Calibration and Unwrapping of the Normalized Scattering Cross Section for the Cyclone Global Navigation Satellite System

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Abstract—This paper develops and characterizes the algorithms used to generate the Level 1 (L1) science data products of the Cyclone Global Navigation Satellite System (CYGNSS) mission. The L1 calibration consists of two parts: the Level 1a (L1a) calibration converts the raw Level 0 delay–Doppler maps (DDMs) of processed counts into received power in units of watts. The L1a DDMs are then converted to Level 1b DDMs of bistatic radar cross section values by unwrapping the forward scattering model and generating two additional DDMs: one of unnormalized bistatic radar cross section values (in units of square meters) and a second of bin-by-bin effective scattering areas. The L1 data products are generated in such a way as to allow for flexible processing of variable areas of the DDM (which correspond to different regions on the surface). The application of the L1 data products to the generation of input observables for the CYGNSS Level 2 (L2) wind retrievals is also presented. This includes a demonstration of using only near-specular DDM bins to calculate a normalized bistatic radar cross section (unitless, i.e., m²/m²) over a subset of DDM pixels, or DDM area. Additionally, an extensive term-by-term error analysis has been performed using this example extent of pixels, or DDM area. The L1 data products are generated in such a way as to allow for flexible processing of variable areas of the DDM (which correspond to different regions on the surface). The application of the L1 data products to the generation of input observables for the CYGNSS Level 2 (L2) wind retrievals is also presented. This includes a demonstration of using only near-specular DDM bins to calculate a normalized bistatic radar cross section (unitless, i.e., m²/m²) over a subset of DDM pixels, or DDM area. Additionally, an extensive term-by-term error analysis has been performed using this example extent of pixels, or DDM area. The L1 data products are generated in such a way as to allow for flexible processing of variable areas of the DDM (which correspond to different regions on the surface). The application of the L1 data products to the generation of input observables for the CYGNSS Level 2 (L2) wind retrievals is also presented. This includes a demonstration of using only near-specular DDM bins to calculate a normalized bistatic radar cross section (unitless, i.e., m²/m²) over a subset of DDM pixels, or DDM area. Additionally, an extensive term-by-term error analysis has been performed using this example extent of pixels, or DDM area.
experiment carried on the UK-DMC satellite, which repeatedly detected signals from ocean, land, and ice surfaces [15], and by the TechDemoSat mission in 2014, which has generated millions of GNSS-R spacecraft measurements [16]. These results demonstrated that GNSS signals are easily detectable from a space platform, with the signals clearly responding to surface conditions. A summary of the GNSS-R technique and its applications can be found in [17]–[19].

After this introduction, an overview of the instrument carried on the CYGNSS observatories is presented in Section II. Section III presents the Level 1a (L1a) calibration algorithm. Section IV describes the forward model and calibration parameters used in the L1b algorithm. Section V describes the L1b calibration algorithm. Section VI provides a brief description of the zenith navigation antenna calibration. Section VII presents a detailed error analysis of the L1 calibration as applied to the CYGNSS DDM area (DDMA) used in L2 wind retrievals, and Section VIII includes a discussion of the results and conclusions.

II. CYGNSS INSTRUMENT SUMMARY

Each CYGNSS spacecraft carries a delay–Doppler mapping instrument (DDMI) capable of locating and tracking GPS signal reflections on the Earth surface and mapping the signal power over a range of time delay and Doppler frequency bins. Each instrument uses two Earth-pointing nadir antennas and a single upward (space)-pointing zenith antenna for navigation and GPS transmitter calibration [1]. The instrument is passive, using the signals being transmitted from the GPS constellation. The instrument autonomously tracks and processes the incoming signal to produce reflected signal power over a range of delay and Doppler bins. It outputs four DDMs every second to the spacecraft onboard computer and has been validated on the TechDemoSat satellite launched in 2014 [16]. The spacecraft then compresses the DDMs and downlinks them for ground processing.

At the receive antenna, the broadband thermal noise up-wellling from the Earth (denoted antenna noise in this analysis) is added to the surface scattered signal. Additional thermal noise generated by the instrument electronics is added as the combined signal passes through the amplification, downconversion, and filtering stages of the receiver. The resulting signal is a combination of these three terms, i.e., one signal and two noise, which is then sampled and processed by the receiver firmware.

For calibration purposes, the DDMI can be modeled by a single gain term applied to the total measured power, where that gain is a combination of hardware and firmware contributions. The complete set of components contributing to the overall gain of the instrument is shown in Fig. 1.

The components in Fig. 1 are briefly summarized as follows:
1) The low-noise amplifier (LNA) provides the initial signal amplification and is located as close as possible to the antenna. In this analysis, this term includes input and output cabling losses. The input to this stage comes directly from the science antenna or the blackbody load resistor (located in the LNA itself).
2) Within the receiver front end, the signal passes through a commandable gain control, which will be initially calibrated on the ground using a cold load input source.
3) The signal then passes through several downconversion and filtering stages in the instrument front end to convert the signal from L-band to an intermediate frequency suitable for digital processing.
4) The downconverted signal is then sampled and quantized by the instrument in preparation for the digital signal processor. The aforementioned commandable gain control will be set to achieve optimal digital sampling at the analog-to-digital converter.
5) The digital signal processor consists of an FPGA-and coprocessor-based system, which cross-correlates the digital samples, generating the raw Level 0 DDM measurements. This block includes the instrument digital processing unit described in more detail as follows.

A. Antennas

For science operations, each CYGNSS satellite carries two six-element array left-hand circularly polarized nadir antennas with a peak gain of approximately 14.5 dBi (from measurements of the 18 flight antennas). The two science antennas are mechanically rolled approximately 20° to project their main beams out in a wide cross-track pattern, each to opposite sides of the satellite ground track. Each antenna has, approximately, a 37° half-power beamwidth in the cross-track direction and a 24° half-power beamwidth in the along-track direction. Additionally, the spacecraft has a low-gain (approximately 4 dBIC) right-hand circularly polarized (RHCP) zenith antenna for use in platform navigation and in estimating the GPS signal transmit power level. More details on the ground coverage of the observatory science antennas is included in [2].

B. Blackbody Calibration Loads

A calibration switch is included in the LNA for each of the nadir and zenith antennas and its dedicated instrument channel. The switch connects the input port of the receiver either to the antenna or to a blackbody calibration target. This permits frequent monitoring and correction for the variations...
in the receiver gain by the L1a calibration algorithm. The
temperature of the blackbody load resistor is monitored with a
thermistor placed within each LNA. Initial thermal analysis has
shown that the range of temperatures that the LNAs (and hence
the blackbody load resistor) are expected to see is between
approximately 14 °C and 20 °C, with slight variations between
the three LNAs due to their locations in the spacecraft.

C. Digital Processing Unit

After the antenna and LNA, the signal enters the receiver,
where it is downconverted, digitized, and processed by a delay–
Doppler mapping coprocessor. The incoming data are processed
using a frequency-dimension-based fast Fourier transform
(FFT) technique known as a “Zoom” Transform Correlator
(ZTC) [20]. The output of the ZTC is a mapping of the signal in
frequency, i.e., 20 bins at 500-Hz steps, and delay over 128 bins
in 0.25-chip steps. The Level 0 DDM downlinked from the
spacecraft includes both signal pixels from the physical surface
area in the vicinity of the specular reflection point and averaged
noise pixels preceding the specular point in delay. The scattered
signal power is processed using a 1-ms coherent integration
interval in each DDM bin, which is followed by 1 s of non-
coherent averaging.

