CYCLONE GLOBAL NAVIGATION SATELLITE SYSTEM (CYGNSS)

Algorithm Theoretical Basis Document
Level 1 & 2 Trackwise Corrected Climate Data Record

UM Doc. No.	**148-0389**
SwRI Doc. No.	**N/A**
Revision	**Rev 1**
Date	**26 March 2020**
Contract	**NNL13AQ00C**

Algorithm Theoretical Basis Documents (ATBDs) provide the physical and mathematical descriptions of the algorithms used in the generation of science data products. The ATBDs include a description of variance and uncertainty estimates and considerations of calibration and validation, exception control and diagnostics. Internal and external data flows are also described.

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REVISION NOTICE

Document Revision History		
Revision	**Date**	**Changes**
PRE-RELEASE DRAFT	25 Nov 2019	n/a
INITIAL RELEASE	6 Dec 2019	
REVISION 1	26 Mar 2020	Updated for changes in data filtering and QC; SPRL document assigned.

Table of Contents

1 Mission Summary

CYGNSS is a spaceborne earth observation mission designed to collect measurements of ocean surface winds through variations in the direct vs reflected Global Positioning System (GPS) signals. The observatory portion of this mission consists of a constellation of eight satellites that were launched into circular orbits at ~520 km altitude and 35^o inclination on 15 December 2016. The CYGNSS mission will provide new information about ocean surface winds in Tropical Cyclones (TC), enabling advances in the knowledge of TC genesis and intensification.

The goal of CYGNSS is to understand the coupling between ocean surface properties, moist atmospheric thermodynamics, radiation, and convective dynamics in the inner core of TCs. This directly supports the NASA strategic objective to enable improved predictive capability for weather and extreme weather events. Near-surface winds are major contributors to and indicators of momentum and energy fluxes at the air/sea interface. Understanding the coupling between the surface winds and the moist atmosphere within the TC inner core is key to properly modeling and forecasting its genesis and intensification. Of particular interest is the lack of significant improvement in storm intensity forecasts over the past two decades, relative to forecasts of storm track. Advances in track forecast have resulted in large part from the improvements that have been made in observations and modeling of the mesoscale and synoptic environment surrounding a TC. The CYGNSS team hypothesizes that the lack of an accompanying improvement in intensity forecasting is largely due to a lack of observations and proper modeling of the TC inner core. The inadequacy in observations results from two causes:

1. Much of the inner core ocean surface is obscured from conventional remote sensing instruments by intense precipitation in the eye wall and inner rain bands.

2. The rapidly evolving genesis and intensification stages of the TC life cycle are poorly sampled by conventional polar-orbiting, wide-swath imagers.

CYGNSS addresses these two limitations by combining the all-weather performance of GPS based bistatic scatterometry with the spatial and temporal sampling properties of a constellation of observatories. The constellation consists of individual GPS bistatic radar receivers flown on eight microsatellites. This provides the ability to measure the ocean surface winds with high temporal resolution and spatial coverage under all precipitating conditions, up to and including those experienced in the hurricane eyewall.

The baseline CYGNSS instrument is a Delay Doppler Mapping Instrument (DDMI) that resides on each observatory in the constellation. The DDMI is a Global Navigation Satellite System (GNSS) Receiver-Remote sensing Instrument. Each instrument will use two nadir pointing antennas for collecting reflected GPS signals and a zenith facing antenna to collect direct GPS signals. The GPS transmission frequency enables the instrument to make surface scattering observations during most precipitation conditions.

2 Trackwise Correction Algorithm

2.1 Trackwise Correction Motivation

Determination of the normalized bistatic radar cross section (NBRCS) of a scattering surface from CYGNSS measurements of received power requires that the effective instantaneous radiative power (EIRP) of the L1 signal transmitted by the GPS satellite in the direction of the specular reflection point be known [Gleason et al., 2016]. EIRP is the product of the GPS transmit power and transmit antenna gain in the direction of the specular reflection point. Since NBRCS is used to estimate ocean surface wind speed [Clarizia and Ruf, 2016], retrieval of wind speed also requires knowledge of the EIRP. The Level 1 calibration algorithm converts raw received power into calibrated NBRCS. The L1 algorithm uses GPS transmit antenna gain patterns provided by the GPS manufacturers. The power transmitted by each GPS satellite was initially determined from measurements made by an accurately calibrated ground based GPS power monitor [Wang et al., 2018]. A single value for transmit power was determined for each GPS satellite from measurements made over many days. This implicitly assumes that the power transmitted by each GPS satellite does not vary over time. This approach is used for L1 science data products version 1.0, 1.1, 2.0 and 2.1, and for the corresponding L2 and L3 products derived from them. Analysis of GPS power monitor measurements since CYGNSS launch has shown that GPS transmit power variations have in fact occurred, sometimes suddenly for short periods of time, and sometimes more gradually over long time periods. The L1 trackwise correction algorithm is intended to correct for those variations.

