Coherent GNSS-Reflections Characterization Over Ocean and Sea Ice Based on Spire Global CubeSat Data

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Abstract—This paper assesses the coherency of GNSS signals reflected off the oceans and sea ice under grazing angle geometries and received aboard Low Earth Orbit (LEO) CubeSats for precision altimetry applications. The coherency is characterized as a function of ocean surface conditions and reflected signal parameters based on Spire Global CubeSat data collected during Jan-Apr. 2019. The data contain 50 Hz GPS L1 and L2 carrier phase estimations obtained by open-loop tracking. Indicators based on the circular statistics of the excess-phase noise are developed to identify coherent and semi-coherent reflections. Based on these indicators, we found that $\sim 1\%$ and $44\%$ of GPS reflections over ocean and sea ice respectively have potential for precision altimetry. The coherent and semi-coherent reflection rate reaches $23\%$ in areas less than 200 km from the coastline and under calm sea conditions. Over young sea ice over the Arctic, this rate can be as high as $70\%$. There is a strong relationship between coherency and signal strength, and the coherency occurrence rate improves as the grazing angle decreases. The quality of the L1 and L2 coherent reflections are similar over sea ice while for reflections over the ocean, L1 signals are predominantly noisier and less coherent than the L2 signals. Using a post-processing filtering method, the semi-coherent reflections can achieve a similar level of altimetry precision as that of the coherent ones, thereby increasing the along track length of the retrieved altimetry profile.

Index Terms—carrier phase estimations, coherent reflections, GPS reflection, ocean surface, precision altimetry, sea ice, semi-coherent reflections.

I. INTRODUCTION

The current global gridded sea surface topography maps are provided by satellite radar altimeters such as Jason-3 and Sentinel 3A [1]. These maps cannot resolve features with a spatial scale of less than $\sim$100 km and their re-visit time is $\sim$10 days. To improve ocean and climate modeling, better spatial and temporal resolution of mesoscale Sea Surface Height (SSH) observations are needed [2]. The upcoming Surface Water and Ocean Topography (SWOT) satellite mission is expected to offer a 2D spatial resolution of 10 km $\times$ 10 km along its swath, although its performance at the mesoscale and sub-mesoscale remains to be demonstrated [3].

A potential alternative to improve the SSH sampling is to operate a constellation of low-cost CubeSats on Low Earth Orbits (LEO) that collect the Global Navigation Satellite System (GNSS) signals reflected off the ocean surface. It relies on the bi-static GNSS Reflectometry (GNSS-R) technique applied to space-based platforms, first suggested by Martin-Neira in 1993 [4]. Remote sensing using signals-of-opportunity such as GNSS reflected off the ocean surface has found applications including ocean winds [5], Significant Wave Height (SWH) [6], sea roughness [7], and ocean altimetry [8], [9], [10]. Several GNSS-R missions have been deployed in recent years. For example, the Delay Doppler Maps (DDM) produced from the UK TechDemoSat-1 (TDS-1) and NASA’s Cyclone Global Navigation Satellite System (CYGNSS) demonstrated the feasibility of the GNSS-R for ocean altimetry, even though the receiver systems were optimized for ocean wind [8], [11]. The DDMs represent the power of the reflected GNSS signal as a function of code-delay and Doppler frequency via cross correlation with a locally generated reference signal. Since they are based on the chip length of the GNSS ranging code, they produce along track SSH at meter-level precision and tens of km footprint size that are inadequate for mesoscale oceanography (e.g. [8], [12]). However, first evidence of mesoscale ocean eddies signature has been detected by combining the dense spatial and temporal data coverage of the CYGNSS constellation [13].

To improve the altimetric precision, GNSS-R carrier phase observables are used. If the GNSS reflections have sufficient coherent energy, then the carrier phase can be estimated with cm-level precision at $\sim$1-3 km spatial resolution at low grazing angles. This enables the application to surfaces that are smooth relative to the GPS L-band wavelength ($\sim$20 cm). Low grazing angles over sea ice or relatively calm ocean surfaces help to reduce the surface roughness effect on the carrier signal. At the extreme near tangent to the surface angles, spaceborne interferometric carrier phase reflected off sea-ice were initially observed during a CHAMP occultation [14] but these near zero grazing angles are too low for precision altimetry. Experiments on coherent reflection tracking for altimetry have been conducted on ground-based GNSS receivers [15], [16], [17], [18], [19] and on airborne receivers [20], [21] including stratospheric balloons [22]. The design of coherent GNSS-R from a CubeSat was first proposed in [23]. Simulation studies were conducted to formulate the pre-requisites and retrieval expectations of spaceborne ocean phase-altimetry [24]. Recently, processing of raw intermediate frequency (IF) GNSS-R signal recorded on TDS-1 and the CYGNSS satellites demonstrated that carrier phase altimetry
from space can achieve better than 10-cm precision over sea ice [25], lakes [10], [26], a river [27], calm oceans [9], [10], and rain forest [10].

Experiments with airborne receivers found that the reflection signal grazing elevation angles within 5-30 degrees and over surface with low wind speeds are more likely to provide coherent GNSS ocean reflections [20]. The first analysis of CYGNSS carrier-phase altimetry data over the oceans around Central America confirms that under grazing geometries coherency occurs for wind speeds < 6 m/s and wave-heights less than 1.6 m [9]. Spaceborne studies show that sea-ice has the potential for strong GNSS coherent reflections [25], [28], [14], [29]. But not enough real data have been collected to determine if the phase-delay altimeter technique from space is viable over a wide range of ocean conditions.

Since 2019, Spire Global Inc. has been operating several polar-orbiting GNSS radio occultation (RO) CubeSats in GNSS-R mode for ocean altimetry by updating their onboard receiver software. These CubeSats already provide atmospheric profiles that are incorporated into weather forecasting models [30]. The new altimetry mode tracks the GPS L1 and L2 signal carrier phases reflected off the ocean surface at grazing angles. Initial results show that the data capture coherent reflections over sea-ice and ocean [29], [31], [32] with altimetry retrievals at cm level over sea-ice and ~2 cm RMS relative to a Mean Sea Surface (MSS) over the ocean [33].

This paper assesses the quality of phase-delay altimetry data collected by 4 Spire CubeSats from January to April 2019. Two characteristics of the Spire CubeSats differ from TDS-1 and CYGNSS. First, unlike the CYGNSS and TDS-1 which use nadir pointing antennas to receive the reflection signals, the Spire CubeSat side-looking RO antennas are repurposed for collecting reflection data at grazing angles. The antenna gain is low for signals with elevations above the Brewster angle because the signals are predominately Left Hand Circular Polarization (LHCP) [34]. The Brewster angle is about 30°, 18°, and 7° for first/multi-year sea-ice, new/young sea ice, and sea-water respectively at GPS L-band frequencies [35], [36]. Second, the Spire CubeSats track both L1 and L2 frequencies, which should improve the ionospheric correction. However, the hardware biases in the current Spire CubeSats receivers are not accurately calibrated which impact the absolute ionospheric correction.