D. CYGNSS L1 Data Products and DDM

Compression Algorithm

A summary of the CYGNSS L1 data products is included in
Table I. The L1 data products are calculated from the Level 0
DDMs and metadata generated by the instrument. The Level 0
DDMs are compressed on board the spacecraft, as described in
the following.

The raw DDM generated by the instrument is compressed to
meet the downlink requirements. The DDM data compression
and decimation algorithm preserves the information needed to
support L1 calibration and L2 wind speed retrieval algorithms
in ground processing. It assumes that all individual pixels in the
DDM are retained, if they lie within approximately 50 km of the specular point. It also averages and calculates statistics on
the noise pixels preceding the signal in delays without scattered
signal power to allow for an accurate estimate of the noise floor.
Account is taken of the following:

1) The uncertainty in the actual location of the specular point
in the DDM computed by the instrument. The instrument
uses a coarse targeting algorithm accurate to only 1 km,
which can result in over 3 chips of error in the targeted
DDM center.
2) The region of the DDM in delay and Doppler space that
lies within a 50-km radius of the specular point.
3) The number of bits of information contained in each pixel
of the DDM is determined based on the detected most
significant set bit in each pixel value. The compression
algorithm stores a sufficient number of bits to capture all
of the information in every pixel, without information loss.
4) The DDM samples with delay values before the specular
point (which contain no reflected signal power), which are
used to estimate the DDM noise floor.

The compressed DDM includes a total of 17 delay bins (at
0.25-chip spacing) and 11 Doppler bins (at 500-Hz spacing).
The specular point is targeted for delay bin 9 (allowing eight
delay bins after specular and eight behind), and the specular
Doppler is targeted for the center bin 5. The total range of delay
samples is given by the sum of the range of delays, over which a
50-km footprint can span, plus the uncertainty in determination
of the delay value of the true specular point in the DDM by the
compression algorithm.

The true location is estimated by the compression algorithm
to within 1 GPS C/A code chip (approximately 300 m) as the
location of the maximum value of a low-pass filtered version of
the full DDM. Subsequently, a more precise geolocation of the
specular reflection point is computed during ground processing,
using the method derived in [2]. Noise samples outside the
compressed 17 × 11 DDM are sent to the ground separately.
Rows preceding the specular point by at least a chip plus the
margin of targeting error are used to ensure that there is no
ocean surface scattered signal present. At a minimum, the mean
value of noise pixels and some associated statistics will be sent
to the ground for every compressed DDM.

By design, the DDM compression algorithm will preserve
all DDM information provided by the instrument with no loss
of information, while minimizing the number of bits needed to
store the DDM. Additionally, any specular point location errors
by the instrument will be corrected on the ground and will affect
neither L1 calibration nor subsequent wind estimation accuracy.

III. L1A CALIBRATION ALGORITHM: COUNTS TO WATTS

The L1a calibration converts each bin in the Level 0 DDM
from raw counts to units of watts. Individual bins of the DDM
generated by the DDMI are measured in raw and uncalibrated
units referred to as “counts.” These counts are linearly related
to the total signal power processed by the DDMI. In addition to
the ocean surface scattered GPS signal, the total signal includes
contributions from the thermal emission by the Earth and the
noise generated by the DDMI itself. The power in the total
signal is the product of all the input signals, which is multiplied
by the total gain of the DDMI receiver. A block representation
of the L1a calibration procedure is shown in Fig. 2. The top box
describes the open ocean calibration used to update the instru-
ment noise lookup tables after launch. The middle box shows
the periodic generation of blackbody calibration DDMs (which
are used during both the open ocean and routine calibrations).
The third box shows the routine calibration performed on every
DDM, i.e., four times per second. The value of a DDM bin in
counts is related to the arriving signal power in watts by

\[ C = G(P_a + P_r + P_b) \]  

(1)

where \( C \) are the DDM values in counts outputted from the
instrument at each delay/Doppler bin. \( P_a \) is the thermal noise

<table>
<thead>
<tr>
<th>Data Product</th>
<th>Dimensions</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Level 1a</td>
<td>17 delay x 11 Doppler DDM</td>
<td>Power (Watts)</td>
</tr>
<tr>
<td>Level 1b σ</td>
<td>17 delay x 11 Doppler DDM</td>
<td>(unitless)</td>
</tr>
<tr>
<td>Level 1b Area</td>
<td>17 delay x 11 Doppler DDM</td>
<td>Area (m^2)</td>
</tr>
</tbody>
</table>

TABLE I

SUMMARY OF CYGNSS L1 DATA PRODUCTS

This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.
power generated by the antenna (in watts). $P_r$ is the thermal noise power generated by the instrument (in watts). $P_s$ is the scattered signal power at the instrument (in watts), and $G$ is the total instrument gain applied to the incoming signal (in counts per watt). The terms $C$ and $P_r$ are functions of delay and Doppler, while $P_a, P_s,$ and $G$ are assumed to be independent of the delay/Doppler bin in the DDM. Noise information is calculated separately for each DDM, using pixels where no signal power is present. Previously, in the literature, this region of the DDM has been referred to as the “Forbidden Zone” [21]. These delay and Doppler bins provide an estimate of the DDM noise power, which is expressed in counts as

$$C_N = G(P_a + P_r).$$  

(2)

Assuming that $P_a$ and $P_r$ are independent of delay and Doppler, all of the DDM samples without signal can be used to estimate the noise level in counts.

A. Noise Power Expressions

All of the expressions in the following describe noise-only power representations and are not calculated from the DDMs. The calibration switch selects between the nadir antenna and a blackbody target as the source of the input signal to the DDMI. When switched to one of the nadir antennas, the signal will consist of both thermal emission from the Earth and the scattered GPS signal. The external antenna noise-only portion of this input can be expressed as

$$P_a = kT_a B_W$$

(3)

where $T_a$ is the top of the atmosphere brightness temperature integrated over the receive antenna pattern, $k$ is Boltzmann’s constant, and $B_W = 1/T_i = 1000$ Hz is the processed signal bandwidth. The bandwidth of the processed GPS signal at the antenna is determined by the coherent integration processing interval, which is $T_i = 1$ ms. When the calibration switch is directed to the blackbody target, the thermal noise power entering the DDMI becomes

$$P_B = kT_B B_W$$

(4)

where $P_B$ and $T_B$ are the blackbody load noise power and the effective temperature of the instrument blackbody load source, respectively. Because there is no external antenna input when the blackbody load is switched in, there is no signal power present. When the CYGNSS observatory is over an area of open ocean, with no land present in the main beam of the instrument surface antenna footprint, the noise power present in the noise-only pixels of the DDMI can be expressed as

$$P_O = kT_O B_W$$

(5)

where $P_O$ and $T_O$ are the noise power and antenna beam-integrated brightness temperature of the ocean, respectively. The value of $T_O$ can be estimated using a microwave radiative transfer model forced by known environmental conditions, which are derived either from climatology or by numerical forecast models such as GDAS or ECMWF. The model temperatures will be generated using daily inputs of sea surface salinity and temperature obtained from the NOAA Global Real-Time Ocean Forecast System.

