Foreword to the Special Issue on GNSS Reflectometry

TWO years have been passed since IEEE'S JOURNAL OF SELECTED TOPICS IN APPLIED EARTH OBSERVATIONS AND REMOTE SENSING published a special issue on GNSS reflectometry [vol. 7, no. 5]. Although short, this time span brought us a remarkable uplift of the reflectometry field, boosted by the launch of the UK TechDemoSat-1 (TDS-1) satellite that provides unprecedented amount of space-borne reflectometry data. GNSS-R is defined as the use of digital signals—here signals from Global Navigation Satellite Systems (GNSS)—as sources of illumination in a bistatic radar system. Martín-Neira [1] first proposed the application of GNSS reflectometry for altimetry in 1993, while Garrison *et al.* demonstrated in 1998 that the GNSS signal reflections can be used to sense ocean surface roughness and related wind [2]. More recently, Torres and Lawrence [3] extended GNSS-R to other sources of opportunity, for example, direct broadcast TV-satellites. General reviews of the GNSS-R technique and its geophysical applications can be found in a few textbooks and tutorials, e.g., [4, Ch. 16], [5, Ch. 8–11], and [6]. Examples of early papers and experiments can be found in (e.g., [7]–[15]).

International meetings on GNSS reflectometry have been held periodically, starting in the late 1990s. In recognition of the growing interest in this technique, the IEEE Geoscience and Remote Sensing Society cosponsored for the first time a GNSS-R meeting in 2010, Barcelona, Spain. Selected papers from that conference were published in a special issue of Radio Science [vol. 46, no. 6, 2011]. The success of the meeting motivated a subsequent IEEE cosponsored meeting, the Workshop on Reflectometry using GNSS, and Other Signals of Opportunity (GNSS+R 2012), held in October 2012 at Purdue University, USA, which culminated with the first IEEE-JSTARS special issue on GNSS-R [16]. GNSS+R is currently established as a biannual symposium with the IEEE-Geoscience and Remote Sensing Society (GRSS) technical cosponsorship. The last meeting was held at the GeoForschungsZentrum Potsdam, Germany (GNSS+R 2015) and the next will be held at Ann Arbor, Michigan, USA, in 2017 (GNSS+R 2017). Selected contributions from GNSS+R 2015 are compiled in this special issue, the second IEEE-JSTARS devoted to this topic.

Looking two years back and comparing both GNSS-R special issues, one notices the remarkable growth in this research field and its scientific community; from 17 papers published in 2014 issue to 33 papers in the present one, essentially doubling the amount of involved centers and countries, and with the irruption of Asian contributions. At the time of publication of this special issue, two GNSS-R missions are orbiting the Earth (TDS-1 and ³Cat-2, see below). This represents a major change in the scientific scenario that is also reflected in the contents of the issue. For example, nearly 70% of the papers are based on the experimental data (32% of which use actual space-borne GNSS-R data), while approximately only half of those in the 2014 issue were based on the experimental measurements. The current issue also represents consolidation of low-altitude ground-based GNSS-R, sharing infrastructure with geodesy agencies, and, thus, providing cost-effective means for other geophysical applications. In 2014, nearly 40% of the experimental papers studied these low-altitude applications, and now the number has steadily grown to more than 45%. Despite the achievements and increased maturity reached in these two past years, the concept continues to pose challenges. For example, technology is a key aspect receiving close attention and is explicitly present in a third of the papers. This fact highlights the potential role of the IEEE GNSS and Signals of Opportunity Working Group, under the auspices of the GRSS Instruments and Future Technologies Technical Committee [17].

Expectantly, the progression of the field will continue to grow with the upcoming launch of a constellation of GNSS-R orbiters, the NASA's CYclone GNSS (CYGNSS) mission (planned by Q4 2016) [18] and the remaining preparations for ESA's GNSS-R experiment aboard the International Space Station, GEROS-ISS (see below).

The 33 papers in the present issue are organized around seven topics, four of which relate to specific scientific application areas [altimetry (six papers), ocean scatterometry (five), land applications (six), and cryosphere (four)]. The issue opens with the description of five space-borne missions, two of them are already in orbit (TDS-1 and, ³Cat-2). It continues with the geoscientific applications, and closes with technological aspects (five, of which three describe dedicated GNSS-R receivers) and scattering and signal propagation modeling (two). A brief summary of the contributions in each of these topics is given below.

