NASA/CP–2015-218993

NASA CYGNSS Mission Applications Workshop

Compiled by

Aimee V. Amin
Science Systems and Applications, Inc., Hampton, Virginia

December 2015

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Proceedings of NASA CYGNSS Mission Applications Workshop sponsored by the National Aeronautics and Space Administration and held in Silver Spring, Maryland
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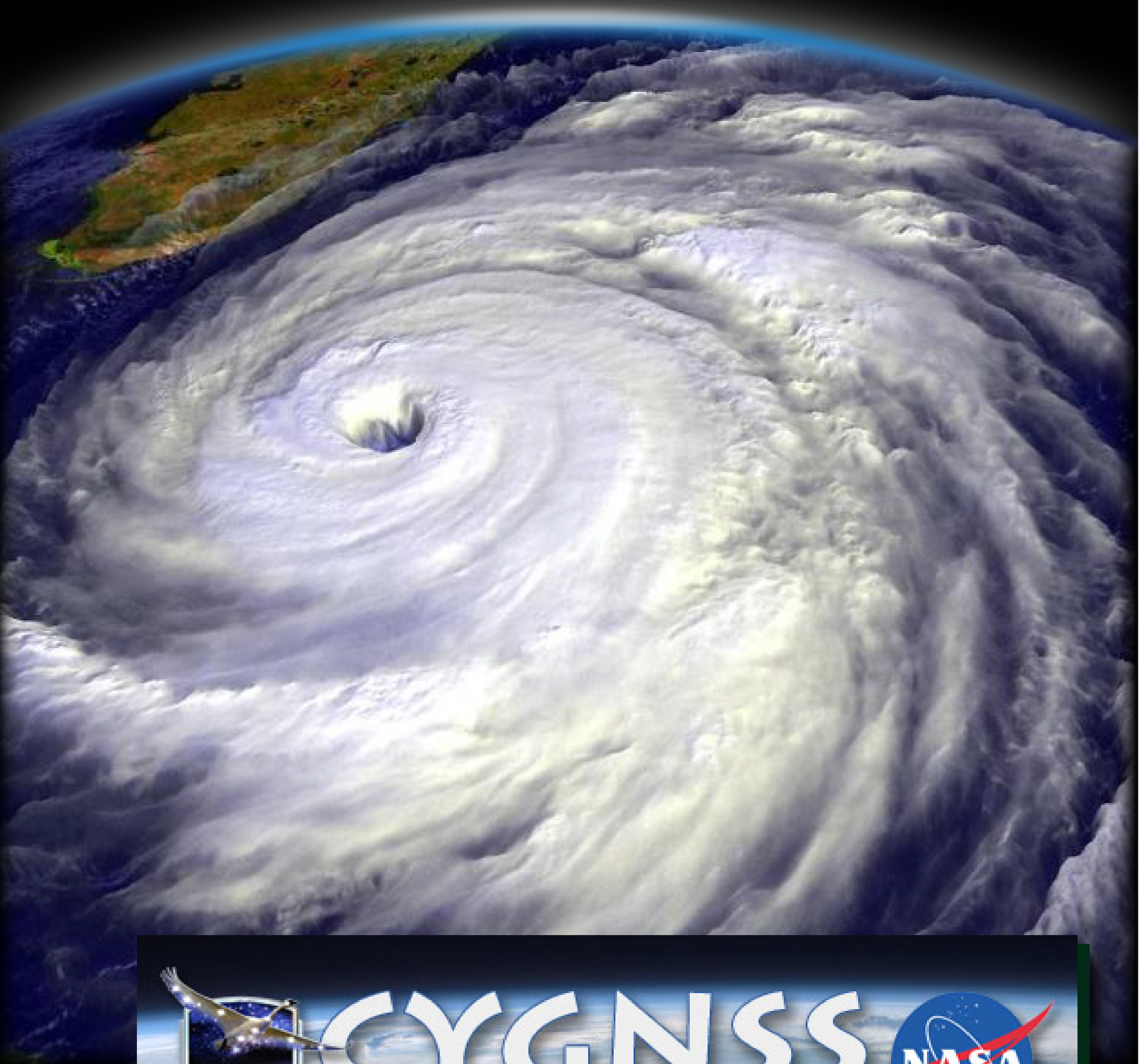
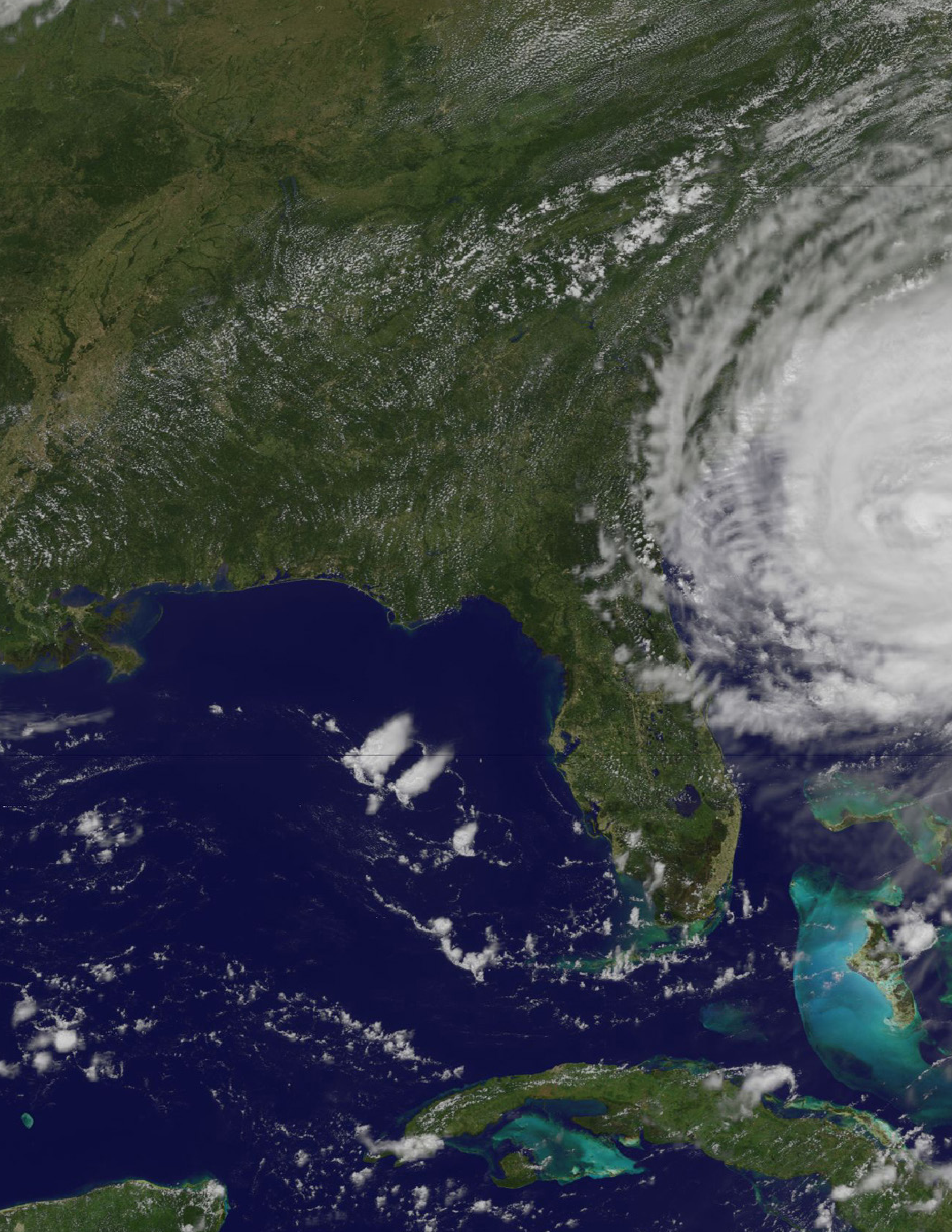


CYGNSS Applications Workshop



Report on the NASA CYGNSS Mission Applications Workshop

May 27-29, 2015 | Silver Spring, MD

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6. Univ. Colorado | 7. ERT Inc. | 8. NOAA NESDIS | 9. NASA GSFC | 10. NASA GMAO
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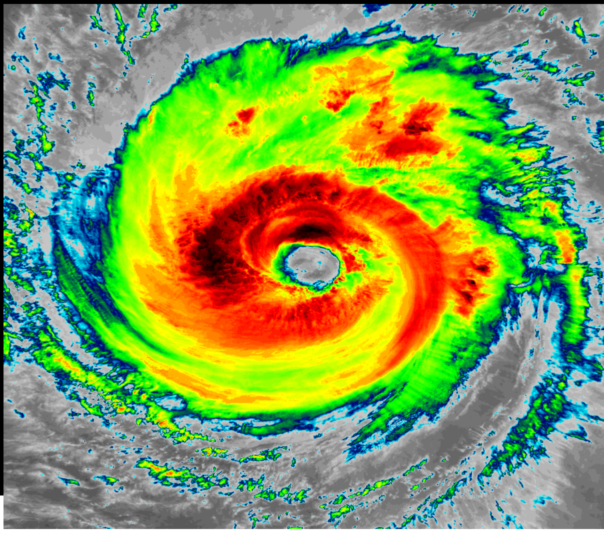


EXECUTIVE SUMMARY

NASA's Cyclone Global Navigation Satellite System, (CYGNSS), mission is a constellation of eight microsatellites that will measure surface winds in and near the inner cores of hurricanes, including regions beneath the eyewall and intense inner rainbands that could not previously be measured from space. The CYGNSS-measured wind fields, when combined with precipitation fields (e.g., produced by the Global Precipitation Measurement [GPM] core satellite and its constellation of precipitation imagers), will provide coupled observations of moist atmospheric thermodynamics and ocean surface response, enabling new insights into hurricane inner core dynamics and energetics.

The CYGNSS data will enable scientists to probe key air-sea interaction processes that take place near the core of the storms – processes that are rapidly changing and play a critical role in the genesis and intensification of hurricanes. The surface wind data collected by the CYGNSS constellation of microsatellites is expected to lead to:

- Improved spatial and temporal resolution of the surface wind field within the precipitating core of hurricanes.
- Improved understanding of the momentum and energy fluxes at the air-sea interface within the core of hurricanes and the role of these fluxes in the maintenance and intensification of these storms.
- Improved forecasting capabilities of hurricane intensification.

In addition to addressing these primary mission areas, this workshop also explored applications of soil moisture, hydrology, coastal flooding, ocean wave modeling and data assimilation. Combined, these accomplishments will allow NASA scientists and hurricane forecasters to provide improved advance warning of hurricane intensification, movement and storm surge location and magnitude, thus aiding in the protection of human life and coastal community preparedness.

The outcomes of this workshop, which are detailed in this report, comprise two primary elements:

- A report of workshop proceedings, and;
- Detailed Applications Traceability Matrices with requirements and operational considerations to serve broadly for development of value-added tools, applications, and products;

In addition, this workshop successfully assembled a broad user team to ensure we are reaching a large applications community that will improve and use applications enabled by the participants of this workshop, and establish a plan for a products working group.

In the areas of Modeling, Forecasting, and Tropical Convection applications, we recommend using CYGNSS to improve forecast model representation of the Madden-Julian Oscillation (MJO). The ability to provide fast-repeat wind sampling unbiased by the presence of precipitation should enable improved observations of convectively induced phenomena such as Westerly Wind Bursts (WWBs) and gust fronts. While lower data latency is always preferred, an MJO can last for several weeks, and CYGNSS data at standard latencies should still make a positive impact in longer-term forecasts of MJO position and strength. For these same reasons, CYGNSS will be a valuable source of observations for the verification of other ocean surface wind measurements and numerical weather forecasts. There also are studies planned and applications that may be developed where the current data latency will not be a concern. Additionally, we noted that the CYGNSS fast-repeat wind sampling, especially in precipitating regions, will complement existing polar satellite ocean surface winds and should improve the prediction of atmospheric phenomena with connections to the tropics, such as monsoons, atmospheric rivers, and the extratropical transitions of tropical cyclones. For these forecasting applications, a lower data latency would be needed. We also noted that CYGNSS observations will provide a unique data source for coupled atmosphere/wave/ocean data assimilation and modeling - an active area of research which promises to extend numerical weather forecasting to the subseasonal to seasonal range.

For monitoring of Tropical Cyclones, we recommend the use of CYGNSS surface wind data to assess the intensity and intensity change rate that is critical for coastal preparations to protect life and property in landfalling storms. Of course, real-time monitoring applications will depend on rapid dissemination of data. Tropical Cyclone applications that will also benefit from CYGNSS wind data are coupled atmosphere-ocean model numerical forecasts than can assimilate the unique inner-core observations. In addition, these data may lead to better understanding of the energy and momentum transfers in tropical cyclones which are important for improved predictions.

In the area of Coastal, Terrestrial, and Hydrological applications, we recommend pursuing soil moisture and wetlands extent mapping when CYGNSS samples the continental surfaces. These two applications are the most mature and aligned with the existing capabilities of the L-band sensor and mission design. The fast-repeat sampling characteristics of CYGNSS measurements of soil moisture would add value to existing sensors and possibly allow studies of sub-diurnal soil moisture, crop evolution, and flood forecasting. The forward-scattering geometry also makes wetlands extent mapping a logical application and would be high impact since other sensors have difficulty in these conditions. To achieve these two application goals, we strongly recommend that a variable or shorter incoherent integration time be implemented for the land and inland water surface-reflected signals (potentially using a land mask). A shorter integration time would allow better along-track spatial resolution and subsequent discrimination of changes in surface properties.

In the areas of Physical Oceanography and surface wave applications, we recommend performing the retrospective research required to improve stand-alone global predictions of the ocean and surface waves, and also to improve coupled atmosphere-ocean-wave forecasts for both regional TC and global weather prediction applications. Optimal assimilation of CYGNSS wind measurements by atmospheric models now, and by all components of coupled prediction systems in the future using coupled assimilation methods, is the key step toward achieving forecast improvements. More accurate estimation of surface fluxes along with improved surface wind analysis products generated using CYGNSS observations will be highly valuable for evaluating and improving the performance of ocean and wave models within coupled systems. This retrospective work can be performed using the initial planned data latency while successful demonstration of improvements can provide justification for the reduced latency required to improve operational real-time forecasts. Another application achievable in a reasonable time frame is to use Level 3 CYGNSS products in conjunction with other atmosphere-ocean observations to study climate modes such as the MJO and ENSO cycle that have signatures over the tropics and subtropics.

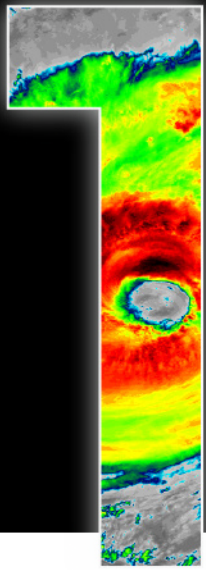
The CYGNSS Mission was initially conceived to address the need to improve tropical cyclone intensity forecasts. More broadly, in the areas of numerical weather forecasting, and storm surge forecasting, the potential value of developing a fully coupled atmosphere and ocean model and data assimilation strategy stands out. This coupling of weather, air-sea interactions and dynamical oceanography is something that the members of the CYGNSS science definition team have already started to address, and there is general agreement that the pay-off in developing applications based on this capability could be huge. For example, in the terrestrial hydrology area, there is an immediate need for a calibrated Level 1 science data product over land. The current Level 1 calibration is specific to the ocean and uses an Earth surface geoid model, rather than the Digital Elevation Map (DEM) needed to work for land surfaces that are not close to sea level. After that, Level 2 algorithm development might be undertaken to produce science data products like soil moisture and related applications. These Level 2 products would then need to be calibrated and validated, and this effort could possibly leverage the instrumented watersheds that have already been developed by NASA for SMAP. Finally, there was a broad and general consensus in each of the workshop breakout sessions that lower data latency would be required to support the development of applications for a wide range of operational data users. This cuts across all of the application areas to some degree, and for some of them, it is a critical enabler that must be considered.

Several months after the launch of the CYGNSS Mission, currently scheduled for October 2016, the constellation of eight GNSS-equipped satellites which comprise the CYGNSS constellation is planned to have dispersed into formation to provide reflected GNSS data over wide areas. Before then, however, the TechDemoSat-1 mission, a technology demonstration satellite which was launched in July 2014 has been taking data from a single receiver. This data was scheduled for released in the fall of 2015, and it is hoped that it will provide valuable insights for the planning of the next CYGNSS Applications workshop, anticipated for soon after the CYGNSS mission is launched.

Building upon the first Workshop which is the subject of this report, and which entailed the identification of fundamental sciences questions and their potential applications, the focus of the second workshop will be on applications needs and opportunities for the entire panoply of CYGNSS applications to end-users. These users are expected to represent a very broad and diverse swath of the public and private sectors. This will better orient NASA to conduct the Observing System Simulation Experiments

(OSSEs), modeling and data assimilation, and the sector-specific research that will be needed to build viable applications for CYGNSS data. A concurrent effort for effective outreach and operational implementation through robust activities such as an Early Adopter program will also be conducted.

While NASA is not an operational agency, it produces ground-breaking technologies, data and information and accelerates its transition to operations. The NASA Applied Sciences Program's Disasters Area is taking the lead in the development and operational implementation of these applications, many of which are hoped to improve various aspects of national and international disaster planning, response, recovery and mitigation. To accomplish this, NASA will continue to work closely with the science and applications communities and, especially, to identify and engage the many potential end-users of CYGNSS data and products.



INTRODUCTION

Scientists from the federal government, research, academia and the private sector met at the NOAA Federal Complex in Silver Spring from May 27-29 for the first CYGNSS Applications Workshop. The overall focus of the first CYGNSS Applications Workshop was to create an initial bridge between science and applications. As such, it was science and research oriented, but with applications as the driver. The primary goal of the workshop was to foster community awareness and engagement with government, academia and private sector to identify CYGNSS applications and related science research needs to maximize impact and benefits of the mission. To accomplish this, 73 participants from key organizations participated, comprising a diverse group of representatives from NASA HQ and four NASA Centers, 5 NOAA Line Offices (operations and research); the US Navy (ONR/NRL), NCAR/UCAR, 13 Universities, and 10 private sector companies. Appendix B is germane.

Over the course of the three days, keynote addresses were given by Dr. Jack Kaye and Mr. Lawrence Friedl of NASA, Dr. Dan Eleuterio of ONR and Dr. Steve Volz, Dr. Rick Spinrad and Dr. Sandy MacDonald of NOAA. To accomplish the workshop's goals and objectives, three breakout teams were comprised, which identified fundamental science questions and related applications development information for the mission. It is their work which forms the crux of this report.

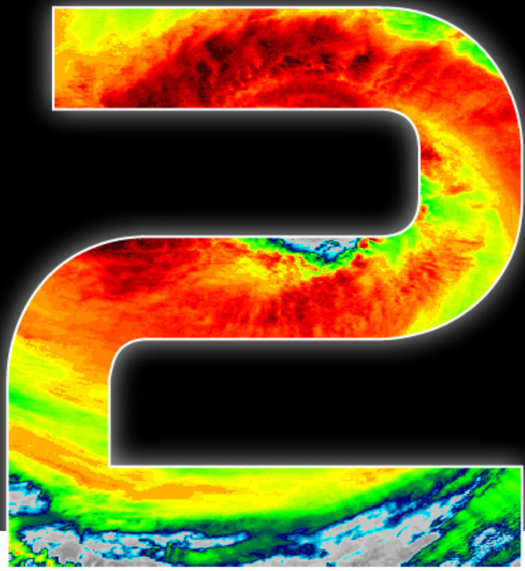
There were a number of key outcomes from this workshop which are expounded upon in detail in this report. Summarizing them at a very high level, the workshop identified applications for the following three areas which are listed in the Applications Traceability Matrices contained in Appendix B of this report:

- Modeling and Forecasting Applications (Data Assimilation, Tropical Cyclone intensity, Tropical Convection forecasting, Atmospheric Rivers, ENSO, MJO),
- Oceanographic Applications (winds, currents, storm surge, and related applications for users ranging from FEMA to maritime and wind power industries) and,
- Terrestrial Applications (soil moisture and concomitant areas including, floods, landslides; coastal inundation, wetland management, alone or with a potentially heavy reliance on complimentary observing systems).

