GEROS Mission Requirements Document

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## CHANGE LOG

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<thead>
<tr>
<th>Issue 1</th>
<th>Revision 0</th>
</tr>
</thead>
</table>

Table of contents:

1 INTRODUCTION ................................................................................................................. 4
  1.1 Scope of the document ........................................................................................................ 4
  1.2 Applicable documents ........................................................................................................ 4
  1.3 Reference documents ......................................................................................................... 4
  1.4 Universal Resource Locators (URL).................................................................................... 9
  1.5 Acronyms and abbreviations .............................................................................................. 9
  1.6 Definitions ....................................................................................................................... 11
2 BACKGROUND AND MISSION OVERVIEW ..................................................................... 12
3 SCIENTIFIC JUSTIFICATION ............................................................................................ 12
  3.1 Measuring ocean surface height at the mesoscale (primary mission objective) ............. 12
  3.2 Monitoring ocean surface roughness (secondary mission objective) ......................... 15
  3.3 Additional objectives ....................................................................................................... 15
4 MISSION OBJECTIVES ..................................................................................................... 18
5 SCIENTIFIC L2 MISSION REQUIREMENTS ................................................................... 20
  5.1 Level-2 geophysical mission requirements ...................................................................... 20
    5.1.1 Sea surface height (SSH) ............................................................................................ 20
    5.1.2 Ocean surface roughness (mean square slope) ........................................................... 21
    5.1.3 Additional mission data .............................................................................................. 22
      Vertical atmospheric profiles ............................................................................................. 23
6 DATA PROCESSING AND RETRIEVAL ............................................................................ 24
  6.1 Level-1 to Level-2 retrievals ........................................................................................... 24
    6.1.1 Sea Surface Height (SSH) ......................................................................................... 24
    6.1.2 Mean Square Slope (MSS) ........................................................................................ 25
    6.1.3 Land surface parameter from GNSS scatterometry .................................................... 26
    6.1.4 Vertical profiles of atmospheric parameters ............................................................ 27
  6.2 Level-1 observation requirements .................................................................................... 28
7 PRELIMINARY MISSION CONCEPT .............................................................................. 32
8 DATA PRODUCTS AND USAGE ....................................................................................... 33
9 SYNERGIES AND INTERNATIONAL CONTEXT ............................................................ 35
1 INTRODUCTION

1.1 Scope of the document

This document reviews and formulates scientific and technical requirements for the GEROS-ISS mission concept (GNSS Reflectometry, Radio Occultation and Scatterometry onboard the International Space Station). It is a Mission Requirements Document (MRD), which defines unambiguous and traceable requirements for the GEROS-ISS concept (‘GEROS’ or ‘the mission’ in the text that follows). The scope of the GEROS MRD includes the end-to-end Earth observation system including scientific requirements, mission operations, data product development and processing, data distribution and data archiving. The GEROS MRD is managed by the GEROS Mission Scientist (M. Kern) according to the procedure set out in [AD-1].

1.2 Applicable documents

The applicable documents are identified within this MRD as [AD-n] or by the first author and date of publication.

AD-1 Procedure for Earth Observation Mission Requirements Definition and Management, QMS-PR-MMAN-2050-EOP

1.3 Reference documents

The reference documents are identified within this MRD as [RD-n] or by the first author and date of publication. All documents are peer-reviewed papers and are available through the individual journals and publishers indicated in the references or upon request from the corresponding authors.


Paloscia, S. et al. (2012). GNSS reflectometry analysis for biomass monitoring. ESA contract 40000103329/11/NL/CVG.


board the International Space Station. Proposal in response to Call ‘ESA Research Announcement for ISS Experiments relevant to study of Global Climate Change’.


1.4 Universal Resource Locators (URL)
The following URL links contain relevant information.

[URL-1] ESA Living Planet programme [http://www.esa.int/esaLP/index.html](http://www.esa.int/esaLP/index.html)
[URL-2] ESA web site [http://www.esa.int/](http://www.esa.int/)

1.5 Acronyms and abbreviations

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>CYGNSS</td>
<td>CYclone Global Navigation Satellite System</td>
</tr>
<tr>
<td>COSMIC</td>
<td>Constellation Observing System for Meteorology, Ionosphere and Climate</td>
</tr>
<tr>
<td>DDM</td>
<td>Delay-Doppler Map</td>
</tr>
<tr>
<td>DMC</td>
<td>Disaster Monitoring Constellation (SSTL satellite)</td>
</tr>
<tr>
<td>EPS-SG</td>
<td>EUMETSAT Polar System — Second Generation</td>
</tr>
<tr>
<td>ESA</td>
<td>European Space Agency</td>
</tr>
<tr>
<td>EUMETSAT</td>
<td>European Organisation for the Exploitation of Meteorological Satellites</td>
</tr>
<tr>
<td>Galileo</td>
<td>European Navigation Satellite System</td>
</tr>
<tr>
<td>GEROS-ISS</td>
<td>GNSS Reflectometry, Radio Occultation and Scatterometry onboard ISS (also referred in the document as GEROS)</td>
</tr>
<tr>
<td>GLONASS</td>
<td>Global Navigation Satellite System (Russia)</td>
</tr>
<tr>
<td>GNSS</td>
<td>Global Navigation Satellite System</td>
</tr>
<tr>
<td>GNSS-R</td>
<td>Global Navigation Satellite System Reflectometry</td>
</tr>
<tr>
<td>GNSS-RO</td>
<td>Global Navigation Satellite System Radio Occultation</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System (U.S.)</td>
</tr>
<tr>
<td>ISS</td>
<td>International Space Station</td>
</tr>
<tr>
<td>MRD</td>
<td>Mission Requirements Document</td>
</tr>
<tr>
<td>MSSH</td>
<td>Mean Sea Surface Height</td>
</tr>
<tr>
<td>MSS</td>
<td>Mean Square Slope</td>
</tr>
<tr>
<td>PARIS</td>
<td>Passive Reflectometry and Interferometry System</td>
</tr>
</tbody>
</table>
PAZ       Spanish Radar Satellite
PDF       Probability density function
POD       Precise orbit determination
PRN       Pseudo-Random-Noise
QZSS      Quasi-Zenith Satellite System (Japanese Navigation Satellite System)
RMS       Root-mean square
RO        Radio occultation
SMAP      Soil Moisture Active-Passive mission
SMOS      Soil Moisture and Ocean Salinity mission
SSH       Sea Surface Height
SSTL      Surrey Satellite Technology Ltd
TBC       To Be Confirmed
TBD       To Be Determined
TDS-1     TechDemoSat-1 (UK satellite)
TOA       Top Of Atmosphere
1.6 Definitions

Accuracy. The accuracy is the root mean square (r.m.s.) difference between the actual measurement and the truth, including random and systematic errors.

Latency. The latency is the time elapsed between observation by the satellite and the availability of the product at a user interface, including the nominal dissemination time.

Precision. The difference between one result and the mean of several results obtained by the same method, i.e. reproducibility (includes random errors only). Precision describes the spread of these measurements when repeated.

Spatial resolution. The spatial resolution is the minimum spatial scale resolved by the observing system.

Temporal resolution. The temporal resolution is the temporal frequency of systematic acquisition over a specified area.
2 BACKGROUND AND MISSION OVERVIEW

The European Space Agency (ESA) directorate on Human Space Operations released an announcement of opportunity in July 2011 in coordination with the directorate of Earth Observation Programmes soliciting scientific experiments for the International Space Station (ISS) relevant to global climate change studies. 25 Letters of intent were received from 237 science team members. After a peer-review of the received proposals and a scientific and technical evaluation, the GEROS-ISS proposal was accepted to proceed to Phase A studies (feasibility phase).

