SURREY SATELLITE TECHNOLOGY LTD

Scout-2 HydroGNSS Mission Requirements Document

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Last Edited Date	Revision Number	Status	Edited By	Pages/Paragraph Affected	Change Ref
01/07/2021	1.0	Release	MJU	Clean release	
07/09/2021	2.0	Release	SD/MJU/LR	Expanded Uniqueness and Complementarity discussion Added fast delivery of products of 1 week Added Level 0 requirements section Expanded mission success section Comment within MRD-260 updated as agreed during negotiation meeting MRD-530,540 made consistent. Added Freeze /Thaw and wetlands validation comments. Added new mission patch. MRD-550, added "including antenna polarisation settings"	S4.3 S6.2.6 S6.4 S8 S6.3, S6.4
24/02/2024	3.0	Release	MJU	Definition of L2G, and adjustment to allow product validation at Level 3, not just Level 2, L2G. Allowance for smaller DDMs Minor rewordings reflecting mission, e.g. allowing for second satellite, ground station expectations, mission architecture diagram.	S1.6.1 S5.1 S5.3 S6.2, 6.3 S7, 8

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1 INTRODUCTION

1.1 SCOPE

This document stipulates scientific and technical requirements for the ESA Scout-2 HydroGNSS mission (GNSS Reflectometry). It is a Mission Requirements Document (MRD), which defines unambiguous and traceable requirements for the ESA Scout **HydroGNSS** mission (referred to as 'HydroGNSS' or 'the mission' in the text that follows). The scope of the HydroGNSS MRD concerns the end-to-end Earth observation system including scientific requirements, mission operations, data product development and processing, data distribution and data archiving. The Science Advisory Group (SAG) is responsible for the adequacy of the mission requirements and their assessment, as well as for consulting wider scientific support needed to ensure scientific readiness targets. The HydroGNSS MRD is managed by SSTL with signatures from ESA and the chair of the SAG.

1.2 APPLICABLE DOCUMENTS

Applicable Documents identified in the following text are identified by AD-n, where "n" indicates the actual document, from the following list:

AD#	Title	Doc #	Revision	Date
AD-01	Earth Observation Science Strategy for ESA	SP-1329/1		Feb 2015
AD-02	ESA's Living Planet Programme: Scientific Achievements and Future Challenges	SP-1329/2		Feb 2015
AD-03	Science Readiness Level (SRL) Handbook	EOP-SM/2776 /MDru-mdru	-	2015

1.3 REFERENCE DOCUMENTS

Documents referenced in the following text, are identified by RD-n, where "n" indicates the actual document, from the following list:

RD#	Title	Doc No.	Revision	Date
RD-01	WMO List of Essential Climate Variables (see in particular Soil Moisture and Above-ground Biomass)	https://gcos.wmo.int/en/essential-climate-variables/table		Accessed Jun 2021
RD-02	ESA Space Debris Mitigation Compliance Verification Guidelines	ESSB-HB-U-002	Issue 1, Rev 0	19/02/2015
RD-03	HydroGNSS Scout Bid MCDJD 2_Science File	#0341585	003	Aug 2020
RD-04	HydroGNSS Scout Bid MCDJD 3_System Definition File	#0341586	002	13/07/2020
RD-05	HydroGNSS Scout Bid MCDJD 4_System Justification File	#0341587	003	13/07/2020
RD-06	HydroGNSS Scout Bid MCDJD 5_Management PA and Costing File	#0341586	003	28/08/2020
RD-07	WMO Vision For The WIGOS Component Systems In 2040 WIGOS Vision Space 2040	IPET-SUP-3/INF 6.1	DRAFT v1.1	5 May 2019
RD-08	Uncertainty Information in Climate Data Records from Earth Observation, J.Merchant et al.	https://essd.copernicus.org/articles/9/511/2017/		21 Feb 2017

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1.5 ACRONYMS AND ABBREVIATIONS

Acronym	Definition
AGB	Above Ground Biomass
AGC	Antenna Gain Control
AGSP	Antenna Gain at Specular Point
ANN	Artificial Neural Networks
AOCS	Attitude and Orbit Control System
ASCAT	Advanced SCATterometer
ASI	Agenzia Spaziale Italiana
CCI	Climate Change Initiative
CEOS	Committee on Earth Observation Satellites
CIMR	Copernicus Imaging Microwave Radiometer
CONAE	Comisión Nacional de Actividades Espaciales
CSG	COSMO-SkyMed Second Generation
CSK	COSMO-SkyMed
CYGNSS	Cyclone Global Navigation Satellite System
DDM	Delay Doppler Map
DDMR	Delay Doppler Mapping Receiver
DEM	Digital Elevation Model
DMC	Disaster Monitoring Constellation
ECV	Essential Climate Variable
EO	Earth Observation
EOL	End Of Life
ESA	European Space Agency
FMI	Finnish Meteorological Institute
FT	Freeze Thaw
GCOM	Global Change Observation Mission
GCOS	Global Climate Observing System
GEO	Global Earth Observations
GEOS	Goddard Earth Observing System Model
GEOSS	Global Earth Observation System of Systems
GEWEX	Global Energy and Water Exchanges Project
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
GTN-H	Global Terrestrial Network on Hydrology
HKTM	Housekeeping Telemetry
IEEC	Institut d’Estudis Espacials de Catalunya

IF	Intermediate Frequency
IFAC	Institute of Applied Physics
IOCR	In-Orbit Commissioning Review
IPCC	Intergovernmental Panel on Climate Change
ISMN	International Soil Moisture Network
JAXA	Japan Aerospace Exploration Agency
LEOP	Launch and Early Orbit Phase
LHCP	Left Hand Circular Polarisation
LNA	Low Noise Amplifier
LTAN	Local Time of Ascending Node
MRD	Mission Requirements Document
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index
NGI	Nottingham Geospatial Institute
NISAR	NASA-ISRO SAR Mission
NOC	National Oceanography Centre
NSIDC	National Snow and Ice Data Center
NWP	Numerical Weather Prediction
PALSAR	Phased Array type L-band Synthetic Aperture Radar
PDGS	Payload Data Ground Segment
RF	Radio Frequency
RHCP	Right Hand Circular Polarization
rms	Root Mean Square
RMSE	Root Mean Square Error
ROSE-L	Radar Observing System for Europe - L-Band
SAG	Science Advisory Group
SAOCOM	SAtélite Argentino de Observación COn Microondas
SAR	Synthetic Aperture Radar
SCAN	Soil Climate Analysis Network
SGR	Space GNSS Receiver
SMAP	Soil Moisture Active Passive
SMOS	Soil Moisture and Ocean Salinity
SNR	Signal to Noise Ratio
SRL	Science Readiness Level
SSTL	Surrey Satellite Technology
TDS-1	TechDemoSat-1
TOPC	Terrestrial Observation Panel for Climate
TT&C	Telemetry and Telecommanding

UNFCC	United Nations Framework Convention on Climate Change
WIGOS	Integrated Global Observing System
WMO	World Meteorological Organization
ZTC	Zoom Transform Correlator (On-board processing algorithm)

1.6 DEFINITIONS

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

Ancillary Data. Data generated on-board in support of the observation data, both by the instrument and the platform, such as, navigation, temperature, Housekeeping Telemetry (HKTM), timing data and configuration. When generated by the instrument they are called “instrument ancillary” when by the platform “platform ancillary”.

Auxiliary Data. In the ground segment this is the data needed to perform ground processing and not part of the measurement data set generated on board (this might include e.g. pre-launch calibration data and Land Cover database).

Coverage. <within a given time interval delta-t>. Accumulated active sensing area on the Earth’s surface during the interval delta-t. The sensing area is considered to be active when at least one reflection is available at the sensor field of view at the required SNR, at a defined resolution on the ground. Coverage can be referred to either as ‘full coverage’ when related to the whole Earth’s surface, or as ‘coverage of <target>’, when related to a specific subset of the Earth’s surface.

End-to-End Simulator. As a minimum, the E2E simulator shall implement Scene Generation and Satellite Geometry providing the input parameters for the instrument simulation generating measurements as if from spacecraft (Level 0B in the case of HydroGNSS). A Level 1 Processing Module and a Level 2 Retrieval Model generating the Level 1 and 2 data products for the performance analysis specified in the Performance Evaluation Module shall complement the simulator.

Metadata. Data that accompanies measurements or main products that are needed to calibrate or use the measurements or products and can included Ancillary and Auxiliary data as well as other terms.

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.

Revisit Time. Time between two consecutive observations of a defined target area on the Earth’s surface.

Sensing Area. Area on the Earth’s surface within the remote sensor field of view, at a given instant t.

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 on the Earth surface.

Timeliness. The timeliness (also referred to as latency) is the time elapsed between observation by the satellite and the availability of the product at a user interface.

Measurement Uncertainty. Defined as a parameter associated with the result of a measurement that characterises the dispersion of the values that could reasonably be attributed to the measurand. The careful application of uncertainty information is important in climate data records [RD-08]

1.6.1 Product Data Level Definitions

Level 0A – Raw sampled data from RF front-ends, at intermediate frequency (IF) or baseband, prior to processing by instrument. These cannot be stored or downloaded from the instrument except for short captures (seconds or minutes) for diagnostic purposes.

Level 0B – Delay Doppler Maps (DDMs) containing Earth-reflected GNSS reflections, processed on-board from raw sampled data, giving compression that allows near-continuous collection and download capability.

Level 1A – Level 0B DDMs decompressed, in user accessible format (e.g. NetCDF) and accompanied by Metadata retrieved from the satellite (e.g. GNSS position fix, direct tracking powers, geometric terms)

Level 1B – Level 1A DDMs with L1A metadata and derived corrections including enough information to calibrate DDMs and derive surface reflection parameters, plus quality warning flags. (Potentially more than one approach could be applied to derive GNSS transmit powers)

Level 2 – is the Essential Climate Variable (ECV) related product, inverted from Level 1, and represented along individual reflected measurement tracks.

Level 2G – is a type of Level 2 product that has been gridded within the track to a specified grid resolution. Each L2G point may be the combination of several L1 measurement points.

Level 3 – is the ECV-related product that is gridded to specified resolution and temporally averaged over a specified time period. The product combines L1-L2 products from multiple tracks and multiple satellites, and can be represented on a map.

Product data levels are illustrated in Figure 1-1.

