IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

SPECIAL SECTION ON ADDRESSING ECONOMIC, ENVIRONMENTAL AND HUMANITARIAN CHALLENGES IN THE POLAR REGIONS

Received December 21, 2017, accepted February 4, 2018, date of publication March 9, 2018, date of current version March 28, 2018.

Digital Object Identifier 10.1109/ACCESS.2018.2814072

GNSS Transpolar Earth Reflectometry exploriNg System (G-TERN): Mission Concept

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This work was supported in part by the Spanish under Grant ESP2015-70014-C2-2-R and Grant ESP2015-70014-C2-1-R and in part by the Specific Expedition Budget of GFZ. The work of S. V. Nghiem was supported in part by the NASA Cryospheric Sciences Program and in part by the NASA Land Cover and Land Use Change Program.

ABSTRACT The global navigation satellite system (GNSS) Transpolar Earth Reflectometry exploriNg system (G-TERN) was proposed in response to ESA's Earth Explorer 9 revised call by a team of 33 multi-disciplinary scientists. The primary objective of the mission is to quantify at high spatio-temporal resolution crucial characteristics, processes and interactions between sea ice, and other Earth system components in order to advance the understanding and prediction of climate change and its impacts on the environment and society. The objective is articulated through three key questions. 1) In a rapidly changing Arctic regime and under the resilient Antarctic sea ice trend, how will highly dynamic forcings and couplings between the various components of the ocean, atmosphere, and cryosphere modify or influence the processes governing the characteristics of the sea ice cover (ice production, growth, deformation, and melt)? 2) What are the impacts of extreme events and feedback mechanisms on sea ice evolution? 3) What are the effects of the cryosphere behaviors, either rapidly changing or resiliently stable, on the global oceanic and atmospheric circulation and mid-latitude extreme events? To contribute answering these questions, G-TERN will measure key parameters of the sea ice, the oceans, and the atmosphere with frequent and dense coverage over polar areas, becoming a "dynamic mapper" of the ice conditions, the ice production, and the loss in multiple time and space scales, and surrounding environment. Over polar areas, the G-TERN will measure sea ice surface elevation (<10 cm precision), roughness, and polarimetry aspects at 30-km resolution and 3-days full coverage. G-TERN will implement the interferometric GNSS reflectometry concept, from a single satellite in near-polar orbit with capability for 12 simultaneous observations. Unlike currently orbiting GNSS reflectometry missions, the G-TERN uses the full GNSS available bandwidth to improve its ranging measurements. The lifetime would be 2025–2030 or optimally 2025–2035, covering key stages of the transition toward a nearly ice-free Arctic Ocean in summer. This paper describes the mission objectives, it reviews its measurement techniques, summarizes the suggested implementation, and finally, it estimates the expected performance.

INDEX TERMS Polar science, GNSS, reflectometry, GNSS-R, sea ice, altimetry, polarimetry, radio-occultation, Low Earth Orbiter.

I. INTRODUCTION

A novel remote sensing technique based on signals of the Global Navigation Satellite System (GNSS) reflected off the Earth surface, the so called GNSS reflectometry (GNSS-R), was suggested in the nineties for ocean altimetric [1] and scatterometric [2] applications. As investigations progressed, experimental campaigns, dedicated modelling activities and the analysis of actual spaceborne data sets have expanded the range of applications of the GNSS-R, which so far have generated two special issues of the IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing (J-STARS) [3], [4], an IEEE GRSS tutorial [5] and dedicated book chapters [6]–[8]. The cryosphere and polar areas are some of the new scientific targets of this technique.

Komjathy *et al.* [9] pioneered the research on GNSS-R for cryosphere information acquiring and analyzing data collected from airborne instruments. Their experimental results indicated the potential of reflected GNSS signals to provide information on the presence and condition of sea and fresh-water ice, as well as the freeze/thaw state of frozen ground. The Arctic sea ice data set was analyzed afterwards confirming its potential for ice scatterometric applications in [10], [11]. Reflected signals captured from a GNSS Radio Occultation satellite were preliminary inverted to sea ice and Greenland ice sheet altimetry under very slant geometries [12], while data obtained from a dedicated GNSS-R spaceborne experiment demonstrated the feasibility of acquiring signals reflected off sea ice from space at near nadir geometries [13], [14], even when a relatively low gain antenna was used. Dedicated coastal experiments based in Greenland [15] firstly investigated polarimetric responses of GNSS reflection off sea ice [16] and the trackability of the electromagnetic carrier phase after sea ice reflections, enabling precise phase-delay altimetry of the coastal ice [17]. Mid latitude snow properties were found to be characterized from reflected signals unintentionally captured in ground-based geodetic GNSS stations (e.g. [18]–[20]), while the interaction of GNSS signals with the dry snow in polar ice sheets was theoretically tackled in [21] and experimentally investigated [22]. Penetration depths down to a few hundred meters were reported in Antarctica ice sheet.

More recently, new sets of GNSS-R data have enabled to test some of these polar remote sensing concepts from space-borne scenarios. One of the data sets has been acquired from the Soil Moisture Active Passive (SMAP) mission, as the transmitting chain of its L-band radar failed and the receiving chain was tuned to collect GNSS reflected signals. The novelties of SMAP GNSS-R over other GNSS-R missions are the reception in two polarizations (two orthogornal linear base) and the high gain of its 6 meter antenna. These data have enabled GNSS-R to detect the land surface freeze/thaw state [23] and distinguish between ocean water and sea ice through the polarimetric response [24]. SMAP GNSS-R data were opportunisitc, limited and are not available to the community, and they mostly cover continental areas (target of the SMAP mission). On the other hand, the UK TechDemoSat-1 (TDS-1) polar satellite operated a GNSS-R payload in a 2 out of 8 days cycle since July 2014 to July 2017, the data were open but the antenna was in a single polarization and of much moderate gain (13 dBi). The extensive sets of TDS-1 data over the poles have resulted in ice sheet altimetry studies [25], different algorithms to detect sea ice [26], [27], to estimate sea ice concentration [28], to perform sea ice altimetry using the group-delay of the reflected echo [29] or by using its carrier phase delay [30]. The latter reports negative correlation between the ice thickness and the altimetric solution, both presenting variations of the same order of magnitude. These findings might be an indication that the altimetric response comes from the ice-water interface (draft), which if confirmed would suppose a new and complementary way of extracting sea ice thickness.

The GNSS-R technique is proposed in a polar-science oriented mission [31], in response to the ESA EE9 Revised Call [32]. Unlike the GNSS-R spaceborne payloads deployed so far, the GNSS Transpolar Earth Reflectometry exploriNg system (G-TERN) proposes to implement a different acquisition technique to access the full GNSS transmitted bandwidth and a system of antennas tailored to altimetric applications. This approach follows the steps of the ESA's PAssive Reflectometry and Interferometry System In-Orbit-Demonstration (PARIS-IOD) [33] and the ESA's GNSS rEflectometry, Radio Occultation and Scatterometry on board the ISS (GEROS-ISS) [34], both missions focused on

GNSS-R altimetry and having succesfully passed their irrespective industrial feasibility studies (Phase-A). G-TERN was proposed by a multidisciplinary international team of 33 scientists and engineers experts in GNSS remote sensing, polar sciences, oceanography, hydrology and space technology, to attempt to contribute solving a relevant scientific problem within the constraints of the ESA EE9 'Revised Call'. The call, issued in December 2016, asked for missions to address a relevant Earth scientific problem, while fitting in a reduced budget and short implementation time, using innovative techniques but based on proved concepts. Different aspects of the mission concept and suggested implementation are detailed in the following sections, together with the simulation exercises to assess the performance of the system.

