ABSTRACT

Earth’s surface bistatic reflectivity $\Gamma_{LHCPCyGNSS}$ profiles are obtained using Global Navigation Satellite Systems Reflectometry (GNSS-R) products from NASA’s Cyclone Global Navigation Satellite Systems (CyGNSS). The focus of this study is to evaluate the influence of the GNSS satellites’ elevation angle $\theta_e$ on $\Gamma_{LHCPCyGNSS}$. Specific target areas with differentiated scattering media are selected to characterize these profiles as a function of the land-cover type and the wind-speed regimes for ocean-surfaces. In the former case, the main interest is to further understand the function $\Gamma_{LHCPCyGNSS} = f(\theta_e,...)$ in preparation of the potential application of the so-called Tau-Omega model to GNSS-R. In the latter case, the objective is to analyze the impact of the coherent scattering component in GNSS-R observables. Preliminary results show $\Gamma_{LHCPCyGNSS}$ increases $\sim 3.7$ dB over land and $\sim 5.3$ dB ocean, as $\theta_e$ moves from $\sim [70,90]^\circ$ to $\sim [20,40]^\circ$.

INDEX TERMS— GNSS-R, CyGNSS, bistatic reflectivity, elevation angle, coherent and incoherent scattering

1. INTRODUCTION

Improving the spatio-temporal sampling properties of GNSS-R [1-3] depends on the number of in-orbit receivers, the use of beam-forming strategies, and the directivity of the down-looking antennas. GNSS-R sampling properties improve the performance for mesoscale studies, Soil Moisture Content (SMC) determination, and Vegetation Water Content (VWC) monitoring, as compared to conventional Nadir-looking missions. The interferometric GNSS-R (iGNSS-R) proposes the use of several high-gain beams to increase the altimetric precision (Root Mean Square Error RMSE), while providing good sampling properties. On the other hand, the use of the conventional GNSS-R (cGNSS-R) for scatterometry purposes requires only relatively low-gain antennas. The recently launched CyGNSS 8-microsatellite constellation provides an unprecedented spatio-temporal sampling of the Earth’s surface. The selected signal correlation technique is cGNSS-R, the Left Hand Circular Polarization (LHCP) down-looking antennas gains is $\sim 14.7$ dB (antenna boresight), and the orbital inclination is $\sim 35^\circ$ [4]. The mission key-requrement is to provide wind speed estimation over tropical cyclones.

Here, CyGNSS Level 1 Science Data Record is used trying to extend the mission scientific applications [4,5] also to land surfaces. In particular, the objective of this work is to evaluate the impact of the GNSS satellites’ elevation angle $\theta_e$ on the reflected signals’ power levels for different surface types. GNSS-R land applications require further research due to the complex properties of this scattering media as compared to ocean. In the past, several research groups provided useful information about the scattering properties and the possibility e.g. to apply GNSS-R for SMC determination. More recently, new important conclusions were derived: a) over nearly bare-soil target areas, the measured sensitivity to SMC using data from UK TDS-1 was $\sim 38$ dB/(m$^2$/m$^3$) [6]; b) over the complete Earth’s surface, 1-year averaged Polarimetric Ratio (PR) from a GNSS-R experiment onboard SMAP and SMC based on the multi-temporal dual-channel algorithm [7] showed a Pearson $r \sim 0.6$ [8]; c) $\theta_e$ should be considered to apply the so-called Tau-Omega model in the GNSS-R case [6], d) the vegetation introduces short-term (volume scattering) and long-term (interference from “big” scatterers and canopy inhomogeneity) fluctuations on the GNSS signals [9].

2. GNSS-R BISTATIC REFLECTIVITY AS A FUNCTION OF THE ELEVATION ANGLE

The signal power received by a GNSS reflectometer [1,4,8] at a certain polarization $p$ or $q$, can be derived under the bistatic radar equation as follows [10]:

$$
\left| Y_r(t,f) \right|^2 = \frac{P_T^2 K^2}{(4\pi)^2 R_{T}^2 R_{R}^2} G_T G_R \rho |\chi(t,f)|^2 \sigma_p^0 \rho^2, \tag{1}
$$

where $P_T$ is the transmitted power, $G_T$ and $G_R$ are the transmitter and receiver antenna gains, $\chi$ is the Woodward Ambiguity Function (WAF), $R_T$ and $R_R$ are respectively the ranges from the transmitter and the receiver to the specular point, $\sigma_p^0$ is the bistatic scattering coefficient, and $\rho$ is the polarization of the emitted GNSS signals.