The GEROS-ISS mission (Wickert et al., 2011) seeks to exploit signals of opportunity from Global Navigation Satellite Systems (GNSS) for ocean, atmosphere and land cover remote sensing. It will make use of the innovative GNSS reflectometry (GNSS-R) and GNSS radio occultation (GNSS-RO) sensors to be deployed on the International Space Station (ISS). Reflected and bent GNSS signals by the Earth's surface (reflectometry) and Earth's atmosphere (radio occultation) are used to derive essential climate change relevant parameters for the sea-surface, the atmosphere and the land surface, mainly in the tropics and mid-latitudes.

The scientific objective of GEROS-ISS is all-weather mapping of:

- Sea surface height at mesoscale or longer (primary objective)
- Sea surface roughness, in terms of Mean Square Slope (secondary objective)
- Land surface sensing and atmosphere sounding parameters (additional objectives)

Hereby GEROS will make use of the unique ISS platform to generate an unprecedented data set to advance the exploitation of GNSS based Earth Observation techniques to provide climate-relevant measurements, which represent the forerunner of a future operational mission capable of delivering a long-term climate record of the Earth.

3 SCIENTIFIC JUSTIFICATION

3.1 Measuring ocean surface height at the mesoscale (primary mission objective)

A major challenge for physical oceanography today is to better map the complex mesoscale structure (10-100km or longer) of the ocean circulation in the open ocean and in the coastal regions. The need for observations has further amplified over the past decade. Mesoscale altimetry mission concepts, such as the Wide Swath Ocean Altimetry mission (Fu et al., 2003) have long been proposed (and have now been accepted: the Surface Water and Ocean Topography, or SWOT mission to be launched in 2019) to address the shortcomings of nadir-pointing pulse-limited altimeters in terms of their narrow swaths and relatively large cross-track separation. The GAMBLE project (Cotton et al., 2004) reviewed various mission concepts to address this issue, putting forward recommendations for future missions. Ten years later, with operational ocean models now routinely generated on global 1/12th degree resolution grids (Bahurel et al., 2012), and the operating NASA/CNES Ocean
Science and Topography Mission (OSTM) Jason-n series of nadir altimeters following the TOPEX/POSEIDON mission launched two decades earlier, the need for finer scale and more frequent monitoring of ocean surface height field has become ever more pressing. There are also growing evidences from scientific research further emphasizing the critical contribution of oceanic mesoscale variability at enhanced spatial and temporal scales to the understanding of global oceanic circulation, its transports and exchanges with the atmosphere under an increasingly warmer climate.

The potential of GNSS-R for ocean altimetry was identified about 20 years ago (Martin-Neira, 1993). GNSS-R presents several unique advantages, which complement traditional nadir-pointing or the new SAR radar altimetry. Depending on the characteristics of the GNSS-R receiver and antenna, one GNSS-R receiver can potentially track up to 30 separate GNSS reflections (Martin-Neira et al., 2011) to provide wide-swath sampling. Therefore the spatiotemporal resolution compared to nadir-looking satellites can be significantly improved. In contrast to traditional altimetry, obtaining sea surface height measurements with GNSS-R with sufficient accuracy poses serious technological challenges, but the averaging of abundant and overlapping observations could enable the reduction of errors in the sea surface height measurements.

The GEROS experiment represents the first spaceborne mission that will be dedicated to GNSS-R for high spatio-temporal mapping of the ocean focused on altimetric applications. It would enable – for the first time - to collect and analyse large datasets from spaceborne GNSS-R equipment for this purpose, to examine GNSS-R signals, the derived sea surface height (SSH) and mean square slope (MSS) observations and their associated errors over a wide range of ocean conditions. With appropriate processing and averaging strategies, GEROS may also be able to demonstrate for the first time that GNSS-R provides invaluable SSH observations of eddies and ocean variability at the mesoscale (10-100 km) to complement current and future radar altimeter missions (conventional satellite altimetry data cannot resolve scales smaller than 100 km due to wide spacing between the present altimeter satellite ground tracks). At L-band, GNSS-R observations, as compared to Ku- or Ka-band altimeter systems, will be significantly less affected by heavy rains and will thus provide a unique data set of sea surface topography heights under all weather conditions, including during extreme weather conditions. This is of interest in particular in the tropical areas frequently inundated with occurrence of cyclones.

Satellite radar altimetry operation under extreme weather events is still largely unknown, at best observed well after and not during when the storms were happening. Depending on the size (typically from 60 km to 500 km) and intensity, translation speed, and ocean upper layer stratification, tropical extreme cyclone events leave impressing trenches ahead in their wakes with sea surface height anomalies that can often reach 0.5 m or higher, thus requiring a sea surface height retrieval accuracy of at least 50 cm (goal: 20 cm). Decorrelation times of these phenomena are a few days. Given the ISS orbit (tropical and mid-latitude coverage) and with the expected improved temporal sampling and mapping (4 days or less), it should thus be possible to assess – for the first time - in more details the time evolution of the storm-induced displacements that control the intensification of these extreme events in the tropics as well as in the mid-latitudes because of the ISS coverage.
Similar to traditional nadir-pointing radar altimetry missions, the success of the GEROS experiment critically depends on the ability to accurately geolocate the phase centre position of the GNSS-R antenna in a well-defined Earth-fixed terrestrial reference frame. For this purpose Precise Orbit Determination (POD) using GNSS carrier phase tracking data, collected by a dedicated zenith-looking antenna, is a prerequisite and thus a key task of the GEROS experiment. First experiences with the analysis of carrier phase tracking data from spaceborne GPS receivers for POD was gained in the early nineties using data from the TOPEX/POSEIDON altimetry mission (Bertiger et al., 1994). With the advances in spaceborne GPS receiver technology and the success of the TOPEX/POSEIDON mission, more space vehicles are relying on GPS carrier phase data for POD. Most stringent POD accuracy requirements, typically demanding (1-D) position RMS errors of few centimeters, are today needed for gravity missions such as CHAMP (Reigber et al., 2003), GRACE (Kang et al., 2006), and GOCE (Bock et al., 2011), and altimetry missions such as Jason-2 (Flohrer et al., 2011). Especially the radial component is crucial for the altimetry missions to derive high quality data products. With the availability of steadily improving background models, limiting factors of GPS-based POD have been further confined to the precise modeling of the phase center location of the onboard GPS receiver antennas, which is essential for reduced-dynamic and, in particular, kinematic approaches (Jäggi et al., 2009).

Today, off-line reduced-dynamic POD technique based on dual-frequency GPS data has been evolved to a mature and well established technique offering cm-accuracies, provided that the attitude motion of the onboard GNSS receiver antennas in inertial space is precisely known from additional measurements, e.g., star camera readings, and/or using additional GNSS antennae. As demonstrated for the GOCE mission, only marginally worse accuracies are today achieved in the kinematic mode if the number of simultaneously and continuously tracked GPS satellites is sufficiently large (Bock et al., 2011). Whereas reduced-dynamic POD of the center-of-mass position of a smaller satellite such as GOCE is in principle “straightforward”, a much greater challenge is posed by large platforms such as the ISS. Significant errors might be introduced by the inaccurate knowledge of the center-of-mass position with respect to the POD antenna phase center, the poor knowledge of deformations and vibrations of the platform structure for example due to Earth shadowing effects, and the presence of signal obstruction effects degrading the number of simultaneously tracked satellites even for zenith-looking POD antennas, e.g., caused by the huge solar panels in the case of the ISS. Montenbruck et al. (2011) have shown that the ISS orbit can be reconstructed offline with 1 m RMS position accuracy when using single-frequency data and dynamic POD approaches. Even when using dual-frequency data, however, it would be a challenge to achieve sub-decimeter orbit accuracies for the ISS relying on dynamic POD. Due to these difficulties the kinematic determination of the phase center position of the POD antenna is more promising for the GEROS experiment.