I. SPACE-BORNE MISSIONS

The UK TDS-1 satellite has been in orbit since July 2014. This small technological demonstration satellite carries the Space GNSS Receiver-Remote Sensing Instrument (SGR-ReSI), which has generated by far the major volume of space-borne GNSS-R data up to day. In fact, more than 20% of the special issue papers have used data from TDS-1. Unwin *et al.* [19] describe the GNSS-R payload, its early operations, and the data dissemination through a dedicated website. It also compiles the preliminary data assessments on ocean winds, land, and ice collections in preparation for further data exploitation.

Another GNSS-R mission that is orbiting since August 2016 is ³Cat-2, a six-units cubesat. It will test several receiver acquisition techniques (conventional, interferometric, and reconstructed—cGNSS-R, iGNSS-R, and rGNSS-R, respectively) for the first time from space. It is also the first polarimetric

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GNSS-R experiment from a Low Earth Orbiter (LEO). Carreño-Luengo *et al.* [20] describe the mission and the related preparation activities. Two other papers in the present issue relate to ^{3}Cat-2, Carreño-Luengo and Camps [36] (presented in the land applications section) and Olivé *et al.* [45] (in the technology section).

Wickert et al. [21] describe ESA's GNSS rEflectometry, Radio Occultation and Scatterometry on board the International Space Station (GEROS-ISS). GEROS-ISS would represent the first GNSS-R spaceborne mission primary focused on the altimetric retrievals of sea surface height of the oceans, with system requirements driven by this purpose (e.g. more than 24 dB directive antennas). Besides altimetric and scatterometric ocean applications, other secondary mission goals are atmosphere/ionosphere sounding using refracted GNSS signals (Radio Occultation, GNSS-RO) and remote sensing of land surfaces using GNSS-R. The paper describes the mission objectives and its design, and it reviews the current status and ongoing activities presenting selected scientific and technical results of the GEROS-ISS preparation phase. Two other papers in this special issue relate to this mission: [24], and [25], presented under the altimetric applications section.

Juang *et al.* [22] present a development plan of a space-borne GNSS-R experiment as a part of the 12 satellite FORMOSAT-7/COSMIC-2 mission (Taiwan/USA) for atmosphere sounding using the GNSS Radio Occultation technique. The experiment is planned aboard an additional (thirteenth) satellite FORMOSAT-7-NSPO Build (FS7-NB). The first launch with six satellites is expected by 2017. The design of the GNSS-R receiver payload is discussed with emphasis on the processing of Satellite Based Augmentation System (SBAS) and Regional Navigation Satellite System (RNSS) signals. It is shown that SBAS/RNSS signals can enhance the potential of GNSS reflectometry mission in terms of increase of reflection events and repetition of the reflection location, while evidences of SBAS reflection on UK TDS-1 data are reported. Another paper in the present issue relates to the FORMOSAT-3/COSMIC mission, Li *et al.* [26] described in the altimetry section.

Finally, Martín-Neira *et al.* [23] present a concept for GNSS remote sensing constellation, called "Cookies." These small satellites are capable of receiving direct and reflected signals, in both right-hand (RH) and left-hand (LH) circular polarizations, from any of the GNSS systems, and from virtually any arrival direction in both the upper and lower field-of-view hemispheres. The on-board remote sensing payload produces interferometric observables to provide, in parallel, GNSS-RO and GNSS-R observations. A constellation of three Cookies has been simulated and its sampling performance was characterized.

II. Applications: Altimetry

The first two papers of this section assess the effects of Radio Frequency Interferences (RFI) in GNSS-R observables and their altimetric performances. Onrubia *et al.* [24] focus on the effects of the distance measurement equipment, and the TACtical air navigation systems, which are two radio navigation systems that transmit in the GPS L5 and Galileo E5 bands with powers up to 3.5 kW. Pascual *et al.* [25] assess about the crosstalk, a phenomena that occurs when the Delay-Doppler Map (DDM) of a tracked satellite overlaps others from undesired satellites. Both studies are applied to a GNSS-R payload that is currently planned to be installed aboard the international space station: the GEROS-ISS experiment [21]. Onrubia *et al.* [24] show that the received interference power in space will be strong to degrade the system's performance by increasing the noise floor, but the sea altimetry precision will still be accurate enough for scientific studies. Pascual *et al.* [25] find out that crosstalk would happen in $\sim$10% of the GEROS-ISS reflection events, but could be mitigated using high-directive antennas. Crosstalk impact using a seven-element hexagonal array still induces large errors on ground, but reduces to centimeter level on airborne receivers, and is negligible from the ISS.