The workshop also initiated Early Adopters outreach, and ended with a discussion on next steps, including the planning of the next CYGNSS Applications Workshop. It is envisioned that it will shift emphasis from the basic science needed to develop applications to the user-based applications development needed to address the full gamut of NASA Applied

Sciences Applications areas, the transition of these applications to the operational forecasting community and to other elements of the public and private sector for which they may provide much-needed capabilities.

The general consensus was that this workshop was a watershed event for all of the attendees, their affiliated organizations and all interested parties to begin to begin to work together to develop the many needed applications that will maximize the utility and impact of CYGNSS.



2.1 SCIENCE MOTIVATION

Previous spaceborne measurements of ocean surface vector winds have suffered from degradation in highly precipitating regimes, as was the case for QuikScat. As a result, in the absence of reconnaissance aircraft, the accuracy of wind speed estimates in the inner core of the hurricane is often highly compromised. Mesoscale Convective Systems (MCSs) contribute more than half of the total rainfall in the tropics and serve as the precursors to TCs. Over the ocean, the organization of the fluxes depends on a complex interaction between surface level winds and storm dynamics. Their development and characteristics depend critically on the interaction between ocean surface properties, moist atmospheric thermodynamics, radiation, and convective dynamics.

Most current spaceborne active and passive microwave instruments are in polar low earth orbit (LEO). LEO maximizes global coverage but can result in large gaps in the tropics [Schlax et al, 2001] present a comprehensive analysis of the sampling characteristics of conventional polar-orbiting, swath-based imaging systems, including consideration of so-called tandem missions. The study demonstrates that a single, wide-swath, high-resolution scatterometer system cannot resolve synoptic scale spatial detail everywhere on the globe, and in particular not in the tropics. The irregular and infrequent revisit times (ca. 11-35 hrs) are likewise not sufficient to resolve synoptic scale temporal variability. As a striking example, Figure 1 shows the percentage of time that the core of every tropical depression, storm and cyclone from the 2007 Atlantic and Pacific seasons was successfully imaged by QuikScat or ASCAT. Missed core imaging events can occur when an organized system passes through an imager's coverage gap or when its motion is appropriately offset from the motion of the imager's swath. The figure highlights the many cases in which TCs are resolved much less than half the time. One particularly egregious case is Hurricane Dean, which was sampled less than 5% of the time possible by ASCAT.

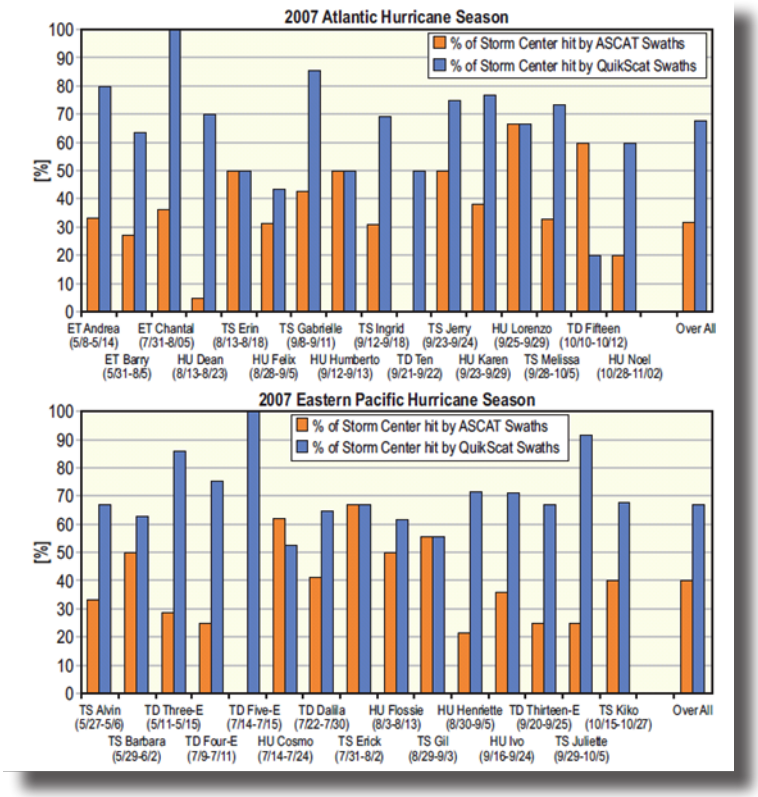


Figure 1. Percentage of time the center of named storms was observed with either QuikScat (blue) or ASCAT (orange) polar-orbiting scatterometers during the 2007 Atlantic (top) and Pacific (bottom) hurricane season. Poor performance results from the coverage gaps and infrequent revisit times that are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

2.2 MEASUREMENT METHODOLOGY

Figure 2 illustrates the propagation and scattering geometries associated with the GNSS approach to ocean surface scatterometry. The direct GPS signal provides a coherent reference for the coded GPS transmit signal. It is received by an RHCP receive antenna on the zenith side of the spacecraft. The quasi-specular forward scattered signal from the ocean surface is received by a downward looking, LHCP antenna on the nadir side of the spacecraft. The scattered signal contains detailed information about its roughness statistics, from which local wind speed can be derived [Zavorotny and Voronovich, 2000]. The scattering cross-section image produced by the UK-DMC-1 demonstration spaceborne mission is shown in Figure 2. Variable lag correlation and Doppler shift, the two coordinates of the image, enable the spatial distribution of the scattering cross section to be resolved [Gleason et al., 2005; Gleason, 2007]. This type of scattering image is referred to as a Delay Doppler Map (DDM). Estimation of the ocean surface roughness and near-surface wind speed is possible from two properties of the DDM. The maximum scattering cross-section (the dark red region in Figure 2) can be related to roughness and wind speed. This requires absolute calibration of the DDM. Wind speed can also be estimated from a relatively calibrated DDM by the shape of the scattering arc (the red and yellow regions in Figure 2). The arc represents the departure of the actual bi-static scattering from the purely specular case that would correspond to a perfectly flat ocean surface, which appear in the DDM as a single point scatterer. The latter approach imposes more relaxed requirements on instrument calibration and stability than does the former. However, it derives its wind speed estimate from a wider region of the ocean surface and so necessarily has poorer spatial resolution.

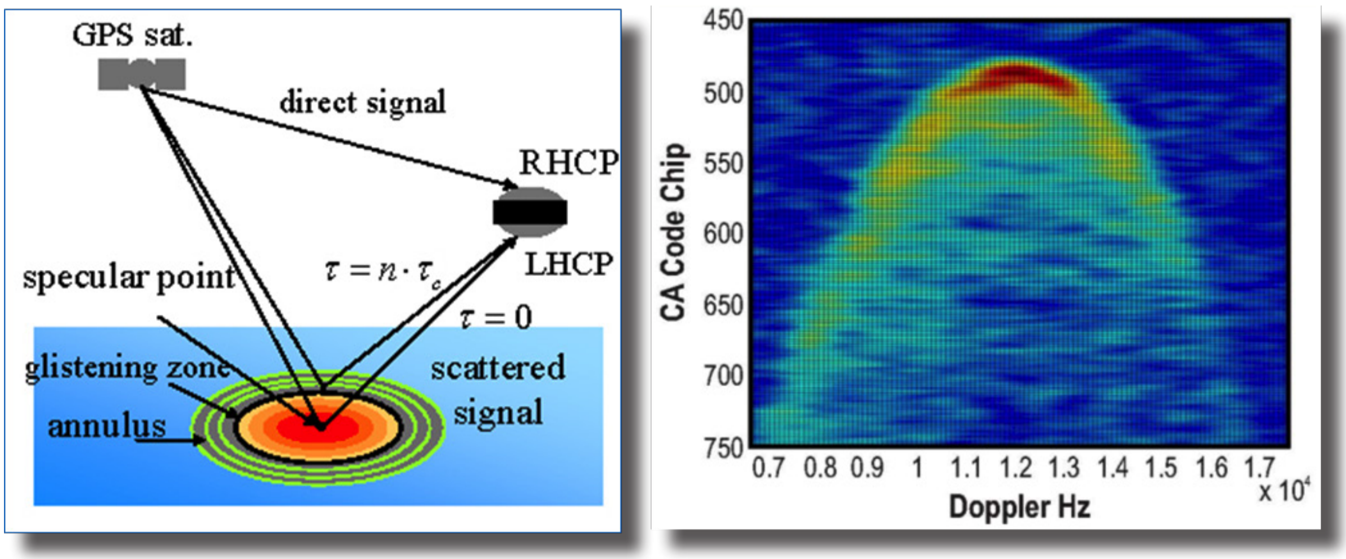


Figure 2. GPS signal propagation and scattering geometries for ocean surface bistatic quasi-specular scatterometry. (right) Spatial distribution of the ocean surface scattering measured by the UK-DMC-1 demonstration spaceborne mission - referred to as the Delay Doppler Map (DDM) [Gleason, 2007].

2.3 MISSION DESIGN

The CYGNSS mission will employ a constellation of eight microsatellite Observatories in LEO (510 km altitude at 35 degree orbit inclination). Each CYGNSS Observatory will consist of a microsatellite platform hosting a GPS receiver modified to measure surface reflected signals. Similar GPS-based instruments have been demonstrated on both airborne and spaceborne platforms to retrieve wind speeds as high as 60 meters per second (a Category 4 hurricane) through all levels of precipitation, including the intense levels experienced in a TC eyewall [Katzberg et al, 2001].

Each observatory simultaneously tracks scattered signals from up to four independent transmitters in the operational GPS network. The number of Observatories and orbit inclination are chosen to optimize the TC sampling properties. As shown in Figure 3, the result is a dense cross-hatch of sample points on the ground that cover the critical latitude band between ±35 degrees.

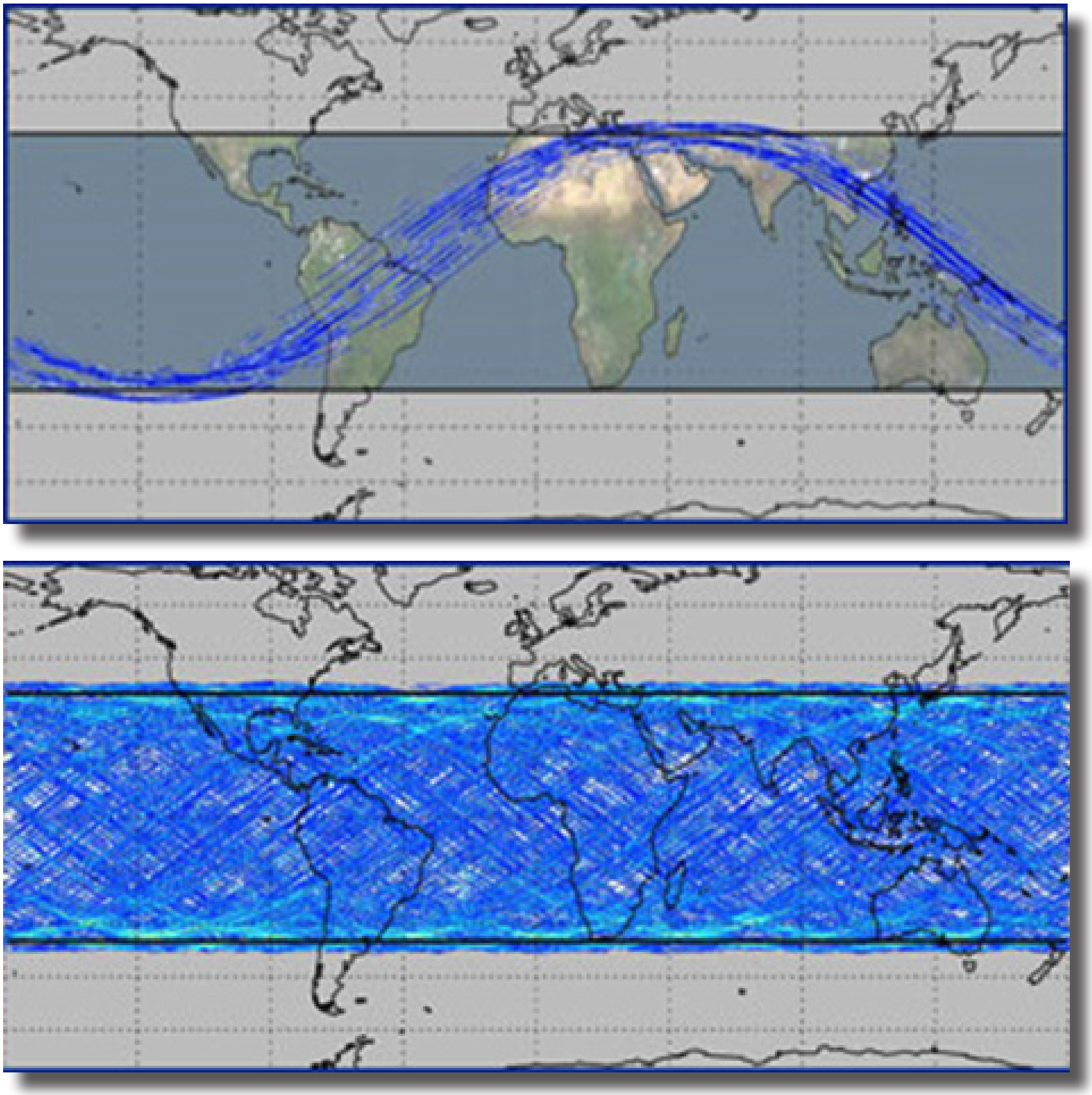
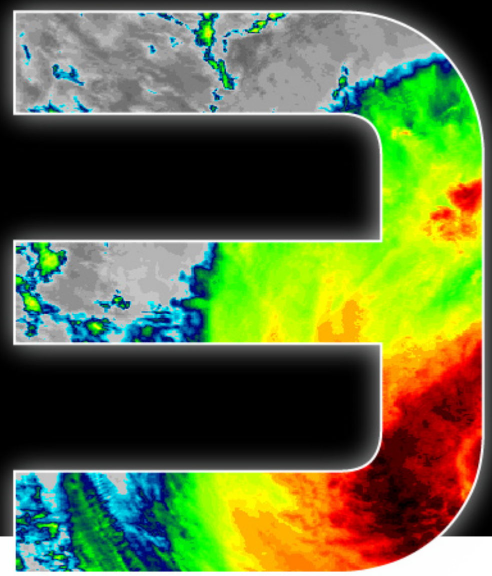


Figure 3. The eight CYGNSS Observatories will orbit at an inclination of 35 degrees and are each capable of measuring four simultaneous reflections, resulting in 32 wind measurements per second across the globe. Ground tracks for 90 minutes (top) and for a full day (bottom) of wind samples are shown above. The number of CYGNSS Observatories, their orbit altitudes and inclinations, and the alignment of the antennas, will be optimized to provide unprecedented high temporal-resolution wind field imagery of TC genesis, intensification and decay.

A comprehensive overview of the CYGNSS mission is available here: http://clasp-research.engin.umich.edu/missions/cygnss/appswkshp2015/presentations/Ruf_CYGNSS_Apps_Wkshp_150527.pdf .



3.1 REMARKS AND KEYNOTE ADDRESSES FROM FEDERAL AGENCY PRINCIPALS

3.1.1 Dr. Jack Kaye, NASA Science Mission Directorate, R&A Programs

Jack Kaye (NASA HQ) provided welcoming remarks and presented a summary of recent activity at NASA's Earth Science Division (ESD). This included the status of missions launched in the past year (the five from 2/14 through 1/15 that served as the basis for the "Earth Right Now" campaign), the operating missions, and missions in development, formulation, and preformulation. He also described airborne activities, as well as current activities within the research and analysis program. He reviewed some of the major interagency and international activities in which ESD is engaged and described the broader external environment in which ESD functions.

3.1.2 Mr. Lawrence Friedl, Director, NASA Applied Science Program

Lawrence Friedl (NASA HQ) also welcomed the workshop attendees and thanked the host and organizers of the workshop. He briefly described the NASA Applied Sciences Program and its three main lines of business on applications, capacity building, and support to mission planning. He focused on NASA's activities to include end users and applications-oriented people in the mission development phases, especially so they can begin using the data soon after it becomes available. He noted that the use of the observations to inform near-term decisions increases the value of the missions beyond their research benefits. He commented that NASA Earth Science has pursued several paths to increase the involvement of applications communities in the missions, such as workshops and an Early Adopters program. He noted that NASA has already seen where the involvement of applications users in mission planning has led to insightful feedback on data products and changes that would make the data more broadly usable. He expressed his appreciation to the CYGNSS team for their attention to applications as part of their overall mission. He commented that he was looking ahead to the findings and wished everyone a productive workshop.

3.1.3 CAPT Joe Pica, NOAA Operations Officer

Captain Joe Pica, Acting Director for the National Weather Service (NWS) Office of Observations, welcomed everyone to the workshop on behalf of NOAA. He outlined his role in managing the new Observation Portfolio in the NWS addressing observation requirements to support mission service areas that provide for a Weather Ready Nation, one where the public/users makes informed decisions based on forecasts. He reflected on his personal experience as commanding officer of two of NOAA's scientific ships and utilizing forecasts to avoid tropical systems and safely conduct operations at sea. In conclusion, Captain Pica provided his wishes for a productive and outstanding workshop.

3.1.4 Dr. Steven Volz, Assistant Administrator, NOAA National Environmental Satellite Data and Information Service, Summary of Improved Services through the NASA/NOAA Earth Science Partnership Presentation

Dr. Volz began his presentation with introductory points where he discussed how NASA can assist NOAA to address the challenges of developing a cost-effective satellite architecture, which evolves from today's model of a limited number of complex platforms with many sensors and limited orbital planes, to a disaggregated heterogeneous satellite architecture with many platforms and many orbital planes, but with limited number of sensors and decreased platform size and complexity.

In addition to system engineering, Dr. Volz outlined where NASA and NOAA have many opportunities for collaborative research in weather, climate, water, energy cycle, and earth surface understanding, all of which have the potential for tangible societal benefits. Dr. Volz provided a roadmap of how science/service collaboration could be linked directly to specific high impact weather predictability such as hurricane track forecasts, winter storm warnings, and seasonal predictions of drought and water resources.

In closing, through the CYGNSS mission, Dr. Volz discussed how NASA and NOAA can build on their shared history of collaboration to identify opportunities for leveraging hybrid observing system architectures, developing innovative data assimilation and applications, and ultimately providing improved service to society. Dr. Volz's presentation is available here:
http://clasp-research.engin.umich.edu/missions/cygnss/appswkshp2015/presentations/cygnss_keynote-dr-volz-28may2015-rev1.pdf .

3.1.5 Dr. Daniel Eleuterio, Office of Naval Research

Dr. Eleuterio began his presentation with an overview of Navy Oceanography challenges. He emphasized that the mission of Naval Oceanography is to provide worldwide analysis and forecasts to support Navy Operations – from the tropics to the poles, from the depths of the ocean to the edges of space and across coastlines to support stability of operations, humanitarian assistance, and disaster relief.