An alternative approach is to embed the POD antenna as part of the GEROS antenna itself, removing the need for auxiliary attitude knowledge of the ISS. For a most reliable kinematic determination of the POD antenna, the GEROS receiver should track GNSS-L-band dual frequency signals, at least L1 and L5 from GPS and Galileo, preferably in addition GLONASS, BeiDou and others, e.g., QZSS. Multi-frequency capabilities in both
GNSS-R and POD payloads are also required for proper correction of the ionospheric effects for altimetric height retrievals.

3.2 Monitoring ocean surface roughness (secondary mission objective)

Ocean surface wind and wave conditions can change very rapidly in both time and space, in particular in the vicinity of extreme atmospheric events such as tropical cyclones. Operational tropical cyclone forecasting centres depend crucially on satellite observations of surface winds to predict the evolution, intensity and track of developing weather systems. In turn, operational storm surge and wave forecasting systems rely on accurate atmospheric modeled winds in order to issue advance warnings of coastal flooding and dangerous sea states (e.g. Chang and Jelenak, 2006). These applications have enormous societal and economic impact and are driving ever-increasing observational requirements for improved sampled ocean winds and sea state.

The capabilities of spaceborne GNSS-R for ocean scatterometry have been established with the pioneering GNSS-R experiment, which piggy-backed on the United Kingdom's Disaster Monitoring Constellation (UK-DMC) satellite in 2004. UK-DMC provided GNSS-R data that demonstrated for the first time the possibility of detecting GNSS-R signals from 750 km altitude and of retrieving ocean MSS measurements (Gleason, 2006; Gleason et al., 2005; Clarizia et al., 2009). While the UK-DMC data satisfactorily demonstrate the concept, the amount of spaceborne GNSS-R data remains too small to permit statistically robust retrieval performance assessment, particularly in extreme winds and cyclone conditions.

Several GNSS-R missions over the next few years will aim to acquire more spaceborne GNSS-R data over a wider range of conditions to refine the error characterisation of these measurements. These include the UK TechDemoSat-1 mission (launch expected late 2013), the Spanish Cubecat-2 satellite (launch expected 2015) and NASA's CYGNSS mission (launch expected 2016). Unlike these GNSS-R missions, GEROS will be installed on a large platform, with less limiting physical constraints, enabling more complex hardware and processing capabilities. Therefore, the GEROS experiment would specifically contribute to provide much needed spaceborne GNSS-R data to answer the important and long-standing scientific questions. The denser coverage of GEROS over low to mid-latitudes, where tropical and mid-latitude cyclones are known to preferentially occur, will be especially valuable to increase the chances of acquiring a unique set of both GNSS-R altimetric (SSH) and roughness (MSS) data and maps in extreme wind, heavy rain and cyclone conditions.

3.3 Additional objectives

Land surface investigations

The application of GNSS-Reflectometry to provide observations of land surface properties (soil moisture, biomass, e.g. Egido, 2013) was not included in the original GEROS proposal (Wickert et al., 2011), but is regarded by the GEROS science advisory group as an
additional and important mission objective due to the strong synergy with the ocean surface roughness objective.

Soil moisture affects evapotranspiration, heat storage, thermal conductivity; it controls the redistribution of rainfall among infiltration, runoff, percolation, and evapotranspiration. The ESA Living Planet Programme foresees, among others, a better understanding of the hydrological cycle throughout a mapping of the soil moisture at global scale, and the improvements of weather and flood forecasts by assimilating soil moisture observations into models. Vegetation constitutes the link between water cycle and carbon cycle, since moisture dynamics impacts vegetation structure and growth and, in turn, the soil-plant-atmosphere system. Vegetation participates to the oxygen, carbon dioxide and water vapour exchanges by means of photosynthesis and evapotranspiration processes. Forests, in particular, can store large amount of CO2, and therefore are involved in the carbon cycle, which influences greenhouse effect, global and local climatic change. Finally, vegetation cover is much exposed to anthropogenic pressure: fires, deforestation and pollution are typical examples of human ability to disturb the vegetation environment which needs to be surveyed at both local and global scale, and both short and long time scale.

There are and have been attempts (e.g. Paloscia et al. 2012; Egido et al., 2012) to acquire sufficiently representative GNSS-R data sets for sensitivity study on vegetation biomass (herbaceous crops and forests), as well as combined effects of soil moisture and surface roughness (Gleason, 2006; Katzberg et al., 2006). Interference patterns between direct and reflected signals have also been exploited on ground to derive soil moisture and snow parameters (Larson et al., 2008; Rodriguez-Alvarez et al., 2011). However, bistatic signals from land surfaces are characterised by lower average returns, contribution from coherent and incoherent scattering, and larger variability of the signals compared to signals scattered from the ocean surface (Pierdicca et al., 2013). GEROS could provide spaceborne observations of GNSS-R over different land cover types and test the capabilities of GNSS-R to retrieve land surface parameters.

GNSS Atmospheric sounding

A further additional objective, which was identified already in the GEROS proposal is GNSS based radio occultation (RO) for precise sounding of the neutral atmosphere and the ionosphere.

GNSS RO data are currently already operationally available from several missions, e.g., FORMOSAT-3/COSMIC, Metop-A/B, GRACE or TerraSAR-X (Anthes et al., 2008; Wickert et al., 2009) and several new operational missions with GNSS RO will be realized (e.g., COSMIC-2, EUMETSAT Polar System – Second generation, EPS-SG). Therefore the need to get RO data from GEROS is less compelling and is regarded as mission goal with lower priority, compared to GNSS based ocean remote sensing.
Nevertheless there are several aspects supporting RO measurements within GEROS. These are:

- Innovation for the RO technique: The ISS inclination allows for better data coverage and stronger RO signals in the tropics and the mid-latitude regions compared to the polar/near-polar orbiting RO missions. GEROS might enable initial application of Galileo and GLONASS signals for RO, as well as initial application of the polarimetric occultation concept for the detection of strong precipitation events (e.g., Cardellach et al., 2010, Cardellach et al., 2013b) in parallel and to continue measurements of the Spanish PAZ satellite.

- Strong complementarity to the GNSS reflectometry approach, the coherent reflectometry measurements for altimetric measurements of sea and ice surface topography (part of the primary mission goal, Cardellach et al., 2004; Beyerle et al., 2002).

- Provision of useful additional atmospheric (dry and wet tropospheric) and ionospheric delay information partially collocated with the GEROS GNSS-R measurements and relevant for the analysis and correction of the reflectometry measurements for ocean surface height measurements obtained aboard ISS.
4 MISSION OBJECTIVES

The main goal of GEROS-ISS is to demonstrate the innovative and versatile capabilities of GNSS remote sensing to derive geophysical parameters of ocean, ice and land surfaces, which are associated with geophysical research with special focus on relevant climate change phenomena.

GEROS-ISS represents the first dedicated experiment to assess the usefulness of spaceborne GNSS-Reflectometry to detect and map ocean surface height at the mesoscale (10-100 km or longer scale) under all-weather conditions. The GEROS measurements of sea surface height will complement SSH data from the multi-satellite constellation of traditional radar altimeters, leading to better monitoring of the ocean mesoscale variability at a finer spatial scale closer to 10 km, which is not achievable by current nadir altimeters. A major advance afforded by the GEROS data set will be to determine the value of GNSS-R as a means of providing long-term sustained observations of eddies and their variability.

This first objective is complemented by the second objective, which seeks to refine our understanding of the retrieval performance of GNSS-R for ocean surface roughness, in particular in extreme winds, heavy rain and hurricane conditions which frequently occur in the tropical areas covered by the ISS.

Additional objectives of lower priority consist of the exploitation of the GNSS-R technique for land surface observation and the application of the GNSS Radio Occultation technique for atmospheric sounding.

Precise Orbit Determination using GNSS signals is a key task of the GEROS experiment and will be applied to support the remote sensing observations.

