CYCLONE GLOBAL NAVIGATION SATELLITE SYSTEM (CYGNSS)

Algorithm Theoretical Basis Document Level 3 Storm-Centric Gridded Wind Speed	UM Doc. No.	148-0400
	SwRI Doc. No.	N/A
	Revision	Initial Release
	Date	3 March 2021
	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

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1. Summary

This document describes the algorithm and data processing implementation used to produce CYGNSS Level 3 storm-centric gridded wind speed science data products. The algorithm uses as its input the Level 2 wind speed science data products, which provide wind speed values at the time and location of the surface reflection. This product reports averaged wind speeds in a regular 7.2^{o}x7.2^o grid centered on the tropical cyclone. Gridded wind speeds are reported every 6 hours for each tropical cyclone, though some grids may be empty. Each wind speed measurement is made by a particular combination of CYGNSS spacecraft and Global Positioning System (GPS) spacecraft. Because there are 8 CYGNSS spacecraft and 32 GPS spacecraft, there are 256 different combinations of spacecraft which combine to make measurements. Much work has been done to minimize differences between the spacecraft, but there are small remaining differences and possible anomalies. This product only reports wind speeds which have passed an inter-track comparison test (need to define track before-hand) to increase reliability.

1.1 Introduction and Background

1.1.1 The CYGNSS mission

The CYGNSS constellation is comprised of 8 observatories, evenly spaced about a common orbit plane at 510 km altitude and 35° inclination angle. Each observatory contains a Delay Doppler Mapping Instrument (DDMI) which consists of a multi-channel GNSS-R receiver, a low gain zenith antenna for reception of the direct signals, and two high gain nadir antennas for reception of the surface scattered signals (Ruf *et al.*, 2015). There are typically many specular reflections from the surface available at any given time due to the large number of GPS transmitting satellites. Each DDMI selects the four specular reflections located in the highest sensitivity region of its nadir antenna pattern and simultaneously computes DDMs centered on each of them. Individual DDM integration times last one second and wind speeds are derived from measurements over a 25x25 km^2 region centered on the specular point (Clarizia, 2015). This results in a total of 32 wind measurements per second by the full constellation. CYGNSS spatial sampling consists of 32 simultaneous single pixel “swaths” that are 25 km wide and, typically, 100s of km long, as the specular points move across the surface due to orbital motion by CYGNSS and the GPS satellites. Temporal sampling occurs randomly due to the asynchronous nature of the CYGNSS and GPS satellite orbits. As a result, the CYGNSS revisit time is best described by its probability distribution. The distribution, shown in Fig 1, is derived empirically using a mission simulator to determine the time and location of each sample within the ±38^o latitude coverage zone and then examining the time difference between samples at the same location.

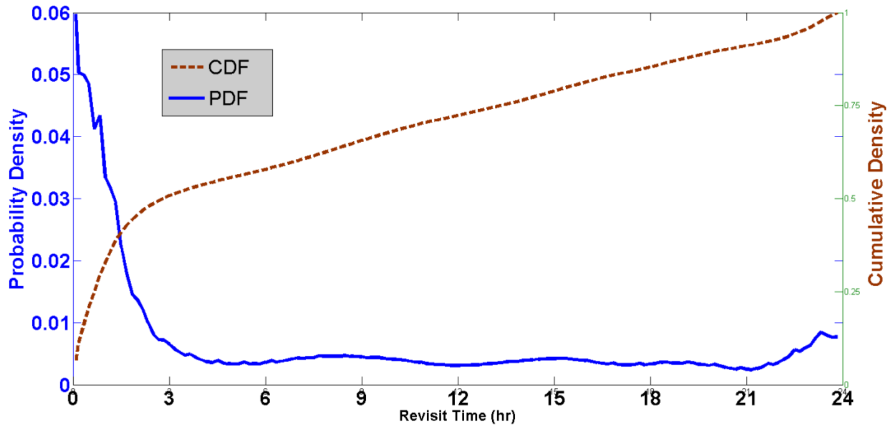

Fig. 1. Temporal sampling is characterized by the probability and cumulative density functions of revisit time. The median and mean revisit times are, respectively, 2.8 and 7.2 hours.

