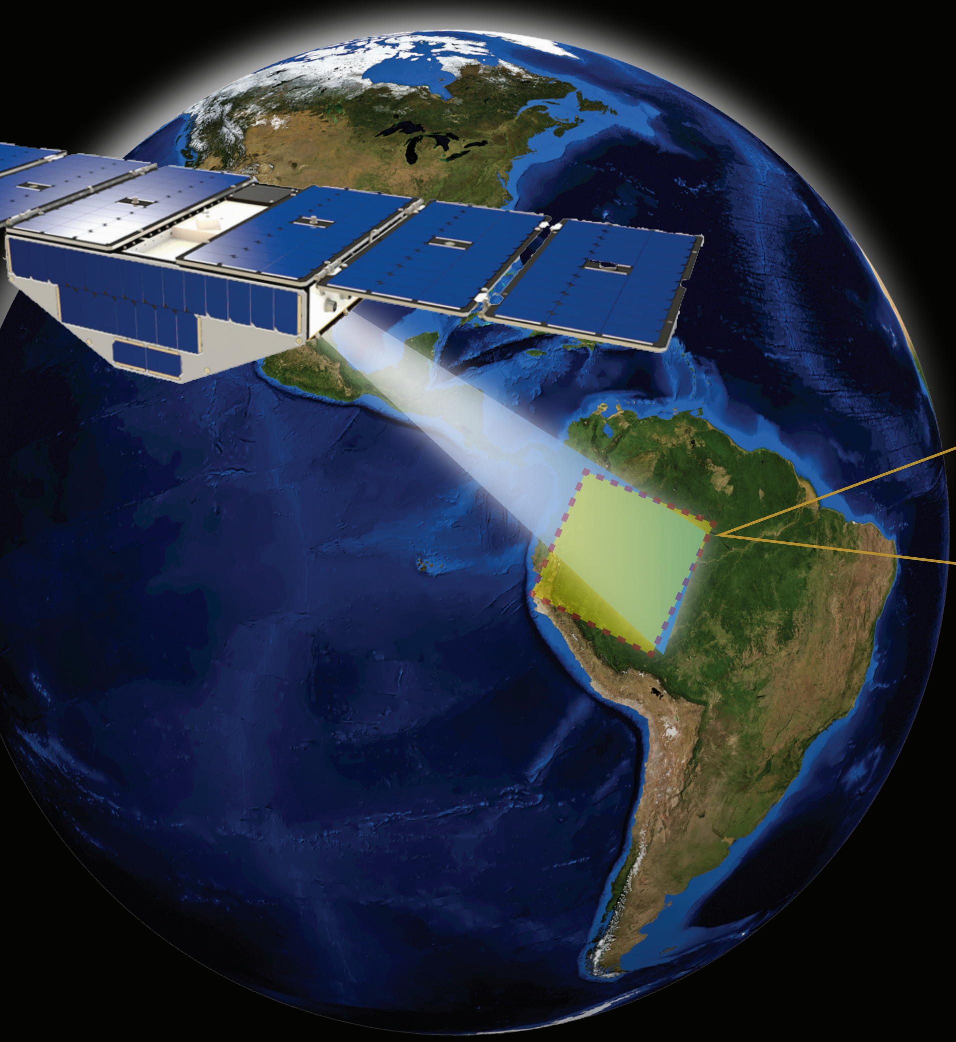
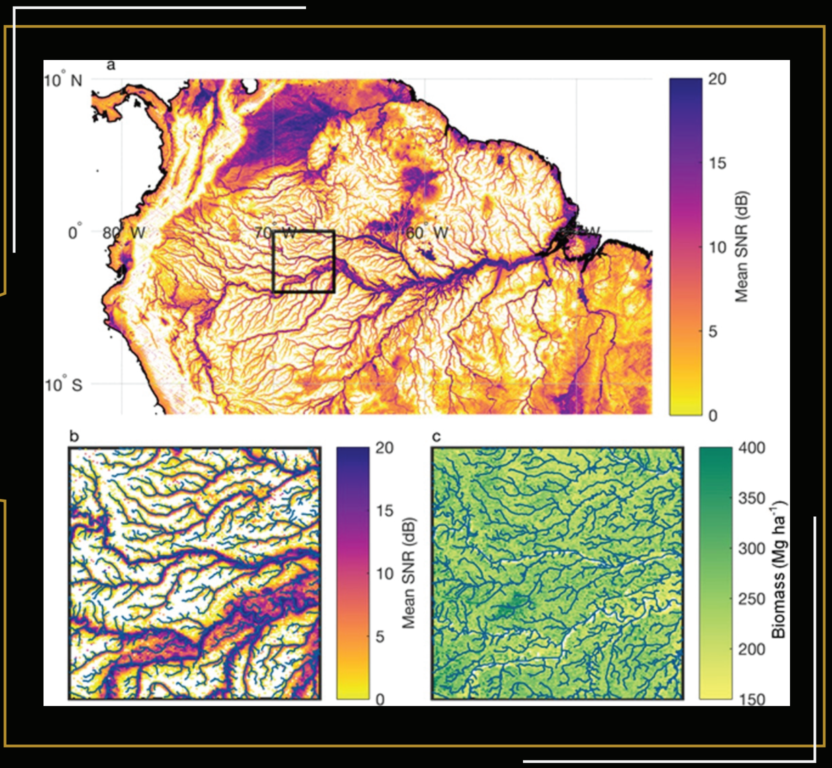
National Aeronautics and Space Administration





CYGNSS

Applications Workshop II

CYCLONE GLOBAL NAVIGATION SATELLITE SYSTEM (CYGNSS)

Applications Workshop II
Summary Report

Sponsored by:
NASA Earth Science Division
Applied Sciences Program

Monterey, CA
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NASA Applied Sciences
DISASTERS