Therefore the main mission objectives of GEROS are (in order of priority):

1. To measure and map altimetric sea surface height of the ocean using reflected GNSS signals to allow methodology demonstration, establishment of error budget and resolutions and comparison/synergy with results of satellite based nadir-pointing altimeters. This includes Precise Orbit Determination of the GEROS payload.

2. To retrieve scalar ocean surface mean square slope (MSS), which is related to sea roughness, wind speed, with a GNSS spaceborne receiver to allow methodology testing, establishment of error budget and resolutions. In addition, 2D MSS (directional MSS, related to wind direction) would be desirable.

3. To assess the potential of GNSS scatterometry for land applications and in particular to develop products such as soil moisture, vegetation biomass, and mid-latitudes snow/ice properties and to further explore the potential of GNSS radio occultation data (vertical profiles of atmospheric bending angle, refractivity, temperature, pressure, humidity and
electron density), particularly in the Tropics, to detect changes in atmospheric temperature and climate relevant parameters (e.g., tropopause height) and to provide additional information for the analysis of the reflectometry data from GEROS.

Objective 3 shall not drive the instrument and mission development.
5 SCIENTIFIC L2 MISSION REQUIREMENTS

5.1 Level-2 geophysical mission requirements

According to the main mission goals of GEROS, the primary parameters to be determined are listed below including requirements:

- Sea surface height (SSH)
- Ocean surface roughness or mean square slopes (MSS)

The primary parameters shall drive the system requirements. The basis for the explicit numbers in the SSH and MSS related requirements are based on the investigations by Lee et al. (2013) and the numbers given by Chang and Jelenak (2006). Additional observation system simulator activities and campaign data will be needed to confirm these (where applicable).

5.1.1 Sea surface height (SSH)

The parameter to be derived is altimetric sea surface height (SSH), which is the height of the ocean surface above a reference ellipsoid (e.g., WGS-84) expressed in meters.

Sea surface height is derived from the delay difference between the direct and reflected paths and precise knowledge of the GNSS transmitter and GNSS-R receiver positions. SSH includes instrument and media corrections, and contributions from the oceanographic processes such as tides, atmosphere, circulation, etc.

The scientific requirements for GEROS on SSH are as follow:

<table>
<thead>
<tr>
<th>REQ</th>
<th>GEROS shall provide sea surface height maps with GNSS-R with an accuracy of 50 cm or better (goal: 20 cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>REQ-2</td>
<td>GEROS shall provide wide-swath, all-weather GNSS-R SSH data based on reflections from multiple GNSS constellations</td>
</tr>
<tr>
<td>REQ-3</td>
<td>GEROS shall provide GNSS-R SSH data with lengths scales at 10–100 km or longer, to improve our ability to monitor oceanic mesoscale eddies, in particular in the tropical and mid-latitude regions</td>
</tr>
<tr>
<td>REQ-4</td>
<td>To demonstrate the potential of GNSS-R as a new and cost-effective means of providing long-term sustained observations of sea surface height</td>
</tr>
</tbody>
</table>

The observation requirements for GEROS on SSH are as follow:

<table>
<thead>
<tr>
<th>Spatial coverage</th>
<th>Tropical and mid-latitudes (51.6° N to 51.6° S) as bounded by the ISS orbital inclination</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spatial resolution</td>
<td>10 km (across track)-100km (along track)</td>
</tr>
<tr>
<td>Temporal revisit</td>
<td>4 days or less</td>
</tr>
<tr>
<td>Product Latency</td>
<td>no need identified</td>
</tr>
</tbody>
</table>
A key task for the accurate GNSS-R based SSH retrieval is the Precise Orbit determination of the GEROS payload. The GEROS orbit accuracy should be comparable to radar altimeter satellites, therefore:

| REQ-5 | The system shall be able to determine the 3D-accuracy of the GEROS payload with at least 5cm accuracy. |

5.1.2 **Ocean surface roughness (mean square slope)**

The strength of the bistatically scattered GNSS-R L-band signals from the ocean surface is directly related to the ocean surface roughness. A common way to describe surface roughness is through the probability density function (PDF) of the surface slopes. The variances of the sea surface slopes in the upwind and crosswind directions are known as the mean square slopes (anisotropic or directional MSS) i.e. \( \text{mss}_{\text{upwind}} \) and \( \text{mss}_{\text{crosswind}} \). The scalar/total MSS can be defined as \( 2\sqrt{(\text{mss}_u \cdot \text{mss}_c)} \). No specific user requirements on these parameters could be found in the literature.

GNSS signals are transmitted at L-band and are sensitive to ocean roughness features at scales of the order of and longer than the electromagnetic (EM) wavelength, around 0.20-0.25m. Typically, the high-frequency cut-off that defines the ocean roughness affecting L-band scattering has typically been set to 3 times of EM wavelengths, i.e. around 0.60-0.75 m, although there is no consensus in the literature about this value. This roughness scale is much longer than the fine scale roughness generated instantaneously by the wind blowing on the surface. Thus, scattered L-band signals respond to roughness caused by both wind speed and waves, depending on the type of sea conditions (wind-dominated, mixed seas, swell). For this reason, GEROS aims solely to provide L-band roughness parameters, as a complement to existing wind and waves data sources (models and observations), and to help characterizing other relevant aspects of the air-sea interaction, such as stage of development of the sea.

The scientific requirements for GEROS on MSS are as follow:

| REQ-6 | GEROS shall provide all-weather scalar MSS with GNSS-R with an MSS accuracy equivalent to a wind accuracy of 10% or 2 m/s whichever is greater |
| REQ-7 | GEROS mission shall be designed to determine the accuracy of GNSS-R MSS for wind speeds between 3 m/s and 45 m/s, with focus on larger wind speeds occurring in tropical regions (>20 m/s) |
The observation requirements for GEROS on MSS are as follow:

<table>
<thead>
<tr>
<th><strong>Spatial coverage</strong></th>
<th>Tropical and mid-latitudes (51.6° N to 51.6° S) as bounded by ISS orbital inclination</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Spatial resolution</strong></td>
<td>10 km or finer</td>
</tr>
<tr>
<td><strong>Temporal revisit</strong></td>
<td>4 days or less</td>
</tr>
<tr>
<td><strong>Latency</strong></td>
<td>No need identified (GEROS is an experimental, not an operational mission, and has to comply with operational constraints of the ISS)</td>
</tr>
</tbody>
</table>

5.1.3 Additional mission data

Land surface parameters

Over land envisaged products are soil moisture and vegetation biomass; there are also potential for retrieving mid-latitude snow/ice parameters. Those products can be derived from the scatterometric mode of operation, i.e., basically the same operation suitable for deriving the ocean MMS. In fact, the bistatically scattered GNSS-R signal over land is a function of soil roughness and surface permittivity, the latter being strictly related to soil moisture. In vegetated areas the attenuation through the canopy makes the signal magnitude be a function of the biomass. Calibrated reflectivity (or bistatic scattering coefficient), especially if collected at different polarizations, provides the necessary independent pieces of information to estimate those parameters. Scattering measured at different angles (around specular direction as usual, but possibly also close to the backscattering configuration) may further help since different targets have different scattering directional patterns.

The scientific requirements for GEROS on land surface are as follow:

- To demonstrate that the GNSS-R signal from land is sensitive to land parameters such as soil moisture and vegetation biomass
- To demonstrate the feasibility to estimate land parameters by a spaceborne GNSS-R receiver and evaluate the achievable product quality (including accuracy) as compared to user requirements (for instance 0.05 m³/m³ accuracy in volumetric soil moisture).
- To demonstrate the feasibility of measurement of changes of snow surface and depth.