Once the high-rate carrier phase data is gathered, a coherency detection scheme is required to separate signals with precise range information from random noise. The detectability of coherent phase measurements depends on the receiver platform and hardware, carrier phase tracking software, reflection surface properties, and the incident angle of the GNSS signal at the specular point (SP). For signals reflected over smooth ocean surfaces, we expect the coherently reflected signal phase to last over a reasonable amount of time. Techniques to separate the coherent and non-coherent part of the reflection signal waveform based on coherent and non-coherent averaging have been tested on ground, airborne, and space-based platforms (e.g. [22], [37], [38]). For example, [16] applied a maximum phase gradient algorithm to obtain the continuous coherent phase observations for data obtained from a ground-based GNSS interferometric receiver over Disco Bay. For the same experimental setting, [18] implements an algorithm based on the circular nature of the carrier phase to improve the tracking performance over rough-sea states.

For spaceborne observations, the reflection geometry and the speed of the receiver platform are different from the ground-based systems. There are several on-going investigations for ways to detect coherently reflected GPS signals in CYGNSS data. For example, the Phase Power method argues that if the phases are coherent the signal power will systematically increase with the integration time relative to a nominal power, while this is not true for non-coherent reflections characterized with random phases [39]. The Entropy method is based on the assessment of the principal axis decomposition of the zero-delay Doppler waveform: if there is mainly one principal axis of energy direction, the signal is coherent [40]. The third method analyzes the extent of power spread in the delay Doppler space from the CYGNSS level 1 DDM data product: the wider the power spread the less coherent are the reflections [41]. These methods are all based on indicators derived from reflected signal power. Analysis indicates that they offer similar coherent detection results over homogeneous land surfaces [42].

Not all these detection schemes can be applied to the Spire 50Hz phase-delay observations due to the lack of access to the power waveform from the correlator’s output. Moreover, signal power alone may not be a reliable indicator of the usability or quality of the carrier phase measurements. Our examination of 3-month Spire GNSS-R data indicates that a high signal power does not always correspond to high quality carrier phase estimations (see discussions in Section IV). Alternative approaches that directly utilize carrier phase measurements must be explored for reliable coherent detection schemes. [29] presented a GNSS-R signal coherency test based on the circular nature of the excess-phase measurements. [32] proposed a support vector machine (SVM)-based machine learning method that utilizes the circular statistics-based coherency test as its feature and demonstrated 98% detection accuracy when applied to the Spire data. In this paper, we introduce two additional coherency detectors based on the carrier phase circular statistics: one derived from the excess-phase rate and the other from phase noise. These detectors not only detect coherent signals but can also be used to identify semi-coherent reflections. The semi-coherent reflections can be further processed to yield precision phase range for altimetry applications. The introduction of the semi-coherent reflections allows us to extend the altimetry measurement intervals.

The remainder of the paper is organized as the following. Section II describes the Spire CubeSat data used in this study. Section III focuses on the methodologies of carrier phase estimation, the coherency detectors extraction, the detector’s sensitivity analysis, and the classification of coherency regimes. Section IV presents the results of applying the coherency detection and classification to GPS L1 and L2 reflection data collected by Spire CubeSats in Jan-Apr. 2019. A comparison of the results with the signal-to-noise ratio (SNR)-based indicator is presented. The detected coherent and semi-
coherent signal levels as functions of sea surface conditions, spatial patterns, satellite elevation angle, received signal SNR, and dependence on wind speed, wave-height and ice age, as well as the quality of the L1 and L2 reflection signals are discussed in this section. Section V provides examples of altimetry retrievals to validate the performance of the indicators. Conclusions are drawn in Section VI.

II. Spire Global GNSS-R Data

Spire Global Inc. started building commercial GNSS RO CubeSats in 2016. By July 2019, it had about 25+ operational commercial CubeSats orbiting at ∼500 km altitude in various inclinations performing GPS-RO measurements over the ocean and poles. The Lemur-2 micro-satellites are equipped with a dual-frequency (L1 and L2) zenith antenna for precise orbit determination (POD) and high-gain forward- or backward-looking antennas to collect dual-frequency RO data. They carry the proprietary STRATOS payload. The STRATOS receiver outputs are used to retrieve atmospheric profiles and ionospheric measurements. For more information on Spire CubeSat capabilities, readers are referred to [43].

Starting in 2019, Spire reprogrammed some of their operational STRATOS receiver software onboard the CubeSats to operate in a phase-delay altimetry mode. The CubeSats collect the direct and reflected signals using the same side-looking RHCP antenna which was originally intended for RO measurements. Only incident GPS reflection signals at low grazing angles between 5° and 30° over ocean surface and lasting between 1 and 5 minutes are collected. The onboard software performs Open-Loop (OL) tracking of the direct and reflected GPS L1 and L2 carrier signals to generate 50 Hz carrier phase estimations [44].

We evaluate observations collected between January and April 2019 from four Spire LEO CubeSats (SVN 84, 86, 88 and 90) with a total of 2500 reflection events. Fig. 1 shows the SP tracks of these reflection events, color-coded according to the reflection signal SNR values. Table I list the date and number of events for each Spire CubeSat. The variations in the collection dates and number of events are due to the fact that not all four Spire CubeSats are in the GNSS-R altimetry mode during the same time period. The number of daily events collected may not represent the full capacity of a functional altimetry mode during the same time period. The number of daily events for each Spire CubeSat is estimated from the in-orbit measurements. Only incident GPS reflection signals at low grazing angles between 5° and 30° are collected. The onboard software performs Open-Loop (OL) tracking of the direct and reflected GPS L1 and L2 carrier signals to generate 50 Hz carrier phase estimations [44].

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### TABLE I

| Spire SVN | 084 | 086 | 088 | 090 |
|-----------|-----|-----|-----|-----|
| Dates (2019) | 3/21-4/18 | 1/8-1/26 | 3/15-4/18 | 1/24-2/10 |
| # of events | 998 | 276 | 738 | 484 |

Fig. 1. Spire Global CubeSat GNSS-R data coverage map. The tracks of reflections specular points (SP) are color coded according to the received GPS L2 signal SNR averaged over 1 second. Reproduced from [29] Fig. 2.

III. METHODOLOGIES

A. GNSS-R Carrier Phase Estimation Method

The OL carrier phase tracking algorithm employed by the Spire CubeSats generates a local carrier signal replica based on a priori phase model $\phi_0$. The residual carrier phase $\delta \phi$ is the difference between that of the received signal $\phi$ and the local replica $\phi_0$. Both $\delta \phi$ and SNR are estimated from the in-phase ($I$) and quadratic phase ($Q$) components of the prompt correlators at a 50 Hz sampling rate:

$$\delta \phi_L = \arctan(Q_L/I_L)$$  \hspace{1cm} (1)

$$\text{SNR}_L = a_L \sqrt{I_L^2 + Q_L^2}$$ \hspace{1cm} (2)

where the subscript $L = 1, 2$ indicates GPS L1 and L2 carriers respectively, and $a_1 = 0.1263$ and $a_2 = 0.0736$ [44].

The residual phase and the a priori phase model are used to obtain phase estimation:

$$\phi_L(t) = \phi_{L0}(t) + \delta \phi_L(t) + 2n\pi$$ \hspace{1cm} (3)

where $n$ is an integer carrier cycle ambiguity constant along each SP track (event). The onboard a priori phase model $\phi_{L0}$ estimates the SP on the WGS84 reference ellipsoid based on the locations of the GPS satellite and the CubeSat following geometric optics reflection laws. The SP footprint of the carrier phase estimations is represented by the First Fresnel Zone (FFZ) and for a flat surface its size increases as the SP satellite elevation decreases [24], [46]. For a CubeSat at an altitude of ∼500 km, the instantaneous footprint is an ellipse with a major axis extent $\sim 1.4-5$ km in the along-track direction and a relatively constant minor axis extent $\sim$1km. For the Spire events collected in a RO setting with a horizon-looking antenna, the SP ground speed decreases with satellite elevation and the steepness of the change depends on the geometry evolution. Table II lists footprint size and typical ground scan speed for a range of elevations. The phase coherency indicators presented in this paper use 1-second 50 Hz phase measurements. The along track resolution of the indicators is $\sim$6-8 km for signal elevation between 5° and 30°.