In a general scenario, the $p$-polarized bistatic scattering coefficient can be theoretically defined as the sum of the cross-polar $\sigma_{pq}^0$ and the co-polar $\sigma_{pp}^0$ terms [11]:

$$
\sigma_p^0 = \sigma_{pq}^0 + \sigma_{pp}^0 = \frac{4\pi R_{T}^2 |E_{s\rho}|^2}{|E_{s\rho}|^2 A_0 \sin \theta_e} + \frac{4\pi R_{R}^2 |E_{s\rho}|^2}{|E_{s\rho}|^2 A_0 \sin \theta_e}, \tag{2}
$$

where $\theta_e$ is the elevation angle of the scattered signal, $E_{s\rho}$ and $E_{s\rho}$ are the scattered and the incident electromagnetic fields, and $A_0$ is the area of the scattering surface projected over the horizontal plane.
GNSS satellites signals are emitted at Right Hand Circular Polarization (RHCP), although with a certain degree of ellipticity. After scattering over a surface, they become LHCP for $\theta_s$ higher than the Brewster angle, while they are mainly RHCP for lower $\theta_s$. Additionally, the scattering over the biomass introduces a significant degree of depolarization in the signals. The two components RHCP (co-polar) and LHCP (cross-polar) should be considered simultaneously in this case.

The scattering over land and ocean surfaces is composed of both a coherent $\sigma_{p,coh}^0$ and an incoherent $\sigma_{p,incoh}^0$ contributions in different proportions depending on the properties of the scattering medium, and the directions of incoming and outgoing electromagnetic waves. Thus, the bistatic scattering coefficient can be assumed to be composed of two different terms as follows:

$$\sigma^0 = \sigma_{p,incoh}^0 + \sigma_{p,coh}^0.$$  \hspace{1cm} (3)

The calculation of $\sigma^0$ based on models requires several hypothesis, such as e.g. about the dielectric permittivity of the lower media (soil, water, ice, ocean) and the distribution of the surface elevation slopes $Z_s = \sigma_{RMSE}/L$ [12]. The RMSE of the surface height variation $\sigma_{RMSE}$ and the surface correlation length L describe the statistical variation of the random component of surface height relative to a reference surface.

In the framework of this study, using CyGNSS mission LHCP products, the main interest is on the cross-polar reflectivity term $\Gamma_{pq}$, corresponding to both the incoherent $\Gamma_{pq,incoh}$ and the coherent $\Gamma_{pq,coh}$ scattering regimes [13]:

$$\Gamma_{pq,incoh} = \frac{1}{4\pi} \int_{0}^{\pi/2} \int_{0}^{\pi} \vert \sigma_{pq,incoh}(\hat{k}_r,\hat{k}_t) \vert \cos \theta_e d\theta_\phi d\theta_s,$$  \hspace{1cm} (4)

$$\Gamma_{pq,coh} = \frac{1}{4\pi} \int_{0}^{\pi/2} \int_{0}^{\pi} \vert \sigma_{pq,coh}(\hat{k}_r,\hat{k}_t) \vert \cos \theta_e d\theta_\phi d\theta_s,$$  \hspace{1cm} (5)

where $\hat{k}_r$ and $\hat{k}_t$ are the unit vectors in the receiver and transmitter directions, and $\theta_\phi$ is the azimuth angle of the scattered signal. Here, it should be considered that GNSS-R scattering is strong only over an area around the nominal specular point ($\theta_s = \theta_e = \theta_\phi$). CyGNSS experimental reflectivity $\Gamma_{LHCP,CyGNSS}$ includes both coherent and incoherent contributions. It is estimated as the peak of the reflected $Y_{r,Peak,LHCP}$ and the direct $Y_{d,Peak,RHCP}$ power waveforms peaks, after compensation of the noise power floor and the antennas' gains as a function of the elevation angle:

$$\Gamma_{LHCP,CyGNSS} = \left( \frac{\left| Y_{r,Peak,LHCP} \right|^2}{\left| Y_{d,Peak,RHCP} \right|^2} \right).$$  \hspace{1cm} (6)
Fig. 3. Normalized (probability density function estimate) histograms of $\Gamma_{\text{LHCP, CYGNSS}}$ over croplands (a,b), Amazonian rainforest (c,d), Seas of Indonesia (e,f), and Indian Ocean (g,h) at $\theta_e \sim [70, 90]^0$ (a,c,e,g), and $\theta_e \sim [20, 40]^0$ (b,d,f,h). It is worth noting that high values of kurtosis [Tables I&II] are observed over the Indian Ocean, where the scattering is mainly/totaly incoherent.