The Leading Edge Slope (LES) Level 1 data product is derived from calibrated measurements of the scattering cross section as the slope of the leading edge of the delay waveform at the specular point [Clarizia and Ruf, 2016]. LES calibration similarly requires knowledge of the GPS EIRP and the trackwise correction algorithm is also applied to it.

CYGNSS data acquired prior to 1 Aug 2018 were measured with the flight GPS navigation receiver commanded to operate in automatic gain control (AGC) mode, which automatically adjusts receiver gain so the strength of direct (not scattered) signals received from the constellation of GPS satellites is restricted to a narrow dynamic range prior to signal processing. AGC mode is intended primarily to compensate for expected variations in received signal strength due to changes in the distance between transmitter and receiver and in a number of other characteristics of the signal propagation. It also inadvertently compensates for changes in the GPS transmit power. The AGC mode was disabled on all eight observatories in August 2018 in order to enable the use of the received direct signal strength to monitor the GPS transmit power level, determine the GPS EIRP, and use that information to better calibrate the L1 NBRCS and LES. L1 and higher data products beginning with version 3.0 will use the new real-time GPS EIRP monitoring capability to correct for its variations in the L1 calibration algorithm. The trackwise correction algorithm is intended to mitigate the effect of variations in GPS transmit power on the NBRCS and LES calibration for measurements made prior to August 2018. The data products produced with it are considered Climate Data Records (CDRs) in the sense that they are reprocessed products which rely on the use of ancillary reanalysis products (MERRA-2 in this case) to improve the calibration and represent a “best effort” attempt to produce data products with reliable, long term calibration stability.

2.2 Trackwise Correction Overview

CYGNSS surface scattering measurements are made by, first, identifying a GPS satellite for which the specular reflection point on the surface between it and the CYGNSS satellite lies in the CYGNSS receive antenna pattern, and then processing the scattered signal received using matched filter correlation with the unique pseudo-random number (PRN) code used to modulate the transmissions from each GPS satellite [Gleason and Gebre-Egziabher, 2009]. The matched filter correlation includes a final incoherent integration time of 1 second, and an output measurement is produced once every one-half or one second that is proportional to the strength of the scattered signal. This is the Level 0 CYGNSS data that are converted to NBRCS and LES. A CYGNSS “track” is defined as the continuous measurements made while a single CYGNSS observatory processes scattered signals from a single GPS PRN. The length of the track is determined by the time over which its specular reflection point stays within the CYGNSS receive antenna mainbeam. In practice tracks last between 10s of seconds and > 1000 seconds, with an average length of ~650 seconds. Given the orbit velocities involved, this corresponds to an average track length of ~3000 km.

The trackwise correction algorithm acts, as its name implies, on individual tracks. All ocean samples in a track are used. Each sample is matched to an independent estimate of the ocean surface wind speed. The independent wind product is NASA's Modern-Era Retrospective analysis for Research and Applications version 2 (MERRA-2). It uses Goddard Earth Sciences Data and Information Services Center's (GES DISC) inst1_2d_asm_Nx V5.12.4: a 2d, 1-Hourly, Instantaneous, Assimilation, Single-Level Diagnostics dataset providing ocean surface vector winds (u,v) on a global 0.5 deg x 0.625 deg grid. Co-located MERRA-2 wind speeds are computed as $(u^2+v^2)^{0.5}$. More details about this data product can be found at: https://disc.gsfc.nasa.gov/datasets/M2I1NXASM_V5.12.4/summary?keywords=%22MERRA-2%22. The MERRA-2 wind speed is applied in reverse to the geophysical model functions that are normally used by CYGNSS to infer wind speed from measurements of NBRCS and LES [Ruf and Balasubramaniam, 2018]. In this case, NBRCS and LES are estimated from wind speed. For each track, this produces a population of observed (by CYGNSS) and modeled (from MERRA-2) values. A scale difference between them can be explained by a change in the transmit power of the GPS PRN that is responsible for the specular reflection. An offset difference between them can be explained by a change in the noise floor of the received signal, which is sensitive to the sum of transmit powers of all visible GPS satellites. The trackwise correction algorithm consists of applying a linear regression to the two populations and applying its regression coefficients to the CYGNSS observations. Deviations of the slope of the regression from unity can be related to deviations of the true GPS PRN transmit power from the mean value used in the L1 calibration algorithm. In practice, this correction can also mitigate other scale errors in the L1 algorithm. Likewise, the y-intercept (offset) correction will mitigate multiple sources of change in the noise floor, in addition to changes in the transmit power of the overall GPS constellation.

