CYCLONE GLOBAL NAVIGATION SATELLITE SYSTEM (CYGNSS)

Algorithm Theoretical Basis Document Level 3 Gridded Wind Speed	**UM Doc. No.**	**148-0319**
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	Revision	**Rev 0 Chg 0**
	Date	**8 December 2015**
	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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Prepared by: Chris Ruf, University of Michigan 12/8/2015

Approved by: *Email approval on file* Date: 12/11/15
Chris Ruf, CYGNSS Principal Investigator

Approved by: *Email approval on file* Date: 12/11/15
John Scherrer, CYGNSS Project Manager

Approved by: *Email approval on file* Date: 1/13/16
Randy Rose, CYGNSS Project Systems Engineer

Released by: *Email approval on file* Date: 1/13/16
Damen Provost, CYGNSS UM Project Manager

REVISION NOTICE

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1. Summary

This document describes the algorithm and data processing implementation used to produce a CYGNSS Level 3 gridded wind speed science data product. The algorithm uses as its input the mission baseline Level 2 wind speed science data product, which provides its wind speed values at the time and location at which the measurements were made (i.e. in sensor-specific latitude, longitude and time coordinates) for each of the eight observatories in the CYGNSS constellation and for each of the four bistatic radar channels on each observatory. This Level 3 gridded product combines all 8×4 = 32 wind speed measurement made by the CYGNSS constellation each second, sorts them into a uniform (latitude, longitude, time) grid, and reports certain statistics of the samples in each bin (*e.g.* number, mean value, …), together with a compilation of the quality flags set for each of the samples in the bin.

2. Introduction and Background

2.1. 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° latitude coverage zone and then examining the time difference between samples at the same location.

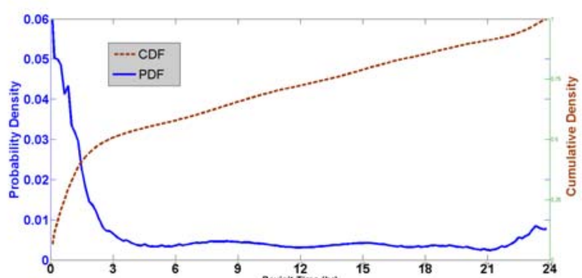

Fig. 1. Temporal sampling is characterized by the probability and cumulative density functions of revisit time. The median and mean revisit times are, respectively, 2.8 and 7.2 hours.

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).

2.2. 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.

3. Algorithm Overview

3.1. Algorithm Objectives

The objective of this algorithm is to produce a gridded wind speed science data product which is uniformly sampled in latitude, longitude and time. This Level 3 product is generated from the full set of Level 2 wind speed samples produced by the constellation of observatories. In addition to a best estimate of the mean ocean surface wind speed within any particular bin, the algorithm also produces statistics of the wind speed that are derived from the population of samples of the Level 2 wind speed made by the constellation within that bin. A compilation of the quality flags associated with the population of individual Level 2 wind speed samples is also produced.

3.2. Input Data Description

The input data required by this algorithm are listed here.

3.2.1. The wind speed data products produced by the Level 2 wind speed algorithm (Clarizia, 2015):

- The Minimum Variance (MV) wind speed estimate
- The uncertainty in the MV wind speed estimate

3.2.2. The wind speed-dependent quality flags produced by the Level 2 wind speed algorithm::

- Non-fatal negative wind speed quality flag (0=wind speed is non-negative; 1=wind speed is negative and greater than or equal to –5 m/s)
- Non-fatal high wind speed quality flag (0=wind speed is less than or equal to 70 m/s; 1=

wind speed is greater than 70 m/s and less than 100 m/s)

- Fatal negative wind speed quality flag (0=wind speed is non-negative; 1=wind speed is less than negative and less than –5 m/s)
- Fatal high wind speed quality flag (0=wind speed is less than 100 m/s; 1= wind speed is greater than or equal to 100 m/s)