We should note that there are other factors besides the...
FFZ that influence coherency and altimetry retrieval precision. For example, the RHCP reflectivity increases as the elevation decreases below the Brewster angle the amplitude of the RHCP reflected signals is larger below the Brewster angle, which includes both coherent and incoherent terms. Another point is a higher coherent-to-incoherent scattering ratio at grazing angles according to the Rayleigh criterion. These factors improve the carrier phase observation quality at low elevations. However, troposphere model corrections have larger errors for very low grazing angle measurements which negatively impact the precision of altimetry retrieval.

| Elevation (°) | 5   | 10  | 15  | 20  | 25  | 30  |
|---------------|-----|-----|-----|-----|-----|-----|
| Semi-major axis (km) | 2.5 | 1.9 | 1.4 | 1.0 | 0.8 | 0.7 |
| Semi-minor axis (km)  | 0.67| 0.58| 0.53| 0.5 | 0.45| 0.43|
| Ground speed (km/s)   | 4   | 4.4 | 4.8 | 5.2 | 5.5 | 5.7 |

**B. GNSS-R Carrier Phase Coherency Indicators**

Determination of the level of coherence in the reflected carrier phase time series is the pre-requisite to the utilization of the carrier phase estimations for precision altimetry applications. Fig. 2 illustrates the difference between coherent and non-coherent reflected signals. Fig. 2a shows two 2-second segments of reflected GPS PRN24 L2 carrier phase estimations collected on February 1, 2019 by Spire SVN090 CubeSat. The coherent nature of the phase measurement is apparent in the top left plot as indicated by the continuous phase values with a relatively constant phase rate, while the top right plot shows random phase values which are characteristics of non-coherent signals. If the phase is coherent, then we should be able to express the phase variation as a rotating phasor in time. For the non-coherent signal, its corresponding phasor is a bundle of random points. These are indeed the cases as shown in Fig. 2b. The coherency detectors described below are derived from the phasor representation of the phase measurements.

Before we dive into the specific coherency detectors, it is important to address the phase measurement model. The reflection signal excess phase is the difference between the received and the modeled phase $\phi_{L0}$. It is computed in real-time by the GNSS receiver onboard a CubeSat. The reflected signal phase model $\phi_{L0}$ is based on the geometric range between the GPS satellite, the SP computed on the WGS84 ellipsoid, and the Spire CubeSat antenna. The reflection signal excess phase includes unmodeled errors in the GPS satellite and the cubeSat positions, instrument and clock bias, atmospheric and ionospheric effects, as well as an error due to the unknown height of the reflection surface. At grazing incident angles and for receivers onboard the CubeSats, the spatial scale variations of the atmospheric and ionospheric effects are much larger than that of the sea surface variations along the $\sim$4 km ground track covered over 1 second. Therefore, the excess phase delay variations are mainly driven by the unmodeled changes in the signal propagation geometric path. The reflection surface height above the ellipsoid over the coherent footprint typically varies slowly along this $\sim$4 km ground track over ocean and sea ice. Consequently, when the phase is coherent its phase-rate is expected to change continuously and gradually.

Since the time interval between two adjacent measurements is constant, the phase rate is directly dependent on the angular phase increment between two adjacent measurements $\delta \phi_L = \delta \phi_L(i + 1) - \delta \phi_L(i)$. If the phase rate is relatively constant, then in a polar coordinate, $\delta \phi_L$ samples should cluster along a narrowly focused direction. When the phase is completely non-coherent, the $\delta \phi_L$ samples are uniformly distributed around the unit circle. Fig. 2c) shows $\delta \phi_L$ samples in the polar coordinates for the coherent and non-coherent segments of data. The clear distinctions between the phase rate in the polar representation for these two examples indicate that it may serve as an indicator for signal coherency.

The circular statistics derived from the phase rate in the polar representation has been applied to ground-based GNSS-R altimetry to detect coherent segments [18] and to estimate the sea-surface-height [47]. We apply the same concept to the space-based GNSS-R measurements. Roesler et al. [29] used two parameters, the circular-length and the circular-kurtosis...
to determine whether an angular set $a_i, i = 1, 2, \ldots, N$ is uniformly distributed around the unit circle. The definitions for the two parameters are based on [48]:

- **Circular-length**: defined as the length of average of the unit vectors of the data set:
  \[
  \zeta = \frac{1}{N} \sum_{i=1}^{N} \cos a_i + \frac{1}{N} \sum_{i=1}^{N} \sin a_i
  \]  
  (4)

- **Circular-kurtosis**: a measure of the “peakedness” of an angular data set:
  \[
  K = \frac{1}{N} \sum_{i=1}^{N} \cos (2(\alpha_i - \bar{a}_i))
  \]  
  (5)

where $\bar{a}_i$ is the mean of the data set. If $a_i$ is uniformly distributed over the unit circle, then $\zeta = 0$ and $K = 0$. If the data set is completely coherent, the phasors should be aligned in one direction and $\zeta = 1$ and $K = 1$. The closer the $\zeta$ and $K$ values are to 1, the more coherent the signal is. The phase rate circular-length and circular-kurtosis are the indicators used in [29].

In this paper, we introduce the circular statistics for phase-noise $\epsilon_{\delta \phi}$ and compare its performance with that of the phase rate $\delta \phi_L$. The phase-noise $\epsilon_{\delta \phi}$ is computed by subtracting a smoothed version of the excess phase. The phase-noise $\epsilon_{\delta \phi}$ for the same two segments of data shown in Fig. 2a are plotted in the polar coordinate in Fig. 2d. For completely non-coherently reflected signals, $\epsilon_{\delta \phi}$ behaves like noise. For coherent reflections, $\epsilon_{\delta \phi}$ varies smoothly and contains information about the reflection surface properties. Reference [49] shows that the additive noise on the phase delay of a GNSS signal follows a von Mises distribution, which is also referred to as the circular normal distribution. A higher noise power is associated with a wider distribution peak. For the examples given in Fig. 2, the polar plots for the phase rate $\delta \phi_L$ and phase noise $\epsilon_{\delta \phi}$ are similar for the non-coherent phase. When the phase is coherent, the mean phase noise direction is near zero, as shown in Fig. 2d. In the following section, we show that the phase-noise statistics is more sensitive to the phase-rate variations within 1 s period and is a better indicator of coherency than that of the phase-rate.

### C. Phase Coherency Indicators Sensitivity Analysis

We use a 2-second excess phase $\delta \phi$ data segment collected by a Spire CubeSat to analyze the sensitivity of the phase-rate and phase noise circular statistics to the coherency level. The first 1-second data is coherent while the remaining 1-second is non-coherent, as shown in Fig. 3. From this 2-second data, we created 11 sets of 1-second data segment by sliding a 1-second window from left to right as illustrated in Fig. 3. These 1-second data segments progressively evolve from being completely coherent in Set 1 to completely non-coherent in Set 11. We then add random noise from a circular Von Mises distribution to each data segment, with noise levels ranging from 0° to 180°. Each noise level is simulated 1000 times to produce a statistical performance measure. At each noise level, the circular length and kurtosis are computed for the phase-noise $\epsilon_{\delta \phi}$ and phase-rate $\delta \phi_L$, for each of the 11 sets.