3 Trackwise Correction Algorithm Description

3.1 Input Data Description

A complete track of observations ($NBRCS_{obs}$) is used for each trackwise correction. (A track is defined as a continuous time series of samples using the same GPS PRN and CYGNSS observatory.) All samples in the track that are over ocean are matched up with the closest (in time and space) wind speed value provided by MERRA-2. Model values for the NBRCS ($NBRCS_{mod}$) and LES (LES_{mod}) are derived from the MERRA-2 wind speed using the L2 wind speed retrieval algorithm GMFs that tabulate wind speed as a function of NRBCS, LES and incidence angle. The samples are then filtered and the subset satisfying the following conditions is selected:

Filter 1: 1.5 m/s < MERRA-2 wind speed

Filter 2: 2. 0 < $NBRCS_{obs}$ < min(GMF(1.5 m/s), $100m^2/m^2$/¼–chip) or 0 < LES_{obs} < min(GMF(1.5 m/s), 50 m^2/m^2 per ¼–chip)

Filter 1 is intended to remove samples with wind speeds below 1.5 m/s, for which the GMF is considered less reliable because the NBRCS and LES become more sensitive to long wave swell that is not as well correlated with local wind speed. Filter 2 is intended to remove samples that are either non-physical (negative values) or are above the GMF value that corresponds to a wind speed of 1.5 m/s (Note: If NBRCS<100 and LES<50 are always less than GMF(1.5m/s) then 100 and 50 are the upper limits. Either way, both filters are applied in the code.). If fewer than 50*sampling_rate samples are available after these filters are applied, then the track is fatally flagged and CDR wind speeds are not produced, where sampling_rate is heuristically determined for each track using the formula: round(track_length_samples / track_duration_seconds) Note: This implementation scheme is independent of sampling rate which may change in the future and can change track by track even now, say when Full DDM collections take place and the rate goes from 2Hz down to 1Hz. For example, this amounts to tw_num<50 for 1Hz, and tw_num<100 for 2Hz.

3.2 Trackwise Correction Processing

The filtered track of observed and modeled samples is ordered by the modeled values from minimum to maximum. The range of values is subdivided evenly into 10 bins and, for every bin with more than 1/20th of the total number of samples, the samples within the bin are averaged. A linear regression is performed of the average values in each bin, with observations as the independent variable. This version of linear regression is used to better balance the contributions of samples across the full dynamic range of values, since with most tracks the distribution of wind speed samples is highly non-uniform and concentrated near 5-9 m/s.

The linear regression coefficients are then applied to the observation samples, resulting in preliminary trackwise corrected values given by

$$NBRCS_{obs2} = m*NBRCS_{obs} + b \tag{1a}$$

$$LES_{obs2} = m*LES_{obs} + b \tag{1b}$$

where m and b are the regression coefficients.

Outlier samples are identified by examining the difference between model and corrected values. Specifically, a sample is considered an outlier if it satisfies

$$|\mathrm{NBRCS}_{\mathrm{obs2}} - \mathrm{NBRCS}_{\mathrm{mod}}| > 16 + 0.5{*}\mathrm{NBRCS}_{\mathrm{mod}} \tag{2a}$$

$$|\mathrm{LES}_{\mathrm{obs2}} - \mathrm{LES}_{\mathrm{mod}}| > 8 + 0.5{*}\mathrm{LES}_{\mathrm{mod}} \tag{2b}$$

All outliers are removed from the population of filtered samples and the linear regression is repeated with the original filtered samples less the outliers. This is done to reduce the influence of outlier samples on the final trackwise correction. After the second iteration of the linear regression, eqn (1) is then applied to all samples in the track, resulting in the final trackwise correction version of the observations given by

$$NBRCS_{obs\_cor} = m{*}NBRCS_{obs} + b \tag{3a}$$

$$LES_{obs\_cor} = m{*}LES_{obs} + b \tag{3b}$$

where m and b are now the regression coefficients from the second iteration of the linear regression.