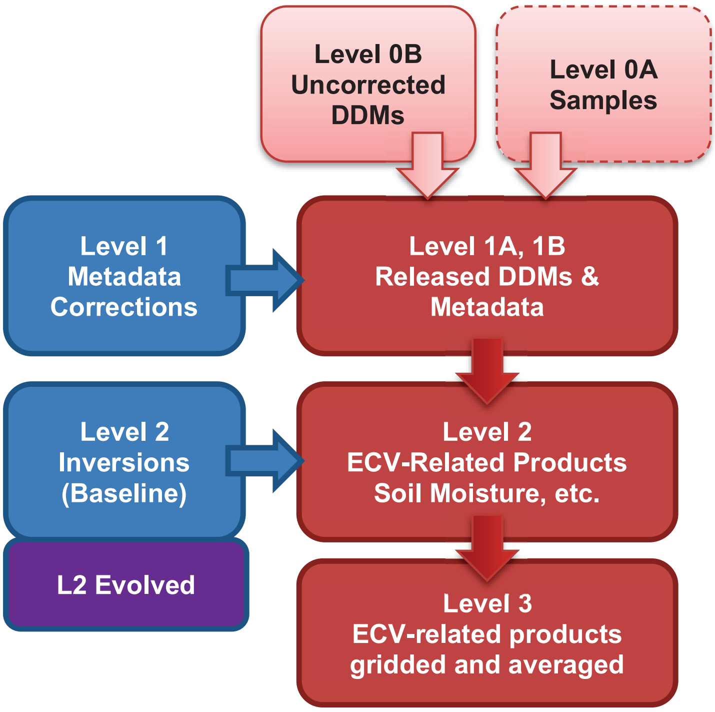

Figure 1-1. HydroGNSS Level Definitions

2 ESA SCOUT-2 HYDROGNSS

Scout missions are a new element in ESA's Earth Observation Programme. The idea is to prove new concepts using small satellites that add scientific value to data from currently flying satellites. Adopting an agile development process, this mission includes the development of the space and ground segments, launch and in-orbit commissioning – and from kick-off to launch within three years within a budget limit of €30m.

The ESA Scout-2 HydroGNSS mission is a scientific demonstrator for a GNSS-R constellation that primarily addresses land. The Mission will initially consist of one or two satellites each approx. 60 kg flying a GNSS Reflectometry instrument at a nominal orbit of 500-600 km and an inclination 98°, phased apart by 180 degrees (if two satellites), with the intent to provide on-board processed reflections (GNSS Delay Doppler Maps, DDMs) collected near continuously over the globe. These DDMs are inverted on the ground into Level 2 products closely related to internationally recognised Essential Climate Variables (ECVs) and delivered to users in a timely manner. Science value is increased through the potential of additional satellites improving the temporal resolution and global sampling of time-critical variables.

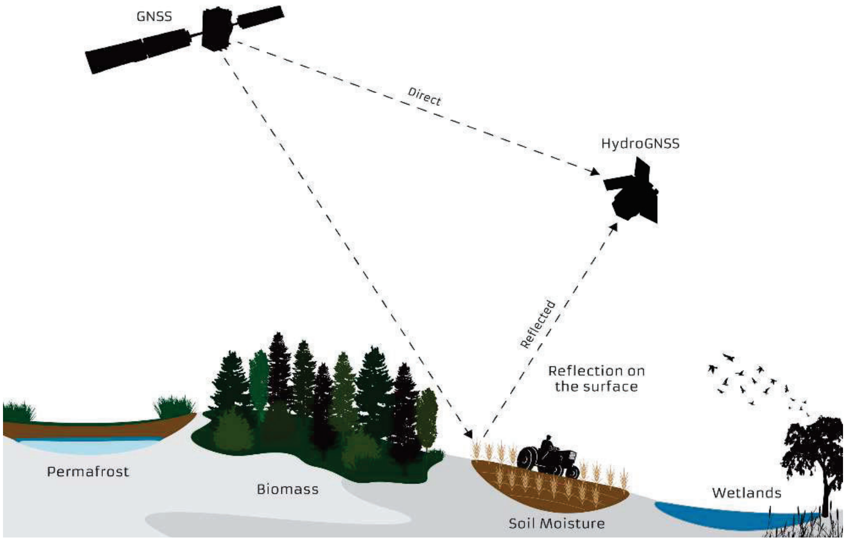

Figure 2-1. HydroGNSS ECV-Related Targets

GNSS Reflectometry uses signals from GNSS navigation satellites as L-band radar sources, and scattered reflections are measured from space to take geophysical measurements. The instrument proposed to be flown on the HydroGNSS mission is the SGR-ReSI-Z instrument. It is derived from the SGR-ReSI used on TDS-1 and CYGNSS, inheriting its functional capability, but brought onto up-to-date technology to overcome limitations of the earlier instrument. New capabilities include both GPS and Galileo reflection reception, dual polarisation reception, the addition of a coherent channel, and the addition of second frequency (E5 / L5) reflection capability. This offers a unique instrument for measuring the four parameters closely related to ECVs. These are **Soil Moisture, Inundation / Wetlands, soil Freeze / Thaw (notably over permafrost), and Above Ground Biomass (AGB)** (Figure 2-1). Secondary products of wind speed and ice extent are foreseen over ocean and ice.

The small size of the mission lends itself to a potential future constellation of similar satellites. The orbit is selected as a sun-synchronous orbit to cover higher latitudes, with an altitude of less than 600 km to optimise the SNR performance of the science instrument and to aid compliance with spacecraft disposal requirements. To expedite schedule and lower costs, a ride-share launch is assumed, into a common 10:30 am / pm orbit, and simulations show for one satellite, a >80% global coverage can be achieved every 30 days at 25 km resolution, and for two satellites can be achieved every 15 days. Adding satellites into the same orbit will increase the frequency of global coverage.

HydroGNSS will play a role in deploying cutting-edge exploratory missions addressing new scientific questions, via a New Space Approach. This is a rapid and cost-effective small satellite mission with some scientific maturity and with reconfigurability that can be deployed rapidly allowing a demonstrably flexible responsive approach.

This small-scale technology is suitable for migrating to affordable and sustainable constellations or hosted payloads to allow migration to Earth Watch, Copernicus or other sustained programmes for longer term monitoring.

3 MISSION OBJECTIVES

The main goal of HydroGNSS ESA Scout is to exploit L-band satellite navigation signals to monitor Earth's water systems at a medium to fine spatial resolution and derive measurements linked to ECVs defined by the Global Climate Observing System. Another objective is to allow for further satellites to be added to the constellation if finer temporal resolution is required.

1. To measure **Soil Moisture** using reflected GNSS signals – including use of dual-polarised reflections to help separate roughness and vegetation effects from soil moisture. Better vegetation penetration and higher resolution may be possible using coherent channel and second frequency reflections.
2. To measure **Inundation / Wetlands** using reflected GNSS signals – including use of the coherent channel to achieve higher resolution. Better vegetation penetration and higher resolution may be possible using second frequency reflections.
3. To measure **Soil Freeze/Thaw** state especially over permafrost regions, identifying the date in the year of state change. Better sensitivity to freeze/thaw may be possible using the coherent channel.
4. To measure **Biomass** using reflections – using attenuation of signals in combination with knowledge of underlying surface and soil moisture characteristics.
5. To measure (as secondary objectives) **ocean wind speed** and **ice extent**, which address GCOS ECVs Ocean Surface Stress and Sea Ice Extent. Other new parameters and products may be investigated using the repertoire of new GNSS-R measurement types (e.g. ocean mean square slope, wind direction, micro-plastics in the ocean, Chl-a, ice concentration, snow water equivalent, sea ice thickness, inland water bodies).

Objective 5 shall not drive instrument, mission development and operations.

4 SCIENTIFIC JUSTIFICATION

The scientific case for HydroGNSS is presented in greater detail in the MCDJD science file [RD-03]. A summary is given below.

4.1 MEASURING ESSENTIAL CLIMATE VARIABLES

Essential Climate Variables (ECVs) are key parameters of the Earth system identified by the Global Climate Observing System (GCOS) [RD-01] to help understand and predict climate change, to guide mitigation measures, and to assess risks, in association with the UNFCC, IPCC and WMO. Soil Moisture, Biomass, Land Cover and Permafrost are some of the key terrestrial ECVs identified by GCOS, the ESA EO Science Strategy and the ESA Climate Change Initiative (CCI) programme for their relevance to understanding the global hydrological cycle.

Figure 2-1 illustrates the four ECV-related targets for HydroGNSS. GNSS reflectometry is the technique of using L-band GNSS signals (from GPS, Galileo, etc.) as bi-static radar sources of opportunity to sense geophysical parameters on the ground. Measurements are collected and processed in the instrument into a "Delay Doppler Map" (DDM) that can be corrected and inverted into Level 2 products such as ocean wind speed, as demonstrated on TDS-1 and CYGNSS missions. Data from TDS-1 and CYGNSS were also used to prove the effectiveness for sensing parameters over ice and land. The rationale for the HydroGNSS ECV-related targets is described below.

Surface Soil Moisture – Soil Moisture is both an indicator and driver of land-air interface, and forms a link between the biosphere, hydrosphere and atmosphere. It has many use cases including climate change, agriculture and operational weather forecasting. Two important missions SMAP and SMOS are near the end of their lifetimes. Data from the CYGNSS mission has demonstrated the potential for soil moisture measurement by GNSS-R. Surface Soil Moisture is defined as a product within the Soil Moisture ECV in the scientific area of the hydrosphere.

Surface Inundation / Wetlands – Inundation status affects surface run-off and flood events, and knowledge has important societal benefits. As well as harbouring biodiverse ecologies, wetlands are an important source of methane, and changes could have a major effect on climate change. GNSS-R has a resolution of around

25 km when diffusely scattered, but over a smooth surface, specular reflection resolutions can approach the Fresnel zone of around 500-1000 metres. Due to the low frequency forward scattering nature, GNSS-R measurements from CYGNSS have been shown to be particularly effective at detecting wetlands and rivers underneath forest canopies. Surface Inundation is defined as a product within the Soil Moisture ECV in the scientific area of the hydrosphere.