The three following papers on ocean altimetry are based on synthetic data. Li *et al.* [26] analyse the capabilities of GNSS-R altimetry for mapping ocean mesoscale sea surface height, assuming six reflection-capable receivers onboard the current Constellation Observing System for Meteorology, Ionosphere, and Climate (FORMOSAT-3/COSMIC) satellites and signals from GPS and GLONASS constellations. Assuming that the Root Mean Square Error (RMSE) of the delay observables is 1 or 2 m (in 1-s integration), the spectral and synoptic analyses suggest that two days of measurements can reproduce mesoscale features down to 100 km horizontal resolution. It also demonstrates the ability of GNSS-R altimetry to suppress large-measurement errors due to the high density of measurements and the potential to constrain mesoscale features down to scales beyond what the constellation of existing nadir-altimeters allows. Ghavidel and Camps [27] use simulated data of GNSS signals scattered over time-evolving 3-D surfaces to assess the impact of rain, swell, and surface currents on the electromagnetic bias. Yan and Huang [28] simulate data to assess the possible detection of tsunamis and the estimation of its parameters from GNSS-R DDMs.

Mashburn [29] close this section performing actual altimetric retrievals from an air-borne experiment using GPS L1 P(Y) signals. This paper compares the performances of different algorithms and observables and contrasts them to independent sea surface height data. The method called HALF (see paper for details) produced the most precise measurements for a 5-s integration time with a standard deviation of 0.6 m.

It is reported here that three other papers present GNSS reflectometry receivers tailored for ground-based altimetry. They are presented in the technical section [46]–[48].

III. Applications: Ocean Scatterometry

The first three papers in this block have used UK TDS-1 data to either test novel retrieval techniques or to assess the sensitivity of the observables to wind, waves, and other oceanic variables. Tye *et al.* [30] present the stare processing retrieval, a technique that utilizes the high-spatial overlap between successive DDMs, to achieve multiple looks at the same surface point. This method recovers the mean-square slope (mss) of the scattering surface with spatial resolutions as fine as 10 km. This is achieved by fitting a slope probability density function to measurements of a surface point over a time series of DDMs. The results of collocations with the global WaveWatch3 (WW3) model show Pearson correlation coefficients of 0.742 between TDS-1 mss and WW3 mss values when compared in decibel units. The sensitivity of the UK TDS-1 measurements to the ocean surface winds and waves are characterized in [31]. The correlation with sea surface temperature, wind direction, and rain are also investigated. Clear sensitivity to wind speeds up to 20 m/s is reported, with apparent sensitivity to 35 m/s wind speeds (sparser dataset). A dependence on the swell is also observed for winds lower than 6 m/s. Finally, Schiavulli *et al.* [32] present a new gridded Normalized Radar Cross-Sectional (NRCS) image product from TDS-1 observables. The product is obtained reconstructing NRCSs from actual TDS-1 DDMs using a deconvolution method based on the 2-D truncated singular-value decomposition.

The last two papers of this block tackle GNSS-R for monitoring tropical cyclones. An upgraded version of the SGR-ReSI GNSS-R receiver aboard TDS-1 will be orbiting in the eight satellite CYGNSS constellation [18]. Said *et al.* [33] assess the capability of CYGNSS to observe winds within 43 tropical cyclones from 2010 to 2011, by using simulated CYGNSS observations. The CYGNSS end-to-end simulator (E2ES) is utilized to generate DDM from which wind speeds are then retrieved. These wind speeds are first compared to the used input of the E2ES. For range corrected gain values greater than 20, the CYGNSS winds have a standard deviation of 0.57 m/s relative to these model values. The CYGNSS winds were also compared to other sources of wind information, being the best comparison against the ASCAT winds (overall bias around -0.4 m/s, standard deviation 1.54 m/s). In [34], actual BeiDou-geostationary reflected signals, received from a coastal experiment during two typhoons (Jebi and Utor 2013) overpassing the site, are used to assess the sensitivities of different waveform observables to the wind speed evolution. Results, based on both the delay- and spectral-related observables, are compared with *in situ* wind measurements collected during these tropical cyclones to confirm that the proposed observables are well correlated with the wind speed evolution.