3.3. Quality Control Considerations

The trackwise correction is assessed for reliability and confidence using several quality control metrics at Level 1. The outlier test described by eqn. (2) is applied to all samples over ocean, for which modeled values of the L1 observables are available, and all outliers are flagged. Samples over land are not able to be tested in this way. The slope of the linear regression from which the trackwise correction is derived (‘m’ in eqn. (3)) is required to be above -0.01 and below 5. Larger slopes are an indication that the scale error in the observations cannot readily be explained by an error in the assumed GPS EIRP, given its expected range of variability. These cases are flagged with low confidence since the root cause of the scale error is not well understood. In practice, all of these QC tests combined together typically flag ~22% of the ocean samples. This number reduces to 13% if samples fatally flagged for other reasons are excluded.. By comparison, the v2.1 L1 data fatally flag all GPS Block IIF samples flagged as having unreliable calibration due to their large GPS transmit power variability. This amounts to ~39% of all potential v2.1 samples.

Level 2 CDR wind speed estimates are derived from the L1 CDR data using the same retrieval algorithm as is used for regular data production. An additional quality control step at L2 consists of comparisons between the L2 CDR wind speeds derived from the NBRCS and LES observables.

The two wind speeds should generally agree, and large differences between them are an indication that something is wrong with one or the other data sample. Samples are flagged as low confidence if the following conditions are satisfied:

$$|u_{\mathrm{NBRCS}} - u_{\mathrm{LES}}| > 2.5 \text{ m/s} \quad \text{if } u_{\mathrm{MERRA\text{-}2}} < 6 \text{ m/s} \tag{4}$$

$$|u_{\mathrm{NBRCS}} - u_{\mathrm{LES}}| > 2.5{*}|u_{\mathrm{MERRA\text{-}2}} - 5|^{0.5} \text{ m/s} \quad \text{if } u_{\mathrm{MERRA\text{-}2}} > 6 \text{ m/s} \quad .$$

where u_{NBRCS} and u_{LES} are the retrieved L2 CDR wind speeds and $u_{\mathrm{MERRA\text{-}2}}$ is the matchup model wind speed. This QC test removes ~3% of the samples.

3.4. Output Data Product Description

The trackwise corrected Level 1 observables, $NBRCS_{obs\_cor}$ and LES_{obs_cor}, are included in the CDR data files as these data fields:

ddm_nbrcs – the trackwise corrected variable $NBRCS_{obs\_cor}$ given by eqn. (3a)

ddm_les – the trackwise corrected variable LES_{obs_cor} given by eqn. (3b)

In addition, a number of ancillary data fields are also output which are related to the trackwise correction. These include:

_tw_outlier (where *l1* = nbrcs or les) – a QC bit signifying that a sample was identified as an outlier, according to the definition given in Section 3.2 above.

*l1*_tw_r2 (where *l1* = nbrcs or les) – the correlation coefficient of the linear regression used to determine the trackwise correction given by eqn. (3)

*l1*_tw_slope (where *l1* = nbrcs or les) – the slope of the linear regression used to determine the trackwise correction, '*m*' in eqn. (3)

*l1*_tw_yint (where *l1* = nbrcs or les) – the y-intercept of the linear regression used to determine the trackwise correction, '*b*' in eqn. (3)

ddm_*l1*_orig (where *l1* = nbrcs or les) – the value of the L1 observable prior to trackwise correction

*l1*_mod (where *l1* = nbrcs or les) – the model value of the L1 observable derived from the matchup MERRA-2 wind speed and the GMF

tw_num – the number of samples within a track that are included in the linear regression used to determine the trackwise correction given by eqn. (3)

merra2_wind_speed – the matchup MERRA-2 windspeed that corresponds to a particular sample

4. Trackwise Correction Performance

4.1. Examples of L1 Trackwise Correction

Two examples of tracks with the trackwise correction applied are presented to illustrate the process. Both include ~900 samples used by the linear regression, with some other samples removed either as outliers or because they were measurements over land. Both are tracks measured on 15 Sep 2019. The first (track #2078 that day) was measured by CYGNSS observatory FM06 with GPS satellite PRN05 as the transmitter. The second (track #2080) was measured by CYGNSS FM01 with GPS PRN15.

Figure 1 shows a time series of the MERRA-2 wind speed that is matched to each CYGNSS L1 sample for (a) track #2078 and (b) track #2080. Note in both cases that there are instances where the wind speed value jumps discontinuously from one sample to the next (e.g. sample 390 for track #2078 and samples 330 and 730 for track #2080). These are instances where the track has crossed over a land mass (in which case MERRA-2 matchups are not possible) and the two adjacent wind speed samples are not actually adjacent in location.

