THE GRSS STANDARD FOR GNSS-REFLECTOMETRY

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ABSTRACT

In February 2019 a Project Authorization Request was approved by the Institute of Electrical and Electronics Engineers (IEEE) Standards Association with the title "Standard forGlobal Navigation Satellite System Reflectometry (GNSS-R) Data and Metadata Content". A Working Group has been assembled to draft this standard with the purpose of unifying and documenting GNSS-R measurements, calibration procedures, and product level definitions. The Working Group (*http://www.grss-ieee.org/community/technical-committees/standards-for-earth-observations/*) includes members, collaborators, and contributors from academia, international space agencies, and private industry. In a recent face-to-face meeting held during the ARSI+KEO 2019 Conference, the need was recognized to develop a standard with a wide range of operations, providing procedure guidelines independently of constraints imposed by current limitations on geophysical parameters retrieval algorithms. As such, this effort aims to establish the fundamentals of a potential virtual network of satellites providing inter-comparable data to the scientific community.

***Index Terms*—** GNSS-R, standard, satellite network

1. INTRODUCTION

The proposed IEEE standard discussed herein will be submitted under the sponsorship of the Geoscience and Remote Sensing Society (GRSS) and will be limited to GNSS-R. The scope of this effort is to develop a standard for data and metadata content arising from space-borne missions [1,2].

The primary objectives of this activity are three-fold:

a) To define a comprehensive, accurate, and clear set of low level parameters that form a standard Level 1-A (instrument measurements) and Level 1-B (calibrated) product. The choice of parameters will be sufficient to enable the accurate retrieval of at least the most common GNSS-R products (for example ocean wind speed and surface altimetry, surface water, soil moisture content, and above ground biomass).

b) To specify the structure and content of the data in order to enable common application of software processing tools and retrieval algorithms. This includes, but is not limited to: units of measure, data organization, data description, data encoding, and data storage format. Data volume must be also considered.

c) To define associated quality flags and metadata that provide as much information as possible to potential users, including the type of GNSS-R instruments, instrument calibration and characterization procedures, description of input signals etc.

Secondary objectives include providing initial definitions for potentially associated L2 geophysical products and of their properties (spatial and temporal resolution, uncertainties, etc).

This paper is organized as follows. Section 2 provides an overview of different GNSS-R techniques with a focus on space-borne applications. Section 3 describes the past, present, and future space-borne missions that host a GNSS-R payload. Section 4 provides an initial assessment of the potential measurements that shall be generated, while Section 5 discusses some technical aspects that are critical for these objectives. Finally, the main conclusions are included in Section 6.

2. GNSS-R TECHNIQUES

It is understood that there are several different techniques for producing GNSS-R measurements, and it is the intention of the Working Group that the standard be applicable generally to all of them. The Working Group has identified, presently, the four current or proposed GNSS-R techniques used in space-borne applications:

- Conventional GNSS-R or cGNSS-R [3-7]: cGNSS-R correlates coherently during T_c seconds (typically 1 ms for GPS and 4 ms for Galileo) the reflected signal with a locally generated replica of the transmitted signal after proper compensation of the Doppler frequency shift, for a number of Doppler frequencies and relative time delays.
- Interferometric GNSS-R or iGNSS-R [3,4]: In iGNSS-R the reflected signal is cross-correlated with the direct signal itself after proper Doppler frequency and delay adjustment.

- Reconstructed-code GNSS-R or rGNSS-R [8,9]: rGNSS-R is similar to the cGNSS-R technique, but semi-codeless techniques are used to reconstruct the P(Y) or other codes which are then correlated with the reflected signal.
- Partial iGNSS-R [10]: Partial iGNSS-R is similar to the iGNSS-R technique, but the P and M code components of the direct signal are extracted from the reference signal (direct signal) by coherent de-modulation, and the direct signal so derived is then applied to the reflected signal.