This introduction was followed by a brief overview of the goals for the interagency collaborative National Earth System Prediction Capability effort between DoD, NOAA, DoE, NASA, and NSF. The ESPC goals are to accelerate research into operational capabilities for improved global medium range (defined as out to ~90 days) and long range (seasonal to decadal) prediction of weather, ocean, and sea ice conditions to address national security and societal impacts of the environment.

Dr. Eleuterio then highlighted the Navy's contribution to ESPC with the ongoing implementation of a future operational global coupled ensemble based on the NAVGEM, GOFS (Global Ocean Forecast system – HYCOM plus CICE), and WaveWatch III models integrated through the Earth System Model Framework (ESMF) architecture. Additionally, ongoing work in coupled air-sea processes is being conducted using the mesoscale COAMPS-TC/NCOM coupled models for tropical and midlatitude processes, and a Regional Arctic Coupled Forecast System is under development. He noted that future capabilities would include coupling with the aerosol forecast model NAAPS in the COAMPS and NAVGEM ensembles.

ONR's Tropical Field Campaigns from the past 20+ years were presented next. The Field Campaigns combine intensive observing periods (with supplemental observing platforms) and a focused research topic aimed at developing an improved understanding of the dynamics and physics of tropical systems. These Field Campaigns started with Tropical Cyclone Motion (TCM) in the 1990's, and continues with CBLAST, TCS-08/T-PARC, ITOP, DYNAMO, and continue to this day with Tropical Cyclone Outflow and Intensification (TCI-14/15) campaign. The objectives for CYGNSS project well onto both the TCI project in the Atlantic/Gulf of Mexico and the upcoming 2018 Field Campaign in the Philippine Sea with its emphasis on the Propagation of Intra-Seasonal Tropical Oscillations (PISTON).

Dr. Eleuterio remarked that CYGNSS observations were complementary to current Navy WindSat ocean surface wind vectors and DoD DMSP SSMIS ocean surface wind speeds, but with the added advantage of being able to penetrate precipitation. He concluded his talk by highlighting several areas of CYGNSS research funded by the Navy. These include assimilation of CYGNSS winds into COAMPS-TC using 4DVar, assimilation of CYGNSS Mean Square Slope into WaveWatch III, and developing advanced reflectivity and emissivity models for L-band passive and active (CYGNSS and SMAP) retrievals under high wind conditions. Dr. Eluterio's presentation is available here:
http://clasp-research.engin.umich.edu/missions/cygnss/appswkshp2015/presentations/Eleuterio-ONR-CYGNSS-Presentation.pdf .

3.1.6 Dr. Rick Spinrad, Chief Scientist, NOAA, Summary of NOAA's Mission-Optimized Research

Dr. Spinrad's introduction, he emphasized that NOAA is a science-based service agency with a mission critically dependent upon understanding and predicting the Earth system. As a service agency, mission-optimized research must have clear alignment with organizational priorities and capabilities. Dr. Spinrad discussed his position as chief scientist which included managing the NOAA research portfolio by articulating research priorities, managing research portfolio investments and facilitating collaboration across NOAA's Line Offices and Cooperative Institutes. Research priorities must be consistent with strategic priorities, to include Office of Science and Technology Policy (OSTP), Department and Agency guidance. Research portfolio has a multi-year strategic time horizon that manages the research-to-operations process.

Dr. Spinrad discussed how the CYGNSS mission aligns with NOAA's high priority research objectives including hurricane inner core dynamics to improve predictability of storm genesis and rapid intensification. He gave examples of how improved understanding of sea surface winds and could lead

to more accurate El Nino seasonal predictions. Finally, Dr. Spinrad highlighted how improved ocean wind characterization could improve understanding of ocean upwelling dynamics, ocean acidification and harmful algal blooms. Dr. Spinrad's presentation is available here:
http://clasp-research.engin.umich.edu/missions/cygnss/appswkshp2015/presentations/Spinrad_CYGNSS_FINAL_NoNotes.pdf .

3.1.7 Dr. Alexander MacDonald, Director NOAA Earth System Research Laboratory and President, American Meteorological Society (AMS), CYGNSS: Earth System Science In Service to Society

Dr. MacDonald's presentation was the final NOAA briefing, complementing Capt. Pica, Dr. Volz, and Dr. Spinrad's briefings with a focus on the nature of long-term predictability, and specifically the influence of the tropics on predictability. Dr. MacDonald provided model simulations which illustrate the exchange of energy from the tropics to the mid-latitudes primarily through recurving tropical cyclones and the resulting influence on mid-latitude waves. His briefing included an example of a Hurricane Sandy tracks affects energy exchange between the tropics, and key to improving multi-week weather forecast. Dr. MacDonald concluded that with CYGNSS improved monitoring of equatorial winds, prediction of energy exchange from the tropics will be improved, and ultimately long-range weather forecasts. Dr. MacDonald's presentation can be found here:
http://clasp-research.engin.umich.edu/missions/cygnss/appswkshp2015/presentations/Macdonald-CYGNSS27may15.pdf .

3.2 TOPICAL PLENARY PRESENTATIONS

3.2.1 Dr. William McCarty, NASA Global Modeling and Assimilation Office, Summary of Data Assimilation Presentation

Dr. McCarty presented a talk entitled, "Data Assimilation for the CYGNSS Mission" that provided an overview of the concept of data assimilation and the role measurements from the mission will play in the field. Fundamentally, data assimilation seeks to combine information from observations and numerical models to provide an estimate of the state of a physical system. For the atmosphere, the observations provide real information, but are disparate and irregular in space and time. They generally have well-behaved and quantifiable error characteristics. Numerical weather prediction provides regularly-spaced and physically consistent information, but the errors are often systematic and difficult to characterize. It is the goal of data assimilation to utilize the strengths of both observations and models to determine the best estimate of the atmospheric state.

In atmospheric data assimilation, there are two key modes of operation. First is weather prediction, which requires timely delivery of the observations for near-real time numerical forecasts. Second is reanalysis, which aims to provide an estimate of the atmospheric state through the use of as many observations as possible regardless of data delivery. Fundamental to these two modes of operation is the issue of latency. Weather prediction requires data delivery to the major centers (e.g. NWS NCEP, ECMWF, NASA GMAO) with a latency typically less than 8 hours. For reanalysis, the latency is not an issue, but major reanalyses are only performed every few years, therefore an assessment of the impact of the assimilating the observations may take years to reach the end user.

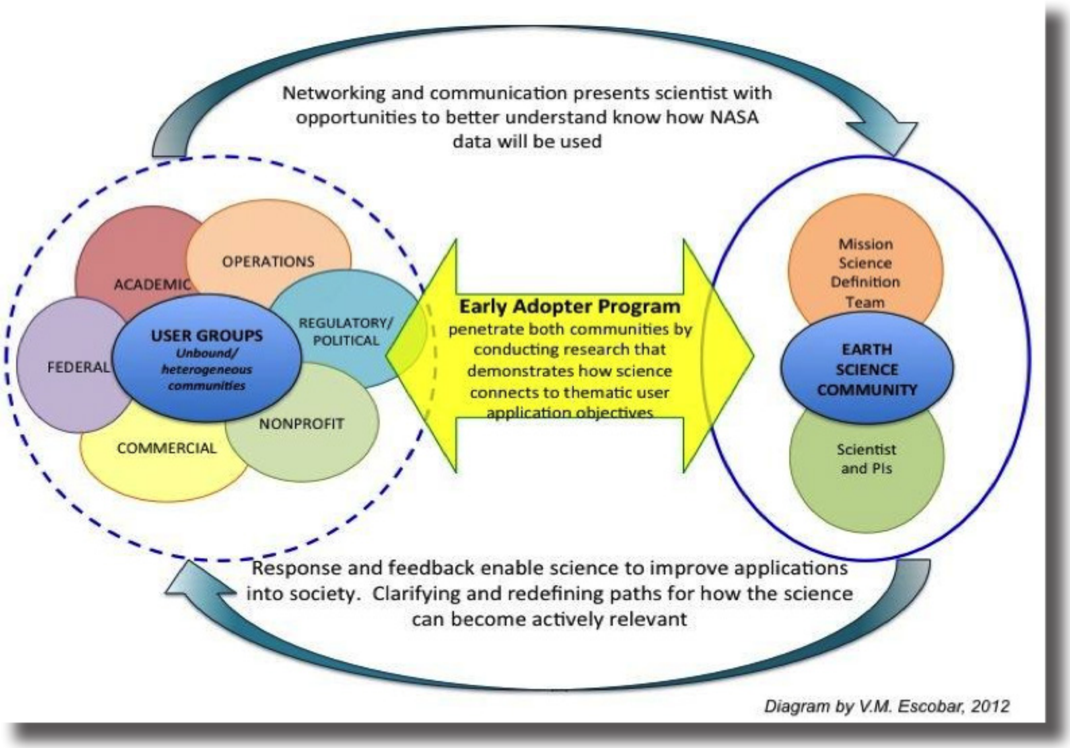
While it is difficult to quantify a priori of the post-launch impact of CYGNSS observations in data assimilation, it is noted, that they will fill an observation void of both very low and very high ocean wind speed measurements in global and regional data assimilation. Furthermore, the extension of modern data assimilation to four-dimensional ensemble/variational hybrid methods and the further increase in numerical model spatial resolution will result in the improved utilization of these observations in the context of data assimilation. Dr. McCarty's presentation is available here:
http://clasp-research.engin.umich.edu/missions/cygnss/appswkshp2015/presentations/McCarty-CYGNSS_Mtg.pdf .

3.2.2 Vanessa Escobar, NASA Goddard Space Flight Center, Summary of Early Adopter Presentation

Ms. Escobar presented a talk titled "Early Adopter Program overview for CYGNSS" in an effort to provide a format for a potential EA program for CYGNSS an establish guidelines for creating Early Adopter case studies. The Early Adopters are a subset of the mission user community and are defined as those:

- groups and individuals who have a direct or clearly defined need for CYGNSS data, who have key application of interest to the mission;
- who have the interest in utilizing proposed CYGNSS product(s); and
- who are capable of applying their own resources (funding, personnel, facilities, etc.) to demonstrate the utility of CYGNSS data for their particular system or model.

The EA program is an unfunded activity formalized with a statement of agreement the mission and the Early Adopter. The value of the EA program is the relationships built between the science community and the early adopter community. Each EA will be partnered with a mission SDT member who is developing a product for guidance and feedback. The EA will receives access to developmental products and interaction with the product developer enabling them to understand and integrate the new products into their systems and bringing added value to the applications of CYGNSS data in specific applications of interest. The CYGNSS SDT member will gain a partner who can evaluate products and offer feedback from a functionality perspective as well as potential calibration and validation information. The success of the Early Adopter program should ultimately be measured by how much increased visibility and uptake of CYGNSS data in decision-making applications has occurred.



Early adopters will agree to:

- Engage in pre-launch research that will enable integration of CYGNSS data after launch in their application;
- Complete the project with quantitative metrics prior to launch;
- Join the CYGNSS Applications User Community and to participate in discussions of CYGNSS mission data products related to application needs; and
- Participate in CYGNSS applications research, meetings, workshops, and related activities.

In turn, the CYGNSS Project agrees to:

- Incorporate Early Adopter contributions into the mission planning;
- Provide Early Adopters with simulated CYGNSS data products via the SDT and DAAC; and/or
- Provide Early Adopters with planned pre-launch calibration and validation (cal/val) data from CYGNSS field campaigns, modeling and synergistic studies

Satellite and airborne remote sensing datasets can be integrated into models and decision support systems that enable improved natural resource management, disaster prevention and response, and other benefits to society. The overarching purpose of the NASA Applied Sciences Program is to discover and demonstrate innovative uses and practical benefits of NASA Earth science data, scientific knowledge, and technology. Products from CYGNSS will yield additional societal benefit by developing a tailored Early Adopter Program. The goal of the CYGNSS Early Adopter Program is to provide specific support to Early Adopters in pre-launch applied research to facilitate feedback on CYGNSS product(s) pre-launch, and accelerate the use of CYGNSS product(s) and applications post-launch.

The CYGNSS Early Adopter (EA) program would promote applications research, fit to the accelerated schedule of the CYGNSS mission. The CYGNSS EA program would provide a fundamental understanding of how CYGNSS data can be scaled and integrated into select organizations' policy, business and management activities to improve decision-making efforts. Through an Early Adopter Program, CYGNSS can leverage existing Early Adopters such as the SMAP Mission Early Adopter community to build an advanced, end user community with sophisticated capabilities of using L-band data for pre-launch research in societally relevant areas of applications. By using the SMAP Early Adopter Program as a guide, CYGNSS can quickly enhance its own application capabilities in weather, oceans and land related applications. Using a select number of Early Adopters, CYGNSS can demonstrate the added value of mission data products in weather, oceans and terrestrial applications.

3.2.3 Dr. Andrew Molthan, NASA Marshall Space Flight Center, SPoRT

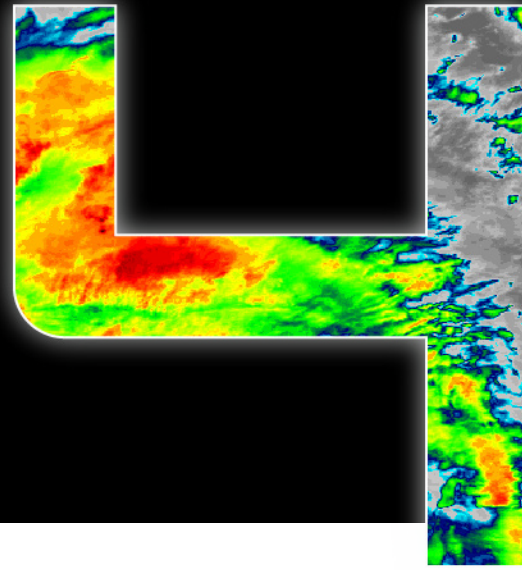
Dr. Molthan presented an overview of the NASA Short-term Prediction Research and Transition Center (SPoRT) plans for transition to operations to support CYGNSS. This included an overview of SPoRT's mission and current activities in partnership with NOAA. Dr. Molthan's presentation is available here: http://clasp-research.engin.umich.edu/missions/cygnss/appswkshp2015/presentations/molthan_cygnss_workshop_2015.pdf .

3.2.4 Mr. David Helms, Technical Director, Technology, Planning and Integration for Observations, NOAA NESDIS

David Helms gave a presentation entitled, "Complementary Observations and Systems - Assessing CYGNSS Potential Impact using NOAA Observing System Architecture Portfolio Management Capability." This entailed five discussion areas:

- NOAA Observing System Architecture Portfolio Management Capability
- Requirements: Ocean Winds, Soil Moisture
- Requirements Satisfaction Assessment
- NOSIA--II NOAA Observing System Impact Assessment
- Preliminary Assessment for CYGNSS

Details of this briefing can be found here:
http://clasp-research.engin.umich.edu/missions/cygnss/appswkshp2015/presentations/molthan_cygnss_workshop_2015.pdf .



4.1 MODELING, FORECASTING AND TROPICAL CONVECTION APPLICATIONS

4.1.1 Introduction

This breakout session focused primarily on developing CYGNSS applications related to atmospheric phenomena. CYGNSS has the potential to benefit a broad group of users through the improved analysis and prediction of ocean surface winds and waves. CYGNSS will use GNSS (GPS) reflectometry at L-band to observe sea surface winds (10-m height), technology that has been proven from both aircraft [Garrison et al., 1998] and space [Gleason, 2006; 2010]. The use of L-band overcomes weaknesses of current C- and Ku-band scatterometers (e.g., ASCAT, RapidScat), which are subject to signal degradation in significant precipitation [Weissman et al., 2002; Tournadre and Quilfen, 2003; Milliff et al., 2004]. The second advantage that CYGNSS will have over existing scatterometer missions is the use of a constellation of eight satellites, which provides rapid temporal updates over the same general (e.g. tropical) region of the Earth. Existing scatterometers are mostly placed in sun-synchronous orbit [Figa-Saldaña et al., 2013], limiting monitoring of the diurnal cycle. RapidScat is in non-sun-synchronous orbit on the International Space Station (ISS) [Rodriguez, 2013], and thus does provide some diurnal cycle information, but only at long time scales (e.g., seasonal to annual). By contrast, CYGNSS will have the ability to overfly the same region with a repeat cycle on the order of minutes to hours.

Many potential applications are directly related to the main purpose of CYGNSS (observing hurricane-force winds in tropical cyclone eyewalls). However, the breakout session determined that CYGNSS potentially has broad applications covering many additional topics, including other tropical hazards like convective and gap wind events, monitoring sub-seasonal and seasonal variability in the tropics (e.g., monsoons), improving tropical atmospheric state representation in global forecasting models, and assisting with wind energy production planning. These other applications leverage two key advantages of CYGNSS: being able to measure the diurnal cycle of winds in a manner that is unbiased by the presence of precipitation (useful for seasonal to annual climate scales), and high temporal resolution, all-weather sampling of winds (useful for near real-time applications or retrospective case studies of individual events). All told, nearly 30 potential applications of varying maturity levels were discussed and recorded. Below we highlight a few potential applications for CYGNSS data related to modeling, forecasting, and tropical convection.

Tropical cyclone intensity and track forecasting	Monitoring Equatorial winds, ITCZ, ENSO
Tropical cyclogenesis forecasting	Wind and oil energy industries, fishery management
Quantifying air-sea fluxes in high winds	Search and rescue assistance
Observations of extratropical transitions	Forensic meteorology
Forecast model verification	Atmospheric Rivers
Coupled ocean/atmospheric data assimilation	Sea salt aerosol production
Monsoons and Madden-Julian Oscillation	3D winds and model (re)analyses
Observing non-TC high wind events	Retaining high winds in data assimilation systems

Table 1. Summary of Interests of Tropical Cyclone and Forecasting Breakout Session Participants

The workshop presentation on this topic is available here:
http://clasp-research.engin.umich.edu/missions/cygnss/appswkshp2015/presentations/Uhlhorn_CYGNSS-Modeling-and-Forecasting-Applications_UhlhornBaker.pdf .

4.1.2 Tropical Cyclone Applications

Hurricanes, and tropical cyclones (TC) in general, are among the most destructive natural hazards. TCs frequent the tropical and middle latitudes of all ocean basins except for the south Atlantic, and the coastlines of these basins are susceptible to the damaging impacts of these storms when they make landfall. TCs are primarily monitored globally by a network of geostationary and polar-orbiting satellites, which provide information on storms' locations and indirect data on intensity (Velden et al. 2006). Additionally, the north Atlantic basin benefits from aircraft reconnaissance providing direct in situ and remote observations, although still relatively infrequently (~30% of forecast cycles). Since a TC's intensity is defined as the maximum surface wind speed over a specific averaging time period (e.g., 1 min in the U.S., NWS 2010), regular observations of surface wind are important for model initialization analysis and forecasts. Prediction of TC intensity has lagged track forecasting in part due to uncertainties in the actual intensity of a storm, estimated to be on the order of +/-10% at any time (Landsea and Franklin 2013), even with available aircraft observations. Space-borne scatterometers have been useful for measuring surface winds in TCs globally, but several limitations, in particular the negative impact of precipitation on wind observations, have been well-documented (e.g., Brennan et al. 2009, Weissman et al. 2012).

To improve surface wind measurement in TCs, the CYGNSS constellation will provide some unique capabilities that have been previously unavailable. Of note, the low-microwave (L-band) frequency of operation is able to "see" through precipitation far better previous satellite systems, and thus provide wind data in the TC's eyewall. Also, the constellation of orbiting receivers will maintain frequent revisits of the TCs to monitor rapid changes in intensity, which is a forecast challenge priority. Workshop participants identified 8 partially overlapping TC application areas for CYGNSS data when it becomes available. These applications address both the operational analysis of TC intensity using near-real time surface wind data, as well as utilizing the data in numerical models to improve TC intensity forecast guidance.

