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The NASA Cyclone Global Navigation Satellite System SmallSat Constellation

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ABSTRACT

The NASA Cyclone Global Navigation Satellite System (CYGNSS) mission consists of a constellation of eight microsatellites launched on 15 December 2016 into a common circular orbit at ~525 km altitude and 35 deg inclination. Each observatory carries a four channel bistatic radar receiver to measure GPS signals scattered by the Earth surface. Over ocean, near-surface wind speed, air-sea latent and sensible heat flux, and ocean microplastic concentration are derived from the measurements. Over land, near-surface soil moisture and inland water bodies extent are derived. The measurements penetrate through all levels of precipitation and most vegetation due to the 19 cm wavelength of GPS L1 signals. The sampling produced by the constellation makes possible the reliable detection of short time scale weather events such as flood inundation dynamics immediately after a tropical cyclone landfall and rapid soil moisture dry down immediately after major precipitation events. The sun-asynchronous nature of the CYGNSS orbit also supports full sampling of the diurnal cycle of hydrological dynamics within a short period of time. Summaries are presented of engineering and science highlights of the CYGNSS mission, with particular emphasis on those aspects most directly enabled by the use of a constellation of SmallSats.

INTRODUCTION

The Cyclone Global Navigation Satellite System (CYGNSS) constellation of eight satellites was successfully launched in December 2016 into a low inclination (tropical) Earth orbit [1]. Each satellite carries a four-channel bi-static radar receiver which measures signals transmitted by Global Positioning System (GPS) satellites and scattered back into space by the Earth surface [2]. Over the ocean, surface roughness, near-surface wind speed and air-sea latent heat flux are estimated from the direct measurements of surface scattering cross section [3, 4]. Over the land, estimates of near-surface soil moisture and imaging of flood inundation are also possible [5, 6]. The measurements are able to penetrate through all levels of precipitation due to the low microwave frequency at which GPS operates [7]. The spatial density and revisit time of sampling resulting from the number of satellites in the constellation and from their continuous data-taking operation makes possible the reliable detection of tropical cyclone intensification and the resolving of diurnal cycles of tropical winds and soil moisture variability [8]. Engineering commissioning of the constellation was completed in March 2017 and the mission is currently in its science operations phase.

CYGNSS is the first NASA Earth Science mission to use a constellation of SmallSats. The constellation consists of 8 spacecraft distributed around a common circular orbit at 520 km altitude and 35o inclination. The mean revisit time of the full constellation is ~7 hours [9]. An illustration of the coverage provided after one orbit and one full day are shown in Figure 1.

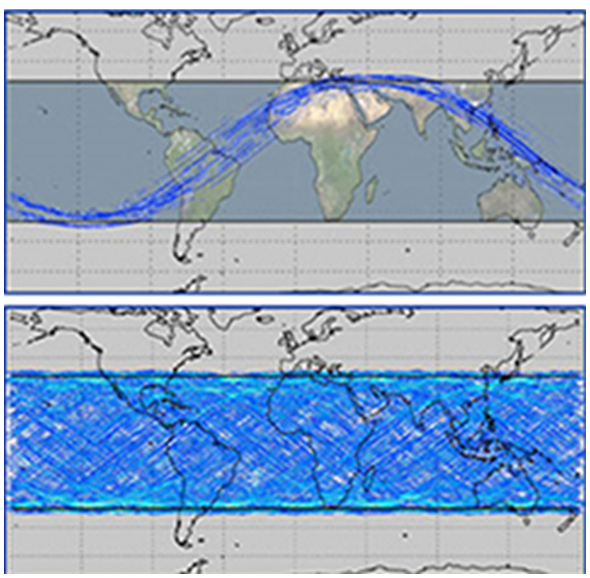

Figure 1: Spatial coverage by the full CYGNSS constellation of 8 spacecraft after one orbit, or 95 min [top], and after 24 hours [bottom].

The Level 1 engineering data products include scattered signal power and SNR and the bistatic radar cross section of the surface. Level 2 science data products have been developed for near surface (10 m referenced) ocean wind speed, ocean surface roughness (via the mean square slope statistic) and latent heat flux. Level 3 gridded versions of the L2 products are also available [10]. A set of Level 4 products have also been developed specifically for direct tropical cyclone overpasses. These include the storm intensity (peak sustained winds) and size (radius of maximum winds), its extent (34, 50 and 64 knot wind radii), and its integrated kinetic energy. Assimilation of CYGNSS L2 wind speed data into the HWRF hurricane weather prediction model has also been studied, and their impact on forecast skill demonstrated [11, 12]. Level 2 science data products over land related to near-surface volumetric soil moisture content and flood inundation extent are also in development [5, 6].