The empirical distribution features a high probability of very short revisit times (e.g. resulting from sequential samples by trailing satellites spaced tens of minutes apart) and a long, tapering "tail" at higher revisit times. Its median value is 2.8 hours and the mean revisit time is 7.2 hours.

CYGNSS combines the all-weather performance of GPS based bistatic scatterometry with the spatial and temporal sampling properties of a constellation of observatories. The GPS frequency of operation enables the instrument to make surface scattering observations through most precipitating conditions. 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 8 microsatellites are launched on a single Deployment Module that is attached to a NASA government furnished equipment Pegasus launch vehicle (Ruf *et al*., 2013; Ruf *et al*., 2016).

1.1.2 Science Goals, Objectives and Requirements

The CYGNSS goal is to understand the coupling between ocean surface properties, moist atmospheric thermodynamics, radiation, and convective dynamics in the inner core of TCs. The goal of CYGNSS 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:

- 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.

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

The CYGNSS science goals are enabled by meeting the following mission objectives.

• Measure ocean surface wind speed in most naturally occurring precipitating conditions, including those experienced in the tropical cyclone eyewall

• Measure ocean surface wind speed in the tropical cyclone inner core with sufficient frequency to resolve genesis and rapid intensification.

The CYGNSS baseline science requirements are:

1) The baseline science mission shall provide estimates of ocean surface wind speed over a dynamic range of 3 to 70 m/s as determined by a spatially averaged wind field with resolution of 5x5 km.

2) The baseline science mission shall provide estimates of ocean surface wind speed during precipitation rates up through 100 millimeters per hour as determined by a spatially averaged rain field with resolution of 5x5 km.

3) The baseline science mission shall retrieve ocean surface wind speed with a retrieval uncertainty of 2 m/s or 10%, whichever is greater, with a spatial resolution of 25x25 km.

4) The baseline science mission shall collect space-based measurements of ocean surface wind speed at all times during the science mission with the following temporal and spatial sampling: 1) temporal sampling better than 12 hour mean revisit time; and 2) spatial sampling 70% of all storm tracks between 35 degrees north and 35 degrees south latitude to be sampled within 24 hours.

5) The CYGNSS project shall conduct a calibration and validation program to verify data delivered meets the requirements within individual wind speed bins above and below 20 m/s.

6) Support the operational hurricane forecast community assessment of CYGNSS data in retrospective studies of new data sources.

2. Algorithm Overview

2.1 Algorithm Objectives

The objective of this algorithm is to produce regular 6-hourly gridded wind speeds for tropical cyclones (TCs) with increased reliability by incorporating averaging and comparisons between co-located measurements. This product, which is only available around TCs, is a more sophisticated version of the globally available standard CYGNSS L3 product. All reported wind speeds in this storm-centric product are an average of wind speeds from at least two different “tracks” (combinations of CYGNSS receiver and GPS transmitter) that agree reasonably well. This removes most problematic data and wind speeds which are biased from track to track. Averaging also works to reduce noise in the measurement. Storm-centric coordinates are utilized to allow for a larger temporal averaging window without smearing between grid cells. A large temporal averaging window increases the typical number of tracks in each grid cell, allowing for more frequent inter-track comparisons to be made.

2.2 Input Data Description

The input data required by this algorithm are listed here.

1. Wind speed inputs are CYGNSS Level 2 SDR Version 3.0 (Clarizia, 2015; Ruf et al., 2019). These wind speeds incorporate improvements made to the Level 1 SDR calibration to compensate for variations in GPS transmit power level (Wang et al., 2021)
2. Best Track storm center locations (Landsea & Franklin, 2013)

2.3 Data Organization

The standard CYGNSS Level 3 wind speed product is a standard gridded wind speed. The surface of the Earth is divided into a 0.2x0.2-degree grid. All wind speed samples which fall into a grid cell in an hour are combined via an inverse-variance weighted average of the wind speeds. This product is available globally and is only restricted to where CYGNSS can make wind speed measurements.