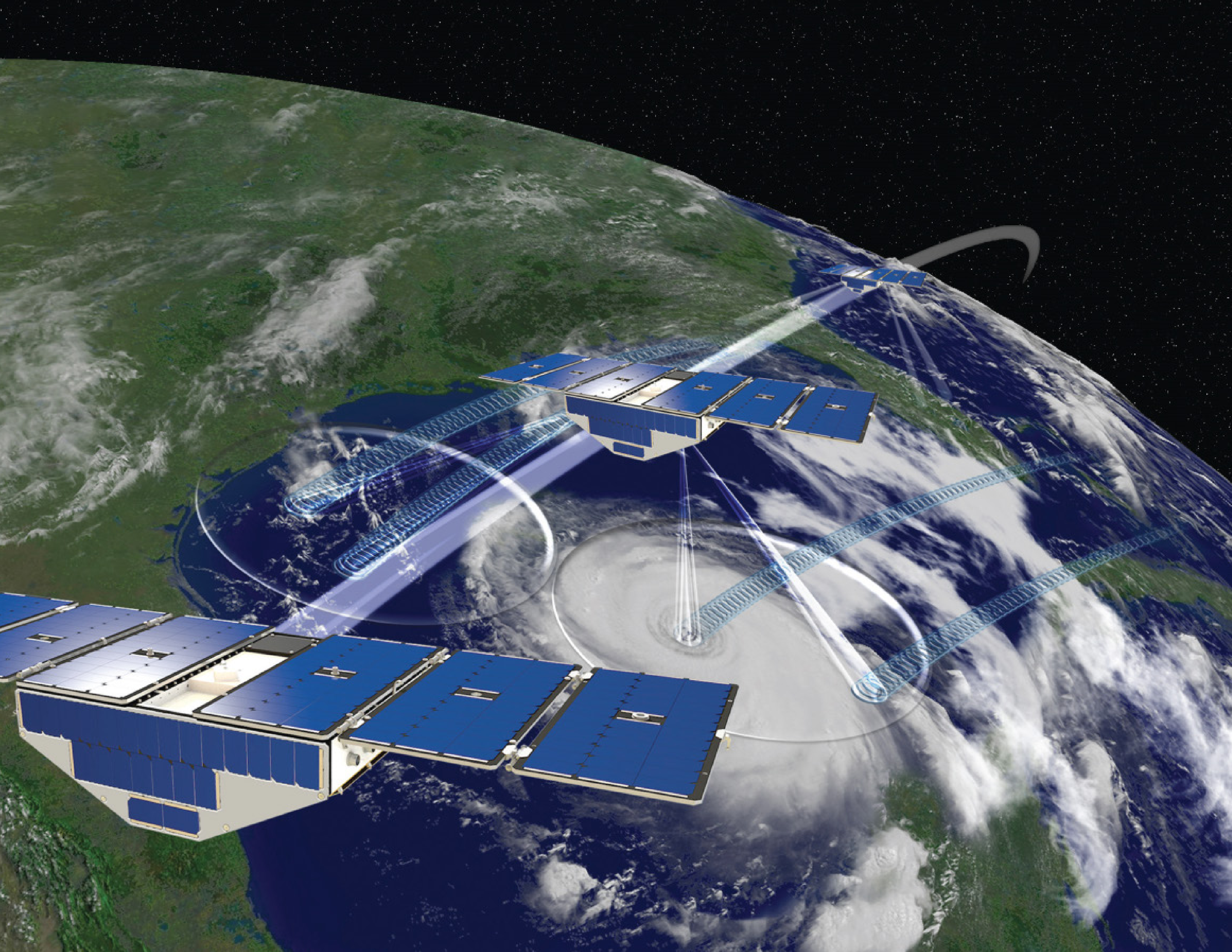

TABLE OF CONTENTS

CYGNSS Mission Background

Overview

The National Aeronautics and Space Administration (NASA) Cyclone Global Navigation Satellite System (CYGNSS) mission is a constellation of eight microsatellites that were successfully launched on 15 December 2016. The constellation frequently measures ocean surface winds in the tropics, with a primary objective of monitoring the location, intensity, size and development of tropical cyclones.

CYGNSS was selected by the National Aeronautics and Space Administration (NASA) as its first Earth Venture mission under NASA's Earth System Science Pathfinder (ESSP) program. CYGNSS is a Category 3 Class D mission, and as such had a limited cost-capped budget and aggressive schedule, particularly for an eight-satellite constellation.

The CYGNSS mission is led by the University of Michigan. The Southwest Research Institute led the engineering development and manages the operation of the constellation. The University of Michigan Climate and Space Sciences and Engineering department leads the science investigation, and the Earth Science Division of NASA's Science Mission Directorate oversees the mission. For further details, please note that this report contains hyperlinks throughout the text which provide more information on the topics summarized herein.

Mission Design and Objectives

The CYGNSS constellation of eight microsatellites operates in a common orbit plane at ~530 km altitude and 35 degree inclination with respect to the equator. Each observatory carries a four-channel bistatic scatterometer receiver to measure near surface wind speed over the ocean. The transmitter half of the scatterometer system is the constellation of GPS satellites.

CYGNSS is designed to address the inadequacy in observations of the inner core of tropical cyclones (TCs) that result from two causes: 1) much of the TC inner core is obscured from conventional remote sensing instruments by intense precipitation in the eye wall and inner rain bands; and 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.

Figure 1. The NOAA satellite GOES-16 captured this geocolor image of Hurricane Irma passing the eastern end of Cuba at about 8:00 a.m. EDT on September 8, 2017.

The retrieval of wind speed by CYGNSS in the presence of heavy precipitation is possible due to the long operating wavelength used by GPS (19 cm), at which scattering and attenuation by rain are negligible. Improved temporal sampling by CYGNSS is possible due to the use of eight spacecraft with 4 scatterometer channels on each one. Median and mean revisit times everywhere in the tropics are 3 and 7 hours, respectively.

Wind speed referenced to 10m height above the ocean surface is retrieved from CYGNSS measurements of bistatic radar cross section in a manner roughly analogous to that of conventional ocean wind scatterometers. The technique has been demonstrated previously from space by the United Kingdom Disaster Monitoring Constellation (UK-DMC) and TechDemoSat (UK-TDS) missions.

The CYGNSS baseline science requirements, defined to meet the mission objectives, are:

1. The baseline science mission shall provide estimates of ocean surface wind speed over a dynamic range of 3 to 70 m/s as determined by a spatially averaged wind field with resolution of 5x5 km.

2. The baseline science mission shall provide estimates of ocean surface wind

speed during precipitation rates up through 100 mm per hour as determined by a spatially averaged rain field with resolution of 5x5 km.

3. The baseline science mission shall retrieve ocean surface wind speed with a retrieval uncertainty of 2 m/s or 10%, whichever is greater, with a spatial resolution of 25x25 km.

4. The baseline science mission shall collect space-based measurements of ocean surface wind speed at all times during the science mission with the following temporal and spatial sampling: 1) temporal sampling better than 12 hour mean revisit time; and 2) spatial sampling 70% of all storm tracks between 35 degrees north and 35 degrees south latitude to be sampled within 24 hours.

5. The CYGNSS project shall conduct a calibration and validation program to verify data delivered meets the requirements within individual wind speed bins above and below 20 m/s.

6. The mission shall support the operational hurricane forecast community assessment of CYGNSS data in retrospective studies of new data sources.

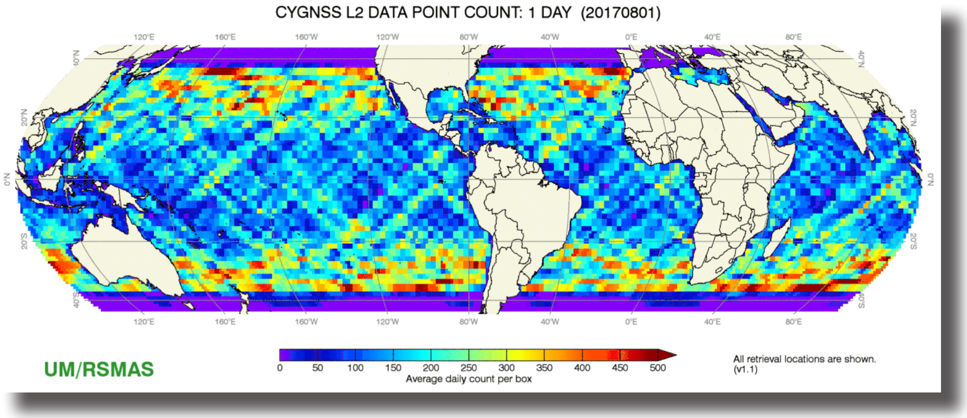

Figure 2. L2 data, average daily count for 70-day period, 2° grid.

Delay Doppler Mapping Instrument

The Delay Doppler Mapping Instrument (DDMI) is the sole science instrument on each CYGNSS μSat. Each DDMI is comprised of a multichannel Global Navigation Satellite System Reflectometry (GNSS-R) receiver, a low-gain zenith antenna for reception of the direct signals, and two high-gain nadir antennas to receive the scattered surface signals [6]. Due to the large number of GPS-transmitting satellites, there are typically a number of specular reflections from the surface visible to each receiver. Each DDMI selects the four specular reflections located in the highest sensitivity region of its antenna pattern and simultaneously computes DDMs (see Figure 3) at 1 Hz, centered on each specular point over a 25 × 25 km region.

