Earth Observations from Constellations of Smallsats: The 2023 Joint Applications Workshop on NASA's CYGNSS and TROPICS Missions

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LIST OF ACRONYMS

ABI	Advanced Baseline Imager
AOML	Atlantic Oceanographic and Meteorological Laboratory
AOS	Atmosphere Observing System
API	Application Programming Interface
ARPEGE	Action de Recherche Petite Echelle Grande Echelle
ARSET	Applied Remote Sensing Training Program
ATMS	Advanced Technology Microwave Sounder
AWIPS	Advanced Weather Interactive Processing System
BRCS	Bistatic Radar Cross Section
BUFR	Binary Universal Form for the Representation of meteorological data
CGMS	Coordination Group for Meteorological Satellites
CIMAS	Cooperative Institute for Marine and Atmospheric Studies
CIMSS	Cooperative Institute for Meteorological Satellite Studies
CIRA	Cooperative Institute for Research in the Atmosphere
CSA	Canadian Space Agency
CSU	Colorado State University
CU	University of Colorado
CYGNSS	Cyclone Global Navigation Satellite System
DAAC	Distributed Active Archive Center
DDM	Delay Doppler Map
DDMI	Delay Doppler Mapping Instrument

DISC	Data and Information Services Center
DPC	Data Processing Center
DPR	Dual-frequency Precipitation Radar
ECMWF	European Center for Medium-Range Weather Forecasts
EO	Earth Observation
EOSDIS	Earth Observing System Data and Information System
ESA	European Space Agency
ESD	Earth Science Division
ESO	Earth System Observatory
ESSC	Earth System Science Center
ESSIC	Earth System Science Interdisciplinary Center
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
EVI	Earth Venture Instrument
FDS	Fully Developed Seas
GeoIPS	Geolocated Information Processing System
GeoTIFF	Georeferenced Tagged Image File Format
GES	Goddard Earth Science
GIS	Geographic Information System
GMF	Geophysical Model Function
GLM	Geostationary Lightning Mapper
GMI	Global Precipitation Measurement Microwave Imager
GNSS	Global Navigation Satellite System

GOES	Geostationary Operational Environmental Satellite
GOES-R	Geostationary Operational Environmental Satellite-R Series
GPM	Global Precipitation Measurement
GPROF	Goddard profiling algorithm
GSFC	Goddard Space Flight Center
HAFS	Hurricane Analysis and Forecast System
HISA	Hurricane Intensity and Structure algorithm
HRD	Hurricane Research Division
HQ	Headquarters
IBTrACS	International Best Track Archive for Climate Stewardship
IMERG	Integrated Multi-satellitE Retrievals for Global Precipitation Measurement
INCUS	Investigation of Convective Updrafts Mission
IR	Infrared
ISRO	Indian Space Research Organization
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
JPSS	Joint Polar Satellite System
JTWC	Joint Typhoon Warning Center
L1, L2, L3	Level 1, Level 2, Level 3 data/products
LaRC	Langley Research Center
MHS	Microwave Humidity Sounder

MIRS	Microwave Integrated Retrieval System
MIT LL	Massachusetts Institute of Technology Lincoln Laboratory
MSFC	Marshall Space Flight Center
MSLP	Minimum Sea-Level Pressure
MSWS	Maximum Sustained Wind Speed
MW	Microwave
NASA	National Aeronautics and Space Administration
NetCDF	Network Common Data Form
NISAR	NASA-ISRO Synthetic Aperture Radar
NESDIS	National Environmental Satellite, Data, and Information Service
NGO	Non-Governmental Organization
NHC	National Hurricane Center
NOAA	National Oceanic and Atmospheric Administration
NPP	NASA Postdoctoral Program
NRL	Naval Research Laboratory
NRT	Near Real-Time
NWP	Numerical Weather Prediction
NWS	National Weather Service
OPC	Ocean Prediction Center
PI	Principal Investigator
PMW	Passive Microwave
PO.DAAC	Physical Oceanography Distributed Active Archive Center

PRPS	Precipitation Retrieval and Profiling Scheme
RSMAS	Rosenstiel School of Marine and Atmospheric Studies
SAL	Saharan Air Layer
SAR	Synthetic Aperture Radar
SMAP	Soil Moisture Active Passive
SMOS	Soil Moisture and Ocean Salinity
SNPP	Suomi National Polar-orbiting Partnership
SNWG	Satellite Needs Working Group
SPoRT	Short-term Prediction Research and Transition
SSEC	Space Science and Engineering Center
SSMI/S	Special Sensor Microwave Imager/Sounder
SSTL	Surrey Satellite Technology Ltd.
STAR	Center for Satellite Applications and Research
SWOT	Surface Water and Ocean Topography
Tb	Brightness Temperature
TC	Tropical Cyclone
TCIE	Tropical Cyclone Intensity Estimate algorithm
TMS	TROPICS Millimeter-wave Sounder
TPW	Total Precipitable Water
TRMM	Tropical Rainfall Measuring Mission
TROPICS	Time-Resolved Observations of Precipitation Structure and Storm Intensity with a Constellation of Smallsats

UAH	University of Alabama in Huntsville
UCSD	University of California San Diego
UKSA	United Kingdom Space Agency
UM	University of Miami
UMBC	University of Maryland Baltimore County
UMD	University of Maryland
UN	United Nations
UNITAR	United Nations Institute for Training and Research
UNOSAT	United Nations Satellite Centre
USAID	United States Agency for International Development
USGS	United State Geological Survey
UW	University of Wisconsin
VEDA	Visualization, Exploration, and Data Analysis
WFP	World Food Programme
WMO	World Meteorological Organization
WPC	Weather Prediction Center
WRF	Weather Research and Forecasting
YSLF	Young Seas with Limited Fetch

Background

In December 2016, the National Aeronautics and Space Administration (NASA) launched its first constellation of Earth-observing smallsats, the Cyclone Global Navigation Satellite System (CYGNSS). Leveraging Global Navigation Satellite System (GNSS) reflectometry, the constellation of eight satellites was designed to measure surface wind speed over the ocean, particularly within tropical cyclones. With a 35-degree orbital inclination, CYGNSS greatly increased the availability of wind speed observations in the tropical regions of the globe (Fig. 1). Despite a design life of 24 months, seven of the eight satellites continue to operate nominally after more than six years on orbit, with indications that they could last a further four to seven years. Over these six years, new applications of CYGNSS's unique data have been revealed, including detection of soil moisture and inundation over land masses and microplastics in the ocean. CYGNSS has demonstrated its value through numerous process-based studies and applications of its retrievals in model data assimilation schemes to improve numerical weather prediction.

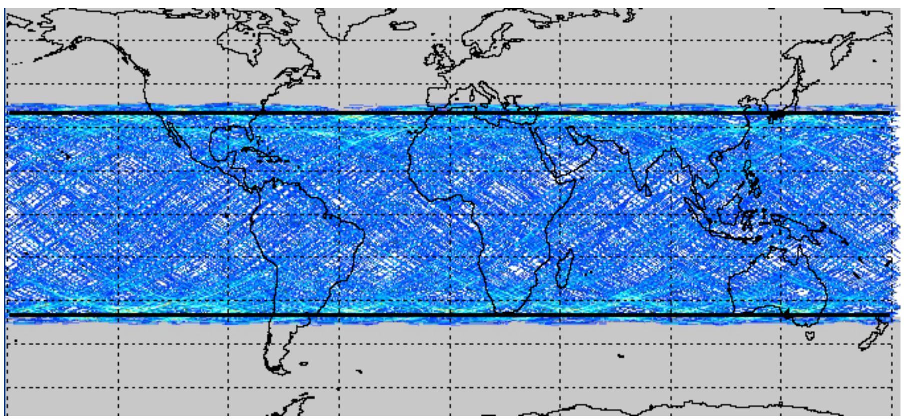

Figure 1. A day of observation coverage by the CYGNSS constellation, showing nearly full coverage between 35 degrees south and 35 degrees north latitude. Image credit: Christopher Ruf, University of Michigan.

Also in 2016, NASA selected the Time-Resolved Observations of Precipitation structure and storm Intensity with a Constellation of Smallsats (TROPICS) mission as a new project in its Earth Venture Instrument (EVI) program. TROPICS is a constellation of four smallsats containing passive microwave radiometers designed to retrieve brightness temperatures at 12 channels in the 91-205 GHz band. Additional products provided by TROPICS include vertical profiles of temperature and humidity, rain rate, and tropical cyclone intensity estimates. The TROPICS orbital configuration – two orbital planes with a 30° inclination – is designed to maximize observations over the tropical regions of the globe, with particular focus on tropical cyclones.

The TROPICS qualification unit was launched as a Pathfinder vehicle June 30, 2021, aboard a SpaceX Falcon 9 rideshare into a sun-synchronous orbit. The Pathfinder is nearly identical to the constellation satellites, and its presence on orbit for more than two years has allowed preliminary results to be produced and communications systems and data processing algorithms to be tested prior to constellation launch. As of October 2023, Pathfinder continues to provide data from polar orbit. The constellation of four satellites was successfully deployed on two separate launches provided by Rocket Lab on May 8, 2023 and May 26, 2023. Testing during the Pathfinder phase enabled accelerated spacecraft commissioning and calibration/validation for the Constellation, with first light images released on July 19, 2023 (Fig. 3).

Figure 2. Mission patches for the two TROPICS Constellation launches on May 8 and 26, 2023. Image credit: Rocket Lab

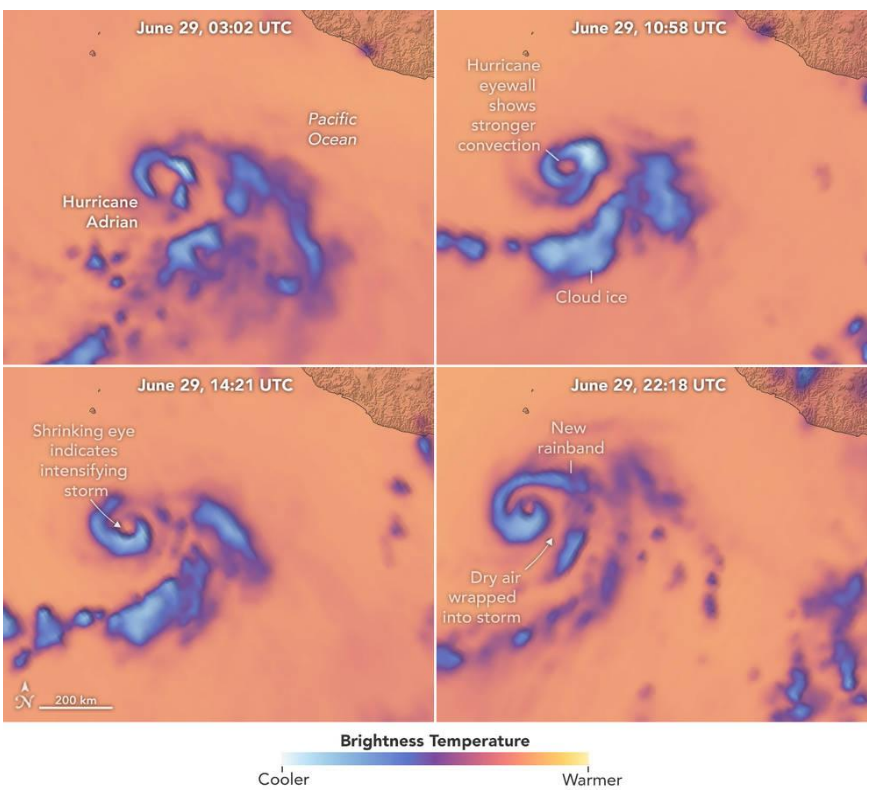

Figure 3. TROPICS first-light imagery released on July 19, 2023 showing the evolution of 205-GHz brightness temperatures in Hurricane Adrian over the Eastern Pacific Ocean on June 29, 2023. Image credit: Lauren Dauphin, NASA Earth Observatory

The unique sampling characteristics of CYGNSS and TROPICS provide observations of land surface and atmospheric variables at unprecedented temporal resolution in the global tropics. The missions have also pioneered the use of smallsat constellations to achieve high sampling rates at much lower cost than geostationary platforms. These sampling rates enable unique scientific investigations of rapidly evolving processes, and with low-latency operations for TROPICS, new near-real-time tools for operational forecasters.

Workshop Purpose and Objectives

With similar mission objectives and orbital inclinations, there is a great opportunity for synergistic applications of CYGNSS and TROPICS data. Although some of these synergies have been previously exploited through collaborative data assimilation efforts conducted by the two science teams, there remained unexplored synergies that could enhance the applications value of both missions. Furthermore, as the first two constellations of Earth-observing smallsats in NASA's portfolio, many lessons have been learned about the unique advantages, challenges, and future opportunities presented by smallsat missions. For these reasons, a joint applications workshop was held at the University of Miami, FL April 11-13, 2023. Eight specific objectives, listed below, guided the presentations and discussions held during the workshop:

1. Update the community on current and future availability of CYGNSS and TROPICS data products.
2. Determine current and future needs in the CYGNSS and TROPICS applications communities that can be addressed using current and upcoming datasets. Which needs should be top priority and what would be the impact?
3. Identify ways in which the CYGNSS and TROPICS science teams and applications communities can collaborate to produce new science or products to address community needs.
4. Discuss synergies between CYGNSS, TROPICS, and other satellite missions to address persistent community needs.
5. Identify ways in which lessons learned from CYGNSS and TROPICS can inform future smallsat constellation missions, including NASA and private sector missions.
6. Determine further refinements to data products that would have the most positive impact on applications (latency, uncertainty characterization, spatial and temporal resolution, etc.)
7. Identify data access enhancements that would better enable science and applications (APIs, cloud services, applications-ready data, data formats, etc.)
8. Discuss future opportunities for private sector involvement in smallsat technology development and applications utilization.

Workshop Organization

The workshop program was organized by a planning committee composed of 21 scientists from the CYGNSS and TROPICS mission science teams, NASA, the National Oceanic and

Atmospheric Administration (NOAA), academia, and private-sector partners. A full list of planning committee members is provided in Appendix A. The committee was designed to have representatives from both missions, along with government and private-sector stakeholders.

Since the previous [CYGNSS Applications Workshop in 2017] and [TROPICS Applications Workshop in 2020], both missions have developed new products and refined existing products that address a variety of applications needs. The expansion of the missions required a workshop agenda of three full days, which was organized around eight topical focus areas identified by the planning committee to be most important for the two missions. These focus areas were divided into four sections:

1. Land surface, Inundation, and Precipitation
2. Tropical cyclones, Data Assimilation, and Oceans
3. Private sector and international partners
4. Synergies with other satellite missions

Given that the workshop united two science teams and applications communities, particular emphasis was placed on breakout sessions and plenary open discussion sessions to allow maximum interaction between the two teams. A total of 29 oral presentations and seven poster presentations were given, with their placements in the agenda designed to stimulate open exchange of ideas during breakouts and open discussions. Cross-cutting topics throughout the workshop included data product and latency needs for CYGNSS and TROPICS stakeholders, and how collaboration between the two missions and other missions can satisfy these needs.