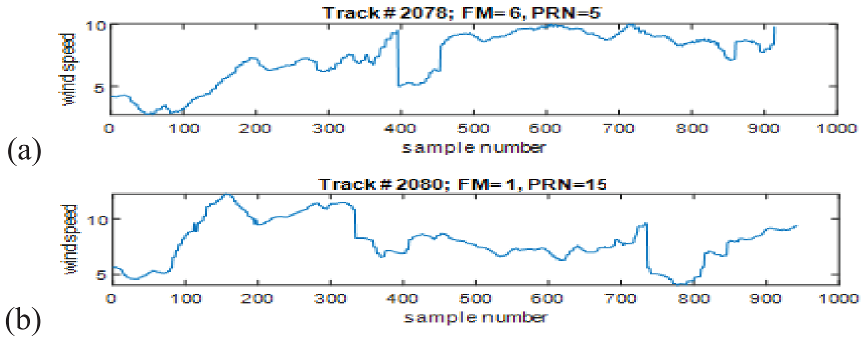

Figure 1. Time series of MERRA-2 matchup wind speeds for two CYGNSS tracks on 15 Sep 2019: (a) Track #2078 for FM06 and PRN 05; (b) Track #2080 for FM01 and PRN16.

Using the MERRA-2 wind speeds, modeled L1 measurements are derived using the GMFs. Scatterplots of the observed and modeled L1 data for each track are shown in Figure 2. In both cases, the majority of samples have a generally linear relationship between observation and model. With track #2080, a smaller fraction of the samples are seen to have an anomalous relationship, with the observations scattered significantly higher in value than their corresponding model values. These are considered outlier samples which cannot be corrected with confidence and which should not be used when deriving the linear regression coefficients used by the trackwise correction algorithm. Such cases as these were the original motivation behind the two-step linear regression procedure that is used by the algorithm.

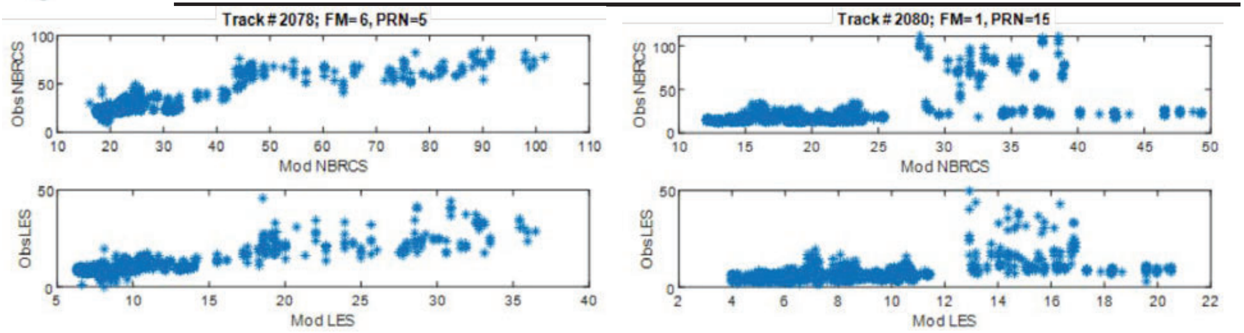

Figure 2. Scatterplots of modeled and observed L1 data for Track #2078 (left) and Track #2080 (right). Both the NBRCS (top) and LES (bottom) observables are shown.

The trackwise correction algorithm produces corrected versions of the observations. Scatterplots of the corrected data versus the same modeled values are shown in Figure 3. Also shown are the samples identified as outliers, as well as the bin-averaged values of the original, uncorrected, data which are used by the linear regression algorithm to compute the coefficients in the trackwise correction algorithm (see Section 3.2 for details).