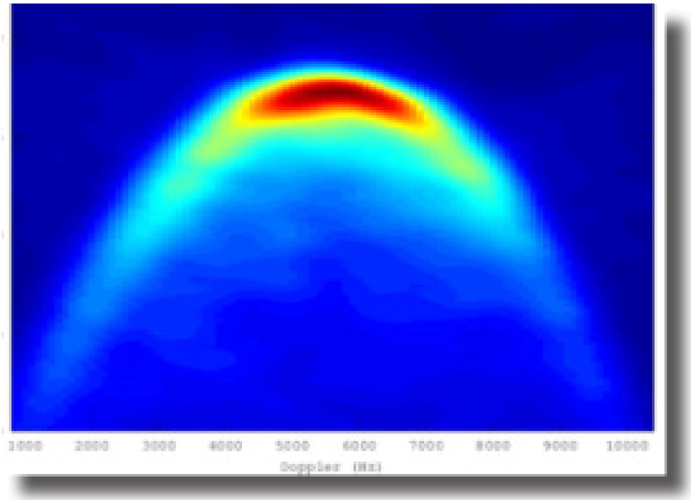

Figure 3. Delay Doppler Map (DDM)

Data Products

The primary science product of CYGNSS is the Delay Doppler Map (DDM). Figure 3 shows an early DDM measured by CYGNSS. It is a map of the power in the Global Navigation Satellite System (GNSS) signal scattered by the ocean surface after the signals are filtered by time delay (difference in time of arrival between the direct and reflected signals) and Doppler shift (difference in frequency between the two signals).

Both delay and Doppler vary across a range that includes the (delay, Doppler) coordinates of the nominal specular point with respect to mean sea level. Compared to the specular point delay and Doppler, shorter delays generally correspond to locations above the surface; while longer delays correspond to increasing distances from the specular point along the surface. Doppler values larger and smaller than the value at the specular point correspond to iso-Doppler contours on the surface that extend to either side. The DDM is therefore a map of the diffuse surface scattering in the vicinity of the specular point. The shape of the DDM changes with ocean surface roughness, which gives rise to the wind speed measurement.

Workshop Purpose and Objectives

The second CYGNSS Applications Workshop was conducted from 31 October through 2 November 2017 in Monterey, CA. It consisted of both plenary and breakout sessions, as well as two panel discussions. This workshop was convened post-launch with four primary objectives:

1. Mission status update with a summary of routine and major operations and observations.
2. Applications community engagement to provide opportunity to fully develop applications science and data assimilation for CYGNSS observations.
3. End-user community engagement to address the development of specific applications for CYGNSS observations.
4. Broad stakeholder engagement to address issues such as data latency and the complementarity of CYGNSS with current and future satellite and non-satellite missions.

This meeting comprised a post-launch, Phase-E (operational observations) applications workshop. A pre-launch CYGNSS applications workshop was held in June 2015 to explore and define the potential applications space and to develop an applications traceability matrix for the mission. An extensive report from that workshop is also available which provides additional detail to that in some of the overview sections of this report and allows us to focus more on post-launch results and the current applications space.

Workshop Summary

Workshop presentations focused on current and potential operational or application areas of CYGNSS data related to the core science team measurements and products. The workshop began with a series of presentations by the CYGNSS leadership, describing mission status and operations, as well as results from the 2017 hurricane season. These presentations were followed by presentations from the end-user and stakeholder communities which were divided into five application areas:

1. Tropical Cyclones and Convection
2. Tropical Forecasting and Process
3. Terrestrial and Hydrological
4. Oceanographic
5. Data Assimilation and Tropical Numerical Weather Prediction

The workshop participants then engaged in two breakout sessions organized by the aforementioned thematic groups, as well as two panel discussions. The first panel addressed future paradigms and partnerships for SmallSat missions, while the second focused on CYGNSS mission synergies. The following sections summarize key discussions, end-user inputs, and conclusions for each of the meeting sessions.

Mission Status and Summary

Following launch on 15 December 2016, the first month on orbit was spent transitioning the constellation of eight spacecraft from their initial launch operating configuration to their engineering mode of operation. During the subsequent two months, commissioning of each spacecraft bus was performed. Following spacecraft commissioning, the science payloads – the four channel GNSS-R receivers on each spacecraft – were commissioned in March and April 2017. In May 2017, after proper functional performance of the science payloads was verified, provisional public release of the science data products by the NASA PO.DAAC began. Since that time, Level 1, 2 and 3 science data products have been continuously produced and distributed by the PO.DAAC. The Version 1.0 and 1.1 data available at the PO.DAAC are provisional in the sense that Level 1 calibration of the engineering measurements was still being refined and Level 2 and 3 wind speed data products are still being validated against available ground truth measurements. Version 2.0 data, released in December 2017, represents the first "post-provisional" release of the CYGNSS Level 1, 2 and 3 science data products generated using calibrated processing algorithms which were trained and validated against inter-comparison wind speed measurements made during the 2017 Atlantic hurricane season.

Summary of Application Area Findings

Tropical Cyclones and Convection Applications

CYGNSS was designed to address inadequate observations of the inner core of tropical cyclones (TCs), though its utility extends far beyond its original design purpose. The broad TC applications are based on improved representations of surface winds in TCs due to the fact that CYGNSS data extends into regions with heavy precipitation, and with greater sampling frequency than other space-based wind measurements. These data, in turn, are expected to advance the scientific understanding of important physical processes in TCs and, if available in near real time, to improve operational analyses and predictions of TCs through both forecaster analysis and numerical weather prediction. Specific examples are provided in the following paragraphs.

Five presentations were given in this application area. The first three emphasized operational applications of CYGNSS data, and specifically the need to forecast tropical cyclone structure and intensity, which is critical for storm surge prediction and the timing of the issuance of watches, warnings, and evacuation decisions. Statistical and dynamical forecast models are also initialized with observational data and specific information on the wind field structure such as the Radius of Maximum Wind (RMW), and the radii of the 34-kt, 50-kt and 64-kt surface winds in each quadrant. Also, forecasters at the operational U.S. TC forecast centers are required to estimate these key parameters as part of their forecast product generation, many of which are then archived in the Automated Tropical Cyclone Forecast System (ATCF) database for future application development and potential climate studies. Given the known limitations in aircraft and scatterometer data coverage, additional wind data obtained in near real time (less than 3 hours after the observation time) and incorporated into operational decision support platforms are expected to be helpful in improving analyses of TC structure and intensity. If the data are sufficiently timely and accurate, CYGNSS-based estimates of these parameters can potentially contribute to these important applications. CYGNSS data could be useful for post-storm analysis, regardless of the data latency.

Potential applications that require accurate estimates of TC structure include wind probabilities, wind radii climatology and persistence models, infrastructure, wave forecasts, and TC conditions of readiness. Synergies between CYGNSS wind speed data and winds from NASA's Soil Moisture Active and Passive (SMAP) satellite were also discussed. Finally, the efficient application of CYGNSS data in the computation of the aforementioned surface wind parameters (intensity, size, and also integrated kinetic energy) using parametric models was presented. These parameters can also be estimated through the assimilation of the CYGNSS data into full-physics numerical models, as is discussed in the data assimilation section of this report.