The effect of wind-induced roughening of the ocean surface on its microwave brightness temperature is accounted for in the CYGNSS ocean brightness model, using the excess emissivity model developed for the NASA Aquarius mission, which includes a radiometer operating at 1413 MHz [22]. The underlying specular emissivity model used for CYGNSS is adjusted slightly, relative to the one used by Aquarius, to account for the difference in operating frequency (1575 MHz for CYGNSS) and for the different range of incidence angles over which CYGNSS views the ocean. However, the wind roughening effect, which is quite small, is assumed to be the same as for Aquarius. Since radiometric calibration of the CYGNSS instruments is performed using average measurements of the ocean over weeks, observations in higher wind conditions will be filtered out to reduce the sensitivity of the calibration to errors in the excess emissivity model and in the reanalysis model estimates of the wind speed.

The thermal noise power of the DDMI instrument can be expressed as a function of its noise figure, or

$$P_r = kT_r B_W = k \left[ (NF - 1)290 \right] B_W$$

(6)
where \( P_r \) and \( T_r \) are the instrument noise power and temperature. The receiver noise figure \( NF \) is directly related to the instrument noise temperature.

### B. Generating the L1a Data Product

1) **Open Ocean Calibration:** The open ocean calibration is used to update the instrument noise \( (P_r) \) and receiver gain \( (G) \) lookup tables in orbit. As part of the open ocean calibration, two DDMI measurements are used together to estimate the instrument noise and gain. These are the following:

1) DDMI noise floor measurements made over areas of open ocean (as determined by the science operations center). This calculation is made using the noise-only pixels of the DDM.
2) Measurements of the blackbody target noise levels calculated using a blackbody noise-only DDM. The ocean noise temperature and the blackbody noise temperature provide low- and high-power anchor points with which a linear calibration curve can be derived. Expressions for the Level 0 DDM measurements in the open ocean and blackbody states are given by

\[
C_O = G(P_O + P_r) \quad (7)
\]

\[
C_B = G(P_B + P_r). \quad (8)
\]

The receiver gain is found by differencing the average blackbody and open ocean counts, resulting in the cancelation of the receiver noise power \( P_r \), i.e.,

\[
C_O - C_B = G(P_O + P_r) - G(P_B + P_r) = GP_O - GP_B. \quad (9)
\]

Solving for the instrument gain, we obtain

\[
G = \frac{C_O - C_B}{P_O - P_B}. \quad (10)
\]

Substituting (10) into (7) gives the instrument noise power as

\[
P_r = \frac{P_O C_B - P_B C_O}{C_O - C_B}. \quad (11)
\]

2) **Routine DDM Calibration:** The routine DDM (in counts) is expressed in (1), which includes the received signal power in watts \( P_g \). In the case of the routine calibration, the individual DDM noise floor and the blackbody noise temperature provide low- and high-power anchor points used to derive a linear calibration equation. The first step in the routine DDM calibration is to correct every DDM by the estimated noise floor using (2), such that we are left with a signal-only DDM, which is scaled by the instrument gain, as follows:

\[
C_g = C - C_N = GP_g. \quad (12)
\]

The instrument gain can be expressed by rearranging (12) and setting this equal to the instrument gain estimated directly from the blackbody load DDM calculated from

\[
G = \frac{C - C_N}{P_g} = \frac{C_B}{P_B + P_r} \quad (13)
\]

where \( C_B \) is the mean count value of the blackbody load DDM, and \( P_B \) is the estimated blackbody load noise power estimated using the thermistor temperature reading near the blackbody load in the LNA input into (4). \( P_r \) is the best estimate of the instrument noise power, which was estimated from a noise–figure–versus–temperature lookup table and validated during the open ocean calibration sequence. By substituting (13) into (12) and solving for the signal power term \( P_g \), we arrive at the final expression for the L1a calibrated DDM as follows:

\[
P_g = \frac{(C - C_N)(P_B + P_r)}{C_B}. \quad (14)
\]

### C. Consideration of Time and Temperature Dependencies

All of the terms in (14) are collected at slightly different times than the actual science measurements themselves, and during these time intervals, it is possible that the noise temperatures can vary slightly from the measurement time. The routine 1-Hz calibration assumes that gain \( G \), antenna noise temperature \( T_a \), and instrument noise power \( P_r \) remain reasonably constant over the combined collection interval for (1) (DDM to be calibrated), (2) (noise floor estimate for the DDM being calibrated), and (8) (the blackbody load noise DDM). Time dependence of each of the terms in the L1a calibration equation (14) are addressed as follows:

1) The science measurement \( C \) is made once per second and provides the reference time for all of the other parameters.
2) The noise measurements \( C_N \) for each science DDM are made at delays without signal power, which are only of the order of a handful of microseconds from the time of the science measurement.
3) The blackbody target power \( P_B \) is determined from a physical temperature sensor measured at 1 Hz and is near enough in time to the 1-Hz science measurements that the physical temperature will not have changed significantly between the thermistor reading and the science measurement.
4) The receiver noise power \( P_r \) is estimated using a lookup table derived from extensive prelaunch measurements and updated on orbit during the open ocean calibration sequence using (11). It is expected that the LNA performance will change slightly as the devices age, and the periodic open ocean calibrations will track these changes over the mission lifetime.
5) The blackbody target measurement \( C_B \) is made within 30 s of the science measurement, and close enough in time that the receiver gain and noise figure have not changed significantly. Additionally, the blackbody measurements will be interpolated to the time of the measurement during ground processing.

The open ocean calibration will occur multiple times every orbit, and the blackbody calibration will be performed every 60 s on orbit for each nadir science antenna. The routine calibration will be performed at 1 Hz on all DDMs output by the DDMI (four per second). Fig. 3 illustrates the actions performed and intervals, for all of the CYGNSS L1a calibration steps.
D. LNA Gain and Noise Figure Temperature Characterization

The LNA noise figure (related to the instrument noise power $P_r$) will be thoroughly characterized as a function of temperature and stored in a lookup table. The LNA gain and noise figure profiles over the expected operating temperatures that the device will experience on the spacecraft will be generated prelaunch and periodically updated on orbit using the open ocean calibration estimates of the instrument gain and noise figure, as expressed in (10) and (11), respectively.

The lookup table is indexed using the physical temperature sensor reading located in the LNA. The dependence of $G$ and $P_r$ on temperature will initially be characterized in prelaunch environmental testing, and the first flight lookup tables will be derived from those test data. Once on orbit, open ocean measurements will be used to track changes in $G$ and $P_r$ as the LNA ages.

E. Illustration of Noise Averaging Effects on L1a Algorithm

The L1a calibration algorithm has been validated using simulated DDMs from the CYGNSS E2ES and by independent analysis. An example of a simulated Level 0 DDM (in counts) and a calibrated L1a DDM (in watts) are shown in Figs. 4 and 5, respectively.

The maximum value in counts of the Level 0 DDM (see Fig. 4) will depend on the simulated or actual signal power, and it is generally on the order of several thousands of counts based on preliminary testing. This includes all the analog and digital processing gain in the instrument processing chain. The L1a DDM (see Fig. 5) is calculated using (14) and is essentially a linear scaling of the Level 0 DDM based on the following: a) the blackbody load power ($P_B$), b) the estimated instrument noise power ($P_r$), and c) the blackbody load DDM mean counts ($C_B$). These values will be constant over all pixels for any individual L1a DDM calibration.