3.2.3. The rolled-up versions of the quality flags from the Level 1B radar scattering cross section algorithm (Gleason, 2014) that are produced by the Level 2 wind speed algorithm. These quality flags include:

- Large spacecraft attitude error (N = # of DDMs used for which the flag was set to 1 = true)
- Negative signal power In L2 DDMA area (N = # of DDMs used for which the L1a calibration resulted in at least one bin in the L2 DDM Area (DDMA) having a negative power value.)
- Negative Sigma0 In L2 DDMA area (N = # of DDMs used for which the L1a calibration resulted in at least one bin in the L2 DDM Area (DDMA) having a negative power value.)
- Low confidence in DDM noise floor estimate (N = # of DDMs used for which the flag was set to 1 = true)
- Low confidence in open ocean noise floor estimate (N = # of DDMs used for which the flag was set to 1 = true)
- Low confidence in open ocean noise temperature estimate (N = # of DDMs used for which the flag was set to 1 = true)
- Land present in DDM (N = # of DDMs used for which the flag was set to 1 = true)
- Specular point over open ocean (N = # of DDMs used for which the flag was set to 1 = true)
- Large step change in DDM noise floor (N = # of DDMs used for which the flag was set to 1 = true)
- Large step change in LNA temperature (N = # of DDMs used for which the flag was set to 1 = true)
- Direct signal in DDM (N = # of DDMs used for which the flag was set to 1 = true)
- Low Rx antenna range corrected gain (N = # of DDMs used for which the flag was set to 1 = true)
- High specular point incidence angle (N = # of DDMs used for which the flag was set to 1 = true)
- High cross-correlation power present (N = # of DDMs used for which the flag was set to 1 = true)
- Low confidence in GPS EIRP estimate (N = # of DDMs used for which the flag was set to 1 = true)

3.3. Algorithm Production Overview

The binning algorithm produces a minimum variance estimate of the mean wind speed in the bin over the spatial and temporal intervals specified by the bin's boundaries. This is done using an inverse-variance weighted average of all L2 samples of the wind speed that were made within the bin. Specifically, for bin boundaries Lat_{min}, Lat_{max}, Lon_{min}, Lon_{max}, T_{min} and T_{max}, let ***S*** be the set of all L2 samples of the wind speed that do not have either of their fatal quality flags set and which satisfy the following conditions

$$\boldsymbol{S} = \{Sample_i \mid Lat_{min} \le Lat_i < Lat_{max}; Lon_{min} \le Lon_i < Lon_{max}; T_{min} \le T_i < T_{max}) \quad (1)$$

where the i^th sample has bin coordinates (Lat_i, Lon_i, T_i). Sort all L2 wind speed samples, together with their uncertainties, that are in ***S***. The uncertainties are the estimated standard deviations of the wind speed estimates. The Level 3 wind speed estimate for that bin is given by

$$u_{L3}(\boldsymbol{S}) = \frac{\sum_{i\in S} u_i \sigma_i^{-2}}{\sum_{i\in S} \sigma_i^{-2}} \quad (2)$$

where u_i is the i^th L2 minimum variance wind speed in S and σ_i is its uncertainty.

The uncertainty (i.e. standard deviation) in u_{L3} is given by

$$\sigma_{L3} = \sqrt{\frac{1}{\sum_{i\in S} \sigma_i^{-2}}} \quad (3)$$

Relevant quality flags from the L2 wind speed algorithm are compiled into an aggregate set of quality flags for the L3 wind speed produced here. Specifically, for the wind-speed-dependent quality flags:

- Fatal negative wind speed quality flag (N = # of wind speed samples in ***S*** for which the flag was set to 1= wind speed less than –5 m/s)
- Fatal high wind speed quality flag (N = # of wind speed samples in ***S*** for which the flag was set to 1= wind speed greater than 100 m/s)
- Non-fatal negative wind speed quality flag (N = # of wind speed samples in ***S*** for which the flag was set to 1= wind speed between –5 m/s and zero)
- Non-fatal high wind speed quality flag (N = # of wind speed samples in ***S*** for which the flag was set to 1= wind speed between 70 m/s and 100 m/s)