Tropical Forecasting and Process Applications

There are many important and impactful phenomena in the tropics and subtropics that would benefit from improved surface wind observations from CYGNSS, in particular observations available in all-weather conditions and with rapid updates. The Madden-Julian Oscillation (MJO) is the dominant mode of variability in the tropics on intra-seasonal time-scales. The phase and amplitude of the MJO have been associated with many other phenomena, such as the frequency of tropical cyclones in particular basins, mid-latitude weather regimes, and even the Arctic and Antarctic Oscillations. As such, improved prediction of the MJO is of interest itself, but the application of CYGNSS data to improve forecasting of the MJO would be highly valuable, given its impact on phenomena around the globe. Another phenomenon of great concern and impact is the monsoon, a large-scale mode of tropical variability that affects multiple continents. The timing of monsoon onset and active and break periods, and individual monsoon-related events like depressions, can have tremendous humanitarian impacts (e.g., floods). Other phenomena that originate in the tropics and subtropics can have a great impact on mid-latitude weather. These include tropical cyclones that undergo extratropical transition, mid-latitude cyclones that form in the sub-tropics, and atmospheric rivers. CYGNSS has the potential to fill critical gaps in monitoring and forecasting of these impactful phenomena.

Dr. Timothy Lang (NASA MSFC) provided the overview of tropical process applications for CYGNSS. The sub-diurnal sampling of CYGNSS, with a 2-3 hour revisit time, is particularly useful for observing the diurnal cycle associated with land-sea breeze circulations as well as mesoscale convective systems and their associated gust fronts, which are key source of maritime hazards. He noted that there are many potential tropical process applications for CYGNSS (aside from tropical cyclones) that were identified in the previous workshop, and he focused on four of these (MJO, monsoons, extratropical cyclones including the extratropical transition of tropical cyclones, and atmospheric rivers or ARs) in his presentation. CYGNSS observations for these phenomena can aid with both real-time monitoring and forecasting through data assimilation.

In his conclusions, Tim noted that given its rapid update and ability to sample rainy regions, CYGNSS observations may be able to observe mesoscale variability that is masked in more traditional methods. To take full advantage of CYGNSS observations, numerical weather prediction (NWP) models must incorporate improved model physics near the ocean surface, and will be most useful when supplementing other global observations. There is a need to blend diverse wind products into a coherent 3D wind product. While low-latency data are important, there are some extended-range forecasting where longer-latency may be tolerable.

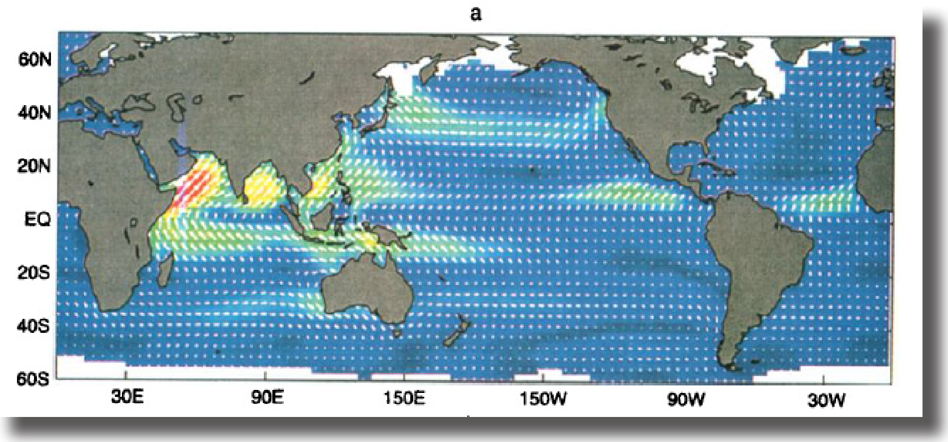

Figure 4. Resolution and coverage of CYGNSS can extend monitoring and forecasting monsoons to short time scales where variability is driven by the diurnal cycle.

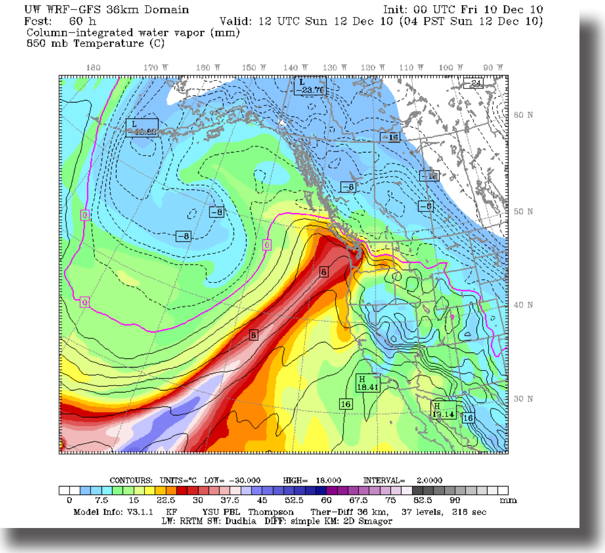

Figure 5. CYGNSS can improve atmospheric river forecasts due to its ability to view near surface oceanic winds in heavy precipitation.

Terrestrial Hydrology

CYGNSS makes measurements continuously over both ocean and land. The ocean data are used to estimate surface wind speed. The land data are sensitive to the moisture content of the soil and, in the most extreme circumstances, can be used to detect and image flood waters. The focus of this application area is the use of NASA CYGNSS data for terrestrial hydrology, such as crop soil moisture monitoring to inform plant development, drought extent and recovery, and wetland monitoring and change detection to inform policy and decision making.

The CYGNSS mission acquires data over land at high temporal resolution, suitable for capturing high frequency dynamics of tropical land processes, but currently only L1B data products are delivered, and no L2 are planned within the project resources. Some of the current limitations on land data are that data processing is optimized for wind fields, with 1 sec incoherent averaging, limiting resolution. Additionally, the current on-board tracking algorithm is optimized for ocean surface, with corrections to account for topography still under development.

Though CYGNSS was not designed for land applications the potential value of CYGNSS data to the terrestrial community highlights the importance of identifying steps required to deliver a mission data product that meets the needs of these end users. Such steps include algorithm development and validation and uncertainty quantification. It is recommended that the CYGNSS project team secure dedicated resources to develop the basic land L2 data product for distribution to the community.

From the analysis of GNSS-R data over land from aircraft and space (TDS) it emerges that reflections from bound bodies of water are coherent, in contrast with those from wind driven oceans, and as a result the peak power SNR is considerably higher over such scenes than over ocean and dry land. An example of a map of peak SNR values in the Amazon region, from aggregated CYGNSS data in April-May 2017, is presented in Figure 6.

This illustration confirms that CYGNSS is sensitive to the presence of water in the measurement footprint, even when the bodies of inland water are partially obstructed by vegetation.

A simple geophysical model function (GMF) has been obtained by representing a vegetation-obstructed wetland as a bulk medium with effective dielectric constant determined by the weighted average of water and a non-reflective material, where the weight is the fraction of water present in the measurement footprint, implying that to first order the effect of attenuation by the vegetation is negligible. This simple model has been tested against the CYGNSS data in the Amazon, using the MODIS 30 m water mask for the same time frame as ground truth. The approach has produced a first example of an inundation map for the region.