A full error analysis of the L1a calibration is performed in Section VII. However, we have included here an example of the effect of the number of noise bins used during the L1a calibration, as an illustration of its significance. An example of the L1a calibration accuracy as a function of the number...
of noise samples (i.e., pixels used in the estimation of \( C_N \)) is shown in Fig. 6. As part of the CYGNSS observatory onboard compression algorithm, mean noise levels are sent to the ground for every DDM. Currently, we plan to average a total of 52 delay rows (1040 total noise pixels) when estimating the individual DDM noise floor during the routine calibration. This is based on two criteria: a) the “knee” in the curve shown in Fig. 6 and b) the usable range of DDM bins which can be guaranteed not to have signal power present (including the maximum instrument targeting error). Row 52 was selected since it is 12 rows behind the nominal center of the DDM (row 64), and accounts for specular point targeting errors by the instrument. For the case of the blackbody DDMs, all 128 delay rows will be averaged because no signal is present anywhere in the DDM.

IV. FORWARD MODEL OF SCATTERED SIGNAL POWER

A full expression for the GPS scattered signal power was previously derived and published in 2000 [4], as shown in (15). The original representation has been slightly modified in form and variables as follows:

\[
P_{\tau,f} = \frac{P^T A^2}{(4\pi)^3} \int_A \frac{G^T_{x,y} G^R_{x,y} F_{x,y}}{R_{x,y}^2 L_a} \text{d}x \text{d}y
\]

where \( P^T \) is the coherently processed scattered signal power in watts, \( P^T \) is the GPS satellite transmit power, and \( G^T_{x,y} \) is the GPS satellite antenna gain. \( G^R_{x,y} \) is the CYGNSS instrument receiver antenna gain. \( R_{x,y}^2 \) and \( L_a \) are the transmitter-to-surface and surface-to-receiver ranges, respectively. \( L_a \) is the GPS signal spreading function in delay and \( S_{f,x,y} \) is the frequency response of the GPS signal. Exact definitions of these functions can be found in [23]. The surface integration area \( A \) includes the entire region of diffuse scattering over the whole DDM. Within this area, the scattered signal power is processed over a range of relative delays \( \tau \) and Doppler frequencies \( f \). Equation (15) assumes a 1-ms coherent integration time during signal processing. The coherent integration time of 1 ms is based on preliminary analysis performed in [14] and [24]. The former showed the signal coherence to be slightly less than 1 ms for a lower orbiting (i.e., faster moving) platform, and the later showed some evidence that the coherence was longer than 1 ms for a higher orbiting satellite. The fact is that the true coherence of the scattered signal for CYGNSS is not precisely known and is an active area of research. The 1-ms coherent integration time has been partially chosen as a matter of convenience due to the GPS C/A code repeat interval.

Equation (15) can be simplified by calculating effective values for each term under the integral which varies over the extent of the DDM. These values are calculated using the GPS spreading terms over individual delay and Doppler bins. Ideally, all of the terms in the area included in each DDM pixel should be calculated using a full surface integration at a given reflection geometry. However, in some cases, average or specular point values can be used as approximations. Therefore, (15) can be simplified using the effective values of several variables in each bin, resulting in an expression for individual bins of the DDM, i.e.,

\[
P_{\tau,f,x,y} = \frac{P^T \lambda^2 \hat{G}^T_{\tau,f,x,y} \hat{G}^R_{\tau,f,x,y} \bar{A}_{\tau,f} L_a L_a}{(4\pi)^3 \left( \hat{R}_{\tau,f}^2 \right)^2 \left( \hat{R}_{\tau,f}^2 \right)^2 L_a L_a}
\]

where \( \hat{G}^T_{\tau,f,x,y} \) is the effective receiver antenna gain at each delay/Doppler bin, \( \hat{R}_{\tau,f}^T \) and \( \hat{R}_{\tau,f}^R \) are the effective range losses at each delay/Doppler bin, and \( \bar{A}_{\tau,f} \) is the effective surface scattering area at each delay/Doppler bin. The effective scattering areas are calculated based on the measurement specific reflection geometry and include the GPS specific delay and Doppler spreading functions.

Note that a bar above a variable in (16) indicates that that value is an “effective” value, which implies the inclusion of the GPS spreading functions in delay and Doppler for each DDM pixel. The difference between effective and average values for the example of the receiver antenna gain is described in more detail in Section V.

A. Specular Point Calculation

The L1 data product are calibrated and geolocated using a precise surface specular reflection point calculation on the ground using the CYGNSS E2ES. The E2ES implements a fast iterative method for solving the specular point on the WGS-84 Earth model, given the receiver and transmitter locations. Each iteration actually finds the specular point using a spherical Earth approximation; however, the radius of the spherical Earth is determined from the full WGS-84 ellipsoid model at the previous iteration’s specular point location. This results in a fast solution that quickly converges to the true specular location, and this method has been validated by comparing results from the more rigorous method described in [17]. More details on the specular point calculation can be found in [2].
V. L1B CALIBRATION ALGORITHM: WATTS TO SIGMA0

The L1a calibrated DDM represents the received surface signal power in watts over a range of time delays and Doppler frequencies. Before any geophysical parameters can be estimated, these power values must be corrected for non-surface-related terms by inverting the forward model shown in (16), based on the familiar radar equation. In effect, this equation is unwrapped or solved for the parameter of interest, i.e., the bistatic radar cross section. The CYGNSS L1b calibration generates two data products associated with each L1a DDM: 1) a bin-by-bin calculation of the surface bistatic scattering cross section \( \sigma \) (not normalized by scattering area) and 2) bin-by-bin values of the effective scattering areas (calculated as described in the following). These two products will allow users to normalize values of \( \sigma \) to values of \( \sigma^0 \) (scattering cross section per meter squared), over configurable surface extents using the effective scattering area of each DDM bin. The L1a values are corrected for the effects of the transmit and receive antennas, range losses, and other non-surface-related parameters. An overview of the CYGNSS L1b calibration is shown in Fig. 7.

The aforementioned left box shows a summary of the metadata collected by the spacecraft and sent to the ground. The flow down from the top right is the estimation of the GPS transmitter power and antenna gains. The bottom right box shows the CYGNSS E2ES inputs and outputs. All of these elements come together in the middle during the L1b calibration.

A. Calculating an NBRCs

The bin-by-bin sum of scattering cross sections (\( \bar{\sigma}_{\text{total}} \)) and the bin-by-bin sum of effective scattering area (\( \bar{A}_{\text{total}} \)) can be calculated using individual DDM pixels to arrive at an effective normalized radar cross section value, i.e., \( \bar{\sigma}^0 \), over selected regions of the DDM. The resulting expression for \( \bar{\sigma}^0 \) is given by

\[
\bar{\sigma}^0 = \frac{\bar{\sigma}_{\text{total}}}{\bar{A}_{\text{total}}} = \frac{\sum_{i=1}^{N} \sum_{j=1}^{M} \bar{\sigma}_{\tau, f, i}}{\sum_{i=1}^{N} \sum_{j=1}^{M} \bar{A}_{\tau, f, i}} \tag{17}
\]

where \( N \) and \( M \) represent the range of DDM bins for delay and Doppler, respectively, used in calculating both the scattering cross section and effective scattering area DDMs. Depending on the application and the L2 remote sensing algorithm and surface resolution requirements, different regions of the DDM can be used to calculate a single or multiple values of \( \bar{\sigma}^0 \).