SCIENTIFIC RESULTS OVER OCEAN

One scientific benefit of an eight spacecraft constellation is the frequency with which tropical cyclones can be sampled throughout their life cycle. This is illustrated in Figure 2, which shows when and how well CYGNSS sampled every major storm (Category 3 or greater) between 2018 and 2020. In the figure, the red lines are the track of each storm throughout its life cycle, the dots are where there was a CYGNSS overpass, and the color of the dot indicates the density of samples within the inner core of the storm.

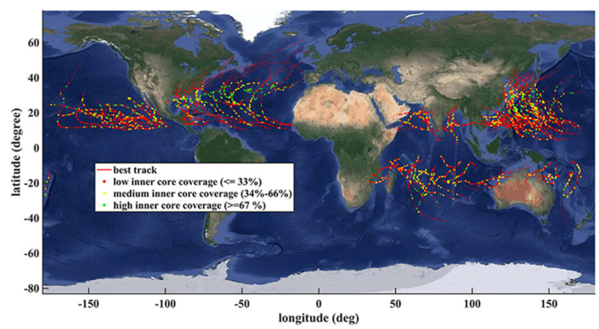

Figure 2: CYGNSS overpasses of all major storms during 2018-2020. Every storm is sampled between one and three times a day, which helps monitor its development and capture sudden changes such as rapid intensification.

Ocean Surface Wind Speed

CYGNSS produces several different ocean surface wind speed products [13, 14]. The product most commonly used one for global scientific investigations is its Science Data Record (SDR) Fully Developed Seas 10 meter–referenced neutral stability-equivalent wind speed (FDS). The current public release version (v3.1) is available at the NASA PO.DAAC <https://doi.org/10.5067/CYGNS-L2X31>. Its performance is illustrated in Figure 3, which shows the root-mean-square difference (RMSD) between it and co-located ERA5 winds for a one year population of matchups. The RMSD is below 2 m/s for wind speeds below ~10 m/s and increases at higher winds due to a gradually diminishing sensitivity. Performance is not significantly impacted by variations in the incidence angle.

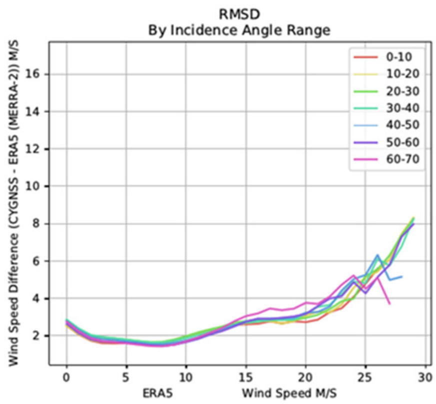

Figure 3: Root-mean-square difference (RMSD) between CYGNSS SDR FDS v3.1 wind speed and co-located ERA5 10 m referenced neutral stability wind speed for all of calendar year 2019. Samples partitioned by incidence angle.

Hurricane Prediction and Data Assimilation

With its seven-hour revisit time, CYGNSS observations of ocean surface winds in the hurricane environment and inner core region facilitate both hurricane weather research and forecasting studies. CYGNSS wind products have been assimilated into various research and operational numerical weather prediction (NWP) models to demonstrate their usefulness in improving hurricane forecasting. Studies using the National Oceanic and Atmospheric Administration's (NOAA) National Centers for Environmental Prediction (NCEP)'s Hurricane Weather Research and Forecasting (HWRF) regional model and a three-dimensional, hybrid ensemble-variational data-assimilation system have suggested that assimilation of the CYGNSS data results in improved hurricane track and intensity simulations of Hurricanes Harvey and Irma, both of which occurred in 2017. The improvements in the track and intensity forecasts are the result of improved representation of surface wind fields, hurricane inner-core structure—see Figure 4—and surface fluxes (not shown). These results indicate that CYGNSS Level-2 (L2) retrieved-wind data products could be a valuable data source for operational uses to complement available routine observations.