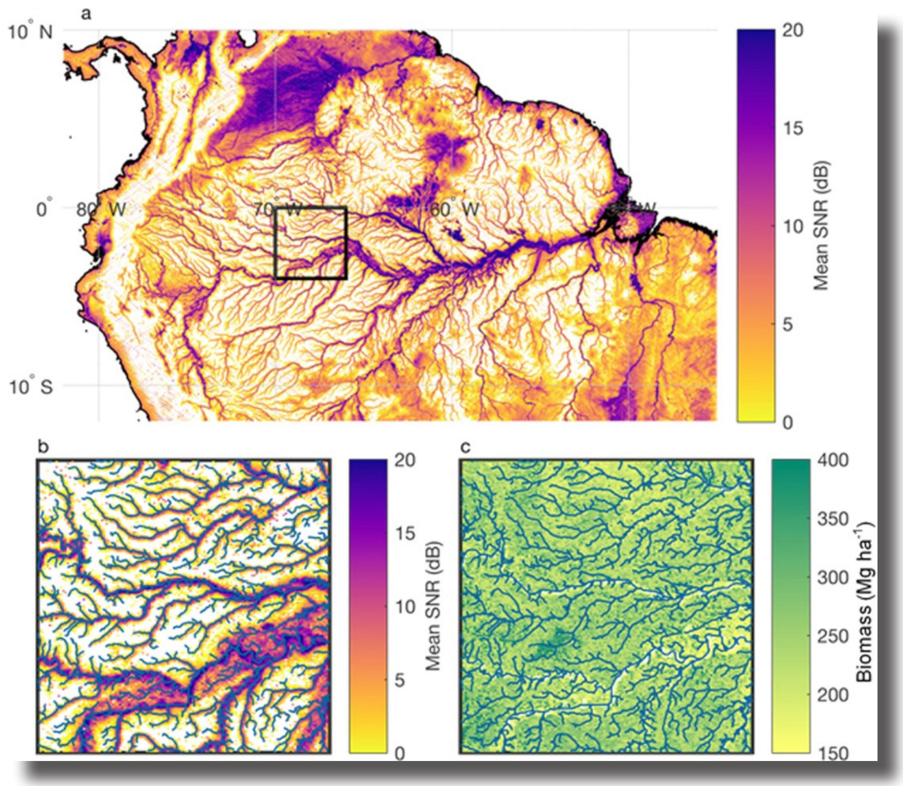

Figure 6. CYGNSS mapping of inland waterways in the Amazon. (a) Mean SNR, gridded to 3 km, over the Amazon for the time period 18 Mar – 29 Dec 2017. Areas with surface elevation >600 m above sea level have been masked out due to a limitation in the CYGNSS on-board data compression algorithm. Corrective flight software was uplinked to the constellation in Dec 2017. (b) Inset of the black outlined box in (a), with river outlines from HydroSHEDS overlaid in green. (c) Biomass map for the black outlined box in (a), with river outlines from HydroSHEDS overlaid.)

Soil moisture is important for a number of applications including hydrologic monitoring, weather prediction, and flood as well as drought monitoring. Soil moisture estimates are important in agricultural applications for irrigation scheduling and assessing suitability of a field for farm operations. Soil moisture information could contribute significantly to improved estimates of evapotranspiration and elements in the water cycle, including runoff projections, and to assess the impacts of climate change. Additionally, soil moisture is a critical variable for estimating potential for flooding. During periods where soils are highly saturated, water may not be able to be moved quickly enough to satisfy flood control needs.

Although these results are preliminary and more thorough corrections to the peak SNR values are needed (and will be implemented as the CYGNSS project releases new versions of the data), they nevertheless point to a clear sensitivity of SNR to soil moisture. More work is needed to formulate a GMF that will isolate the contribution of soil moisture from those of confounding variables (roughness, vegetation, transmitted power, etc.) but these preliminary results are very encouraging.

Soil moisture as a measurement could significantly improve understanding of water supply and demand variables, especially as a contribution to a number of modeling efforts through assimilation. Two examples of needs in the near-term at different spatial scales are given here: 1) at continental scales, the USDA and the National Integrated Drought Information System (NIDIS) have established a partnership with the goal of coordinating the development of an integrated national soil moisture network as part of the National Drought Resilience Partnership; and 2) soil moisture observations at local scales, e.g., the watershed level, provide valuable insight into the amount of runoff, e.g., when soils are dry, nearly 80% of precipitation goes into the soil, when soils are wet, runoff into the reservoir is markedly increased.

Ground-based observations of soil moisture in the United States at available at state-level climatic networks in Illinois, Oklahoma, Nebraska and West Texas and are available via the Soil Climate Analysis Network (SCAN). However, there are no consistent measurement standards between the newer and older sensors, the ground-based networks are generally point measurements with small sampling volumes, and the network itself is still relatively sparse. Because of the challenges, soil moisture observations are not yet integrated into forecast models, yet they have a profound impact on runoff, storage, and flood control. Further, obtaining soil moisture data from ground-based networks is a challenge as they are generally point measurements.

Remotely sensed soil moisture from missions like the NASA Soil Moisture Active Passive (SMAP) mission can provide spatially consistent observations to help provide information in remote regions and also a homogenous quality of measurements over large regions. However, these remote observations have temporal revisit of several days and may have coarse spatial resolution relative to the ground-based measurements.

Analysis of CYGNSS variations of peak SNR in Australia on a monthly scale have been shown to correspond very closely to variations of soil moisture captured by SMAP, as illustrated in Figure 7 below for the period early/late April 2017.

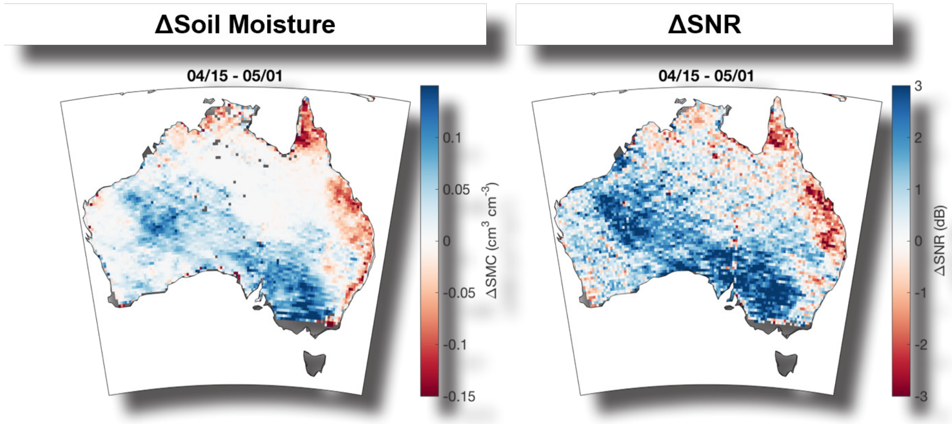

Figure 7. Change in soil moisture retrieved by SMAP (left) and change in SNR imaged by CYGNSS (right) during the same week.

The use of data from CYGNSS to estimate near-surface soil moisture variations is a promising method to obtain field averages of soil moisture at higher temporal resolution than traditional systems. These estimates could help fill the gap between the ground-based observations and remotely sensed soil moisture estimates.