B. Region of DDM Used in CYGNSS L2 Wind Retrievals

The L2 CYGNSS wind retrieval data products use a subset of pixels of the downlinked compressed DDM consisting of 3 delay bins and 5 Doppler bins centered at the specular point. This subset of DDM bins is used to calculate \( \bar{\sigma}^0 \) for the baseline CYGNSS L2 wind retrieval algorithm. This region corresponds roughly to a 25 km \( \times \) 25 km surface region, often less, enabling averaging of consecutive DDMs during retrievals. The wind estimation retrieval model used to generate the baseline CYGNSS L2 wind retrievals is described in [3]. This value of \( \bar{\sigma}^0 \), which is specific to the CYGNSS L2 baseline wind retrieval algorithm, is calculated using (17) with \( N = 3 \) and \( M = 5 \), respectively. This is referred to in the following as the DDMA used specifically for the CYGNSS L2 wind retrievals.

C. Expression for Bistatic Radar Cross Section

The final expression for the L1b \( \bar{\sigma} \) DDM can be derived from the expression of the signal forward model, as shown in (16), by solving for the NBRCs term \( \bar{\sigma}^0 \). Since the L1b sigma product will not be normalized, we have removed \( \bar{A} \) from (16) and replaced the normalized radar cross section \( \bar{\sigma} \) with the unnormalized \( \bar{\sigma} \). The result expression for \( \bar{\sigma} \) is given by

\[
\bar{\sigma}_{\tau, f} = \frac{P_{o, \tau, f} (\frac{4\pi}{\lambda^2})^2 L_{a1} L_{a2} I_{o, \tau, f}}{R_{\text{SP}}^T G_{\text{SP}}^T G_{\text{SP}} R_{\text{total}}^T} \tag{18}
\]

where the individual terms in (18) are as follows:

1. \( P_{o, \tau, f} \) is the L1a calibrated signal power at a specific delay (\( \tau \)) and Doppler (\( f \)) bin.
2. \( R_{\text{SP}}^T \) is the total range loss from the transmitter to the surface plus the surface to the receiver at the specular point. When using a relatively small area of the DDM near the specular reflection point, this value can be approximated as the total range from the transmitter to the specular point to the receiver. This term is included in the denominator because it is calculated as a loss \( R_{\text{total}}^T = (1/R^T)(1/R^T) \).
3. \( L_{a1} \) and \( L_{a2} \) are the estimated atmospheric loss corrections from the transmitter to the surface and surface to receiver, respectively.
4) $I_{\tau,f}$ is an additional term used to correct for losses introduced by the DDMI. These include the 2-bit sampling correction and possibly a roll-off correction in the outer Doppler bins due to processing losses inherent in the ZTC of the instrument [20].

5) $P^T$ and $G^T_{SP}$ are the GPS satellite transmit power and antenna gain at the specular point, respectively. These values are estimated as part of mapping the GPS satellite effective isotropic radiated power (EIRP) pattern of the GPS transmitters.

6) $G^{R}_{SP}$ is the receiver antenna gain at the specular point. When using a relatively small area of the DDM near the specular reflection point, and making the measurement with a relatively wide-beam antenna, the difference between the specular, average, and effective values is acceptably small. The difference between the specular point and effective receiver antenna gain is analyzed further in the next section.

D. Effective and Average Calibration Parameters

The influence of the spreading functions and the impact of simplifications during the L1b calibration needs to be carefully considered. The primary simplifications in this regard are using the specular point values of receiver and transmitter antenna gains and path loss values in place of effective values. The CYGNSS measurements have been modeled in detail using the E2ES [2]. Using a long-duration E2ES run, we assessed the impact of using specular point approximations for several parameters on the L2 wind retrievals. This analysis showed that approximating the specular point, gain, and path losses at the specular point still allowed us to meet our wind speed retrieval requirements [3]. With regard to the receive antenna pattern, given its relatively wide main beam and surface footprint, the difference between the effective and specular point values of the receiver antenna gain (over an approximately $25 \text{ km} \times 25 \text{ km}$ area) is reasonably close. When using a relatively small area of the DDM near the specular reflection point, and making the measurement with a relatively wide-beam antenna, the difference between the specular, average, and effective values is acceptably small. The difference between the specular point and effective receiver antenna gain is analyzed further in the next section.

1) Difference Between Effective and Physical Receiver Antenna Gain: The effective receiver gain can be expressed as

$$G^{R}_{Eff}(\hat{\tau}, \hat{f}) = \int \int \int \int \int A \hat{\tau}, \hat{f}, \hat{x}, \hat{y} \Lambda^{2}, \hat{S}^{2}_{\hat{x}, \hat{y}} \, dx \, dy.$$ (19)

Meanwhile, the average value of the receiver gain in each DDM pixel can be expressed as

$$G^{R}_{Average}(\hat{\tau}, \hat{f}) = \frac{1}{A_{\hat{\tau}, \hat{f}}} \int \int \int \int \int A \hat{\tau}, \hat{f}, \hat{x}, \hat{y} \Lambda^{2}, \hat{S}^{2}_{\hat{x}, \hat{y}} \, dx \, dy.$$ (20)

Fig. 8 shows the difference between a) the receiver antenna gain at the specular point, b) the average receiver gain over physical surface area bins within the $3 \times 5$ DDMA, and c) the effective antenna gain over the same physical surface area bins within the $3 \times 5$ DDMA. The average antenna gain is calculated using (20), while the effective values are calculated using (19). Subsequently, the offset between the curves is removed to show the relative difference between the values as a function of incidence angle. It is evident that, over the physical area on the surface roughly corresponding to the $25 \text{ km} \times 25 \text{ km}$ observation resolution, all three values (after offset removal) are close. By removing the offset between the curves, the relative difference in the variables can be observed. The averaged values and the effective value within the near-specular point pixels are all within a couple tenths of a decibel of each other over the complete range of reflection geometries, and within the order of magnitude of errors examined in the error analysis as follows. However, as more pixels in the DDM are included, the effective values can start to diverge from the average and near-specular effective values. This could very well result in the use of effective values resulting in improved L2 wind speed retrievals for techniques that use larger areas of the DDM.

2) Calculating Effective and Physical Scattering Areas: A single delay/Doppler bin will contain the captured scattered power from a distinct physical region on the ocean surface. For each delay/Doppler bin in the DDM, this region will vary both in actual physical size (on the ground surface area) and effective area (including GPS spreading functions). The GPS spreading functions (in both delay and Doppler) increase the effective area (including GPS spreading functions). The GPS spreading functions (in both delay and Doppler) increase the effective area of each delay/Doppler bin, causing power to be “spread” into adjacent delay and Doppler bins from outside the geometry-determined physical scattering area. These functions change the overall power observed. These values are calculated within the CYGNSS E2ES using a surface integration and bin-by-bin application of the GPS spreading functions using an FFT technique [2]. The physical area of each DDM bin can be calculated as follows:

$$A_{\hat{\tau}, \hat{f}} = \int \int \int \int \int A \hat{\tau}, \hat{f}, \hat{x}, \hat{y}.$$ (21)

An example of the physical scattering area for a typical DDM is shown in Fig. 9. Note that points up to and before the specular point bin (i.e., at delays shorter than the specular reflection point delay) have no physical surface scattering area. The power received in the bins before the specular point is due to power
Fig. 9. Physical scattering area (in square meters) for an example DDM reflection geometry. Note that delays before the specular reflection point and delays at and ahead of specular at increasing Doppler also do not correspond to any physical surface region.