For TC intensity observations, a key application will be frequent observation of winds the high-wind, heavy-precipitation inner core (eyewall). The requirements for observing intensity as defined are high spatial resolution (~1 km, Nolan et al. 2009) consistent with the maximum 1-minute average wind speed, and measurements throughout the eyewall so as to not under-sample the storm (Uhlhorn and Nolan 2012, Nolan et al. 2014). The CYGNSS wind speed L2 product could fulfill the needs for these data, particularly with ancillary wind measurements from other airborne instruments such as GPS dropwindsondes (Hock and Franklin 1999) and stepped-frequency microwave radiometers (Klotz and Uhlhorn 2014).Additionally, frequent overflights of the storm (6-8 in quick succession) would be important for observing rapid intensity changes, which is crucial for coastal warnings and evacuations.

While weather observations depict current and past weather, numerical weather prediction (NWP) provides the means to effectively extend observation information into future weather (forecasts). Improvements to TC forecasts could possibly use CYGNSS L2 wind speed data by assimilating these observations (along with other data including satellite and aircraft in situ and remote-sensing data) into high-resolution numerical modeling systems. In order to maximize the weather forecast benefit from CYGNSS observations, it will be necessary to develop advanced data assimilation methods to extend the ocean surface wind speed to model levels above the surface, and to analysis variables other than wind speed (e.g., wind directional information, humidity, and temperature). Currently, operational TC model initialization schemes are still rather simple compared to global forecast systems (e.g., GFS), due in part to the relative sparseness of available data at the surface within the planetary boundary layer. More sophisticated 4D assimilation procedures (variational, ensemble, or hybrid approaches) could benefit from high-resolution, accurate surface wind data, both in the eyewall and extended radii to provide more accurate initial conditions.

However, CYGNSS observes the tropics and subtropics, where the balance between the mass and wind fields is not controlled by geostrophic coupling, and varies according to the synoptic situation. The challenge will be for the data assimilation systems to provide balanced increments, or changes to the NWP model fields due to the assimilation of observations, so that the observation information is retained. This will be especially important for successful assimilation in regions where CYGNSS observations will likely be inconsistent with the NWP model forecast, such as precipitating tropical cyclones cores, or other areas of intense tropical convection. Successful assimilation of CYGNSS observations has the potential to improve the analysis in these dynamically active areas. In turn, this could lead to better forecasts of tropical cyclone tracks, intensity and structure changes, and modulations in the larger scale circulations associated with the Madden-Julian Oscillation (MJO) and links to extratropical circulations.

The working group noted that CYGNSS L2 retrievals of wind speed and MSS (mean square slope) have the potential to provide a unique and valuable data source for coupled atmosphere/ocean/wave data assimilation and modeling. Coupled assimilation and modeling are likely to prove crucial for extending predictability to sub-seasonal and seasonal forecasts. The working group also noted that CYGNSS L1 DDM measurements might be useful to guide coupled atmosphere/ocean/wave modeling and data assimilation development.

4.1.3 Tropical Convection Applications

Since CYGNSS will provide resolution of the diurnal cycle of wind speeds, unbiased by the presence of precipitation, this will enable a number of applications related to monitoring and forecasting tropical convection and weather. These include helping monitor and predict: monsoon variability, tropical equatorial wind changes associated with El Niño/Southern Oscillation (ENSO), and convection in the Inter-Tropical Convergence Zone (ITCZ).

Specifically, one application CYGNSS can address is monitoring and helping forecast the MJO. The MJO is a global-scale atmospheric mode that has significant impacts on weather within the tropics and extra-tropics [Madden and Julian, 1971; 1972]. Because its return period is ~40-50 days, the impact of CYGNSS' 2-6 day data latency is minimized (though reduced latency would be helpful for this and many other applications).

There is a predictability barrier when the MJO, which initiates over the Indian Ocean, reaches the Maritime Continent (MC; e.g., Indonesia). This barrier is likely due to poor model treatment of the diurnal cycle of tropical convection in that region [Peatman et al., 2014]. Since CYGNSS can resolve the diurnal cycle of convectively driven winds better than existing scatterometer missions, assimilation of its data into tropical forecasting frameworks (even with some latency) should help with properly resolving MJO interaction with the diurnal cycle in this region. This should help reduce the predictability barrier and thereby improve regional and global forecasting of MJO-related weather effects.

For this application, L2 CYGNSS wind speed data are required. The data will need spatially and temporally resolved quality indicators, and should be made available in BUFR (Binary Universal Form for the Representation of meteorological data) Format. Ancillary data sources that would enhance the impact of CYGNSS for this application include Global Precipitation Measurement (GPM) mission products (which also can resolve the diurnal cycle); ground radar data (including data from Indonesia and the Philippines); wind vectors from other satellite scatterometers, ground observations, and radiosondes; and geostationary visible/infrared observations from geostationary satellite.

Though planned products are sufficient for this application, enhancements to CYGNSS products would be welcome. Apart from latency reduction, these include model and data assimilation enhancements to better preserve CYGNSS-measured winds within forecasting frameworks, CYGNSS data reprocessing to improve spatial resolution near coasts (particularly helpful in the island-rich MC), and further investigation into the viability of wind direction retrievals from CYGNSS.

Expected end user groups for this application include global and regional weather forecasting agencies, local/regional water resources agencies and agricultural industries, and militaries - including the United States Navy, which is planning a field campaign in the coming years to address the MJO predictability barrier near the MC.

L3 CYGNSS products also could play a role in tropical convection applications. For example, global wind products enhanced by CYGNSS L3 gridded winds could aid with the monitoring and forecasting Gulf of California surges, ENSO-induced winds, ITCZ, and onset of monsoons in India, Southeast Asia, southwest United States, and Australia.

The workshop presentation on this topic is available here:
http://clasp-research.engin.umich.edu/missions/cygnss/appswkshp2015/presentations/Lang_Tropical_Convection_Intro.pdf .

4.1.4 Global Applications

At the longer forecast ranges, the forecast skill improvements enabled by CYGNSS could extend globally, through the meteorological connections between tropical and extratropical circulations. CYGNSS wind speed observations will provide a rich data source for both atmospheric process studies and monitoring weather pattern changes on the sub-seasonal to seasonal time scale (S2S). The high temporal and spatial resolution, plus the ability to retrieve wind speed within precipitating regions, will capture aspects of diurnal variability not represented by other satellite observations. For many of these applications, the CYGNSS L3 gridded wind speed products will be especially useful, and the projected data latency will be less of a concern.

The working group identified several potential applications that could benefit from CYGNSS L3 gridded wind speed products. For example, coastal and high seas hazards warnings (high winds, waves and storm surges) for non-tropical cyclone weather regimes could benefit. Coastal examples include such as gap winds (e.g., Tehuantepec), strong offshore winds events, or persistent seasonal winds along coastlines. These events can contribute to SST changes and ocean upwelling. Persistent ocean winds near the coast tend to force upwelling of cooler ocean waters. These nutrient rich waters attract fish and other sea life, and are typically good fishing areas. In turn, the cooler ocean waters contribute to cooler temperatures for coastal areas, and thus play a role in energy use (e.g., air conditioning use) inland. CYGNSS wind speed measurements would also be useful to identify locations for offshore wind energy production enterprises.

Other applications include forensic meteorology, and search and rescue operations. Improved prediction of ocean surface winds and waves will be a benefit for forecasting the movement of ocean debris, such as that from oil spills, tsunamis, and aircraft/ship debris, or even flood debris. Longer range guidance for Search and Rescue (SAR) applications was noted as being important during the recent search for MH370 off the coast of Australia, given the long transit times to the search area which limit the amount of time (fuel) available for searching once on site. Retrospective analyses of winds and waves were used to predict debris drift and guide search regions, an application which would benefit from the high temporal resolution, all-weather sampling provided by CYGNSS.

CYGNSS L3 gridded wind speed products have the potential to enhance the monitoring and prediction of atmospheric phenomena are driven by surface winds or low-level winds, such as sea salt aerosol production, and trans-oceanic transport of air pollution, smoke from large-scale burning of the tropical rainforests, and subtropical desert dust.

A very different application of CYGNSS L2 and L3 wind speeds would be for the cross-calibration, validation and quality monitoring of remotely sensed satellite and conventional (e.g., fixed and drifting buoys, ships, wave gliders) observations. The working group commented that CYGNSS could be used to improve the forward models for scatterometers (or microwave imagers) in the presence of precipitation. In order to have the greatest benefit for these applications, the L3 products should have good metadata for describing the data quality, areal binning, and observation time information.

4.1.5 Summary

There were many recurring themes discussed during the breakout session. Despite the diversity of applications, one common theme is that nearly every atmospheric application would benefit from reduced data latency. In particular, for forecasting-related applications, latencies on the order of hours rather than days are preferred. Without the lower latency, applications would shift toward retrospective case studies, hindcasts, model validation, reanalyses, etc. Many S2S forecasting applications (e.g., MJO, monsoons, ENSO, etc.) would still benefit from CYGNSS, even with the planned 2-6 day data latency.

Another common theme is that CYGNSS is best used in concert with other data sources. These can include precipitation from the GPM, vector winds from other scatterometers (e.g., Advanced Scatterometer or ASCAT on the MetOp satellite series), and cloud parameters from geostationary visible/infrared channels. In particular, there was substantial interest in using CYGNSS as one component of a 3D wind product.

In terms of immediate needs for implementing TCF applications in the near-term, the breakout recommended continued support for data assimilation research using the CYGNSS End-To-End Simulator (E2ES) to explore CYGNSS' potential impact in a variety of model (global and regional) and forecast target scenarios (e.g., TCs, MJO, etc.). In particular, additional data assimilation work needs to be done to explore how to improve retention of high wind information from CYGNSS in forecast models. Also, the use of direct DDM assimilation into coupled ocean-atmospheric model systems needs further research. In addition, there is a need to design and implement reprocessing of CYGNSS data to provide enhanced coverage in coastal regions. This has been done for previous scatterometer missions [Owen and Long, 2009] and has provided substantial benefits to spatial coverage.

The primary long-term recommendation of the TCF breakout to CYGNSS program management, as well as other possible stakeholders (e.g., NOAA), is that the long data latency issue be addressed. Reduced latency would benefit nearly every application discussed during the TCF breakout. One of the chief benefits of existing scatterometers is that their low latency enables assimilation of their observations into global and regional forecast models. These wind products provide substantial benefits to weather forecasts [Atlas et al., 2001].

4.2 PHYSICAL OCEANOGRAPHY AND WAVE APPLICATIONS

4.2.1 Introduction

This breakout session focused primarily on developing CYGNSS applications related to ocean and surface gravity wave research, analysis, and prediction. Scientific interests of breakout group members are listed in Table 2. CYGNSS has the potential to impact a broad suite of ocean applications. Many applications take advantage of the enhanced sampling capability over the tropical/subtropical ocean compared to scatterometers wind measurements. This enhanced capability includes the more rapid temporal update rate in general, and more specifically the ability to measure the surface wind field within high rainfall regions, in particular the inner core of TCs and other regions of intense tropical convection such as the ITCZ. CYGNSS will therefore provide more accurate wind fields to drive ocean models and to improve our ability to analyze and understand air-sea fluxes, particularly within the inner core region of TCs. A total of 15 potential applications of varying maturity levels motivated by 13 specific science questions were identified that both include, and extend beyond, the direct impact of improved wind fields. The recommendations of the breakout with respect to both analysis/forecast and research applications follow.

Physical Oceanographic modeling and prediction	Coupled TC research and prediction
Ocean data assimilation	Air-sea interaction and surface fluxes
Surface gravity wave research, modeling, and prediction	Sea spray
Ocean-atmosphere climate modes	Surface wind analysis products
Internal waves and tides	Coastal oceanography and river plumes
Satellite altimetry	Satellite scatterometry wind measurements
Satellite salinity measurements	Laser/Lidar measurements in oceanography
Satellite precipitation measurements	

Table 2. Summary of Interests of ocean/wave breakout group attendees.

The workshop presentation on this topic is available here:
http://clasp-research.engin.umich.edu/missions/cygnss/appswkshp2015/presentations/Halliwell_CYGNSS_ocean_waves_20150527.pdf .

4.2.2 Ocean and Wave Forecast Applications

Six scientific questions related to ocean/wave analysis and forecasting were identified:

- Can CYGNSS improve hurricane intensity forecasts by improving ocean and wave model performance?
- Can regional to globe ocean and wave forecasts be improved using CYGNSS observations?
- Can CYGNSS improve coastal ocean and wave forecasts, including coastal upwelling and biogeochemical responses?
- Can CYGNSS improve storm surge prediction?
- Can CYGNSS improve tsunami prediction?
- Can CYGNSS improve hurricane surface wind analysis products provided to the public?

Ocean and wave prediction systems at operational forecast centers (e.g. Chassignet et al., 2007) are presently forced by output from Numerical Weather Prediction (NWP) models. CYGNSS therefore has the potential to improve ocean and wave analysis and forecast products by reducing errors in air-sea fluxes provided by atmospheric models through the assimilation of CYGNSS wind measurements as described in Section 4.1.2. Ocean and wave prediction systems are presently uncoupled and independent forecasts generated by the atmospheric model are used to drive the ocean and wave forecasts. Therefore, assimilation of CYGNSS winds into the atmospheric model has the potential to reduce errors in the initial states of both the atmospheric and ocean/wave models and thus produce more accurate atmospheric and ocean/wave forecasts. The same is true for coupled prediction systems, including TC forecast models. The potential to significantly improve atmospheric and oceanic initialization of TC prediction models within the inner core region of storms is a unique capability provided by CYGNSS that will be highly beneficial (Halliwell et al., 2011). Improved forecasts from these prediction systems can also provide initial and boundary conditions to auxiliary prediction systems such as storm surge models.

CYGNSS wind measurements can also be used in conjunction with other atmospheric measurements to improve TC wind analysis products such as those used for research and forensic (e.g. insurance and re-insurance) applications. Although CYGNSS will initially provide only wind speed estimates, their assimilation into atmospheric models along with wind analyses will provide the vector wind and wind stress fields required to force the ocean and wave models. Since fields such as these have been produced on a 3h cycle when TCs are within aircraft reconnaissance range, these fields have been used by NASA, ESA, and ONR to assess performance of remote sensing systems in high winds. They could therefore be used to help evaluate CYGNSS winds within TCs. Wind analysis products such as these require stress to be estimated using bulk formula if it is to be used to force ocean and wave models.

All of these analysis/prediction applications will require research to determine the extent of improvements achieved through the use of CYGNSS wind measurements. They will also require research to develop optimum techniques for assimilating CYGNSS winds into atmospheric models as described in Section 4.1.2. For coastal ocean and wave prediction applications, research is required to optimally map the structure of surface winds near land-sea boundaries which significantly affects ocean currents (He et al., 2004). Coastal regions are very important for marine ecosystems and fisheries, and any improvement in our ability to study and predict ocean currents in these regions will be highly beneficial.

TC prediction will benefit from a scientific process study designed to improve representation of the thermohaline feedback that can limit SST cooling beneath storms. Heavy precipitation in the inner core region reduces salinity and increases stratification near the ocean surface. If a TC moves slowly enough, the increased stratification can significantly limit SST cooling. CYGNSS measurements along with satellite and in-situ salinity measurements are necessary to perform such a study. Hurricane Isaac (2012) in the Gulf of Mexico provides a good example because it moved slowly and extensive in-situ ocean observations were available.

The ability to use CYGNSS to monitor and predict storm surge and tsunamis requires substantial research to determine feasibility. The breakout group discussed the possibility of extracting satellite altimetry measurements from CYGNSS, which requires access to both level 1 products and metadata. Although RMS errors in these measurements will be very large, there is high value in being able to detect very large signals that require the rapid temporal sampling that CYGNSS can provide, specifically tsunamis and storm surges.

The relatively long data latency in the initial suite of CYGNSS products will limit forecast applications to retrospective studies. These studies are important to develop methods to improve the quality of ocean and wave forecasts through the use of CYGNSS products. However, the greatest benefit to society will be achieved by providing CYGNSS wind measurements as rapidly as possible (time scale of hours) to the Global Telecommunications System (GTS) for assimilation into NWP models. To realize this benefit, the breakout group recommends that additional funding be sought to increase download bandwidth to enable level 2 products to be rapidly generated and sent to the GTS.

4.2.2 Ocean and Wave Forecast Applications

The breakout group discussed a number of potential research applications to increase scientific understanding, improve model performance, improve measurements obtained by other observing platforms and instruments, and derive new products. Concerning research applications, the following scientific research question was posed:

- Can CYGNSS improve our understanding of coupled climate modes with large footprints in the tropical/subtropical ocean?

CYGNSS measurements can potentially make significant contributions to climate research once sufficiently long time series are obtained. Potential phenomena of interest include the Madden-Julian Oscillation (MJO) and ENSO, both of which can affect interannual variability in the number and intensity of TCs. These studies can be conducted using global atmospheric reanalysis products that assimilate CYGNSS wind speed in conjunction with ocean analyses forced by these atmospheric reanalyses. In the future, coupled global ocean/atmosphere reanalysis products will become available for this purpose. CYGNSS level 3b wind speed fields combined with separate ocean analysis products can also be used for such studies, but this will require development of an algorithm to derive vector wind maps. Delayed mode determination of vector wind fields is possible using CYGNSS measurements. The breakout group recommends that the additional research and development required to extract vector winds be conducted in the near future.

The breakout group discussed one model improvement question:

- Can CYGNSS products be used to improve ocean wave models?

Surface gravity wave models must use an assumed parameterization for the high wavenumber tail of the wave spectrum. The CYGNSS level 2b mean-square slopes (MSS) can potentially be used to determine the structure of this tail within a limited wavenumber range. Any correction of this spectrum has the potential to significantly improve model performance, so the group recommends that research be conducted to determine the feasibility of this approach.

The breakout group discussed several research applications with the potential of improving measurements collected by other platforms and instruments motivated by the following questions:

- Can CYGNSS be used to improve satellite ocean salinity retrievals?
- Can CYGNSS be used to correct other satellite measurements affected by radio frequency occultation (RFI)?
- Can CYGNSS improve atmospheric profile measurements determined by radio occultation (RO)?

CYGNSS measurements of surface roughness can potentially be used to improve the roughness correction required to derive satellite salinity measurements produced by L-band radiometers. CYGNSS data may be useful in the characterization of radio-frequency interference (RFI) statistics in the GPS L1 wavelengths. As noted by Dr. Chris Ruf during the workshop, because these wavelengths are slightly different than the protected bands used by microwave radiometry, the usefulness of this RFI characterization to other sensors, such L-band radiometers, remains to be seen. Provided that CYGNSS can detect and mitigate RFI it is subjected to, potential exists for CYGNSS measurements to be used as ancillary products in the retrieval algorithms of other remote sensing systems. CYGNSS measurements can also be used to improve RO measurements of atmospheric density profiles, particularly with respect to extending profiles closer to the ground and into the planetary boundary layer. If assimilation of such profiles into NWP models sufficiently improves representation of the planetary boundary layer it could lead to more accurate surface fluxes that drive ocean and wave models.

The breakout group identified a scientific question with regards to development of a new product:

- Can bulk drag coefficient (C_d) and momentum flux be estimated from CYGNSS observations?

Because of the importance of momentum flux in forcing ocean currents and surface waves, the breakout group discussed the possibility of directly estimating C_d and wind stress from CYGNSS measurements. The consensus was that this would be very difficult but not impossible. Given that the C_d is an increasing function of roughness length z_0, a key difficulty is determining the relationship between CYGNSS MSS estimates and z_0 (Charnock, 1955; Hwang, 2006). Another issue is that the z_0 depends on wind stress and wave age (Janssen 2004). It has been found that C_d levels off and possibly declines with increasing wind speed above hurricane force (Powell et al., 2003; Holthuijsen et al., 2012). Although difficult, research to determine the feasibility of directly recovering stress should be considered due the high value of a dependable wind stress retrieval algorithm.