II. SCIENTIFIC OBJECTIVES

Advancing the understanding of the cryosphere in a changing climate has been identified as a 'Grand Challenge' by the World Climate Research Programme (WCRP). Components of the cryosphere play a central role in several processes that remain an important source of uncertainty in projections of future climate change. Examples of such processes are the prospect of an ice-free Arctic Ocean in contradistinction to Antarctic sea ice increase; the role of ice-sheet dynamics in amplification of Greenlands and Antarcticas contribution to the global sea-level rise; the fate of mountain glaciers providing fresh water to hundreds of millions of people worldwide; and the strength of positive feedbacks between the warming climate and natural emissions of greenhouse gases from the thawing permafrost [35]. Furthermore, a particular issue has emerged in past Intergovernmental Panel on Climate Change (IPCC) Assessments [36] as topic of considerable uncertainty: the ability of models to simulate recent declines and future changes in sea ice. Recent studies have linked changes in snow and ice to circulation changes, weather extremes, and the obvious impacts on terrestrial and marine ecosystems, which create a great sense of urgency [37]. For the reasons discussed below, G-TERN primarily aims to contribute to understanding sea ice processes, their evolution and interactions with the rest of the climate systems.

The sea ice cover is a crucial component of the polar and global systems, influencing and influenced by changes across a wide range of temporal and spatial scales. A recent attempt to quantify the overall impact of sea ice on the current climate found that sea ice and anthropogenic greenhouse gas emissions are of similar magnitude in terms of their influence on the global heat budget [38]. Sea ice plays a number of key roles in moderating global climate, not only by influencing the planetary heat budget but also by interacting with the oceanic and atmospheric circulation systems as well as the terrestrial environment [39]–[50]. These complex feedback mechanisms link the atmosphere, sea ice, ocean, seafloor, and land, and many of them are not yet fully understood [46]. For example, winds and ocean currents can alter the distribution of sea ice. These changes in the sea ice cover can then affect large-scale circulation patterns in the atmosphere (e.g. [41], [43]) and the ocean (e.g. [39]), which in turn may impact weather and the global climate system. Moreover, the Southern and Arctic Oceans are different dynamic systems. On one hand, surface waters in the Southern Ocean have experienced less warming than has been observed in other areas. On the other hand, the Arctic sea ice has decreased rapidly, and recent reports indicate that it could be largely free of sea ice in summer as early as the late 2030s, only two decades from now.[1] Climate models face a challenging paradox when attempting to predict the evolution of the polar systems: whereas the historical trend in Arctic sea-ice extent is underestimated by the models, the simulated downward trend in Antarctic sea-ice extent is at odds with the small observed positive trend that has been further complicated by unusual weather events shrinking Antarctic sea ice in the last season. The polar sea ice paradox remains one of the most challenging science issues to be resolved regarding climate change science [51]–[54].

Arctic sea ice prediction has inherent limitations due to the stochastic nature of the climate system. These limitations are poorly understood, especially across the full range of timescales and variables of scientific and societal interest. Advances in understanding these limitation and in the seasonal-to-decadal predictive capabilities require enhancements of our theoretical, observing, and modeling capabilities [55]. The recent decline in the extent of Arctic summer sea ice has resulted in a dramatic shift in its composition, first-year sea ice become dominant over multiyear sea ice (e.g. [47], [55], [56]), which reduces its size, remains younger and thinner [57], [58]. This rapid change to a new state is likely to have important implications for sea ice variability, predictability and even Arctic halogen photochemistry [59]–[62]. In the face of this significant transition, there is the need to identify and understand whether and how key parameters are properly modeled. Currently, sea ice models' treatment of ice dynamics and thermodynamics employs parameterizations that were often developed based on observations taken in a primarily multiyear ice regime, and they may not apply in the new state, in which the surface albedo heat balance are profoundly altered. Moreover, it is likely that if, as expected, the substantial ice retreat continues and the remaining ice transforms to a largely seasonal character, the oceanic and atmospheric circulation and thermodynamic structure will respond to the changes in the surface state, affecting large-scale patterns. The regime shift may also cause changes in physical and biochemical processes that have not been adequately accounted for in current models.

Over Antarctica, it is not yet well established quantitatively the relative contributions from multiple mechanisms to explain the observed variability and the slight increase in overall Antarctic sea ice extent, as many local,

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[1] AMAP Snow, Water, Ice and Permafrost. Summary for Policy-makers. This document presents the policy-relevant findings of the AMAP 2017 assessments of snow, water, ice and permafrost in the Arctic (SWIPA), 2017.

regional, and global processes influence sea ice growth and melt. Different theories suggest different potential explanations to this phenomena, including the role of feedbacks between the ocean and sea ice; possible tropical Pacific and Atlantic teleconnections; and effects of winds and ocean currents controlled by topography and bathymetry [63]. Understanding the mechanisms and processes driving sea ice variability and trends in the Southern Ocean is limited by the lack of proper observations to quantify sea ice characteristics and processes [63], [64]. Changes in the Antarctic, where average sea ice extent is approximately 20% greater than in the Arctic [64], could result in relatively significant changes to planetary albedo. Furthermore, feedbacks between sea ice production and ocean water temperature and salinity may play a role in determining the stability of Antarcticas massive sheets of glacial ice [65]–[67]. Understanding sea ice variability and trends may thus be important for anticipating the rate of ice sheet melt and sea level rise in the coming decades. Process-based understanding is critical for improving our knowledge of the mechanisms of Antarctic sea ice variability, but they require high-resolution atmosphere and ocean products, especially for resolving some of the features such as eddies, polynyas/ice formation, and katabatic winds/cyclogenesis. These complexities demand major advances to observe the Southern Ocean.

Furthermore, extreme events such as polar lows and anomalous winds due to dipole anomalies [47] may combine with preconditioning and ice-albedo feedback to result in abrupt changes, e.g., a large decrease of sea ice in a short time [57], [68]–[71], with decadal impacts. For example, drastic loss of perennial sea ice owing to persistent wind patterns in 2005 and 2007 [42] may influence the long-term sea ice trends. Models can simulate extreme events of this type (e.g. [72]) but the accuracy of how simulated extreme events modify key parameters of the ice needs to be further assessed.