In contrast, this new CYGNSS Level 3 wind speed product with storm-centric averaging is only available within 400 km of the center of a tropical cyclone (TC). The primary function of this new product is to use inter-track comparisons to identify and remove outlier tracks. Note that a track is defined as a particular combination of GPS and CYGNSS satellite whose specular point on the ocean's surface traces a continuous curved path or 'track'. Inter-track comparisons are valuable if a GPS/CYGNSS satellite combination has an unforeseen bias or calibration issue. To perform inter-track comparisons with most CYGNSS measurements, samples from multiple tracks must be co-located a significant fraction of the time. The fraction of co-located samples is a function of the temporal and spatial windows used in the co-location. To retain high-resolution storm information, the width of the spatial window should not be made much larger than the spatial resolution of CYGNSS (25 km). The maximum temporal window depends on the speed of the storm (movement of the storm center, not the wind speed). Typical TCs can move up to about 25 kilometers per hour, so a temporal window of just 1-2 hours can cause smearing of the TC wind field.

Storm-centric coordinates (relative latitude/longitude pairs rather than absolute) are used in this algorithm to widen the temporal window of co-location without smearing the TC wind field. A time-continuous storm center location is required to compute relative latitude and longitude coordinates for each sample. To approximate this, Best Track storm centers (available at primary synoptic hours) are linearly interpolated (Landsea & Franklin, 2013).

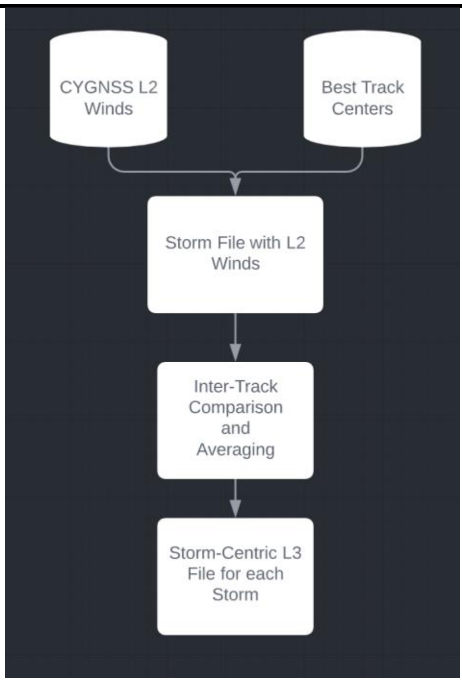

Fig. 1. Data flow in the storm-centric Level 3 algorithm

The National Hurricane Center Best Tracks show when TCs are active and provides storm center locations every 6 hours. First, CYGNSS Level 2 wind speeds within a 4.0x4.0-degree box centered on a TC are selected. Every 6 hours (0, 6, 12, 18 UTC), a 3.6x3.6-degree grid centered on the Best Track storm center is populated with CYGNSS wind speeds according to the temporal window and the grid spacing. Each 6-hourly grid contains wind speeds from +/- 6 hours which means there is some overlap between the two adjacent synoptic times. To prevent redundancy, data from +/- 3 hours is required for a grid cell to report a wind speed. At least one track in a cell must be from +/- 3 hours, but other data from a larger window of +/- 6 hours is used for inter-track comparison. A +/- 6-hour window was chosen to balance data availability and error due to real change in the TC's wind field. For example, a +/- 24-hour window is too large in most cases because the storm's size and intensity are likely to change significantly over 48 hours. Even a +/- 6-hour window is too large in some cases. The Best Track storm intensity and wind radii are reported along with the storm-centric Level 3 winds to inform the user of how quickly the storm is changing. There is also a "quality_status" parameter which rates the consistency of tracks relative to storm intensity.