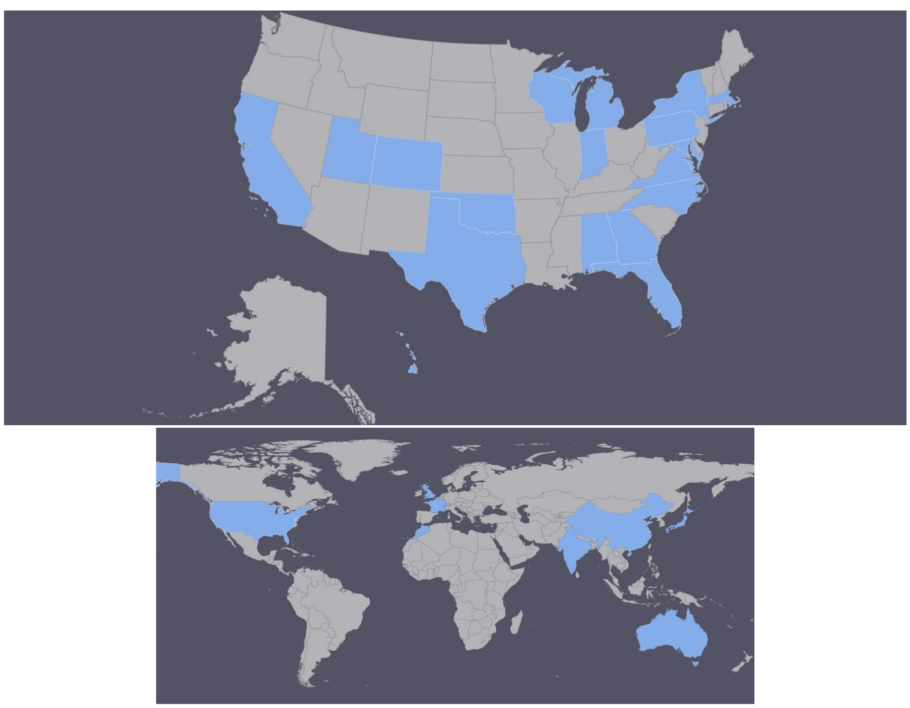

Figure 4. Representation of workshop attendees by US state (17 states + Washington, D.C.) and country (10 countries). Image credit: Jason Dunion, University of Miami

A total of 134 attendees registered for the workshop, with 64 attending in person and 70 virtually. Participants represented a diverse cross-section of the research and applications communities, including representatives from four US federal agencies, 22 US universities, 11 international entities, and five private-sector partners. Both in-person and virtual attendees were able to attend and contribute to all sessions, including breakouts and open discussions. Each group of stakeholders identified unique needs for and potential contributions to the two missions.

Each session, including breakout sessions, were led and attended by members of the workshop planning committee, along with student note takers from the University of Miami. The breakout leads and student note takers produced a comprehensive set of notes upon which this report is based.

Fig. 5. Group photo of workshop in-person attendees.

Overview of Mission Data Products and Data Access

Both missions have developed new products and refined existing products since their previous applications workshops. CYGNSS currently has three levels of data products, and TROPICS currently has two levels. The products are briefly described in the next section; more in-depth information on the products can be found in the CYGNSS Handbook and TROPICS Users Guide.

Data archives for the two missions are stored at two NASA Earth Observing System Data and Information System (EOSDIS) Distributed Active Archive Centers (DAACs): The Physical Oceanography Daac (PO.DAAC) for CYGNSS and the Goddard Earth Sciences Data and Information Services Center (GES-DISC) for TROPICS. As products become available, the data files are posted, along with associated documentation.

CYGNSS Data Products

Level 1 Delay Doppler Map

The Level 1 Delay Doppler Map (DDM) product provides geolocated information on reflected GNSS signals received by the CYGNSS Delay Doppler Mapping Instrument (DDMI). Raw sensor counts are calibrated to power received (Watts) and Bistatic Radar Cross Section (BRCS; m^2). These values are mapped in delay-doppler space, using the time delay of the reflected signal relative to the signal received directly from the GNSS transmitter, together with the doppler shift of the reflected signal.

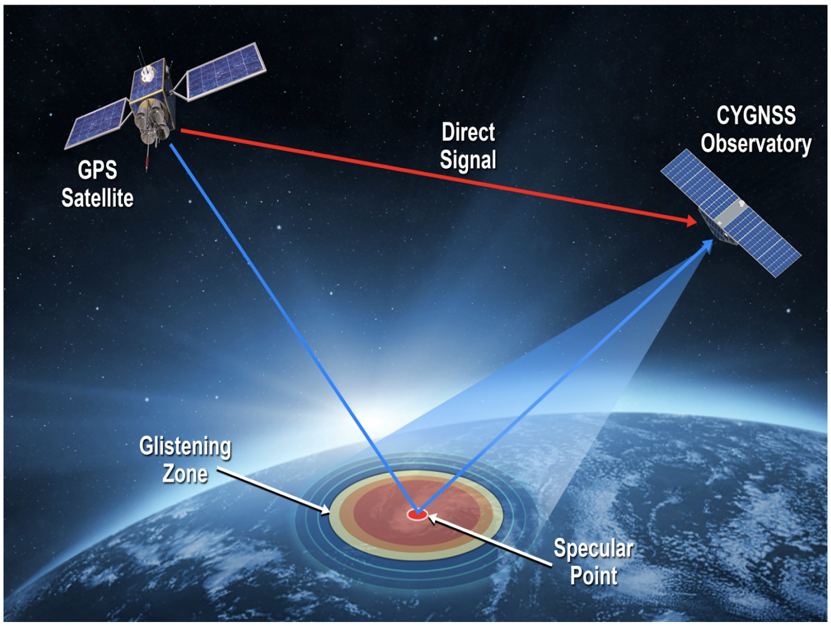

Figure 6. Illustration of reflected and direct GPS signals used to derive CYGNSS Level 1 products. Image credit: Christopher Ruf, University of Michigan

When plotted (Fig. 7), the resulting DDM is usually horseshoe-shaped, with the region of maximum returned power corresponding to the "specular point" and other areas of the DDM with reflected signal termed the "glistening zone." The shape of the DDM and distribution of returned power or BRCS within the glistening zone provides information on surface characteristics, including soil moisture or inundation over land and surface roughness over the ocean.

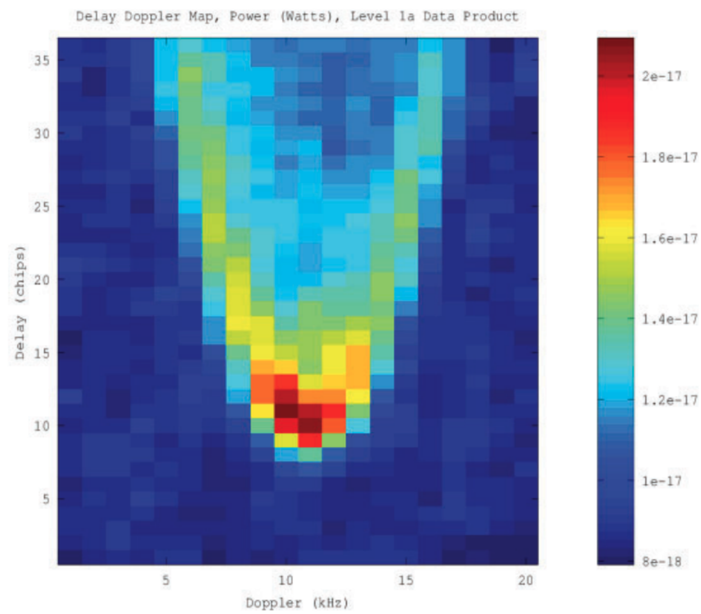

Figure 7. CYGNSS Level 1 Delay Doppler Map of returned power (W) in delay and doppler space. Image credit: CYGNSS Level 2 Wind Speed Retrieval Algorithm Theoretical Basis Document

Level 1 Raw IF

Level 1 Raw IF data are raw sensor counts from the CYGNSS DDMI, which are intermittently available when a series of specular points passes over an area of interest. The primary advantage of the Level 1 Raw IF is that the lack of post-processing allows the highest possible resolution of a particular feature of interest in delay-doppler space. Raw IF are downlinked from a satellite only on command, with a typical duration of 30-90 seconds as the specular points track across the given feature of interest.

Level 2 Average Wind Speed and Mean Square Slope

Different configurations of GNSS transmitters and CYGNSS DDMI receivers produce tracks of specular points along Earth's surface. Each specular point is associated with a DDM, from which the wind speed and mean square slope can be empirically derived using a geophysical model function (GMF). CYGNSS employs two primary GMFs for wind speed: the Young Seas with Limited Fetch (YSLF) GMF and the Fully Developed Seas (FDS) GMF. Generally, the YSLF winds are the best approximation for regions of strong winds (such as a hurricane inner core) and FDS winds are best in regions of fairly light winds, where ocean swells dominate the signal rather than locally produced waves. Both products have a spatial resolution of 25 km.

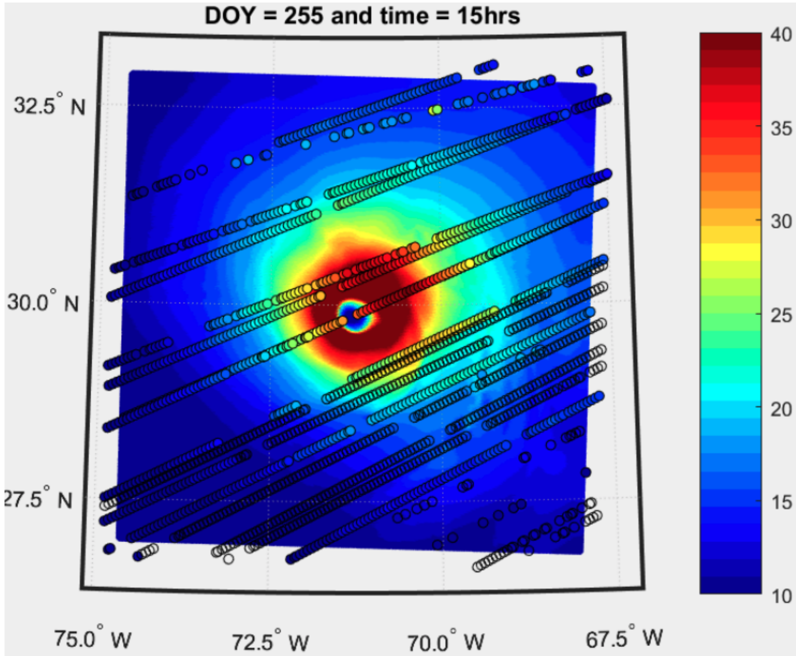

Figure 8. CYGNSS Level 2 YSLF wind speed estimates (m s^{-1}) in Hurricane Florence (2018) along specular point tracks (streaks of dots), overlaid on wind speed from the Hurricane Weather Research and Forecasting Model (contours). Image credit: Darren McKague, University of Michigan

<u>**Level 2 Ocean Surface Heat Flux**</u>

The CYGNSS Level 2 Ocean Surface Heat Flux product uses CYGNSS YSLF and FDS surface wind speed, together with ERA5 reanalysis temperature and humidity to estimate surface heat flux over the ocean. The product is verified for wind speeds up to 25 m s^{-1}, with latent heat flux and sensible heat flux output separately for each specular point contained in the Level 2 wind speed datasets.

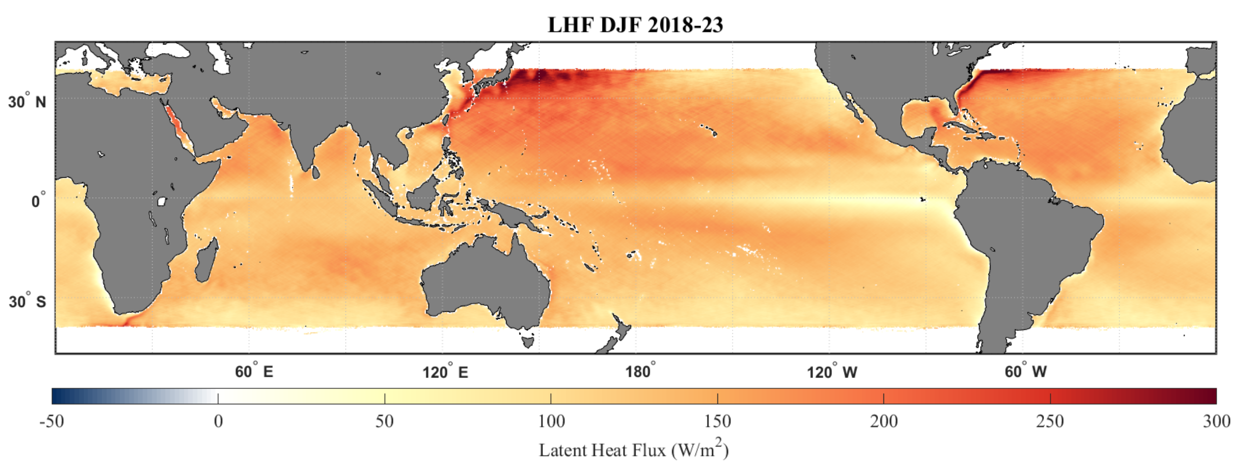

Figure 9. Mean CYGNSS latent heat flux (W m^{-2}) averaged over December, January, and February during the years 2018-2023. Image credit: Juan Crespo, UCLA/Jet Propulsion Laboratory.

Level 3 Gridded Wind Speed

The Level 3 Gridded Wind Speed product provides daily netCDF-4 files with average wind speed and MSS on a 0.2x0.2 rectangular grid, together with the standard deviation and the number of samples used to compute the averages.

Level 3 Storm-Centric Gridded Wind Speed

The Level 3 Storm-Centric Gridded Wind Speed product uses storm tracks from the International Best Track Archive for Climate Stewardship (IBTrACS) database to composite CYGNSS wind speeds around tropical cyclone storm centers. This storm-centered dataset eliminates the effect of storm motion, which acts to smear out wind speed observations as the storm moves, and increases the data coverage over the storm by using a 12-hour averaging window to compute storm-centered wind speed. This averaging comes as the expense of an underestimation of the highest wind speeds in the storm.