The Arctic Marginal Ice Zone (MIZ) and the Antarctic Frontal Ice Zone (FIZ) are the areas where sea ice is more exposed to weather and ocean phenomena [63], together with advection zones (AZ) in coastal areas. Moreover, near costal areas, warm waters from river discharge can bring significant heat to melt sea ice effectively. From Arctic rivers, massive discharges carry an enormous heating power of 1.0×1019 J/yr for each 1°C of the warm river waters above freezing [49]. River discharges, which vary weekly, rapidly warm up sea surface temperature by more than 10°C at the scale of ∼150 km away from the coast and 2°C as far as ∼450 km out in the ocean [49]. These phenomena not only melt the sea ice, but also alter the air-sea interactions in the boundary layer through variations in the air-sea temperature difference that impacts the Monin-Obukhov length and the friction velocity. The ice in these areas is therefore highly dynamic, and proper understanding and quantification of its rapid response to quick evolving episodes of winds, waves, polar lows and discharge episodes would enhance our knowledge of the interactive mechanisms leading to the ice variability (see Figure 1). This could be achieved with observations of these forcing phenomena, together and synchronized with frequent quantification of ice production and deformation processes, including divergence in polynyas near the coast, evolution of the MIZ and FIZ formations, and ice mass variations.

Earth system components in order to advance the understanding and prediction of climate change and its impacts on the environment and society. The mission addresses the World Climate Research Programme (WCRP) Scientific Challenge on Melting Ice and Global Consequences, including the rapid transition towards an ice-free Arctic Ocean and its impact on the large-scale atmospheric circulation, extreme weather and climate conditions. G-TERN also aims to contribute resolving the challenging polar sea-ice paradox. These objectives are articulated through three key questions:

- MAIN OBJECTIVE, QUESTION-1: In a rapidly changing Arctic regime and under the resilient Antarctic sea ice trend, how will highly dynamic forcings and couplings between the various components of the ocean, atmosphere and cryosphere modify or influence the processes governing the characteristics of the sea ice cover (ice production, growth, deformation and melt)?
- MAIN OBJECTIVE, QUESTION-2: What are the impacts of extreme events and feedback mechanisms on sea ice evolution?
- MAIN OBJECTIVE, QUESTION-3: what are the effects of the cryosphere behaviours, either rapidly changing or resiliently stable, on the global oceanic and atmospheric circulation and mid-latitude extreme events?

The secondary objectives of G-TERN address complementary cryospheric science questions as well as other climate relevant applications. The first secondary objective aims to demonstrate the suitability of the G-TERN mission technique, the reflectometry using navigation signals (GNSS-R), to sense other cryosphere products. If successful, these products would complement the investigations on the main objective with potential to become a breakthrough in other cryospheric questions.

- SECONDARY OBJECTIVE-1, COMPLEMENTARY CRYOSPHERE PRODUCTS: Which is the potential of the G-TERN techniques to extract geo-physical information about
  - snow cover over sea ice, its thickness and density;
  - sea ice permittivity, density and/or brine content;
  - sea ice surface melt onset and melt pond fraction;
  - distinction between modal (thermodynamic) and dynamical (deformation) growth of the sea ice;
  - ice sheets and large caps, their surface elevation changes, mass balance, run offs, melting episodes, surface and sub-surface snow properties;
  - permafrost active layer changes, freeze and thaw phase, surface deformations;
  - seasonal snow in mid latitudes, its thickness and snow properties; and
  - glacier evolution?

Finally, the last secondary objective addresses selected contributions of the land component into the global warming scenario. In particular, G-TERN aims to contribute quantifying the biomass and its variations as well as the extension of the flooded areas within wetlands (i.e. inundated wetland extent), including densely vegetated ones (e.g. forested swamps). Both variables play essential roles in the water and energy cycle, linking hydrological, ecological and atmospheric carbon sciences.

- SECONDARY OBJECTIVE-2, LAND COMPONENT:
  - How the water coverage is changing in wetland areas (particularly swamp forests) in view of the rapid rate of wetland collapse?
  - What is the role of wetlands in methane emission processes, especially in view of new pathways for methane emissions that can be potentially identified with frequent observations including densely vegetated and forested regions?
  - How regional conditions, especially soil moisture, impact wetland inundation dynamics and affect regional atmospheric patterns (e.g., by altering the Bowen ratio) that in turn impact the transport and distribution of methane emitted from wetlands?

A. OBSERVATIONAL REQUIREMENTS

The observational requirements of G-TERN are driven by the primary objectives. To properly contribute answering the primary scientific questions, G-TERN will measure key parameters of the sea ice, the oceans and the atmosphere with frequent and dense coverage over polar areas, becoming a ‘dynamic mapper’ of the ice conditions, ice production and loss in multiple time and space scales, and surrounding environment. Frequent mapping is very important for better observing and understanding multi-scale interaction processes. For example, the causes and effects of deformation events on changes of the sea ice mass balance. Global interactions and their impacts will also be explored through generating global datasets of ocean and atmospheric observations suitable for assimilation in numerical models.

Given that at polar areas the rapid and violent weather systems have typical temporal scales of days to a week, river discharge change significantly over weekly scales, and given that these events are relevant target phenomena to be observed (QUESTION-1 and -2), their temporal scales constraint the time resolutions of G-TERN over polar areas to a few day periods. Particularly important during the spring-summer transition is the albedo switch from high to low values that crucially impact the surface heat balance and thus sea ice melt processes. Such albedo switch may occur on a weekly temporal scale [73], and thus demanding sub-weekly ($\sim$3 days) observations to account for the Nyquist temporal sampling requirement. The albedo change is dependent on different distribution of melt pond fraction over the synoptic sea ice classes including first-year (seasonal) and multi-year (perennial) sea ice in the Arctic [74], and over different Antarctic sea ice classes [63] depending on the sea ice roughness, including the FIZ with spatial scales as little as 100 km [63]. Indeed, understanding the causes and effects of deformation events on changes of the sea ice mass balance requires rapid repeat observations over the

TABLE 1. **Observational requirements to address G-TERN's primary scientific objectives (level-3 products' requirements).**

launch is planned in 2025 and the nominal mission duration is five years. Table 2 summarizes the main mission characteristics.

TABLE 2. **Overview on the main G-TERN mission characteristics.**

In group-delay altimetry the observable of interest is the delay (or range) of the reflected signal. In interferometric GNSS-R technique, planned for G-TERN, the delay is understood as the time lapse between the arrival of the reflected radio link and the arrival of the line-of-sight radio link (non-reflected, also called 'direct' signal). Among the GNSS community it is common to work with ranges or distances rather than the time lapses needed for the signal to travel them. The term 'delay' is then used indistinctly for both concepts, and often expressed in units of length (as range/distance). Given that these measured ranges include systematic effects such as drifts in the clocks, atmospheric delays, or instrumental biases, they should be called pseudo-ranges. As explained before, the GNSS-R observable is the DDM or its central slice, the waveform. The determination of the arrival time of the reflected signal is equivalent to finding the point along the waveform or DDM that corresponds to the reflection off the specular point. Signals reflected off a roughness-free surface (e.g., very calm waters or smooth sea ice) present a non-distorted correlation function, and the specular delay corresponds to the delay of its peak. This is also the case in standard GNSS navigation receivers for determining the arrival time of the line-of-sight signals. In general, though, this does not apply in Earth reflectometry. For rough surfaces such as the ocean or rigged ice, the peak of the waveform is typically shifted from the specular delay because of the surface roughness, which induces scattering off surface elements around and even away from the specular point. Then, the arrival time of the shortest-specular-delay corresponds to some point between the rising of signal power and its peak, an unknown point along the leading edge of the waveform. Several approaches have been suggested to determine this point (e.g. [102], [103], [105], [118]), among others, the peak of the first delay-derivative of the waveform, a certain fraction of its power, or fitting a theoretical model (e.g., match filter).

