DESERT ROUGHNESS RETRIEVAL USING CYGNSS GNSS-R DATA

Mehrez Zribi ¹, Donato Stilla ¹,², Nazzareno Pierdicca²

¹ CESBIO; (CNES/CNRS/INRAE/IRD/UPS), 18 av. Edouard Belin, bpi 2801, 31401 Toulouse cedex 9, France; donystilla@hotmail.it; mehrez.zribi@ird.fr
² Department of Information Engineering, Electronics, Telecommunications, Sapienza University of Rome, Via Eudossiana 18, 00184 Rome, Italy; nazzareno.pierdicca@uniroma1.it

ABSTRACT

The aim of this study is to assess the potential use of data recorded by the Global Navigation Satellite System Reflectometry (GNSS-R) CYGNSS constellation to characterize desert surface roughness. The study is applied over the Sahara, the largest non-polar desert in the world. This is based on a spatio-temporal analysis of variations in Cyclone Global Navigation Satellite System (CYGNSS) data, expressed as changes in reflectivity ($\Gamma$). In general, the reflectivity of each type of land surface (reliefs, dunes etc.) encountered at the studied site is found to have a high temporal stability. A grid of CYGNSS $\Gamma$ measurements has been developed, at the relatively fine resolution of 0.03° x 0.03°, and the resulting map of average reflectivity, computed over a 2.5-year period, illustrates the potential of CYGNSS data for the characterization of the main types of desert land surface (dunes, reliefs, etc.). A discussion of the relationship between aerodynamic roughness and CYGNSS reflectivity is reported. An aerodynamic roughness ($Z_0$) map of the Sahara is proposed, using four distinct classes of terrain roughness.

Keywords—CYGNSS; GNSS-R; roughness; desert

1. INTRODUCTION

Desert areas play an essential role in regional climates, due primarily to the transfer of aerosols. In this context, numerous studies have mapped the properties of desert surfaces, in particular parameters such as their aerodynamic roughness [1-2].

In this context, over the last fifteen years we have witnessed the arrival of GNSS-R (Global Navigation Satellite System Reflectometry) technology, which initially demonstrated its considerable potential for the characterization of ocean surface properties (waves, etc.) [3-4]. It was then tested over continental surfaces, where it revealed its strong potential for the monitoring of various surface parameters, such as the water content of the soil or vegetation biomass [5-7]. The CYGNSS mission, developed by the University of Michigan and the Southwest Research Institute and sponsored by National Aeronautics and Space Administration (NASA), was launched in 2017 [8]. It was designed to improve hurricane forecasting with measurements of wind speed, and to study interactions between air and water surfaces during the tropical cyclone season, including in high precipitation conditions. This satellite system comprises eight micro-satellites, fitted with the Global Positioning System (GPS) receiver payloads. These are referred to as Delay Doppler Map Instruments (DDMI), and their operating principle relies on the reception of the GPS signal power reflected by the Earth’s surface, given as a function of the delay and Doppler shift.

The aim of the present study is to analyse the potential of CYGNSS GNSS-R data for desert surface applications. This paper is organized as follows: section 2 provides a general description of the studied site and the datasets considered in this study. Section 3 describes the methodology used to interpret and map the CYGNSS data recorded over the Sahara. Section 4 focuses on the results, and discusses the relationship between reflectivity and surface roughness (aerodynamic or geometric). Our conclusions are provided in section 5.