3. PAST, PRESENT, AND FUTURE SPACE-BORNE GNSS-R MISSIONS

In defining the standard, a top priority is that it be applicable to the wide range of past and present space-borne GNSS-R missions including:

Mission	Date	GNSS-R type	Band/Pol used	GNSS system used
UK-DMC [11]	2003	cGNSS-R	L1/ LHCP	GPS
UK-TDS-1 [12] (Fig. 1)	2015	cGNSS-R	L1/ LHCP	GPS
CYGNSS [2] (Fig. 2)	2016	cGNSS-R	L1/ LHCP	GPS
3Cat-2 [13]	2016	cGNSS-R rGNSS-R iGNSS-R	L1 + L2/ LHCP + RHCP	GPS GLONASS Galileo BeiDou
SMAP GNSS-R [14]	2017	cGNSS-R	L2/ H+V	GPS
BuFeng-1 A/B [15]	2019	cGNSS-R	L1/ LHCP	GPS BeiDou
Spire [16]	2019	cGNSS-R	L1/ LHCP	GPS Galileo

Planned future missions are also under development:

Mission	Date	GNSS-R type	Band/Pol used	GNSS system used
Fengyun-3 series [17]	2020	cGNSS-R	L1/ LHCP	GPS Gailleo BeiDou
3Cat-4 [18]	2020	cGNSS-R	L1+ L2/ LHCP	GPS Galileo
3Cat-5 A/B (FSSCat mission) [19]	2020	cGNSS-R	L1/ LHCP	GPS Galileo
PRETTY [20]	2021	iGNSS-R	L1/ RHCP	GPS Galileo
HydroGNSS [21]	2024	cGNSS-R	E1+E5/ LHCP+ RHCP	GPS Galileo

Fig. 1. Artist view of the UK-TDS-1 mission.

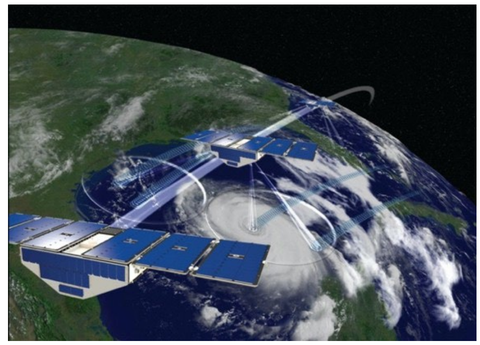

Fig. 2. Artist view of the NASA's CYGNSS constellation.

4. PRELIMINARY L1 DATA PRODUCTS GENERATED ON-GROUND FROM ON-BOARD MEASUREMENTS

A set of required measurements is being actively defined by the Working Group with the purpose of enabling a common data and processing framework among several satellites. The preliminary set has been defined and is expected to include at least the following parameters:

Fundamental measurements:

- **ddm_complex:** This field includes the after-correlation in-phase I (real part) and quadrature Q (imaginary part) components in raw counts. GNSS-R sensors of the c- and r-type shall ideally provide two ddm_complex observables, one for the direct and one for the reflected signal. The GNSS-R sensors of the i-type only need to produce one ddm_complex measurement. The nominal specular point location may be accurately and efficiently computed using e.g. the DTU 10 model over ocean and e.g. the MERIT or Earth 2014 Digital Elevation Model (DEM) over land (or a "reduced" version of these models). Over land, several specular reflection points may be encountered. The number will depend on facet size, but on surface roughness as well as it widens the angular pattern of the scattered signal. If it is too rough, the pattern will be too wide and it will not be coherent anymore. These considerations lead to the fundamental question of how to define the specular point: minimum delay?, incidence angle equals scattering angle? The array size shall be sufficiently large to account for the complete spreading of the Delay Doppler Maps (DDMs) in delay and Doppler domains. State-of-the-art values are ~ 4 GPS C/A chips x 5000 Hz [2] or ~ 30 GPS C/A chips x 10000 Hz [12] for the C/A code systems. The optimum delay and Doppler bins size are also being analysed. The bin size shall be defined considering the scientific requirements versus the peak uncertainty. Coherent integration time shall be assumed to be a variable. All information defining the processing approach shall be included as metadata. It is recommended to study the possibility of using direct and reflected signals synchronized in the same correlation channel for system autocalibration.