An alternative approach has been developed to directly assimilate CYGNSS L1 engineering data, rather than L2 retrieved wind speed, using a two-dimensional variational analysis method. In addition to data assimilation efforts, CYGNSS data products are a valuable means to build a database for tropical cyclones (TC). Its L3 Storm Centric Gridded product is derived from the L2 retrieved ocean wind products. It determines wind speed from aggregated measurements made by the entire CYGNSS constellation. This data product is intended for historical storm analysis.

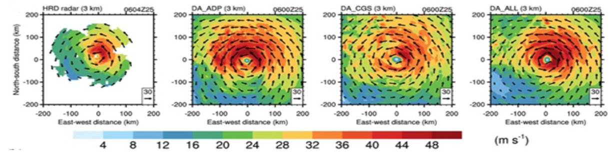

Figure 4: HRD radar analysis at 3 and 4 km height wind speeds (shaded contours) and vectors of Hurricane Harvey at 0600 UTC August 25, 2021 compared to three assimilation experiments: DA_AD, conventional data only [second column], DA_CGS, CYGNSS data only [third column], and DA_ALL, both conventional and CYGNSS data [fourth column].

Heat Flux at the Air/Sea Interface

Latent and sensible heat fluxes (LHF and SHF) at the ocean surface LHF and SHF are functions of wind speed, as well as air–sea humidity and temperature differences, respectively. The CYGNSS wind speed product, combined with reanalysis data for the thermodynamic variables, are used to produce LHF and SHF data products [4, 15]. The CYGNSS LHF and SHF products are used in recent Madden–Julian Oscillation (MJO) convection and extratropical cyclone (ETC) analyses. Figure 5 shows CYGNSS wind speed and flux observations of a rapidly developing ETC. CYGNSS is able to observe the equatorward side of the system, which contains the strongest winds and air-sea temperature differences, leading to strong LHF and SHF values. These observations provide details about the impact of the heat fluxes on ETC genesis and evolution.

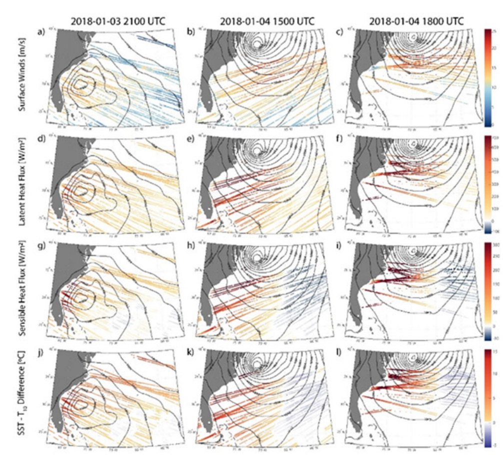

Figure 5: CYGNSS observations of surface winds (m/s) [first row], LHF (W/m2) [second row], and SHF (W/m2) [third row], along with temperature differences (ºC) [fourth row] between the sea surface (SST) and 10 m from collocated MERRA-2 for an ETC in the western Atlantic Ocean at: 2100 Jan 3 [first column], 1500 Jan 4 [second column], and 1800 Jan 4 2018 [third column].