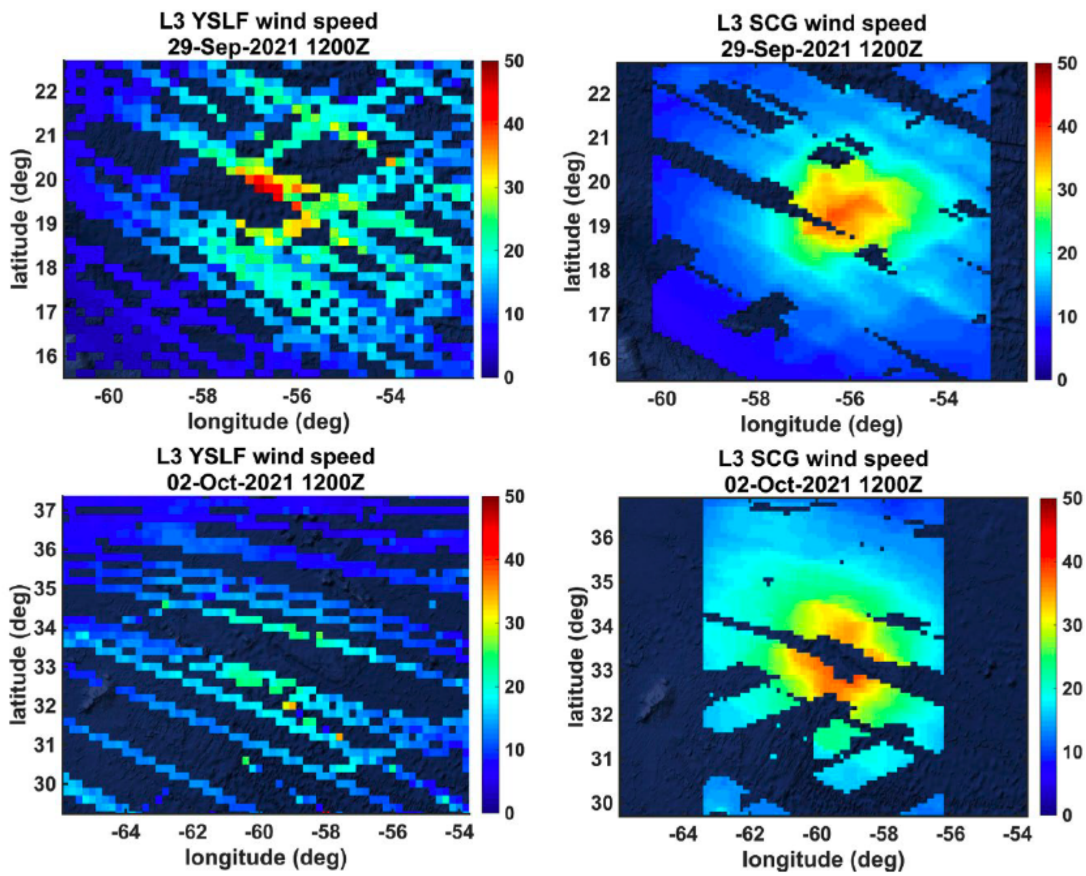

Figure 10. Comparison of the CYGNSS L3 YSLF Gridded Wind Speed (left panels) to CYGNSS L3 storm-centered Gridded Wind Speed (right panels) for Hurricane Sam (2021). Image credit: April Warnock, SRI International

Level 3 Soil Moisture

The Level 3 Soil Moisture product uses observations from the Soil Moisture Active/Passive (SMAP) instrument to relate CYGNSS L1 reflectivity to volumetric water content. Water content is estimated over the 0-5–cm soil surface layer and is reported at 6-hour intervals.

TROPICS Data Products

Level 1A Antenna Temperature (Radiance)

The Level-1a Antenna Temperatures are geolocated antenna temperatures (radiance) (K) that are timestamped to UTC and are reported at native spatial resolutions. The TROPICS Millimeter-wave Sounder (TMS) provides temperature profiles using seven channels near the 118.75-GHz oxygen absorption line, water vapor profiles using three channels near the 183-GHz water vapor absorption line, imagery in a single channel near 90 GHz for precipitation measurements, and a single channel near 205 GHz that is more sensitive to cloud-sized ice particles.

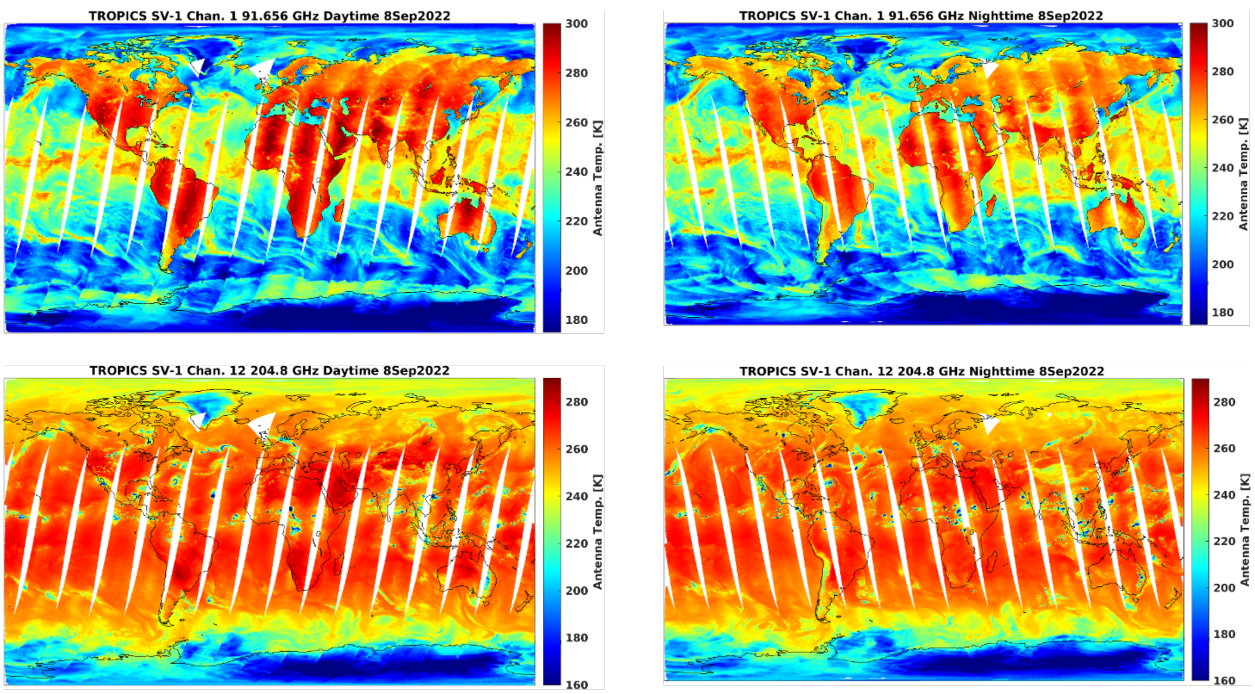

Figure 11. A day of antenna temperatures observed by the TROPICS Pathfinder at 91.656 GHz (top panels) and 204.8 GHz (bottom panels). Image credit: Bill Blackwell, MIT Lincoln Laboratory

Level 1B Brightness Temperature

The Level-1b Brightness Temperatures are geolocated, calibrated brightness temperatures (radiance; K) with the bias removed that are timestamped to UTC and are reported at native spatial resolutions. The addition of a 205 GHz ice particle sensitive channel has particular utility in resolving fine structures in tropical cyclone eye walls and rainbands, providing key TC structure information for assessing intensity.

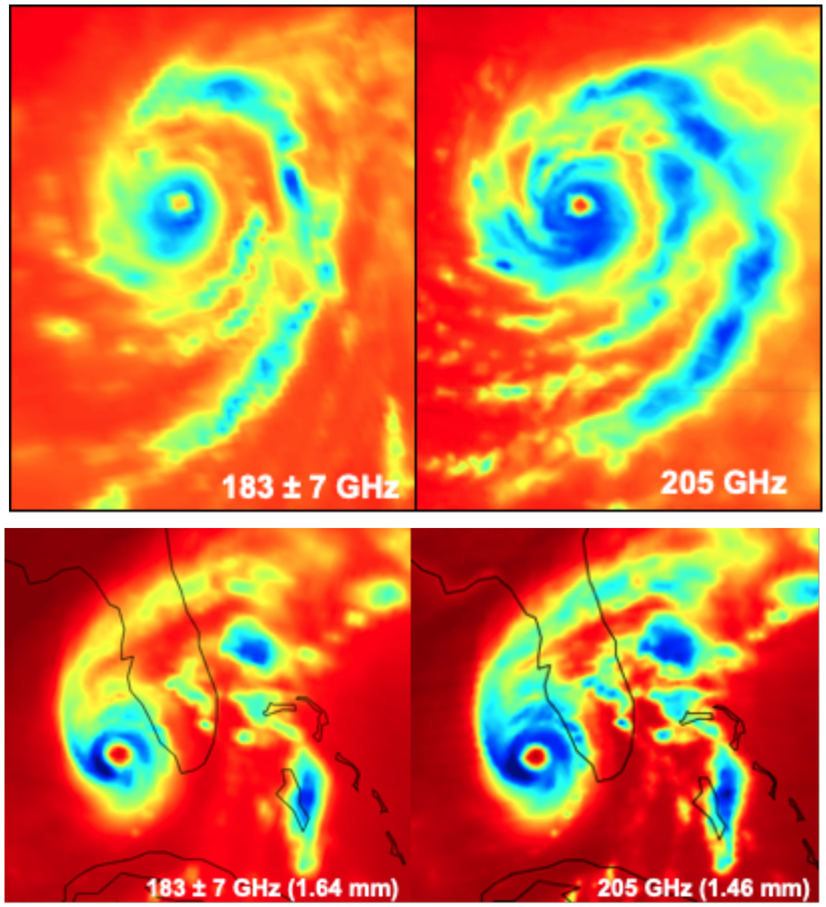

Figure 12. Tropical cyclone microwave comparisons from a) Super Typhoon Mindulle (top panels) (26 Sept 2021) from SNPP satellite (183 GHz) and TROPICS Pathfinder (205 GHz), and b) Hurricane Ian (bottom panels) (28 Sept 2022) from NOAA-20 (183 GHz) and TROPICS Pathfinder (205 GHz). Image credit: Bill Blackwell, MIT Lincoln Laboratory

Chan.	Center Freq. (GHz)	Bandwidth (GHz)	RF Span (GHz)	Beamwidth (degrees) Down/Cross	Nadir Footprint Geometric Mean (km)	Expected NEdT (K)
1	91.655 ± 1.4	1.000	89.756-90.756, 92.556-93.556	3.0/3.17	29.6	0.60
2	114.50	1.000	114.00-115.00	2.4/2.62	24.1	1.00
3	115.95	0.800	115.55-116.35	2.4/2.62	24.1	0.90
4	116.65	0.600	116.35-116.95	2.4/2.62	24.1	0.90
5	117.25	0.600	116.95-117.55	2.4/2.62	24.1	0.90
6	117.80	0.500	117.55-118.05	2.4/2.62	24.1	0.90
7	118.24	0.380	118.05-118.43	2.4/2.62	24.1	0.90
8	118.58	0.300	118.43-118.73	2.4/2.62	24.1	1.00
9	184.41	2.000	183.41-185.41	1.5/1.87	16.1	0.60
10	186.51	2.000	185.51-187.51	1.5/1.87	16.1	0.60
11	190.31	2.000	189.31-191.31	1.5/1.87	16.1	0.60
12	204.8	2.000	203.8-205.8	1.4/1.76	15.2	0.60

Table 1. TROPICS channel characteristics. Table credit: Vince Leslie, MIT Lincoln Laboratory

Level 2A Unified Brightness Temperature

The Level 2A Unified Brightness Temperature product coarsens the G-band moisture channels (Channels 9-12) data to the same resolution as the F-band temperature channels (Channels 2-8). This product is used in the Level 2 Atmospheric Vertical Temperature Profile retrieval algorithm to reduce noise in the G-band channels.

Level 2B Instantaneous Surface Rain Rate

The Level 2B Instantaneous Surface Rain Rate product provides estimates of surface rain rate (mm h^{-1}) at G-band spatial resolution using the NASA Goddard Precipitation Retrieval and Profiling Scheme (PRPS). At the time of the workshop this product was still under development, but preliminary analyses of daily mean precipitation over a one-year period reveals good agreement between the TROPICS estimates and estimates from the NOAA-19 Microwave Humidity Sounder (MHS) using the Goddard Profiling Algorithm (GPROF; Fig. 13).

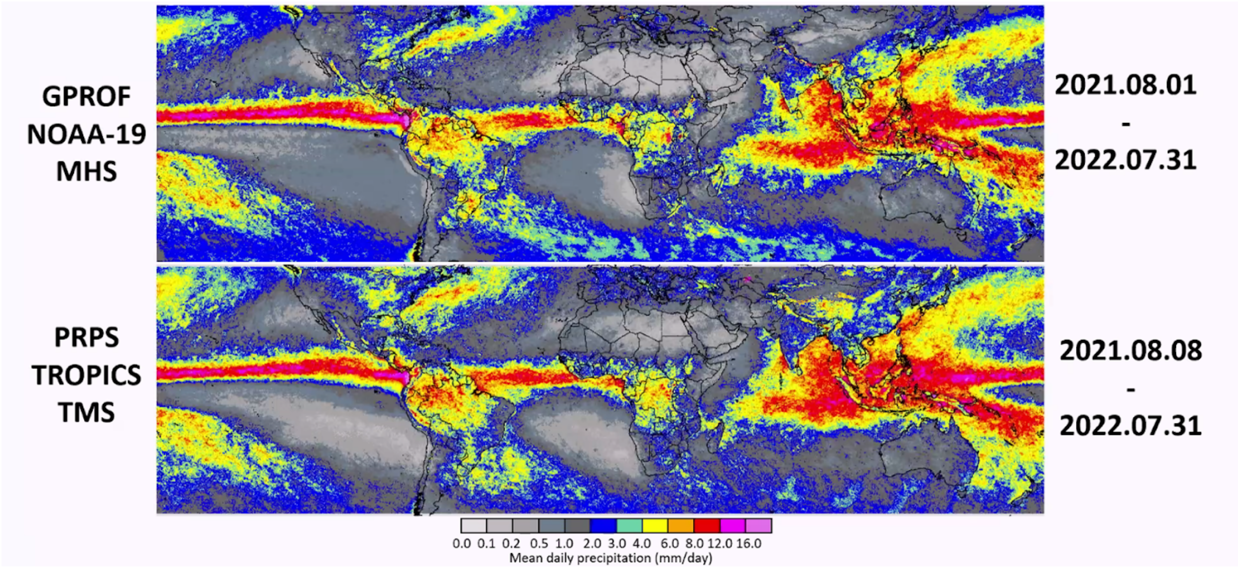

Figure 13. Mean daily precipitation (mm/day) from NOAA-19 MHS using the Goddard Profiling (GPROF) algorithm (top) compared to the TROPICS PRPS algorithm (bottom). Image credit: Chris Kidd, University of Maryland

Level 2B Atmospheric Vertical Temperature and Moisture Profiles

TROPICS provides vertical profiles temperature (K) from the surface to 20-km altitude at F-band spatial resolution and humidity (g kg^{-1}) from the surface to 10-km altitude in non-precipitating conditions at G-band spatial resolution. The profiles, along with total precipitable water (TPW; mm) at G-band spatial resolution, are generated by the NOAA/NESDIS/STAR Microwave Integrated Retrieval System (MIRS).

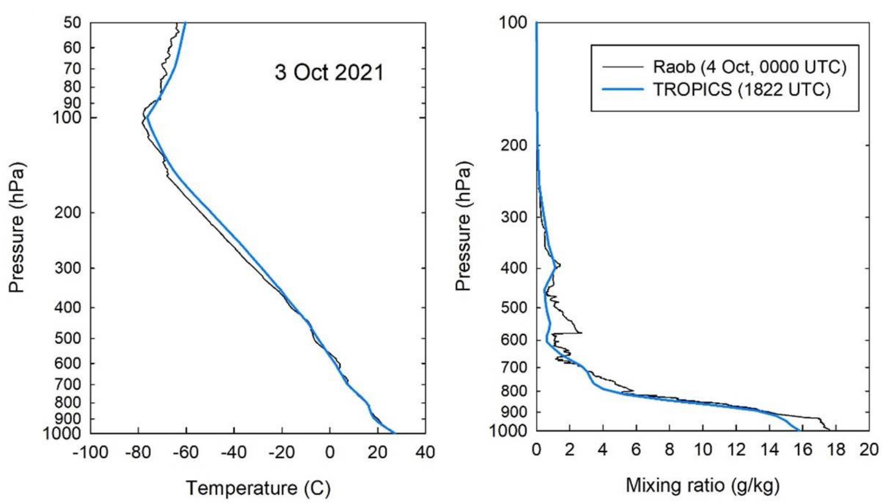

Figure 14. Temperature (left panel) and mixing ratio (right panel) profiles as compared to a RAOB sounding from 3-4 Oct 2021. Image credit: Tom Greenwald, University of Wisconsin-Madison.