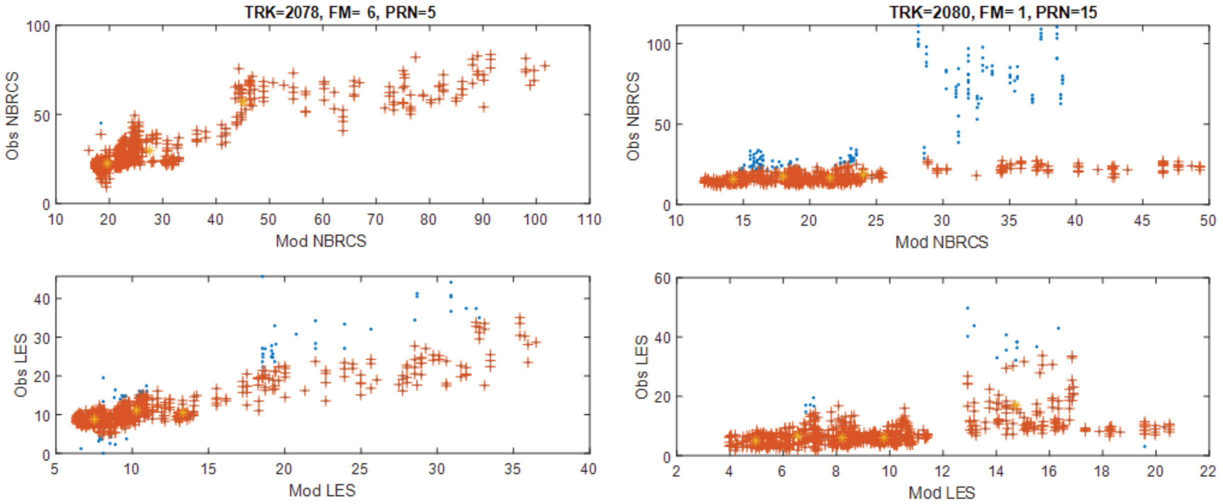

Figure 3. Scatterplots of modeled and trackwise corrected L1 data for Tracks #2078 (left) and #2080 (right) for NBRCS (top) and LES (bottom) observables. Samples identified as outliers are shown as blue '•'. The average values in each bin which are used by the linear regression are shown as orange '' (see Section 3.2 for details). The good trackwise corrected samples are shown as red '+'.*

4.2. Effect of Trackwise Correction on L2 Wind Speed

Comparisons between the trackwise corrected L2 CDR and MERRA-2 wind speeds are made to illustrate the performance of the correction algorithm. Figure 4 shows the RMS difference between the two as a function of the MERRA-2 wind speed using all measurement from 1 Jan 2018 through 31 Dec 2018. Also shown is the RMS difference between MERRA-2 and the v2.1 L2 wind speeds which were derived from the original, uncorrected, L1 observables. The trackwise correction algorithm reduces the difference at all wind speeds. Note in particular that the increase in RMS difference with wind speed above ~12 m/s has been significantly reduced from v2.1 to the CDR winds. Calibration errors such as are caused by the use of erroneous GPS EIRP values tend to have a larger effect at higher wind speeds due to the decrease in sensitivity of the L1 observables to wind speed [Ruf et al., 2018].

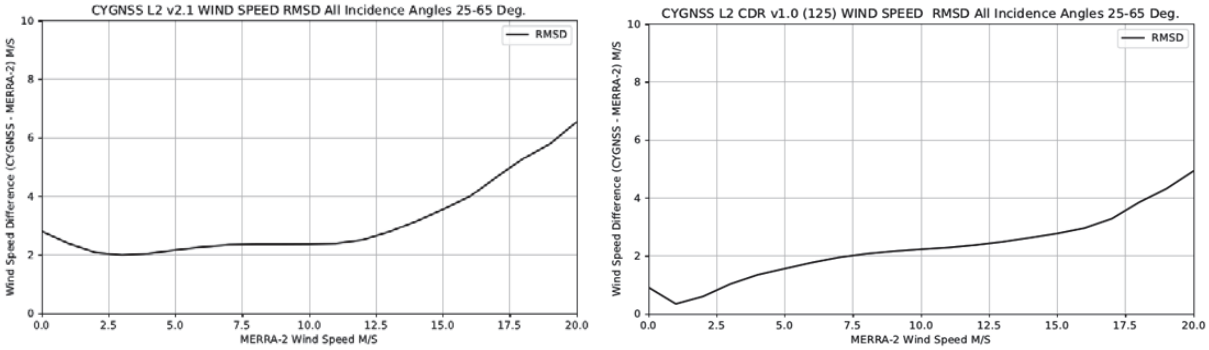

Figure 4. RMS difference between MERRA-2 and v2.1 (left) or trackwise corrected CDR (right) CYGNSS wind speed as a function of the MERRA-2 winds using all measurements in calendar year 2018.

Perhaps a more important diagnostic for the behavior of the CDR data product than RMS difference, for purposes of climate-related studies, is the stability of its mean difference, or bias, both temporally and geographically. A time series of the mean difference between the CDR and MERRA-2 winds from 18 Mar 2017 through 30 Sep 2019 is shown in Figure 5. Both daily and monthly running averages of the mean are included. Also included is the same mean difference time series for the v2.1 L2 wind speed. Large shifts in the v2.1 bias are caused by known changes in GPS transmit power which are associated with its "flex power" transitions. This is true of both the very sharp increase in bias that occurred on a single day in May 2018, as well the more gradual change in bias that occurred over a period of months in Fall 2018. Smaller changes in the bias at intermediate time scales may also be due to GPS flex power transitions, but this is less clear. Whatever their cause or causes, the changes in retrieval bias that are evident in the v2.1 wind speed data product have been largely removed by the trackwise correction algorithm.