Oceanographic

Paul Chang (NOAA/NESDIS/STAR) provided an overview of ocean weather now-casting and forecasting, as well as applications supported by surface wind measurements, including Safety at Sea and short-term warnings. The importance of collaboration and partnerships between data/product providers and data users for successful application of data was emphasized. Short-term ocean analysis and forecasting (less than or equal to one week) was identified as a potential application of CYGNSS data. Global and regional ocean analysis-forecast systems are forced by surface fields derived from global weather forecast models (near-real-time ocean analysis and prediction); improvement of these products will require CYGNSS observations to be uploaded to the GTS in a timely manner for assimilation; a long latency period for observations is a major problem. CYGNSS data can be used for retrospective analysis and prediction, to test and improve ocean analysis-forecast systems. Potential future applications that were highlighted include storm warnings, ship routing, monitoring of oil production and spills, search and rescue, recreational boating warnings, and icing information important to fisheries management.

Jeff Paduan provided an overview of Ocean Observing Systems which have traditionally been single PI driven research on process experiments in the ocean. Large-coordinated experiments such as MODE or WOCE are exceptions. Availability of new instrumentation has always been a driver. WOCE occurred in the 1990s. Of the many buoys, 4 have wind sensors. Developments added accelerometers as wave sensors as well as hundreds of drifters and thousands of subsurface floats. The Ocean Observatories Initiative (OOI) sponsored by NSF and the Integrated Ocean Observing System (IOOS) is sponsored by NOAA. OOI supports cabled array in regional scale and Juan de Fuca ridge, coastal mooring/buoy sections from WHOI and OSU, as well as deep-ocean mornings in Southern Ocean sites that may fall to budget cuts. It is TBD whether remote sensing missions such a CYGNASS can fill some of these possible gaps. IOOS supports eleven regional associations focused on locally important coast ocean observations. Some observations are common such as HF radar networks and glider sections. HF radar (10 m wavelengths) provides derived surface currents off of the coast. There are 50 sites in CA. affiliated with CENCOOS. They are primarily supported for oil spill mitigation and for search and rescue. 6km and 2 km resolution is available. Transition from R2O needs focused funding, transition plans, and sustained resources for ops/maintenance in the mission agencies, or contract vehicles for private sector implementation.

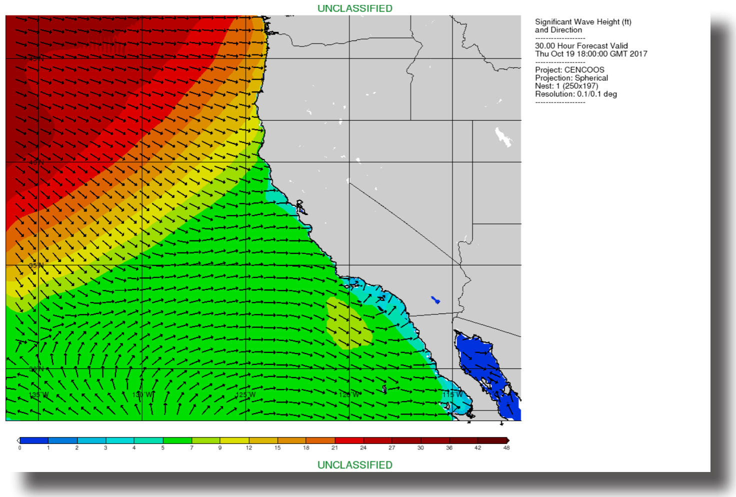

Figure 8. CENCOOS Signification Wave Height product example.

Possible synergies and gap fillers between ocean observations and CYGNSS include HF radar which may be able to provide surface wind direction. Usually CYGNSS gets only to 25 km off the coast. HF typically goes out to 150-180 km (there is overlap). Ocean observations from global programs may have more direct impact on CYGNSS validation, e.g., global drifter program's distributed observations of SLP, wind, and someday waves. Development and validation of NEXGEN wave models should be directly relevant to CYGNSS.

Paul Wittman provided and overview of Operational wave models at FNMOC. Wave data assimilation (DA) can improve wave forecast bias and RMSE about 30% at the early forecast time, after which the effect diminishes since it is very wind driven. Additional surface winds from CYGNSS would help. The WW3 deterministic wave model currently provides ½ degree resolution with plans to upgrade to ¼ degree. It includes assimilation from altimeters and is forced with marine surface winds from NAVGEM. The forecast is out to 180 hours, and it provides local boundary conditions (LBCs) for the Navy's mesoscale model, COAMPS. Wave DA is part of NCODA and uses a 3DVAR scheme. It relies on 5 orbiting altimeters for significant wave height corrections usually, on the order of a meter or less over a few regions. FNMOC has strong wind bias and strong wave bias. Similar to CYGNSS data challenges, it is difficult to de-couple winds and waves and separate wave biases from the NWP model. The FNMOC ensemble is currently combined with NCEP 21 members WW ensemble. Environment Canada will contribute in the near future. The ensemble mean is superior to the deterministic model after about 72 hours, but ensemble mean fields are generally not realistic. FNMOC uses the ensemble member closest to mean to get around that problem. COAMPS WW3 has the capability to output wave spectral boundary conditions for SWAN and Deflt3D to provide daily and monthly wave height verification graphics.

The FNMOC presentation provided 3 primary conclusions. First, wave model skill is dominated by the forecast skill of the NWP model forcing it. Second, Wave DA can improve wave forecast bias and RMSE at the early forecast time after which the wind forcing overwhelms the correction. Better NWP winds are needed. Third, CYGNSS does see some significant wave height sensitivity, but not below 2 meters. Data above 2 meters could still be very important. Accurate wind data requires accurate wave data. The measurement responds to both winds and waves.

CYGNSS has the ability to be a powerful complement to existing observing systems; with its unique orbit characteristics, frequent temporal sampling and non-sun-synchronous observations CYGNSS provides an opportunity to improve understanding and sampling of diurnal changes and rapidly changing events. Applications supported by wind measurements: weather forecasting, storm warning, ship routing, oil production and spills (oil changes surface signature), fisheries (icing information), search and rescue, recreational boating.

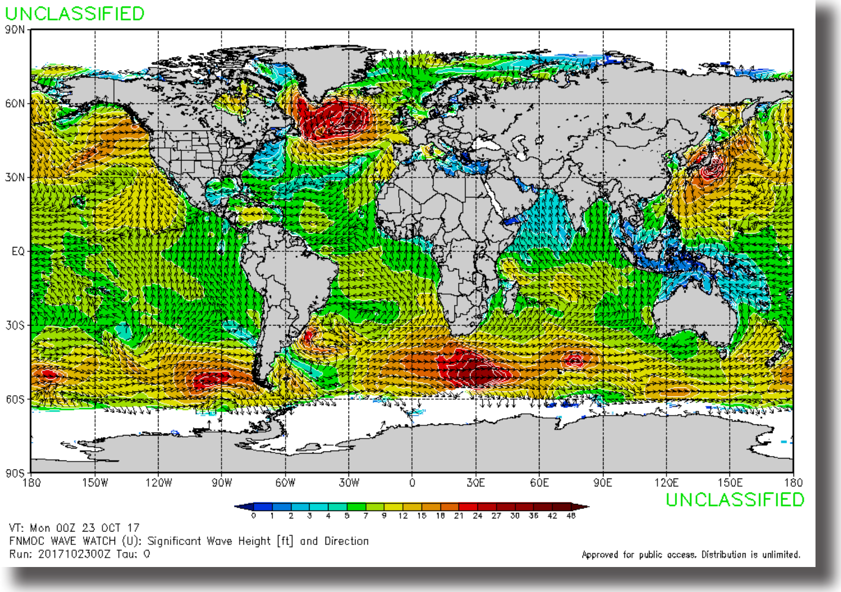

Figure 9. U.S. Navy Significant Wave Height product example.