![Fig. 3. Two-seconds of excess-phase $\delta \phi$ observations with the first 1 s being coherent followed by 1 s non-coherent data. From this 2 s data, we created 11 sets using a 1 s sliding window sliding at 0.1 s increment.](image)

Fig. 4 shows the scatter plots of the phase rate and phase noise mean circular length $\bar{K}$ versus mean circular kurtosis $\bar{K}$ as well as their 1σ-standard deviation of the 11 sets of data for 6 added noise levels: 0°, 18°, 45°, 72°, 108°, 162°. Without additional noise (0°), the phase-rate indicators show the largest separation in $(\bar{K}, \bar{\zeta})$ for all 11 sets of data. As the noise level increases, the mean values decrease while their standard deviations increase, and the values for the data sets also become closer to each other. At noise level 162°, all the sets are non-coherent. The mean circular lengths for the phase-rate $\bar{\delta \phi}$ and phase-noise $\bar{\epsilon}_{\delta \phi}$ fall in the range (0.1, 0.35) and (0.3, 0.6), respectively. Based on examinations of the CubeSat data, a reasonable range of noise is between 45° and 72°.

### D. Coherency Classification Based on Phase Noise Circular Statistics

Based on the discussions above, we focus on using phase noise circular statistics as a coherency indicator to classify the three regimes of coherency over 1-second segment of Spire CubeSat observations: coherent, semi-coherent, and non-coherent. A coherent segment allows precise range estimation of the reflected signal. A non-coherent segment is dominated by noise. When a segment is semi-coherent, it contains a mixture of coherent and non-coherent observations. It can be viewed as “noisy” coherent measurements with a higher probability of carrier phase cycle slips [50]. The question is: what are the boundary values of the circular statistics that define these three regimes?

To obtain the boundary values, we compute the phase-noise statistics over non-overlapping 1-second segment data listed in Table I. Fig. 5 are scatter plots of $\zeta$ and $K$ for reflections over ocean and sea ice. The parallel lines in Fig. 5 divide the data points into “zones”. A higher zone value corresponds to higher $\zeta$ and $K$ values which are characteristic of more coherent reflections.

To obtain a more quantitative indication of the coherency level, we define $P_1(z)$ and $P_2(z)$ as the probability of having at least one and three cycle slips respectively within a zone $z$. For
cycle slips contained by 1-second coherent segment is 15%, semi-coherent reflection is between 15% and 80%, and non-coherent reflections is more than 80%. These boundary values are used to classify the data points in Fig. 5 into coherent, semi-coherent, and non-coherent for ocean and for sea ice.

The boundary values set above also have correspondences with the noise levels shown in Fig. 4. For example, $B_c$ maps to $\zeta = 0.9$ and $K = 0.63$ in Fig. 4 which corresponds to the coherent data segment 1 in Fig. 3 with a 45° added Von Mises noise. $B_{sc}$ maps to $\zeta = 0.72$ and $K = 0.35$ in Fig. 4 which corresponds to the coherent data segment 1 in Fig. 3 after adding 108° Von Mises noise.

We further plotted the pdfs of $\zeta$ and $K$ for the data collected over ocean and sea ice on a log scale in Fig. 7. Over the ocean the dominant non-coherent distribution ends around ($K = 0.4; \zeta = 0.6$), while over sea ice the coherent part starts around ($K = 0.7; \zeta = 0.8$). Furthermore, the extracted distributions of the coherent and semi-coherent intervals appear to follow bell-curve features which again enhance the validity of this classification. Note that the bell-curves are slightly better defined in the circular-length domain.

The boundary values are also consistent with the altimetry retrieving results. Data segments that fall within the coherent regime defined by the boundary value $B_c$ resulted in consistent high precision altimetry results. Data segments from the semi-coherent reflections zones contain weak coherent components that can be easily perturbed by the diffusive scattered signals. For semi-coherent reflections, the phase estimations contain range information but have a low level of cycle slip corruption which can be filtered for precise altimetry applications [50].

Table III summarizes the boundary conditions for the two coherency indicators. In addition, the coherency test requires that a Spire L2 reflection signal SNR > 15 v/v. This value is chosen as the mean + one-standard deviation of the non-coherent ocean SNR (zones 1 to 11). Over sea-ice the value is in the same range. Our analysis indicates that the L2 SNR criteria and the phase noise statistics test yield consistent classification 92% of the time. Close to the boundary zones, there is not always a one-to-one correspondence for levels of coherency between the phase noise and phase rate indicators.
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1) Coherency Occurrence Rate: There is a total of 540,985 consecutive 1-second segments are analyzed for ocean and sea ice as a function of reflected L2 signal SNR. For both ocean and sea ice, the coherency rate increases with the SNR. Based on the occurrence plot, 80% of the reflection is coherent or semi-coherent for SNR > 35 v/v over sea ice. Over the ocean, to have 80% coherent or semi-coherent reflections, the SNR must be over 45 v/v. For SNR at 25 v/v, about 20% and 50% of the reflections are coherent or semi-coherent over ocean and sea ice respectively. To use a detection theme based on the SNR threshold such as SNR > 40 v/v would miss valuable information captured at lower SNR levels and sometimes misinterpret high SNR segments with coherency especially below 60 v/v.

2) Coherency Dependence on SNR: Fig. 8 shows the global maps of the SP tracks of detected coherent and semi-coherent reflections. The left map is color-coded according to the type of surface (ocean and sea ice) and coherency level (coherent and semi-coherent) determined by the phase noise circular statistics. The right map is color-coded according to the reflected signal SNR at L2 band. Comparison between the two maps indicates that in general, the higher L2 SNR values obtained in the Spire data correspond to more coherent reflections. However, there are deviations from this relationship as shown by the green tracks in the map on the right which are associated with reflections that are non-coherent according to the circular statistics but whose SNR values are greater than 18 v/v.

To obtain a more quantitative relationship between coherency levels and the reflection signal SNR, Fig. 9 plots the number of 1-second coherent and semi-coherent segments (left) and their accumulated occurrence rate (right) for ocean and sea ice as a function of reflected L2 signal SNR. For both ocean and sea ice, the coherency rate increases with the SNR. Based on the occurrence plot, 80% of the reflection is coherent or semi-coherent for SNR > 35 v/v over sea ice. Over the ocean, to have 80% coherent or semi-coherent reflections, the SNR must be over 45 v/v. For SNR at 25 v/v, about 20% and 50% of the reflections are coherent or semi-coherent over ocean and sea ice respectively. To use a detection theme based on the SNR threshold such as SNR > 40 v/v would miss valuable information captured at lower SNR levels and sometimes misinterpret high SNR segments with coherency especially below 60 v/v.

3) Coherency Dependence on Elevation Angle: The coherency dependence on elevation has been analyzed in [29]. The conclusion still holds true here even though the coherency indicator is different. For both surface types, the probability of coherency decreases with increasing incident signal elevation angle. This is expected because the relative surface roughness decreases with elevation. In addition, at grazing angles, the RHCP component of the reflected signal is expected to be increasingly dominant with decreasing elevation over both surface types. Consequently, the reflection signal power for the RHCP antenna on Spire CubeSats is higher at lower elevation which may enable better detection of coherent signals at lower elevation [33].