Being land observation a secondary and additional experimental objective, Level 2 product user requirements are not specified. Generation of Level 2 products will be part of the scientific R&D activity. As land application will not drive the system design, observation requirements are aligned with the ones defined for SSH and MSS.
Vertical atmospheric profiles

Precise and globally distributed vertical profiles of atmospheric parameters, as refractivity, pressure, temperature, water vapour and electron density can be derived from GNSS radio occultation (RO) measurements. The technique is widely acknowledged by the community of atmospheric scientists, e.g., atmospheric data products from several GNSS RO satellite mission are currently operationally used by the world-leading weather centres to improve their global numerical forecasts. Moreover, since the radio occultations have the ability to monitor the ionosphere along its platform orbit, they might also be used to properly correct the ionospheric effects in some of the GEROS GNSS-R SSH estimates. In addition to the atmospheric applications it has been shown that the RO signals can also be used for the derivation of altimetric heights of water and snow surfaces. Therefore GNSS RO was identified as additional mission goal for the GEROS experiment.

The scientific requirements for GEROS on the derivation of vertical atmospheric profiles from GNSS radio occultation measurements are as follow:

- To demonstrate that GNSS signals, recorded by the GEROS payload, from at least setting or rising GNSS satellites can be used to derive state-of-the-art precise vertical atmospheric profiles.
- To demonstrate that polarimetric GNSS RO signals can be used to derive information on strong precipitation events.
- To demonstrate that GNSS occultation signals, recorded by the GEROS payload, can be used to derive sea surface heights in the vicinity of the GNSS RO point of closest approach.

Being RO observations a secondary and additional experimental objective, Level 2 product user requirements are not specified. Generation of Level 2 products will be part of scientific R&D activities. As RO application will not drive the system design, observation requirements are aligned with the ones defined for SSH and MSS.
6 DATA PROCESSING AND RETRIEVAL

6.1 Level-1 to Level-2 retrievals

The following paragraphs give an incomplete overview of GEROS data product retrievals and proposed methods for the primary parameters mentioned above.

6.1.1 Sea Surface Height (SSH)

A concept for GNSS-based altimetry was first proposed by Martin-Neira (1993). GNSS satellites transmit low power signals consisting of an L-band carrier with phase modulation in the form of Pseudo-Random-Noise codes (PRN), different for and characteristic of each of the transmitters. GNSS-R involves receiving simultaneously direct and surface-reflected GNSS signals and processing them taking into account the appropriate time delay and Doppler shift induced by the geometry. This can be done by cross-correlation of each radio-link with respect to a known code (conventional approach), or by cross-correlation of the line-of-sight signal stream against the surface reflected one. The latter approach, here called interferometric, generates the auto-correlation function (ACF), as suggested by Martin-Neira et al. (2011). Finally, high-gain antennas directly pointing to the source could enable semi-codeless techniques to use precise encrypted codes in the reflected signals.

These approaches permit to obtain the time of arrival and the power distribution of the scattered signals originating from surface cells near the specular point with respect to the direct, line-of-sight signals. D'Addio and Martin-Neira (2013) and Cardellach et al. (2013) estimate that the interferometric approach is at least two times more accurate than the conventional C/A code reflectometry. In the conventional approach this information is obtained from two separate waveforms (result of two, direct and reflected, separate code-correlations), of typically narrower bandwidth, given by the bandwidth of the known code. The interferometric approach extracts this information from a single waveform, the ACF, of sharper leading edge induced by the wider bandwidth of the entire set of codes embedded in the transmitted signal, regardless of their public availability. In semi-codeless techniques, the unknown codes are partially estimated from the up-looking line-of-sight signals. Re-tracking algorithms may be required to align the time series of waveforms before further integration.

These relative time-arrivals are the basic piece of information required to infer the sea surface heights. The way they are extracted from the waveforms/ACF is a key step of the retrieval process because, unlike line-of-sight waveforms, the shape of the reflected ones is distorted by the effect of the surface roughness (see next subsection: MSS). The main techniques to identify the delay of the specularly reflected radio-link within the waveform are either to fit a model (e.g. Lowe et al. 2002a), or to assume that the specular delay corresponds to the peak of the first derivative of the leading edge of the waveform (suggested in Hajj and Zuffada 2003 and further developed and verified in Rius et al. 2010). The derivative-approach helps separating between the geometric (altimetric) and the surface roughness effects (scatterometric) with no need of a-priori information on the latter. A model of the average received echo of a bistatic altimeter for ocean applications is
described in Picardi et al (1998) and a model for the GNSS reflected waveforms was given in Zavorotny and Voronovich (2000).

Once the relative arrival time is obtained, a set of corrections must be applied to separate the geometric contribution of the delay from other sources of delay: atmospheric and ionospheric effects, and instrumental errors. The geometric delay is finally inverted into sea surface height when combined with information on the precise positioning of the antennas, the transmitter source, and an a-priori knowledge of the surface elevation.

The altimetric applications of the GNSS-R have been tackled in a variety of publications: Hajj et al (1999) elaborate on characteristics of bistatic altimetry such as coverage, resolution, accuracy and general feasibility. In LeTraon et al. (2001), the contribution of GPS altimetry for the mapping of ocean mesoscale circulation was quantified using the Los Alamos North Atlantic model, resulting in significant impact. Martin-Neira et al. (2001) show an experimental demonstration of sea surface altimetry using a GPS reflector on a bridge. Lowe et al. (2002a) showed P(Y)-code GPS altimetry at 5-cm precision; Lowe et al. (2002b) presented first spaceborne observation of Earth-reflected GPS signals from Shuttle/SIR-C. Masters (2004) showed the results of comparisons between GNSS-R altimetry and aircraft altimetry. Ruffini et al. (2004) showed altimetric results with accuracies on the order of 10 cm and spatial resolution of 20 km. Using carrier-phase GNSS-signals at grazing angles of elevation, Semmling et al. (2011) and Fabra et al. (2011) elaborated on the accuracy of sea surface height estimates at 10 cm at L1 and about 20 cm at L2. All these examples used the conventional (code-correlation) approach. On the interferometric approach, Rius et al (2011) implemented an interferometric GNSS-R instrument and validated its altimetric performance from a 18-m high Bridge: 3-cm precision level SSH is obtained. A more recent experiment, aboard a 3000-m altitude aircraft flight, has measured 2-cm/km mean surface slopes using the interferometric approach (Cardellach et al., 2013).

6.1.2 Mean Square Slope (MSS)

Similar to the pioneering work by Martin-Neira (1993) for altimetry, Garrison et al (1998) proposed to use GNSS-R to sense sea surface roughness based on the distribution of reflected signal power. This is closely related to surface winds for oceans and surface dielectric constant for land surfaces (for soil moisture retrievals). Determining sea roughness from GNSS-R data requires (Germain et al., 2003): (i) a parametric description of the sea surface, (ii) an electromagnetic model for sea-surface scattering at L-band and (iii) the choice of a GNSS-R data product to be inverted. The scattering of GNSS signals is often modelled as a Geometric Optics process, see Cox and Munk (1954). The Delay-Doppler map (DDM) is an often used waveform for GNSS-R scatterometry. The DDM evaluates the power distribution of the reflected signal for different delays and Doppler frequency with respect to the specular point. The higher the sea roughness, the higher the power return of patches further from the specular point, see e.g. D’Addio and Buck (2008). Germain et al (2009) reported on the first inversion of GNSS-R full DDM for the retrieval of the sea-surface directional mean square slope. While most of the approaches applied involved normal bivariate distributions for the Probability Density Function (PDF) of the
surface slopes, Cardellach and Rius (2008) proposed to extract a set of discrete samples of this PDF directly from the GNSS-R data. Recently, NASA selected the Cyclone Global Navigation Satellite System (CYGNSS), a constellation of eight LEO satellites at ~35° inclination orbits carrying GNSS-R receivers. CYGNSS measures ocean surface wind speed in all precipitating conditions, including those experienced in a tropical cyclone eyewall, with sufficient frequency to understand hurricane genesis and intensification. Because the ISS orbit favours the observation of not only for tropical and also for mid-latitude cyclones, it is possible that GEROS will be able to overlap with CYGNSS at times, thus providing a means to cross-calibrate and validate independent measurements of sea surface (and also land surface). Because GEROS performs ocean altimetry, its implementation, in addition to more latitude coverage (to mid-latitudes within ±51.6°), will likely have a higher antenna gain and other improvement than CYGNSS, and thus it will enhance its sensitivity.