For the rolled-up versions of the quality flags produced by the L1B DDM algorithm:

- Large spacecraft attitude error (M = # of DDM samples in ***S*** for which the flag was set to 1 = true)

- Negative signal power In L2 DDMA area (M = # of DDM samples in ***S*** for which the L1a calibration resulted in at least one bin in the L2 DDM Area (DDMA) having a negative power value.)
- Negative Sigma0 In L2 DDMA area (M = # of DDM samples in ***S*** for which the L1a calibration resulted in at least one bin in the L2 DDM Area (DDMA) having a negative power value.)
- Low confidence in DDM noise floor estimate (M = # of DDM samples in ***S*** for which the flag was set to 1 = true)
- Low confidence in open ocean noise floor estimate (M = # of DDM samples in ***S*** for which the flag was set to 1 = true)
- Low confidence in open ocean noise temperature estimate (M = # of DDM samples in ***S*** for which the flag was set to 1 = true)
- Land present in DDM (M = # of DDM samples in ***S*** for which the flag was set to 1 = true)
- Specular point over open ocean (M = # of DDM samples in ***S*** for which the flag was set to 1 = true)
- Large step change in DDM noise floor (M = # of DDM samples in ***S*** for which the flag was set to 1 = true)
- Large step change in LNA temperature (M = # of DDM samples in ***S*** for which the flag was set to 1 = true)
- Direct signal in DDM (M = # of DDM samples in ***S*** for which the flag was set to 1 = true)
- Low Rx antenna range corrected gain (M = # of DDM samples in ***S*** for which the flag was set to 1 = true)
- High specular point incidence angle (M = # of DDM samples in ***S*** for which the flag was set to 1 = true)
- High cross-correlation power present (M = # of DDM samples in ***S*** for which the flag was set to 1 = true)
- Low confidence in GPS EIRP estimate (M = # of DDM samples in ***S*** for which the flag was set to 1 = true)

3.4. 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}.

Fatal negative wind speed quality flag (N = # of wind speed samples in the lat,lon boundary of ***S*** but not included in ***S*** because the wind speed is less than –5 m/s)

Fatal high wind speed quality flag (N = # of wind speed samples in the lat,lon boundary of ***S*** but not included in ***S*** because the wind speed is greater than 100 m/s)

Non-fatal negative wind speed quality flag (N = # of wind speed samples in ***S*** for which the = wind speed is between –5 m/s and zero)

Non-fatal high wind speed quality flag (N = # of wind speed samples in ***S*** for which the wind speed is between 70 m/s and 100 m/s)

Large spacecraft attitude error (# of true DDM samples)

Negative signal power In L2 DDMA area (M = # of DDM samples in ***S*** for which the L1a calibration resulted in at least one bin in the L2 DDM Area (DDMA) having a negative power value.)

Negative Sigma0 In L2 DDMA area (M = # of DDM samples in ***S*** for which the L1a calibration resulted in at least one bin in the L2 DDM Area (DDMA) having a negative power value.)

Low confidence in DDM noise floor estimate (# of true DDM samples)

Low confidence in open ocean noise floor estimate (# of true DDM samples)

Low confidence in open ocean noise temperature estimate (# of true DDM samples)

Land present in DDM (# of true DDM samples)

Specular point over open ocean (# of true DDM samples)

Large step change in DDM noise floor (# of true DDM samples)

Large step change in LNA temperature (# of true DDM samples)

Direct signal in DDM (# of true DDM samples)

Low Rx antenna range corrected gain (# of true DDM samples)

High specular point incidence angle (# of true DDM samples)

High cross-correlation power present (# of true DDM samples)

Low confidence in GPS EIRP estimate (# of true DDM samples)

3.5. 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)

4. References

Clarizia, M. P., "Algorithm Theoretical Basis Document Level 2 Wind Speed Retrieval," CYGNSS Project Document, SPRL 148-0138, Rev 2, Chg 2, 19 Nov. 2015.

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