Finally, the group identified a question that impacts all atmospheric and oceanic applications:

- How does heavy precipitation and surface contaminants affect CYGNSS roughness estimates?

Both heavy precipitation and surface contaminants have the potential to significantly bias wind retrievals in some cases, particularly in the inner-core region of TCs. The group recommends that thorough and careful comparisons to measured winds be conducted in such regions so that uncertainties in wind retrievals can be quantified.

4.2.4 Summary

One requirement that spans many of the ocean/wave applications is that both wind speed and direction are necessary. Although many of the applications are related to model evaluation, retrospective reanalyses, and retrospective research studies, applications related to improving real-time ocean and wave forecasting for maximum benefit to society, both within and outside TCs, will benefit from reducing data latency to no more than a few hours. Most applications cited above require that CYGNSS observations be used in conjunction with other in-situ and satellite measurements. In all cases, varying degrees of research will be required to validate these applications, and it is unlikely that all will prove to be viable.

Given the potential importance of each application, the breakout group recommends that the required research to validate or reject each application be supported and that funding be sought to reduce data latency for real-time forecast applications. Research should be conducted to quantify improvements to ocean/wave analysis and forecast products resulting from the assimilation of CYGNSS winds by the atmospheric models that provide surface forcing to the ocean/wave models. Research should be conducted to derive vector wind fields from CYGNSS measurements, and to extend CYGNSS products as close as possible to land for coastal applications. Research to improve our ability to model the thermohaline feedback mechanism within TCs should lead to improved coupled TC forecasts. Research to improve the wave spectrum representation in wave models holds the promise of improving model performance. Research to determine if altimeter measurements can be extracted, although difficult and with large error bars, should be undertaken to determine of the rapid CYGNSS sampling can detect storm surge and tsunamis shortly before landfall. Research to determine whether CYGNSS measurements can be used to reduce retrieval errors from other instruments that measure ocean salinity, RO for atmospheric profiles, or instruments that are degraded by RFI should be undertaken. Determination of whether wind stress and drag coefficient information can be directly extracted from CYGNSS measurements is important. Finally, thorough and careful comparisons between CYGNSS and measured winds must be conducted in regions of high precipitation and where surface contaminants are encountered so that uncertainties in wind retrievals caused by these factors can be quantified.

4.3 COASTAL, TERRESTRIAL, AND HYDROLOGICAL APPLICATIONS

4.3.1 Introduction

Besides open ocean sea surface roughness and wind speed estimates, the CYGNSS constellation of eight small satellites will also make measurements of GPS bistatic radar signals forward-scattered from coastal areas, inland water bodies, and land surfaces. Although not the primary mission objective nor defined as actual data products, these measurements may yield novel and innovative CYGNSS applications nonetheless. The Coastal, Terrestrial, and Hydrological (CTH) Applications breakout was charged with reviewing these measurements and their expected characteristics and identifying possible science applications. Unlike the other breakout sessions within the workshop that will employ higher level L2 and L3 products in their applications, the CTH breakout required starting at a lower level of understanding of the basic CYGNSS measurement technique and scattering mechanisms. As well, the domain of the CTH breakout spanned varying surface types, from different wet/dry/snow-covered/frozen land surfaces to inland rivers, lakes, wetlands, and flood inundated areas. Previous work in GNSS bistatic radar applied to these surface regimes is limited to a few campaigns and aircraft flight measurements, so the CTH breakout was in many respects a brainstorming session.

The attendees of the CTH breakout spanned many application areas and included remote sensing experts in GNSS bistatic radar, traditional radiometry and scatterometry, and scattering theory. Table 3 lists a summary of interests expressed by the attendees.

Agricultural crop modeling/hydrology (LAI, biomass, etc.)	soil moisture operational systems (NOAA NESDIS STAR)
Sea ice forecasting	Wetlands mapping
Land surface energy (weather hazards)	Tropical storm timing and areal flooding
Flooding extent for insurance/reinsurance	Soil moisture retrievals and varying applications
Sea winds for navigation	Freeze/thaw detection
Scatterometry	Data assimilation soil moisture for crop models
AMSR, SMAP, Aquarius soil moisture retrieval and cal/val	Data assimilation of remote sensing data in hydrological applications
Soil moisture for mobility applications	Surface scattering theory

Table 3. Summary of interests of Coastal, Terrestrial and Hydrological Breakout Session Participants.

As noted, previous work studying and applying GNSS bistatic radar to surfaces other than the rough ocean is sparse. To date, many of these investigations were conducted as aircraft campaigns flew over areas of land surfaces en route to measure ocean reflections. Participation in the aircraft component of the Soil Moisture Experiment (SMEX) campaigns in 2002-2005 demonstrated the sensitivity of the of GNSS bistatic radar applied to soil moisture due to the L-band penetration of the topsoil surface [Masters et al., 2004; Katzberg et al, 2006]. Measurements from fixed, high towers were also collected with collocated soil moisture sampling and correlated with rain and snowfall events [Masters, 2004]. Participation in the series of Cold Land Processes Experiments (CLPX) also showed GNSS reflections from snow surfaces, but only cursory investigation of these data was completed [Cline at al., 2009]. In many of these initial investigations, surface roughness effects were ignored, and the change in the bistatic radar cross section was assumed to be due to spatial and temporal changes in the surface dielectric properties caused by moisture content or soil type. The bistatic cross sections of sea ice were also measured and yielded correlation with ice age [Rivas et al., 2010; Komjathy et al., 2000]. Mapping of wetlands was only cursorily investigated, but it was noted that GNSS reflections from these inland water bodies were often strong and most likely coherent, even through vegetation canopies [Ngheim et al., 2014]. Recently, a few European groups have collected controlled soil surface measurements from towers using dual polarization antennas to characterize and compare these measurements with scattering models for soil moisture retrievals [Egido el al., 2012; 2014; Pierdicca et al., 2014], as well as aircraft campaigns to study snow, ice, and land reflections [Cardellach et al, 2011]. Recent use of the interferometric technique with ground-based GNSS receiver networks has yielded promising results for estimating soil moisture [Larson et al., 2008; Chew et al., 2014], snow depth [Larson et al., 2009], vegetation water content [Small et al., 2010; Larson et al., 2014; Chew et al., 2015], and even ocean tides [Larson et al., 2013].

The CYGNSS primary mission is sea surface winds, which has a long aircraft measurement heritage [Garrison & Katzberg, 1998; and some examples from space using the UK-DMC and TechDemoSat-1 satellites [Gleason, 2006; 2010]. But CYGNSS will also operate over continental land surfaces, and this creates an opportunity to use continental reflections for unique applications. Since many of these applications have limited evidence, the breakout session summarized the current understanding of what CYGNSS will measure over terrestrial and inland water surfaces. Since the CYGNSS mission does not have any requirement nor plan for processing reflections from these areas, the starting point for CTH applications will be the low-level, L1B bistatic radar cross section (BRCS) from the delay-Doppler maps (DDM), i.e., no “soil moisture” or “water extent” products have been planned. Therefore, the breakout group noted that investigation of the CTH applications requires more understanding of the GNSS bistatic radar technique than traditional applications users.

The breakout noted that a simplistic understanding of the expected CYGNSS CTH measurements is that of L-band signals forward scattered with sensitivity to surface reflectivity and roughness, most likely analogous to L-band radiometry. The CYGNSS BRCS measurements will most likely be able to distinguish among varying surface types, monitor temporal evolution of surface properties (soil wetness, vegetation, snow cover, freeze/thaw), and map the spatial extents of water bodies (rivers, lakes, flood inundated areas, and wetlands). Additionally, CYGNSS L-band measurements will be able to operate in all-weather conditions. The breakout also noted that two unique traits of CYGNSS measurements: 1) fast revisit times (minutes to hours) at varying incidence and azimuth angles might afford new applications not met by other instruments and 2) forward scattering might have benefits over or be synergistic with radiometry or traditional backscatter radars.

The nominal spatial resolution defined by the first bistatic radar range cell (around the specular reflection point) will be an ellipse on the order of 10-15 km diameter smeared 7 km along-track (due to the 1-sec incoherent integration time). This area will be the spatial resolution is the surface is electromagnetically "rough." But a large percentage of CTH reflections may be coherent (stronger signal with reduced fading) due to smooth surface reflection, and this may be an advantage in discerning abrupt changes in surface type (e.g., at wetlands/dry land transitions) and penetrating vegetation cover (less significant when underlying surface is a coherent reflector). The spatial resolution of coherent reflections will be on the order of the 1-2 km defined by the diameter of the first Fresnel zone surrounding the specular reflection point. The breakout noted that the CTH CYGNSS spatial resolution will require a degree of interpretation depending on the observed signal characteristics, and this should be further studied. Likewise, scattering models for both incoherent and coherent reflections have not been thoroughly validated for GNSS bistatic radar although the theoretical basis has been demonstrated in other fields of study [Ulaby et al., 1981; Beckmann & Spizichinno, 1987]. These models should be incorporated into the existing CYGNSS End-to-End Simulator (E2ES) and released to the applications working group for analysis.

The breakout noted that over CTH areas, each CYGNSS sat will collect four, L1 (1.5 GHz), left-circularly polarized, 1-sec DDMs in the two antenna FOVs (same operating mode as oceans) in a equatorial/subtropical latitude band ±35 degrees. This will cover varied terrain (coasts, agricultural lands, forests, mountains, alpine, and snow-covered regions) but will not sample permanent ice sheets or sea ice. Like the ocean, potentially only the peak of DDM (first range and Doppler bins) will most likely be useful due to signal-to-noise and spatial resolution requirements. CTH applications will use the planned low-level products (e.g., L1A DDM of reflected signal power and L1B DDM geolocated map of the BRCS). CYGNSS will have an infrequent raw sampling mode, which could be important to characterize the properties of the reflected signals from different surface types.

In its preliminary brainstorm, the breakout also noted CYGNSS CTH measurement synergies with current and proposed Earth science assets. These include (but are not limited to):

- SMAP, Aquarius, SMOS (L-band sensors)
- Flood mapping with satellite sensors (e.g., the Dartmouth Flood Observatory)
- Ground-based GNSS networks measuring soil moisture, snow, biomass (e.g., PBO H20)
- SWOT (requires inland water body detection and extents)

The workshop presentation on this topic is available here:
http://clasp-research.engin.umich.edu/missions/cygnss/appswkshp2015/presentations/Masters_Coastal-Terrestrial_Hydrological-Applications.pdf .

4.3.2 Identified Applications

After identifying the expected characteristics of CYGNSS CTH measurements, the breakout identified a large list of science questions and potential applications. These questions and applications were then grouped into four basic measurement categories: soil moisture, vegetation/biomass, surface water extent mapping, and cryosphere. The large list was then further consolidated and narrowed to those science questions and applications anticipated to be the best addressed by CYGNSS measurements. The next sections describe these narrowed applications in more detail (the full list of questions and applications is available in Appendix A).

4.3.2.1 Soil Moisture Applications

Since the GNSS signals used by CYGNSS are L-band, soil moisture remote sensing was easily identified as one of the better potential applications. Past aircraft campaigns in SMEX and recent use in ground-based GNSS networks to sense soil moisture give evidence that CYGNSS should be sensitive to soil moisture as well. The breakout noted that the L1B BCRS should be spatially and temporally sensitive to changes in dielectric properties of the soil, and that CYGNSS would make measurements that would be synergistic with SMAP-type swath measurements.

Five science questions and resulting applications were identified that largely fall within the scope of sensing soil moisture:

- What is the sub-daily, temporal evolution of soil moisture?
- Can sub-daily soil moisture improve crop model assimilation results?
- What is the evolution of rainfall, runoff, and soil moisture event dynamics?
- What is the potential for landslides due to soil saturation?
- What is the expectation of river flooding due to dynamic precipitation/thaw events?

These questions share many characteristics of those addressed by SMAP, but were viewed as added-value due to the unique fast-sampling of CYGNSS. Some will require lower latency (than the current 1-2 days estimated for CYGNSS) to be useful for applications that require closer to real-time data (e.g., river flooding or crop modeling). The breakout also noted that a shorter integration time over land is key to many of the questions that rely on the potential for coherent reflections and subsequent reduction of the footprint to 1-2 km. With an enforced 1-sec integration time over land and 7 km along-track resolution, the benefits of coherent reflection may be substantially reduced.

It was noted that CYGNSS soil moisture estimates will require similar ancillary inputs as SMAP, such as surface roughness and soil type maps. Therefore, leveraging SMAP (and other L-band sensor) experience and algorithm development would be useful in developing CYGNSS algorithms. Further work is needed on land scattering model development, analysis of TDS-1 data collocated with other L-band and in situ soil moisture measurements, and possibly combining a future L2 CYGNSS soil moisture product with SMAP to create a L3/4 value-added product.

Potential soil moisture applications users identified were: NWS, USDA, USDM, DoD, DOT, FEMA, USGS, state and local governments, universities, the Red Cross, and Insurance/reinsurance companies.

4.3.2.2 Vegetation/Biomass Applications

The breakout identified that CYGNSS rapid repeat measurements may answer a popular request for information on sub-daily changes in vegetation water content (VWC). Recent use of ground-based GNSS networks to sense changes in vegetation biomass [Larson et al., 2014; Chew et al., 2015] give evidence that CYGNSS could be sensitive to VWC as well. The breakout noted that the rapid sampling of the L1B BCRS should be temporally sensitive to changes in VWC and possibly observe sub-daily evolution, a unique application not addressed by other sensors.

One science question and resulting application was identified for vegetation/biomass sensing:

- What is the sub-daily evolution of vegetation water content?

This application will not require lower latency to be useful for research studies, but the breakout noted that active crop monitoring would necessitate this requirement. A shorter integration time over land may be useful for higher spatial resolution, but was not deemed critical since the expected scattering will most likely contain an incoherent component (and revert to the nominal radar range resolution). It was noted that CYGNSS VWC estimates may require combining the measurements with SMAP or other L-band sensor data, as well as a valid mixing model and similar ancillary inputs as SMAP, such as surface roughness and soil type maps. Further work is needed on land/vegetation scattering model development, analysis of TDS-1 data collocated with other L-band and in situ vegetation measurements, and possibly combining a future L2 CYGNSS vegetation/biomass product with SMAP to create a L3/4 value-added product.

Potential vegetation/biomass application users identified were: USDA, FAS, FAO, USAID, and NAS.

4.3.2.3 Surface Water Extent Mapping Applications

Since the GNSS signals used by CYGNSS are forward-scattered rather than back-scattered (as in a typical radar), flood and wetlands mapping was also easily identified as one of the better potential applications. In the CYGNSS bistatic case, these areas show up as strong returns while in monostatic radars, they show up as missing data due most of the signal scattering in the forward direction away from the radar. Past aircraft campaign data show strong reflections from calm inland water bodies characteristic of flooded areas and wetlands and give evidence that CYGNSS should be sensitive to these areas as well. The breakout noted that the L1B BCRS should be spatially and temporally sensitive to changes in water extent, and that CYGNSS would make measurements that would be synergistic with larger swath microwave and visible measurements.

Two science questions and resulting applications were identified that largely fall within the scope of sensing water extents:

- What are the extents and temporal evolution of flood disasters?
- What is the current extent of wetlands (methane sources), and how are they evolving?

These questions share many characteristics of those addressed by SMAP and other microwave sensors, but were viewed as added-value due to the unique fast-sampling of CYGNSS. Mapping the extents and temporal evolution of flood disasters will require lower latency to be useful. The breakout also noted that a shorter integration time is key to questions that rely on the potential for coherent reflections from smooth water surfaces and subsequent reduction of the footprint to 1-2 km. The benefits of finer mapping with coherent reflection may be substantially reduced with the 1-sec integration time.

Further work is needed on implementing a coherent component into the water surface scattering model and analysis of TDS-1 data collocated with other measurements of water extents.

Potential surface water extent mapping applications users identified were: FEMA, USGS, state flood control, insurance/reinsurance companies, emergency operations, EPA, IPCC, and climate assessment agencies.

4.3.2.4 Cryosphere Applications

The breakout noted that although CYGNSS will be limited to the subtropical band around +- 35 degrees latitude, it will still sense areas of snow-covered and frozen ground. The potential exists as well for future GNSS bistatic radar missions that could fly in higher inclination orbits (e.g., COSMIC-2). Therefore, the breakout identified a few cryosphere questions and applications. Past aircraft campaign data show strong reflections from snow melt (transition to liquid water phase) and give evidence that CYGNSS should be sensitive to these areas as well. Similarly, the freeze/thaw transition of soil and permafrost may be observable with CYGNSS. Past GNSS bistatic radar sea ice studies also indicate that future CYGNSS-like missions could hold potential for mapping sea ice extents and discriminating sea ice type. The breakout noted that the L1B BCRS should be spatially and temporally sensitive to changes in snow extent and ground freeze/thaw, and that CYGNSS would make measurements that would be synergistic with larger swath microwave and visible measurements.

Three science questions and resulting applications were identified that largely fall within the scope of sensing the cryosphere:

- How is the snow extent line changing on sub-daily timescales?
- Is the soil and permafrost freeze/thaw state changing with climate?
- What are the extents and age of sea ice and how are they changing with climate?

These questions share many characteristics of those addressed by SMAP and other L-band microwave sensors but were again viewed as added-value due to the unique fast-sampling of CYGNSS repeat measurements. Only the sub-daily change in the snow line extent would require lower latency measurements, and only for applications related to near real-time monitoring of flood risk from snow melt. The breakout also noted that a shorter integration time is again key to these questions that rely on the potential for coherent reflections from smooth surfaces near the snow line boundary and subsequent reduction of the footprint to 1-2 km. The benefits of finer mapping with coherent reflection may be substantially reduced with the 1-sec integration time.

Further work is needed on implementing scattering models (both coherent and incoherent components) for cryosphere surfaces, including snow, frozen ground, and sea ice. Since TDS-1 samples much higher latitudes and includes measurements of permanent ice sheets and sea ice, further analysis of TDS-1 data was suggested.

Potential cryosphere applications users identified were: NOAA, USDA, NSIDC, Navy, oil exploration, and shipping companies.

4.3.3 Summary & Recommendations

Overall, the CTH breakout was successful in identifying a realistic set of applications and goals for the coastal, terrestrial, and hydrological opportunities presented by the CYGNSS mission. Four main applications were identified, with specific science questions addressed under each topic. These specific applications would take advantage of unique traits afforded by CYGNSS measurements, most importantly the rapid resampling by the constellation geometry and the expected coherent properties of reflections from smooth surfaces that could potentially improve the along-track sampling resolution. A number of recommendations were identified, and these are detailed in the following sections.

The CTH breakout noted a few recurring themes across the identified applications. These included:

- CYGNSS CTH measurements by themselves will not replace other L-band sensor measurements, such as SMAP or Aquarius, but will offer advantages that these sensors lack
- The fast repeat sampling afforded by the CYGNSS constellation is a unique trait and may allow observation of phenomena occurring at faster timescales than currently observed, e.g., sub-diurnal soil moisture and VWC evolution and flood dynamics
- Bistatic radar forward scattering measurements will offer benefits in certain cases (e.g., wetlands, smooth water surfaces) due to coherent reflection and will be synergistic with traditional radiometry and backscatter radar
- Reduction of the CYGNSS incoherent integration time over smoother terrestrial surfaces would allow better along-track spatial resolution and correspondingly enable more applications of CYGNSS data
- Likewise, reduction of the CYGNSS data latency would enable more applications that need near real-time data, such as forecast model assimilation or flood prediction/monitoring
- Existing knowledge bases of L-band sensors should be harnessed to aid in the interpretation and development of CTH retrieval algorithms from CYGNSS L1B data.