Fig. 10. Effective scattering area (in square meters) corresponding to the physical scattering area shown in Fig. 9. This DDM of effective scattering area is a key output product of the L1b calibration, which allows users to calculate normalized values of $\sigma^0$.

being spread into these bins by the GPS spreading functions from physical areas near the specular point. The effective surface scattering area for each delay/Doppler bin is expressed as the ambiguity function weighted surface integration, i.e.,

$$
\bar{A}_{\tau,j} = \int_{A} A_{\tau,x,y}^{2} S_{j,x,y}^{2} dxdy
$$

where the delay spreading function $A_{\tau,x,y}$ and the Doppler spreading function $S_{j,x,y}$ are integrated over the physical surface corresponding to each individual delay/Doppler bin. Fig. 10 shows the effective scattering area DDM corresponding to the physical scattering areas illustrated in Fig. 9.

E. Characterizing the GNSS Transmitters

The GPS transmitted power $P_T$ and transmitter antenna gain $G_T$ can be estimated using a parameterized model of the GPS antenna pattern and a locus of measurements over the entire bottom sphere of the GPS antenna pattern using direct signal power measurements from the DDMI zenith navigation antenna. The baseline GPS antenna patterns will be based on the patterns released in [25] and [26]. Currently, the yaw attitude of the GPS constellation satellites is not being considered but could be if necessary using the model published by Bar-Sever [27]. The known patterns are consistent enough in yaw as to be within the allocated margin of error. With the off-boresight angle $(\theta)$ and azimuth angles $(\phi)$ calculated relative to the GPS satellite frame of reference, the GPS transmitter EIRP, which includes the GPS transmit power $P_T$ and antenna gain $G_T$, can be estimated using the radar equation and indexed as follows:

$$
\text{EIRP}^a = (P_l^d G_T^d) \left(\theta, \phi\right) = \frac{P_l^d R_D^2 (4\pi)^2}{G_D \lambda^2}
$$

where $P_l^d$ is the received direct signal power from satellite $l$, $R_D$ is the direct signal range (the distance between the GPS transmitter and the receiver), $G_D$ is the zenith antenna gain, and $\lambda$ is the GPS L1 wavelength.

F. Validation of the L1b Algorithm

The L1b algorithm was validated using CYGNSS E2ES simulations. The L1b $\sigma$ DDM calculated from the L1a DDM in Fig. 5 is shown in Fig. 13. The DDM of $\sigma$ together with the DDM of effective scattering areas (shown in Fig. 10) were used to calculate $\sigma^0$ observables for a 13-day Nature Run simulation, which included a realistic hurricane [2]. The Nature Run hurricane simulation is described in detail in [28]. The 13 days’ worth of DDMs where then calibrated and inputted into the CYGNSS L2 wind speed retrieval algorithm.

The results of the L1a and L1b DDMA as with respect to Nature Run wind speeds are shown in Figs. 11 and 12. When designing the L2 wind retrieval model functions, the calibration to the L1b DDMA is essential to maintain the required wind speed sensitivity in the wind speed retrieval. The improvement in the spread of the model function relationship between the
observable and Nature Run reference wind speed is clearly evident in Fig. 12 after the application of the L1b calibration. Complete details of the L2 wind retrieval algorithm and validation are included in the companion paper [3].

VI. ZENITH ANTENNA CALIBRATION

The zenith antenna gain is used in the mapping of the GPS transmit power and antenna gains described in Section V-E. The calibration (signal power in watts) of the direct signals received by the zenith antenna is performed along the same general lines as the nadir antennas, with a number of important differences. The power estimates of the received direct signals are used to map the power and antenna gains of the GPS transmit antennas. Important considerations in the calibration of the zenith signal power (with respect to the nadir antenna channels) include the following:

1) The zenith antenna calibration load cannot be switched as often as the nadir antennas because switching to the blackbody calibration load on the zenith channel will cause a navigation outage (and a corresponding science data outage) for up to 30 s.
2) The reference noise floor is not computed as noise samples in a DDM, but as the output of a separate noise channel.
3) The reference noise floor is more susceptible to biases due to cross-correlated power of other GNSS satellites in view. The effect of cross-correlated power on the noise floor estimate will be tested prelaunch and a correction applied if necessary.
4) The cold source reference antenna noise temperature is the deep space noise temperature (as opposed to the open ocean noise temperature).

The longer blackbody calibration interval means that the calibration algorithm has to rely more strongly on a well-characterized LNA noise figure as a function of temperature to estimate changes to the zenith channel receiver noise. Accurately determining the zenith LNA temperature performance and limiting the gradient of the temperature fluctuations seen by the LNA will be of critical importance to accurately determining the noise and signal power coming from the zenith antenna channel.

VII. ERROR ANALYSIS

During this error analysis, the uncertainties present in the CYGNSS L1 calibration algorithm are generally considered as independent uncorrelated error sources. The method for this error analysis is based on that presented in [29].

A. Error Analysis Methodology

The total error in the L1a or L1b calibrated DDM is the root of sum of squares (RSS) of the individual error sources in the independent terms of their respective expressions, which can be expressed generically as

$$\Delta L_{1a,b} = \left( \sum_{i=1}^{x} [E(q_i)]^2 \right)^{\frac{1}{2}}$$

where $L_{1a,b}$ is the L1a or L1b calibrated DDM values, $x$ is the number of independent error terms, and $q_i$ are the respective error parameters. The individual error terms can be estimated by taking the partial derivatives of the calibration equation, such that each error term in the process can be quantized as

$$E(q_i) = \left| \frac{\partial L_{1a,b}}{\partial q_i} \right| \Delta q_i.$$  (25)

B. Quantifying L1a Errors

In the case of the L1a calibration, the final expression for the L1a DDM in (14) can be substituted into (25), such that

$$E(p_i) = \left| \frac{\partial P_r}{\partial p_i} \right| \Delta p_i.$$  (26)

where the individual error quantities are defined as follows: $p_1 = C$, $p_2 = C_N$, $p_3 = P_B$, $p_4 = P_r$, and $p_5 = C_B$. The 1-sigma uncertainties in these quantities are expressed as $\Delta p_i$. Evaluating the partial derivative error terms, we obtain

$$E(C) = \frac{P_B + P_r}{C_B} \Delta C$$

$$E(C_N) = \frac{P_B + P_r}{C_B} \Delta C_N$$

$$E(P_B) = \frac{C - C_N}{C_B} \Delta P_B$$

$$E(P_r) = \frac{C - C_N}{C_B} \Delta P_r$$

$$E(C_B) = \frac{(C - C_N)(P_B + P_r)}{C_B^2} \Delta C_B$$

where the error terms are defined as follows:

1) $\Delta C$: The error inherent in the Level 0 DDMs from the instrument is due to the quantization error in the raw DDM bins. From the CYGNSS DDM compression algorithm, each DDM bin will be quantized over a range of 9 bits, resulting in an error of $1/2^9$.

2) $\Delta C_N$: The error in the estimate of the normal DDM noise floor is a function of the number of noise samples available. See Fig. 6.