Freeze/Thaw & Permafrost – Environmental processes that occur over northern land areas and high elevations are influenced by the seasonal transition between frozen and non-frozen soil conditions. Unseasonal changes in the permafrost cycles could potentially release larger quantities of methane, which risks exacerbating global climate change. Preliminary work shows that GNSS-R has good sensitivity for Freeze-Thaw sensing in the active zone over permafrost. Limited measurements and modelling indicate that GNSS-R can help in permafrost characterisation, but more measurements and research are required. Freeze/Thaw is defined as a product within the Soil Moisture ECV in the scientific area of the hydrosphere.

Above-Ground Biomass – Vegetation biomass is a crucial ecological variable for understanding the evolution and potential future changes of the climate system. Photosynthesis withdraws CO_2 from the atmosphere and stores carbon in vegetation in an amount comparable to that of atmospheric carbon. Research using GNSS-R measurements from terrestrial, balloon-based and spaceborne receivers (including a SMAP-hosted experiment) indicates that biomass can be measured using GNSS-R and that there is promise from dual-polarised collection. The forthcoming ESA Biomass mission targets biomass but will benefit from complementary measurements especially where Space Objects Tracking Radar prevents it from operating over America and Europe, and for faster temporal updates. Above Ground Biomass is defined as an ECV in the scientific area of the biosphere.

In addition to longer term climate observations, soil moisture and inundation measurements from GNSS-R can provide important information for short term operational purposes, for example, towards Numerical Weather Prediction (NWP) and flood warnings following rainfall events.

4.2 SECONDARY OBJECTIVES

The technique of GNSS-Reflectometry is furthermore known to have potential for the measurement of other important variables relating to sea state, ocean winds, ice extent, ice concentration, ice thickness, and snow water equivalent, many of which relate to ECVs in other domains. The techniques for ocean wind speed and sea ice extent retrieval are well known and documented and will be implemented for HydroGNSS, e.g. (Foti, et al., 2015), ocean winds and soil moisture have complementary value in NWP.

4.3 UNIQUENESS AND COMPLEMENTARITY

HydroGNSS fits well into the context of current and future missions and addresses shortcomings.

As illustrated in Figure 4-1 HydroGNSS augments current capabilities through additional density of measurements, adds new synergic ECV observations that extend from current sensing techniques, offers timely continuity over a potential gap in L-band missions, reaches geographic areas not covered by Biomass, and demonstrates a low-cost small satellite approach that is sustainable for the future.

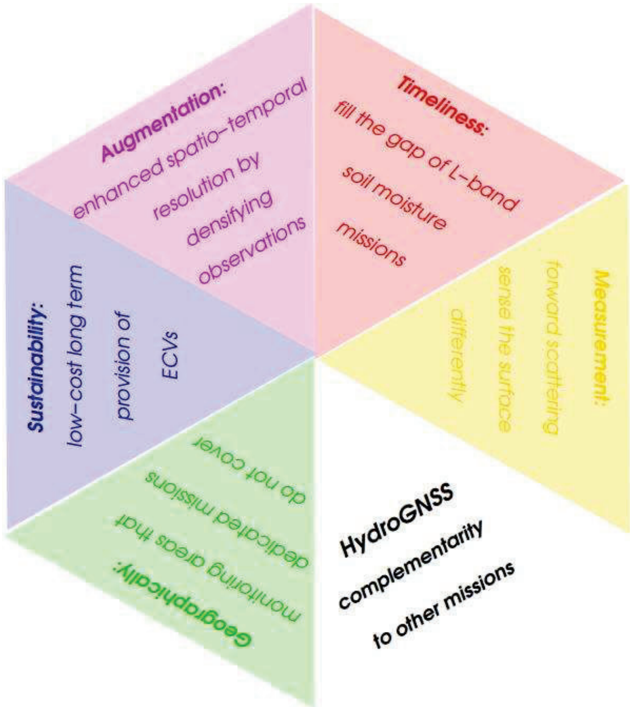

Figure 4-1: Uniqueness and complementary of HydroGNSS

SMOS and SMAP missions provide global coverage of soil moisture at L-band through radiometry, achieving resolutions of around 30-40 km, but both have exceeded their design life and do not have immediate replacements. Other remote sensing low-resolution satellites, e.g., MetOp/ASCAT and GCOM-W, use C-band, so cannot penetrate vegetation so well.

Higher resolution satellites have limitations, e.g. Sentinel-1 uses C-band, so will be complemented well by HydroGNSS, for instance as now done with the blended Sentinel-1 and SMAP SM product. Other missions, such as SAOCOM, CSK/CSG and PALSAR developed by CONAE, ASI and JAXA, do not have continuous coverage, or operational soil moisture products, and are not designed to support European operational services. Some overlapping acquisitions could be envisaged with the NASA NISAR mission that could provide an opportunity to combine L-band backscatter and forward scattering observations, at least for research purposes.

Future High Priority Copernicus Missions, i.e., the L-band ROSE-L SAR and the CIMR microwave radiometer, though yet to be finally approved, will be very capable L-band missions, and similarly SMOS HR has recently been initiated by CNES. They will have some limitations with coverage (ROSE-L, with 12 days revisit by a single platform) and resolution (CIMR, about 60 km resolution at L-band), that can be complemented well by HydroGNSS. More than that, as their launches are not expected until after 2026, the gap in L-band observation of soil moisture and F/T by a European space infrastructure in between SMOS end of life and launch of the HPCMs will only be covered by HydroGNSS.

Radar sensitivity to biomass is generally affected by a saturation for high biomass values, even at L-band. Very low frequencies are needed to sense dense tropical forests, such as P-band implemented by the ESA Biomass Earth Explorer which however will have coverage limitation (due to overlap with radar frequency) and a low temporal resolution. HydroGNSS will offer useful complementary measurements to complement Biomass, albeit at lower resolution, also thanks to the less early saturation of L-band forward scattering and the better revisit useful to monitor disturbances.

HydroGNSS offers medium to high resolution using techniques compatible with small satellites, and hence may be an order lower cost than many other missions, allowing plans for a future sustainable constellation. Six small HydroGNSS satellites would be required to match the coverage of SMOS at a fraction of the cost, while exceeding its resolution. Further HydroGNSS satellites could be added at low cost to achieve unprecedented spatial and temporal measurements of the globe.

As an L-Band forward scattering sensor, the measurements from HydroGNSS are expected to have strengths and weaknesses compared to other data sources. The greatest value of the HydroGNSS mission will be achieved if results from a HydroGNSS constellation can be used to complement other missions, as encouraged by international collaborations such as GEO (Global Earth Observations).

4.4 RELEVANCE TO EO SCIENCE STRATEGY

The HydroGNSS mission directly addresses a number of challenges set out in ESA's Earth Observation Science Strategy.

- Addressing the measurement of hydrological cycle parameters that affect water resources, geographical shifts in habitat conditions, climate extremes such as droughts, and hazards such as flooding, and with an impact on food security.
- The mission addresses topics in ESA's Climate Change Initiative, including several ECVs.
- Datasets are planned to be made available with extensive metadata and mirrored to long term storage.
- Interfacing with international collaborators to allow movement towards GEOSS.
- Translational science through the release of data, visualisation, maps and outreach activities.

The HydroGNSS mission shall help to address some of ESA's challenges set out in the "ESA's Living Planet Programme: Scientific Achievements and Future Challenges", in particular the Land Surface. No one sensor can solve the challenges, and an assimilation of many data sources into detailed models is required, but hydrological parameters are under-determined at present, and this mission can potentially provide important inputs. Hence HydroGNSS addresses the following 5 land surface challenges:

- **Challenge L1:** Natural Processes and human activities and their interactions on the land surface.
- **Challenge L2:** Interactions and Feedbacks between global change drivers, biogeochemical drivers, water cycles, rivers lakes, biodiversity and productivity.
- **Challenge L3:** The structure and functional characteristics of land use systems to manage sustainably food, water and energy supplies
- **Challenge L4:** Land Resource utilisation and resource conflicts between urbanisation, food and energy production and ecosystems.
- **Challenge L5:** How Limiting factors (e.g. freshwater availability) affect processes on the land surface and how this can adequately be represented in prediction models

The WMO Vision for the WIGOS Component Systems in 2040 calls for a GNSS Reflectometry mission with GNSS-R instrumentation included under "Component 2" category of the backbone to measure geophysical variables: surface wind and sea state and permafrost changes / melting.

4.5 EVIDENCE OF GNSS-R SUITABILITY FOR LAND SENSING

The MCDJD Science File [RD-03] demonstrates the sensitivity of GNSS-R to the target ECVs and the feasibility to retrieve them with the related achievable accuracy, based on an extensive review of literature, on previous ESA projects involving analysis of ground-based, airborne and spaceborne GNSS-R data (e.g., ESA contracts N. 22117/08/NL/AF, 4000103329/11/NL/CVG, and 4000120299/17/NL/AF/hh), as well as from the outcome of the Scout Consolidation Study (detailed in MCDJD Justification file RD-05). A short resume of that survey is reported hereafter.

The main mechanism enabling the retrieval of the ECV-related parameters through measurement of signal reflected off the Earth's surface is common to many microwave remote sensing techniques. First, it is the change of permittivity of the target due to changes in the water content or state (e.g., change in soil moisture, change from soil to flood water, change due to freezing). Second, it is the scattering phenomena undergoing in inhomogeneous media, such as vegetation, which attenuates the soil reflection and introduces an incoherent diffuse signal. GNSS-Reflectometry uses bi-static forward scatter reflections that give stronger echoes and finer resolution over smooth surfaces, as opposed to classical back-scatter measured by mono-static radar. It is known that L-Band offers deeper penetration of soil, vegetation and snow than C-band and higher frequency radars. The combination of these two features and the difference between backward and forward scattering mechanisms give to GNSS-R the unique capability to sense the target parameters but also to complement traditional backscattering measurements.