The group-delay altimetry has been tested from ground-based and airborne campaigns, for both conventional GNSS-R and interferometric GNSS-R. The experiments have applied the same principles, regardless of the acquisition approach (cGNSS-R vs iGNSS-R), being the main difference between them the bandwidth (thus range resolution) of the signals involved in the processing. The improvement in precision in iGNSS-R compared to cGNSS-R is in the range 2 to 6 [96], [100]–[102], [105]. Airborne iGNSS-R experiments have reported precisions in the range of 0.25 to 0.6 m in 10 seconds observations [119], largely limited by the noise of the aircraft trajectory (see Figure 4), which agrees with the precision predicted by the theoretical models evaluated at these airborne scenarios [102], [105].

Group-delay spaceborne altimetry has also been reported from TDS1 satellite, over ocean and sea ice surfaces. Because TDS-1 does not implement the interferometric capabilities, the results correspond to cGNSS-R. Over smooth sea ice in Hudson Bay the reported precision is 0.96 m in 0.5 seconds and 3.5 km sampling [29]. Over open ocean, [118] reports show that phase altimetric retrievals are sensitive to anomalies of the ocean topography and that an altimetric precision of 10 cm in 1 second observation is possible in this respect [124]. At angles of elevation below 10°, critical uncertainties were found to be induced by residuals of the tropospheric delay, degrading the precision to about 30 cm. In general, a limit for phase altimetry is set by the diffuse character of L-band reflections off the rough surface that impede the retrieval of coherent phase observations. However, the diffuse reflection limit depends on the surface roughness and the signal incidence/elevation angle. Coastal experiments demonstrated carrier phase delay altimetry for wind speeds up to 10m/s [125] and significant wave heights$<$ 0.6 m [108]. Airborne experiments revealed the sensitivity of carrier phase retrievals to geoid undulation [126] sea surface topography [82] over rough open waters in the Mediterranean Sea. Figure 5 shows phase altimetric retrievals from an airship experiment. The 20 cm geoid undulation along the 15 km reflection track is resolved with 3-4 cm precision. The phase-altimetric precision relies on a model-based retracking of the signal, using geometric and atmospheric corrections. A general difficulty arises from the apriori unresolved phase ambiguity. A reference height is provided by the nearby tide gauge stations to fix the ambiguity at the crossover point. In spaceborne scenarios, crossover points with reflected GNSS signals from other transmitters and other altimetric sensors would allow to mitigate the uncertainty of the phase ambiguity. The previous coastal and airborne experiments over sea surfaces have shown that carrier phase altimetry works for reasonable range of elevation angles at the reflection point (5°-30°). At higher elevation angles coherent observations off the wind-driven sea are much less frequent due to diffuse reflection. At lower elevations the tropospheric residual usually impedes precise altimetric retrievals.

The presence of sea ice at the water surface significantly shifts the diffuse reflection limit and improves the phase coherence of L-band observations [17], [128] and phase delay altimetry was conducted with a few cm precision from a 700 m cliff in Greenland [17]. In fact, smooth carrier phase observations have even been obtained at much higher elevation angles ($\sim$50° incidence) over smooth sea ice from the TDS-1 mission [30], with preliminary analysis showing precisions of 4.7 centimetres in 20 millisecond observations. In addition to the tracks analyzed in [30], other phase delay data obtained from TDS-1 over sea ice seems to confirm the possibility of tracking the carrier phase when reflected off sea ice surfaces (see Figure 6). Also continental ice sheets yield rather distinct than diffuse reflections [22] that can be suitable for phase altimetry. The ability of phase altimetry to use data at low elevation angles increases the swath significantly compared to near-nadir configurations. An extension of the elevation range from grazing and slant observations also towards higher angles is expected for sea ice and ice sheet altimetry. The reason is the reduced roughness of some types of sea ice and ice sheet surfaces, that yields reduced diffuse scatter and coherent phase observations.

FIGURE 5. Panel (a): Example reflection track (blue) over Lake Constance obtained from a GNSS-R payload aboard a zeppelin. A crossover reference S0 is indicated which allows to solve the phase ambiguity. The reference is based on lake level estimates from the gauge stations (red circle) nearby. Panels (b) and (c) show the phase altimetric solution (gray) for right- and left-handed polarization retrievals, respectively. Due to crossover referencing the total height level H can be estimated. For comparison, the geoid undulation G along the track is plotted as blue line, taken from GCG05 model [127].

An important question, which requires further investigations, is the L-band signal penetration into the snow cover on sea ice, sea ice itself and ice sheets. In [11] the penetration into sea ice was estimated between 30 and 70 cm, while over dry snow over ice sheets [22] reported reflections from subsurface layers down to 200-300 meter at Concordia Station, Antarctica. In general, L-band signals are more transparent to snow than other instruments at higher frequency bands, thus representing an advantage to minimize the contamination of the retrievals induced by the snow cover (issues in Cryosat-2 and ICEsat/ICEsat-2).

C. iGNSS-R SCATTEROMETRY

During the initial stages of the GNSS reflectometry, the target of the incoherent reflection measurements was the wind speed and wind direction (e.g. [129], [130]), when precisions of the order of 2 m/s in wind speed and 20 degrees in wind direction were reported. However, it was soon understood that the wavelengths of L-band signals were sensitive to a combination of other ocean surface parameters, such as wind, swell and wave age, reason for which the term ‘L-band roughness’ was introduced. The mean square slopes, mss–dispersion of the surface slopes–was thus the preferred parameter in some other studies (e.g. [131]–[133]). The ‘L-band roughness’ has

FIGURE 6. In addition to the TDS-1 phase-delay altimetry over sea ice shown in [30], other sets of data provide further evidences of the trackability of the phase in sea ice GNSS reflections. Top-left: Three GNSS reflected tracks over sea ice, acquired in raw data mode by TDS-1 on March 24th, 2015. The red segments correspond to the portions where phase-delay altimetry is applied. Top-right and bottom panels: Carrier phase altimetry obtained with the data sets, and compared to the mean sea surface (DTU13 model). TDS-1 raw data made available by SSTL and processed by W. Li (ICE-CSIC/IEEC).

interest as complementary information required in sea surface salinity measurements performed with L-band radiometry (ESA's SMOS, NASA's Aquarius), as well as potential source of air-sea interaction and dragging, when combined with independent wind estimates.