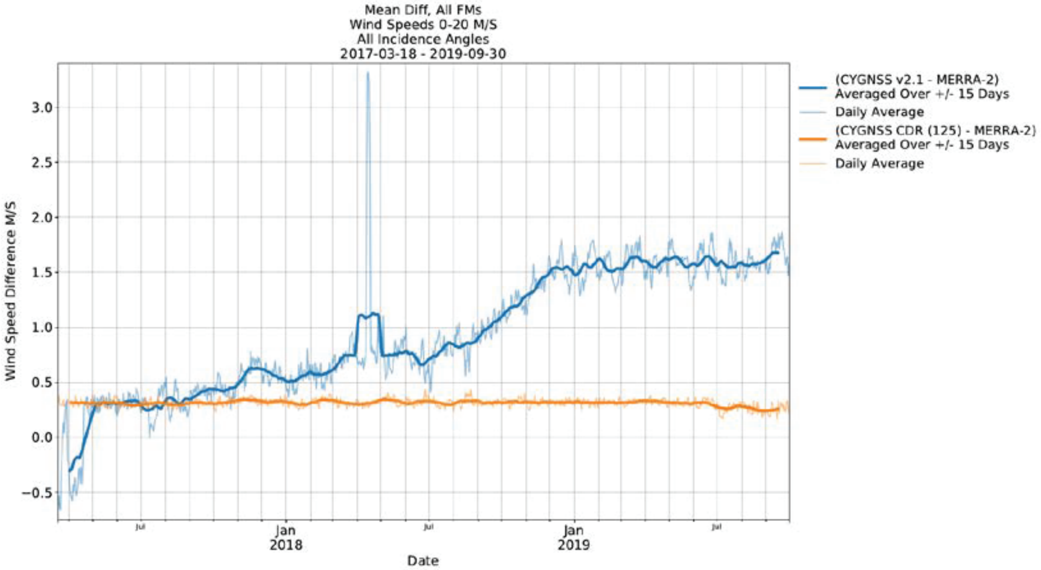

Figure 5. Mean differences between MERRA-2 and v2.1 (blue) or trackwise corrected CDR (green) beginning on the first day of science operations (18 Mar 2017) through 30 Sep 2019. Both daily and monthly running average mean values are shown.

GPS flexpower transitions are understood to occur episodically in time and also at some locations more so than others. If left uncorrected, this will introduce location-specific structure to the L2 retrieval bias. The mean bias as a function of location, averaged over the full calendar year 2018, for both the v2.1 and trackwise corrected CDR wind speeds is shown in Figure 6. Localized conditions of high or low bias are evident in the v2.1 winds and they are largely removed in the trackwise corrected CDR case. Notably, some geolocated structure to the bias is still present in with CDR winds, e.g. a small positive bias in the equatorial Pacific near the inter-tropical convergence zone (ITCZ). This structure does not coincide with known behavior of the GPS flex power transitions and may be an indication of geophysical oceanographic features. For example, persistent deviations of boundary layer atmospheric stability in the ITCZ from its global average state would alter the sensitivity of ocean surface roughness there to near surface winds, thereby shifting the bias relative to MERRA-2. This is an area of active research.

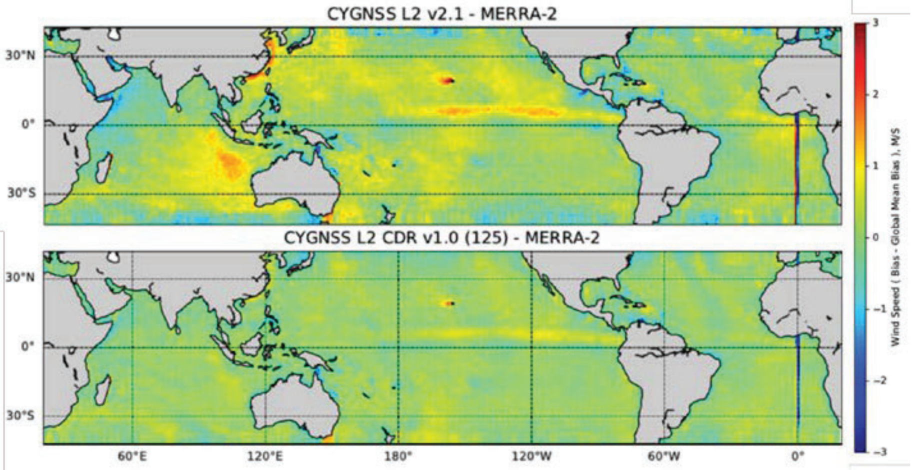

Figure 6. Mean difference between MERRA-2 and v2.1 (top) or trackwise corrected CDR (bottom) CYGNSS wind speed using all measurements in calendar year 2018.