3. IMPACT OF THE ELEVATION ANGLE ON SPACEBORNE GNSS-R EXPERIMENTAL DATA

Figures 1a-f show 1-month (September-October 2017) of averaged reflectivity $\Gamma_{\text{LHCP, CYGNSS}}$ values over land [Figs. 1a,c,e] and ocean [Figs. 1b,d,f], for elevation angles in the ranges $\theta_e \sim [70,90]^0$ [Figs. 1a,b], $\theta_e \sim [45,65]^0$ [Figs. 1c,d], and $\theta_e \sim [20,40]^0$ [Figs. 1e,f]. The averaging is performed using a 0.1° by 0.1° latitude/longitude grid, in steps of 0.1°. It appears that the reflectivity $\Gamma_{\text{LHCP, CYGNSS}}$ increases from $\theta_e \sim [70,90]^0$ to $\theta_e \sim [20,40]^0$: $\Gamma_{\text{land,70<\theta_e<90}} \sim -15.8$ dB, $\Gamma_{\text{land,20<\theta_e<40}} \sim -12.1$ dB, $\Gamma_{\text{ocean,70<\theta_e<90}} \sim -19.4$ dB, and $\Gamma_{\text{ocean,20<\theta_e<40}} \sim -14.1$ dB; but it decreases from $\theta_e \sim [70,90]^0$ to $\theta_e \sim [45,65]^0$ because the incoherent scattering term could be dominant in this range: $\Gamma_{\text{land,45<\theta_e<65}} \sim -17.7$ dB, $\Gamma_{\text{ocean,45<\theta_e<65}} \sim -20.3$ dB. Also it is worth noting that the Brewster angle could potentially appear in the range $\theta_e \sim [20^0, 40^0]$. In this situation, the co-polar reflected signal would overpass the cross-polar one. Nonetheless, $\Gamma_{\text{LHCP, CYGNSS}}$ appears larger than in the range $\theta_e \sim [70^0, 90^0]$ [Fig. 1]. It could be expected $\Gamma_{\text{LHCP, CYGNSS}}$ would decrease for lower $\theta_e < 20^0$, especially over vegetated surfaces. This study over specific target areas [Figs. 2,3 and Tables I&II] is useful to analyze separately the impact of different surface properties on $\Gamma_{\text{LHCP, CYGNSS}}$.

Over land-surfaces [Figs. 1a,c,e], there is a coherent component $\sigma_{\text{coh}}^p$ [14]. The width of the correlated waveform (WF) [10] is much narrower than over the ocean surface. In this situation, the footprint is roughly limited by half of the first Fresnel zone. This improved spatial resolution $\sim 150$ m (depending on the geometry) and the high spatio-temporal variability of the permittivity over land surfaces, explain the significant variability of reflectivity values $\Gamma_{\text{LHCP, CYGNSS}}$ [Figs. 1a,c,e].

The biomass attenuates and depolarizes the GNSS signals. The attenuation due to vegetation can be modeled as $L_{\text{canopy}} = e^{\tau_{\text{canopy}}/\sin(\theta_e)}$, where $\tau_{\text{canopy}}$ is the Nadir optical depth of the vegetation layer [6]. This attenuation is due to signal propagation through vegetation, and thus it increases for lower $\theta_e$. On the other hand, the vertical stalks scatter more vertically polarized waves, contributing to depolarize the GNSS signals [8].

In this work, the effect of vegetation is assessed over two different target areas:

a) Cropland [Figs. 2a, 3a,b and Tables I&II]: The mean $\Gamma_{\text{LHCP, CYGNSS}}$ values increase $\sim 4.2$ dB for decreasing $\theta_e$, as an indication of a higher signal coherence for lower $\theta_e$ values [14,15].

b) Amazonian Rainforests [Figs. 2b, 3c,d and Tables I&II]: The high Above Ground Biomass (AGB) values up to $\sim 350$ tons/ha attenuates strongly the GNSS signals. However, the $\Gamma_{\text{LHCP, CYGNSS}}$ increment due to the coherent scattering over the soil and inland water bodies compensates this attenuation. As a consequence, there is a global $\Gamma_{\text{LHCP, CYGNSS}}$ increment $\sim 3.4$ dB. On the other hand, the shape of the histograms remains approximately like a Rayleigh one, as an indication of a total incoherently scattered electromagnetic field [14].