The previous statements were first supported by a wide diversity of air-borne and stratospheric experiments performed at different altitudes, receiver speeds, instrumental equipments, and analysis techniques (e.g. [129]–[140]). At least eight different techniques were used in the listed references, of different degree of complexity and elaboration, different final product (scalar roughness, directional roughness, non-Gaussian features). Recently, intensive work has been done to extract wind and roughness information from GNSS-R spaceborne missions, such as TDS-1 and CYGNSS, mostly constraining the source of information around the peak of the DDM [90], [141], [142] or inspecting the geophysical informational content in DDM cells further away from the specular [143], [144]. In all these inversion schemes the starting point is the bi-static radar equation from which the radar cross section or the probability density function of the slopes is inferred. Over the oceans, given the G-TERN specifications one expects similar scatterometric performance as for the CyGNSS mission, with finer spatial resolution (provided by the iGNSS-R technique).

Characterization of sea-ice has been also reported from experimental GNSS scatterometric work [11], [16]. Over ice, mss derived from the decay rate of the GNSS reflected waveforms was also reported as a valuable indicator of the ice surface roughness, as it is linearly related to the standard deviation of the surface elevation [11]. These airborne campaigns showed good agreement with the surface elevation dispersion obtained from GPS reflections and those measured with a lidar aboard the same aircraft. Similarly, an efficient permittivity of the ice, obtained from the received GNSS-R power, correlated with the ice age. A combination of both power and decay characterize the ice age or type. From the TDS-1 spaceborne platform, high accuracy in sea ice detection has been obtained using DDM observables [26] through investigating the degree of coherence of the waveform extracted from DDM [27] or using neuronal networks [28]. Moreover, the signatures around the peak of the DDM have also been used in these neuronal networks to estimate the sea ice concentration [28], with an overall discrepancy with respect to independent concentration estimates at 1% level.

D. iGNSS-R POLARIMETRY

Polarimetry is a powerful tool for radar remote sensing of our planet. It consists in observing the polarization properties of the electromagnetic wave scattered by the target for any polarization of the impinging wave illuminating the target. The strength of the technique stems from the capability to identify the main scattering mechanisms involved in the interaction of the signal with the target, each mechanism being characterized by its own polarization signature. A number of measurements has to be performed, which consists in observing in two orthogonal polarizations the scattered signals obtained when illuminating the target with as many polarizations of the impinging waves. Depending on the polarization base we consider, e.g., horizontal (H) and vertical (V); or right handed circular (R or RHCP) and left handed circular (L or LHCP), we have to measure HH, VV, HV and VH or RR, LL, RL, LR. Note that we have to measure not only the signal strength (i.e., its power) but also the phase difference between incidence and scattered polarization components. We can translate measurements in the circular polarization base into measurements in the linear polarization base [145]. Some of these measurements can be redundant (e.g., VH and HV in backscattering) or can bring poor information content, so that we can reduce the number of observations keeping the relevant information for target characterization.

The GNSS transmitters radiate a wave whose polarization is nominally RHCP. To carry out a fully polarimetric measurement one should measure the co-polar (R)ight but also the cross-polar (L)eft component due to transmitting antenna polarization imperfections, and then receive at the same time the Right and Left polarized scattered signals in amplitude and phase. Monostatic radars are already exploiting polarimetry from satellites, but G-TERN will provide for the first time polarimetric spaceborne measurements of the signal reflected around the specular direction, with high potential in the cryosphere domain, but also capable to fulfil many secondary objectives of the mission. A critical aspect (especially at RHCP, as it can be several dBs below LHCP) is the sensitivity required to cover the full dynamic range of the signal associated to different surface conditions. This requires a suitable gain of the system and in particular of the nadir-looking antenna. Additional critical aspects can be the effects of surface topography and land cover heterogeneity, especially if they change within the area of the first Fresnel zone. Those are challenges of GNSS-R over land that G-TERN could help to tackle and solve.

For cryosphere applications, the polarimetric response of the scattering is well recognized by the scientific community as an essential aspect of the remote sensing of sea ice (e.g. [146]). At L-band, the Fresnel reflection coefficients of the circular polarization base show sensitivity to water-ice transition and, in lower degree, also to ice properties through its permittivity changes (e.g. brine content). At relatively low angles of elevation (large incidence) such as the geometries planned for the phase-delay altimetry, these changes affect both the ratio between the power of the two polarized scattered signals (e.g. LHCP/RHCP) as well as their phase shift (here called POlarimetric Phase Interferometry, POPI, [15], [16]). Figure 7-left shows the polarimetric ratio and POPI of sea water and sea ice as obtained from their Fresnel coefficients (from formulations in [147]). The figure clearly shows two separate regions, for sea water and for ice. Actual measurements are also affected by the textures of the roughness, the purity of the transmitted signals and the receiver instrumental response. These ideas were tested during an ESA field campaign conducted between November 2008 and May 2009 from a 700 m cliff overlooking Disko Bay, Greenland (ESA's GPS-SIDS campaign). Despite the polarimetric ports were not calibrated, signatures consistent with the sea ice concentration were found (Figure 7-right). The ideas on polarimetric response of water/ice surfaces were also tested in a shipborne experiment, conducted 2016 in Fram Strait, which provided reflectometry data during drift and fast ice periods [148] in two orthogonal polarizations for reflections at slant elevation angles (5°-30°) (Figure 8). The power loss observed in LHCP data during the transition from calm open-water to the regime of high sea ice concentration agrees with model predictions. Recently, the receiver chain of SMAPs radar, working at two linear polarizations, has been used to search for GNSS reflected signals. For the first time it has been possible to obtain from a spaceborne platform the polarimetric signatures of GNSS reflected signals. Over polar regions, the polarimetric ratio, here defined in linear base and at smaller angle of incidence (40°) has shown sensitivity to sea ice [24].

The combination of different geometries (from nadir to 45° incidence and 5° to 30° elevation) accumulated in a few days within a relatively small area, together with the polarimetric capabilities of G-TERN may have potential to discern leads and polynyas and melt onset; or to help characterizing the snow cover above the sea ice and the phase of permafrosts active layer [23]. These potential products are some of the demonstration activities envisaged as secondary objective of the mission.

E. GNSS RADIO OCCULTATION

An additional, but secondary, objective for G-TERN is GNSS based radio occultation (RO) for precise sounding of the neutral atmosphere and the ionosphere. Global and precise atmosphere sounding using GNSS radio occultation has matured in recent years from experimental proof-of-concept missions to well-established and operational applications (e.g. [149]). Outstanding examples for this progress are the results from CHAMP (e.g. [149], [150]),

are widely used for space weather related but also climatological studies related to the variability of the Earth's ionosphere [153], [184]–[186]. Complementary results verified the potential, according to classical Chapman theory, to monitor climatologically parameters of the thermosphere such as the scale height by measuring the equivalent slab thickness. Recent computations based on measurements of the total electron content (TEC) and the peak electron density, have indicated a cooling of the thermosphere above northern Germany during the recent solar cycle [187]. It has been recently proven to be a much better description of the topside electron density profile in terms of a linearly varying scale height (Vary-Chap model), in agreement with the first principles prediction (based on an increasing electron temperature with height in such a region [188]). GNSS RO enables measurements all over the globe, in particular also at low latitudes where highly dynamic electron density variations and plasma turbulences occur but the data base is far from being sufficient and will profit from the G-TERN data. The impact of a better modelling of the ionospheric contribution to the bending angle is receiving as well an increasing interest [189].