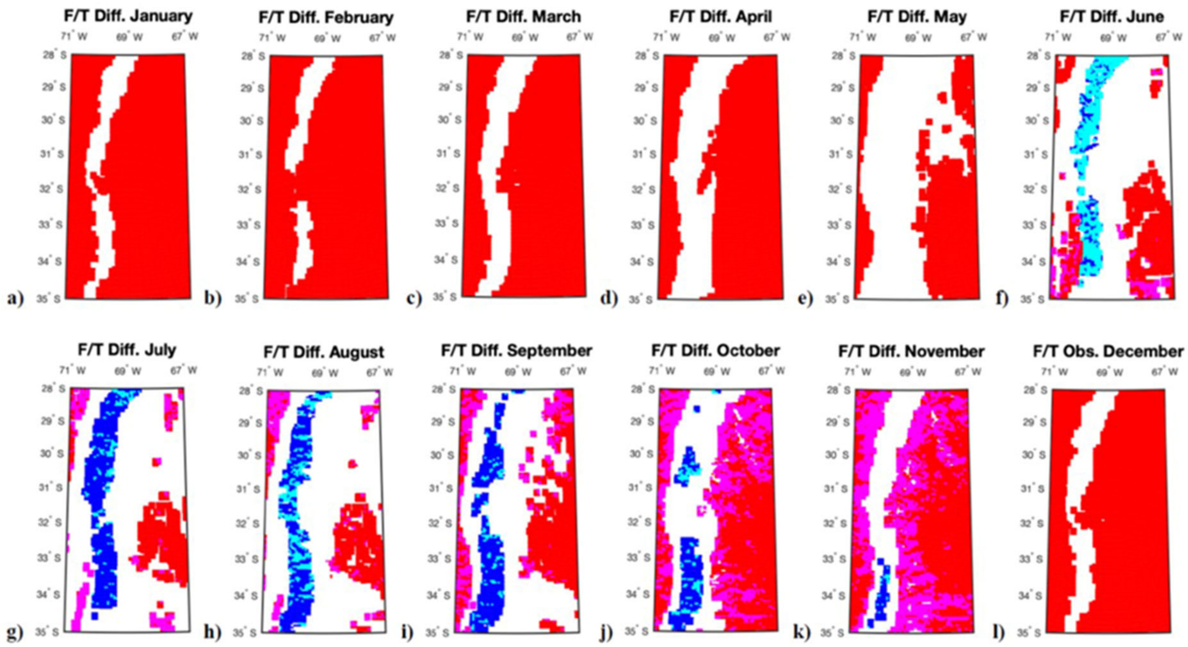

Figure 6: Annual freeze/thaw transitions in the Andes Mountains over the course of one year. The transition from thawed to frozen state in winter along the highest altitude ridge of the Andes is easily distinguishable.

SCIENTIFIC RESULTS OVER LAND

The CYGNSS constellation of satellites operate with a 100% duty cycle, making scientific observations continuously over both ocean and land. Reflections of GPS signals from land surfaces also contain geophysical information which can be interpreted for scientific uses.

Soil Moisture

CYGNSS GNSS reflectivity is dependent on the dielectric constant of the ground surface, which in turn is sensitive to near-surface soil moisture content. An initial soil moisture product was released by the University Corporation for Atmospheric Research (UCAR) on a 36 km grid at 6 and 24 hour intervals [5]. The product is derived from co-located matchups between CYGNSS reflectivity and soil moisture retrievals by NASA's Soil Moisture Active Passive (SMAP) radiometer. The product has been validated using over 200 in situ soil moisture probes from 5 networks, with an overall unbiased root mean square error of 0.047 cm3/cm3. Several newer soil moisture products are currently in development.

Freeze/Thaw Detection

Changes in CYGNSS reflectivity are also able to detect transitions in the Freeze/Thaw state of land surfaces [16]. This capability has been applied to observations over an area in South America covering the Andes Mountains and the Argentinian Pampas, with results shown in Figure 6. The results show that CYGNSS is responsive to changes in surface permittivity, which is then leveraged to detect transitions of freeze-thaw surface state. The CYGNSS observations were shown to have superior spatiotemporal sampling as compared to previous missions. The method used in this study was based on a Seasonal-Threshold Algorithm (STA) and validated using surface temperature data from the fifth-generation European Centre for Medium-range Weather Forecasts (ECMWF) Reanalysis (ERA5) land numerical reanalysis model.

Inland Water Body Extent

The surface of inland water bodies tends to be smooth enough to reliably support coherent reflection by GPS signals at a wavelength of 19 cm. As a result, CYGNSS measurements of these reflections are both significantly stronger than ocean or land reflections and they have a significantly smaller horizontal resolution. This has led to a number of studies related to the imaging of inland water body extent [17–20]. Notably, this imaging capability is not significantly degraded by the presence of precipitation or of a dense vegetation canopy, both of which tend to degrade or make impossible the imaging of inland water body extent by other types of spaceborne sensors.

One example of the inland water body imaging capability of CYGNSS is shown in Figure 7 for measurements over the Amazon Basin.