Once relevant data have been selected within the temporal window of +/- 6 hours, the data are divided into grid cells. The grid cell spacing or reporting interval is 0.15 degrees (16.7 km). When populating each grid cell, data is taken from a square of +/- 0.30 degrees which is twice the grid spacing. This creates an overlap with adjacent cells and the grid spacing is an oversampling of the wind field. Figure x demonstrates how the cells overlap and where the data are selected. The red dot in the grid center is the grid cell that is the focus of this example. The black lines represent a portion of the grid. The shaded red region, which overlaps with all surrounding cells, is the area from where data can be taken to populate the center cell.

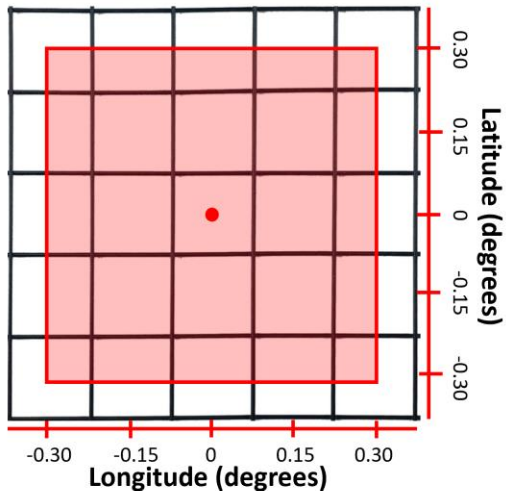

Fig. 2. The red dot is the center of an arbitrary grid cell. The reporting interval is 0.15 degrees and is represented by the black squares. Each black square is a different grid cell which contains its own set of CYGNSS samples and its own averaged wind speed. The red square represents the area from which the center grid cell derives its CYGNSS samples.

The maximum distance between samples in a cell is 0.85 degrees but a typical distance is smaller than this. Note that samples are averaged together within a cell so the effective spatial resolution will become coarser. The impact on spatial resolution depends on the distribution of the samples within the cell.

Using the gridding system explained above, a typical cell has 1.2 tracks per cell. Note that a minimum of 2 tracks is required to report a wind speed.

2.4 Inter-Track Comparison and Averaging

The reported wind speed of a cell and the handling of multiple tracks is determined by the number of tracks T in the cell. Each cell must contain wind speed measurements ("samples") from at least two tracks for a cell-averaged wind speed to be reported. If there is only one track in a cell, there is no way to verify that the wind speeds of that track are not problematic. When there are two tracks or more in the cell, the mean track wind speed $\bar{u}_t$ is computed for each track. There are N samples in the cell and T tracks with N_t samples in the t^{th} track. The mean track wind speed for the t^{th} track is given by

$$\bar{u}_t = \frac{1}{N_t}\sum_{j=1}^{N_t} u_j \tag{1}$$

where u_j is the wind speed of the j^{th} sample in the t^{th} track. For the case $T = 2$, $\bar{u}_t$ must agree to within the threshold.

$$|\bar{u}_{t1} - \bar{u}_{t2}| < 0.4\bar{u}_C + 3 \tag{2}$$

where $\bar{u}_C$ is the average of all wind speeds in the cell expressed as

$$\bar{u}_C = \frac{1}{N}\sum_{t=1}^{t=T} N_t \bar{u}_t \qquad (3)$$

The threshold as a function of the mean cell wind speed is derived empirically from the behavior of a large populations of samples. If the difference between the two mean track wind speeds is below the threshold, the mean cell wind speed $\bar{u}_C$ is reported as Equation 3 directly above. If the difference is above the threshold, no wind speed is reported for the cell. When there is a large difference between two tracks, there is no way to determine which mean track wind speed should be used.