GNSS RO data are currently already operationally available from several missions, e.g., Metop-A/B, GRACE, TerraSAR-X, TanDEM-X, and the dying FORMOSAT-3/COSMIC mission. Several new operational missions with GNSS RO started recently or will be realized in near future, e.g., COSMIC-2, EUMETSAT Polar System - Second generation (EPS-SG), FengYun-3 (FY3), Spire. Therefore, the need to get RO data from G-TERN seems less compelling and is regarded as mission goal with lower priority, as compared to GNSS based ice and ocean remote sensing. Nevertheless, the case for increasing the number of RO measurements is clear [163].

Moreover, there are several highly innovative aspects supporting GNSS-RO measurements within the G-TERN mission. These are:

- Exploring new capabilities: Galileo, GLONASS and BeiDou signals for RO. In addition to the new signal structured in the new GNSS constellations, G-TERN would also use the modernized GPS system. Therefore, G-TERN will provide a unique data set for scientific investigations to improve POD and RO data analysis and related product quality.
- Provision of high quality RO data in the lower troposphere due to high-gain antenna, which is not possible from current missions.
- Strong complementarity to the grazing angle GNSS reflectometry approach, the coherent reflectometry observations for altimetric measurements of ice and ocean surface topography, which are part of the primary mission goals [12], [122]. This also represents provision of important additional atmospheric (dry and wet tropospheric) and ionospheric delay information partially collocated with the coherent G-TERN GNSS-R measurements and of relevance for the analysis and correction of the grazing reflectometry measurements for ice and ocean surface height measurements obtained aboard the G-TERN satellite.
- Omnidirectional downlooking RHCP for reflectometry allows the reception of side-looking RO events, which last significantly longer than the standard occultation data events and are not available from current and future operational RO missions. They cover larger horizontally atmospheric regions and contain more atmospheric information as the currently used RO data products. The value of these data to improve global weather forecasts would be investigated in cooperation with the leading NWP centers. Experiments for a GNSS RO based monitoring system using 12 beams in parallel could be conducted from G-TERN (see Figure 9 for example of 24 hours coverage). This would allow assessing the potential of new scientific applications in polar but also non-polar regions, e.g., 3D atmospheric reconstructions to investigate meso-scale atmospheric phenomena, as, e.g. atmospheric waves.

Off-line dynamic and reduced-dynamic POD based on dual-frequency GPS data has evolved to a mature and well established technique, offering cm-accuracies. As a prerequisite the attitude motion of the onboard GNSS receiver antennas in inertial space needs to be precisely known, e.g. from star tracker measurements, and GNSS sensor locations need to be well specified by proper calibrations on ground such that only small systematic errors remain in the data, e.g. antenna phase center variations, that may be calibrated in orbit [195]. Compared to dynamic and reduced-dynamic orbit determination only marginally worse accuracies are today achieved in the kinematic mode if the number of simultaneously and continuously tracked GPS satellites is sufficiently large.

V. IMPLEMENTATION

A. INSTRUMENT

The instrument concept is based in previous studies led by Airbus DS Space System España, (former EADS CASA Espacio), namely: the ESA PARIS In Orbit Demonstration (PARIS-IOD) Critical Technology-1; the ESA PARIS-IOD GNSS-R Feasibility Study; and the ESA GEROS-ISS industrial feasibility (mission's phase-A) study.

This section provides a brief overview of the main characteritics of the payload. The instrument will work in two RF frequency bands simultaneously L1 (1570.809 MHz) and L5 (1189.35 MHz) that are converted to intermediate frequency by means of a local oscillator. The bandwidths are set to 47.322 MHz and 63.9 MHz at L1 and L5 respectively. Many parameters will change from one operational observation to the next, mainly driven by the selected application (altimetry, scatterometry, grazing altimetry, radio occultation) and acquisition geometry. Even during the observation, adaptation of parameters is required, i.e. delay coefficients, beams, etc.

All these particulars prompt to plan a flexible commanding technique that is able to cope with a multitude of user demands and needs. In principle, the commanding concept provides the capability to program an operational run of the instrument in form of a series of user defined antenna modes and applications states during a swapping period. Each application state can be split into different sub-states reflecting beam pointing changes during the state. Each antenna mode, application state pair reflects the complete parameter setting for a dedicated instrument operation and selectable time duration.

These features are planned to be implemented in the G-TERN instrument through the following elements, sketched in a blocks diagram in Figure 10:

- Instrument RF Front-End including:
  - 1 Double side (Up and Down) antenna Array
  - 31 Calibration and Low Noise Amplifiers Modules (CAL/LNA)
  - 4 Beam Forming Network Units (BFN)
- Instrument Back-end including:
  - 4 Signal Processor Unit (SPU)
  - 1 Instrument Control Unit (ICU)
  - 1 Precision and Orbit Determination Receiver (POD)
  - 1 Power Supply Unit (SPU)

For instrument time synchronization it is convenient to use the GPS/POD time as a highly accurate atomic time scale. This time scale is available in both the ground segment and the satellite, on ground by conversion of UTC time to GPS time and onboard due to the use of POD receiver. The onboard POD receiver outputs a PPS (pulse per second) time tick signal which will be used onboard as a 1 Hz synchronization signal. This synchronization signal coincides with the GPS epoch with a very high precision and fixes the exact moment of GPS time validity. Hence, any onboard event can be dated accurately in terms of GPS time by means of time measurements with respect to the PPS signal and by assigning the absolute GPS time to the relevant PPS epoch.

A set of instrument modes is introduced to ease the operation of the instrument from ground on one hand and to clearly structure the control of the instrument according to the system hierarchy on the other hand. The instrument is set into the desired mode by processing the commands from ground. The instrument control expands or converts the commands into an appropriate sequence of instrument internal commands that will be sent to other units and modules. The on-ground telecommand generation should follow a simple approach. First, the user must select the GNSS to be tracked. Depending on the desired application the instrument must point the antenna towards the direct signal and/or the reflected one. Second, the user establishes a sequence of observation states (applications) within a swapping period and some parameters that configure the selected application such as integration times. Based on the parameter information the instrument control composes and sends the required commands to the CAL/LNA, BFN and SPU units. Imaging of desired ground scenarios is planned and prepared in advance on ground. During this planning phase the desired orbit position and the related OBT time are predicted for each observation and are included in the corresponding time-tagged Configuration commands.

The instrument electrical concept is the result of a trade-off between instrument complexity and the survival of all mission applications. The Instrument Control Unit is the central element in charge of instrument operation. The front-end and back-end elements respond to ICU commands. The operational synchronization of all elements is under this unit responsibility. The SPU is based on the signal processing cores developed for PARIS-IOD and GEROS-ISS missions, the 'PARIS COrrelator' (PACO) unit [204]. The SPU control is basically the PACOs control. Each PACO has one Spacewire interface that shall be used by the ICU to control all PACO internal parameters and configurations. The same Spacewire interface is used for housekeeping and scientific telemetry.