- **ddm_complex_cal:** This is the calibrated ddm_complex.
- **ddm_power:** This is the uncalibrated power value produced by the receiver in raw counts, that is, the squared modulus of the ddm_complex. The incoherent integration time shall be assumed to be a variable. Default values for land and ocean surfaces shall be specified for each type of surface. These values shall be included in the nominal operational mode of the receiver. The location of the specular point corresponding to the ddm_power shall be identified. This information shall be included as metadata. ddm_power observables may be produced on-board but also on-ground.
- **ddm_power_cal:** This is the calibrated power that would have been measured by an ideal GNSS-R sensor. An ideal GNSS-R sensor is one with isotropic antennas and known instrumental gain, delays and offsets, having no quantization errors. Calibration procedures both in delay and amplitude shall be defined including those for cGNSS-R [3-7], iGNSS-R [3,4], rGNSS-R [8,9], and partial iGNSS-R [10]. Different options for calibration exist. The calibration method shall be included in the metadata. Direct and reflected signals may be routed to a calibration switch circuit inserted between them and their Low Noise Amplifiers (LNAs) which allows for accurate delay and amplitude calibration [4]. Other calibration approaches including the injection of Pseudo-Random Noise (PRN) signals or using the same antenna for direct and reflected signal are possible [22]. The calibration method shall be included in the metadata.
- **phase:** This value is the phase [deg] at the peak of the complex DDMs (ddm_complex_cal). In the case of GNSS-R sensors of the c- and r-type, phase shall include both direct and reflected correlation channels. The phase shall be corrected for path and atmospheric delays. Such correction shall be also included, in the metadata.
- **power:** This value is the peak power of the complex (ddm_complex_cal) and power (ddm_power_cal) DDMs. In the case of GNSS-R sensors of the c- and r-type the power shall include both direct and reflected correlation channels. The power unit shall be [dB]. Automatic Gain Control (AGC) shall be stable, and it is recommended to remove any AGC influence by using a constant gain channel.

Fundamental observables:

- **brcs:** This is the bistatic scattering radar cross-section [m^2]. The impact of any coherent scattering term shall be separated. This term shall be also considered for the computation of the overall path loses. The level of the reflected signal relative to the direct signal shall be accurately estimated using preferably the direct signals themselves instead of a look-up table [4,5]. The GNSS satellites antenna radiation pattern in the direction of the up-looking antenna and the specular point (SP) may be assumed to be similar [23] or estimated.
- **effect_area:** This is an estimate of the effective surface scattering area [m^2] that contributes power to each DDM bin, after accounting for the GNSS signal spreading function. It may be calculated by convolving the GNSS Woodward Ambiguity Function (WAF) with the surface area that contributes power to a given DDM bin as determined by its delay and Doppler values and the measurement geometry. The specular point bin location matches the specular point bin location in the brcs [24]. State-of-the art procedures use an "end-to-end simulator" such as the CYGNSS or the PAU-PARIS simulator [25]. This information shall be included as a look-up table.
- **nbrcs:** This value is an estimation of the normalized bistatic scattering radar cross-section [dB]. For wind speed retrieval, a window of delay and Doppler bins centered in the nominal SP corresponding to the nominal spatial resolution on Earth's surface should be used (typically) ~ 25 km x 25 km for systems using the L1 C/A code (3 delay and 5 Doppler bins in CYGNSS [26]). This window size may be assumed to be a variable, and information shall be included as metadata.
- **snr:** This value is the Signal-to-Noise Ratio (SNR) of the complex and power DDMs [27], taking the level of noise floor as reference, in [dB]. In the case of GNSS-R sensors of the c- and r-type, snr shall include both direct and reflected correlation channels.
- **n_floor:** This value is the noise floor of the complex (ddm_complex) and power (ddm_power) DDMs. In the case of GNSS-R sensors of the c- and r-type, n_floor shall include both direct and reflected correlation channels. The units of the n_floor are arbitrary units. The computation of n_floor shall account for the type of surface i.e. ocean vs. land, including the effect of topography if needed [1,28]. It shall be computed as the average over the number of bins before beginning of the leading edge, for all Doppler frequencies in the DDM.
- **gamma:** This value is the reflectivity using power (ddm_power_cal) DDMs [dB]. The use of an "empirical" estimation has been evaluated because both the coherent and the incoherent scattering terms contribute to the peak power of the DDMs [29].
- **area_vol:** This value is the area/volume of power (ddm_power_cal) DDMs. In the case of GNSS-R sensors of the c- and r-type, area_vol shall include both direct and reflected correlation channels. Simulation work indicates that the volume and the area of the DDMs are related to the changes in the contribution to the brightness temperature of the ocean induced by the roughness [30,31].
- **te/le:** This value is the trailing/leading edge width of power (ddm_power_cal) DDMs in [m]. In the case of GNSS-R sensors of the c- and r-type the te/le shall include both direct and reflected correlation channels. The power threshold information shall be included as metadata.
- **del:** In the case of GNSS-R sensors of the c- and r-type this value is the delay between the peak of the direct power DDM and the point of maximum derivative of the reflected power DDM. In the case of GNSS-R sensors of the i-type del is the delay at the peak.
- **coh_to_incoh:** This value is the coherent-to-incoherent scattering ratio [32,33].
- **coh_comp:** It is the coherent term of the DDMs. It shall be computed as in [32,33]. The same observables as for the "full DDMs" shall be included in this list.