Soil Moisture – At least three different approaches have been shown in the literature to successfully retrieve soil moisture, generally using CYGNSS data in comparison with SMAP mission soil moisture results, achieving results in the region of GCOS target, though limited to SMAP's resolution of 36 km. (Al-Khaldi M., 2019) uses a change detection algorithm exploiting time-series of CYGNSS normalized radar cross section showing an RMSE in the order of 0.04 cm^3/cm^3 and a correlation around 0.82. (Clarizia, Pierdicca, Costantini, & Floury, 2019) introduced a trilinear regression exploiting CYGNSS reflectivity only and ancillary data from SMAP (vegetation optical depth and roughness) to derive daily soil moisture estimates giving an RMSE of around 0.06 cm^3/cm^3 when trained at regional scale. (Eroglu, 2019) uses an artificial neural network (ANN) trained using in situ data. The method combines observables from CYGNSS (e.g., reflectivity, trailing edge slope, incidence angle) and ancillary data (e.g., NDVI, surface height and slope). The product validation resulted in an unbiased root mean square error (ubRMSE) of 0.05 cm^3/cm^3 and a correlation coefficient of R=0.9.

During the HydroGNSS Consolidation Study an algorithm for soil moisture retrieval from CYGNSS reflectivity based on an ANN approach and integrating ancillary data has been trained and tested using SMAP products (only 1% of SMAP data used for training and the rest used for testing). An example of the map generated compared to a SMAP product is shown in Figure 4-2 and the test resulted in a RMSE of 0.06 m^3/m^3. (Santi, et al., 2020)

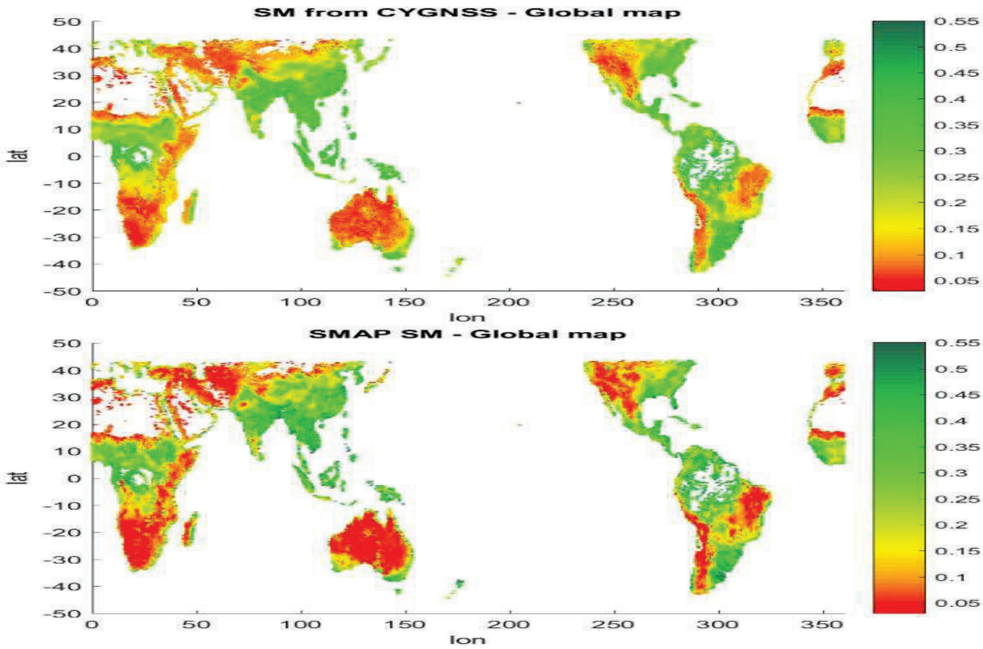

Figure 4-2. Example of the CYGNSS-based SM product developed in the frame of the HydroGNSS Consolidation Study (upper panel), comparison with the SMAP product (lower panel).

Inundation – GNSS-R L-band forward scattering has been shown to be very effective at detecting flat and smooth surfaces, similar to those expected when soil is inundated. In particular, the reflection is strong enough to allow detection of wetlands and rivers underneath forest canopies with the high resolution enabled by a coherent type of reflection. A clear example of such capability is presented in Figure 4-3 where water bodies and river maps derived from CYGNSS data are compared to those derived from the SMAP radiometer and the SMAP radar. Research indicates that potential resolution of edges is in the order of Fresnel Zone, i.e. 1 km.

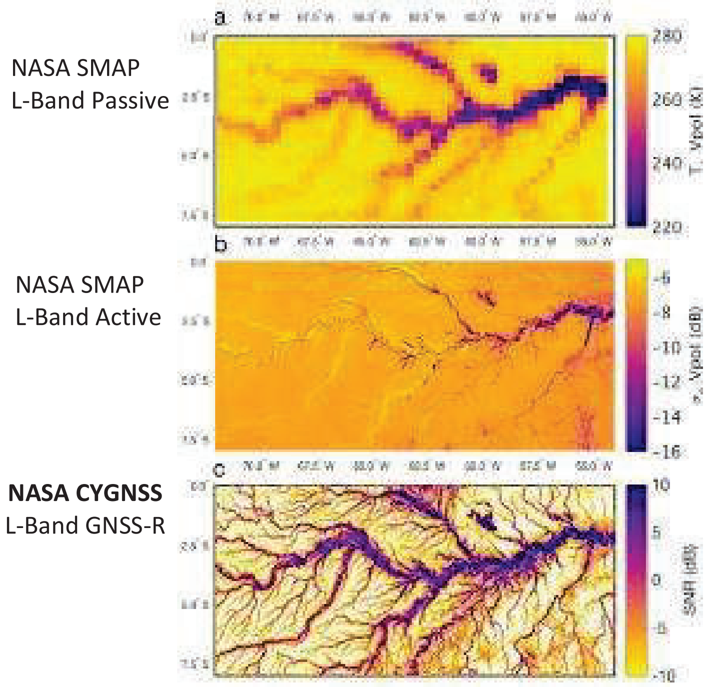

Figure 4-3: SMAP vs CYGNSS observations of Amazon basin streams and tributaries (Chew C., 2017)

Freeze / Thaw - Data from TDS-1 have recently shown that GNSS-R is sensitive to high latitudes freeze/ thaw (FT) cycles of the active layer due to the strong contrast between thawed and frozen L-band soil specular reflectivity. The poor sampling of TDS-1 (the GNSS-R payload did not operate continuously) forced to limit the analysis to monthly means of TDS-1 reflectivity, but the correlation with monthly means of the SMAP Level 2 FT fraction and SMAP Level 3 FT state products is evident in many areas of Siberia characterized by sparse vegetation and high latitude. The correlation was poorer at lower latitudes where spatially and temporally inhomogeneous FT transitions may occur that were not possible to discriminate due to the poor coverage of TDS-1, and also in highly vegetated areas, an issue that needs more investigations.

Similar conclusions were drawn using signals collected by the SMAP radar receiver operating for a certain period of time after the radar failure as a GNSS-R payload. (Chew, et al., 2017) simulated the reflection contrast between frozen and thawed soil conditions starting from the FT state provided by the SMAP radiometer and compared them with the actual spaceborne reflections in horizontal and vertical polarization acquired by the SMAP radar in GNSS-R (passive) mode. GNSS-R results indicated a difference of about 4-5 dB between frozen and thawed states (Figure 4-4).

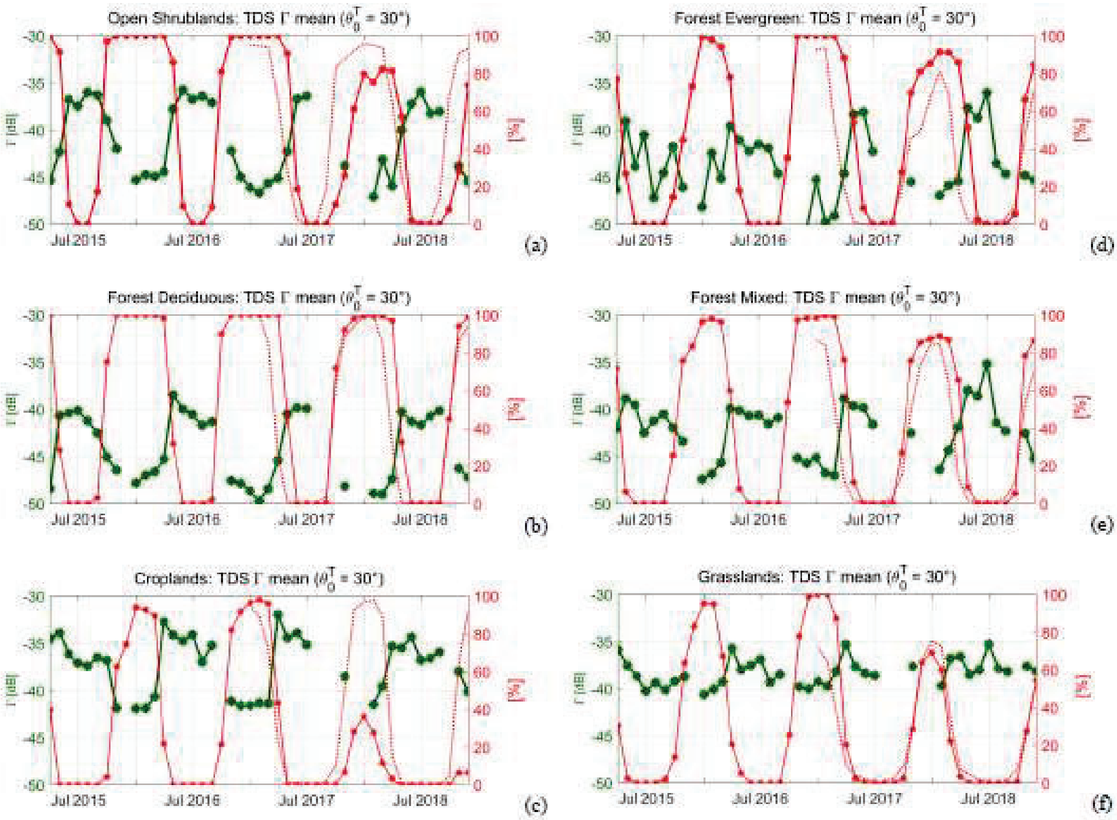

Figure 4-4. Time series of monthly average reflectivity derived from TDS-1 (green) compared against the SMAP L2 FT fraction (red) and SMAP L3 FT state (also monthly averaged) over six selected ROIs: Open Shrublands (a), Forest Deciduous (b), Croplands (c), Forest Evergreen (d), Forest Mixed (e) and Grasslands (f). From (Comite, Cenci, Colliander, & Pierdicca, 2020).

