CYCLONE GLOBAL NAVIGATION SATELLITE SYSTEM (CYGNSS)

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

UM Doc. No.	**148-0389**
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Revision	**Rev 1**
Date	**1 May 2022**
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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SPACE PHYSICS RESEARCH LABORATORY

REVISION NOTICE

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REVISION 1	1 May 2022	Updated with project document number; updated for use of SDR v3.1 and ERA5 reference winds; updated QC filters; added description of debiasing step.

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° 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 book]. The matched filter correlation includes a final incoherent integration time of 1 second, and an output measurement is produced once every 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 once-per-second 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 ECMWF's fifth generation atmospheric reanalysis product (ERA5). The ERA5 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 ERA5) 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 ERA5. Model values for the NBRCS ($NBRCS_{mod}$) and LES (LES_{mod}) are derived from the ERA5 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:

1. 1.5 m/s < ERA5 wind speed
2. 0 < $NBRCS_{obs}$ < GMF(1.5 m/s) or 0 < LES_{obs} < GMF(1.5 m/s)

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. If less than 50 samples are available after these filters are applied, then the track is fatally flagged and CDR wind speeds are not produced

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 $1/20^{th}$ 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

$$|\mathrm{NBRCS_{obs2}} - \mathrm{NBRCS_{mod}}| > 40 \tag{2a}$$

$$|\mathrm{LES_{obs2}} - \mathrm{LES_{mod}}| > 20 \tag{2b}$$

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

$$NBRCS_{obs\_cor} = m*NBRCS_{obs} + b \quad (3a)$$

$$LES_{obs\_cor} = m*LES_{obs} + b \quad (3b)$$

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 and below 3. Negative slopes indicate a non-physical dependence of the L1 observable on wind speed. Slopes larger than 3 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. The y-intercept of the linear regression ('b' in eqn. (3)) is required to be between -20 and +50 for the LES and between -40 and +100 for the MBRCS observable. These ranges are a consistent with expected levels of bias correction. The explained variance (*i.e.* the r^2) of the linear regression is required to be greater than 0.02. This is an indication of non-negative correlation between the measured and modeled observable. Violations of any of these conditions are flagged with low confidence in the linear regression-based correction since the behavior of the correction is not consistent with expected behavior. In practice, all of these QC tests combined together typically flag ~22% of the 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. Hence, the same quality control filters are used.

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:

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

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

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

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

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

l1*_mod* (l1* = nbrcs or les*) – the model value of the L1 observable derived from the matchup ERA5 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)

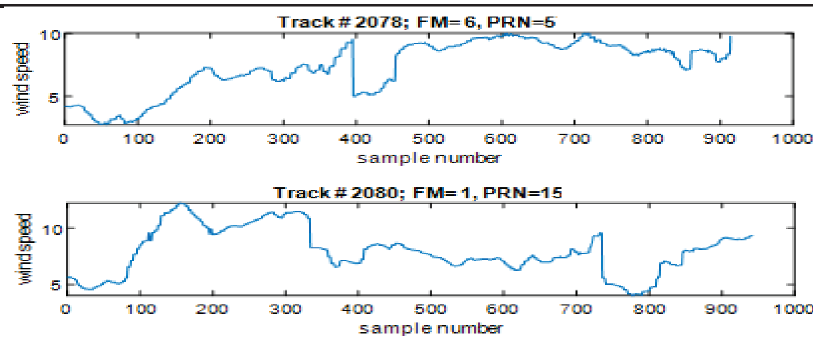
era5_wind_speed – the matchup ERA5 wind speed that corresponds to a particular sample

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 model 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 model matchups are not possible) and the two adjacent wind speed samples are not actually adjacent in location.



(a)

(b)

Figure 1. Time series of model 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 model 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.