4.3. Effect of Trackwise Correction on Global Coverage

The quality control flags used for v2.1 wind speeds include a fatal flag of all samples for which the GPS satellite used was a block type IIF. Those satellites have been found to exhibit a significantly larger amount of variation in their transmit power levels. This would have resulted in unacceptably large errors in the retrieved wind speeds given the static GPS EIRP values assumed by the v2.1 L1 calibration algorithm. Currently, 12 of the 31 operational GPS satellites are block type IIF, meaning that approximately 39% of the potential samples have been fatally flagged for this reason. The trackwise correction algorithm corrects for GPS transmit power variations with all block types, including IIF. As a result, the QC fatal flag for IIF samples is not necessary with the CDR wind speeds.

Figure 7 shows the global 24 hour coverage provided by v2.1 and CDR v1.0 wind speed along with the projected performance for v3.0. As described above, v3.0 will use direct GPS signal measurements to correct for changes in transmit EIRP in data after August 1, 2018. Both CDR v1.0 and v3.0 provide better coverage than v2.1 by enabling use of the full GPS constellation.

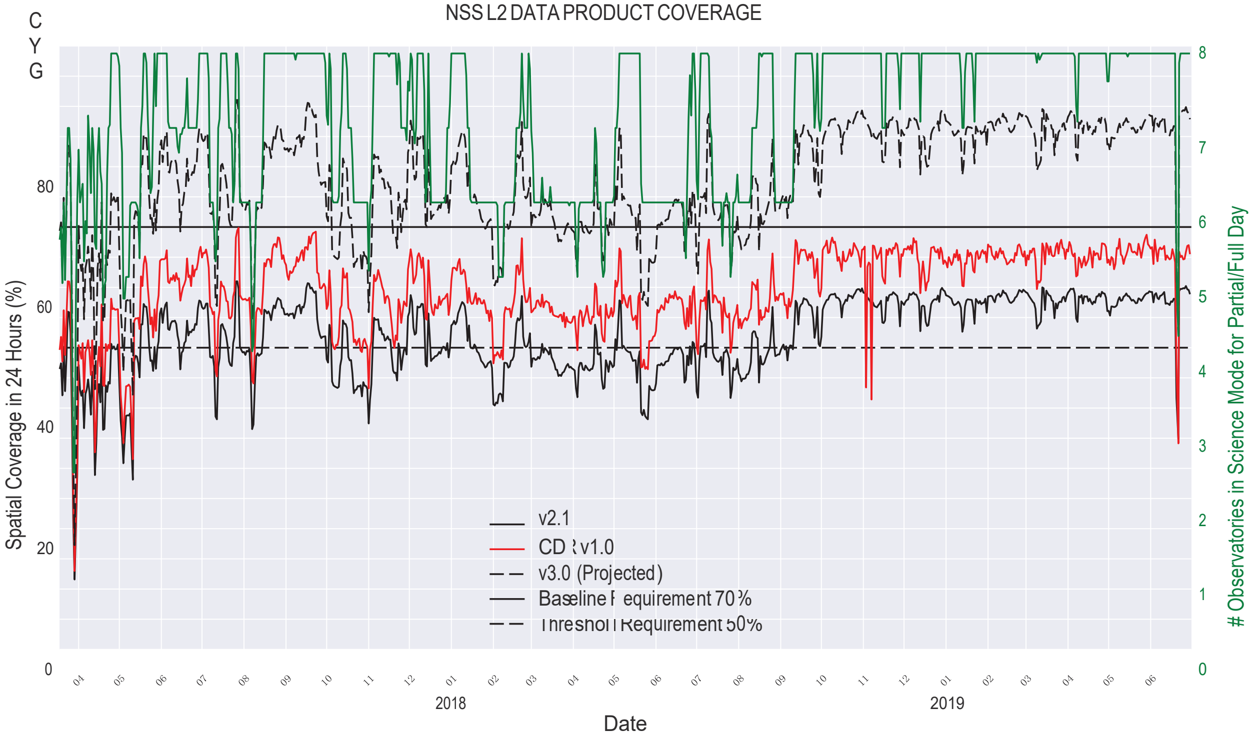

Figure 7.Global 24 hour coverage by v2.1, CDR v1.0 and v3.0 (projected) science data products. Note that v3.0 coverage prior to August 2018 is only hypothetical because the necessary flight hardware changes had not yet been enacted.

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