When there are more than two tracks in a cell ($T > 2$), an outlier test is done to check if any mean track wind speeds $\bar{u}_t$ are anomalous. Track *x* is not an outlier if its mean track wind speed is within 3 standard deviations of the mean cell wind speed computed without track *x*. This is represented by the following condition

$$\bar{u}_C^{-x} - 3\sigma_C^{-x} < \bar{u}_x < \bar{u}_C^{-x} + 3\sigma_C^{-x} \qquad (4)$$

where the superscript -*x* indicates that track *x* is excluded when computing the term and where

$$\sigma_C^{-x} = \sqrt{\frac{1}{(T-1)-1}\sum_{t\neq x} |\bar{u}_t - \mu|^2} \qquad (5)$$

and

$$\mu = \frac{1}{T-1}\sum_{t\neq x} \bar{u}_t \qquad (6)$$

Any outlier tracks that are flagged by this method are removed from further consideration. Before moving on, the algorithm checks to see if the removal of outlier track(s) removed all the samples within +/- 3 hours. If there are no remaining samples within +/- 3 hours, no wind speed is reported for the cell. This is because there are no measurements in the +/- 3-hour window of the cell that support that support the wind speed which would be reported.

Next, the variation of the mean track wind speeds $\bar{\mu}_t$ is examined to see if the spread is typical. This is done whether outliers were found or not. First, the expected standard deviation is computed from the following relation

$$\sigma_{Expected} = 0.26\ x\ (\bar{u}_{top2} - 3.5) \qquad (7)$$

where $\bar{u}_{top2}$ is the average of the two highest mean track wind speeds $\bar{\mu}_t$ after removal of outlier track(s). If the standard deviation of the mean track wind speeds is more than 3 greater than the expected standard deviation, no wind speed is reported for the cell.

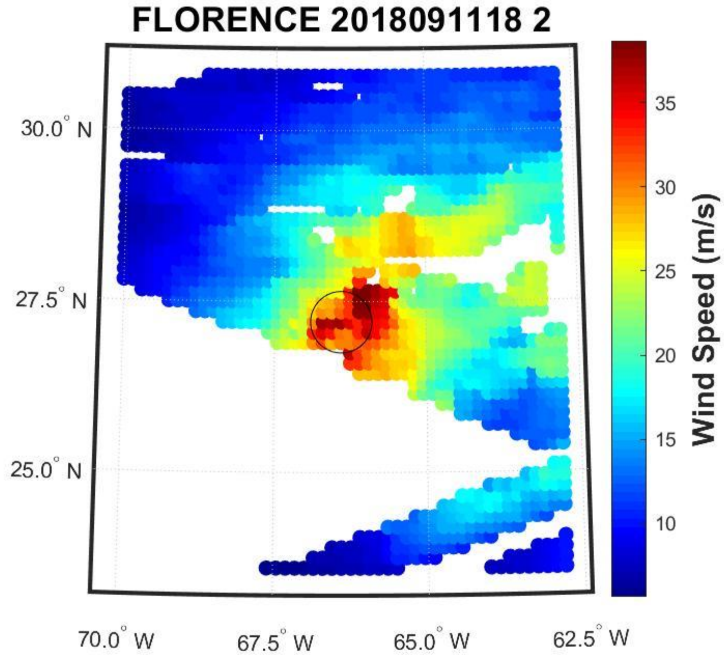

Fig. 3. A typical storm-centric Level 3 gridded wind field. The black circle indicates the storm center location. The gaps are either cells which do not contain CYGNSS samples from multiple tracks or which have disagreement between tracks.

$$\sigma_C^{-Outliers} > \sigma_{Expected} + 3 \quad (8)$$

If the condition in Equation 8 is not met, then the wind speed for the cell is reported as Equation 3 but with outlier track(s) excluded.

This inter-track comparison algorithm is done for all grid cells. When complete, a typical final gridded wind speed product looks like Figure 3.