### 6.1.3 Land surface parameter from GNSS scatterometry.

The signal scattered from land is a mixture of coherent signal, mainly coming from the first Fresnel zone on the surface, and incoherent signal (Pierdicca et al., 2013). The latter comes from a larger area which, depending on receiver height, is limited either by the downlooking antenna footprint (beam limited case), the chip delay resolution (range limited), or the Doppler bandwidth (Doppler limited) determined by the coherent integration time. The relative magnitude of coherent and incoherent components is related to the bistatic scattering properties of the surface, as for instance very rough surfaces (roughness at scale of the wavelength) do not produce significant specular reflection but rather diffuse incoherent scattering.

LHCP signal amplitude is the main observable used to extract the surface reflectivity. It can be normalized by the direct power level or even calibrated with observations over smooth water bodies. To account for the dependence on surface roughness, it can be exploited the assumption that the received signal power is proportional to the product of two factors: a polarization sensitive factor dependent on the soil dielectric properties and a polarization insensitive factor that depends on the surface roughness. Therefore, the ratio of the two orthogonal polarizations excludes the roughness term and retains the dielectric (i.e., soil moisture) effects (Zavorotny et al., 2003; Egido et al. 2012).

LHCP signal amplitude is also the main observable sensitive to vegetation, as the coherent reflection from the soil is attenuated by the vegetation layer as a function of total biomass (Ferrazzoli et al., 2010). To achieve this aim, a proper signal integration strategy is required to minimize the additive contribution from the incoherent vegetation scattering, which would reduce the overall sensitivity to biomass.

The starting point for generating the land products are the calibrated reflected signal amplitudes at LHCP and, possibly, RHCP polarizations, and the direct RHCP signal amplitude providing the reference for deriving the calibrated surface reflectivity (or better the calibrated bistatic scattering coefficient). The amplitude of the waveform peak is the minimum piece of information required, but the DDM may provide a further insight on the
incoherent component associated to surface roughness and volume scattering useful in the inversion.

If the downlooking antenna had suitable gain and pointing capabilities, the calibrated scattering coefficient could be measured over surface areas which are not located necessarily around specular direction, but possibly observed in a direction close to the condition of backscatter (minimum bistatic scattering angle). This can provide additional pieces of information within multi-angle inversion algorithms, to be assessed on an experimental basis.

Polarimetry may include measurements of phase difference between signals at two orthogonal polarizations, another observable which has been investigated as being sensitive is the snow surface and dielectric properties of the surface. Both uplooking RHCP and LHCP antennas are necessary for an accurate characterization of polarimetric properties of surface reflection.

A critical aspect (especially at RHCP) is the sensitivity required to cover the full dynamic range of the signal associated to different surface conditions. 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 GEROS could help to tackle and solve.

GNSS-R over land can potentially measure land topography and if a digital elevation model is known, changes of the land surface can potentially be measured. As one of the secondary mission objectives, it is proposed that GNSS-R be used to measure snow depth over specific land regions. The resulting GNSS-R topographic change measurements have to be corrected for firn and compaction density, L-band radar penetration, media delays and other geophysical corrections, such as solid Earth tides.

6.1.4 Vertical profiles of atmospheric parameters

GNSS radio occultation is an established atmospheric remote sensing technique, applied aboard several satellites; the retrieval of the vertical atmospheric parameters from Level 1 to Level 2 is well described and overviewed in numerous scientific papers (e.g., Wickert et al., 2009, Anthes et al., 2008). GNSS RO derived atmospheric data from several satellite missions are currently operationally assimilated to global numerical forecasts by all leading weather centres since 2006 (e.g., Healy, 2007), which indicates the high level of acceptance of the GNSS RO data in the atmospheric community. Advanced signal tracking and analysis techniques were developed and operationally applied to process occultation data of the current missions (e.g., Beyerle et al., 2006). Current challenges in GNSS RO data processing is the improvement of the data quality in the lower troposphere and upper stratosphere and the application of multi-GNSS signals for atmosphere sounding. GNSS RO aboard ISS could contribute to accept these challenges with several aspects, which were summarized already in sect. 2.2 (Multi-GNSS, low inclination orbit of ISS, supporting atmospheric information for reflectometry and polarimetric occultation). Given the GEROS platform, the RO experiment could be focused on cyclones, convective storms, and
other tropical atmospheric processes. This could provide a new and unique data set for scientific studies.

6.2 Level-1 observation requirements

Based on the Level 2 product definition and the retrievals from Level-1 to Level 2, Level 1 observation requirements can be derived. A schematic view of the GEROS concept is shown in Figure 1.

![Schematic view of the GEROS mission for oceanic remote sensing on board of the International Space Station.](image)

The main requirements can be summarised as follows:

**Sea surface height and surface roughness**

Reflected signals, required for altimetry and scatterometric applications (ocean, ice and land) can be provided at different delay, Doppler and polarizations. Thus different Level 1 products can be specified as well as raw data. The associated data volume can be significantly different so that their generation (and corresponding instrument modes of operation) shall be scheduled according to type of selected target (and application), but also based on communication channel and on-board memory resource availability.
The GEROS payload shall be controllable regarding the generation of the Level 0 (raw) observations. The scheduling shall be steerable according to selected target as well as communication channel and on-board memory resource available.

The GEROS payload shall be able to provide complex reflected waveforms obtained by coherent integration over the coherence time of the ocean (on the order of 1 ms).

The GEROS payload shall be able to record GNSS surface power reflected waveforms with a delay span, number of samples, data rate and Doppler bins sufficient to fulfil the scientific requirements. These power measurements shall be calibrated to properly measure absolute power or relative to the direct line-of-sight one.

Land surface applications

Some priorities are identified here for Level 1 data suitable for future land algorithm development. Calibrated measurements are mandatory, with, in order of priority: i) calibrated surface reflectivity corresponding to the peak of the waveform and sampled each second with coherent integration time suitable for the application; ii) availability of RHCP polarization in addition to LHCP; iii) surface scattering coefficient (or normalized bistatic radar cross section) as function of delay (waveforms) or delay and Doppler (DDM) with coherent integration time suitable for the application (this overcomes item i); iv) calibrated scattering coefficient measured over surface areas observed in a direction close to the condition of backscatter (minimum bistatic scattering angle) could be acquired on an experimental base to exploit multi-angle inversion algorithms; v) calibrated land topography heights from GNSS-R.

GNSS radio occultation

GNSS radio occultation measurements would be of interest (phase and amplitude at least L1 and L5) in OpenLoop mode with at least 100 Hz data, recorded for different signal polarisations (horizontal/vertical) to derive information on strong precipitation events in addition to the thermodynamic atmospheric parameters. GNSS RO data also would potentially contribute to the reduction of troposphere induced offsets in potential coherent altimetry GEROS measurements in limb sounding geometry, and ionospheric corrections to a number of GEROS GNSS-R SSH measurements.

Mission duration

The minimum mission duration shall be at least one year (excluding commissioning phase). Further extension up to 5 years to expand the scientific exploitation is targeted given the life-time constraints posed by the ISS.

The GEROS payload shall be designed for a minimum mission duration of one year.
Spatial coverage

The ISS orbital inclination restricts the potential areas to be observed to 51.6° N to 51.6° S. Tropical to mid-latitudes ocean and land areas are to be covered for secondary parameters and for demonstration of techniques (e.g., sites covered by the International Soil Moisture Network, see http://ismn.geo.tuwien.ac.at/, and tropical forests).