Level 2B Tropical Cyclone Intensity

The Level 2B products feature algorithms covering the Maximum Sustained Wind Speed (MSWS) and Minimum Sea-Level Pressure (MSLP) metrics of TC intensity. Both the MSWS (m s^{-1}) and MSLP (hPa) products provide two estimates of intensity: 1) Tropical Cyclone Intensity Estimate algorithm (TCIE) developed at the University of Wisconsin/CIMSS and 2) Hurricane Intensity and Structure Algorithm (HISA) developed at Colorado State University/CIRA. Both intensity estimates were still under development at the time of the workshop, but initial results (Fig. 15) compare well to central pressure observed by aircraft reconnaissance. For the very intense Typhoon Mindulle, for which aircraft data were not available, the intensity estimate agreed very well with an established satellite intensity estimation technique (CIMSS Satellite Consensus) and the intensity estimate determined by forecasters at the US Navy's Joint Typhoon Warning Center (JTWC).

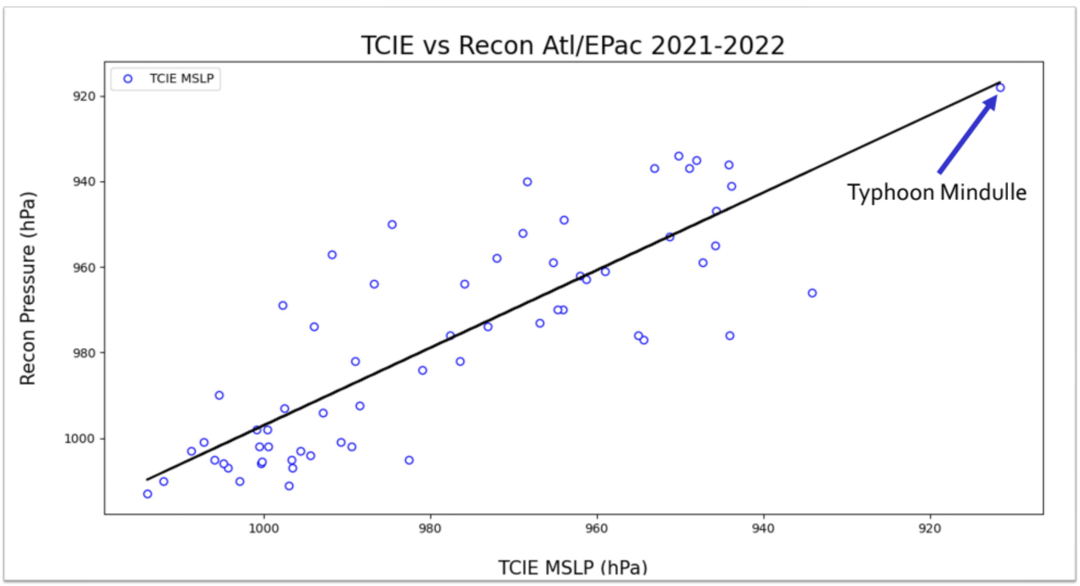

Figure 15. Comparison of minimum sea level pressure (MSLP; hPa) observed by aircraft reconnaissance (vertical axis) and estimated by the TCIE algorithm using TROPICS data (horizontal axis). Image credit: Derrick Herndon, University of Wisconsin, Cooperative Institute for Meteorological Satellite Studies

Workshop Discussions and Outcomes

The workshop began with introductory remarks given by the principal investigators and project managers of each mission, followed by presentations and discussion of land surface, inundation, and precipitation applications for the two missions.

Land Surface, Inundation, and Precipitation Applications

Land surface and inundation products developed from CYGNSS data are an example of an unexpected use of a dataset, and the development of valuable products is a success story for the applications community. An outcome of the 2017 CYGNSS Application workshop in Monterey was the observation that CYGNSS's forward scattering observations could detect inland water during day and night and in all weather conditions, and by exploiting these satellite observations, novel high resolution flood inundation and wetland mapping could be developed. It was recommended that product developers should continue to advance these capabilities and engage with interested stakeholders to utilize them.

This year's applications workshop featured successful examples of this application. Most of the products shown use normalized signal to noise ratio products to locate water surfaces, with resolution as fine as 150 meters of average. Monthly difference products of SNR allow enough overpasses to accumulate to produce a useful time series comparison. Likewise, large spatial extent products are useful due to the coverage of the satellites. Multi-sensor approaches using Ka- and L-band together (e.g., CYGNSS and SMAP) were shown to help quantify flood severity to help interpret flood observations based on a longer-term (multiyear) record.

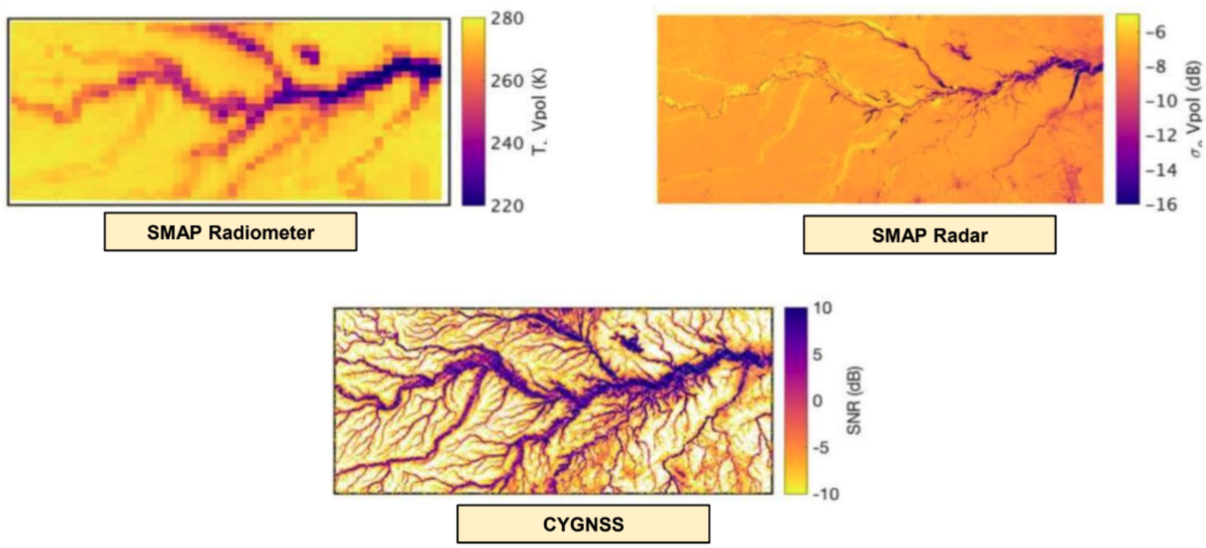

Figure 16. Comparison of CYGNSS retrievals of inland water bodies (bottom) to the SMAP radiometer (top left) and SMAP radar (top right). Image credit: Clara Chew, Muon Space

A key takeaway for these use cases is that, generally, near-real time information was not required to provide actionable information to end users. These products were demonstrated to show their greatest benefit at examining the inundation from extreme or otherwise unusual flooding events.

Products showing the severity and extent of extreme flooding are particularly of interest to organizations like the UN World Food Programme, the Food and Agriculture Organization of the UN, and USAID, and other response organizations. These products are currently in use by the WFP, which helps them triage response measures and estimate resources required to adequately respond to disasters.

CYGNSS showed utility in observing "brown ocean" related flooding events by comparing the pre- and post-event analysis of locations impacted by tropical storms. The brown ocean effect occurs when, under certain circumstances, very warm, moist soils can act like an ocean, maintaining or even strengthening landfalling tropical cyclones through latent heat flux as the moisture evaporates from the land surface. This application was demonstrated in a post-event analysis showing imagery from Hurricane Harvey and Hurricane Erin. CYGNSS could aid in the continued study of these events and possibly lead to products that aid situational awareness for TC forecasters.

Other novel applications that could be further developed for CYGNSS include drought and hydrologic monitoring products for observing river basin flow rate, water reservoir storage estimation, and lake extent over time. These uses also benefit from fairly fine scale observations and are not detrimentally affected by the lack of NRT data products. With real-time data availability, additional applications are enabled, including forecasting and response to flash flooding and landslides.

The success of CYGNSS helps inform a broad user community and applications best practices for the TROPICS mission. For example, many of the international food security and drought monitoring agencies that utilize CYGNSS data could utilize TROPICS, and those organizations have a list of requirements for potential data. Large spatial extent imagery, time-series information, and a way of analyzing the impact of extreme or unusual events were stated as valuable to these end users. Regarding the latter, the development of merged products that indicated soil moisture, flooding, precipitation, etc., in easily interpretable images was strongly desired. Merged, monthly, and/or time-series products also help improve the coverage of a product; end users expressed difficulty with the use of swath data in general. In particular, the need for a Level 3 precipitation product from TROPICS was mentioned. Data provided in GIS-friendly formats is universally acceptable and allows data and derived products to be ingested into the existing visualization and data portals used by these organizations. These recommendations largely came from discussions between end users and product developers, indicating the value of these workshops and the need for applications-focused workshops into the TROPICS era.

Tropical Cyclones, Data Assimilation, and Oceans

Tropical Cyclones

As a primary focus of both missions, tropical cyclones feature heavily in scientific research and applications for CYGNSS and TROPICS. Since their inception, both missions have engaged the tropical cyclone forecast communities and data assimilation teams to maximize the utility of mission data. With a median latency of 3 days and 6.5 hours for CYGNSS wind speed and TROPICS brightness temperature products, respectively, a consistent challenge for these applications communities is the timely availability of data. If latency is greater than about three to six hours, the utility of TROPICS and CYGNSS data for TC forecasting and data assimilation is greatly reduced (Fig. 17).

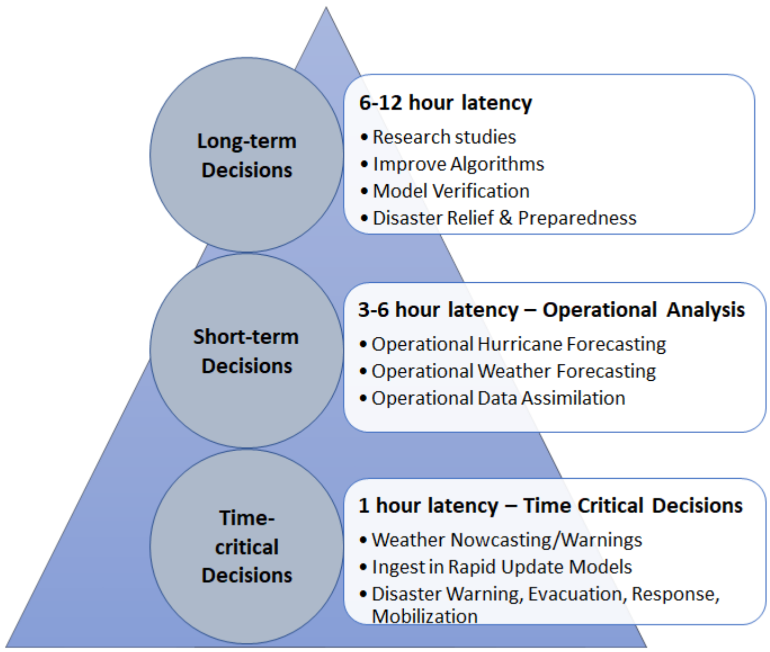

Figure 17. Illustration of latency requirements for a variety of applications relevant to CYGNSS and TROPICS. Image credit: Emily Berndt, NASA SPoRT

In response to recommendations from the 2nd TROPICS Mission Applications Workshop held in 2020 (Berndt et al. 2020), the TROPICS science team has vigorously pursued augmentations from multiple sources to reduce the mission latency from an average of about 6.5 hours to about 1 hour. Funding was obtained from the Office of Naval Research to support low-latency operations for the Pathfinder in 2023, and from the National Oceanic and Atmospheric Administration for the full constellation during the 2023 North Atlantic hurricane season. These low-latency efforts broaden the applications utility of TROPICS data from long-term decisions such as research studies and model verification to also include short-term and time-critical decisions such as operational hurricane forecasting and disaster response (Fig. 17).

Also in response to recommendations from the 2nd TROPICS Mission Applications Workshop, efforts were undertaken to incorporate TROPICS data into decision support systems at the US Navy's Joint Typhoon Warning Center (JTWC) and the US National Hurricane Center (NHC). Scientists at the Cooperative Institute for Research in the Atmosphere coordinated with the TROPICS data processing center (DPC) to produce specially formatted data for display in the Automated Weather Interactive Processing System (AWIPS) workstations used at JTWC and NHC. TROPICS Pathfinder data are currently being used in operations at JTWC (Fig. 18), and the transition to AWIPS at NHC is nearing completion.

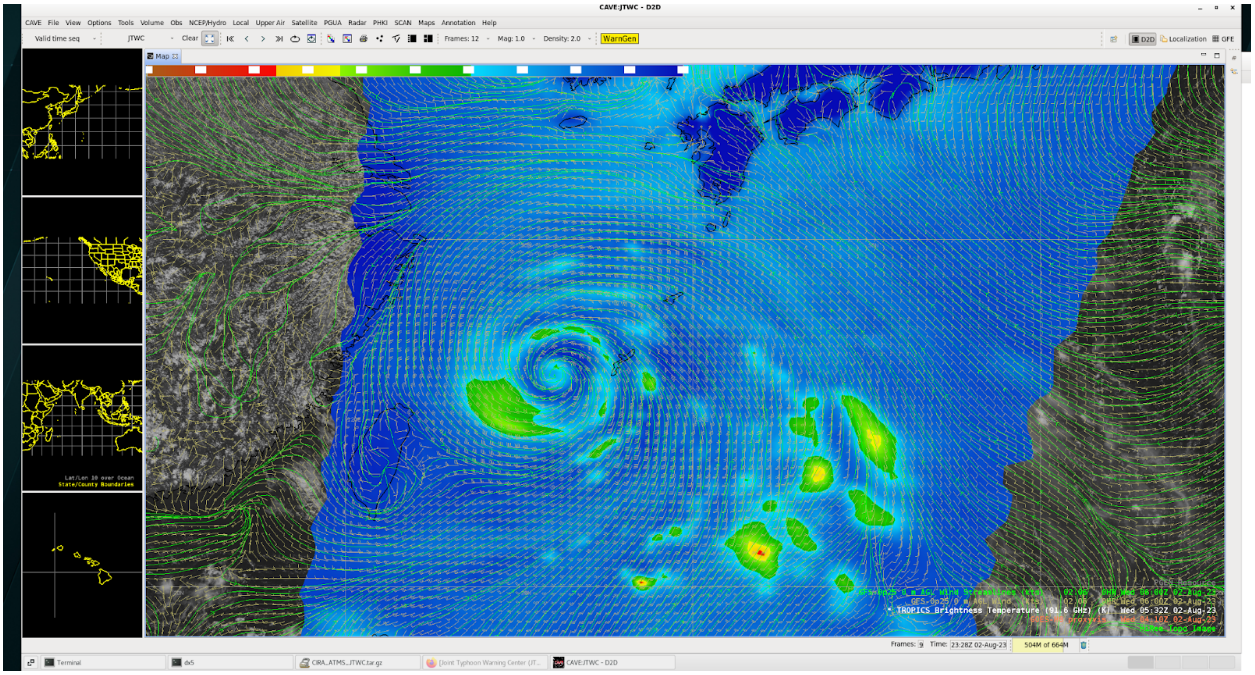

Figure 18. TROPICS Pathfinder 91-GHz brightness temperature imagery (filled contours) displayed along with other datasets in the Joint Typhoon Warning Center's decision support system. Image credit: Jim Darlow, Joint Typhoon Warning Center.