5. TECHNICAL CHALLENGES

5.1 Signal Calibration

The absolute power calibration of GNSS-R measurements requires knowledge of many parameters, including:

- Power of the transmitted signal used, which can vary with the GNSS satellite observed, but also in time and across different regions (strictly speaking and for a well amplitude-calibrated GNSS-R sensor, the knowledge of the transmitted signal is not required as reflectometry observations, understood as reflected relative to direct measurements, are performed - the transmitted power cancels out in this process).
- Antenna gain of the GNSS satellite in the direction of the observed specular point on Earth's Surface.
- Antenna gain of the GNSS-R satellite in the direction of the observed specular point on Earth's Surface.
- Ranges from the transmitter and receiver satellites to the specular points.
- Velocities of the transmitter and receiver satellites.
- Compensation of any gain and delay variations in the receiver satellite.
- Radio frequency interference from sources external and internal to the receiver platform. This can include that from GNSS transmitters other than the current observed.

All of these factors require careful consideration in order to achieve precise GNSS-R measurements, and the differing GNSS-R methods have differing approaches to addressing the estimation of these parameters. The GNSS-R Working Group is currently working to develop recommended best practices for calibration to ensure that cross comparison of GNSS-R nbrcs datasets is possible as additional datasets become available.

5.2 Definition of Performance Requirements

While the efforts of the Working Group are focused on the creation of standards for L1 products (i.e. calibrated instrument reported measurements), the Working Group is conducting these efforts with guidance based on expectations for the production of geophysical products, including ocean wind speed, ocean altimetry, land surface soil moisture, and other products. Accordingly, evidence of the coupling between desirable science product accuracies and associated requirements on L1 products are being compiled from the evidence of past and future planned missions. These analyses will be incorporated into the Standard produced as guidelines for the production of mission datasets, again with the goal of achieving at least partial interoperability of datasets from current and future missions.

6. FINAL DISCUSSIONS

The GNSS-R community has been growing rapidly during recent years. In the next decade, constellations of small satellites are expected to be launched into space, and efforts have also proposed larger satellites. As such, we should plan future data sets so that valuable and inter-comparable products will result with a view to enabling long-term stability and retrieval consistency in support of science applications.

Future advancements on satellite subsystems and retrieval algorithms will further explore the performance of GNSS-R to derive geophysical parameters of interest such as wind speed, ocean altimetry, soil moisture content, and above ground biomass. As such, this standard is focused in the definition of the L1 parameters required for the generation of scientifically valuable products. We aim to provide a profound basis for GNSS-R data to further explore and expand the limits of this technique.

This is a heterogeneous Working Group with professionals working on both fundamental and applied research topics, industry, and space agencies. We hope to establish this standard based on our common understanding and agreement. Once the first consolidated version of the standard is available, it will be open for review and comment from new members and communities having interest in GNSS-R systems for Earth observations.

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