IV. Applications: Land

The first block of papers tackling land applications present experimental studies with data obtained from a LEO, a stratospheric balloon, and a small aircraft and report sensitivity, to soil moisture in bare terrains, to forest heights, and to soil types, respectively. In [35], the UK TDS-1 GNSS-R data are collocated with SMOS soil moisture measurements, MODIS Normalized Difference Vegetation Index (NDVI) data, and land use data. The results for low NDVI values show a large sensitivity to soil moisture and a relatively good Pearson correlation coefficient. As the vegetation cover increases (NDVI increases) the reflectivity, the sensitivity to soil moisture and the Pearson correlation coefficient decrease yet remain significant. Carreno-Luengo and Camps [36] test the first ever dual-frequency multiconstellation GNSS-R observations over boreal forests and lakes using GPS, GLONASS, and Galileo signals. The instrument flew on-board a stratospheric balloon and demonstrated the feasibility of tracking the coherent component of the scattering over boreal forests and lakes even from high-altitude platforms. The coherent-to-incoherent scattering ratio over boreal forests is found to be as large as $\sim$1.5, while over lakes it is as high as 16.5. This has enabled to estimate the height distribution of the scatterers from the fluctuations of the phase of the complex waveforms peak. It was also possible to reconstruct the GPS P(Y) code, despite the high altitude and large dispersion of the signal after the scattering over the boreal forests. Jia *et al.* [37] investigate the feasibility of obtaining surface characteristics from the power ratio of LH reflected signal-to-noise ratio (SNR) over direct RH. The analysis was done regardless of the surface roughness and the incoherent components of the reflected power, and included data collected by a GNSS receiver prototype installed on a small aircraft. This system was calibrated with water-reflected signals. The reflectivity and the estimated permittivity showed good correlation with the types of underlying terrain.

The second block of papers on land applications use ground-based stations and enhanced versions of the interferometric pattern technique (GNSS-IR) also called multipath reflectometry. While Small *et al.* [38] aim to improve the soil moisture retrievals taken into account the effects of the vegetation, Chen *et al.* [39] focus on the extraction of the Vegetation Water Content (VWC). *In situ* soil moisture observations from 11 GPS sites are used in [38] to compare the performance of three different GNSS-IR retrieval algorithms that represent vegetation effects with different degrees of complexity. The retrievals that presented least error are based on an algorithm that adjusts for vegetation effects using variations in the amplitude of the SNR interferogram. The RMSE are found to be at $0.038\ \mathrm{cm}^3{\cdot}\mathrm{cm}^{-3}$ using this algorithm, below the typical limit required for validation of satellite data. Chen *et al.* [39] applied GNSS-IR techniques to data received with a horizontally polarized antenna. The observable shows a linear relationship with *in situ* measurements of VWC over a range of 0 to 6 $\mathrm{kg/m^2}$, which is much greater than the range obtained with GNSS-IR using a geodetic antenna (0 to 1 $\mathrm{kg/m^2}$). Finally, Roussel *et al.* [40] propose a GNSS-IR technique to estimate the temporal variations of the soil moisture content of the ground surrounding a geodetic antenna, based on the inversion of three parameters from SNR observables: amplitude and phase of the multipath contribution, and effective antenna height. The method is tested with data from an actual station and the 10-min sampling rate results present a correlation coefficient of 0.95 with *in situ* 2-cm depth measurements. Elevation angles higher than 30° can also be included in the analysis.

V. Applications: Cryosphere

The cryospheric section opens showing the capacity of spaceborne UK TDS-1 GNSS-R data to detect presence of sea ice [41]. The detection scheme is applied on an adaptive incoherent summation of the DDMs to increase SNR while avoiding the averaging between DDMs collected over surfaces of different types. The identification algorithm is based on the DDM spreading along the delay and Doppler axes, and it is tested on five different observables. The feasibility of the method is validated with an accuracy of up to 99.73%.