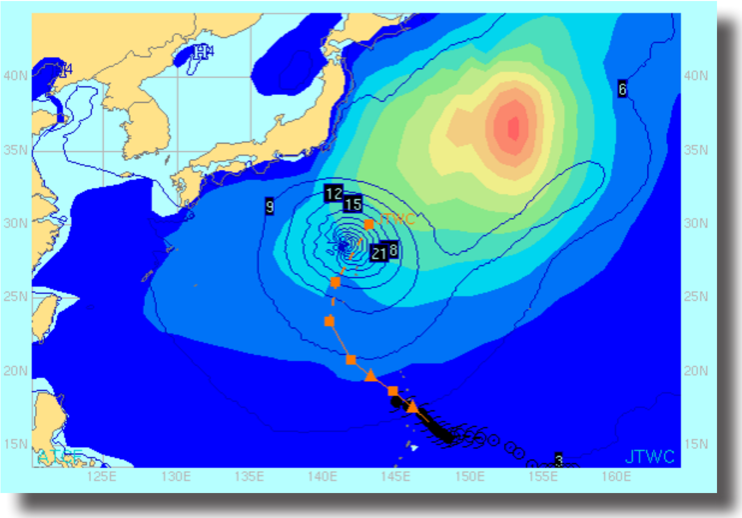

Figure 10. U.S. Navy WW3 Model with hurricane data assimilation.

Data Assimilation and Tropical Numerical Weather Prediction (NWP)

Feixiong Huang (Purdue University) presented a GNSS-R DDM Forward Model status update. The CYGNSS Level-2 wind product uses only 15 out of a total of 187 delay-Doppler bins, limited by the 25-km spatial resolution. Assimilation of the Level-2 winds will lose much information in the measurements. A generalized forward model for direct assimilation of DDMs into hurricane models is developed. The forward model computes an integral over the surface wind field in the glistening zone and generates the full DDM and a partial derivative matrix (Jacobian), which could be used in the Variational Analysis Method (VAM) to assimilate CYGNSS measurements into a wind vector field. The forward model was tested on CYGNSS data from hurricane Irma on Sep. 4, 2017. The comparison between CYGNSS observed DDMs and simulated DDMs showed good match-up and the Jacobian matrix was validated by finite difference. The model will be integrated into the data assimilation code in the near future. An Interface Control Document (ICD) defining the model variables has also been prepared to support further utilization of the model.

Breakout Session Summaries

The goal of the workshop breakout sessions was to identify existing CYGNSS data applications and to have the end user community prioritize future applications. The breakouts were organized according to the identified application areas, and during reconciliation common priorities emerged.

As had been presented in the application area overviews, key current and potential applications identified were related to the two-dimensional surface wind field data products and TC structural parameters. Additional applications included surface fluxes, and surface forcing for convection, necessary for understanding and predicting tropical cyclogenesis. These products would be L2 and L3 data. Several partnerships spanning operational centers, research labs, academia and the private sector were identified. End users include forecasters, emergency managers, and oil and (re)insurance companies. The main benefits, as described above, include an improved understanding of the distribution of the most damaging winds, which is necessary for direct response and for risk mitigation. Emphasis was placed on impact-based forecasting. Several complementary datasets, such as scatterometers, were identified. The key barriers to wide use of the application are latency (3 hours or less required), and additional metadata for the L3 data (e.g. the quality control flag).

Improved forecasting of MJO and Monsoons (in particular the BSISO) were also identified as existing CYGNSS data applications – both in terms of data assimilation/ forecasting and now-casting/situational awareness/hazard identification. Tropical-extratropical linkages (including ARs, extratropical transitions of tropical cyclones, and subtropical cyclones), monsoon depressions, and energy sector applications were identified as potential CYGNSS applications. The energy sector has the potential to entrain new stakeholders and partnerships with the private sector.

The unplanned but exciting utility of CYGNSS data for terrestrial hydrology applications was highlighted during the breakout discussions. Several applications currently being developed are inundation mapping, pre- and post-flood monitoring, and assessing soil moisture, relevant for drought, agriculture and forestry applications. Of the developing and potential terrestrial CYGNSS applications identified, there was consensus that priority be placed on continuing the development of inundation mapping applications. The value of the CYGNSS mission's ability to observe the diurnal cycle due to its temporal coverage was emphasized.

For the identified potential terrestrial applications to be successful, it is important to a) develop a dialogue with a number of different users that could apply the data to ensure that their decision-making process is taken into account, which can further ensure the application of data by a dynamic group of users; and b) understand specifically at what time various actions/interventions can be taken, and at what temporal scale, and compare this with the ability to provide CYGNSS data.
More ambitious potential data applications discussed include longer term trends to answer questions such as the change in frequency and intensity of storms over an extended period, in different regions around the globe. Communities to benefit from such questions include humanitarian development communities, national governments, emergency response planners, and development banks. The realization of such an application would be over many years, with the life cycle of the satellite being the limiting factor.

Some common themes emerged in discussion of these existing and potential applications. It was noted that CYGNSS is complementary to other current observing systems; for example, it can be synergistic with scatterometers and fill the gaps of satellite-derived wind observations in rainy regions. It was also noted that the CYGNSS data needs to be "data assimilation" quality. That is, it needs to be of sufficient quality to add information to the current suite of observations. An essential part of this is that the error characteristics of the data need to be known accurately for it to be useful. In addition, for NWP and hazard identification applications the data latency needs to be 3 hours or less (although for long range forecast utility, data latency of 12-24 h may be acceptable).

As the CYGNSS signal is a function of both swell and wind speed, accurate forward models that account for both will be needed for effective assimilation. This is both a challenge and an opportunity, making CYGNSS data a prime candidate for the emerging field of coupled modeling and data assimilation. Ways to address some of the future challenges include entraining oceanography and hydrology experts, as well as engaging end-users and leveraging connectivity with the TROPICS mission. To deal with the hesitancy of groups to invest in a short-duration mission, opportunities for continuity of operations, such as putting GNSS-R receivers on other platforms (International Space Station [ISS] or flagship missions) or SmallSat launches should be considered. These additional platforms could provide coverage of higher latitudes, expanding the scope of CYGNSS-related applications.

Panel Discussion on Partnerships and Future Paradigms

In order to capture inputs from both government and private sector partners engaged in SmallSat development, a series of short presentations followed by an open discussion period was organized to identify areas of mutual community interest.

Throughout the meeting, it was noted that NASA's role in SmallSat investment is primarily in technology demonstration and evaluating the ability of SmallSats to provide high-quality observations capable of answering scientific questions. Operational agencies, such as the National Oceanic and Atmospheric Administration (NOAA), which incorporates satellite measurements for both situational awareness and numerical prediction, note that they rely on partners like NASA to provide demonstrations of new observation types to understand their value for development of future operational missions. Zorana Jelenak from NOAA NESDIS STAR discussed the large learning curve for operational forecasters in using new satellite technologies, even between similar platforms like scatterometer winds from the Quick Scatterometer (QuikSCAT) and Advanced Scatterometer (ASCAT). Completely new measurements, such as CYGNSS's Global Navigation Satellite System refractometry (GNSS-R) approach will likely require even more training and practice for applications. NASA's investment in CYGNSS is seen as a first step in a process to make these types of data potentially viable for future operational missions at NOAA if the observations are of high enough quality and provide new insight into outstanding operational forecasting challenges.