2. STUDIED SITE AND DATABASE

2.1. Studied site

The results described and discussed in this paper refer to data recorded over the Sahara Desert, in North Africa (Figure 1); the considered areas are situated between 15°0’ N and 37°30’ N, and between 17°0’ W and 39° 30’ E, with some specific areas being selected for further analysis. The Sahara contains a large number of heterogeneous environments: sand dunes, flat rocky surfaces, high mountains and volcanic rocks. Furthermore, the Sahara encompasses various distinctly different climate zones, including a Mediterranean climate along its northern extremity, an extremely arid central zone with rare rainfall events, and a southern zone, which receives some rain during the monsoon season.
2.1. Database

2.1.1 CYGNSS data
The main dataset used for this analysis is the Level 1 (L1) CYGNSS data, version 2.1, obtainable from the Physical Oceanography Distributed Active Archive Center (PODAAC) (https://podaac.jpl.nasa.gov). In this research, almost 2.5 years of CYGNSS acquisitions, recorded between March 2017 and July 2019, have been processed and analyzed. In order to filter the data correctly, bitwise quality flags are provided to select the best data, and in the present study all available quality flags were considered and set to 1. The theoretical footprint of a reflected GNSS signal is ~0.5 × 0.5 km, for the case of a smooth surface and a receiver at the altitude of CYGNSS. The receivers integrate signals over 1 s. During this period of time, the receiver travels ~7 km. Thus, the smallest area of ground from which reflections are received is ~7 × 0.5 km.

The signal over land includes both coherent and incoherent scattering, with relative weight that is subject to discussion. The main observables related to the two mechanisms are the reflectivity and the Normalized Radar Cross Section, respectively. Here we refer to the reflectivity (Γ), which should then be considered as an “equivalent reflectivity” that is derived from the CYGNSS data as suggested by [9] using the following expression:

\[ \Gamma(\theta) = \frac{(4\pi)^2 (P_{DDM} - N) (R_r + R_t)^2}{\lambda^2 G_r G_t P_t} \]  

(1)

where \( P_{DDM} \) is the maximum value of the analog power in the Delay/Doppler Maps (DDM), \( N \) is the noise floor related to the DDM, \( R_r \) is the receiver-specular point (SP) distance, \( R_t \) is the transmitter-specular point (SP) distance, \( \lambda \) is the wavelength, \( \theta \) is the incidence angle, \( G_r \) is the receiver antenna gain in the direction of the specular point (SP) and \( G_t P_t \) is the transmitter equivalent isotropically radiated power (EIRP). The noise floor is computed as the mean value of the DDM subset, when the signal is absent (located above the characteristic horseshoe shape of the DDMs).

The data are collected in daily data frames, taking into account various empirical filters used to remove noisy data, which could otherwise be expected to degrade the quality of the imagery and subsequent analysis.

2.1.2. Ground measurements of aerodynamic roughness
In this study, we made use of ground measurements of aerodynamic roughness, measured over the Sahara Desert, provided in the study of Marticorena et al. (1997) [10]. As listed in Figure 1, 23 areas are considered, corresponding to a wide range of surface conditions (dunes, smooth surfaces, reliefs etc.). The same database was also used in the past to develop aerodynamic roughness maps, based on data recorded by the ERS scatterometer [2].

3. METHODOLOGY

This section proposes a methodology to process CYGNSS data over desert surfaces.

3.1. CYGNSS data normalisation

Several studies have highlighted the influence of incidence angle on reflectivity, and in the present study the role of this effect needs to be assessed for different types of surface topography. In Figure 2, computed reflectivity derived from Eq. 1 is plotted as a function of the incidence angle for two different areas with the whole temporal dataset.

It can be seen that the incidence angle has a very limited effect for incidence angle values between 2° and 30°. As shown in Figure 2, a simple linear normalization is thus proposed, referring to an incidence angle of 20°, in order to account for the small influence of the incidence angle on the reflectivity. We use the following expression:

\[ \Gamma(20^\circ) = \Gamma(\theta) - A \cdot (\theta - 20^\circ) \]  

(2)

where the parameter A is the slope of the retrieved least squares linear relationship between reflectivity and incidence angle, for a given type of surface.