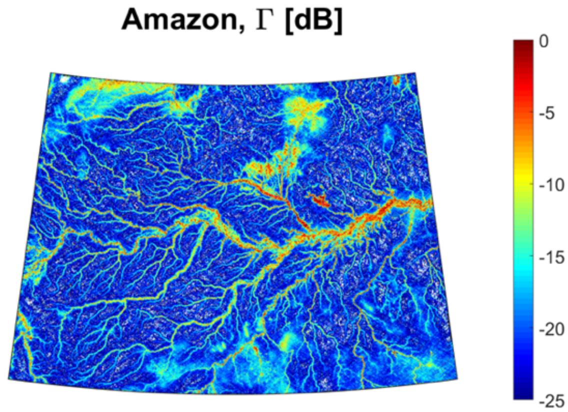

Figure 7: Image of CYGNSS reflectivity over the Amazon, illustrating the high spatial resolution capability as well as the ability to penetrate through dense vegetation canopies.

SUMMARY

Global Navigation Satellite System Reflectometry (GNSS-R) is a relatively new remote sensing method which has demonstrated great promise as a viable, high quality source of geophysical information about the Earth surface. GNSS-R measurements made by the NASA CYGNSS constellation of 8 microsatellites are being used to support a wide variety of science applications. Measurements made over the ocean are directly affected by surface roughness, which is itself affected by the near-surface wind speed. CYGNSS ocean measurements can be used to determine the wind speed. The measurements are not significantly affected by the presence of intervening precipitation and, as a result, it is possible to estimate near-surface winds speeds in the inner core of tropical cyclones where heavy precipitation is commonplace. Wind speed measurements in and near hurricanes have been assimilated into a numerical weather prediction model to demonstrate the improvement in forecast skill that results. The wind speed can also be used to estimate latent and sensible heat fluxes at the air/sea interface by combining them with ancillary thermodynamic conditions. Over land, GNSS-R reflections from soil are sensitive to the dielectric properties of the surface. In its thawed state, a soil's dielectric properties are strongly dependent on its volumetric soil moisture content, and soil moisture can thus be estimated from the CYGNSS observations. The transition of soil from a frozen to thawed state also has a significant impact on its dielectric constant, which allows CYGNSS to detect the freeze/thaw state of the surface. Finally, the presence of inland water bodies support strong coherent reflections of GNSS signals, from which it is possible to product water extent maps with high spatial resolution. For all of these measurements, the presence of eight satellites distributed around the Earth enables frequent temporal sampling and short revisit times over a region. Over the ocean, this is useful to resolve sudden changes in ocean winds, for example due to the rapid intensification of a tropical cyclone. Over land, sudden changes in inland water extent, for example due to flood inundation, can be readily imaged.

All 8 spacecraft in the CYGNSS constellation are still performing nominally after 5+ years in orbit, making continuous observations and producing a range of engineering and science data products for the scientific research community.

Acknowledgments

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References

1. Ruf, C. S., R. Atlas, P. S. Chang, M. P. Clarizia, J. L. Garrison, S. Gleason, S. J. Katzberg, Z. Jelenak, J. T. Johnson, S. J. Majumdar, A. O'Brien, D. J. Posselt, A. J. Ridley, R. J. Rose, V. U. Zavorotny, "New Ocean Winds Satellite Mission to Probe Hurricanes and Tropical Convection," Bull. Amer. Meteor. Soc., doi:10.1175/BAMS-D-14-00218.1, pp385-395, Mar 2016.

2. Gleason, S., C. Ruf, M. P. Clarizia, A. O'Brien, "Calibration and Unwrapping of the Normalized Scattering Cross Section for the Cyclone Global Navigation Satellite System (CYGNSS)," IEEE Trans. Geosci. Remote Sens., 54(5), 2495-2509, doi:10.1109/TGRS.2015.2502245, 2016.

3. Clarizia, M. P., and C. S. Ruf, "Wind Speed Retrieval Algorithm for the Cyclone Global Navigation Satellite System (CYGNSS) Mission," IEEE Trans Geosci. Remote Sens., 54(8), doi:10.1109/TGRS.2016.2541343, Aug. 2016.

4. Crespo, J.A., D.J. Posselt, S. Asharaf, "CYGNSS Surface Heat Flux Product Development," Remote Sens., 11, 2294, doi: 10.3390/rs11192294, 2019.

5. Chew, C. C., E. E. Small, "Soil Moisture Sensing Using Spaceborne GNSS Reflections: Comparison of CYGNSS Reflectivity to SMAP Soil Moisture," Geophys Res. Ltrs., 45(9), 4049-4057, doi: 10.1029/2018GL077905, 2018.