TROPICS data are also available for display at the Naval Research Laboratory's newly revised TCWeb portal, including the 91.66, 117.25, 184.41, and 204.8 GHz brightness temperatures, which are useful for TC analysis. The portal also includes predictions of upcoming satellite overpasses over a given TC, which helps with situational awareness for forecasting, field campaign operations, and satellite intercalibration efforts. The TROPICS DPC also will produce GeoTIFF-formatted files so imagery can be displayed on NASA's Worldview website and a variety of GIS software packages.

One action item identified during the current workshop is that similar efforts should be undertaken for CYGNSS. Even if CYGNSS data are not available in near-real-time, the availability of CYGNSS in AWIPS format could assist in post-season TC reports and reanalysis. For example, NHC includes estimates of the 34-, 50-, and 64-knot wind radii in the "best track" dataset produced at the end of each hurricane season. CYGNSS, with its high revisit rate, can provide valuable information about wind radii in the absence of aircraft reconnaissance and other spaceborne wind sensors. Furthermore, CYGNSS' L-band retrievals allow it to observe wind speed even in regions of heavy rain with no significant degradation. This offers a considerable advantage over Ku-band and even C-band scatterometers and radiometers. If the latency of CYGNSS were reduced to around 3 hours, the data could be quite beneficial for operational hurricane forecasting and operational data assimilation.

Breakout discussions identified the utility of TROPICS for diagnosing eyewall slope and eye diameter, which are relevant to TC structure and intensity change. This structure can be used in deep learning models or other algorithms to derive 2-D winds from TROPICS data, which can then be intercompared with CYGNSS surface wind speed observations. TROPICS also provides important information on the environmental thermodynamic profile around TCs, including the presence of dry air that can inhibit TC intensification. The combination of this data with CYGNSS and the two TROPICS Level 2 TC intensity estimation techniques can provide new insight into environmental effects on TC structure and intensity. Although the visualization efforts undertaken since the previous TROPICS Applications Workshop have improved the ability to use TROPICS data and intercompare TROPICS with other instruments, there remains some demand among the applications community for better web-based tools to visualize and overlay/intercompare passive microwave imagery.

Preliminary TROPICS data have also demonstrated its ability to resolve important inner-core structures in hurricanes, such as secondary eyewall formation and eyewall replacement cycles. The high-resolution 205-GHz channel appears to be particularly well-disposed to this application (e.g., Fig. 19), although applications users are not familiar with how this new channel behaves. Given that this is the first time a 205-GHz imager has flown aboard a spaceborne platform, it is critical that its behavior be documented and put into the context of other, better-known channels such as the 183 GHz channel available on pre-existing instruments such as the Advanced Technology Microwave Sounder (ATMS). A panel of operational forecasters highlighted the need for training to be provided on all the sensor characteristics, including which channels are useful for a given application and the spatial resolution of each channel or product.

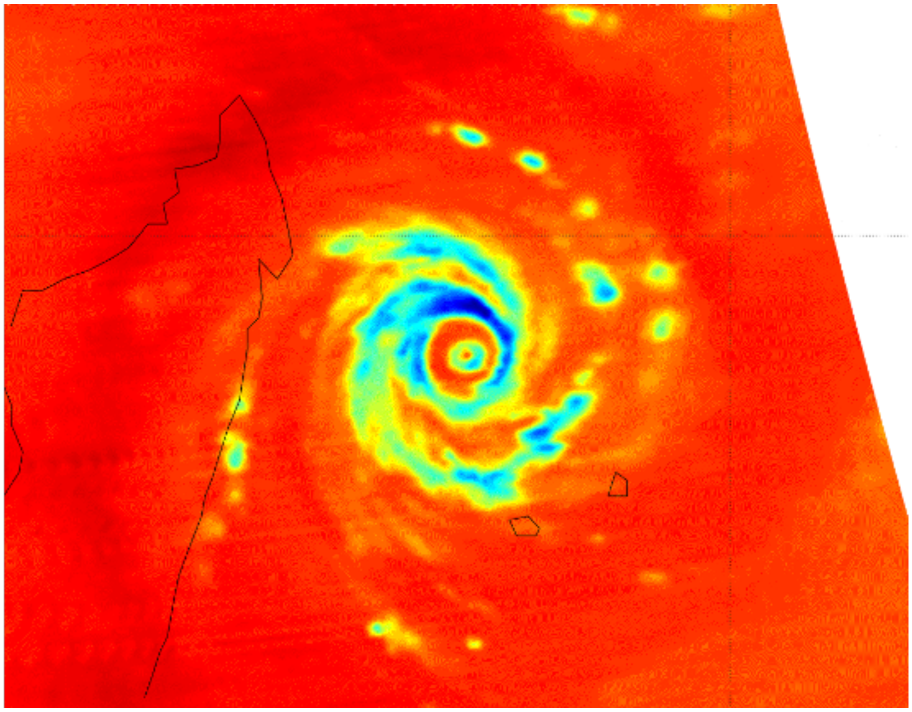

Figure 19. TROPICS Pathfinder 205-GHz brightness temperature image of Cyclone Emnati off the coast of Madagascar shows the ability of the TROPICS 205-GHz channel to resolve a double eyewall structure associated with an eyewall replacement cycle. Image credit: Bill Blackwell, MIT Lincoln Laboratory

Data Assimilation

Data assimilation for TC prediction is a research area on which the CYGNSS and TROPICS science teams have already closely collaborated. Assimilation of CYGNSS and TROPICS data into the Weather Research and Forecasting (WRF) model show the value of both datasets in numerical modeling of TCs. Inclusion of temperature and moisture soundings from TROPICS Pathfinder improved the track forecasts of Hurricane Ida (2021). Assimilating both CYGNSS surface wind speed and TROPICS vertical profiles improved the representation of the storm's rain field, with the simulation including these data (Fig. 20c) more closely matching the rain field retrieved by the Integrated Multi-satellitE Retrievals for GPM (IMERG) dataset (Fig. 20a) than the control simulation without these data (Fig. 20b). These initial experiments indicate the potential value of both missions for improving TC track and rainfall forecasts. More cases are currently being analyzed, as are the error characteristics of each of the TROPICS sensors, with newer Pathfinder data versions performing better than previous versions of the data.

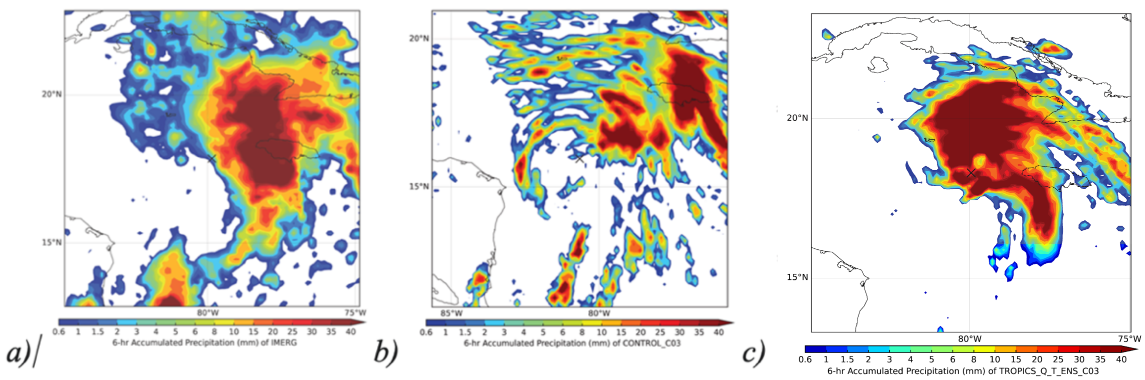

Figure 20. Six-hour accumulated precipitation in Hurricane Ida at 21 UTC 26 August 2021 from (a) IMERG, (b) a control simulation, and (c) a simulation in which CYGNSS surface wind speed and TROPICS temperature and moisture profiles. Image credit: Zhaoxia Pu, University of Utah.

This year, NOAA introduced a new operational TC forecasting model: the Hurricane Analysis and Forecast System (HAFS). The HAFS team has successfully experimented with assimilating both CYGNSS and TROPICS data in a case study of Hurricane Sam (2021). Assimilating TROPICS radiances alone improved forecasts of the TC outer wind field, but at the expense of shifting the maximum wind to the wrong quadrant of the storm. Including CYGNSS together with TROPICS shifted the maximum wind back to where it belonged, demonstrating the value of using both datasets together in data assimilation for TC forecasting. Notably, the largest error reduction for wind radii occurs in the later part of the forecast, where forecast errors tend to be largest. Another benefit of assimilating CYGNSS wind speed is improved modeling of ocean mixing and surface heat fluxes, which exert important influences on both TC structure and intensity.

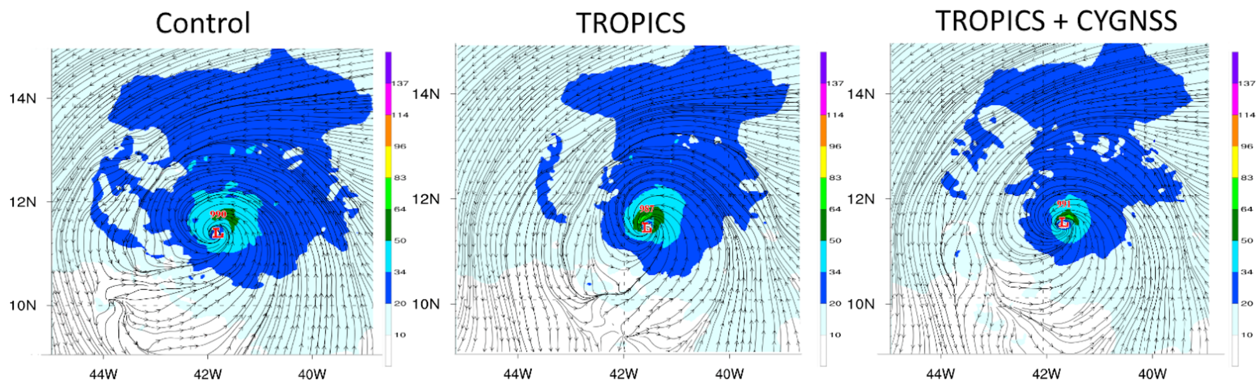

Figure 21. Ten-meter wind analysis of Hurricane Sam (2021) from the Hurricane Analysis and Forecast System. Relative to the control (left) the inclusion of TROPICS correctly shrinks the outer wind field (center), while the inclusion of both TROPICS and CYGNSS (right) leads to a correctly shrunken wind field and a maximum wind correctly placed in the northeast quadrant of the storm. Image credit: Brittany Dahl, University of Miami

From a broader perspective, research performed at the European Center for Medium-Range Weather Forecasts (ECMWF) reveals that the addition of sounders similar to TROPICS improves forecast accuracy. Constellations of eight satellites show significant benefit for data assimilation, with diminishing returns for large 20-satellite constellations. Preliminary work using the initial Pathfinder validated dataset revealed scan and orbital biases in the 118 GHz temperature channels, which the science team is working to remediate. These issues are not as large in the 183-GHz channels, however, and the TROPICS data look similar to that already used in the ECMWF system. Météo-France is also prepared to assimilate TROPICS data in their global model, ARPEGE, and initial work is underway using the calibrated Pathfinder data to characterize observation error.

ECMWF also plans to assimilate CYGNSS data in preparation for the upcoming European Space Agency (ESA) hydroGNSS mission. The lack of near-real-time data from CYGNSS was cited as an impediment to its use in operational forecasting, but experiments with the data will help inform the assimilation of data from hydroGNSS and private-sector missions such as Spire Global's constellation of GNSS-R reflectometers.

As a response to the last applications workshop, TROPICS data were made available in Binary Universal Form for the Representation of meteorological data (BUFR) format, as operational numerical weather prediction (NWP) centers require this format for their data assimilation systems. Both the NOAA BUFR format (required by NOAA's Environmental Modeling Center) and World Meteorological Organization (WMO) BUFR format are being produced by the TROPICS DPC. These files will be made available in near-real-time to NWP centers for assimilation into operational models. If the latency of CYGNSS is able to be reduced to the 3-6 hour range, similar efforts would open the opportunity for many more surface wind speeds over the ocean to be assimilated into operational models. Given the benefits illustrated by presentations at the workshop, and the current and future availability of surface wind speed data from private-sector

GNSS-R missions, pursuing data assimilation efforts for CYGNSS could be beneficial for TC forecasting.

Oceans

A significant strength of both CYGNSS and TROPICS is their orbital configurations, which provide data over the same location at many times throughout the day. This is in contrast with many other earth-observing satellites, which are in sun-synchronous orbits. Although sun-synchronous orbits provide some advantages, a significant limitation is that they cannot resolve the full diurnal cycle in the tropics. The diurnal cycle is an important element of tropical oceanic convection, with a maximum in precipitation, wind speed, and latent heat flux occurring overnight and in the early morning. This cycle, and the coupling between precipitation, wind, and surface fluxes is still not fully understood – partially due to a dearth of observations over the regions where it occurs. CYGNSS has already allowed the diurnal cycle of wind speed and surface fluxes to be better characterized (Riley Dellaripa et al. 2023). Incorporation of TROPICS into these process studies could further enhance understanding of the diurnal evolution of tropical convection. Workshop attendees identified a number of user communities that could benefit from this research, including fisheries, marine traffic, air traffic, shipping, renewable energy, and insurance agencies.