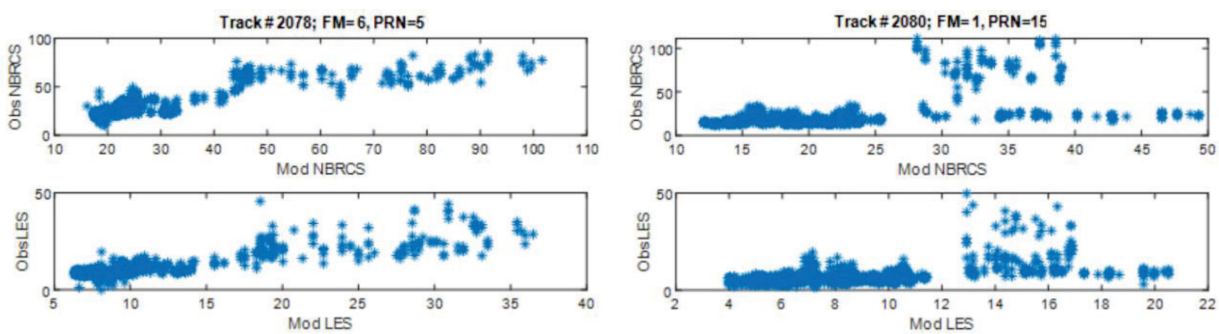


Figure 2. Scatterplots of modeled and observed L1 data for Track #2078 (left) and Track #2080 (right). Both the NBRCS (top) and LES (bottom) observables are shown.

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).

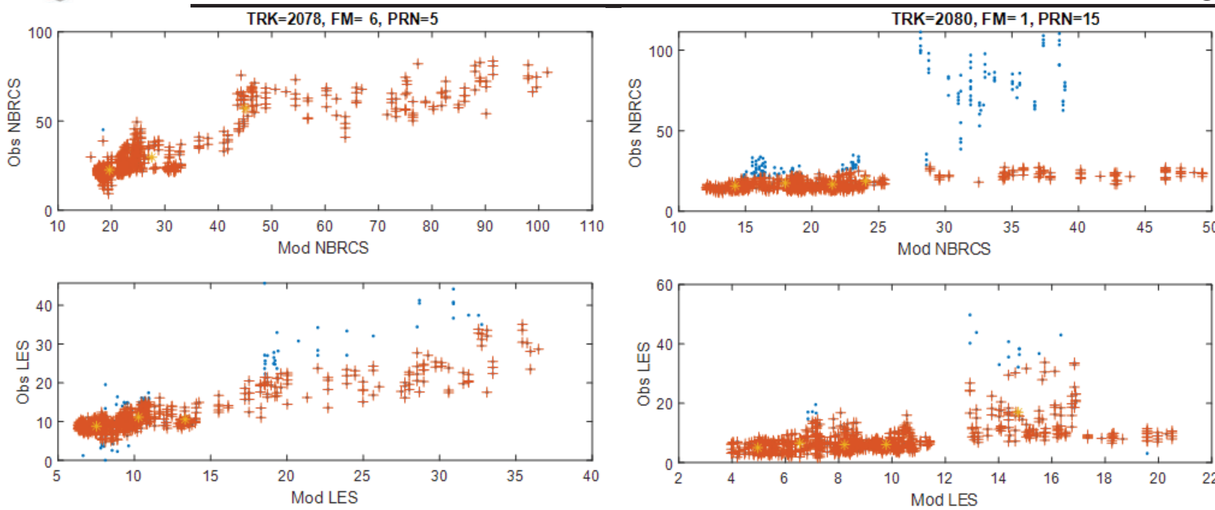


Figure 3. Scatterplots of modeled and trackwise corrected L1 data for Tracks #2078 (left) and #2080 (right) for NBRCS (top) and LES (bottom) observables. Samples identified as outliers are shown as blue '.'. The average values in each bin which are used by the linear regression are shown as orange '' (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 ERA5 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 ERA5 wind speed using all measurement from 1 Jan through 31 May 2019. Also shown is the RMS difference between ERA5 and the v2.1 and v3. SDR L2 wind speeds, which are derived from the original L1 observables without trackwise correction. The trackwise correction algorithm reduces the RMSD relative to SDR v3.1 most notably at wind speeds below 15 m/s. The RMSD for both SDR v3.1 and CDR v1.2 are lower than that for SDR v2.1 at all wind speeds, but most notably above 15 m/s. Calibration errors such as are caused by the use of erroneous GPS EIRP values by SDR v2.1 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].

The overall RMSD between CYGNSS and ERA5 wind speeds, when averaged over all wind speed values, is 2.4 m/s for SDR v2.1, 1.8 m/s for SDR v3.1, and 1.4 m/s for CDR v1.2.