Above Ground Biomass (AGB) - Figure 4-5 shows the comparison between forest parameters (i.e., biomass and tree height) retrieved from CYGNSS data and those used as reference in the training and testing of an ANN retrieval algorithm (Santi, et al., 2020), achieved during the consolidation study. The test of the algorithms using a data set independent of the training set resulted in a correlation coefficient R≃0.8 between retrieved and reference quantities in the various experiments, and 37 t/ha ≤ RMSE ≤ 76 t/ha for local and global AGB retrievals (AGB in the range 0 – 400 t/ha), and 3.1 m ≤ RMSE ≤ 6.5 m for tree height retrieval (H in the range 0 – 45 m). Although forest biomass does not change quickly, the results could be to some extent affected by the poor temporal matching between satellite acquisitions and the considered reference data.

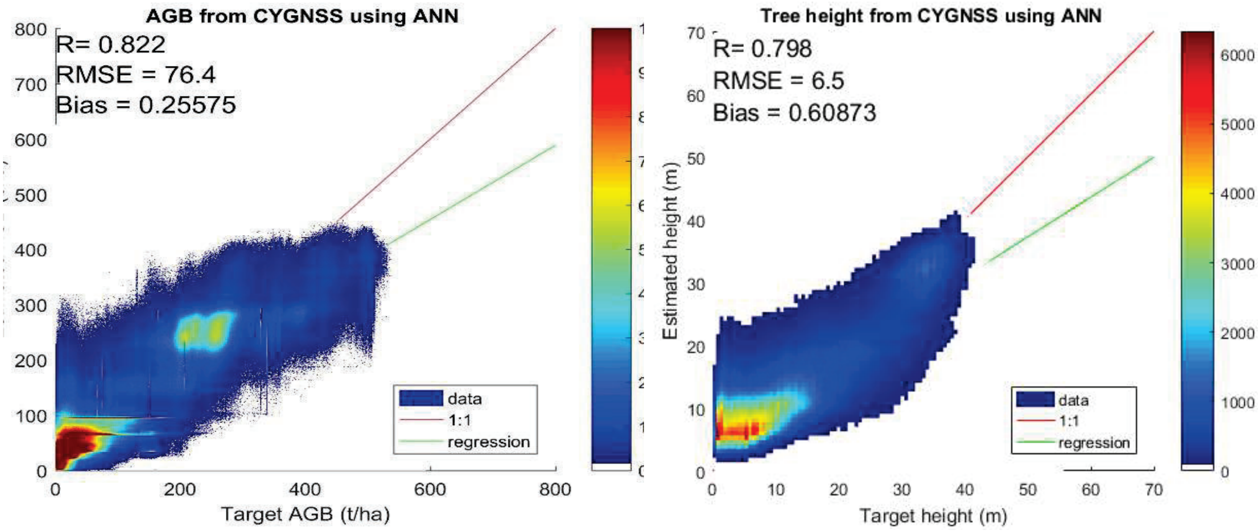

Figure 4-5. AGB and tree height retrieval on a global scale using CYGNSS data. Left: AGB estimated by ANN as a function of the reference from (Avitabile, 2015). Right: tree height estimated by ANN as a function of the reference height from the ICE-GLAS data.

These experimental results collated in the Science File RD-03 (including the few examples reported here) were based mainly on "conventional" GNSS-R data from TDS-1 and CYGNSS. During the Consolidation Study evidence of the usefulness of the new HydroGNSS capabilities (especially polarimetry and the coherent channel) were investigated referring to ground and airborne based experiments and simulation tools, and are reported in MCDJD Justification File RD-05.

5 HYDROGNSS MISSION ARCHITECTURE

5.1 OVERVIEW

The space segment comprises of one or more satellites carrying a GNSS reflectometry payload. The ground segment will be based upon SSTL's Guildford facilities, supplemented by a Svalbard ground station for primary TTC access and payload data downloads. Data will be processed by an updated version of the ground processing system used for TDS-1 (referred to as MERRByS), hosted at SSTL. Data from portal will be freely distributed to collaborators and scientists around the world according to ESA's free and open data policy. The mission architecture is illustrated in Figure 5-1, and timeline in Figure 5-2.

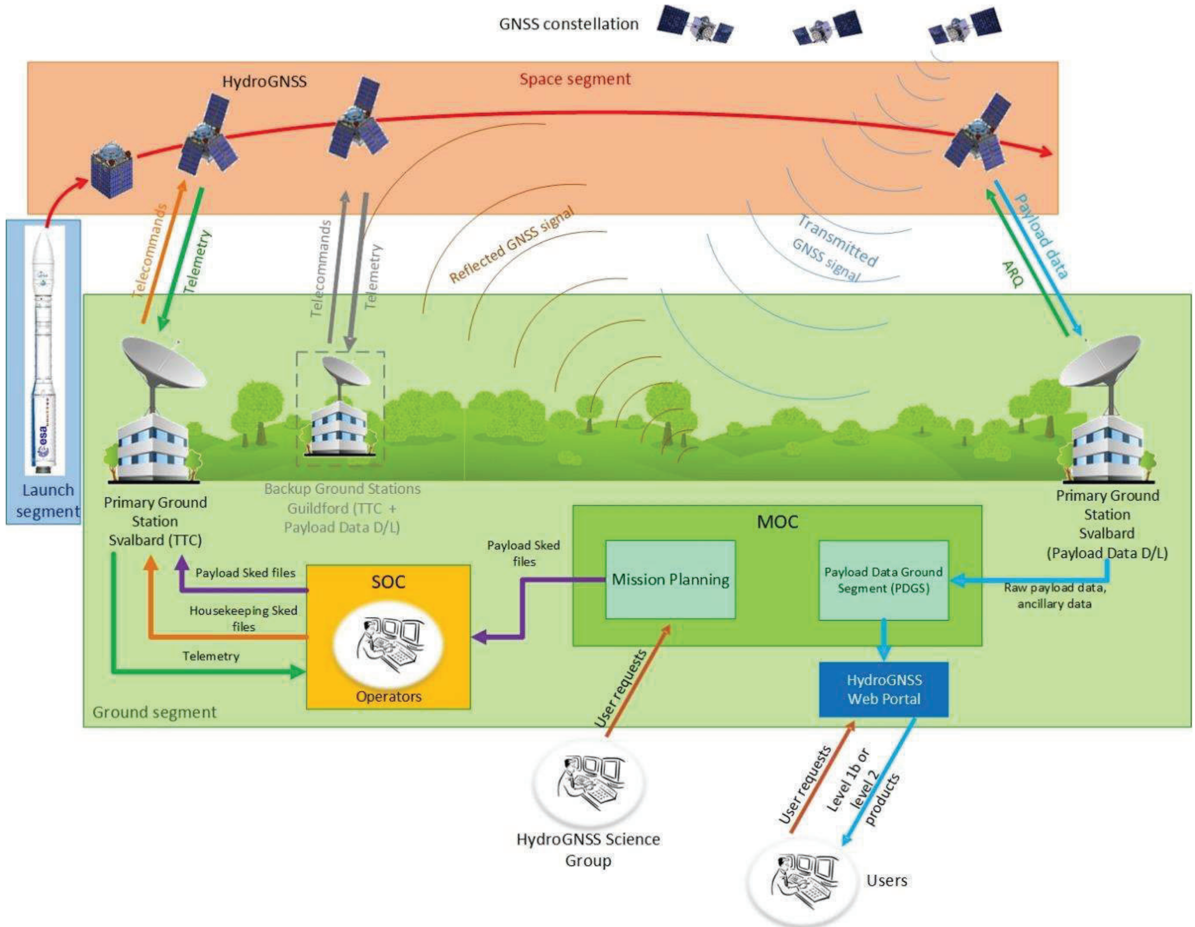

Figure 5-1. Top Level HydroGNSS Mission Architecture

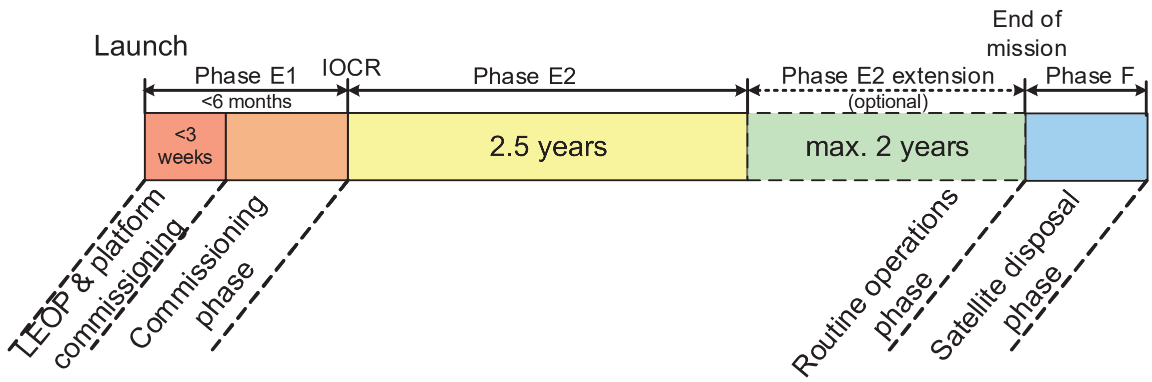

Figure 5-2. HydroGNSS Mission Timeline

5.2 HYDROGNSS PAYLOAD

Figure 5-3 shows a payload outline diagram for HydroGNSS. It comprises zenith and nadir antennas, three LNA (low noise amplifier) modules, the DDMR (Delay Doppler Mapping Receiver) and associated RF cables and harnesses. The "SGR-ReSI-Z" on HydroGNSS is a successor to the "SGR-ReSI" Space GNSS-Receiver – Remote Sensing Instrument, as flown on TDS-1, CYGNSS and DoT-1 but bringing in newer technology and adding new capabilities. As on TDS-1, the core functions are GNSS receiver and reflectometry processor, and there is a high degree of configurability, such that new features and capabilities can be programmed while in orbit.