The breakout participants also noted some open questions and issues regarding CYGNSS CTH applications. These included:

- Will CYGNSS reflections return viable signal-to-noise ratios over all terrain types (especially

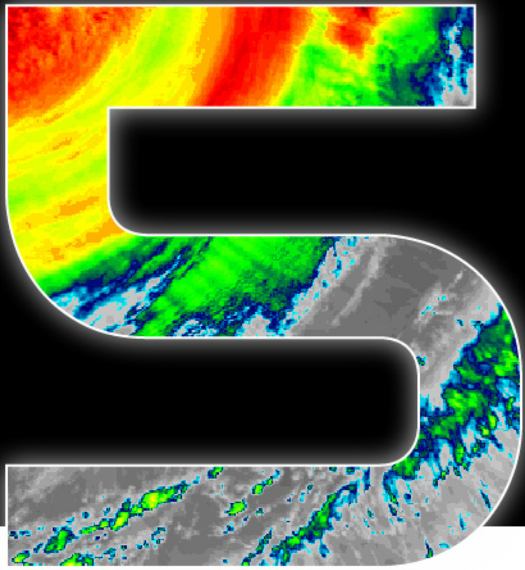
heavily vegetated or dry land)?
- Can the CYGNSS project accommodate instrument mode changes to reduce the incoherent integration time over possible coherent CTH surfaces to improve the along-track spatial resolution?
- Will highly reflective terrestrial objects or RFI in the FOV contaminate CYGNSS data?
- Will CYGNSS single polarization measurements be able to separate surface roughness, biomass, and soil moisture effects?
- Will the CYGNSS spatial resolution be determined by the radar range/Doppler resolutions or a smaller scattering region (i.e., limited to first Fresnel zone)?

Given the launch of CYGNSS is scheduled for 2016, the breakout participants identified a set of immediate needs to address the questions posed above and to insure CTH applications would be possible during the CYGNSS mission. These included:

- Extension of the CYGNSS E2ES to incorporate scattering models for CYGNSS cases over land, wetlands, riverine, flooded, snow environments
- Analysis of existing aircraft data sets to understand signal properties, validate modeling, estimate spatial resolution
- Analysis of TDS-1 data to understand signal properties, validate modeling, estimate spatial resolution
- Funding to the project or members of applications working group to accomplish all of the above prior to launch.

The CTH breakout participants also identified a few items that the CYGNSS project management should consider to increase the utility of the applications it recommended. If adopted by the project, these would increase the probability of successful application of CYGNSS data to coastal, terrestrial, and hydrological applications. These included:

- Along-track resolution should be finer by reducing the incoherent integration times over land surfaces to maximize application efficacy; this would require an onboard land mask and an increase in the data rate
- Use of the raw sampling mode for specific CTH targets to study applications that are not accommodated or could be studied for future missions (e.g., cryosphere applications)
- Since lower data latency increases possible applications, a graph of latency reduction vs. cost would instruct this choice (note: the CYGNSS project has a plan to produce this graph but does not have current funding to realize this goal)



5. CONCLUSION

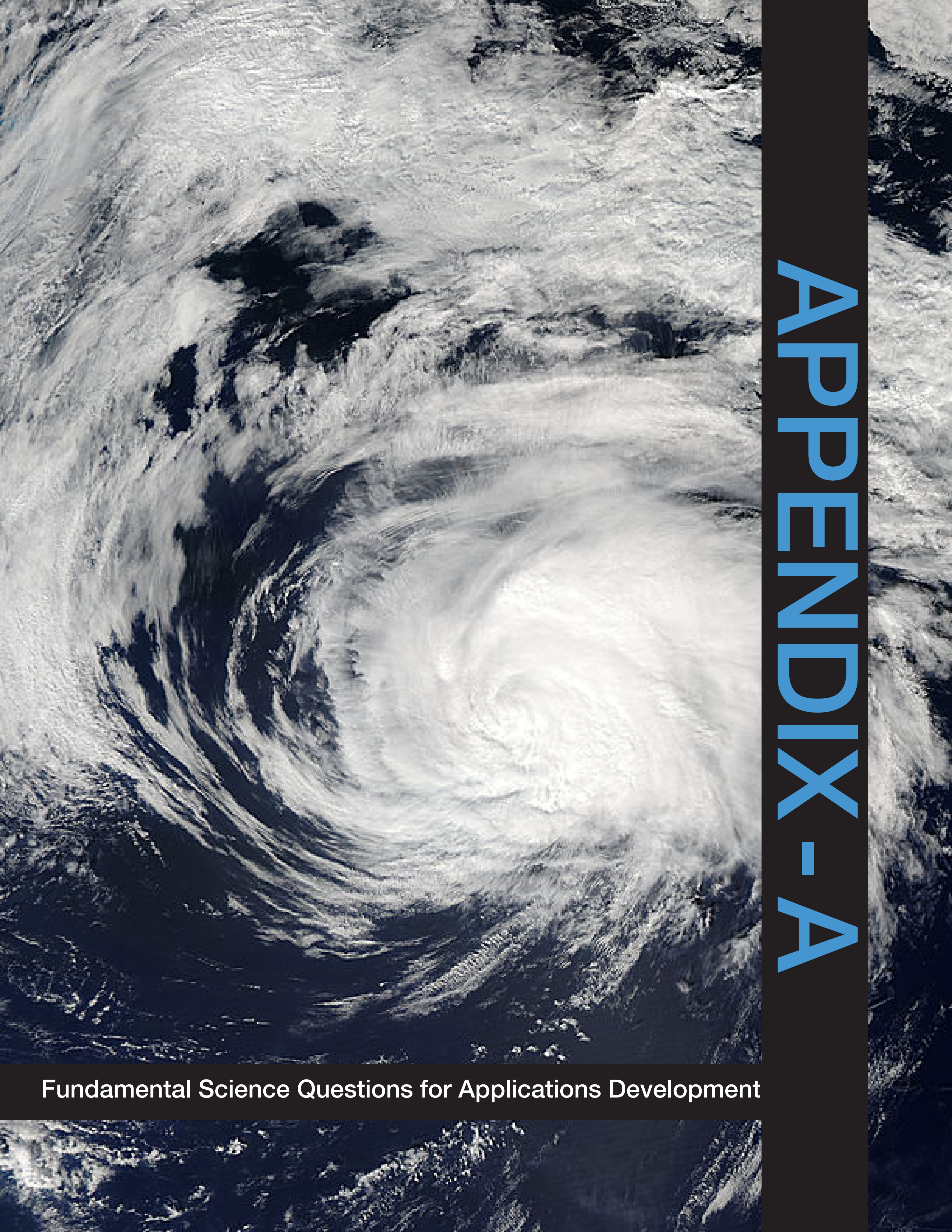
The first Cyclone Global Navigation Surveillance System (CYGNSS) Applications Workshop has provided valuable insights for the development of applications that address critical data gaps. This mission, which was primarily conceived to obtain denser surface wind field observations to improve tropical cyclone intensity forecasts is also expected to provide new insights on air-sea interactions related to tropical convection, measurements of soil moisture and surface water extent, as well as observations of ocean surface dynamics in insufficiently sampled regions bracketing the equator from 35N to 35S latitude. These applications are highlighted in the executive summary and are examined in detail in dedicated chapters and appendices of this report.

Appendix A addresses the fundamental science questions identified in this workshop and Appendix B comprises an Applications Traceability matrix which answers and amplifies each of those questions into the applications domain. Specifically, for each these science questions, the corresponding matrix entry identifies an important applications concept, potential products, their maturity level, area of applicability, measurement requirements (spatial and temporal resolution, and latency), other requirements, related R&D, improvements needed and, most importantly application stakeholders and users. It is strongly recommended that using these two appendices as a guide, the NASA Applied Sciences Program's Disasters area work closely with the NASA Research Division and the CYGNSS Mission Science Team to support and utilize the conduct of related Observing System Simulation Experiments (OSSEs) and the modeling and data assimilation experiments needed to build the full range of applications for CYGNSS.

The development of effective, useful applications is also only possible with the direct involvement of users and stakeholders. Since the CYGNSS mission entails a new measurement concept with a unique set of science questions, our first CYGNSS Applications Workshop focused more on identifying all of the science questions and potential applications of the science. The workshop participants also identified a broad range of potential national and international, public and private end-users and stakeholders. In addition to the U.S. agencies, institutions and private organizations who participated in the primarily science to applications exercise comprising this workshop (see Appendix D) it was felt that the next workshop should strive to bring in stakeholders and end-users at the myriad receiving ends of the CYGNSS applications development process. Thus, at the conclusion of the workshop, it was generally agreed that before the mission launches and CYGNSS data become available for applications development, a second CYGNSS workshop is planned to be held in calendar year 2016 to assemble all of the potential end users and stakeholders who may benefit from the CYGNSS Mission. This would include a wide range of government, private and commercial sectors representing the panoply of the global community that is affected by the phenomena which were addressed in the first workshop. The potential list is quite long, but should include resource, infrastructure, and financial players at a variety of levels. Examples could broadly range from agriculture, energy, transportation, the maritime sector, military, finance, risk assessment and reinsurance, and disaster planning and response, to broad swaths of academia, NGOs, and other organizations. A broad array of these sectors and organizations needs to be identified and invited to future workshops to review, assess, and provide feedback on applications for representative real-world cases which should be developed and incorporated into future workshop agendas.

Preparatory activities related to the potential uses of the data are also needed. These include, but are not limited to a review of any mission-related preparatory research such as the TechDevSat-1 mission and any OSSEs or other research which may have been conducted using this data. This data could also be used to support potential early adopter research or applications development. Further collaboration between the NASA Science Mission Directorate's Research Division and its entire NASA Applied Sciences Program is required to ensure an optimal result.

APPENDIX - A



Fundamental Science Questions for Applications Development

A.1 QUESTIONS/APPLICATIONS FROM THE TROPICAL CONVECTION AND FORECASTING BREAKOUT SESSION

Tropical Cyclone Applications Questions

Could CYGNSS improve wind analysis of TC Inner core?

Can CYGNSS help DA systems get the initial TC position, intensity and structure correct?

Would CYGNSS have the capability to observe TC extratropical transition?

How can CYGNSS data be used for tropical cyclone model verification ?

Is CYGNSS a viable tool for tropical wave tracking and cyclone genesis?

Can CYGNSS surface wind data help to accurately specify the 4 dimensional wind structure in tropical cyclones?

Will CYGNSS winds yield improvements to tropical cyclone intensity forecasts?

Are improvements to surface flux parameterizations in high winds possible using CYGNSS data?

Tropical Convection Applications Questions

Can CYGNSS improve MJO monitoring and forecasting?

Can CYGNSS improve monitoring and forecasting of Gulf of California surges?

Can CYGNSS improve monitoring of Equatorial Pacific trade winds?

Can CYGNSS improve monitoring of non-TC high wind events?

Can CYGNSS improve monitoring and forecasting of monsoon circulations?

Can CYGNSS improve monitoring and forecasting of the ITCZ?

Global Applications Questions

Can CYGNSS assist the wind energy industry?

Can CYGNSS aid in search and rescue?

Can CYGNSS help monitor oil spills?

Can CYGNSS aid in fishery management?

Can CYGNSS aid in forensic meteorology?

Can CYGNSS aid in observing system and model validation?

Can CYGNSS winds and surface roughness improve sub-seasonal to seasonal prediction?

Can CYGNSS contribute to the sea salt aerosol production parameterizations?

Can CYGNSS add value for reanalysis and retrospective analyses?

Can CYGNSS be used to generate 3D world winds?

How can we get NWP models to retain the CYGNSS information?

How can CYGNSS winds help us improve NWP models?

How can CYGNSS DDM contribute to development of coupled models and DA?

Can CYGNSS help monitor and forecast Atmospheric Rivers?

QUESTIONS/APPLICATIONS FROM THE OCEANOGRAPHY BREAKOUT SESSION A.2

Can CYGNSS improve hurricane intensity forecasts by improving ocean model performance?
Can regional to global ocean forecasts be improved using CYGNSS observations?
Can CYGNSS improve coastal ocean forecasts, including coastal upwelling and biogeochemical responses?
Can CYGNSS improve storm surge prediction?
Can CYGNSS improve tsunami prediction?
Can CYGNSS improve hurricane surface wind analysis products provided to the public?
Can CYGNSS improve our understanding of coupled climate modes with large footprints in the tropical/subtropical ocean?
Can CYGNSS products be used to improve ocean wave models?
Can CYGNSS be used to improve satellite ocean salinity retrievals?
Can CYGNSS be used to correct other satellite measurements affected by radio frequency occultation (RFI)?
Can CYGNSS improve atmospheric profile measurements determined by radio occultation?
Can drag coefficient and momentum flux be estimated from CYGNSS observations?
How does heavy precipitation and surface contaminants affect CYGNSS roughness estimates?

A.3 QUESTIONS/APPLICATIONS FROM THE COASTAL, HYDROLOGICAL AND TERRESTRIAL APPLICATIONS BREAKOUT SESSION

Soil Moisture Applications Questions

What is the CYGNSS added value for soil moisture retrievals in crop prediction?

Can CYGNSS detect the differences between soil moisture and vegetation water content?

Will CYGNSS give different information from SMAP or Aquarius?

Will assimilation of CYGNSS data improve soil moisture in models?

Can CYGNSS improve soil type catalogs with higher spatial resolution measurements?

Can CYGNSS add value to mobility mapping?

What are the impacts of land surface roughness?

What are the potential desert applications, such as detection of dry riverbeds or sub-surface moisture?

Rainfall and Run-Off Dynamics Questions

What is the 12-minute response (average CYGNSS rapid repeat time) to precipitation events?

Can CYGNSS help to temporally disaggregate the data to improve short intensity rainfall estimates?

Can CYGNSS help estimate runoff with fast sampling?

Vegetation and Biomass Applications Questions

Can CYGNSS detect the differences between soil moisture and vegetation water content?

Will CYGNSS give different information from SMAP's technique?

Can CYGNSS detect sub-daily changes in vegetation water content?

Can CYGNSS data add value to crop yield models when combined with humidity and air temps?

Surface Water Extent Mapping Applications

Can CYGNSS map wetlands and the changes in wetlands (and through vegetation)?

Can CYGNSS see flood changes in a river in NRT?

Can CYGNSS detect oil leaks/slicks in marine water and lakes?

What is the spatial resolution of CYGNSS measurements near the coast to identify coastal flooding post hurricane?

How CYGNSS measurements impact storm surge?

How does CYGNSS sense roughness for coastal, fetch-limited winds?

Can CYGNSS measure increasing sea surface heights before ocean surge?

Can CYGNSS detect the dynamics of coastal flooding or storm surges?

Cryosphere Applications Questions

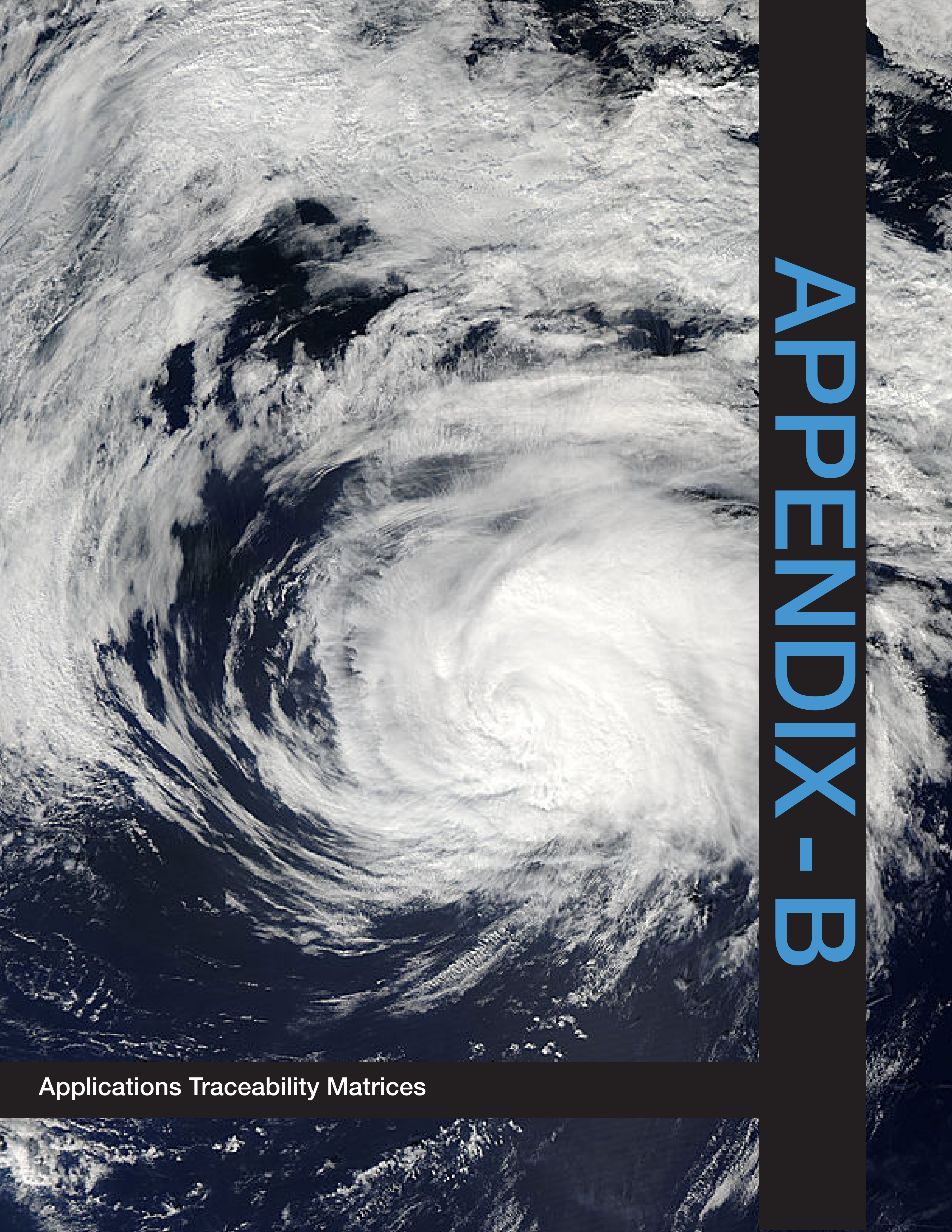
How can CYGNSS contribute to freeze/thaw, permafrost, and methane monitoring?

Permafrost soil, when it's frozen and when it's melting-food access, food security and pipelines?

Can CYGNSS sample sub-daily recession of snow lines, detect the area, and understand the different phases of snow melt?

Can CYGNSS observe changes at freeze-melt time?

Limited snow coverage region but CYGNSS will cover areas of high interest (Himalayas)?