The two G-TERN antennas are arrays of 31 patch elements (up-looking side) and 30 path elements (down-looking side) in a hexagonal array lattice with a separation of 178 mm between patches as shown in Figure 12. The down-looking side of the antenna contains Left Hand

TABLE 4. Main budgets and performances of the G-TERN instrument.

via power, data and mechanical interfaces. The platform uses for the most parts off-the-shelf space-qualified components with Technological Readiness Level (TRL) $\geq$8, while the subsystems, which require minor modifications for the specific mission needs, still reach a TRL $\geq$5/6. The agile 3-axis stabilized platform is able to meet the most stringent pointing requirements. Furthermore, it offers several optional features to adapt to different mission-specific and payload-specific constraints, for example in terms of power generation and storage, payload data handling and transmission. The platform can comply with both uncontrolled and controlled re-entries. Due to its cost-effectiveness and modular decoupled design, providing separation between payload and platform modules and resulting in programmatic savings, the platform is the perfect candidate for the G-TERN mission in the frame of Earth Explorer 9 programme.

The platform is designed to fit either in the lower or upper position - depending on the payload - of the 'extended' VESPA (+500mm) of VEGA, for dual launch. In Figure 14, the spacecraft is depicted, fitting within the useable envelope of Vega upper position. The Launch Vehicle Adapter is a band clamp with a diameter of 937mm. Given the limited information available on Vega-C and the smaller size of current Vega fairing, the conservative approach of fitting the spacecraft inside the current launcher configuration was assumed. In the next phase of the study, following the consolidation of mission, payload and system requirements as well as updated information of the VESPA adaption to Vega-C, a more detailed assessment could be performed on whether and under which conditions/configurations it would be possible to fit the spacecraft inside VESPA, in lower position.

re-entry is required, adaptation of the propulsion system is needed: in the following phase of the development, a consolidation of mission requirements and spacecraft design will allow for detailed re-entry analyses and assessment of casualty risk, to demonstrate compliance with current regulations.

The telemetry and telecommand transmission is performed via S-band while the science data are downlinked via X-band, together with telemetry data for contingency. The payload data handling and transmission subsystem has the following characteristics:

- An Isoflux antenna allows transmission to the ground station
- The high data downlink rate and memory size allow considerable memory margins, even when considering 100% duty cycle with 12 beams and 2 frequencies, i.e. 3.1 Mbit per second of science data.

A downsizing of the payload data handling and transmission subsystem could be performed, if considered necessary, to reduce the design margins in a more mature phase. The data downlink budget was analysed assuming the Kiruna 13 meters dish with 5° minimum elevation angle. As the electrical power generation and distribution system (EPS) is concerned, a solar array driving mechanism coupled with a mounting cant angle, when applicable, allows to achieve high performances by sun tracking. The spacecraft has a 28V unregulated bus with direct energy transfer distribution. The electrical power system is sized for 10 years for a 600 km dawn-dusk orbit (LTAN 06:00), where maximum eclipse reaches 20 minutes duration in winter. The sever square meter solar array is able to provide 1315 W at the power control and distribution unit. Batteries provide 57 Ah at 33.6 V. The power budget in analysed under different modes of operation: 91% of the duty cycle it would operate under nominal operation mode, while the ground station pass mode (payload operational and simultaneous downlink) would happens up to 9% of the duty cycle. This results in an average power budget of 943.8 W, which consistently accounts for the design margins.

The mass budget has been estimated considering a range of margins (from 5% to 30% depending on the subsystem) and including the propellant mass. The total spacecraft wet mass then results in 870 kg, which fits within the constraints of the launcher and the EE9 Call.

VI. EXPECTED PERFORMANCE

The fulfillment of the required critical performances (Table 1) is evaluated by means of end-to-end simulation exercises. The exercises are limited to the altimetric performances, as they represent the most demanding application in G-TERN. The approach comprises the following blocks:

1) Generation of synthetic 1-second level-1 data according to the G-TERN orbital and instrumental characterization, as well as a limited set of sea ice conditions and geometries. These data sets must include the different noise components, in the form of a Monte Carlo like approach.
2) To apply the inversion algorithms to retrieve the group-delay altimetric products (1 Hz level-2 data) from the synthetic level-1 observables generated in block 1 above.
3) To determine the uncertainty of the retrieved 1Hz level-2 group-delay altimetric products over sea ice, by means of comparison with the well-known ground truth (simulation settings) and the dispersion obtained from the Monte Carlo set of samples. Blocks 1 to 3 are presented in Section VI-A. Given that GEROS-ISS mission went through industrial and scientific feasibility studies (Phase-A) and these sort of exercises were done and compiled for Ocean applications in [123], we limit these simulations to sea ice scattering conditions, and will use the outcome of [123] for sea surface altimetric performances.
4) To simulate phase-delay synthetic data and its retrieved altitudes to estimate the 1-second equivalent phase-delay accuracy (Section VI-B).
5) To simulate the location of the specular points that a G-TERN system would collect in 3 days, at 1 second sampling over polar areas (here defined as $|lat| > 60°$). Define a grid of cells sized 30 km × 30 km across the polar zone, and group the 1-second observations by the cell where their specular points belong.
6) With the 1-second uncertainties obtained in blocks 3 and 4 above and the number of 1-second observations within each cell obtained in block 5, compute the overall uncertainty over each cell.
7) Analyze the statistics of the obtained uncertainties at each cell within the 3 days simulationperiod. Blocks 5 to 7 are presented in Section VI-C.

A. GENERATION OF 1HZ-LIKE LEVEL-1 WAVEFORMS AND DERIVED LEVEL-2 GROUP-DELAY ALTIMETRIC ACCURACIES

This section compiles blocks 1 to 3 of the end-to-end simulation description above. The simulations correspond to the G-TERN orbit and instrument (see Sections III and V respectively) in four different geometries and two rather extreme examples of sea ice, the best and worst reflectors. The best case reflector corresponds to smooth ice (low roughness) and more reflecting, i.e. saltier ice such as first-year (FY). For simplicity we will call it FY (despite FY can also be rougher). The worst reflector corresponds to ice with rough surfaces and less reflecting properties, i.e. fresher ice with less salt, such as in multi-year ice (MY), hereafter identified as MY (despite MY ice can present smooth surfaces). The smooth sea ice corresponds to the conditions found in Hudson Bay in TDS-1 TD18, 15th January 2015 [29], [30], providing highly specular reflections. The scattering regime for the MY extreme case considered here has been analyzed through TDS-1 TD51 track, 11 February 2015, from 16:55 to 16:58 UTC, for rough ice conditions. The summary of relevant parameters is given in Table 6, including orbital, instrumental, geometries and characterization of the sea

TABLE 6. **Settings of the simulation to generate the level-1 observables for 1Hz group-delay altimetry over sea ice.**