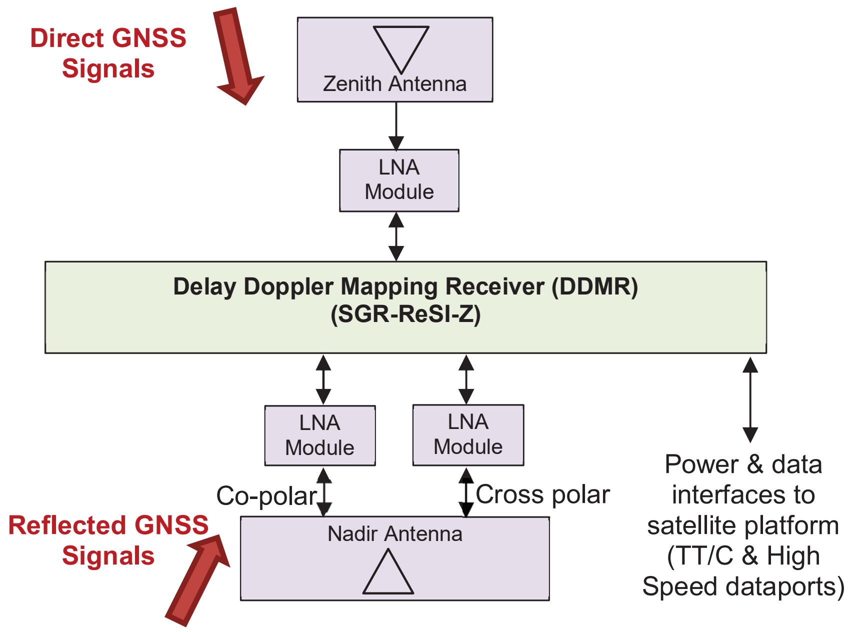

Figure 5-3. SGR-ReSI-Z GNSS Receiver Configuration for HydroGNSS

Similar Low Noise Amplifiers to the SGR-ReSI on TDS-1 are used, and include a "black-body" load and temperature sensor, with dual frequency channels for L1 and L5, but with improved lower loss filtering in front.

The nadir antenna is a fixed dual resonant 2 x 2 all-metal patch array, with dual feeds allowing collection of signals at both polarisations (LHCP and RHCP), giving a gain of approximately 13 dBi. The zenith antenna will be a single RHCP patch element of a similar kind.

The Instrument form factor is based on SSTL's half-module tray standard at 30 x 18 x 3 cm^3, and with a mass of around 1.2 kg. The power draw is approximately 12 watts when operational, operating off a 12 volt power supply from the satellite platform.

5.3 GROUND SEGMENT

Ground infrastructure available to SSTL fulfils the mission requirements, reducing the risk and cost as it is already proven for similar missions and satellite platforms. Ground antennas located at Svalbard will be used for 2 passes per day for S-Band Tracking Telemetry and Commanding (TT&C), and 3 passes per day at Svalbard will be used to download payload data via X-Band downlink. The ground station at Guildford will be available as back-up for both TTC and payload downloads.

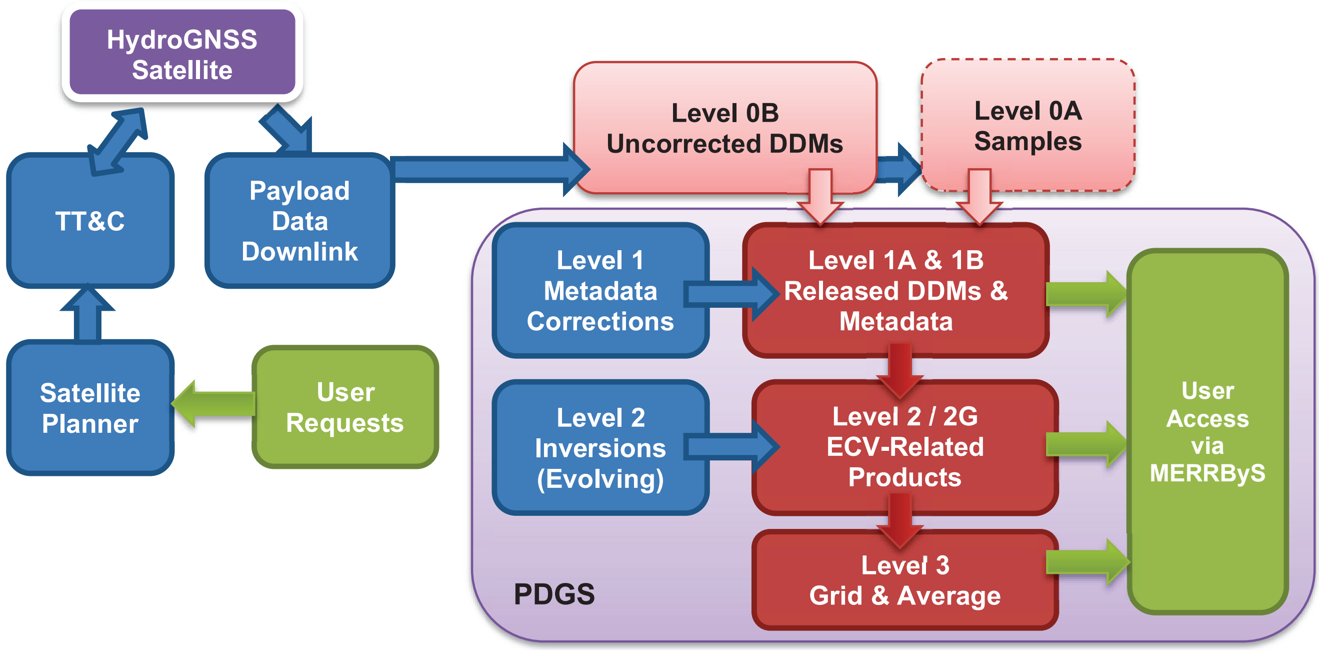

Figure 5-4. HydroGNSS Ground Segment & Products

Figure 5-4 shows a schematic of the ground segment and data products. SSTL's satellite planning tool will be used to manage payload scheduling. The Payload Data Processing Ground Segment (PDGS) will make use of the MERRByS ground infrastructure updated to support the new measurement data. Products will reuse the industry standard NetCDF and will be made available at Level 1A and 1B, together with appropriate metadata, including calibration parameters. During the mission experimental inversions will be deployed to allow access to Level 2 and 3 products such as soil moisture, but these will evolve, and be refined and updated during the mission as the scientific understanding of the new measurements improves.

6 SCIENTIFIC REQUIREMENTS DEFINITION

6.1 MISSION REQUIREMENTS

Reference	Requirement
MRD-010	HydroGNSS is a mission that exploits L-band satellite navigation signals to monitor Earth's water systems over the land. The space segment shall consist of one or more satellites each with a GNSS-Reflectometry payload able to collect measurements from GNSS signals reflected off the Earth's surface. Comment: Initial deployment will be either one or two satellites, but provision will be made for a larger constellation to provide improved temporal resolution.
MRD-020	Each satellite shall take global measurements of ECV-related parameters that will feed into Earth System Models and potentially operational weather and hydrological forecasts. The HydroGNSS mission targets four ECV-related parameters as Level 2 / Level 3 Products: Surface soil moisture, Surface Inundation, Freeze/Thaw State, and Above Ground Biomass. GCOS has defined spatial and temporal resolution and uncertainty required for measurement of these variables.
MRD-030	Each subsequent satellite added shall improve the temporal resolution of the Level 2 / Level 3 products by increasing measurement coverage and decreasing average re-visit times over the land.

6.2 GEOPHYSICAL (LEVEL 2, 3) REQUIREMENTS

The HydroGNSS parameters are based on GCOS ECV requirements as indicated in Table 6-1.

Table 6-1: GCOS-Defined ECV Requirements [RD-01]

ECV	Units	GCOS Resolution target	GCOS Uncertainty target	Ground Coverage Frequency
Soil Moisture: Surface Soil Moisture	m^3/m^3	1-25 km	0.04 m^3/m^3	Daily
Soil Moisture: Surface Inundation	Flag	1-25 km	90% classification accuracy	Daily
Soil Moisture: Freeze/Thaw	Flag	1-25 km	90% classification accuracy	Daily
Above Ground Biomass	t/ha	500m-1 km (based on 100-200m sat obsvns)	<20% error, or 10 t/ha for <=50 t/ha	Yearly

Frequency: The daily temporal resolution required for updated measurements cannot be met by only one or two HydroGNSS satellites, but measurements that contribute towards the GCOS goal will still be recognised as valuable. The SMOS soil moisture measurements, for example, are highly valued, but the mission only revisits the same location every 3 days. The initial HydroGNSS mission offers an important demonstration, and a future constellation could adopt a daily frequency target.

The measurements are taken over the whole Earth's surface. A special region of interest in these targets is permafrost and biomass over boreal forests, which would dictate a polar or near polar orbit. In this case the coverage will be lower at equatorial and higher at the upper latitudes. Frequency targets can be developed based on the coverage possible from two satellites in a polar orbit, bracketed by latitude.

Soil Moisture Resolution - GNSS-R can offer comparable resolution to the soil moisture ECV resolution targets. Under diffuse scattering conditions, GNSS-R shows a resolution of around 25 km, although under coherent conditions, resolutions of 1 km can potentially be achieved. The standard 1 Hz GNSS-R measurements impose a resolution limit of around 6 km, while the higher rate coherent channel planned for HydroGNSS offers an opportunity to access and explore higher resolution goals.

Biomass Resolution –the AGB ECV resolution requirement of 500m-1 km is not currently believed possible using GNSS-R. The diffuse resolution **25 km** will be adopted as the upper requirement for biomass measurements, but higher resolutions are likely to be achievable. Further improvements to the biomass may be possible using wider bandwidth GNSS signals (Galileo E1, or E5), or through post-processing of complex signals acquired at higher sampling rates. To differentiate from the AGB ECV, HydroGNSS Biomass may be referred to as Above Ground Forest Biomass, and a challenge for this mission will be to investigate how to relate GNSS-R biomass measurements to AGB ECV and its applications.

Biomass Limit – Considering the minimum detectable signal observed by GNSS-R, a target for maximum biomass values that can be sensed is 250-350 ton/ha, with upper limit depending on the forest species. This covers the large majority of the world's forest cover (order of 90%).

Timeliness – For climate and scientific applications, a delay on all data products of 31 days is acceptable as a requirement. For operational use of soil moisture, e.g. for assimilation into NWP, a shorter delay is required (Munoz-Sabater, et al., 2019) and data should be available within 24 hours from measurement and preferably within 6 hours. This is set as a future goal for the HydroGNSS mission. Inundation information may be valuable for flood monitoring on a 6 hour basis, but Freeze Thaw state is unlikely to find applications with a shorter delay than 24 hours. Biomass is primarily targeting forests and hence only needs to be reported once per year or every 6 months, although a faster intermediate product may find new applications, such as observation of forest disturbances due to fires.