APPENDIX - B

Applications Traceability Matrices

Appendix B1: CYGNSS Applications Matrix For Tropical and Global (General) Weather Applications

Tropical Cyclone Applications

Science Questions	Applications Concept	Products	Initial ARL	ASP Area	Measurement Requirements	Other Requirements	Other R&D	Improvements	User Groups
Can CYGNSS improve MJO monitoring and forecasting?	Predictability barrier when MJO reaches Maritime Continent, due to poor model treatment of diurnal cycle of convection	Level 2	1	Disaster Management Response, and Recovery	Latency of 6 days or less, Spatially and temporally resolved quality indicators	BUFR Format, GPM, Ground Radars, Wind Direction, 3D Winds, Geostationary VIS/IR	Model and data assimilation enhancements to preserve CYGNSS winds, CYGNSS reprocessing to improve spatial resolution near coasts, Investigation of viability of wind direction retrievals from CYGNSS	Diurnal cycle of winds unbiased by presence of precipitation	Global and regional forecasting agencies, Water resources agencies, Militaries, Agricultural industry
Can CYGNSS improve monitoring and forecasting of Gulf of California surges?	Gulf surges bring enhanced moisture and precipitation to the US Southwest and NW Mexico, lack of observations within Gulf to mointor them and improve forecasts	Level 2	1	Disaster Management Response, and Recovery	Latency of 6 hours or less, Spatially and temporally resolved quality indicators	BUFR Format, GPM, Ground Radars, Wind Direction, 3D Winds, Geostationary VIS/IR	Model and data assimilation enhancements to preserve CYGNSS winds, CYGNSS reprocessing to improve spatial resolution near coasts, Investigation of viability of wind direction retrievals from CYGNSS	High temporal resolution, all-weather sampling	Southwest US NWS WFOs, SMN (Mexico), Water resources agencies
Can CYGNSS improve monitoring of Equatorial Pacific trade winds?	Trade winds near Equatorial Pacific behave differently in El Nino and La Nina years. Equatorial trades may also affect global and regional climate via ocean upwelling changes	Level 3	1	Disaster Management Response, and Recovery	Latency of 6 days or less	BUFR Format, Wind Direction	Model and data assimilation enhancements to preserve CYGNSS winds, Creation of monthly/seasonal CYGNSS wind product, Investigation of viability of wind direction retrievals from CYGNSS	Diurnal cycle of winds unbiased by presence of precipitation	Global climate modeling and forecasting agencies, Water resources agencies, Agricultural industry
Can CYGNSS improve monitoring of non-TC high wind events?	Need for diagnosis and nowcasting of gale/storm-force winds caused by phenomena such as MCS outflow, Tehuantepec gap winds, Westerly wind bursts, etc.	Level 2	1	Disaster Management Response, and Recovery	Latency of 6 hours or less, Spatially and temporally resolved quality indicators	BUFR Format, Wind Direction	Model and data assimilation enhancements to preserve CYGNSS winds, CYGNSS reprocessing to improve spatial resolution near coasts, Investigation of viability of wind direction retrievals from CYGNSS	High temporal resolution, all-weather sampling	Global and regional forecasting agencies, Emergency management agencies, Shipping, aviation, and rail transportation industries, Militaries, Coast Guard
Can CYGNSS improve monitoring and forecasting of monsoon circulations?	Monsoons are defined as seasonal reversals in winds, and lead to active/break precipitation periods and flooding	Level 2	1	Disaster Management Response, and Recovery	Latency of 1 day or less, Spatially and temporally resolved quality indicators	BUFR Format, GPM, Ground Radars, Wind Direction, 3D Winds, Geostationary VIS/IR	Model and data assimilation enhancements to preserve CYGNSS winds, CYGNSS reprocessing to improve spatial resolution near coasts, Investigation of viability of wind direction retrievals from CYGNSS	Diurnal cycle of winds unbiased by presence of precipitation	Global and regional forecasting agencies, Water resources agencies, Disaster response agencies, Shipping industry, Agricultural industry
Can CYGNSS improve monitoring and forecasting of the ITCZ?	ITCZ moves seasonally, but exhibits significant convective variability that is a known aircraft and ship hazard. Due to heavy rain, wind measurements from other scatterometers are biased	Level 2	1	Disaster Management Response, and Recovery	Latency of 1 day or less, Spatially and temporally resolved quality indicators	BUFR Format, GPM, Wind Direction, 3D Winds, Geostationary VIS/IR	Model and data assimilation enhancements to preserve CYGNSS winds, Investigation of viability of wind direction retrievals from CYGNSS	High temporal resolution, all-weather sampling	Global and regional forecasting agencies, Aviation and shipping industries
Is CYGNSS a viable tool for tropical wave tracking and cyclone genesis?	Vorticity tracking (e.g. NPS "Pouch" products); Identification of closed surface wind circulations	wind speed L2	1	Disaster Management Response, and Recovery	Wind vector observation (direction in addition to speed)	microwave sounders and imagers, geostationary imagery, GPM	Obtain wind direction from CYGNSS measurements. Wind direction critical here, but would be great help in all (almost all) other topics	Enhanced temporal contintuity	NOAA; DOD; other operational centers
Can CYGNSS surface wind data help to accurately specify the 4 dimensional wind structure in tropical cyclones?	Propagating surface wind information throughout atmosphere via advanced data assimilation methods	wind speed L2/L3	1	Disaster Management Response, and Recovery	Balance between wind and mass fields (gradient balance for the inner core)	microwave sounders and imagers, geostationary imagery, GPM, dropsondes and other themodynamic data	DA system improvements	Enhanced spatial and temporal surface wind coverate over tropics	NOAA; DOD; other operational centers
Will CYGNSS winds yield improvements to tropical cyclone intensity forecasts?	Increasing numerical forecast skill beyond statistical intensity predictions (e.g., SHIPS)	wind speed L2	1	Disaster Management Response, and Recovery	Accurate (better than 10%) measurement of maximum surface wind speed anywhere in the storm	If successful could provide significant forecast model improvements		Enhanced spatial and temporal surface wind coverate over tropics	NOAA; Emergency management
Are improvements to surface flux parameterizations in high winds possible using CYGNSS data?	Surface winds and waves needed to estimate drag coefficient and roughness length; enthalpy fluxes also rely on accurate exchange coefficients	wind speed, MSS,	1	Disaster Management Response, and Recovery	Highly accurate surface wind speed (better than 1%) and wave spectra, including asymmetries around storms	Near surface thermodynamic observations (temperature, humidity, pressure)	High frequency (turbulent fluctuation) wind measurements	High wind observations without precipiation contamination	Researchers/Academia

Appendix B1: CYGNSS Applications Matrix For Tropical and Global (General) Weather Applications

Tropical Convection Applications

Science Questions	Applications Concept	Products	Initial ARL	ASP Area	Measurement Requirements	Other Requirements	Other R&D	Improvements	User Groups
Can CYGNSS improve MJO monitoring and forecasting?	Predictability barrier when MJO reaches Maritime Continent, due to poor model treatment of diurnal cycle of convection	Level 2	1	Disaster Management Response, and Recovery	Latency of 6 days or less, Spatially and temporally resolved quality indicators	BUFR Format, GPM, Ground Radars, Wind Direction, 3D Winds, Geostationary VIS/IR	Model and data assimilation enhancements to preserve CYGNSS winds, CYGNSS reprocessing to improve spatial resolution near coasts, Investigation of viability of wind direction retrievals from CYGNSS	Diurnal cycle of winds unbiased by presence of precipitation	Global and regional forecasting agencies, Water resources agencies, Militaries, Agricultural industry
Can CYGNSS improve monitoring and forecasting of Gulf of California surges?	Gulf surges bring enhanced moisture and precipitation to the US Southwest and NW Mexico, lack of observations within Gulf to mointor them and improve forecasts	Level 2	1	Disaster Management Response, and Recovery	Latency of 6 hours or less, Spatially and temporally resolved quality indicators	BUFR Format, GPM, Ground Radars, Wind Direction, 3D Winds, Geostationary VIS/IR	Model and data assimilation enhancements to preserve CYGNSS winds, CYGNSS reprocessing to improve spatial resolution near coasts, Investigation of viability of wind direction retrievals from CYGNSS	High temporal resolution, all-weather sampling	Southwest US NWS WFOs, SMN (Mexico), Water resources agencies
Can CYGNSS improve monitoring of Equatorial Pacific trade winds?	Trade winds near Equatorial Pacific behave differently in El Nino and La Nina years. Equatorial trades may also affect global and regional climate via ocean upwelling changes	Level 3	1	Disaster Management Response, and Recovery	Latency of 6 days or less	BUFR Format, Wind Direction	Model and data assimilation enhancements to preserve CYGNSS winds, Creation of monthly/seasonal CYGNSS wind product, Investigation of viability of wind direction retrievals from CYGNSS	Diurnal cycle of winds unbiased by presence of precipitation	Global climate modeling and forecasting agencies, Water resources agencies, Agricultural industry
Can CYGNSS improve monitoring of non-TC high wind events?	Need for diagnosis and nowcasting of gale/storm-force winds caused by phenomena such as MCS outflow, Tehuantepec gap winds, Westerly wind bursts, etc.	Level 2	1	Disaster Management Response, and Recovery	Latency of 6 hours or less, Spatially and temporally resolved quality indicators	BUFR Format, Wind Direction	Model and data assimilation enhancements to preserve CYGNSS winds, CYGNSS reprocessing to improve spatial resolution near coasts, Investigation of viability of wind direction retrievals from CYGNSS	High temporal resolution, all-weather sampling	Global and regional forecasting agencies, Emergency management agencies, Shipping, aviation, and rail transportation industries, Militaries, Coast Guard
Can CYGNSS improve monitoring and forecasting of monsoon circulations?	Monsoons are defined as seasonal reversals in winds, and lead to active/break precipitation periods and flooding	Level 2	1	Disaster Management Response, and Recovery	Latency of 1 day or less, Spatially and temporally resolved quality indicators	BUFR Format, GPM, Ground Radars, Wind Direction, 3D Winds, Geostationary VIS/IR	Model and data assimilation enhancements to preserve CYGNSS winds, CYGNSS reprocessing to improve spatial resolution near coasts, Investigation of viability of wind direction retrievals from CYGNSS	Diurnal cycle of winds unbiased by presence of precipitation	Global and regional forecasting agencies, Water resources agencies, Disaster response agencies, Shipping industry, Agricultural industry
Can CYGNSS improve monitoring and forecasting of the ITCZ?	ITCZ moves seasonally, but exhibits significant convective variability that is a known aircraft and ship hazard. Due to heavy rain, wind measurements from other scatterometers are biased	Level 2	1	Disaster Management Response, and Recovery	Latency of 1 day or less, Spatially and temporally resolved quality indicators	BUFR Format, GPM, Wind Direction, 3D Winds, Geostationary VIS/IR	Model and data assimilation enhancements to preserve CYGNSS winds, Investigation of viability of wind direction retrievals from CYGNSS	High temporal resolution, all-weather sampling	Global and regional forecasting agencies, Aviation and shipping industries

Appendix B1: CYGNSS Applications Matrix For Tropical and Global (General) Weather Applications

Global (General) Applications

Science Questions	Applications Concept	Products	Initial ARL	ASP Area	Measurement Requirements	Other Requirements	Other R&D	Improvements	User Groups
Can CYGNSS assist the wind energy industry?	Wind energy requires knowledge of local wind behavior at different time scales	Level 2, Level 3	1	Disaster Management Response, and Recovery	For placement of wind turbines need wind climatology; For day-to-day operations need latency of 6 hours or less, spatially and temporally resolved quality indicators	Wind Direction, 3D Winds	CYGNSS reprocessing to improve spatial resolution near coasts, Creation of monthly/seasonal CYGNSS wind products, Adjustment of CYGNSS winds to wind turbine height, Investigation of viability of wind direction retrievals from CYGNSS	Diurnal cycle of winds unbiased by presence of precipitation	Wind energy industry
Can CYGNSS aid in search and rescue?	Disaster and emergey response agencies need knowledge of winds to plan for operations, to predict drift of wreckage, etc.	Level 2	1	Disaster Management Response, and Recovery	Latency of 6 hours or less, Spatially and temporally resolved quality indicators	BUFR Format, Wind Direction	Model and data assimilation enhancements to preserve CYGNSS winds, CYGNSS reprocessing to improve spatial resolution near coasts, Investigation of viability of wind direction retrievals from CYGNSS	High temporal resolution, all-weather sampling	Disaster response and emergency management agencies
Can CYGNSS help monitor oil spills?	Oil industry and environmental disaster response agencies need to know the extent and evolution of oil spills	Level 2	1	Disaster Management Response, and Recovery	Latency of 6 hours or less, Spatially and temporally resolved quality indicators	BUFR Format, Wind Direction	Model and data assimilation enhancements to preserve CYGNSS winds, CYGNSS reprocessing to improve spatial resolution near coasts, Investigation of ability of CYGNSS to detect oil slicks, Investigation of viability of wind direction retrievals from CYGNSS	High temporal resolution, all-weather sampling	Disaster response and emergency management agencies, Oil industry, Environmental protection agencies
Can CYGNSS aid in fishery management?	Fisheries are affected by upwelling events, forced by enhanced surface winds	Level 2	1	Disaster Management Response, and Recovery	Latency of 1 day or less, Spatially and temporally resolved quality indicators	BUFR Format, Wind Direction	Model and data assimilation enhancements to preserve CYGNSS winds, CYGNSS reprocessing to improve spatial resolution near coasts, Investigation of viability of wind direction retrievals from CYGNSS	Diurnal cycle of winds unbiased by presence of precipitation	Fishing industry, Fish and wildlife management agencies
Can CYGNSS aid in forensic meteorology?	Insurance industry often needs to understand relative impact of winds versus water in assessing losses	Level 3	1	Disaster Management Response, and Recovery	Latency of 6 days or less, Spatially and temporally resolved quality indicators	Wind Direction, Coastal Flooding Products	CYGNSS reprocessing to improve spatial resolution near coasts, Investigation of viability of wind direction retrievals from CYGNSS	High temporal resolution, all-weather sampling	Insurance industry
Can CYGNSS aid in observing system and model validation?	Models and observing systems are always in need of independent validation datasets, in this case for wind speed.	Level 3	2	Disaster Management Response, and Recovery	Latency of 6 days or less, Spatially and temporally resolved quality indicators	None	CYGNSS reprocessing to improve spatial resolution near coasts (for certain applications), Rigorous Cal/Val of CYGNSS products, Investigation of viability of wind direction retrievals from CYGNSS	High temporal resolution, all-weather sampling	Model and instrument investigators, Forecast agencies
Can CYGNSS winds and surface roughness improve sub-seasonal to seasonal prediction?	For S2S, lagged forecasts to capture late-arriving data might still have utility, especially as we extend our NWP models to longer forecast lead times	winds L2 and MSS L2, possibly DDM at a later point	1	Disaster Management Response, and Recovery	standard products are probably okay	Likely coupled ocean model to extend predictibility much beyond 7-10 days	Forecast model development, coupled ocean/atmosphere modeling and assimilation	Extended range predictions with skill beyond the 7-10 day range	Futures (economic), drought and fire protection, weather-informed water storage (e.g. resevoirs, conservation), advanced purchase/budgeting for energy

Can CYGNSS contribute to the sea salt aerosol production parameterizations?	DA and NWP applications	winds L2, MSSS L2	1	Disaster Management Response, and Recovery	standard products are probably okay	MODIS AOD, Aeronet for verification	Integration of aerosols within forecast models, more sophisticated aerosol DA, esp. within coupled DA context	Better specification of sea salt source production	DoD, aviation, recreation
Can CYGNSS add value for reanalysis and retrospective analyses?	MERRA reanalysis which is used for model intercomparison studies and process studies	winds L2	2	Disaster Management Response, and Recovery	standard	all assimilated data	Forecast model development, coupled ocean/atmosphere modeling and assimilation	captures diurnal variability and winds is regions of persistant convection and precipitation	Model intercomparisons, diagnostic studies, forecast model validation and cross comparison, education
Can CYGNSS be used to generate 3D world winds?	This is related to #11, Atmospheric Rivers	Level 4 merged world winds product	1	Disaster Management Response, and Recovery	standard	AMVs and other surface winds	Methods for blending diverse wind products into a cohernent 3D wind product	captures diurnal variability and winds is regions of persistant convection and precipitation	Recreation, wind energy, education, land use planning,
How can we get NWP models to retain the CYGNSS information?	Need ensemble/hybrid 4D DA	wind speed	1	Disaster Management Response, and Recovery	highest possible	all obs	higher model resolution, non-Gaussian DA,	more accurate analyses and forecasts	NWP and downstream applications
How can CYGNSS winds help us improve NWP models?	TC genesis and decay, TC intensity changes	CYGNSS winds	1	Disaster Management Response, and Recovery	highest possible	all other obs	Improved model physics, esp. w.r.t. momentum, heat and moisture fluxes near the ocean and land surface	captures diurnal variability and winds is regions of persistant convection and precipitation	users of analysis and forecast products, day 0 through seasonal prediction. Climate variability/change assessment
How can CYGNSS DDM contribute to development of coupled models and DA?	atmosphere, ocean and waves, surface fluxes - analysis and prediction. Use in diagnostic studies	L2 winds and MSS initially, later DMM	1	Disaster Management Response, and Recovery	highest possible	Many other observations to help constrain the analysis solution	Improved model physics, esp. w.r.t. momentum, heat and moisture fluxes near the ocean and land surface	NWP models better capture TCs, tropical weather systems and links between tropics and extratropics	users of analysis and forecast products, day 0 through seasonal prediction. Climate variability/change assessment
Can CYGNSS help monitor and forecast Atmospheric Rivers?	3D Winds for moisture transport from deep tropics	winds L2 and L3	1	Disaster Management Response, and Recovery	standard	Supplemental global observations of winds, humidity, pressure, temperature	Methods for blending diverse wind products into a cohernent 3D wind product		hydrological, lowering resevoirs in anticipation of heavy rains, or not prematurely releasing water from resevoirs

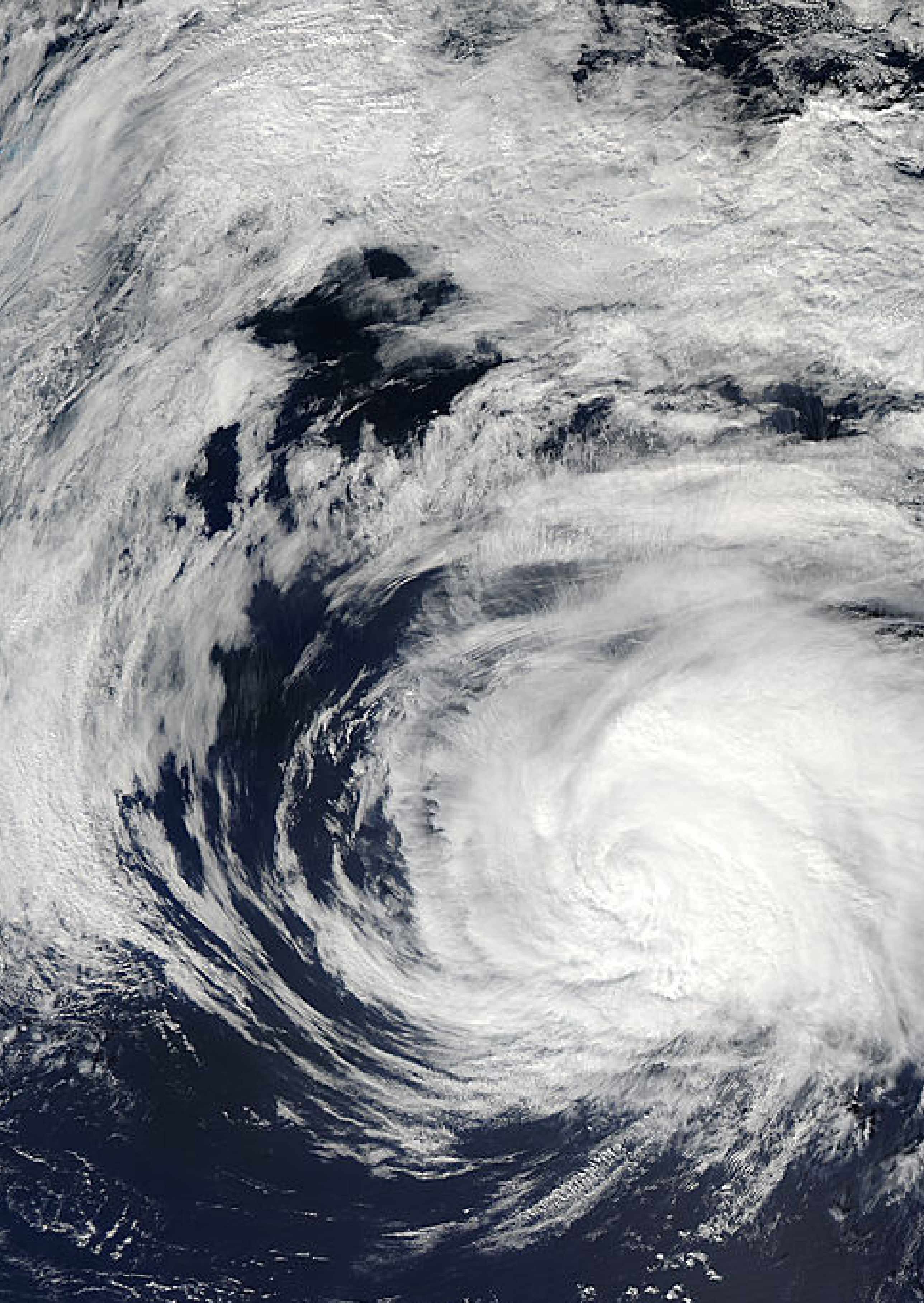
Appendix B2: CYGNSS Applications Traceability Matrix for Oceanography Applications