4) Coherency Duration: The duration of coherency, as computed by aggregating consecutive 1-second coherent segments, is longer over sea ice. On sea ice, 25% coherent or semi-coherent observations are over one minute, compared to 2% over the ocean, where most durations are less than 10 seconds.

The coherency duration is also dependent on the sea state and incident signal elevation. Fig. 10 is a scatter plot of Significant Wave Height (SWH) versus coherency duration and
TABLE IV
SUMMARY OF COHERENT MEASUREMENTS BASED ON GPS L2 PHASE-NOISE CIRCULAR STATISTICS.

| Surface type | # of events | # of events with coherent and semi-coherent reflections | # of seconds collected | % coherent and semi-coherent reflections |
|--------------|-------------|--------------------------------------------------------|------------------------|----------------------------------------|
| Ocean        | 2066        | 126 215                                                | 540,985                | 0.4% 0.6%                              |
| Sea ice      | 476         | 295 346                                                | 50,631                 | 23.5% 20.8%                           |

Fig. 8. Left: Tracks of the 1-second coherent reflection specular point tracks color coded according to the reflection surface type (ocean and sea ice) and coherency type (coherent and semi-coherent). Right: L2 SNR. The green tracks are not coherent based on the phase noise circular statistics indicator but have SNR > 18 v/v.

Fig. 9. The reflection signal coherency dependence on received mean L2 signal SNR for ocean (blue) and sea ice (orange). Left: Number of coherent reflection (including semi-coherent) seconds. Right: occurrence rate of coherent reflections normalized by the total number of coherent and non-coherent observations within each SNR bin.

the data points are color-coded according to the incident signal elevation. The figure shows that while there is a widespread of SWH for short coherent duration, longer duration are associated with relatively low SWH. And coherent reflections at higher elevations predominantly occur when the SWH is low and their duration is relatively short.

B. Coherency Spatial Distribution and Dependence on Wind Speed and SWH

Fig. 8 clearly shows that other than a few exceptions off the northwest coast of the USA and one to the east of South Africa, most of coherent and semi-coherent reflections occur near coastal areas. Previous studies have shown that coherent scattering is more prevalent in areas such as Seas of Indonesia where the wind speed is in general low [9], [51]. Our analysis confirms the previous findings. The areas encompassing the Pacific Ocean and East Indonesian Seas are characterized by relatively high coherency occurrence. This is correlated with the relatively low wind speed in these areas. Fig. 11a plots the SP tracks of the coherent and semi-coherent reflections in the area. The area defined by the red rectangle is the Indonesian Archipelago within which the coherency rate is even higher. Fig. 11b shows the probability of low wind speed in the same region. The two maps show that the coherent tracks occur more frequently in regions of high probability of low winds and low SWH. The thresholds used to create the map of low wind occurrence are 7m/s wind speed and 1.5m SWH, similar to values used in [9].

Table V lists the coherent and semi-coherent reflection occurrence rate within 200 km from coast lines and under...
three wind speed thresholds (6, 7, and 8 m/s) for worldwide, the Pacific and East Indonesia Seas area, and the Indonesian Archipelago. The local SWH threshold is 1.5 m.

| Wind Speed Limit (m/s) | None | <6 | <7 | <8 |
|------------------------|------|----|----|----|
| Worldwide              | 5.5% | 15%| 13%| 10%|
| Pacific and East Indonesia Seas | 9%  | 18%| 15%| 13%|
| Indonesian Archipelago  | 11%  | 23%| 20%| 18%|

Table V: Rate of coherent and semi-coherent reflections dependence on wind speed within 200 km from coastlines.

Note that low wind speeds are not a sufficient condition for coherency. For instance, the presence of ocean swells or oil slicks modify the surface roughness regardless of the local instantaneous wind speed, and the local SWH depends on the history of the winds over the previous hours.

To perform a more quantitative analysis of the coherency dependence on wind speed, we identified collocated ASCAT wind speed measurements with the detected coherent reflection from the Spire data. The ASCAT data covers 1800 km wide swaths and are sampled every 25 km along its track. We define collocated ASCAT measurements as data gathered within 2 hours and 20 km radius of Spire ocean data. We sampled the Spire data over 5-second intervals which translates into an along-track sampling ∼25 km. The coherency level of these intervals is set to the maximum coherency level among the 5 seconds of data. This led to 18,500 collocated 5-second intervals. The plots illustrate that for a given satellite elevation bin, the SNR decreases for increasing wind speed until the SNR reaches the cut-off level of ∼15 v/v, below which the signal is too weak to contain any information. As the satellite elevation bin increases from the [5° - 10°] to the [25° - 30°] bin, the peak SNR values within the bins decrease from ∼50 v/v to 20 v/v, while the wind speed corresponding to the cut-off SNR value also decreases.

Because only a limited set of coherent Spire reflections has collocated ASCAT wind speed data, we obtained European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 hourly reanalysis data of wind speeds on 0.25°×0.25° grids, and SWH on 0.5°×0.5° grids [52], [53]. We limit the wind speed data to be within the latitudes range of [−60° 40°] which contains 74,000 5-second data segments. The relationship between the Spire SNR binned by elevation and ERA5 wind speeds behave similarly to the ASCAT wind speeds as shown in Fig. 12 middle panel. We also have the L2 SNR versus SWH for the same satellite elevation angle bins as shown in Fig. 12 bottom panel. Here, the SNR decreases with increasing SWH until it reaches the background level of ∼15 v/v. As the satellite elevation bin increases from [5° - 10°] to [25° - 30°], the peak SNR values decrease from over 50 v/v to 35 v/v while the SWH corresponds to the cut-off SNR decreases from ∼4 m to ∼1.5 m. Those levels are somewhat high, most likely due to increased uncertainty in the SWH values provided by ERA5. Increasing the background SNR level from 15 v/v to 18 v/v would decrease the SWH cut-off from 0.5 to 2 m.

If we assume that ocean data with SNR >15 v/v corresponds to reflections over low wind/wave type surfaces, then only 10% of the data under low wind/wave conditions are coherent.
according to Fig. 12. And they occur mainly close to shore with a 1-sigma distance from coast being less than 100 km. This result over the global ocean is much less than the 33% mentioned in [9] which is based on the CYGNSS carrier-phase observations in a restricted region around Central America with signals at low grazing angles and data collected under low wind/wave conditions. Note that we heuristically selected 15 v/v as the background wind threshold value based on the lowest SNR from the ocean coherent class and the ASCAT wind speed trend. The ERA5 data seem to indicate that a higher background wind threshold level of 18 v/v is more reasonable. With this higher threshold values, the global statistic reaches to 30% of the data over low wind/wave conditions are coherent.

C. Coherence Dependence on Incident Signal Elevation

The upper two panels in Fig. 13 show that most of the wind speed for coherent reflections is below 7m/s with a few values up to 8.5m/s regardless of incident signal elevation at the SP, while the upper SWH levels decrease with elevation from about 2 m to 0.5 m. The strongest SNRs occur at low grazing angles and low wind speeds, which is consistent with the theory. In particular, the ocean reflection below the Brewster’s angle of \( \sim 7^\circ \) is dominantly RHCP which increases the SNR because the Spire antennas have a RHCP configuration. The bottom two panels in Fig. 13 emphasize that the coherency levels are not always related to the SNR levels, and that regardless of elevation, higher coherency levels are observed mainly in the lower SWH boundaries. We get the same pattern using ASCAT-Spire collocated coherent events though the number of collocations is low (150 versus 1000 for ERA5).