A suite of three papers investigates the retrieval of snow depth surrounding GNSS ground stations, essentially existing geodetic stations. All of them enhance the GNSS-IR technique in different ways. In [42], the algorithm used so far, based on GPS L2C data, is adapted to GPS L1 signals to enable the extraction of longer snow depth time series that are needed by climate scientists. Snow depth estimates are derived for 23 sites for five years and compared with existing snow depth time series, derived from the L2C signal and *in situ* measurements. The L1 results show an average bias of 1 cm and correlation of 0.95 with respect to the L2C ones, and −4-cm bias with respect to *in situ* data (−6 cm for L2C). On the other hand, Vey *et al.* [43] tackle the accuracy problems of GNSS-based snow depth measurements in built-up areas with several constructions in the proximity of the station. This contrasts with previous studies where the GNSS ground-based stations were situated on bare soil or grassland. As a way to help separating the GNSS reflections from the ground and from surrounding buildings, the authors have modified the interference approach previously used for snow-depth estimation using the phase of the multipath interference pattern instead of their frequency. The technique has been tested in an urban GNSS station at Wettzell, Germany. The results, validated against independent data, show a few centimeter-level RMSE and 1-cm bias. Finally, Qian and Jin [44] focus on GLONASS signals, assessing the performance for both SNR and phase observables, as well as the geometry-free linear combination (L4). GPS and GLONASS results are compared and present similar performances, except for the different coverage provided by each constellation.

VI. Technology

This block contains five papers that tackle technological problems, mostly receiver approaches and observables, but also tools to evaluate SNR degradations due to RFI and their mitigation strategies. In addition to these five papers, scattered throughout the issue, we find seven other contributions that have addressed technological issues. For example, the receivers described in each of the mission papers [19]–[23] or the RFI effects in altimetric retrievals [24], [25]. The weight of these studies highlights the technological challenges that the GNSS-R technique still faces today.

Three software receivers are described in this issue: the first corresponds to one of the operation modes of the ^{3}Cat-2 GNSS-R payload. Olivé *et al.* [45] propose a solution for this payload based on a Software Defined Radio (SDR) connected to a nadir looking array of dual-band and dual-frequency and dual-polarization antennas to capture the reflected GNSS signals, and to a zenith looking patch antenna to capture the direct ones. The SDR is controlled by the payload computer, which retrieves the binary samples and processes the raw data to obtain DDMs via various techniques. Preliminary laboratory tests of the instrument with simulated and real GPS signals show promising results in conventional and interferometric modes. Field tests have shown good results with real BeiDou signals as well. On the other hand, both [46] and [47] present receivers based on SDR for reflectometry at ground-based stations. While in [46], the goal is to perform GLONASS reflectometry (GLONASS-R) using entirely off-the-shelf components, Lestarquit *et al.* [47] focus on the use of open source tools, such as GNSS-SDR and GNU-RADIO. The interest of [48] is set on new observables for tracking of the reflected signals, when both direct and reflected links present the same dynamics (ground-based stations). In particular, the observable serves to acquire accurate pseudoranges by means of code and phase delay integration.

Querol *et al.* [49] developed the SNR degradation in GNSS-R measurements due to RFI through the spectral separation coefficient. The authors developed a model to evaluate the degradation of the SNR across the cGNSS-R and iGNSS-R DDMs as a function of different RF contributions (including intra-/inter-GNSS, external RFI, and nonstationary RFI). The results show that high-directive antennas are required to avoid intra-/inter-GNSS interferences and mitigation techniques are essential to keep GNSS-R measurements unaffected by external RFI.

VII. Understanding Scattering and Propagation

The special issue closes with a couple of papers that develop models and tools to better understand the propagation and scattering of the signals. Benzon *et al.* [50] develop a wave propagator of GNSS reflected signals off the Ocean to simulate the received electromagnetic field (amplitude and phase). The wave propagator developed in this study, does not include the effects of GNSS code modulation; thus, the delay between the reflected and direct radio links must be shorter than the modulation chip (e.g., in grazing angle geometries). Geremia-Nievinski *et al.* [51] measure the sensitivity kernel (spatially continuous area within the effective footprint) of GPS coherent reflections as captured on ground-based stations. Based on actual measurements and simulated data, the kernel was found to represent a diffraction pattern which exhibited oscillations along the plane of incidence, peaking near the specular point, and persisting in its decay well beyond the first Fresnel zone (FFZ). Within the FFZ, sensitivity was found to be skewed toward the antenna. This experiment suggests the feasibility of overcoming the diffraction limit and resolving features smaller than the FFZ.

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