Science Questions	Applications Concept	Products	Initial ARL	ASP Area	Measurement Requirements	Other Requirements	Other R&D	Improvements	User Groups
Can CYGNSS improve hurricane intensity forecasts by improving ocean model performance?	Improve atmospheric model initialization in coupled hurricane forecast models	Level 2a winds for assimilation into atmospheric model	1	Disaster Management Response, and Recovery	Existing capabilities OK for retrospective studies	Low latency required for real-time tests; In-storm atmospheric wind measurements for evaluation	Initialize atmospheric model with and without CYGNSS data input - determine impact on ocean model.	Improve estimates of intensity, size, (RMW, radii of hurricane and TC winds), structure, center of TCs. This should improve ocean model response	TC forecast centers (EMC, NHC,…). Emergency management (FEMA, state,local)
Can CYGNSS improve hurricane intensity forecasts by improving ocean model performance?	Use CYGNSS in conjunction with satellite salinity estimates (Aquarius, SMAP, …) to study thermohaline feedback effects on ocean cooling	Level 1b	1	Disaster Management Response, and Recovery	Research topic - existing capabilities are OK	Wind direction; Salinity measurements from other satellites, in-situ profilers (e.g. gliders)	Basic research needed to understand potential improvement.	Understand impact of evolving thermohaline profiles on ocean cold wake.	hurricane and storm surge modeling communities
Can CYGNSS improve hurricane wind analyses provided to the public?	Example: add CYGNSS winds to the full suite of wind measurements analyzed by HWIND Scientific to produce the H*WIND analysis product	Level 2a	1	Disaster Management Response, and Recovery	Research topic - existing capabities are OK	Wind direction	Research to understand properties of CYGNSS wind products such as space/time resolution	More accurate hurricane wind maps made available to the public	Hurricane and storm surge scientists; Insurance industry
Can CYGNSS improve storm surge prediction?	Extract altimetry measurements from CYGNSS observations	Level 1b plus metadata	1	Disaster Management Response, and Recovery	Process additional information (model timing of pixels in DDM, time delay from direct signal)	Wind direction; Measurements from altimetry satellites; Sea level measurements from GPS buoys	Large uncertainty. Basic research must demonstrate if signal is large enough to be detected.	Resolve surge along with forced shelf waves that can precede surge.	Emergency managers (FEMA, state, local)
Can CYGNSS improve storm surge prediction?	Improved wind products derived from CYGNSS plus other satellites to drive storm surge models	Level 2a or level 3 winds	1	Disaster Management Response, and Recovery	Rapid-refresh wind measurements are critical. Low latency required for real-time forecasts	Wind direction	Research required to determine if improvement can be achieved	Improved surge prediction accuracy	Emergency managers (FEMA, state, local)
Can CYGNSS improve tsunami prediction?	Extract altimetry measurements from CYGNSS observations	Level 1b plus metadata	1	Disaster Management Response, and Recovery	Process additional information (model timing of pixels in DDM, time delay from direct signal)	Measurements from altimetry satellites; Sea level measurements from GPS buoys	Large uncertainty. Basic research must demonstrate if signal is large enough to be detected.	Any means of detection is an improvement - earlier warnings possible	Emergency managers (FEMA, state, local)
Can CYGNSS improve coastal ocean analyses and forecasts, including coastal upwelling and biogeochemical responses?	Improved maps of coastal wind field wind, particularly within ~40 km of the coastline	Level 2a or level 3 winds	1	Disasters, and Ecological Forecasting	Existing capabilities OK for retrospective studies.	Wind direction; Other satellite wind measurements, offshore ship and buoy wind measurements	Determine how close to land good wind estimates can be made. Research to detect and remove land signal.	More accurate coastal ocean analyses and forecasts	Coastal oceanographers, coast guard, offshore engineers, wind farms and energy; air quality warnings, fishermen
Can CYGNSS be used to improve ocean salinity retrievals?	Use CYGNSS data to correct for surface roughness	Level 1, 2b MSS	1	Disasters, and Ecological Forecasting	Research topic -existing capabilities are OK	Other satellite salinity measurements, in-situ surface drifters that measure salinity.	Research in progress; future research should incorporate CYGNSS data	Independent roughness dataset; improved river and rain impacts; Improve ocean circulation and climate representation	TC forecasters, ocean climate researchers
Can CYGNSS improve ocean wave models?	Use CYGNSS MSS to verify and potentially improve the wave spectrum used by the models within a limited wavenumber range	Level 2b MSS	1	Disasters, and Ecological Forecasting	Research topic - existing capabilities are OK.	In-situ wave measurements from buoys and other sources	Compare CYGNSS mean square slopes to wave model spectrum	Improve wave model skill in predicting spectral tail	Wave modelers, marine transportation, fluxes in coupled hurricane models
Can CYGNSS improve our understanding of coupled climate modes with large footprints in the tropical/subtropical ocean	Analyze air-sea interactions associated with coupled climate modes	Level 3b gridded and optimized wind speed	1	Disasters, and Ecological Forecasting	Initial products OK, but need long time series	Wind direction; Atmospheric reanalyses with CYGNSS wind assimilation,	Need research to demonstrate that long-term biases in CYGNSS observations are small	Improved air-sea fluxes will improve understanding of ocean role in climate modes.	Ocean climate researchers and modelers.

Can regional to global ocean forecasts be improved using CYGNSS observations?	Assimilate CYGNSS wind measurements into the global atmospheric prediction models that drive the ocean models	Level 2a winds for assimilation into atmospheric model	1	Disasters, and Ecological Forecasting	Must provide CYGNSS wind estimates to GTS with low latency		Ocean response research to determine if errors in ocean analyses are significantly reduced	More accurate ocean analyses and forecasts.	Ocean forecasting community (NOAA, Navy, international).
Can drag coefficient and momentum flux be estimataed from CYGNSS observations?	Roughness estimates in storm quadrants	Level 1; Level 2b MSS	1	Disaster Management Response, and Recovery	Research topic - existing capabilities are OK	Wind direction	Relationship of CYGNSS MSS versus z0; Dependence of the relatiosnip between drag coefficient and z0 on wind speed; Impact of foam and sea spray	More accurate air-sea flux estimates.	Ocean modeling and forecasting communities; hurricane forecasters
How does heavy precipitation and surface contaminants affect CYGNSS roughness estimates?	Rain attenuation can have large impact on CYGNSS wind retrieval that requires correction; uncertainty estimates	Level 1; level 2b MSS	1	Disasters, Water Resources and Ecological Forecasting	Existing products are adequate	Windsat, GPM, SAR, precipitation radar	Compare CYGNSS to other measurements to infer uncertainties	Improve CYGNSS retrieval algorithm	All CYGNSS users; not confined to ocean applications.
Can CYGNSS be used to correct other satellite measurements affected by radio frequency interference?	CYGNSS measurements are not degraded by RFI; Identify regions of strong RFI where corrections are necessary	Level 1; Level 2b MSS	1	Disaster Management Response, and Recovery	Existing products are adequate		Research to demonstrate corrections to other satellite measurements affected by RFI.	CYGNSS can provide data where RFI interferes with other measurements	Ocean satellite community
Can CYGNSS improve atmospheric profiles in the PBL determined by radio occultation (RO)?	Combine CYGNSS and RO observations	Level 1 plus metadata	1	Disasters, Water Resources and Ecological Forecasting	Existing products are adequate	RO measurements, atmospheric dropsonde profiles.	Research required to determine if density profiles can be extended below 100 m	Improve air-sea flux estimates that force the ocean, particularly within TCs.	Hurricane forecast community.

Appendix B3: CYGNSS Applications Tracebility Matrix for Terrestrial, Hydrological and Coastal Applications

Science Questions	Applications Concept	Products	Initial ARL	ASP Area	Measurement Requirements	Other Requirements	Other R&D	Improvements	User Groups
Soil Moisture Applications									
What is the temporal, sub-daily evolution of soil moisture?	Soil moisture dynamics; Value added product over other sensors (SMAP)	Soil moisture derived from the BRCS (L1B)	2	Disasters, Water Resources and Ecological Forecasting	Shorter integration time over land for finer along-track sampling; sensor intercalibration	Soil roughness, type maps; vegetation cover; e.g., similar to SMAP ancillary requirements	Bistatic land surface scattering model development; existing TDS-1 and aircraft data analysis; combining with L2 CYGNSS combined with L-band sensors to create value-added products	Finer resolution history of soil moisture at each location; augment spatial and temporal coverage of other sensors	USDA, USDM, DOD, universities
Can sub-daily soil moisture improve assimilation results?	Finer temporal sampling of soil moisture for assimilation into short-term forecasting; crop modeling	Soil moisture derived from the BRCS (L1B)	1	Disasters, Water Resources and Ecological Forecasting	Shorter latencies for NRT applications; shorter integration time over land for finer along-track sampling; sensor intercalibration	Soil roughness, type maps; vegetation cover; e.g., similar to SMAP ancillary requirements	Bistatic land surface scattering model development; existing TDS-1 and aircraft data analysis	Finer resolution history of soil moisture at each location for improved weather, crop forecasting	NWS, USDA, USDM, DOD, universities
What is the evolution of rainfall, runoff, and soil moisture event dynamics?	Flood dynamics and modeling; soil saturation	Soil moisture derived from the BRCS (L1B)	1	Disasters, Water Resources and Ecological Forecasting	Shorter integration time over land for finer along-track sampling; sensor intercalibration	Rainfall input; soil roughness, type maps; vegetation cover; e.g., similar to SMAP ancillary requirements	Bistatic land surface scattering model development; existing TDS-1 and aircraft data analysis	Finer resolution history of soil moisture at each location for flood dynamics studies and modeling	Insurance/reInsurance, FEMA, state and local governments, USGS, universities
What is the potential for landslides due to soil saturation?	Landslide hazard monitoring	Soil moisture derived from the BRCS (L1B)	1	Disaster Management Response, and Recovery	Shorter latencies for NRT applications; shorter integration time over land for finer along-track sampling; sensor intercalibration	Slope map; rainfall input; soil roughness, type maps; vegetation cover; e.g., similar to SMAP ancillary requirements	Bistatic land surface scattering model development; existing TDS-1 and aircraft data analysis	Fast repeat sampling of soil moisture for landslide monitoring	Red Cross, FEMA, insurance/reinsurance, DOT, National Guard, state and local governments
What is the expectation of river flooding due to dynamic events?	Flash flood forecasting	Soil moisture derived from the BRCS (L1B)	1	Disaster Management Response, and Recovery, Water Resources	Shorter latencies for NRT applications; shorter integration time over land for finer along-track sampling	Rainfall input; soil roughness, type maps; vegetation cover; e.g., similar to SMAP ancillary requirements	Bistatic land surface scattering model development; existing TDS-1 and aircraft data analysis	Fast repeat sampling of soil moisture for river flood monitoring	Red Cross, FEMA, insurance/reinsurance, DOT, National Guard, state and local governments
Vegetation/Biomass Applications									
What is the sub-daily evolution of vegetation water content?	Vegetation water content change sub-daily. Vegetation water content (sub diurnal) for crop forecasting.	Vegetation index derived from the BRCS (L1B)	1	Ecological Forecasting	Mixing models; shorter integration time over land for finer along-track sampling; sensor intercalibration	Soil roughness, type maps; e.g., similar to SMAP ancillary requirements	Bistatic land surface scattering model development; existing TDS-1 and aircraft data analysis; combining with L2 CYGNSS combined with L-band sensors to create value-added products	Fast repeat sampling to enable crop growth dynamics and monitoring	USDA, FAS, FAO USAID, NAS
Surface Water Extent Mapping Applications									
What are the extents and temporal evolution of flood disasters?	Wetlands, river flooding, and coastal inundation	Water detection derived from the BRCS (L1B)	1	Disaster Management Response, and Recovery, Water Resources	Shorter latencies for NRT applications; shorter integration time over land for finer along-track sampling	Inland water body extents maps	Bistatic water surface scattering model development (coherent component); existing TDS-1 and aircraft data analysis	Disaster response monitoring with short revisit times	FEMA, state and local governments, USGS, insurance/reinsurance
What is the current extent of wetlands (methane sources) and how are they evolving?	wetland maps for methane inventory and monitoring	Water detection derived from the BRCS (L1B)	1	Water Resopurces	Shorter integration time over land for finer along-track sampling	Wetlands/Inland water body extents maps	Bistatic water surface scattering model development (coherent component); existing TDS-1 and aircraft data analysis	Higher spatial resolution value added to existing maps	IPCC, GHG policy REDD+
Cryosphere Applications									
How is the snow extent line changing sub-daily?	Evolution of snow line with higher temporal sampling	Snow detection derived from BRCS (L1B)	1	Water Resources	Shorter integration time over land; polar orbit for cryosphere sampling	Other snow sensor fusion	Bistatic snow surface scattering model development; existing TDS-1 and aircraft data analysis	Monitoring of sub-daily snow line retreat/advance due to melt/accumulation	NOAA, NSIDC, USDA, polar programs
What are the extents and age of sea ice and how is it changing?	Value added product from using higher temporal sampling of sea ice	BRCS (L1B)	1	Water Resources, Ecological Forecasting	Shorter integration time over land; polar orbit for cryosphere sampling	Other sea ice sensor fusion	Bistatic sea ice surface scattering model development; existing TDS-1 and aircraft data analysis	Sea ice movement monitoring with potential sub-daily sampling; potential ice type classification	NOAA, NSIDC, Navy, polar programs, shipping
Is the soil and permafrost freeze/thaw state changing with climate?	Freeze/thaw ground mapping	BRCS (L1B)	1	Ecological Forecasting	Shorter integration time over land; polar orbit for cryosphere sampling	Other sea ice sensor fusion	Bistatic frozen surface scattering model development; existing TDS-1 and aircraft data analysis	Monitoring of sub-daily and longer freeze/thaw state	NOAA, NSIDC, USDA, polar programs



APPENDIX - C

Applications Traceability Matrices

C

C.1 Mission Overview References

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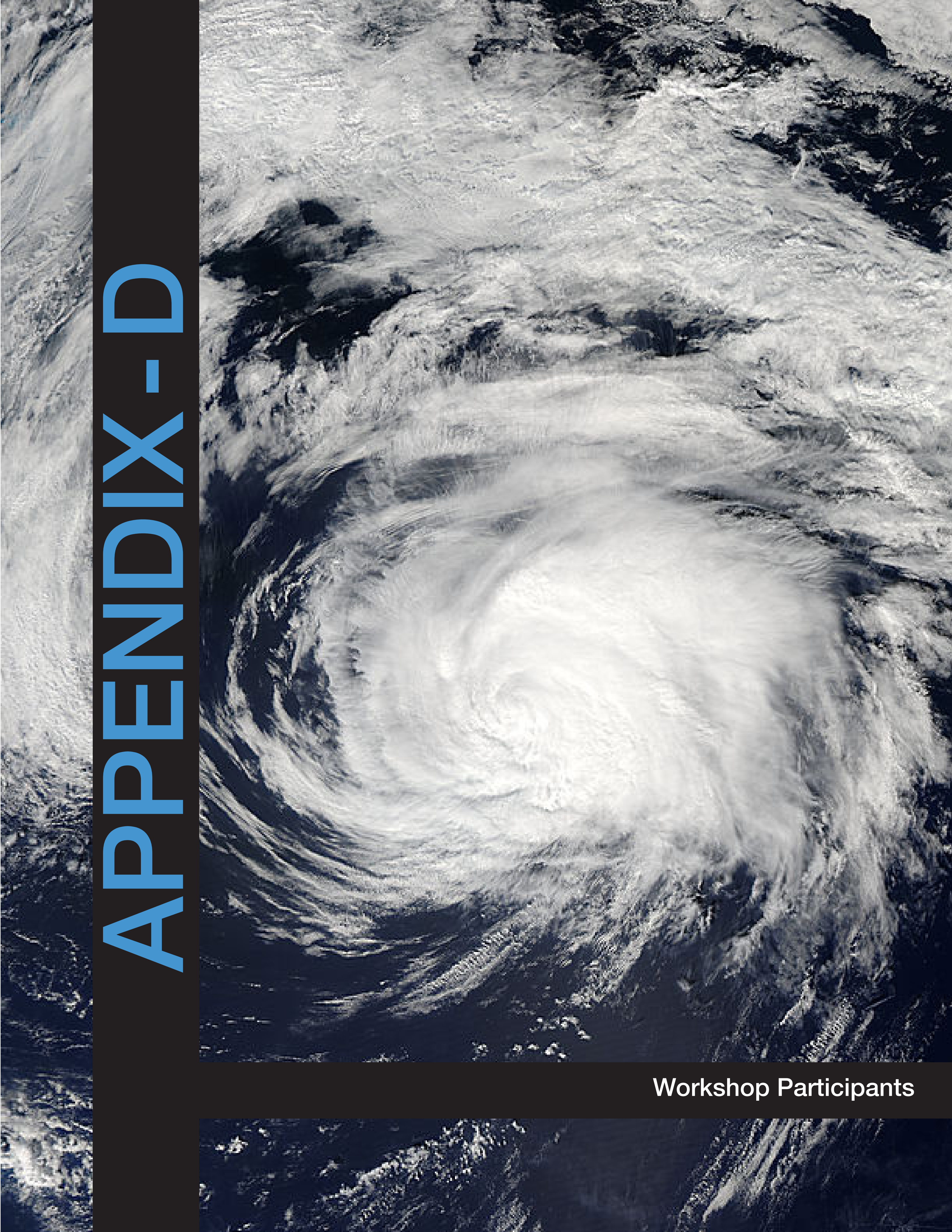

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14. ABSTRACT
NASA's Cyclone Global Navigation Satellite System, (CYGNSS), mission is a constellation of eight microsatellites that will measure surface winds in and near the inner cores of hurricanes, including regions beneath the eyewall and intense inner rainbands that could not previously be measured from space. The CYGNSS-measured wind fields, when combined with precipitation fields (e.g., produced by the Global Precipitation Measurement [GPM] core satellite and its constellation of precipitation imagers), will provide coupled observations of moist atmospheric thermodynamics and ocean surface response, enabling new insights into hurricane inner core dynamics and energetics. The outcomes of this workshop, which are detailed in this report, comprise two primary elements:1. A report of workshop proceedings, and; 2. Detailed Applications Traceability Matrices with requirements and operational considerations to serve broadly for development of value-added tools, applications, and products.

15. SUBJECT TERMS
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