**REQ-12**
The GEROS payload shall be capable to take measurements up to the maximum latitude range as bounded by the ISS orbit inclination

Field-of-view

In order to capture larger eddies of up to 500 km, a large field of view over the Earth is required.

**REQ-13**
The GEROS payload shall have the maximum field of view over the Earth surface given ISS constraints around nadir (Goal: 500 km)

Frequency and multi-GNSS capability

Tracking different GNSS transmitting stations is one of the aims of GEROS. In particular, it would be possible for the first time to acquire Galileo transmitting satellites by a GNSS-R system from space. The payload should have at least the capability to track all common GNSS transmitting satellites.

**REQ-14**
The GEROS payload shall have the capability to track GNSS L-band dual frequency signals, at least L1 and L5 from GPS and Galileo, preferably in addition GLONASS, BeiDou and others, e.g., QZSS

In order to provide wide-swath coverage, separate, simultaneous GNSS reflections should be possible to be tracked by the GEROS payload. The ISS position will limit the number of possible simultaneous reflection points.

**REQ-15**
The GEROS payload shall have the capability to track several reflection points simultaneously, preferably as many as possible.

Polarisation

Reflected signals from a perfectly flat surface can be approximated as a single ray path. In this case, reflected signals appear very similar to the direct signals, though delayed by the path length difference and predominantly left-hand circular polarised when elevation angle is high. GEROS should provide i) left-hand circular polarised (nadir-looking) signals as a minimum, right-hand circular pol considered as an additional option to exploit polarimetric inversion techniques; ii) right-hand circular polarised (zenith-looking) as a
minimum, left-hand circular pol considered as an additional option to enable accurate and calibrated polarimetric measurements.

**REQ-16** The GEROS payload shall have the capability to receive left-hand circular polarised Earth reflected signals as a minimum and preferably right-hand circular polarised in parallel

**Precise orbit determination**

Dual-frequency receiver. 5 cm (3D) accuracy. It is preferred to perform the precise orbit determination by the GEROS payload itself, i.e. that the POD antenna is the (or part of the) GEROS up-looking antenna itself. If the POD antenna is a dedicated antenna located at some distance from the GEROS antenna, the uninterrupted availability of ISS attitude data hereby is crucial to minimize attitude errors for deriving the (kinematic) geolocation of the reflector antenna from the (kinematically) derived position of the POD antenna. Ideally attitude measurements are performed by star tracker instruments mounted as close as possible to the GEROS antenna phase centre, and with possible additional GNSS antennae to improve attitude determination, in order to mitigate deteriorations caused by vibrations and deformations of the ISS structure.
7 PRELIMINARY MISSION CONCEPT

In reference to the GEROS-ISS proposal (Wickert et al., 2011), the mission objectives are addressed with the following payloads embarked on the ISS:

a) Incoherent GNSS-R: A GNSS receiver with a nadir-pointing high-gain polarimetric phased-array antenna to measure SSH and MSS from multiple GNSS reflections simultaneously. This measurement concept has been validated extensively with many experiments from ground stations, aircraft and stratospheric balloons, but has not so far had the opportunity of a dedicated spaceborne mission. This kind of Geros measurements is regarded as the most innovative component, because altimetric height (SSH) and also surface structure (MSS) could be derived. The nadir-pointing polarimetric receiver will also enable to assess novel satellite land applications of GNSS scatterometry.

b) Coherent GNSS-R: A horizon-pointing GNSS antenna and receiver for L-band carrier phase tracking of coherent reflections from low elevation GNSS satellites to measure ocean SSH. This technique has been proven for stationary ground-based receivers. Initial satellite based results with low-gain antennas and state-of-the-art GPS radio occultation receivers were reported by Beyerle and Hocke (2000), Beyerle et al. (2002) and Cardellach et al. (2004), which measured the surface height at 0.7 m precision in 0.2 second averaging (1 km resolution). It is expected that dedicated firmware modifications to the systems used for these early results could significantly increase the reported accuracy of several decimetres being the tropospheric induced delays the largest source of systematic offsets. Coherent GNSS-R is based on a radio occultation like geometry and is therefore highly synergistic with GNSS-RO measurements, which provides in addition tropospheric information for the offset reduction/elimination of the coherent GNSS-R measurements.

c) GNSS radio occultation: A horizon-pointing GNSS antenna and receiver, the same as in b). This technique is well proven and has been flown successfully and also operationally applied on various satellites, as, e.g., CHAMP, GRACE, COSMIC, Metop and will be also onboard future satellites, as, e.g., COSMIC-2 or GRACE-FO.

d) Polarimetric GNSS-RO: In addition to c) additional horizon-pointing GNSS antenna, but with another polarization. A novel untested addition to GNSS-RO, but currently also foreseen for the Spanish PAZ satellite (e.g. Cardellach et al., 2013b).

e) Precise Orbit Determination (POD): A zenith-pointing GNSS antenna and receiver to provide improved POD of the Geros antenna phase centre and the ISS, in support of the main mission objectives a) and b), but also for the secondary objectives c) and d).

One significant simpler implementation (compared to the original proposal) of the Geros experiment could involve only nadir and zenith-looking GNSS antennas and receiver(s) to focus only on the primary science objectives. If a horizon pointing antenna will be included, the potentials of the coherent reflectometry could be investigated in more detail and directly compared to those of the scatterometry. GNSS occultation measurements in this
case are consequently included, due to the strong synergy to coherent reflectometry (e.g., Beyerle et al., 2002; Cardellach et al., 2004).

8 DATA PRODUCTS AND USAGE

The GEROS mission concept foresees the classical Level 0 to Level 2 data product generation chain. Level-2 products will be the main products for the user community. Additional products and higher level products (Level 3) are expected to be derived by scientific institutions and national groups interested in the GEROS data.

**Determination of the Sea Surface Height**

| Level 1 products | Time collocated waveforms of the reflected signals |
| Level 2 products | Sea surface height |

**Determination of the Mean Square Slope (MSS)**

| Level 1 products | Waveforms or Doppler Delay Maps of the reflected signals |
| Level 2 products | Surface roughness, wind speed |

**Precise Orbit Determination**

| Level 1 products | Dual-frequency GNSS Pseudorange and carrier phase observations of the GNSS-R antenna phase centre |
| Level 2 products | GNSS based predicted and final GEROS GNSS-R antenna phase centre position  
Multi-GNSS combined final GEROS GNSS-R antenna phase centre position, Inter-constellation bias data |

The following measurements and Level 1 products can become available if the instrument is defined to fulfil these additional objectives.

**Scatterometry over land**

| Level 1 products | Waveforms or Doppler Delay Maps of the reflected signals (adjustable coherent integration time or complex values) |

**GNSS Radio Occultation**

| Level 1 products | Observations which can be provided by the instrument relevant for RO, once the instrument is defined to fulfil the higher priority mission requirements. |
Auxiliary information

Auxiliary information is needed to perform Level-1 to Level 2 retrievals. A preliminary list of auxiliary data and their requirements is listed in the table below.