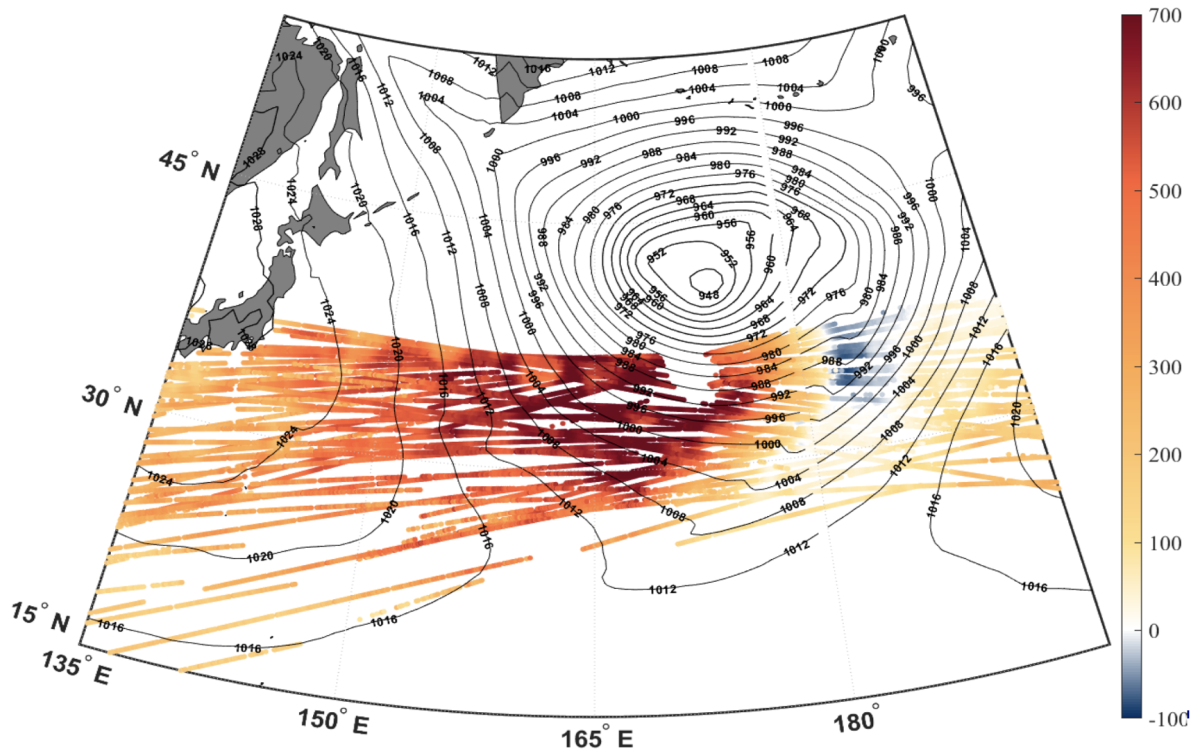

Figure 22. CYGNSS latent heat flux (W m^{-2}; filled dots) and sea-level pressure in an extratropical cyclone over the Northwest Pacific Ocean. Image credit: Juan Crespo, UCLA/Jet Propulsion Laboratory

In addition to applications for tropical oceanic convection, CYGNSS can characterize winds and surface fluxes in the subtropics. The CYGNSS surface flux product has been used to characterize sensible and latent heat flux within extratropical cyclones and atmospheric rivers (Crespo et al. 2021), with increased cloud cover correlated with higher surface fluxes. Incorporating TROPICS brightness temperatures, rainfall, and vertical thermodynamic profiles could further illuminate these relationships.

International and Private Sector Partnerships

The launch of large constellations of CYGNSS-like and TROPICS-like sensors by private-sector firms presents a unique opportunity for science investigations relating to the focus areas discussed at the workshop. Since these constellations consist of a larger number of satellites in a variety of orbits, these missions can also provide low revisit rates across a larger region of the globe, enabling new science in the midlatitude and polar regions. Given the feedback from the applications communities on the importance of low-latency data, obtaining these data in a timely manner also presents a unique challenge. How will NASA, NOAA, and other government agencies obtain these data in a timely and cost-effective fashion? Targeted low-latency operations for anticipated high-impact events could be a cost-effective path forward to balance user community needs with the fiscal realities of a cost-capped mission.

The CYGNSS and TROPICS satellite missions present unique opportunities to partner with the private sectors for current and future commercial missions. These partner sectors can best be categorized as 1) commercial hardware/software development, 2) data products and applications, 3) data visualization and decision-maker applications, and 4) operational end-users.

Breakout and plenary discussions identified primary barriers and opportunities toward data transition and partnerships. As previously discussed, data latency was resoundingly indicated as the primary barrier to all sectors dealing with data, applications, and end-users, and thus the highest priority issue for private and public sector participants. There were several private/commercial specific issues/barriers raised throughout the workshop, which are summarized below:

- The need to engage with private sector partners earlier in the process. Regardless of the individual sector, the common theme centered around NASA fostering more open exchange between the agency, private sector partners, and operational end-users. These exchanges need to occur in the pre-competitive stage in order to get open dialogue from commercial applications and private sector partners.

- The need to understand how the data will be used by operational end-users and decision-makers. This discussion point centered around the need to understand the customer needs to aid in focusing on the types of products that could be used and whether a customer base even exists for potential derived products.

- The need for more broadly accessible georeferenced data formats. Operational end-users and downstream decision-makers indicated that GIS-enabled data formats, such as GeoTIFFs and GeoJSON, are more readily accessible for GIS users and web mapping applications. Offering data in these formats significantly lowers the barriers toward integration and use by downstream decision-makers in the disasters communities.

- There are both barriers and opportunities toward commercial - government collaborations with respect to commercial data buys. NASA can provide calibration/validation knowledge to the table toward assisting the development of derived products from commercial data. Cal/Val stamp of approval from NASA would go a long way toward encouraging the community to adopt commercial data.

- Open science and data agreements can be tricky with respect to commercial data buys and the development of derived products. Would those commercial data and derived products be freely publicly available? Are there mechanisms to provide purchased commercial data to non-governmental organizations for the public good (open science, disaster response, etc.) Government needs to understand they could cannibalize the market and harm long-term continuity of missions if price is undercut. It is noted that relevant experience on these questions is being gained with radio occultation data-buys at NOAA and EUMETSAT, in particular with respect to reconciling commercial interests and established international data sharing principles.

- The need to build trust in the data and products with the operational end-user community. Use case examples and success stories, along with applications/product training, will help drive the private sector's integration of key products into their customer-facing data feeds, software, decision support systems, web-interfaces/web-mapping services.

- The need to educate and build awareness on future missions, data, and potential products/applications both pre- and post-launch. This will assist in educating the commercial/private sectors on the mission and help build a customer base for these data, products, and applications.

- The need to reach out to non-traditional downstream sectors, such as transportation, shipping, logistics, etc. to understand gaps and needs in those sectors.

- The need to provide a single site repository of CYGNSS/TROPICS data, products, and visualizations. End-user participants expressed challenges in finding microwave and other small-sat products/imagery. This is a significant barrier to integration for non-AWIPS users in the operational weather community.

Synergies with other Satellite Missions

NASA, NOAA, and the Indian Space Research Organization (ISRO) have multiple ongoing or planned satellite missions focused on observing TCs and their surrounding environment, which have potential synergy with the NASA CYGNSS and TROPICS missions. The CYGNSS and TROPICS missions offer unique capabilities for providing rapid refresh observations of the Earth system and have numerous potential synergies with other existing and planned satellite missions.

Atmosphere Observing System (AOS): NASA is developing the AOS mission as part of its Earth System Observatory (ESO) in response to priorities identified in NASA's 2017 Earth Science Decadal Survey. AOS is currently in Phase A, the concept and technology development phase, with plans for satellite launches in the late 2020s and early 2030s, and suborbital measurements to include field campaigns after those satellite launches. AOS will collect measurements of aerosols, clouds, convection, and precipitation using a variety of satellite and suborbital platforms.

- The TROPICS 91-205 GHz microwave channels complement several of the planned AOS objectives to measure aerosols, clouds, convection, and precipitation.

GOES-R: NOAA's GOES-R geostationary satellite series provides operational data from a multitude of sensors; most relevant to CYGNSS and TROPICS are the synergies with the Advanced Baseline Imager (ABI), the Geostationary Lightning Mapper (GLM). Impactful applications synergies readily identified in the workshop are as follows:

- TROPICS imaging channels will provide critical information for TC center fixing, supplementing information provided by the geostationary IR imagery.
- CYGNSS surface winds help TC forecasters understand the extent of tropical storm force winds.
- TROPICS moisture profiles can help identify low- to mid-level dry air associated with the Saharan Air layer (SAL), providing needed context beyond water vapor imagery available in ABI.
- Ongoing research has linked the intensity, length, and location of lightning activity, as observed by GLM, in TCs exhibiting rapid intensification. GLM observations combined with TROPICS imaging channels will help us understand the structural changes, including convective bursts, associated TC intensification and lightning activity. Likewise, instantaneous rain rate data from TROPICS is also a proxy for changes in TC structure and likely indicative of intensification of TCs.

Combining these observations is a robust field of research, but early work suggests that forecasters can use a combination of geostationary IR, GLM, CYGNSS winds, and TROPICS datasets to inform their guidance and learn to anticipate rapid intensification via a variety of methods.

NASA-ISRO Synthetic Aperture Radar (NISAR): The NISAR mission is a joint project between NASA and the Indian Space Research Organization (ISRO) to co-develop and launch a dual-frequency synthetic aperture radar (L-band and S-band) on an Earth observation satellite. It is designed to observe and measure some of the planet's most complex natural processes, including ecosystem disturbances, ice-sheet collapse, and natural hazards such as earthquakes, tsunamis, volcanoes and landslides.

- Surface water and floods: The CYGNSS Soil Moisture Product provides volumetric water content estimates for soils between 0-5 cm depth at a 6-hour discretization for most of the subtropics. This product could be used to supplement the analysis of flooding events that are mapped by NISAR.
- Ocean winds: Although not a planned objective of NISAR, other SAR instruments (e.g., Sentinel-1 and RADARSAT-2) have been used successfully to collect high-resolution observations of surface wind speed over the ocean. These SAR wind products are able to detect small-scale features in the inner cores of TCs that are not resolved by lower-resolution scatterometers and radiometers. If NISAR is able to retrieve wind speed, its combination with CYGNSS could provide accurate inner-core winds where the lower resolution of CYGNSS does not perform as well, while CYGNSS can provide winds outside of the inner core, where the smaller gradients allow CYGNSS to perform better.

Surface Water and Ocean Topography (SWOT): The SWOT mission is a joint effort developed and operated by NASA and CNES, the French space agency, in partnership with the Canadian Space Agency (CSA) and UK Space Agency (UKSA). It employs a satellite altimeter to make the first global survey of the Earth's surface water, to observe the fine details of the ocean surface topography, and to measure how terrestrial surface water bodies change over time. Altimetry data from the SWOT mission will make it possible to measure floodwater levels.

- Surface water and floods: The CYGNSS Soil Moisture Product could be used to supplement the analysis of flooding events that are mapped by the SWOT. When combined with rain rate data from TROPICS, the full hydrometeorological evolution of flood events in the tropics can be observed more thoroughly.

Global Precipitation Measurement Mission (GPM): GPM is a joint mission between JAXA and NASA as well as other international space agencies to make frequent (every 2–3 hours) observations of Earth's precipitation. The constellation employs a Dual-frequency Precipitation Radar (DPR) operating at Ku-band (13.6 GHz) and Ka-band (35.5 GHz) and provides 3-D observations of precipitation structure, precipitation particle size distribution, and precipitation intensity and distribution.

- Rain rate: TROPICS rate data could be used to supplement high-resolution precipitation observations from the GPM constellation of satellites.

- Precipitation structure: TROPICS (e.g., 91 and 184 GHz) and GPM (89 and 183 GHz) microwave channels can provide rapid refresh sampling of evolving precipitation structures in tropical convection and tropical cyclones.
- Diurnal variability of rainfall: the rapid refresh of the TROPICS constellation (<1 hr) and constellation of 12 GPM satellites allow for detailed observations of rainfall diurnal variability. TROPICS data can supplement diurnal precipitation sampling provided by GPM.
- Correction for diurnal drift in the satellite record: A significant source of error in tropical tropospheric temperature trends is diurnal drift, which results from steady changes in equator crossing time over the period of years. This diurnal drift aliases onto climate-scale temperature trends computed from polar-orbiting microwave sensors, introducing significant and poorly characterized error (Po-Chedley et al. 2015). TROPICS presents a unique opportunity to develop new corrections for the effect of diurnal drift in climatological temperature records by better characterizing the diurnal cycle of tropospheric temperature.

NASA Investigation of Convective Updrafts Mission (INCUS): INCUS is expected to launch in 2027 as part of NASA's Earth Venture Program and will include a collection of three SmallSats, flying in tight coordination to address why convective storms, heavy precipitation, and clouds occur exactly when and where they form. It will use a novel time differencing approach to detect updrafts and estimate convective mass flux in convection.

- The TROPICS microwave channels could provide additional rapid refresh observations to improve the context and evolution of convective areas that are sampled by INCUS. Temperature and humidity soundings from TROPICS could provide information on the pre-convective environment and how the environment evolves around convective systems.

European Space Agency HydroGNSS: The European Space Agency (ESA) selected HydroGNSS from Surrey Satellite Technology Ltd. (SSTL) for its second Scout Earth Observation small satellite mission. HydroGNSS is a 40-kg satellite that is being built and operated by SSTL with plans to launch in 2024. HydroGNSS will take measurements of key hydrological climate variables, including soil moisture, freeze thaw state over permafrost, inundation and wetlands, and aboveground biomass, using GNSS reflectometry. It will complement missions such as ESA's SMOS and Biomass, Copernicus Sentinel-1 and NASA's SMAP.

EUMETSAT Sterna: EUMETSAT is currently considering a constellation of small satellites in polar orbits carrying MW sounding sensors measuring in the 50, 183, and 325 GHz bands, complemented by other window channels. The orbital configuration is still to be finalized, aiming at 6 satellites in three polar planes, complementing the established 3-orbit constellation of the Coordination Group for Meteorological Satellites (CGMS) baseline.

Future Directions and Summary of Recommendations

Based on early feedback from the TROPICS Early Adopters community provided at previous workshops (Zavodsky et al. 2017; Berndt et al. 2020), mission latency was reduced from the several days initially planned (Blackwell et al. 2017) to only 45 minutes for the Pathfinder satellite. This is a testament to the success of not only the Early Adopters program, but also the mission PI, science team, and funding agencies (NOAA and the Office of Naval Research) who made it possible. The availability of low-latency data from the full TROPICS constellation remains a high priority for the mission and is currently being pursued. Such pursuits could also be valuable for CYGNSS, as it has demonstrated operational utility for a variety of applications.

Through breakout and open discussion at the workshop, a wide variety of additional recommendations were made for CYGNSS, TROPICS, and other missions, including:

1. **Develop tools that facilitate intercomparison of data from multiple missions.**
   There is a need for tools that enable intercomparison of CYGNSS and TROPICS data with other satellite observations in TCs. For example, the high-resolution wind speed observations provided by SAR over the ocean presents an opportunity to further understand fine-scale TC structure, and its relationship to winds and convection observed by CYGNSS and TROPICS. A tool that allows a user to easily identify coincident overpasses over a given geographic area was identified by multiple participants as highly useful.
2. **Develop training for operational forecasters and the research community.**
   Researchers and operational forecasters in attendance expressed a need for training on mission datasets. Both short-form and long-form training were identified as needs, with the potential for NASA's Applied Remote Sensing Training (ARSET) Program, NASA's Short-Term Prediction Research and Transition (SPoRT) Center, and NOAA's Cooperative Institute for Research in the Atmosphere (CIRA) to produce these trainings and provide them to the stakeholder community. Pre-recorded videos, in-person meetings, and webinars were all specifically mentioned, along with brief quick guides that can be rapidly referenced by end users.
3. **Develop Level 3 products for TROPICS to expand applications user base.**
   Attendees highlighted the difficulty of working with Level 1 swath products and suggested a need for TROPICS Level 3 products, including daily gridded files similar to the CYGNSS Level 3 gridded wind product. These products will enable users to more easily leverage the data and intercompare the data to other gridded datasets. The availability of Level 3 products will broaden the TROPICS user community, especially in climatological research and applications and disaster response.
4. **Engage with the operational weather community to communicate error and validation of derived or integrated products to build trust in Level 3 products.**
   Although the need to lower barriers for users was emphasized, some attendees expressed concern that integrated products can be too smoothed out, eliminating important information, or have other errors that are not well characterized. The error introduced by

integrating or gridding products should be well-documented so that any potential weaknesses are known to the user.