6. Chew, C., J. T. Reader, E. Small, "CYGNSS data map flood inundation during the 2017 Atlantic hurricane season," Scientific Reports, doi: 10.1038/s41598-018-27673-3, 2018.
7. Balasubramaniam, R., C. Ruf, "Characterization of Rain Impact on L-Band GNSS-R Ocean Surface Measurements," Remote Sensing of Environment, 239(15), doi: 10.1016/j.rse.2019.111607, 2020.
8. Ruf, C. S., S. Asharaf, R. Balasubramaniam, S. Gleason, T. Lang, D. McKague, D. Twigg, D. Waliser, "In-Orbit Performance of the Constellation of CYGNSS Hurricane Satellites," Bull. Amer. Meteor. Soc., 2009-2023, doi: 10.1175/BAMS-D-18-0337.1, 2019.
9. Ruf, C.S., C. Chew, T. Lang, M.G. Morris, K. Nave, A. Ridley, R. Balasubramaniam, "A New Paradigm in Earth Environmental Monitoring with the CYGNSS Small Satellite Constellation," Scientific Reports, doi: 10.1038/s41598-018-27127-4, 2018.
10. Ruf, C., P. Chang, M.P. Clarizia, S. Gleason, Z. Jelenak, J. Murray, M. Morris, S. Musko, D. Posselt, D. Provost, D. Starkenburg, V. Zavorotny, "CYGNSS Handbook," Ann Arbor, MI, Michigan Pub., ISBN 978-1-60785-380-0, 154 pp, 1 Apr 2016.
11. Cui, Z., Z. Pu, V. Tallapragada, R. Atlas, C. S. Ruf, "A Preliminary Impact Study of CYGNSS Ocean Surface Wind Speeds on Numerical Simulations of Hurricanes," Geophys. Res. Ltrs., doi: 10.1029/2019GL082236, 2019.
12. Mueller, M, B. Annane, M. Leidner, L. Cucurull, "Impact of CYGNSS-derived Winds on Tropical Cyclone Forecasts in a Global and Regional Model, "Monthly Weather Review, DOI:10.1175/MWR-D-21-0094.1, 2021.
13. Ruf, C., R. Balasubramaniam, "Development of the CYGNSS Geophysical Model Function for Wind Speed," IEEE J. Sel. Topics Appl. Earth Obs. Remote Sens., doi: 10.1109/JSTARS.2018.2833075, 2018.
14. Pascual, D., M. P. Clarizia, C. S. Ruf, "Improved CYGNSS Wind Speed Retrieval Using Significant Wave Height Correction," Remote Sensing, doi: 10.3390/rs13214313, 2021.
15. Crespo, J.A., D.J. Posselt, C.M. Naud, C.D. Bussy-Virat, "Assessing CYGNSS's Potential to Observe Extratropical Fronts and Cyclones," J. Appl. Meteorol. Climatol., 56, 2027-2034, doi: 10.1175/JAMC-D-17-0050.1, 2017
16. Carreno Luengo, H., C. S. Ruf, "Retrieving Freeze/Thaw Surface State from CYGNSS Measurements," IEEE Trans. Geosci. Remote Sens., doi: 10.1109/TGRS.2021.3120932, 2021.
17. Warnock, A., C. Ruf, "Response to Variations in River Flowrate by a Spaceborne GNSS-R River Width Estimator," Remote Sens., 11(20), 2450, doi: 10.3390/rs11202450, 2019.
18. Gerlein-Safdi, C., C. S. Ruf, "A CYGNSS-Based Algorithm for the Detection of Inland Waterbodies," Geophys. Res. Ltrs., doi: 10.1029/2019GL085134, 2019.
19. Gerlein-Safdi, C., A. A. Bloom, G. Plant, E. Kort, C. S. Ruf, "Improving representation of tropical wetland methane emissions with CYGNSS inundation maps," Global Biogeochemical Cycles, doi: 10.1029/2020GB006890, 2021.
20. Morris, M, C. Chew, J. T. Reager, R. Shaw, C. Zuffada, "A novel approach to monitoring wetland dynamics using CYGNSS: Everglades case study," Remote Sens. Environ., doi: 10.1016/j.rse.2019.111417, 2019.