6.2.1 Surface Soil Moisture

Reference	Requirement
MRD-040	HydroGNSS shall provide as a Level 2 and/or Level 3 product at each location Surface Soil Moisture to an uncertainty of better than 0.08 m^3/m^3 (requirement), 0.04 m^3/m^3 (goal), and resolution 25 km or better (requirement), 1 km (goal).
MRD-050	HydroGNSS shall provide global maps of Surface Soil Moisture with a temporal update according to the number of HydroGNSS satellites deployed. Note: One HydroGNSS satellite is estimated to cover 80% of the globe every 30 days. Two satellites would cover 80% of the globe every 15 days.

6.2.2 Inundation / Wetlands

Reference	Requirement
MRD-060	HydroGNSS shall provide as a Level 2 and/or Level 3 product a flag at each location indicating whether the land surface is inundated or not, with a classification accuracy of at least 90% and resolution of 25 km or better (requirement), 1 km (goal).
MRD-070	HydroGNSS shall provide global maps of Inundation/Wetlands with a temporal update according to the number of HydroGNSS satellites deployed. Note: One HydroGNSS satellite is estimated to cover 80% of the globe every 30 days. Two satellites would cover 80% of the globe every 15 days.

6.2.3 Freeze/Thaw State

Reference	Requirement
MRD-080	HydroGNSS shall provide as a Level 2 and/or Level 3 product a flag at each location indicating whether the land surface is frozen or not (Freeze/Thaw state), with a classification accuracy of at least 90% and resolution of 25 km or better (requirement), 1 km (goal).
MRD-090	HydroGNSS shall provide global maps of Freeze/Thaw state with a temporal update according to the number of HydroGNSS satellites deployed. Note: One HydroGNSS satellite is estimated to cover 80% of the globe every 30 days. Two satellites would cover 80% of the globe every 15 days.

6.2.4 Above Ground Forest Biomass

Reference	Requirement
MRD-100	HydroGNSS shall provide as a Level 2 and/or Level 3 product at each location Above Ground Forest Biomass to an uncertainty of: 30% (requirement) or 20% (goal), or 10 t/ha for biomass values < 50 t/ha, resolution of 25 km or better (requirement), 1 km (goal). Note: Biomass measurement limit expected at 250-350 t/h
MRD-110	HydroGNSS shall provide global maps of Above Ground Biomass every 6 months.

6.2.5 Secondary Objective Requirements

Reference	Requirement
MRD-120	HydroGNSS as a goal should provide as Level 2 and/or Level 3 products Ocean Wind Speed to an uncertainty of 2 m/s or better at winds up to 20 m/s (compared to retrospective wind models, e.g. ERA-5), and Sea Ice Extent to a classification accuracy of at least 90%. This objective shall not drive the mission design, schedule or costs.
MRD-130	HydroGNSS should provide global maps of Ocean Wind Speed and Sea Ice Extent with a temporal update according to the number of HydroGNSS satellites. This objective shall not drive the mission design, schedule or costs.

6.2.6 Timeliness

Reference	Requirement
MRD-140	HydroGNSS Level 2 and Level 3 products for climate monitoring applications shall be available on the end-user portal within 31 days from measurement (standard delivery). Biomass delivery is only required every 6 months.
MRD-150	For faster operational applications, HydroGNSS as a goal should deliver Level 2 and Level 3 products within 1 week from measurement (fast delivery) for Surface Soil Moisture, Inundation/Wetlands and Freeze/Thaw.

6.2.7 Coverage

It should be noted that the global coverage and the temporal resolution (revisit time) offered by a satellite with GNSS Reflectometry depend on the resolution of the measurements taken. If a resolution of 25 km is assumed, a higher coverage of the globe will be achieved in a defined time period than if the finest measurement resolution of 1 km is achieved. It will take longer to cover the globe when taking measurements at a finer resolution. It is known GNSS-R measurement resolution varies depending on the terrain, which makes setting a coverage target for HydroGNSS a challenge. These coverage targets are therefore defined at a single resolution, to provide a practical coverage metric.

Reference	Requirement
MRD-160	The HydroGNSS orbit(s) shall be selected to address the spatial and temporal coverage and uncertainty of the targets defined in MRD-020 and MRD-030.
MRD-170	One HydroGNSS satellite measurements should cover > 80% land in 30 days, assuming measurement resolution of 25km. Two HydroGNSS satellites measurements should cover >80% land in 15 days, assuming measurement resolution of 25km. (These values exclude latitudes >80deg and assuming a grid cell of 0.25°)
MRD-180	One HydroGNSS satellite should achieve average revisit time of better than 4 days over land, assuming measurement resolution of 25km. Two HydroGNSS satellites should achieve average revisit of better than 3 days over land, assuming measurement resolution of 25km. (These values exclude latitudes >80deg and assuming a grid cell of 0.25°)

6.2.8 Primary Objective Level 2 Product Quality

Reference	Requirement
MRD-210	Level 2 products shall be accompanied by uncertainty parameters and quality flags.
MRD-220	Level 2 products shall be traceable back to Level 1 measurements through documented algorithms and versions.

6.3 LEVEL 1 REQUIREMENTS

The Level 2 ECV-related products will be derived from GNSS-R Level 1 measurements using inversion algorithms based on simulation models. TDS-1, CYGNSS and SMAP spaceborne missions, through extensive demonstration data sets, have proved that GNSS-R signals in the form of incoherently integrated DDM at 1 Hz rate are sensitive to the geophysical parameters linked to the main objective of the mission. The instrument GNSS-R signal link budget at L1/E1 has also been proven to be acceptable in the case of UK-DMC, TDS-1, and CYGNSS. The antenna gain is a trade-off between signal to noise (required for attenuation due to vegetation, and weaker cross-polarised signals) and footprint coverage on the ground (i.e. the number of reflections that can be collected simultaneously). Four DDMs are simultaneously allocated to collect measurements from the reflections of four separate GNSS satellites. Therefore, the baseline Level-1 observations will continue the heritage of these former missions. Level 1 Delay Doppler Maps directly reflect the Level 0B DDMs generated on-board the satellite.

For land applications, it has also been shown that the effects of moisture, roughness and vegetation are entangled, but that each of them is separable from the other two by other mechanisms (coherent integration to attenuate diffuse component, and polarimetry to separate vegetation from roughness effects). Second frequency civil signals are also available from GPS and Galileo satellites (L5/E5) that have wider bandwidth, and could therefore offer higher resolution measurements. Therefore, to allow for more advanced and robust inversion algorithms, the addition of these new capabilities to the HydroGNSS mission is required. These are incorporated in the HydroGNSS Level 1 suite of observables.

The non-coherent Delay Doppler Map nominal settings for an optimised signal to noise are envisaged to be 250 incoherent summation of 4 ms coherent integrations, up to 128 delay pixels, 250 ns per pixel, 20 Doppler pixels, 125 Hz per pixel. Up to 32 bits amplitude per pixel (variable bit-depth without loss of information). A new measurement set is generated once per second.

(Note - this nominal configuration is an alternative to TDS-1 & CYGNSS DDMs which use 1000 summations of 1 ms coherent integrations, with 500 Hz Doppler pixels).

The coherent channel is a subset of the Delay Doppler Map that comprises of one or more pixels centred on the reflection of interest and sampled at a faster rate without incoherent integration. Nominal settings are a coherent integration time 4 ms, with 250 coherent channel values per second per DDM. Complex output of in-phase and quadrature component outputs is anticipated.

Note – as amplitude and phase of complex signals are captured, products using integrated products (e.g. 20 ms) can be constructed from these on the ground to increase processing gain.

Reference	Requirement (Level 1 products)
MRD-230	For each GNSS satellite reflection tracked, Delay Doppler Maps shall be generated on-board the instrument using non-coherent summation of coherent integrations.
MRD-240	A coherent channel shall be allocated to the location of the predicted delay and Doppler of the signal's specular point within the DDM.
MRD-250	Measurements shall be collected simultaneously from either four or five separate GNSS reflected signals which are within the field of view of the antenna. These are selected from both GPS and Galileo constellations according to a figure of merit (e.g. AGSP) to provide the coverage requirements, MRD-160 to MRD-180 inclusive. Note: A trade-off between four or five simultaneous trackable reflections will be assessed to identify the optimal solution that meets the Level 2 / Level 3 product requirements within the constraints of HydroGNSS implementation.
MRD-260	The system shall have the ability to generate 4 different RF signal channels for each Non-coherent DDM and coherent channel: 1. L1 / E1 signals, co-polarised 2. L1 / E1 signals, cross-polarised 3. L5 / E5 signals, co-polarised 4. L5 / E5 signals, cross-polarised Note: The polarisation implementation should provide the best scientific return. The channels listed above are not necessarily to be captured simultaneously for each reflection and selectable configurations will be identified as part of the system and science trade-off's
MRD-270	The DDMs shall be gathered to allow separation of signal from signal-to-noise ratio.
MRD-280	The HydroGNSS Level 1A measurements shall be at least equivalent in performance to SGR-ReSI TDS-1 and CYGNSS DDM measurements, after due consideration of configuration differences.

6.3.1 Level 1 Metadata

The HydroGNSS Metadata is of great importance to the derivation of Level 2 and Level 3 products as they contain radiometric corrections required to adjust for platform and system effects, e.g. Noise and Antenna Gain which are dynamically varied by temperature and satellite attitude.

The instrument provides position, velocity and time from its GNSS function typically to an accuracy of 10 metres, 0.2 m/s. For scatterometric applications, such as HydroGNSS (& TDS-1 & CYGNSS), this is sufficiently accurate. The attitude knowledge (assumed to be provided from on-board AOCS sensors, such as star trackers) and antenna gain characteristics are combined to provide the required antenna gain knowledge.