Figure 2. Plot of variations in CYGNSS reflectivity as a function of incidence angle over Algeria dunes.
3.2. Temporal stability of CYGNSS data

In the case of desert areas, remotely sensed signals, and in particular microwave measurements, are in general found to be very stable. In this context, in order to ensure that the retrieved values of reflectivity are accurate, it is essential to evaluate their temporal stability. Figure 3 plots the signals retrieved over Algerian dunes. A 2.5-year time series is shown, with the plotted values corresponding to the mean reflectivity, within a 3-month period and a relatively small (0.1° x 0.1°) zone. The reflectivity plotted in Figure 3 confirms the high temporal stability of the data, with a negligible standard deviation (std dev), less than 0.5 dB.

![Figure 3. Temporal variations of CYGNSS reflectivity over a period of more than two years over Algerian dunes](image)

3.3. Reflectivity mapping over Sahara

Following normalization of the CYGNSS measurements and validation of the stability of the Sahara’s reflectivity during the studied period, the data were arranged in a grid format, each pixel of which corresponds to the mean value over the full period of observation, i.e. nearly 2.5 years. The challenge of this process is retaining the finest possible grid resolution, with the constraint of using a sufficiently large number of observations to ensure the accuracy of the resulting average value. For this purpose, three different resolutions were tested. Figure 4 shows the reflectivity histograms obtained with resolutions of 0.1°, 0.05° and 0.03° (close to 3.5 km), and simple Gaussian distributions fitting the experimental data. We finally chose the grid at a resolution of 0.03°, thus allowing the finest possible geometrical structures to be resolved from the processed data. It is interesting to confirm that this corresponds to a CYGNSS spatial resolution of about 3.5 km. It is important to note that the purely coherent signal has a spatial resolution corresponding to the first Fresnel zone, whereas the spatial resolution (~25 km) of the purely incoherent signal, represented by an iso-delay ellipse projected on the ground, depends on the chip range resolution (~300 m) of the GPS L1 C/A signal. This empirical result shows that we can distinguish details, which are larger than the Fresnel zone, but also much smaller than the resolution of the incoherent signal.

![Figure 4. Reflectivity histograms for three spatial resolutions: 0.1°, 0.05° and 0.03°, at Kufrah area (Libya)](image)

Grid points that were not covered by at least four measurements were not included in the final grid. These points correspond mainly to high altitude zones (> 650m), for which the data were not analyzed (see before about data filtering). Figure 5 shows the resulting reflectivity map at a resolution of 0.03° x 0.03°, which covers the latitudes between 15° N and 37°30’ N and the longitudes between 17° W and 39°30’ E. In Figure 5, mountains and areas with low received signals are masked with white colour.

![Figure 5. Average reflectivity [dB] map (mosaic) of the Sahara region, with a gridded-pixel size of 0.03° x 0.03°. Mountains and areas with low received signals are masked (white colour)](image)

4. RESULTS AND DISCUSSIONS

In this section we focus on the relationship between the CYGNSS reflectivity and the large-scale roughness observed over different types of Sahara environment. We discuss the influence of the aerodynamic roughness length $Z_0$ on the signals received by CYGNSS.

4.1. Aerodynamic roughness length vs CYGNSS data

This section discusses the influence of aerodynamic roughness. The analysis is based on ground measurements
illustrated in [10]. For each area with available ground
measurements, the mean value of CYGNSS $\Gamma$ is computed.
Figure 6 shows the empirical relationship between
reflectivity $\Gamma$ and $Z_0$ for the ground measurement areas
considered in [10]. An approximately linear trend is found,
with a correlation $R^2$ equal to 0.81.

\[
\Gamma = -26.53 \times Z_0 - 16.9
\]

**Figure 6.** Plot of the aerodynamic roughness length as a
function of CYGNSS reflectivity

In conclusion, the results of this study illustrate the
relevance of CYGNSS reflectivity measurements for the
retrieval of aerodynamic roughness lengths in desert
locations [11].