We also looked at the coherency dependence on the ERA5 sea wave periods. The trend for wind-wave period and swell-wave period versus elevation over the coherent ocean resemble the ones for wind-speed and SWH respectively. Over coherent seconds the wind-wave periods \(< 4s\) have no dependence on elevation; whereas the swell-wave periods have a dependence on elevation, with larger periods up to 10s found at lower elevations and restricted to 4s at 25\(^\circ\) (not shown).

D. Sea Ice Spatial Patterns and Coherency Dependence on Ice Age

Table IV shows that 44.3% of the reflections over sea ice are coherent or semi-coherent. To better visualize the coherency spatial patterns, the SP track over the Arctic is shown in two one-month periods in Fig. 14. The first period is from January 8 to February 10 collected by Spire SVN 090 and 086 (Fig. 14a). The second is from March 15 to April 11 with data from Spire SVN 086 (Fig.14b). Coherent (red), semi-coherent (black), and non-coherent tracks (blue) are shown in the plots. The first period shows more coherent tracks than the second period. During both periods, the central section around the North Pole is less coherent. This less coherent central area corresponds to the location of the Multi-Year (MY) sea ice, obtained from NSIDC [54] (Fig. 14c). As the sea ice ages, the coherency level of the reflections decreases. Fig. 14d plots the percentage of coherent and semi-coherent reflections based on the three types of coherency tracks shown in Fig. 14a.

We further quantify the coherent and semi-coherent events classification according to sea ice age. Table VI lists the results for reflections occurred above 70\(^\circ\)N latitude. The ice age is obtained from the NSIDC map. For reflections over FY ice surface, 35% are coherent, 25% are semi-coherent, and 25% are non-coherent. For MY ice, only 7% reflections are coherent, 22% are semi-coherent, and an overwhelming 71% are non-coherent. This trend is also evident in Fig. 14b where the coherent data are almost non-existent when the FY ice became older and thicker than in the first period. This is consistent with the results provided in [55] that show how sea ice roughness extracted from reflected GPS signals increase as the ice age increases from new to MY ice. MY ice has low salinity content, and its surface is weathered by the melting ponds. The smooth high-salinity content of new-ice roughens as it
We apply the same phase noise circular statistics as the coherency test to signals over ocean and sea ice. The Spire L1 carrier phase estimations must be corrected for half-cycle jumps that arise from the 50 Hz navigation data modulation. The navigation data is removed by aligning the estimated phase with known data bit stream retrieved from the Bit Grabber Network (bitArc) of Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) [57]. Out of the initial 2500 events, navigation data bits were successfully removed from 1800 events. Note that the L1 SNR is not affected by this correction. Below, we compare the SNR and coherency indicator generated from L1 and L2 measurements.

1) L1 and L2 Reflection Signal SNR Comparison: The variations in reflected signal SNR are in part due to the roughness and the electric permittivity of the ocean surface, as well as the GPS and LEO satellite antenna gain patterns. Higher SNRs are typically associated with more coherent reflections but deviations from this trend do occur, as was discussed in Section III. The general accepted rule of thumb is that non-coherent reflections correspond to SNR < 20 v/v on L1 or SNR < 15 v/v on L2. Typically, L1 SNRs are higher than that of L2. However, the Spire L1 SNR fluctuates more. Our survey of the 3-month Spire data shows that for L2 SNR values above 15 v/v, the average L1 and L2 SNR are 31 and 25 v/v respectively. The standard deviation for L1 SNR is 21 v/v, which is 70% of its mean value. In contrast, the L2 SNR standard deviation is 12 v/v, about 50% of its mean. Larger fluctuations in the L1 SNR imply more risks of cycle slips in the phase estimation [58].

An example of the SNR time series from a reflection event over the South China Sea is presented in Fig. 15. The event lasted 180 s and the satellite elevation at the SP decreased from 15° to 7°. The L2 SNR starts at ~25 v/v, reaching a first peak ~45 v/v, before it returned to just above the baseline followed by another peak. According to the circular statistics shown in the bottom plot, the L2 reflection was semi-coherent once the SNR reached 30 v/v and became coherent over the second plateau. The dip between the peaks is almost at the baseline level, but it is classified as semi-coherent because it occurred at a lower elevation angle when the effective ocean roughness was reduced.

The L1 SNR fluctuation patterns follow that of the L2 SNR but at an enhanced level. Even though L1 SNRs are higher, comparison between L1 and L2 circular statistics show that overall, the L1 signal does not provide additional coherent information over the L2 except over a 2-second period, whereas L2 offers an extra 52 seconds of coherency relative to L1.

Fig. 16 further illustrates the evolution of a 14-second segment dual-band excess-phase observations reflected over sea ice. In this case, the L2 SNR is higher than that of L1 and the L2 circular statistics are also above that of L1.

2) L1 and L2 Reflection Signal Circular Statistics Comparison: Fig. 17 (top) shows scatter plots of L2 versus L1 phase-noise circular kurtosis for ocean (left) and sea ice (right) reflections. For the ocean plot, the data points can be separated

| Coherency type | Ice age <= 1 year | Ice age > 1 year |
|----------------|------------------|-----------------|
| Coherent       | 35%              | 7%              |
| Semi-coherent  | 25%              | 22%             |
| Non-coherent   | 25%              | 71%             |

Fig. 14. SP tracks over the Arctic sea ice for (a) 1/8 to 2/10, 2019 and (b) 3/5 to 4/11, 2019 color coded by coherency levels (non-coherent, lavender; semi-coherent, black; coherent, red). (c) Arctic sea ice age from NSIDC [54] during the third week of January. (d) Percentage of sea ice coherency as a function of ice age over the Arctic based on the tracks shown in (a) and (b).
Fig. 15. An example Spire reflection event over South China Sea of GPS PRN 10 signals reflection collected by Spire SVN 84. The satellite elevation angle decreases from 15° to 7°. Top plot shows L1 (black) and L2 (yellow) SNR. Bottom plot is the $\epsilon_{\delta\phi}$ circular statistics converted to the signed distance from the semi-coherent boundary level $B_{sc}$. This distance is normalized so that the $(K, \zeta) = (1, 1)$ for complete coherent reflection. A negative value means the data is non-coherent. Semi-coherent signal corresponds to 0~0.5. The dots in the bottom plot represent the cases where L1 and L2 have the same coherency classification. There are clusters of dark triangles representing the cases where L1 is non-coherent while L2 is coherent. There is only one yellow triangle which represents when L2 is non-coherent while L1 is coherent.

Fig. 16. An example GPS PRN 26 L1 and L2 reflection signal excess phase over sea ice obtained from Spire SVN 090 on Feb. 4, 2019 with 0 seconds at 10:15:32 UTC. From top to bottom: SNR; L1 excess phase $\delta\phi_1$; L2 excess phase $\delta\phi_2$; $\epsilon_{\delta\phi}$ circular length and kurtosis statistics over 1 second data (x for L1 and o for L2, red for coherent, blue for semi-coherent, and gray for non-coherent.

into two distinct sections: a circular area of non-coherent data with low $K$ values spanning the range of [-0.25, 0.25] and an asymmetric cone-shaped extension with an apex at $K = 1$. In the cone-shaped region, the L2 statistics values are higher than that of L1 as shown by the green squares which are the median of the L1 statistic computed over a data bin width of 0.05. Over sea ice, the plot is nearly symmetric around the unit line, demonstrating that L1 and L2 statistics are consistent with one another. The scatter plot of L1 and L2 phase-noise circular length follow the same tendency (not shown) being asymmetric in the coherent region over ocean but almost symmetric over sea ice.