Over ocean-surfaces [Figs. 1b,d,f], the incoherent component $\sigma_{\text{incoh}}^p$ is dominant for moderate-to-strong wind speed conditions [10]. In this situation, the footprint is limited by the first iso-delay...
TABLE I: Statistical analysis of the bistatic reflectivity $\Gamma_{\text{LHCP,CyGNSS}}$ distribution over different target areas for elevation angles in the range $\theta_e \sim [70, 90]^\circ$.

|          | Cropland | Rainforests | Seas Ind. | Indic. Oc. |
|----------|----------|-------------|-----------|------------|
| SD [dB]  | 3.7      | 4.2         | 3.7       | 1.9        |
| Mean [dB]| -9.7     | -15.5       | -17.4     | -20.3      |
| Kurtosis | 4.84     | 2.5         | 4.8       | 8.2        |
| Skewness | -1.26    | 0.17        | 1.1       | 1.7        |

TABLE II: Statistical analysis of the bistatic reflectivity $\Gamma_{\text{LHCP,CyGNSS}}$ distribution over different target areas for elevation angles in the range $\theta_e \sim [20, 40]^\circ$.

|          | Cropland | Rainforests | Seas Ind. | Indic. Oc. |
|----------|----------|-------------|-----------|------------|
| SD [dB]  | 2.8      | 4.4         | 3.3       | 2.8        |
| Mean [dB]| -5.5     | -12.1       | -11.7     | -15.8      |
| Kurtosis | 4.4      | 2.7         | 3         | 6.8        |
| Skewness | -0.76    | 0.15        | 0.2       | 1.3        |

element as a function of the surface elevation slopes $Zs$. The variability of $Zs$ dominates $\Gamma_{\text{LHCP,CyGNSS}}$ over the permittivity changes due to fluctuations on the surface salinity levels. In this sense, the 1-month averaged $\Gamma_{\text{LHCP,CyGNSS}}$ values are mainly linked to the “long-term” winds. Here, the effect of $Zs$ is assessed over two different target areas:
a) Seas of Indonesia (low wind-speed regimes) [Figs. 2c, 3e,f and Tables I&II]: The mean $\Gamma_{\text{LHCP,CyGNSS}}$ values increase $\sim 5.7$ dB for decreasing $\theta_e$. Additionally, the kurtosis of the normalized histograms tends to $\sim 3$. This value corresponds to a Gaussian distribution, indicating the presence of a coherent component in the total scattered electromagnetic field [14].
b) Indian ocean (moderate-to-strong wind-speed regimes) [Figs. 2d, 3g,h and Tables I&II]: The mean $\Gamma_{\text{LHCP,CyGNSS}}$ levels are the lowest being observed in this study. The incoherent scattering term $\sigma_{\text{Linc}}^0$ is dominant. Even in this situation, there is a $\Gamma_{\text{LHCP,CyGNSS}}$ increment of $\sim 4.5$ dB associated to decreasing $\theta_e$.

4. CONCLUSIONS

Preliminary results showed that spaceborne $\Gamma_{\text{LHCP,CyGNSS}}$ profiles are differentially influenced by $\theta_e$ over different surface types. The increment of the scattered signals’ coherence for low $\theta_e$ over soil and inland water bodies, has to be considered for the experimental determination of $\text{L}_{\text{canopy}}$ from a spaceborne sensor. As such, $\theta_e$ plays an important role in the application of the so-called Tau-Omega model. On the other hand, over ocean surface, this study showed that the $\Gamma_{\text{LHCP,CyGNSS}}$ distributions over target areas with expected low-wind conditions tend to be like a Gaussian one. This indicates the presence of a coherent component for low $\theta_e$. For increasing $\theta_e$, there are also relatively high power peaks, however the distribution becomes more like a Rayleigh one. The incoherent scattering dominates in this situation.

As a main conclusion of this work, it has been found a strong increment on $\Gamma_{\text{LHCP,CyGNSS}}$ for $\theta_e \sim [20, 40]^\circ$ over land and ocean surfaces, that could be associated to an amplification of coherent scattering effects because of a lower effective Earth’s surface roughness at L-band.

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