3) $\Delta P_B$ is the error in the estimate of the blackbody load DDM noise power, which is related to the error in the blackbody temperature according to (4) and assumed to be $2^\circC$ in this analysis.
C. Quantifying L1b Errors

In order to assess the error in the normalized radar cross section, i.e., \( \sigma^0 \), expressed in (17), (18) has been normalized by the effective scattering area and considered for DDM bins in the CYGNSS L2 DDMA regions (3 delays \( \times 5 \) Dopplers; see Fig. 13), i.e.,

\[
\bar{\sigma}^0_{\text{DDMA}} = \frac{P_{g,\text{DDMA}}(4\pi)^3L_aL_{a2}}{PT^2\lambda^2G_{SP}^TP_{SP}G_{SP}^R G_{SP}^A_{\text{DDMA}}}.
\]

The total error in the L1b DDM is the RSS of the individual errors contributed by the independent terms of (32). Substituting this equation into (25) results in

\[
E(q_i) = \left| \frac{\partial \bar{\sigma}^0_{\text{DDMA}}}{\partial q_i} \right| \Delta q_i
\]

where the error terms are defined as follows: \( q_1 = P_g \), \( q_2 = L_{a12} \), \( q_3 = R^R \), \( q_4 = R^T \), \( q_5 = P_T \), \( q_6 = G^T \), \( q_7 = G^R \), and \( q_8 = A \), respectively. The partial derivatives of the individual error terms can be expressed as

\[
E(P_g) = \frac{(4\pi)^3}{PT^2\lambda^2G_{SP}^TP_{SP}G_{SP}^R G_{SP}^A_{\text{DDMA}}} \Delta P_g
\]

\[
E(L_{a12}) = \frac{P_{g,\text{DDMA}}(4\pi)^3L_aL_{a2}}{PT^2\lambda^2G_{SP}^TP_{SP}G_{SP}^R G_{SP}^A_{\text{DDMA}}} \Delta L_{a12}
\]

\[
E(R^R) = \frac{2P_{g,\text{DDMA}}(4\pi)^3}{PT^2\lambda^2G_{SP}^TP_{SP}G_{SP}^R G_{SP}^A_{\text{DDMA}}} \Delta R^R
\]

\[
E(R^T) = \frac{2P_{g,\text{DDMA}}(4\pi)^3}{PT^2\lambda^2G_{SP}^TP_{SP}G_{SP}^R G_{SP}^A_{\text{DDMA}}} \Delta R^T
\]

\[
E(P_T) = \frac{P_{g,\text{DDMA}}(4\pi)^3}{PT^2\lambda^2G_{SP}^TP_{SP}G_{SP}^R G_{SP}^A_{\text{DDMA}}} \Delta P_T
\]

\[
E(G^T) = \frac{P_{g,\text{DDMA}}(4\pi)^3}{PT^2\lambda^2(G^T)^2G_{SP}^A_{\text{DDMA}}} \Delta G^T
\]

\[
E(G^R) = \frac{P_{g,\text{DDMA}}(4\pi)^3}{PT^2\lambda^2G_{SP}^R} \Delta G^R
\]

\[
E(A) = \frac{P_{g,\text{DDMA}}(4\pi)^3}{PT^2\lambda^2G_{SP}^R G_{SP}^A_{\text{DDMA}}} \Delta A_{\text{DDMA}}
\]

Again, the error analysis was performed for both cases of winds below 20 m/s (with \( \sigma^0 = 20 \text{ dB} \)) and winds greater than 20 m/s (with \( \sigma^0 = 12 \text{ dB} \)).

Errors for the remaining terms of the L1b calibration were estimated using best estimates. Table IV shows the input error values used for the low-wind and high-wind cases, respectively.

---

**Table II**

**Routine L1a Signal Power Calibration Errors. All Units in Decibels. In Both Wind Cases, the Noise Floor Was Computed Using 52 Rows (20 Pixels per Row) of Noise Pixels**

<table>
<thead>
<tr>
<th>Error Term</th>
<th>Low Winds, ( \sigma^0 = 20 )</th>
<th>High Winds, ( \sigma^0 = 12 )</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>( E(C_g) )</td>
<td>0.002</td>
<td>0.01</td>
<td>Quantization error</td>
</tr>
<tr>
<td>( E(C_N) )</td>
<td>0.10</td>
<td>0.14</td>
<td>Noise floor error, counts</td>
</tr>
<tr>
<td>( E(P_g) )</td>
<td>0.01</td>
<td>0.01</td>
<td>Black body load power error ( \Delta T_B = 2 \text{ deg} )</td>
</tr>
<tr>
<td>( E(P_T) )</td>
<td>0.49</td>
<td>0.17</td>
<td>Instrument noise error</td>
</tr>
<tr>
<td>( E(C_p) )</td>
<td>0.06</td>
<td>0.06</td>
<td>Black body noise floor estimate, counts</td>
</tr>
<tr>
<td>Total RSS Error</td>
<td>0.30</td>
<td>0.23</td>
<td>Equations 24 and 26</td>
</tr>
</tbody>
</table>

---

Fig. 13. L1b DDM of (unitless) \( \sigma \) values. This DDM of \( \sigma \) is combined with the DDM of effective scattering areas to generate \( \sigma^0 \) (\( \sigma \) per square meter) for use in L2 wind speed estimation. The number of pixels used is flexible and will depend on the application and inversion technique. The CYGNSS L2 wind retrieval uses a 3 delay bin \( \times 5 \) Doppler bin DDMA.
This article has been accepted for inclusion in a future issue of this journal. Content is final as presented, with the exception of pagination.

TABLE III
ERROR ALLOCATIONS FOR THE RECEIVER ANTENNA GAIN

<table>
<thead>
<tr>
<th>Error Term</th>
<th>Error Magnitude</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spacecraft Pointing Knowledge</td>
<td>0.9 deg (1 σ)</td>
<td>From AODCS Analysis (with Star Tracker)</td>
</tr>
<tr>
<td>Star Tracker Optical/Mechanical Boresight Misalignment</td>
<td>0.4 deg (1 σ)</td>
<td>Rough Estimate From Mechanical Analysis</td>
</tr>
<tr>
<td>Star Tracker to Nadir Antenna Misalignment</td>
<td>0.4 deg (1 σ)</td>
<td>Rough Estimate From Mechanical Analysis</td>
</tr>
<tr>
<td>Mechanical-Electrical Nadir Antenna Boresight Misalignment</td>
<td>0.5 deg (1 σ)</td>
<td>Expected Antenna Calibration Accuracy</td>
</tr>
<tr>
<td>Repeatability of Antenna Gain</td>
<td>0.2 dB (1 σ)</td>
<td>Based on 18 PM Antenna Pattern Measurements</td>
</tr>
<tr>
<td>Antenna Pattern Uncertainty</td>
<td>0.25 dB (1 σ)</td>
<td>Expected Antenna Calibration Accuracy</td>
</tr>
<tr>
<td>RSS (1 σ) Antenna Gain Error</td>
<td>0.43 dB</td>
<td>From Monte Carlo Simulation</td>
</tr>
</tbody>
</table>

TABLE IV
L1B CALIBRATION ERROR ANALYSIS INPUT PARAMETERS

<table>
<thead>
<tr>
<th>Error Term</th>
<th>Error Magnitude</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>ΔP_g</td>
<td>0.30/0.23 dB</td>
<td>From Level 1a Error Analysis, Table II (low winds/high winds)</td>
</tr>
<tr>
<td>ΔL_{a12}</td>
<td>-0.04 dB</td>
<td>Based on Approximate L-Band Attenuations</td>
</tr>
<tr>
<td>ΔR^R</td>
<td>-1000 meters</td>
<td>Determined by Reflection Geometry</td>
</tr>
<tr>
<td>ΔG^T + ΔG^L</td>
<td>0.4 dB</td>
<td>GPS Tx EIRP error</td>
</tr>
<tr>
<td>ΔG^R</td>
<td>0.43 dB</td>
<td>From Monte Carlo Simulation, Table III</td>
</tr>
<tr>
<td>ΔA</td>
<td>0.2 dB</td>
<td>Determined by Reflection Geometry</td>
</tr>
</tbody>
</table>