2.5 Inter-Track Comparison

One of the primary benefits of using storm-centric coordinates and inter-track comparisons is the additional consistency it imposes on the reported wind speeds. The standard deviation of the wind speeds within each cell can be used to quantify the consistency of the winds which are used to generate the reported cell wind speed. Fig. 4 shows the probability distribution function (PDF) for the standard deviation of individual wind speed samples which are averaged together to produce a grid cell's wind speed before and after applying inter-track quality control. The average standard deviation is 4.53 without the inter-track quality control and this is reduced to 3.53 with inter-track QC applied. As outlier tracks are removed in the inter-track comparison process, the variance within each grid cell decreases. Because of this, there is a much smaller tail of high standard deviations in the distribution when inter-track quality control is applied. The skewness of the distribution decreases from 1.85 to 1.40 which means that more samples are closer to the mean and fewer are in the high standard deviation tail with inter-track quality control.

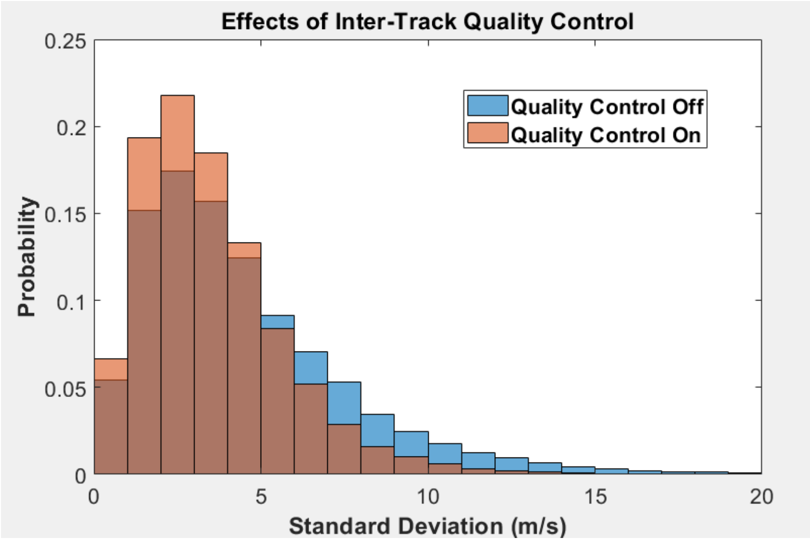

Fig. 4. The probability distribution of wind speed standard deviation within a grid cell with 2 or more tracks. Each grid cell contains many wind speed measurements. The standard deviation of those wind speeds tends to be lower after the inter-track quality control is applied. The average standard deviation is 4.53 and 3.53 without and with quality control, respectively. The skewness is 1.85 without inter-track quality control and 1.40 with.

2.6 Output Data Product Description

u_{L3} The minimum variance estimate of the mean wind speed averaged over the time and space intervals defined by eqn. (1) for a particular bin, as given by eqn. (2) (units of meters/second)

σ_{L3} The standard deviation of u_{L3} for a particular bin, as given by eqn. (3) (units of meters/second)

S Number of samples used to calculate u_{L3}.

2.7 Algorithm Configuration Parameter Values

The principle configuration parameters for this algorithm are the latitude, longitude and time boundaries of the bins. The bins are uniformly spaced every 0.2^o in latitude from -40^o N to +40^o N, every 0.2^o in longitude from 0 to 360^o E and every 1 hour in time. Specifically:

Lat_{min} = -40°, -39.8°, …, +39.8° North latitude

Lat_{max} = -39.8°, -39.6°,…, +40° North latitude

Lon_{min} = 0°, 0.2°,…, 359.8° East longitude

Lon_{max} = 0.2°, 0.4°,…, 360.0° East longitude

T_{min} = (year, day-of-year, 0 hr UT), (yr, DOY, 1 hr UT), …, (yr, DOY, 23 hr UT)

T_{max} = (year, day-of-year, 1 hr UT), (yr, DOY, 2 hr UT), …, (yr, DOY, 24 hr UT)

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