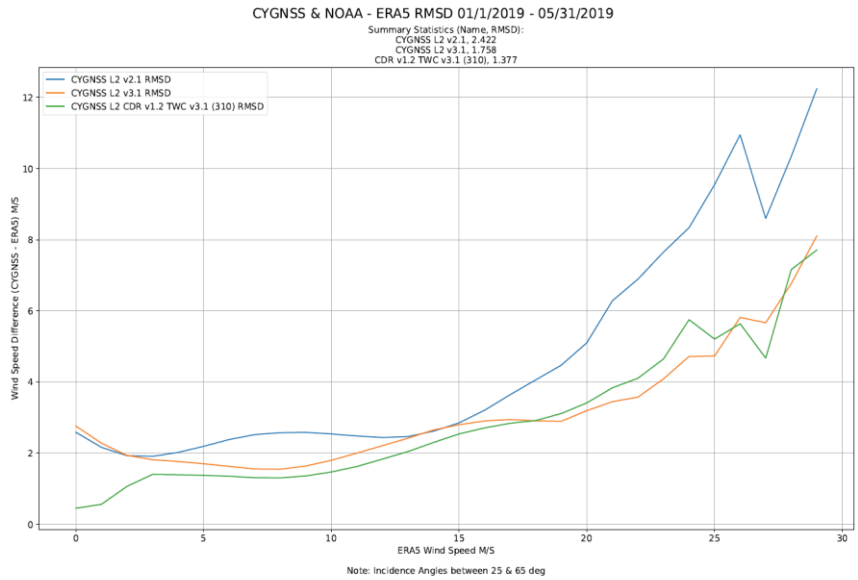


Figure 4. RMS difference between CYGNSS SDR v2.1 (blue), SDR v3.1 (orange) and CDR v1.2 (green) wind speed and coincident ERA5 winds as a function of the ERA5 wind using all measurements from 1 Jan to 31 May 2019.

Another important diagnostic figure of merit for the behavior of the CDR data product, in particular for purposes of climate-related trending studies, is the long term temporal stability of its mean difference, or bias. A time series of the mean difference between the CDR and ERA5 winds beginning in August 2018 is shown in Figure 5. Both daily and monthly running averages of the mean are included. Also included are the time dependent biases in the SDR v2.1 and v3.1 wind speeds. 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 in Feb 2020, as well the more gradual long term drifts in bias that are evident throughout 2019 and 2020. The long term drifts in retrieval bias which are evident in the v2.1 wind speed data product have been largely removed by the v3.1 calibration, which corrects for changes in GPS transmit power. An oscillatory time dependence, with a periodicity of roughly 60 days, is also evident in Fig. 5 for both the SDR v2.1 and v3.1 wind speed biases. Its root caused is believed to be an uncorrected temperature dependence in the Level 1 engineering calibration, which is consistent with a ~60 day oscillation in the physical temperature of the satellites due to periodic changes in the orbit beta angle. A correction to the L1 calibration algorithm is in development and will be incorporated into a future SDR data product release. In the meantime, however, note that the CDR v1.2 bias time series in Fig. 5 demonstrates that the trackwise correction algorithm effectively removes this temperature dependent oscillatory behavior.