5. **Simplify data access and manipulation through web-based platforms.**
   Ease of data access and manipulation was highlighted by a number of user groups as a need for further development. The ability to display CYGNSS and TROPICS data in GIS mapping software would open up the missions to a variety of new stakeholders, especially international and private-sector partners. Hosting the data on a cloud-based platform that allows the data to be quickly and easily subset in both space and time before download also would make using the data easier. Some users highlighted the difficulty of employing swath data, and requested more gridded data products. Specifically, the need for a Level 3 TROPICS gridded precipitation product was mentioned.
6. **Conduct applied research to better characterize the utility of mission data sets.**
   Applied research on the utility of TROPICS and CYGNSS data products for various applications is still needed, especially for novel, less well-characterized products such as the TROPICS 205-GHz imagery and CYGNSS soil moisture. Validation of mission datasets should be an ongoing project; collaboration with the GPM Ground Validation team and the NOAA Hurricane Research Division's Hurricane Field Program were specifically mentioned. Training organizations should work closely with applied researchers and the cal/val teams to identify additional applications and the strengths/weaknesses of each data product for a given application.
7. **Implement strategies to incentivize applications end users to invest time and resources into smallsat missions.**
   A challenge identified for smallsat missions with a short planned lifetime such as CYGNSS and TROPICS is that some end users may not be willing to devote time and resources to learning about the datasets and incorporating them into their workflows if there's no guarantee that the data will be available for an extended period of time (e.g., beyond one year). Each sensor has different error characteristics and calibration, which increases the workload for smallsat missions relative to other missions. For example, developing forward models for data assimilation requires significant effort, and it can be difficult for agencies such as NOAA and ECMWF to invest in those efforts if the missions last only a few years. The TROPICS Pathfinder is an example of a way to mitigate these issues, as it provided nearly two years of time for the general sensor characteristics to be understood and applications end users to begin integrating data into their systems. Future smallsat missions would benefit from a NASA-funded Pathfinder vehicle similar to the TROPICS Pathfinder to enable development of Earth Action applications and to expedite integration of mission data into NASA and stakeholder data visualization and decision-support systems.
8. **Further develop web-based visualization tools.**
   Some attendees highlighted the difficulty of accessing passive microwave data online. Although the data are available in a few places, such as NRL's TCWeb page, they can be

difficult to find and the imagery difficult to manipulate. There is a need for web-accessible microwave imagery that is easy to manipulate and interpret. This could expand the user base to more media outlets, such as The Weather Channel, whose representative at the workshop mentioned the difficulty in finding good microwave imagery to use in on-air weather storytelling.

9. **Develop a CYGNSS data viewer and integrate CYGNSS data into existing web mapping services/data dashboards.**
   CYGNSS would benefit from a data viewer of surface water maps to assist in visualizing surface water and inundation. Several potential platforms were recommended, including a Visualization, Exploration, and Data Analysis (VEDA) dashboard, USGS Earth Explorer, and Google Earth Engine. Digital Earth Australia is also a possible platform, with the benefit of enhancing international collaboration.
10. **Engage with other national/regional weather forecast centers.**
   The missions should begin to engage other operational weather forecasting centers, such as NOAA's Ocean Prediction Center (OPC) and Weather Prediction Center (WPC), and individual National Weather Service offices in the tropics and subtropics who could benefit from mission data.
11. **Engage with international partners and NGOs for applications development.**
   Some attendees expressed a concern that applications for CYGNSS and TROPICS remain US-centered and that the missions should work to further engage international partners. Although there are existing collaborations with ECMWF and Météo-France, there is also an underexplored opportunity to benefit countries with fewer resources in the tropical regions of the globe. Further engagement with the UN Satellite Centre could provide a central point of contact that benefits a broad spectrum of countries. There is also the opportunity to engage with the Australian Bureau of Meteorology on data visualization and forecasting tools development.
12. **Engage and leverage opportunities with Satellite Needs Working Group to develop additional L3 applications products.**
   Attendees suggested that previous responses to the Satellite Needs Working Group (SNWG) could help inform any additional products that could be developed from the mission which would have utility for end users. The mission applications teams should review previous needs identified by the SNWG to help guide future product development.
13. **Pursue follow-on satellite missions with lower-frequency microwave sensors.**
   Applications end users – particularly operational forecasters – continue to emphasize the need for lower-frequency brightness temperature imagery, such as the 37 GHz imagery provided by GPM. This imagery is particularly useful for diagnosing TC structure and intensity, and these data are becoming less available as legacy sensors age out. Technological and size constraints generally preclude the ability to include a 37 GHz imager on a cubesat platform, however, so alternative platforms should be considered.

The discussions and recommendations from the workshop will be used by both missions to guide future end-user engagement and applications initiatives. Collaborative activities between the missions are ongoing, and additional joint activities are under consideration, including joint teleconferences to further enhance collaboration between the two missions.

Appendix A – Organizing Committee

Name	*Affiliation*
Jason Dunion*	University of Miami / CIMAS / NOAA HRD
Patrick Duran*	NASA MSFC / SPoRT / TROPICS Mission Applications Lead
William Blackwell	MIT LL / TROPICS Principal Investigator
Christopher Ruf	University of Michigan / CYGNSS Principal Investigator
Neils Bormann	ECMWF
Scott Braun	NASA GSFC / TROPICS Project Scientist
Lisa Bucci	NOAA NWS National Hurricane Center
Philippe Chambon	Météo-France
Clara Chew	Muon Space
David Green	NASA HQ / TROPICS Program Applications Lead
Ben Kim	NASA HQ / TROPICS Program Executive
Anita LeRoy	University of Alabama in Huntsville / NASA SPoRT
Cameron Matthews	Muon Space
Will McCarty	NASA HQ / TROPICS Program Scientist
Mahta Moghaddam	University of Southern California
John Murray	NASA LaRC
Derek Posselt	NASA JPL
Zhaoxia Pu	University of Utah
Brent Roberts	NASA MSFC
Chris Velden	University of Wisconsin / CIMSS
Ryan Wade	University of Alabama in Huntsville / NASA SPoRT

*Meeting co-conveners

Table 2. List of members of the workshop planning committee.

Appendix B – Agenda

2023 Joint NASA CYGNSS & TROPICS
Applications Workshop

April 11-13, 2023
Rosenstiel School of Marine & Atmospheric Science Auditorium, University of Miami
4600 Rickenbacker Causeway, Miami, FL 33149-1031

Meeting Access for Remote Participants: https://www2.gotomeeting.com/join/151354330

Break-out Session Access for Remote Participants:
Session 1 (Auditorium): meet.google.com/dnv-mddc-qcr
Session 2 (CIMAS Conference Room): meet.google.com/qdj-hrvp-ger
Session 3 (Map & Chart Room): meet.google.com/ynr-xswd-uze

Tuesday, April 11:

8:00a	UM shuttle departs Homewood Suites & Hilton Garden Inn for UM Marine Campus
8:15a - 8:45a	Registration & Light Refreshments
8:45a - 8:50a	*Welcome and Logistics*, **Jason Dunion**, Univ. of Miami/CIMAS – NOAA/AOML/HRD
8:50a - 8:55a	*Summary of Workshop Objectives*, **Patrick Duran**, NASA Marshall Space Flight Center
8:55a – 9:00a	Introductions and NASA Program Applications/Applied Sciences
9:00a - 10:30a	**Mission Overviews** **Session Chair: Ben Kim,** NASA Earth Science Division
9:00a – 9:15a	*CYGNSS Mission Overview and Sensor Status* **Christopher Ruf**, NASA CYGNSS Principal Investigator, University of Michigan
9:15a – 9:45a	*CYGNSS Data Product Overview, Cal/Val Updates, DAAC* **Darren ue**, University of Michigan
9:45a – 10:00a	*TROPICS Mission Overview and Sensor Status* **William Blackwell**, TROPICS Principal Investigator, MIT Lincoln Laboratory
10:00a – 10:30a	*TROPICS Data Product Overview, Cal/Val Updates, DAAC* **Vincent Leslie**, MIT Lincoln Laboratory
10:30a – 10:45a	----- **Morning Break** -----

10:45a – 11:45a	**Presentations on CYGNSS Land Surface & TROPICS Precipitation Products** **Session Chair: Christopher Kidd,** NASA GSFC / Univ of Maryland
10:45a - 11:00a	*CYGNSS Flood Applications: Synergy with other Surface Water Sensing* **Robert Brakenridge**, Dartmouth Flood Observatory, CU-Boulder
11:00a - 11:15a	*Brown Ocean Effect in Land-Falling Tropical Cyclones* **Dev Niyogi**, University of Texas at Austin, Virtual Presentation
11:15a - 11:30a	*Retrieval of Soil Moisture and Inland Water Extent by CYGNSS* **Mohammad Al-Khaldi**, Ohio State University
11:30a - 11:45a	*TROPICS Early-Phase Retrievals with MIRS* **John Yang**, University of Maryland
11:45a – 1:00p	----- **Lunch at RSMAS Commons: SALT Waterfront Restaurant** -----
1:00p - 3:00p	**Afternoon Breakout Sessions** **Session Chair: Derek Posselt,** Jet Propulsion Laboratory
1:00p – 1:15p	*Breakout Logistics and Breakout Lead Introductions*
1:15p – 2:00p	Breakout #1 Concurrent Sessions (discussion points: process studies, data assimilation, modeling, data products, latency needs) ● Session 1: Inundation Applications/Products Breakout Lead: Clara Chew, Muon Space ● Session 2: Precipitation Applications/Products Breakout Lead: Anita LeRoy, UAH ESSC / NASA MSFC SPoRT ● Session 3: Land Surface Applications/Products Breakout Lead: Brent Roberts, NASA Marshall Space Flight Center
2:00p – 2:15p	----- **Afternoon Break (Attendees can switch breakout rooms)** -----
2:15p – 3:00p	Breakout #2 Concurrent Sessions (discussion points: process studies, data assimilation, modeling, data products, latency needs) ● Session 1: Inundation Applications/Products Breakout Lead: Clara Chew, Muon Space ● Session 2: Precipitation Applications/Products Breakout Lead: Anita LeRoy, UAH ESSC / NASA MSFC SPoRT ● Session 3: Land Surface Applications/Products Breakout Lead: Brent Roberts, NASA Marshall Space Flight Center
3:00p – 3:15p	----- **Break (Attendees reconvene in main auditorium)** -----
3:15p – 4:15p	Reconvene/Report out from breakout groups (5 min each) Open Discussion of Actionable Outcomes **Session Chair: Scott Braun,** NASA Goddard Space Flight Center
4:15p – 6:15p	**Icebreaker & Poster Session (Univ. of Miami Commons) – 20-25 posters** **Session Chair: Jason Dunion,** Univ. of Miami/CIMAS – NOAA/AOML/HRD

6:30p	UM shuttle departs UM Marine Campus for Homewood Suites & Hilton Garden Inn

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Wednesday, April 12:

7:15a	UM shuttle departs Homewood Suites & Hilton Garden Inn for UM Marine Campus
7:30a – 8:00a	Registration/Light Refreshments
8:00a – 8:15a	**Review of Tuesday Sessions** **Jason Dunion & Patrick Duran**
8:15a – 10:15a	**Data Products for Tropical Cyclones** **Session Chair: Zhaoxia Pu,** University of Utah
8:15a - 8:30a	*LEO Research on Tropical and Extratropical Weather Systems using CYGNSS Data* **Derek Posselt**, Jet Propulsion Laboratory
8:30a - 8:45a	*Update on the Geolocated Information Processing System (GeoIPS) and TROPICS Tropical Cyclone Products* **Melinda Surratt**, NRL-Monterey, Virtual Presentation
8:45a - 9:00a	*A Comprehensive Assessment of Precipitation Satellite Products at Extreme Events Over a Semi-Arid Region* **Wiam Salih**, Mohammed VI Polytechnic University, Morocco, Virtual Presentation
9:00a - 9:15a	*LEO Product Use at JTWC* **James Darlow**, Joint Typhoon Warning Center
9:15a – 9:30a	----- **Morning Break** -----
9:30a – 10:30a	**Data Assimilation** **Session Chair: Jason Sippel,** NOAA Hurricane Research Division
9:30a - 9:45a	*Prospects for MW sounding constellations and use of CYGNSS data at ECMWF* **Niels Bormann**, ECMWF, Virtual Presentation
9:45a - 10:00a	*Assimilation of TROPICS Radiances and CYGNSS Winds on Tropical Cyclones in HAFS* **Brittany Dahl** and **Bachir Annane**, University of Miami-NOAA/AOML/HRD
10:00a - 10:15a	*Joint Assimilation of CYGNSS and TROPICS Data for Hurricane Prediction* **Zhaoxia Pu**, University of Utah
10:15a - 10:30a	*Preparing the Assimilation of TROPICS Data within the Meteo-France Global Model ARPEGE* **Mary Borderies**, Meteo-France, Virtual Presentation

10:30a - 11:30a **Panel / Open Discussion of Actionable Outcomes on Tropical Cyclones**
Session Chair/Moderator: James Darlow, Joint Typhoon Warning Center
Co-Chair/Co-Moderator: Jason Dunion, Univ. of Miami/CIMAS – NOAA/AOML/HRD
Lisa Bucci, NOAA/NHC; **Mark DeMaria**, CIRA/CSU (virtual); **Derrick Herndon**, University of Wisconsin/CIMSS; **Frank Marks**, NOAA/AOML/HRD; **Stephanie Stevenson**, NOAA/NHC

11:30a – 1:00p ----- **Lunch at RSMAS Commons: SALT Waterfront Restaurant** -----

1:00p – 1:45p **Ocean Data Products**
Session Chair: Derek Posselt, Jet Propulsion Laboratory

1:00p - 1:15p *Diurnal Cyclone of Wind Speed and Precipitation Over the Northern Australia Coast Region: CYGNSS Observations*
Eric Maloney, Colorado State University

1:15p - 1:30p *Wind Retrievals Through Sequential Processing of Level 1a DDMs*
James Garrison, Purdue University, Virtual Presentation

1:30p - 1:45p *The Diurnal Cycle of East Pacific Convection, Moisture, and CYGNSS Wind Speed and Fluxes*
Emily M. Riley Dellaripa, Colorado State University, Virtual Presentation

1:45p - 3:45p **Afternoon Breakout Sessions**
Session Chair: Zhaoxia Pu, University of Utah

1:45p - 2:00p *Breakout Logistics and Breakout Lead Introductions*

2:00p - 2:45p Breakout #3 Concurrent Sessions (discussion points: process studies, data assimilation, modeling, data products, latency needs)

- Session 1: Tropical Cyclone Applications/Products
  Breakout Lead: Derrick Herndon, University of Wisconsin/CIMSS
- Session 2: Ocean Data Applications/Products
  Breakout Lead: Ryan Wade, UAH ESSC / NASA MSFC SPoRT
- Session 3: Modeling and Data Assimilation Applications/Products
  Breakout Lead: Sharan Majumdar, University of Miami