TABLE 8. Total group-delay altimetry uncertainties in the near-nadir field of view (incidence$\leq$45°), including thermal and speckle noise, orbital, tropospheric and ionospheric errors. The noise figures for level-2 sea ice altimetric products have been obtained from a polynomial fit as a function of the incidence angle (θ) of the data in Table 7 for two extreme sea ice conditions (best and worst ice reflectors), and multi-Doppler processing is assumed. For sea surface altimetry, the noise terms have been extracted from the GEROS-ISS studies [123]. POD effects are all set to 5 cm level. Tropospheric effects all set to 1 cm level. Ionospheric effect at polar areas are negligible while 15 cm residual disperion is assumed in the ionospheric-free GNSS combination at non-polar regions. All units in cm.

a step-like height increase of 30 cm. These simulations include the tropospheric, ionospheric and POD systematic effects [123]. After applying the phase delay retrieval algorithms, it is first possible to connect and nearly stop the phases (Figure 20-top). These residual phases are later resolved as height anomalies, recovering the original 30 cm step in the altimetric profile (Figure 20-bottom). The precision of these phase delay measurements are between 0.4 and 0.5 rad, which maps into uncertainties between 1 and 8 cm in 1 second (changing with the geometry, between 60° and 85° incidence). Similar performances are found with shorter surface height steps (20 cm). The performance improves also when higher SNR are assumed. Hereafter we will continue the simulations assuming an equivalent 1 Hz error of ∼5 cm in the phase delay altimetric retrievals.

C. FULFILLMENT OF THE MISSION REQUIREMENTS

The distributions of 1-second observations obtained for the G-TERN system in a particular set of 3 subsequent days (polar areas) and 10 days (globally) have been simulated. The simulations correspond to three scenarios:

- Scenario-1: Availability of up to 12 simultaneous beams pointing within the grazing angle field of view (5° to 30° elevation) over extended polar areas ($|lat| > 60°$). This means that grazing angle GNSS-R phase-delay altimetry could be done in up to 12 different specular points simultaneously.
- Scenario-2: Availabiity of a combination of up to 6 grazing angle and up to 6 near-nadir (incidences smaller than 45°) simultaneous reflections over the extended polar areas ($|lat| > 60°$).
- Scenario-3: Availability of up to 12 simultaneous beams pointing to reflections within the near-nadir field of view (incidences smaller than 45°) over the non-polar areas (here defined as $|lat| < 70°$).

The distributions of 1-Hz measurement points for each of these scenarios correspond to those shown in Figure 21. We remind here that GNSS-R does not follow a repeatable pattern, therefore the actual distribution of observations will change daily, but keeping the latitudinal statistics. At this step of the simulations we have considered that all the 1-second observations are incorrelated. This assumption is too strong, as some of the errors do present spatial or temporal correlations. Nevertheless, this approach permits a quick implementation accounting for all systematic effects without need of simulating natural runs fed by actual tropospheric and ionospheric fields nor POD errors. Therefore, these results might have slightly overestimated the accuracy (underestimate the sigmas), to be partially compensated by certain values of the errors taken on the conservative side.

Using all the 12 G-TERN beams to point at grazing angles of observation, and assuming that the final accuracy of the 1-Hz phase delay observations is at the level of 5 cm (Section VI-B), scenario-1 results in accuracies over 30 km × 30 km cells in 3 days accumulation that fulfills the mission requirements in 99.1% of the cells.

considered to correspond to worst reflector sea ice reflectoins, therefore (Table 8-2nd row): $32.5 - 0.29\theta + 3.5E - 3\theta^2 + 1.9E - 4\theta^3$ cm at 1 Hz, ranging from ~30 cm at nadir to ~44 cm at 45° incidence; measurements done with group-delay observables over ocean waters (Table 8-3rd row) and ice sheets: 30.4 cm. The overall results of combining these 1-second accuracies in 30 km × 30 km cells during 3 days of accumulated data shows that scenario-2 fulfills the altimetric requirements of the mission in a large extent, with 95.5% of the cells performing better than the mission requirements, and an average accuracy of 2.7 cm over regions with $|lat| > 60°$.

Finally, the scenario-3, over global waters (here defined as $-70° \leq lat \leq 70°$) and 0.5°×0.5° cells accummulated in 10 days, results in similar numbers: 97.1% of the cells present accuracies below 10 cm (requirement) while the average accuracy over the cells is 5.3 cm. Figure 22 shows the geographic distributions of the resulting level-3 altimetric accuracies for each scenario, while Figure 23 displays their histogram. The optimal combination of grazing angle phase delay measurements (finer precision) and near nadir group delay measurements (better roughness estimates) would be investigated in future stages of the mission.

VII. CONCLUSIONS

This study summarizes the main aspects of the GNSS Transpolar Earth Reflectometry exploriNg system (G-TERN), a mission proposal submitted in 2017 in response to the ESA Earth Explorer 9 (Revised Call). The mission is foreseen to implement the interferometric GNSS reflectometry technique to address key scientific questions on the inter-relationship between the cryosphere and other main components of the climate system, in view of the global warming. The main focus of G-TERN is set on the sea ice, its dynamic variations and how they both module and are modulated by its surrounding environment, the global atmospheric and ocean circulations as well as extreme weather systems.

The G-TERN satellite should provide altimetric, scatterometric and polarimetric GNSS-Reflectometry based geophysical data products, characterizing the sea ice, oceans, ice sheets and land surface, covering the poles in grids of 30 km × 30 km cells in just 3 days, and the rest of the globe in 10 days over grids of 0.5° × 0.5° cells. The foreseen observation techniques of G-TERN and their preliminary implementation have been introduced. The technical concept is substantially different from other recent GNSS-R missions and includes several novelties and innovation aspects. We highlight in this context: (1) interferometric GNSS reflectometry from space, which provides finer horizontal resolution and higher altimetric accuracy; (2) parallel provision of altimetric, scatterometric and polarimetric GNSS-R data products; (3) twelve simultaneous GNSS-R high-gain beams electronically synthesized and steered to enable observations with unprecedented coverage; (4) combination of slant phase-delay observations and near-nadir group-delay measurements for ice/ocean altimetry with high accuracy; and (5) symbiotic use of GNSS reflectometry and radio-occultation for combined monitoring of the Earth surface and atmosphere/ionosphere.

The G-TERN spacecraft is based on a modernized platform of space-proven components. The main payload, the combined GNSS-R/RO instrument, has strong heritage from two ESA mission studies: the PARIS-IOD and GEROS-ISS concepts. The proposed orbit is near-polar at 600 km altitude, optimally Sun-synchronous at 6AM/6PM.

A set of specific mission simulations was conducted during the proposal preparation to provide first estimates of the altimetric performance of G-TERN over sea ice and oceans. The required geophysical observational needs are essentially met according to the results of these calculations. Accuracies were obtained, better or equal to 10 cm in more than 95% of the sea ice cells in the polar grid in three days integration, and in more than 97% of the global ocean cells in ten days integration. The G-TERN measurements are also expected to prove a set of secondary mission goals, which include the provision of currently not available innovative cryosphere and wetland related data products. These observations would represent a breakthrough in their irrespective science fields. The G-TERN, with its versatile mission scope and unique payload may act as a forerunner for a potential next generation of 'low cost' Earth Observation Systems.

ACKNOWLEDGMENTS

The authors would like to thank SSTL for providing GNSS-R data acquired from the TDS-1 mission that have been used in this study.

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