NASA partners in some instances with the private sector to develop new technologies—as was done with CYGNSS partnering with Southwest Research Institute (SwRI) to build the multiple spacecrafts and manage the ground segment operations for the mission. Randy Rose from SwRI presented on the role his company has played in the CYGNSS mission and shared other work that SwRI has done with NASA's Heliophysics Division and the Department of Defense. Another aspect of the private sector's role in SmallSats was the noted growing number of companies who have invested in ground stations and mission operations. Richard Welle from the Aerospace Corporation and Peter Platzer from Spire Global, Inc. shared their company's investment in ground infrastructure with Aerospace currently having 6 ground stations and Spire having the world's largest low-Earth orbit ground station network with 26 locations in 11 countries. Both Aerospace and Spire noted their capabilities for having end-to-end ownership of SmallSat missions. Marie Colton from Harris Corporation described a framework where the commercial sector is continuously adopting new business strategies to incorporate, support, and monetize SmallSats, and the reduced cost of developing missions has opened up the market to a number of new companies. As a result, the commercial sector could be one avenue for future end-to-end development and production of satellite missions to support government agencies as long as a set of community standards for data quality and consistency across multiple platforms are adopted to ensure confidence and continuity in the observations.

The key takeaway from the discussion period centered on the need for continued dialogue between the science and the technical communities to tell a joint story about the intersection between what is technically possible and what types of measurements are needed to answer outstanding science questions. To ensure that SmallSats add value to the scientific community, there must be specific science questions that are only feasibly answered through the use of SmallSats. It was noted that the major advantage of SmallSat systems is their ability to fly in low-cost constellation formations to collect higher temporal frequency observations than are possible from traditional, single polar-orbiting platforms. Both CYGNSS and its sibling SmallSat mission, TROPICS (Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats), have advantages in providing observations at high temporal resolution, and successful future mission development will rely on mission concepts that both demonstrate a new technology and show that there is a distinct advantage to using that technology over existing capabilities to solve science questions that cannot otherwise be answered. CYGNSS is another great example of using first-of-its-kind technology (GNSS-R) coupled with a SmallSat concept to produce a new type of observation revealing new understanding of the Earth system. The community was encouraged to identify additional mature technology concepts that could be implemented as SmallSats for future NASA proposal opportunities.

Panel Discussion on Mission Synergies

Multiple currently operating or near-future satellite missions could benefit from or be benefitted by CYGNSS. Short presentations representing current or future missions and use of ocean surface winds from previous scatterometer satellite missions were highlighted to demonstrate potential synergies with CYGNSS.

During the workshop, Dr. Dara Entakabi, MIT, SMAP Principal Investigator, gave a keynote address on the SMAP Applications efforts, entitled "Meeting the needs of the Land Hydrology Community with SMAP." During the address, as well as in subsequent breakout sessions and during the panel discussion, potential synergies and collaborative opportunities between SMAP and CYGNSS were explored.

TROPICS is a NASA-funded constellation of SmallSats and a sibling mission to CYGNSS focused on collecting passive microwave observations of temperature and water vapor soundings and precipitation with temporal refresh of better than 60 minutes over the tropics. With a launch scheduled for 2020, it is expected that TROPICS and CYGNSS will both be flying at the same time for at least a year. This overlap will allow researchers the opportunity to see high temporal resolution surface winds from CYGNSS and temperature and water vapor from TROPICS. There will be opportunities to do joint calibration/validation or observing system experiments (OSEs) with data from the two missions, and through merging of capabilities, secondary products, such as a variety of flux parameters may be able to be derived. TROPICS also has similar latency challenges to CYGNSS related to S-band downlink to ground sites. There is the potential that some of the lessons learned between these two missions could result in reduced costs for lower latency observations to support applications.

Synergies with the NASA Soil Moisture Active Passive (SMAP) mission focused on the ability of CYGNSS to produce high-quality soil moisture observations over land with higher temporal and spatial resolution than SMAP. Combining the L-band data from CYGNSS with the passive soil moisture retrieval from SMAP may lead to new data products or cross validation. Additionally, because of the temporal resolution of CYGNSS, diurnal patterns in soil moisture will be more readily observed than from SMAP, which has a 2 or 3 day revisit. Observations from CYGNSS could be used to fill in these temporal gaps in the SMAP data record. In addition, SMAP has the capability of observing wind speed over the ocean, which could potentially be used for cross validation of CYGNSS wind speed observations.

From the operational perspective, NOAA uses ocean winds for data display, situational awareness, and data assimilation to support a number of weather and wave forecasting and transportation applications. NOAA has been provided real-time access to scatterometer wind measurements from previous missions, such as QuikSCAT and ASCAT, because 10% of warning decisions are impacted by wind speeds. Observations from CYGNSS—if data are consistent, reliable, and high-quality—could be used to complement existing scatterometer wind measurements and fill in temporal and spatial gaps where polar-orbiting scatterometer measurements miss some diurnal wind features. NOAA specifically noted a strong need to develop training to support forecaster use of GNSS-R ocean wind speed observations because they are a fundamentally new measurement compared to the previously-used scatterometer winds. Focusing on the strengths and limitations of these new measurements will be critical to get forecaster buy-in for use of these data for operational decision making. Users need to understand how to use this new information as a complementary dataset to other information sources.

Conclusion

The CYGNSS mission status update with a summary of routine and major operations and observations was delivered by the mission Principal Investigator, Dr. Chris Ruf, University of Michigan. An overview of CYGNSS science team activities and results from the 2017 hurricane season was given by Dr. Sharan Majumdar, University of Miami.

The workshop provided several opportunities for the science team to interact and engage with the applications community to fully develop applications science and data assimilation for CYGNSS observations. This entailed a review of applications development projects that were awarded to extended CYGNSS Science Team members via NASA ROSES solicitations. Many of these projects focused on applications concepts identified in a June 2015 pre-launch applications development workshop in Silver Spring, MD. Plenary and breakout sessions identified applications related to tropical cyclones, large and small scale tropical and non-tropical oscillations, terrestrial applications such as soil moisture detection and water mapping, oceanographic applications for ocean currents and wave modeling, and data assimilation considerations related to all these phenomena. The extensive report from the 2015 pre-launch workshop report including detailed Applications Traceability Matrices is available for review here. Additional new and innovative applications projects such as ocean surface topography and tsunami detection were reviewed at the Monterey workshop.

End-user community engagement was emphasized during the breakout sessions to narrow down and prioritize the full spectrum of thematic applications using the three unique classes of CYGNSS data:

1. (Level 1 Oceanic DDM's) Raw Delay Doppler Maps for direct assimilation into weather and ocean models.

2. (Level 2 and 3 Winds) Un-gridded and gridded oceanic surface wind speeds used for wind, weather, oceanographic and hybrid applications.

3. Terrestrial Level 1 data for soil moisture, surface water and wetland mapping.

Broad stakeholder engagement to address issues such as data latency and the complementarity of CYGNSS with current and future satellite and non-satellite missions began with the inclusion of representatives of complimentary missions (SMAP and TROPICS) in the workshop, with a focus on affiliating and leveraging the applications efforts for those missions. The SMAP Principal Investigator, Dr. Dara Entakabi of MIT, also presented a targeted presentation proposing to use CYGNSS to fill key data gaps for his mission and to work with the CYGNSS applications team to cross-pollinate towards this end, and to share applications development expertise. The workshop also focused on improving small sat applications paradigms in general with a superb industry panel conducted for that purpose.

Please refer to the agendas for the 2015 and 2017 applications workshops which contain active links to each of the presentations from these two workshops.