Fig. 17. Top: Scatter plot of phase-noise $\epsilon_{\delta\phi}$ circular kurtosis $K$ for L2 versus L1 over ocean (left) and sea ice (right). Bottom: Number of L2 vs L1 coherent and semi-coherent seconds in each reflection event. There are 130 (260) “coherent” events over the ocean (sea ice).

We also computed the number of seconds when L2 and L1 reflections are coherent or semi-coherent for events that include at least one coherent or semi-coherent second and plotted the results in Fig. 17 (bottom). Generally, L2 provides more coherent observations than L1 over the ocean. Over sea ice, L1 and L2 coherent occurrences are very close. The correlation slopes between the number of L1 and L2 coherent segments are 1.3 and 1.03 over ocean and sea ice respectively. Table VII summarizes the observed coherency occurrence for L1 and L2 over ocean and sea ice and gives the coherency percentages according to whether one of the signals is coherent ($L_1 \cup L_2$), or both are coherent at the same time ($L_1 \cap L_2$).

V. COHERENCY CLASSIFICATION VALIDATION THROUGH ALTIMETRY RETRIEVAL

Previous studies on the Spire data have shown that cm-level reflection surface height profiles can be obtained with better performance over sea ice than the ocean water [33], [58]. The goal here is to assess the soundness of the coherency level classification and evaluate the quality of the altimetry retrievals in the three coherency regimes. In this section, we first describe the process and methodology of the altimetry
retrieval. Retrieval results and analysis over ocean and sea ice for coherent and semi-coherent reflections are then presented.

A. Phase Altimetry Retrieval Method

Phase altimetry retrieval is the estimation of the reflection surface height above a reference height. We achieve it by subtracting the direct signal phase measurements from the reflected signal phase measurements received on the same antenna. The procedure is similar to the ones described in [25], [33], [58]. Fig. 18 illustrates the geometry of the retrieval. The process is summarized below.

![Fig. 18. Phase altimetry retrieval geometry illustration](image)

Step 1: Obtain coherent phase estimations for direct and reflected GPS L1 and L2 signals, \( \phi_D^L \) and \( \phi_R^L \) by adding the unwrapped phase residuals to the accumulated input Doppler range model. Before the direct and reflected signal phase can be used for the retrieval, the L1 excess-phase must be corrected from half-cycle jumps by demodulating the I/Q correlation outputs with the navigation data bits. Then, the coherent quality test is performed to detect segments that contain coherent and semi-coherent reflections from both reflected L1 and L2 signals.

Step 2: Phase estimation filtering. Depending on the amount of ocean scattered signal that contaminates the coherent portion of the reflected signal, the reflected excess phase may be noisy and contain cycle slips, which create decimeter level or larger jumps in the unwrapped phase. The SCANF (Simultaneous Carrier cycle slip reduction and Noise Filtering) algorithm described in [58] is applied to the reflection observations to mitigate cycle-slips and the noise effect.

Step 3: Compute the bistatic path delay between the reflected and the direct signals:

\[
\Delta \rho_{L,\text{mea}} = \lambda_L (\phi_R^L - \phi_D^L) + \lambda_L n_L
\]

where \( \lambda_L \) is the carrier wavelength, \( n_L \) is the integer carrier ambiguity term.

Step 4: Compute \( H_L \), the surface height deviation from a reference surface \( S_{ref} \):

\[
H_L = -\frac{(\Delta \rho_{L,\text{mea}} - \Delta \rho_{L,\text{mod}})}{2 \sin \theta} = -\frac{-\Delta \rho_{L,\text{res}}}{2 \sin \theta}
\]

where \( \theta \) is the GPS satellite elevation angle seen from the SP and \( \Delta \rho_{L,\text{mod}} \) is the modeled bistatic path delay which includes contributions from the geometric range, troposphere delay, ionosphere advancement, and carrier integer ambiguity. Each of these terms must be corrected to retrieve \( H_L \).

The geometric range is estimated based on the precise positions of the GPS satellite, the Spire CubeSat, and the predicted SP location on the reference surface \( S_{ref} \). In this study, \( S_{ref} \) is the combination of the DTU18 Mean Sea Surface (MSS) [59] and ocean tide from the TPXO8 global ocean tide model [60]. The SPs are computed using the iterative approach described in [61]. The receiver position and clock bias are given in the Spire metadata from the post-processed Spire satellite POD solution, which has cm-level precision [44]. The GPS satellite position and clock bias are derived from the IGS precise orbit data product (www.igs.org).

The tropospheric delay is estimated using the daily global grids of zenith delay and VMF3 mapping functions from the Technical University of Vienna [62]. The first order ionospheric carrier phase advance is estimated by differentiating the L1 and L2 observations. The carrier ambiguity is removed by subtracting a bias between the measured and modelled bistatic delay residual \( \Delta \rho_{L,\text{res}} \) to minimize the RMS between \( H_L \) and \( S_{ref} \). Therefore, the altimetry retrieval provides a relative height profile above the \( S_{ref} \) along the specular track.

B. Altimetry Retrieval Result Analysis

Datasets for each coherency regime are processed and the retrieved relative surface height profiles are analyzed. Unlike the earlier studies [33], [58] where the reflection events last more than 1 minute, the dataset used in this study consists of 30s of observations within a specific coherency regime. The 30s duration is a compromise that ensures a sufficient number of segments for analysis while still providing sufficient observations of deviations between the retrieved surface height and the reference surface. The non-coherent regime provides a baseline when there is no information content about the reflected surface.

We found ∼120 coherent and 23 semi-coherent sets that have duration lasting 30 seconds. The smaller number of semi-coherent segment is due to the fact that they are embedded within coherent or non-coherent segments. We randomly selected 120 set of non-coherent segments. Fig. 19 shows example profiles for the semi- and coherent regimes over the
ocean and sea ice, as well as one for the non-coherent regime. A summary of the key parameters and retrieval results for the five example profiles is provided in Table VIII. Below we examine the properties and accuracy of these example profiles.

1) Circular statistics: The two coherent cases have $\epsilon_{\phi}$ circular statistics parameters ($\zeta$, $\bar{K}$) above (0.9, 0.7), while for the semi-coherent examples, the average circular statistics are (0.8, 0.5) with minimum at (0.7, 0.4). The non-coherent case has ($\zeta$, $\bar{K}$) at (0.4, 0.2).

2) Reflection signal SNR: Fig. 19 row two shows the direct and reflection signal SNR for the 5 example profiles. The SNR levels are above 15 v/v except for the non-coherent example where it is $\sim$10 v/v. For the two coherent cases, the SNRs over sea ice are above 60 v/v with L1 levels higher than L2 by 50%. For the coherent example over ocean, the SNR levels are mostly at around 20 v/v but hit a minimum of 18 v/v towards the end of the track. The coherent ocean reflection example SNR levels are similar to that of the semi-coherent example over sea ice. Also notice that the differences in L1 and L2 SNR depend on the data set, due to a combination of factors such as the reflective surface properties, the GPS antenna transmission patterns, and the Spire CubeSat antenna gain patterns.