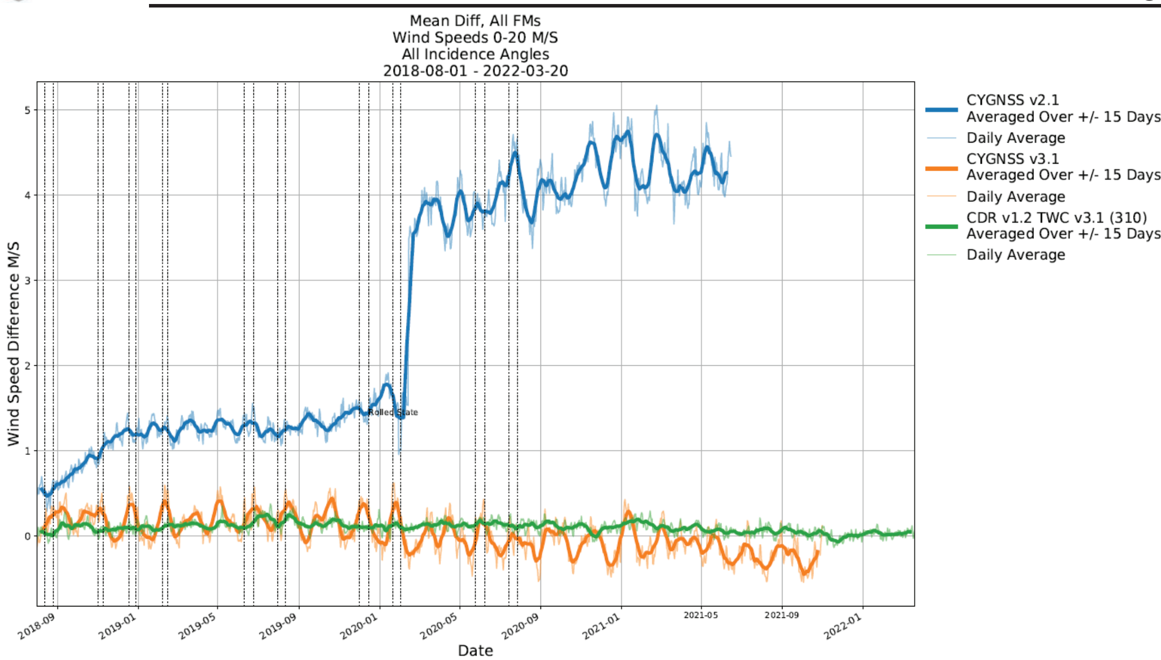


Figure 5. Mean differences between ERA5 and SDR v2.1 (blue), SDR v3.1 (orange), and CDR v1.2 (green) for the period 1 August 2016 through 20 March 20122. Both daily and monthly running average mean values are shown.

5 CDF matching Debiasing

As with the regular Sensor Data Record (SDR) L2 data processing, the retrieved CDR DDMA and LES winds are combined to form the minimum variances (MV) wind speed estimate. This is done only for the fully developed seas (FDS) winds. The weights used to from the MV wind as a function of the mean of the DDMA and LES wind are shown in figure 6. As a final step, this MV wind is matched up with model based estimates as with the performance estimates above, and from these data, a wind speed map from the MV wind retrieval space to a model cdf-matching wind speed is created (Figure 7). The MV weights and cdf-matching debiasing map were created from all data passing the QC steps described above for 2019. Histograms of the model and retrieved CDR winds as a function of CYGNSS FM, antenna, and GPS transmitter are shown in Figure 8. In all cases, the histograms of CYGNSS winds match the model winds quite closely, save for the antenna splits. For this last case, the starboard and port antennas see different distributions of winds as a function of latitude as they look off to each side of the spacecraft, particularly at the extreme high and low latitude ranges of the observations (+/- 40 degrees), where the truth/model estimates differ significantly for each antenna and the wind speed distributions shift correspondingly. This can be seen in the manner that the truth histogram lies directly between the starboard and port histograms in the 7 to 15 m/s range.

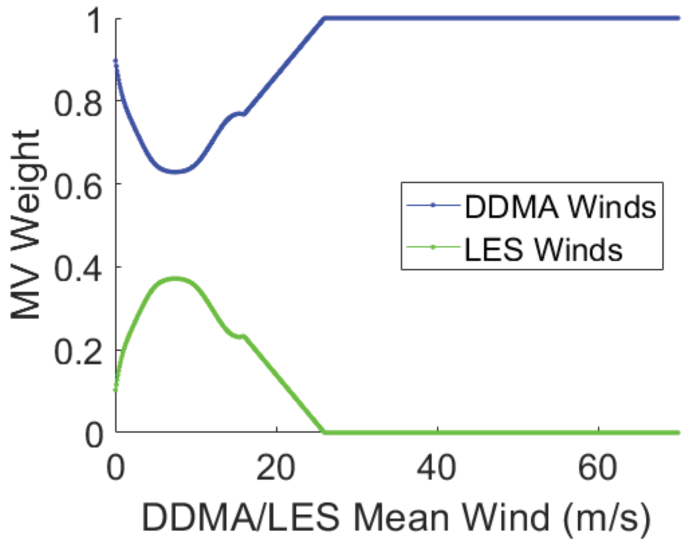


Figure 6. MV weights. These weights are used to combine the DDMA and LES wind speed estimates as a function of the mean of the two estimates to compute the MV wind estimate.

