine-learning scheme [11], and one based on a semi-empirical model combined with SMAP data [12].

A Land Applications Working Group within the CYGNSS science team has been formed to develop and implement a calibration/validation (cal/val) plan. The plan has been partially implemented for some of these products through the deployment of SoilCAPE soil moisture in situ networks networks and associated field campaigns. The cal/val plan takes advantage of some existing in situ sites that were in use for the SMAP mission, but it also includes sites that are being established or augmented specifically to support the CYGNSS mission. The latter include San Luis Valley, CO, White Sands, NM, several sites in New Zealand, and Walnut Gulch, AZ.

Activities are under way to cross-compare and validate several electromagnetic scattering models under development by members of the science team which are focused on CYGNSS land observations. Furthermore, recent studies by the CYGNSS science team have revealed that topography and land-surface heterogeneity are significant influences on bistatic scattering over land. High-resolution Lidar digital elevation models (DEMs) are therefore being acquired to address the need for detailed information about topography. The science team is also working on developing methods for scaling up local small-scale ("electromagnetic-scale" or centimeter scale) roughness maps to the scales of CYGNSS DDM coverage.

3.2 Freeze/Thaw Detection

CYGNSS observations over land are able to distinguish between frozen and thawed states due to the large difference in dielectric constant between liquid water and ice. A study carried out over the Andes Mountains and Argentinian Pampas has demonstrated CYGNSS sensitivity to changes in surface reflectivity associated with the freeze/thaw surface state [14]. CYGNSS observations are shown to have excellent spatio-temporal sampling and the freeze/thaw estimates have been validated using surface temperature data from an ERA5 reanalysis model.

3.3 Mapping Inland Water Bodies, Wetlands, and Flooding

CYGNSS obervations of reflected signals from land have demonstrated a remarkable sensitivity to small water features, some as small as 100 m or less. This sensitivity has led to a number of successful efforts to map dynamic flooding events due to severe weather, seasonal changes in wetland extent, and permanent water bodies which are hidden underneath dense vegetation canopies and are difficult to image using traditional sensors [14]. Fig. 3 provided an example of CYGNSS ability to image inland water bodies. It shows a section of the Amazon River and its tributaries imaged by a composite of multiple overpasses of the region by the CYGNSS constellation. For comparison, images of the same region by other L-Band sensors with poorer spatial resolution area included.

The sensitivity results from several related factors. The relatively long (19 cm) wavelength of GPS signals can penetrate denser canopies than signals with shorter wavelengths, such as the C-band signals used by the Sentinel satellites. The fact that CYGNSS measures quasi-specular forward scattering rather than traditional backscatter allows for a coherent scatterign mechanism to occur provided the surface is smooth enough. And the use of a long wavelength signal means the degree of roughness that constitutes a "smooth" surface is consistent with the typical roughness of most inland water bodies (lakes, rivers, wetlands, and floods).

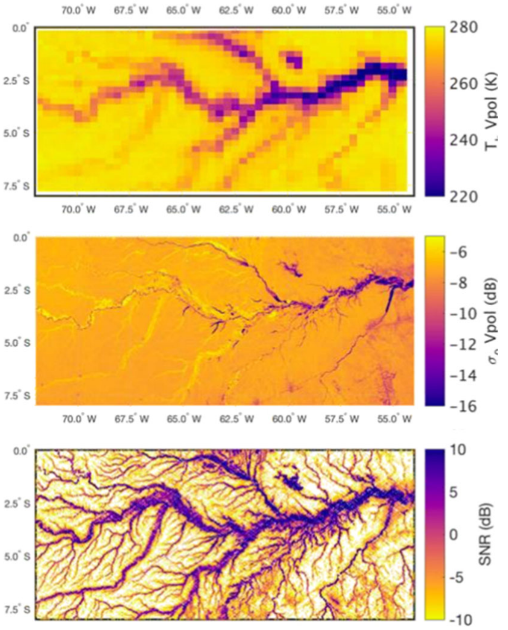

Fig. 3. Images of the same section of the Amazon River and its tributaries by three different L-Band sensors with varying spatial resolution. The top panel is generated by the SMAP microwave radiometer with ~35 km resolution. The center panel is generated by the SMAP L-band radar with ~ 3 km resolution. The bottom panel is generated by CYGNSS and has spatial resolution << 3 km. Determination of the actual spatial resolution of spaceborne GNSS-R sensors, and characterization of its dependencies, is an active topic of research.

4. CONCLUSIONS

The CYGNSS mission has resulted in many and varied scientific applications of its GNSS-R obervations. Ocean wind measurements over storms, the original mission objectives, have been used to image tropical cyclones and to improve our ability to predict their evolution. Ocean measurements away from major storms have been used to identify important linkages between air/sea heat fluxes and tropical and extra-tropical convection. Over land, measurements of reflections from soil allow its freeze/thaw state to be determined and, when thawed, allow the near-surface volumetric soil moisture content to be estimated. Reflections from inland water bodies tend to be sufficiently strong and coherent that the land/water boundaries can be imaged with high spatial resolution, under cloudy and precipitating conditions and even under dense vegetation canopies. All of these capabilities illustrate that breadth of scientific applications that are possible with GNSS-R remote sensing, when implemented using a large constellation of satellites.

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