2:45p – 3:00p ----- **Afternoon Break (Attendees switch breakout rooms)** -----

3:00p – 3:45p Breakout #4 Concurrent Sessions (discussion points: process studies, data assimilation, modeling, data products, latency needs)

- Session 1: Tropical Cyclone Applications/Products
  Breakout Lead: Derrick Herndon, University of Wisconsin/CIMSS
- Session 2: Ocean Data Applications/Products
  Breakout Lead: Ryan Wade, UAH ESSC / NASA MSFC SPoRT
- Session 3: Modeling and Data Assimilation Applications/Products
  Breakout Lead: Sharan Majumdar, University of Miami

3:45p – 4:00p ----- **Afternoon Break (Attendees reconvene in main auditorium)** -----

4:00p – 5:00p	Reconvene/Report out from breakout groups (5 min each) Open Discussion of Actionable Outcomes **Session Chair/Moderator: Robert Rogers,** NOAA Hurricane Research Division
5:15p	UM shuttle departs UM Marine Campus for Homewood Suites & Hilton Garden Inn

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Thursday, April 13:

7:15a	UM shuttle departs Homewood Suites & Hilton Garden Inn for UM Marine Campus
7:30a – 8:00a	Registration/Light Refreshments
8:00a – 8:15a	**Review of Wednesday Sessions** **Patrick Duran & Jason Dunion**
8:15a – 9:15a	**Private Sector and International Partners** **Session Chairs: William Blackwell & Christopher Ruf**
8:15a - 8:30a	*The UN Satellite Centre (UNOSAT) Support of Emergency Response Operations via Satellite Imagery* **Samir Belabbes**, UNITAR-UNOSAT
8:30a - 8:45a	*GNSS-R Data Assimilation Efforts at Spire Global* **Karina Apodaka**, Spire Global, Inc.
8:45a - 9:00a	*Weather Storytelling with Satellite Data* **Matthew Sitkowski**, The Weather Channel
9:00a - 9:15a	*OzReactor: An EO Data Platform for Rapid Experimentation & Prototyping* **Steve Petrie**, Swinburne University of Technology
9:15a – 9:30a	**----- Morning Break -----**
9:30a – 10:30a	**Breakout #5 Concurrent Sessions** **Session Chairs: Christopher Ruf & William Blackwell** (Discussion points: How can CYGNSS and TROPICS help stimulate collaboration with private sector technology development? What further needs do private sector stakeholders have for CYGNSS and TROPICS applications?) ● Session 1: Private Sector Technology Development **Breakout Lead: Cameron Matthews,** Muon Space ● Session 2: Private Sector Applications Needs and Development **Breakout Lead: Matthew Sitkowski,** The Weather Channel
10:30a – 10:45a	**----- Morning Break (Attendees reconvene in main auditorium) -----**

10:45a – 11:30a	Reconvene/Report out from breakout groups (5 min each) Open Discussion of Actionable Outcomes **Session Chairs/Moderators: William Blackwell & Christopher Ruf**
11:30a – 1:00p	**Lunch at RSMAS Commons: SALT Waterfront Restaurant**
1:00p – 1:30p	**Synergy with other Satellite Missions** **Will McCarty,** NASA Earth Science Division
1:00p – 1:05p	NASA Atmosphere Observing System (AOS) **Emily Berndt,** NASA Marshall Space Flight Center, Virtual Presentation
1:05 – 1:10p	NASA-ISRO Synthetic Aperture Radar Mission (NISAR) **Kyle McDonald,** City College of New York
1:10 – 1:15p	NASA Surface Water and Ocean Topography Mission (SWOT) **Margaret Srinivasan,** NASA Jet Propulsion Laboratory, Virtual Presentation
1:15p – 1:20p	NASA Global Precipitation Measurement Mission (GPM) **Andrea Portier,** NASA Goddard Space Flight Center/SSAI, Virtual Presentation
1:20 – 1:25p	NASA Investigation of Convective Updrafts Mission (INCUS) **Ziad Haddad,** NASA Jet Propulsion Laboratory
1:25 – 1:30p	European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) **Christophe Accadia,** EUMETSAT, Virtual Presentation
1:30p – 2:30p	Panel Discussion with other satellite missions
2:30p – 2:45p	**----- Break -----**
2:45p – 3:45p	Breakout #6 Concurrent Sessions Led by Mission PIs (Mission readiness for the TROPICS Pathfinder + Constellation launch) **Session Chair: Jason Dunion**, Univ. of Miami/CIMAS – NOAA/AOML/HRD • Session 1: TROPICS — Breakout Lead: William Blackwell • Session 2: CYGNSS — Breakout Lead: Christopher Ruf
3:45p – 4:00p	**----- Afternoon Break (Attendees reconvene in main auditorium) -----**
4:00p – 4:45p	Reconvene/Report out from breakout groups (15 min/each) Open Discussion of Actionable Outcomes and Closing Discussion **Session Chairs/Moderators: Christopher Ruf & William Blackwell**
4:45p	Adjourn Meeting
5:00p	UM shuttle departs UM Marine Campus for Homewood Suites & Hilton Garden Inn

Appendix C – Attendee List

Akin	Steven	University of Miami/RSMAS
Al-Khaldi	Mohammad	The Ohio State University
Alvey	Trey	University of Miami/CIMAS
Apodaka	Karina	Spire Global
Atlas	Bob	Director Emeritus NOAA/AOML
Belabbes	Samir	United Nations Satellite Centre (UNOSAT)
Beven	Jack	NOAA/NWS/National Hurricane Center
Blackwell	Bill	MIT Lincoln Laboratory
Brakenridge	G. Robert	University of Colorado
Braun	Scott	NASA Goddard Space Flight Center
Bucci	Lisa	NOAA/NWS/National Hurricane Center
Campbell	James	University of Southern California
Chew	Clara	Muon Space
Chirokova	Galina	Colorado State University/CIRA
Crespo	Juan	UCLA/Jet Propulsion Laboratory
Dahl	Brittany	University of Miami/CIMAS and NOAA/AOML/HRD
Darlow	James	Joint Typhoon Warning Center
Dey	Ipshita	Stanford University
Dunion	Jason	University of Miami/CIMAS and NOAA/AOML/HRD
Duran	Patrick	NASA Marshall Space Flight Center
Englert	Kerri	University of Miami
Green	David	NASA HQ Applied Science
Haddad	Ziad	Jet Propulsion laboratory
Herndon	Derrick	University of Wisconsin-Madison/CIMSS
Hill-Beaton	Lauren	NASA Goddard Space Flight Center/GES DISC
Jaimes de la Cruz	Benjamin	University of Miami
Kidd	Chris	University of Maryland/ESSIC & NASA/GSFC
Kim	Ben	NASA HQ
Kim	Hyun-Sook	NOAA/AOML
Ko	Laura	NOAA/AOML/HRD
Lawton	Quinton	University of Miami
LeRoy	Anita	Univ. of Alabama in Huntsville/NASA SPoRT
Leslie	Vincent	MIT Lincoln Laboratory
Majumdar	Sharan	University of Miami
Maloney	Eric	Colorado State University
Marchand	Max	Tomorrow.io
Matthews	Cameron	Muon Space
McDonald	Kyle	The City College of New York
McKague	Darren	University of Michigan
Morgan	Kristan	NASA Goddard Space Flight Center/GES DISC
Munchak	Joe	Tomorrow.io

Nolan	David	University of Miami
Ordaz	Carlos	City University of New York Graduate Center
Papin	Philippe	NOAA/NWS/National Hurricane Center
Petrie	Steve	Swinburne University of Technology
Po-Chedley	Stephen	Lawrence Livermore National Laboratory
Porter	Greg	Tomorrow.io
Posselt	Derek	Jet Propulsion Laboratory
Pu	Zhaoxia	University of Utah
Roberts	Brent	NASA MSFC
Rogers	Robert	NOAA/AOML/HRD
Ruf	Chris	University of Michigan
Serrano	Francis	University of Miami/CIMAS
Sitkowski	Matthew	The Weather Channel
Soden	Brian	University of Miami
Stevenson	Stephanie	NOAA/NWS/National Hurricane Center
Stripling	Scott	NOAA/NWS/National Hurricane Center
Takahashi	Takuya	University of Miami/RSMAS
Wade	Ryan	University of Alabama in Huntsville/NASA SPoRT
Warnock	April	SRI International
Wilson	Alexis	University of Miami
Yang	John Xun	University of Maryland
Yin	Jifu	University of Maryland
You	Yalei	University of North Carolina Wilmington
Annane	Bachir	University of Miami/CIMAS and NOAA/AOML/HRD
Berndt	Emily	NASA Marshall Space Flight Center
Borderies	Mary	Météo-France
Bormann	Niels	ECMWF
Braun	Jessica	University of Wisconsin-Madison/SSEC
Carreno-Luengo	Hugo	University of Michigan
Chambon	Philippe	Météo-France
Christophersen	Hui	Naval Research Laboratory
Cobb	Alison	Scripps Institution of Oceanography, UCSD
Corbosiero	Kristen	University at Albany
De Chiara	Giovanna	ECMWF
Dellaripa	Emily M. Riley	Colorado State University
DeMaria	Mark	Colorado State University/CIRA
Fayne	Jessica	University of Michigan
Gao	Cong	Shanghai Jiao Tong University
Garcia-Rivera	Jose M.	NOAA/NESDIS
Garrison	James	Purdue University
Gramer	Lewis J	University of Miami/CIMAS and NOAA/AOML/HRD
Greenwald	Tom	University of Wisconsin-Madison
Griffin-Elliott	Thia Elinor	NOAA/OAR/AOML

Guzman Rey	Oscar F	Florida International University
Hakimdavar	Raha	Zyon Space
Hawkins	Jeff	University of Wisconsin-Madison/CIMSS
Helms	Charles	University of Maryland, College Park and NASA GSFC
Hossen	Jakir	NOAA/AOML/Hurricane Research Division
Hrpcek	Kevin	University of Wisconsin-Madison
Hu	Chih-Chi	Colorado State University
Iturbide Sanchez	Flavio	NOAA
Jayaluxmi	Indu	Indian Institute of Technology Bombay
Johnson	Nicholas E	University at Albany
Kanemaru	Kaya	National Institute of Information and Communications Technology
Kim	Min-Jeong	NOAA/NESDIS/STAR/Riverside Tech Inc
Kulkarni	Pallavi	Indian Institute of Technology Bombay
Kulkarni	Sayali	University of Virginia
Kwon	In-Hyuk	KIAPS
Landsea	Christopher	National Hurricane Center
Lee	Sihye	Korea Institute of Atmospheric Prediction Systems
Lingo	Francesca	City College of New York Graduate Center
Liu	Chuntao	Texas A&M Corpus Christi
Liu	Zhi	University of Oklahoma
Marks	Frank	NOAA/AOML/Hurricane Research Division
Melebari	Amer	University of Southern Califronia
Melendez	Daniel	NOAA/IMCO
Morgan	Emily	NOAA/NESDIS/STAR
Murillo	Shirley	NOAA/OAR/AOML
Musgrave	Kate	Colorado State University/CIRA
Niyogi	Dev	University of Texas at Austin
Okamoto	Kozo	Japan Meteorological Agency/MRI
Portier	Andrea	NASA/SSAI
Pujiana	Kandaga	University of Miami/CIMAS
Roberts	Dave	NOAA/NWS/National Hurricane Center
Salih	Wiam	Mohammed VI Polytechnic University/IWRI
Setti Jr.	Paulo T.	University of Luxembourg
Sharma	Ajay	Indian Institute of Technology Bombay
Sippel	Jason	NOAA/AOML/HRD
Srinivasan	Margaret	Jet Propulsion Laboratory
Stahl	Holly	NOAA/AOML
Surratt	Melinda	NRL Monterey
Sutton	Jessica	GSFC/UMBC
Tabibi	Sajad	University of Luxembourg
Talukdar	Sasanka	National Institute of Technology Rourkela, India
Tiwari	Alka	Purdue University
Tsontos	Vardis	Jet Propulsion Laboratory

Velden	Chris	University of Wisconsin-Madison/CIMMS
Wang	Tianlin	The Ohio State University
Wei	Jennifer	NASA GSFC
Wen	Yixin Berry	University of Florida
Whitaker	Justin	NASA Postdoctoral Program (NASA MSFC)
Wu	Shun-Nan	University of Oklahoma
Zhang	Zhen	University of Maryland

Table 2. List of workshop attendees.

Appendix D – Breakout and Panel Discussion Session Questions

Breakouts 1-4

1. How do you and your organization used CYGNSS and TROPICS data (or how do you anticipate using these data?)
2. Do you find any other remote sensing products to be particularly helpful in interpreting CYGNSS or TROPICS data for your application?
3. Do you foresee any additional capabilities you or your organization would like to develop or see developed from CYGNSS and TROPICS data?
4. What technical or data needs does your organization need to integrate CYGNSS or TROPICS data into your workflow?
5. What additional CYGNSS / TROPICS products do you need or what gaps need to be filled to assist in your decision-making process? What are your most significant challenges in your decision-making?
6. What existing products would you like to use, but have not yet used due to existing barriers? What are those barriers?
7. What is your organization's process for integrating new data into your workflow or data visualization system?
8. How can the CYGNSS and TROPICS teams lower these barriers to integration?

Breakout 5

1. What additional related products could be produced from a constellation of smallsats that isn't being produced by CYGNSS or TROPICS?
2. What are the barriers to providing value-added products from NASA data to end-users?
3. What direction is the private sector moving toward with respect to the integration of satellite remote sensing data into value-added products for end-users? What do end users really want?
4. What areas would private sector partners like to see NASA move into to support end-users and decision makers?
5. What are the most important issues or limitations with current NASA remote sensing platforms?
6. What technologies would private sector partners like to see NASA invest in to support end users?
7. What potential capabilities can private-sector developers provide for enhanced latency, continuity, and long-term reliability?
8. What are the synergies between government cal/val and sensor development experts and private-sector partners?

Synergy with other Satellite Missions Panel Discussion

1. In what ways can you see your mission's research and applications communities benefiting from CYGNSS and/or TROPICS data?
2. Are there any current or upcoming data products from your mission that you think could benefit the CYGNSS and TROPICS applications communities?
3. Do you see any ways that data from your mission can be combined with data from CYGNSS and/or TROPICS to create value-added products?
4. Are there any barriers to integrating products between your mission and the CYGNSS and TROPICS missions? How can those barriers be lowered?
5. Do your applications communities express any persistent needs that could be partially addressed by CYGNSS or TROPICS data?
6. How has your mission engaged the private sector for applications needs, and do you see any ways CYGNSS and TROPICS can engage those private sector partners?

Actionable Outcomes on Tropical Cyclones Panel Discussion

1. How has your organization included TROPICS or CYGNSS in your product development, workflow, or decision-making process?
2. What future products do you intend to use when they become available, and are there any additional products you would like to see developed?
3. What types of data products should be prioritized in future satellite missions that would better serve your needs?
4. Are there any barriers to integrating TROPICS or CYGNSS products into your workflow/decision-support systems? How can those barriers be lowered?
5. How can other satellite data be integrated with CYGNSS/TROPICS data to produce value-added products to address persistent needs?
6. What is the requirement on the data uncertainty and error thresholds for data assimilation or modeling?

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