TABLE V
L1B CALIBRATION ALGORITHM ERRORS (IN DECIBELS)

<table>
<thead>
<tr>
<th>Error Term</th>
<th>L1b error, dB</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>E(P_g)</td>
<td>Low Winds, Less Than 20 m/s</td>
<td>0.50</td>
</tr>
<tr>
<td>E(L_{a12})</td>
<td>High Winds, Greater Than 20 m/s</td>
<td>0.23</td>
</tr>
<tr>
<td>E(R^R) + E(R^T)</td>
<td></td>
<td>0.04</td>
</tr>
<tr>
<td>E(P_g) + E(G^T)</td>
<td></td>
<td>0.40</td>
</tr>
<tr>
<td>E(G^R)</td>
<td></td>
<td>0.43</td>
</tr>
<tr>
<td>E(A)</td>
<td></td>
<td>0.20</td>
</tr>
<tr>
<td>Margin</td>
<td></td>
<td>0.20</td>
</tr>
<tr>
<td>Total RSS L1b Error</td>
<td></td>
<td>0.82</td>
</tr>
</tbody>
</table>

geometry. Each parameter in the Monte Carlo simulation included in Table III is described as follows:

1) Spacecraft Pointing Knowledge: This is an estimate of the errors in the CYGNSS observatory star tracker attitude estimation knowledge, which is based on the star tracker specification and attitude determination simulations.

2) Star Tracker Optical/Mechanical Boresight Misalignment, Star Tracker to Nadir Antenna Misalignment, and Mechanical-Electrical Nadir Antenna Boresight Misalignment errors: These values have been initially estimated (conservatively) using mechanical, structural, and thermal analysis. However, in addition to a purely analytic/mechanical alignment, an optical alignment cube-based transformation calculation will be attempted, which could significantly decrease this error.

3) Repeatability of Antenna Gain: The 18 CYGNSS flight antennas have been delivered and pattern analysis undertaken. Using the measured standalone antenna gain patterns, the 1-sigma value of the measured pattern variability has been calculated.

4) Antenna Pattern Uncertainty: This estimate was arrived at using a combination of error analysis connected to the anechoic chamber measurement setups and confidence in our modeling tools’ ability to predict the measured patterns. A modeling effort is under way to estimate the changes in the antenna patterns, which will occur when the antennas are added to the spacecraft. Preliminary pattern simulation results and additional baseline pattern testing of an antenna mounted to a spacecraft mock-up have allowed us to generate an estimate we have confidence in for this parameter.

D. Rolled-Up L1 Calibration Errors

The rolled-up L1 calibration error was estimated using the results of the analysis earlier, over all accumulated steps of the L1 calibration. This includes rolling the estimated 1-σ error in the L1a calibration into the results of the L1b error analysis (see Table IV). The final estimate of the total L1 calibration errors at the end of the L1b stage consists in taking the RSS of all of the individual error terms contributing to the L1b correction, including the L1a calibration errors shown in Table II. Quantitative values for the total rolled-up L1 calibration error are included in Table V.

The justification for each of the errors in the rolled-up L1 error budget, which is included in Table V, is discussed briefly as follows:

1) Rolled-up L1a error $E(P_g)$: Values taken from Table II based on the rolled-up RSS analysis for the individual L1a error terms. Analysis was done at two different wind speeds to present a high-wind and low-wind case.

2) Total atmospheric modeling error $E(L_{a12})$: Due to its L-band frequency, the atmospheric attenuation errors are expected to be very small [30]. The GPS constellation is, by design, relatively immune to atmospheric conditions, due to its transmit frequency. One of the advantages of GNSS-R is its ability to “see through” rain and measure the surface.
3) Total range error $E(R^R) + E(R^T)$: This error is determined by the uncertainty in three values: a) the observatory (or receiver) position, b) the GPS satellite (or transmitter) position, and c) the estimate of the specular reflection point on the surface. The receiver position is expected to be accurate to less than 5 m [31]. The GPS transmitter positions will be known during postprocessing to less than 1 m [32]. The specular point accuracy is expected to be accurate to within a kilometer [2]. The total effect of all these errors is expected to be nearly negligible.

4) GPS transmitter EIRP error $E(P_r) + E(G^T)$: As discussed in Section V-E, the GPS transmitter EIRP (transmit power plus antenna gain) will be estimated from a lookup table computed using direct signals. A set of baseline GPS antenna patterns (for approximately 2/3 of the constellation) has been released by Lockheed Martin. These patterns have been used to generate the preliminary error estimates for the uncertainty in the GPS power and antenna gain which inputs into the L1b calibration. However, the unknown GPS transmit power levels have led us to set this error term very conservatively.

5) Receiver antenna gain error $E(G^R)$: This is computed using a Monte Carlo simulation, as described in Section VII-C1 and summarized in Table III.

6) Effective scattering area error $E(A)$: Since the reflection geometry is well known with relatively low errors, the CYGNSS E2ES is able to calculate physical and effective scattering areas to a relatively high accuracy. The values selected were based on the worst case errors that could be expected from the simulator.

The difference in the rolled-up L1a calibration term between the high-wind and low-wind cases is what drives most of the overall difference in L1 calibration error between the two wind speed cases. The aforementioned results show that the L1b calibration for the high-wind case is about 20% better (for this general example) than the low-wind case. Note that this is not an indication that the L2 wind retrievals will be better than high winds, as demonstrated in [3].

VIII. CONCLUSION AND DISCUSSION

This paper has described in detail the CYGNSS L1 calibration algorithms. These data products and the associated metadata will be made publicly available to the scientific community on the NASA PO-DAAC for the development of alternative algorithms.

A complete error analysis was performed based on the baseline CYGNSS L2 wind retrieval algorithm, with the resulting errors expected in the total rolled-up L1 calibration estimated. In Table V, the total error in the L1 calibration is estimated to be 0.82 dB (1-sigma) and 0.70 dB (1-sigma), for the wind speed cases below and above 20 m/s, respectively.

The errors for the high- and low-wind-speed cases studied earlier are both within the requirement allocated for the CYGNSS L1 calibration algorithm. The CYGNSS L1 error requirement is 1 dB (1-sigma).

The error term of greatest concern in the L1a calibration is maintaining an accurate determination of the instrument noise power $P_I$ (particularly after launch as the instrument ages). Errors in the estimation of the instrument noise can greatly affect the L1a calibration, more so at low winds. This places added importance on the open ocean brightness temperature model, which will be used after launch to perform the open ocean calibrations used to update the instrument noise lookup tables.

With regard to the L1b calibration, the term of greatest interest is the GPS transmit power and antenna gains. Since we only have prelaunch patterns of a segment of the constellation, great care will be needed to generate GPS satellite unique antenna patterns and transmit power estimates. By using the direct signal power levels, we expect to be able to gather sufficient measurements of the direct signal power to make accurate maps of transmitted power for each GPS satellite. Additionally, all of the accumulated errors influencing the receive antenna power estimates can have a significant effect on the calibration. This has necessitated detailed modeling of the science antennas as mounted on the spacecraft and required us to take extra steps to ensure accurate knowledge of the alignment between the measured modeled science antenna patterns and the spacecraft attitude control system.

REFERENCES


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