<table>
<thead>
<tr>
<th>Information</th>
<th>Use</th>
<th>Requirement</th>
</tr>
</thead>
<tbody>
<tr>
<td>POD reference point (GNSS-R receiver antenna phase centre)</td>
<td>Precise orbit determination</td>
<td>5 cm</td>
</tr>
<tr>
<td>ISS visibility mask from GNSS-POD and GNSS-R antennas</td>
<td>Measurements scheduling</td>
<td>1 degree</td>
</tr>
<tr>
<td>Attitude of the module</td>
<td>POD of the antennas, synthetic beam-steering</td>
<td>Time-tagged. Precision TBD</td>
</tr>
<tr>
<td>Antennas offsets and phase-pattern file</td>
<td>POD of the antennas, synthetic beam-steering</td>
<td>Offset vector between antenna's reference point and POD: 1 cm (3D)</td>
</tr>
<tr>
<td>Antenna gain pattern and polarisation, pre-launch characterisation</td>
<td>To determine antenna phase offset at each beam direction</td>
<td>1 degree x 1 degree</td>
</tr>
<tr>
<td>GNSS satellites with azimuth and elevation (if not provided in the body of the GNSS-R data)</td>
<td>Data processing</td>
<td></td>
</tr>
<tr>
<td>Control parameters: temperature, log-file manoeuvres</td>
<td>Delay/Doppler alignment, reference solution</td>
<td>D/O 360</td>
</tr>
<tr>
<td>Reference geoid</td>
<td>Delay/Doppler alignment</td>
<td>Horizontal resolution 200 m</td>
</tr>
<tr>
<td>Digital Elevation Model</td>
<td>Delay/Doppler alignment</td>
<td>Vertical resolution 1 m, vertical accuracy 10 m</td>
</tr>
<tr>
<td>Land use / land cover maps</td>
<td>Masking of land/ocean. Flagging. Selection of proper data for running retrieval algorithms</td>
<td>Horizontal resolution 1 km x 1 km or better</td>
</tr>
<tr>
<td>Solid Earth, Ocean and Pole Tides</td>
<td>Altimetric correction</td>
<td>Ocean/solid earth/pole tide models</td>
</tr>
<tr>
<td>Tropospheric information along reflected trajectory</td>
<td>Altimetric correction, refractivity index along radio-link trajectory introduce ancillary delays</td>
<td>Temperature, pressure, water content along rays. Precision TBD</td>
</tr>
</tbody>
</table>
Atmospheric pressure at specular point zone | Altimetric correction: dynamic atmosphere response on ocean surface | Accuracy requirement TBD
---|---|---
Ionospheric information along direct and reflected radio-links | Altimetric correction: it introduces ancillary delays | Accuracy and resolution TBD

Requirements for auxiliary information can be evaluated and quantified once the Level-2 product performance requirements and retrieval algorithms have been further defined.

### Data processing, archiving, usage and latency

The GEROS data products will be made available and archived for the international scientific user community via one or several specialized GEROS scientific data processing and archiving centres. A broad scientific and interdisciplinary GEROS user community will be formed by regularly data user workshops, by joint scientific investigations resulting in publications in leading international geoscience journals and by joint acquisition of third party funded research projects to support the scientific exploitation of the GEROS-ISS data.

GEROS products could contribute to the global data base for operational weather and oceanic forecast systems. Precondition for this purpose is a near-real time provision of the data products (e.g., three hours after measurement for meteorological data), which requires additional specific mission infrastructure elements. Since the GEROS mission is rather an experimental and demonstration mission, such full operational data product provision is not foreseen in the current state of the mission but could be investigated within Phase A.

### 9 SYNERGIES AND INTERNATIONAL CONTEXT

The GEROS mission concept is unique but offers synergistic possibilities with other satellites/concepts in orbit or planned. These include:

#### TechDemoSat-1

TechDemoSat-1 is 160 kg U.K. satellite to be launched by Surrey Satellite Technology Ltd. It includes eight instrument demonstration payloads, one of them is a GPS remote sensing instrument for sea state monitoring. The same GNSS-R payload will also be used for the CYGNSS mission (see below). The launch is foreseen for December 17, 2013. Main goal of the GPS L1 reflectometry with TechDemoSat-1 is the determination of ocean roughness and wind. The data will be used for the preparation of the CYGNSS and GEROS missions.

#### Cubecat-2

Cubecat-2 is a cube-sat satellite to be launched by the Universitat Politècnica de Catalunya (UPC) during 2015. Its main payload is a small dual-band GNSS-R receiver with low power
consumption that uses state-of-the-art GNSS techniques to track both the GPS P and C/A codes in both the up- and downlooking channels (direct and reflected signals).

**CYGNSS**

CYGNSS (CYclone Global Navigation Satellite System) is a constellation of eight micro-satellites carrying the same GNSS-R receiver payloads as flown on the UK TechDemoSat-1. CYGNSS was selected by NASA in the U.S. to provide wind measurements in hurricane conditions, with the aim of measuring strong wind events for the improvement of extreme weather prediction. CYGNSS is funded from U.S. Earth System Science Pathfinder programme for new Earth Observation mission concepts. The expected launch date is 2016.

The characteristics of the platforms hosting these three missions limit the capabilities of their GNSS-R payloads (size, weight, antenna-gain, memory and power consumption). GEROS ISS presents the unique opportunity to work with more demanding GNSS-R payloads, in principle enabling higher performances.

**PARIS In-orbit-demonstrator**

The PARIS In-orbit Demonstration mission is a small-class free-flying satellite that has been studied by ESA through two Phase A parallel studies during 2011-2012. The conclusion of these studies is that a satellite flying along a 600 km altitude near-polar orbit should be capable of achieving better than 30 cm height accuracy over 100 km along track. The payload (a PARIS altimeter) is based on the interferometric processing, with an antenna size of the order of 0.9 m diameter. The proposed PARIS altimeter is capable of processing three reflection points in parallel and continuously corresponding to any GNSS system (GPS, GLONASS, Galileo, BeiDou, etc). Several modes of operation of the instrument are defined including nadir altimetry (incoherent and coherent), limb altimetry, scatterometry and target detection. Some technology activities are currently ongoing within ESA to develop the different sub-systems of the PARIS altimeter, comprising the multi-beam steered up-down antenna package, the back-end correlator unit, and end-to-end instrument tests. Several ground- and airborne-based experiments were conducted and other experiments are on-going to consolidate instrument operation and altimetry retrieval algorithms.

**Radar altimetry satellites**

GEROS SSH data could be compared to the conventional nadir pulse-limited and delay Doppler (or synthetic aperture radar, SAR) radar altimetry mission products from CryoSat-2, Jason-2/-3, AltIka, HY2A and it successors, the pair of Sentinel-3 satellites (launch currently planned for 2014/2015), Jason-CS, and SWOT (planned launch 2019) constellation when available in the GEROS mission lifetime.
SMOS, Sentinel-1/2 and similar missions

MSS data will be useful to correct L-band surface roughness effects in ocean salinity data from missions like SMOS, Aquarius, SMAP and any future L-band radiometer follow-on missions.

The GEROS land surface experiment is complementary to Sentinel-1/2, SMOS-follow-on and SMAP missions for experimental soil moisture activities. A combined exploitation of SAR backscatter and GNSS-R forward bistatic scattering data may help inversion algorithms to cope with dependence on many unknown parameters (i.e., moisture, roughness, vegetation).

The BIOMASS Earth Explorer satellite will provide vegetation and especially forest biomass data that can be compared to and possibly merged (provided suitable intersection of mission lifelong) with the retrieval of biomass from GEROS over land.

GNSS radio occultation missions

The GEROS RO information would be complementary to the GPS only data from the GRAS instruments aboard the European Metop satellites especially over tropical areas (denser data from GEROS due to ISS orbit versus polar orbit for Metop) but also based on the multi-GNSS (+GLONASS, +Galileo) capability of GEROS and also would complement RO data from other satellite mission, as, e.g., the 12 satellite COSMIC-2 constellation (planned launch 2018) or GRACE-FO (planned launch 2017). Polarimetric occultation measurements to detect strong precipitation events will overlap and continue the data from the Spanish PAZ satellite (planned launch 2014).

Scatterometer missions

The availability of RapidScat scatterometer data (2014 deployment) onboard the ISS will offer a unique opportunity to compare the response of L-band and Ku-band scattering in similar wind, sea state and precipitation conditions, and validate both instruments on the same space orbiting platform. The close collocation in time and space (50km, 1hour) required to observe these fast-changing phenomena, is seldom achievable for sensors placed on separate orbiting satellites.