5. CONCLUSIONS

GNSS-R data derived from CYGNSS observations have
been used for the first time for characterizing surface
properties in a major desert area. This study demonstrates
the strong stability of GNSS-R reflectivities ($\Gamma$) in the
Sahara Desert, meaning that a long-term average of the
reflectivity can be used to accurately characterize surface
properties. Thanks to this high stability, a grid could be
produced for the mapping of the average reflectivity, with a
fine resolution of 0.03° x 0.03°. The main structures of the
dunes and reliefs are thus qualitatively observable. Using
ground measurements of aerodynamic roughness, a
relatively strong correlation is observed between the surface
parameters and the reflectivity, with the correlation $R^2$
equal to 0.81 for the aerodynamic roughness.

ACKNOWLEDGEMENTS

This study was funded by GLORI (TOSCA/CNES) project.

6. REFERENCES

[1] B. Marticorena, M. Kardous, G. Bergametti, Y. Callot, P.
Chazette, H. Khatteli, S. Le Hégaret-Mascele, M. Maillé, J. L.
Rajot, D. Vidal Madjar, and M. Zribi, “Geometric and
aerodynamic surface roughness in southern Tunisia and their
relation with radar backscatter coefficient”, *Journal of Geophysical
research*, Vol. 111, F03017, 2006.
[2] C. Prigent, I. Tegen, F. Aires, B. Marticorena, and M Zribi,
“Estimation of the aerodynamic roughness length in arid and semi-
arid regions over the globe with the ERS scatterometer”, *Journal of
Geophysical Research*, Vol. 110, D09205, 12p, 2005.
[3] M. Martin-Neira, “A Passive Reflectometry and Interferometry
System (PARIS)- Application to ocean altimetry”, *ESA J.*, vol. 17,
pp. 331–355, 1993.
[4] V.U. Zavorotny, S. Gleason, E. Cardellach, and A. Camps,
“Tutorial on Remote Sensing Using GNSS Bistatic Radar of
Opportunity”, *IEEE Geosci. Remote Sens. Mag.*, 2, pp. 8–45, 2014.
[5] D. Masters, P. Axelrad, and S. Katzberg, “Initial results of
land-reflected GPS bistatic radar measurements in SMEX02”,
*Remote Sensing of Environment.*, 507–520, 2004.
[6] M.P. Clarizia, N. Pierdicca, F. Costantini, and N. Flourey,
“Analysis of CYGNSS Data for Soil Moisture Retrieval”, *IEEE
Journal of Selected Topics in Applied Earth Observations and
Remote Sensing*, pp.1-9,2019.
[7] E. Motte, M. Zribi, P. Fanise, A. Egidio, J. Darrozes, A. Al-
Yaari, N. Baghdadi, F. Baup, S. Duyau, R. Fieuzal, P.-L. Frison, D.
Guyon, and J.-P. Wigneron, “GLORI: A GNSS-R Dual
Polarization Airborne Instrument for Land Surface Monitoring,”
*Sensors*, vol. 16, no. 5, p. 732, May 2016.
[8] C. Ruf et al., “New ocean winds satellite mission to probe
hurricanes and tropical convection”, *Bull. Amer. Meteorol. Soc.*
vol. 97, pp. 385–395, 2016.
[9] N. Pierdicca, L. Guerriero, R. Giusto, M. Brogioni, and A.
Egidio, SAVERS, “A Simulator of GNSS Reflections from Bare
and Vegetated Soils”, *IEEE Transactions on Geoscience and
Remote Sensing*, 52, pp. 6542-6554, 2014.
[10] B. Marticorena, G. Bergametti, B. Aumont, Y. Callot, C.
N’Doumi, and M. Legrand, “Modeling the atmospheric dust cycle:
2. Simulation of Saharan dust sources”, *J. Geophys. Res.*, 102, pp.
4387–4404, 1997.
[11] D. Stilla, M. Zribi, N. Pierdicca, N. Baghdadi, and M. Huc,
“Desert Roughness Retrieval Using CYGNSS GNSS-R Data”,
*Remote Sens.*, 12, 743, 2020.