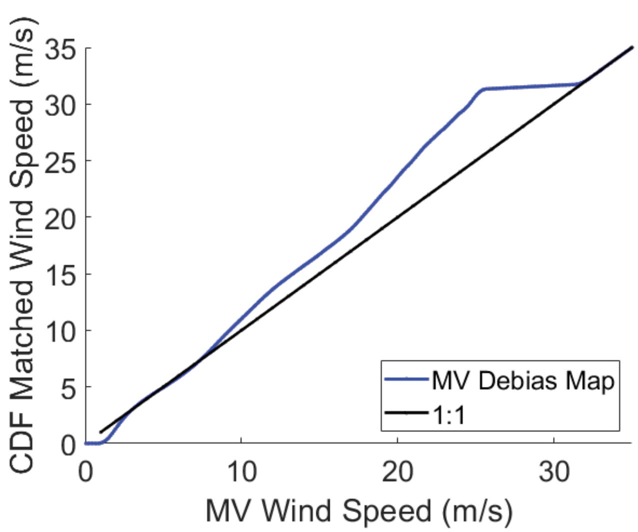
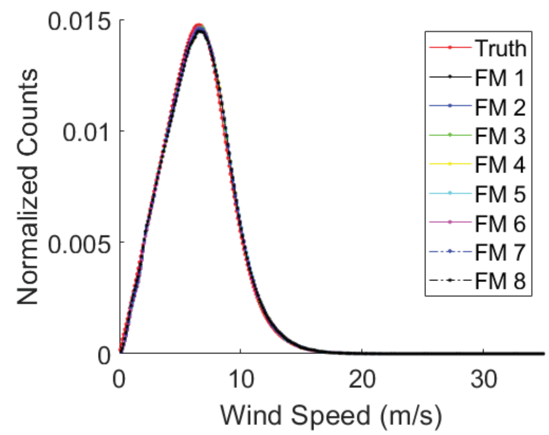
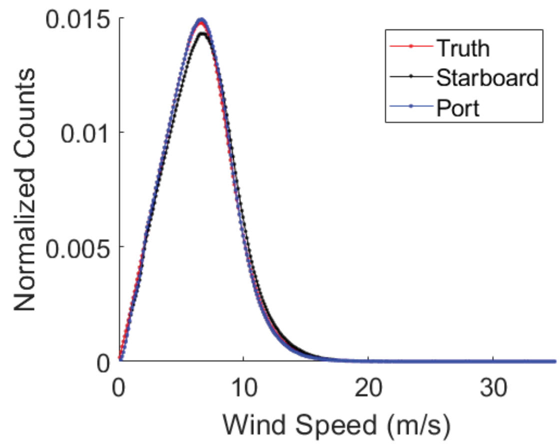


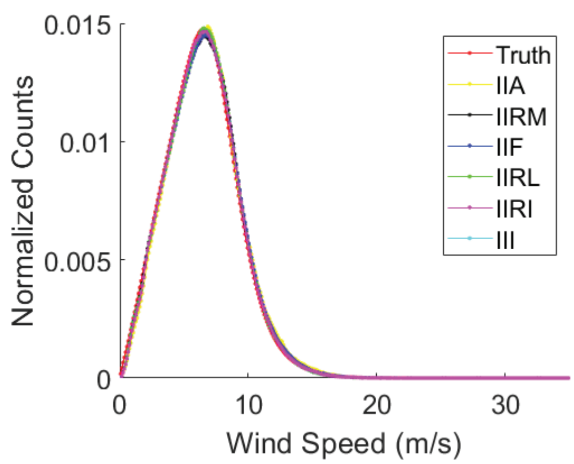
Figure 7. CDF-matching debiasing map. This mapping is applied to retrieved MV wind to form the final reported CDR FDS wind estimate.



a)



b)



c)

Figure 8. Histograms of CDR FDS Winds and model ("Truth") winds separated by a) CYGNSS FM, b) CYGNSS Antenna, and c) BPS block type.

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