3) Phase Discontinuity and Filtering: The SNR level alone is not sufficient to distinguish the coherent regime from the semi-coherent regime. In these examples, the semi-coherent regime is more clearly identified by the discontinuities in the raw L1 and L2 unwrapped phase, shown in the third row of Fig. 19. For the coherent cases, the L2 signal has no discontinuity and there are only a few discontinuities for the coherent ocean case in the L1 band. For the two semi-coherent cases, there are numerous discontinuities in L1 and L2. We applied the SCANF algorithm to reduce the noise and discontinuities in the unwrapped phase measurements. The results are plotted in the 4th row in Fig. 19. We use the RMS difference between the filtered $\delta\phi_{filt}$ and unfiltered $\delta\phi_{unw}$ excess phase as a measure of the improvement in phase discontinuity and noise reduction. The RMS values for the example profiles are listed in Table VIII. The improvement is clearly most prominent for semi-coherent reflections, although the L1 coherent ocean reflection also required extensive repair. In addition, the effect of the ionosphere can be clearly observed by the divergence in the $\delta\phi_{filt}$ between L1 and L2 and can be removed using the difference of the filtered dual-frequency phase estimations.

4) Relative Surface Height Retrieval: The bottom row of Fig. 19 shows the relative surface height retrieval results. The coherent height profiles have an RMS difference of a few centimeters at 50Hz sampling. The semi-coherent examples over sea ice have comparable quality as the coherent ocean example, while the semi-coherent ocean reflection RMS remains within 20 cm. Note that the SP elevation range is lower at $\sim$6° for the semi-coherent ocean case, compared to $\sim$16° in the other sets. This makes its height profile more susceptible to noise in the path delay variations from their $(\sin \theta)^{-1}$ relationship as well as larger troposphere errors. For the non-coherent case, the surface height profile shows no relation to $S_{ref}$, with a large linear trend difference of more than 10 cm/s and a RMS at the meter level, as expected.

Finally, Fig. 20 plots histogram of the RMS height residuals for all cases and for each coherency regime. It shows that the majority of the RMS are below 5cm and above 1m for the coherent and non-coherent regime respectively. The coherent and non-coherent histograms are well separated. The semi-coherent regime seems to have one cluster with the decimeter level RMS values. However, depending on the amount of perturbation within the 30 s duration, the semi-coherent RMS can reach the meter level. If this is the case, the semi-coherent data sets can be further processed either to detect one large jump or be discarded. The median RMS over a 30 s segment is 4.0 cm, 8.5 cm, and 116 cm over coherent, semi-coherent, and non-coherent domain respectively. This result indicates that the introduction of the semi-coherent regime extends the condition to a broader range of measurements that can potentially yield precise altimetry height profiles. More discrimination and quality control can be achieved by studying the RMS between the raw and filtered excess phase.

VI. CONCLUSIONS AND DISCUSSIONS

A. Conclusions

This paper presents an assessment of the coherency of grazing angle reflected GPS signals received by Spire Global CubeSats. The phase coherency is determined using circular length and kurtosis of the excess-phase noise over 1-second segments of data. Boundary values of these two circular statistics indicators are defined to classify the reflection signal as coherent, semi-coherent, and non-coherent based on the occurrence rate of carrier phase cycle slips and validated using altimetry retrieval results. A non-coherent 1 second segment has 80% and 15% or more probability of having 1 and 3 cycle slip occurrence respectively in 1 second segment of data, while a coherent segment has less than 15% probability of having 1 cycle slip and no probability of having 3 cycle slips. A semi-coherent segment has statistics in between these two boundaries. Detecting the semi-coherent segments is especially important over the ocean, because of the relatively low percentage of data in the coherent regime. Analysis of three-month Spire CubeSat data indicates that by combining the semi-coherent and coherent reflections, 1% and 44.3% of GPS L2 reflections contain sufficient coherent energy over ocean and sea ice for altimetry retrieval respectively. These numbers drastically increase if we focus on ocean reflections near coastlines and the sea ice reflections over fresh ice surfaces. For example, the worldwide combined coherent and semi-coherent reflection rate is 5.5% within 200 km from coastlines. Under low wind condition with wind speed less than 6 m/s and SWH less than 1.5 m, this number increases to 15%. In certain areas where the ocean is known to be calm such as the Indonesia Archipelago, the combined coherent and semi-coherent reflection rate can reach 23%. Our analysis also found that while there is a strong relationship between coherency and signal SNR levels, a high SNR is not a sufficient condition for coherency. There are more coherency occurrences as the SP elevation decreases. The quality of the L1 and L2 coherent reflected GPS signals over sea ice are similar, in contrast...
Fig. 19. Five examples of altimetry retrievals over 30s Spire data sampled at 50Hz shown in five columns: (a) Coherent over sea ice; (b) Coherent over ocean; (c) Semi-coherent over sea ice; (d) Semi-coherent over ocean; (e) Non-coherent. The rows from top to bottom are: Specular track; SNR (each horizontal grid line is 20 v/v); Raw unwrapped excess-phase (each horizontal grid line is 50 cm); Filtered excess-phase; Phase-noise $\epsilon_{\delta\phi}$ circular statistics (red: coherent; blue: semi; gray: non-coherent); Altimetry height profile with mean satellite elevation angle over the specular track indicated on the plots.

To noisier L1 reflected signals over ocean. In general, the SNR levels over sea ice are stronger and the coherency duration length longer compared to over the ocean surface. The coherency spatial patterns over sea ice also have a strong dependence on ice age, with the fraction of coherent reflections being higher over younger, newer ice. Based on the Spire data analysis, the coherent and semi-coherent reflection rate is 70% over first year, fresh sea ice in the Arctic region. As the ice ages, this rate goes down to 32%.

Finally, this study shows that by using post-processing filtering methods such as SCANF, the semi-coherent reflection signals can be used to retrieve surface height with nearly the same precision as that of coherent reflection. This is especially true when the semi-coherent segments are embedded within coherent ones. The inclusion of the semi-coherent segments will increase the along track length of the retrieved altimetry profile without the need to change the hardware/software onboard the LEO satellites.
TABLE VIII  
SUMMARY OF CHARACTERISTICS OF THE EXAMPLE DATASETS SHOWN IN FIG. 18

| Minimum SNR (v/v) | (a) Coherent: sea ice | (b) Coherent: ocean | (c) Semi-coherent: sea ice | (d) Semi-coherent: ocean | (e) Non-coherent |
|-------------------|-----------------------|---------------------|---------------------------|-------------------------|------------------|
| L1                | 90                    | 10                  | 20-35                     | 22                      | 10               |
| L2                | 60                    | 25                  | 20                        | 20                      | 20               |
| GPS elevation at SP (°) | 16.5-17.9            | 15.8-17.1           | 17.1-18.5                 | 6.7 -7.8                | 17.9-19          |
| (ς, K) from εϕ | (0.95, 0.8)            | (0.9, 0.7)          | (0.8, 0.5)                | (0.8, 0.6)              | (0.4, 0.2)       |
| RMS(δϕunw − δϕθm) (cm) | L1 0.86              | 75                  | 52                        | 171                     | 275              |
| L2                | 0.93                  | 1.5                 | 82                        | 30                      | 145              |
| RMS(H − Sref) (cm) | L1 3.50               | 4.25                | 3.40                      | 12.30                   | 116              |

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