<table>
<tr><th>Reference</th><th>Requirement (L1A Metadata)</th></tr>
<tr><td>MRD-290</td><td>The Level 1A metadata shall contain all relevant instrument and platform ancillary data and thus is expected to contain:
GNSS receiver reported position, velocity and time
Specular point locations from reported position
Nadir Antenna Gain towards Specular Point (AGSP)
Reflection Incident angle
Zenith antenna gain towards transmit satellite
Correction for any on-board topographic delay offset
Status flags, configuration of measurements, direct cross-over flag</td></tr>
</table>

Level 1B Metadata contains parameters that may have uncertainty in their derivation, and refinements may be developed during the course of the mission to improve Level 2 results. For accurate inversions, the GNSS power density incident on the Earth's surface at the specular point must be estimated accurately, to allow calculation of both reflection coefficient and bistatic scattering coefficient (or sigma-0).

<table>
<tr><th>Reference</th><th>Requirement (L1B Metadata)</th></tr>
<tr><td>MRD-300</td><td>The Level 1B metadata shall contain sufficient information to permit users to calculate reflection coefficient and bi-static scattering coefficient (or sigma-0) from the DDMs and is thus expected to contain:
Instrument gain correction
Measurement of signal to noise ratio of reflected signals
Measured reflected signal power (corrected for noise and gain)
Measured direct signal power (corrected for noise and gain)
Measured cross-polarised signal power (corrected for noise and gain)
Corrected antenna gain zenith towards transmitter
Corrected antenna gain nadir towards specular point (AGSP)
Corrected received zenith GNSS signal
Best estimated EIRP at GNSS transmitter in direction towards specular point
Reflection coefficient at specular point (for land and ice surfaces)
Sigma-0 bistatic normalised radar cross-section at specular point (ocean surfaces)
Coherence coefficient of reflected signal
Include ratio of Right to Left polarisation at specular point
Algorithm version number(s)
Configuration of measurements
Surface flag (land, ocean)
Indications of interference (e.g. Kurtosis flag)
Sea ice detection flag</td></tr>
</table>

6.4 LEVEL 0 REQUIREMENTS

The primary products delivered to end-users are the Level 1 datasets and the Level 2 ECVs. Nevertheless it is also recognised that short captures of the raw sampled data from the on-board instrument RF front-ends, at intermediate frequency (IF) or baseband, prior to processing by instrument, can be valuable for evaluating the instrument performance at the initial in-orbit stages of the mission and to select the optimal instrument configuration for different targets (according to the calibration and validation plan). These datasets, defined as Level 0A collections, provide the opportunity for testing the performance of different hardware configuration and may be of interest for specific research purposes requested by the SAG.

Some potential targets for Level 0A captures are given below:

- Land sites with validation sensing present in-situ, stable conditions;
- Areas with contrasting conditions – dry or wet, frozen or thawed, forested or plain;
- Areas where particularly weak signals are anticipated – E5 collections over vegetation, high biomass zones;
- Areas with short term temporal disturbances – e.g. fire, flooding;
- Areas with long term temporal variation – e.g. deciduous forest changes, freeze /thaw, wetlands cycle;
- Collaboration with other mission measurement campaigns;
- Secondary mission targets – oceans, hurricanes, ice, and snow.

The Level 0A acquisitions will require some metadata in order to allow to identify and process reflections on the ground from the sampled RF signals.

Reference	Requirement (Level 0A datasets)
MRD-510	HydroGNSS shall be able to capture and download the instrument unprocessed digitised RF spectrum within the received bands (L1/E1 and L5/E5), defined as “RAW data”, or “Level 0A”.
MRD-520	The Level 0A data acquisitions shall be recorded simultaneously from the Nadir and Zenith Antennas to allow the identification and ground processing of the reflections.
MRD-530	The Level 0A data acquisitions shall not be part of routine daily operations. Captures shall be scheduled on request up to one per day to allow observation of identified target ECV sites for scientific debugging and development purposes.
MRD-540	The Level 0A capture duration shall be defined such that the GNSS reflections can be extracted via ground processing of the acquired data. Based on previous missions this duration is expected to be 1 minute as a minimum. Note: longer durations can be considered to fully capture a targeted ECV, but higher values might have an impact on routine DDM instrument operations.
MRD-550	The Level 0A metadata shall contain sufficient information to permit users to identify and process reflections from the sampled RF signals, and is thus expected to contain: • Configuration of measurements, including antenna polarisation settings • Capture start time • Spacecraft (instrument antennas) pointing information • Spacecraft orbital elements • Instrument zenith antenna gain pattern • Instrument nadir antenna gain pattern • Instrument front end temperature information • Algorithm version number(s)

MRD-560	Level 0A data shall be treated as "restrained data" in accordance with ESA's policy definitions.

6.5 CALIBRATION REQUIREMENTS

The calibration activities build upon experience gained from using the SGR-ReSI on TDS-1 and from the NASA CYGNSS mission. The primary measurement over the ocean is either the cross-sectional area (sigma-0) from the backscatter radar equation, corrected for scattering area, or alternatively over land, the reflection coefficient is used. Both parameters are dependent on accurately determining the ratio of reflected power to the incident power on the surface. The primary calibration activities are to ensure that these two powers (incident and reflected) are determined as accurately as possible based on measurements taken by the instruments on the satellites and additional information available elsewhere.

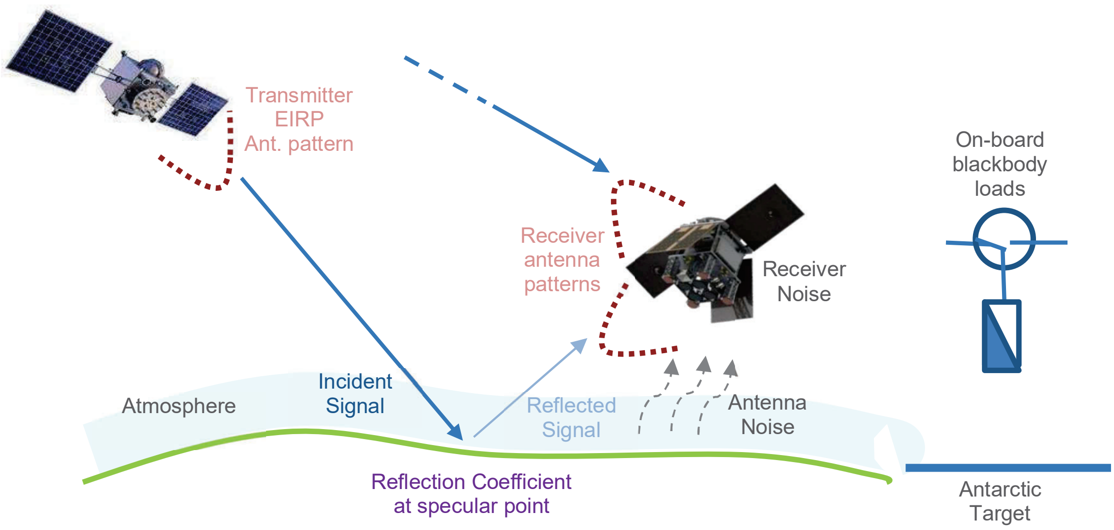

Figure 6-1. Factors Affecting Measurement of Reflection Coefficient at Specular Point

Figure 6-1 shows a schematic of the measurement of Reflection Coefficient, and some of the dominant terms that need to be considered.

Receiver Reflection Measurement: The instrument must be able to stably measure the reflected GNSS signal power. This weak reflected signal is embedded within the system noise (which comprises of antenna plus receiver noise), and can only be detected above the noise floor after correlation with an internally generated version of the expected code. Parameters within the receiver that affect the measurement include temperature and thermal noise, quantisation noise, self-interference (if any), and the signal processing scheme employed (e.g. ZTC per pixel of DDM).

Fixed Gain and Calibration Loads: Most GNSS receivers use an automatic gain control (AGC) which adjusts gain to match the incoming antenna noise, so it is not possible to directly measure absolute signal level, only to measure the signal to noise ratio (SNR). The advantage of SNR as an observable is that any varying gain of the instrument will largely cancel out. It was discovered however that the received antenna noise varies significantly over the globe making it a poor reference for signal measurements. Instead the gain of the receiver is deliberately fixed, and any variation in gain is quantified by regularly switching in a load at a known temperature (blackbody load). The Noise Figure of the LNA, the dominant source of receiver noise and contributor to gain, is also characterised with temperature. This allows the derivation of the absolute antenna noise power, and from that, the received signal power can be recovered from the measurement.

External Reference: Measurements over the Antarctic were found where the antenna noise on TDS-1 were sufficiently stable that they could be used as a reference point for correcting the gain of the system. The Antarctic can be used as an alternative / cross-check method for assessing the blackbody corrections.

Antenna Pattern and Attitude: The gain of the nadir antenna has a significant effect on signal received – there must be some gain towards the specular point otherwise no reflected signal will be seen. The Antenna Gain at Specular Point (AGSP) must be calculated to adjust the received signal power. This requires a good knowledge of the antenna pattern on the satellite, and it also required a good knowledge of the satellite attitude, as uncertainty will translate into an error in the AGSP. Similarly the zenith antenna pattern knowledge will be important for direct signal measurement.

Incident Signal Power: To calculate the incident signal power, the transmit power of the GNSS satellite must be known. As calibration on CYGNSS and TDS-1 missions improved, the uncertainty of the GNSS transmit power soon became one of the dominant if not the most dominant error term, and is also likely to be the largest uncertainty for HydroGNSS. It was discovered that each GNSS satellite may transmit at a slightly different power and that the power may vary over time. This transmit power per satellite can either be modelled, based on measurements that have occurred in the past (e.g. through collection of many direct or ocean reflected measurements), or another method is to directly use the receiver's zenith (or direct) channel to measure the instantaneous received GNSS power, and use that to correct the received signal for variations. This zenith measurement carries unknowns as it is also dependent on the receiver's system noise (antenna noise, LNA noise figure, temperature, antenna pattern and attitude) on zenith channel, and must be corrected for the different angle and path of the incident reflected signal that passes through the atmosphere, but it is available immediately.

Modelling Transmit Powers: Some of the latest work on modelling GNSS transmit powers is given in MCDJD Justification File [RD-05] Section 4.4.

Geometric Parameters: Geometric accuracy is a function of the position of the transmitter, the receiver and the location of the specular point. The receiver itself accurately determines the GNSS satellites' positions, and its own position, velocity and time as part of the GNSS solution, but it makes a simplified on-board estimate of the specular point location in order to position the Delay Doppler Map over the reflected signal. If the reflection is placed in the wrong location within the DDM, this can cause minor distortions in the power measurement. The height of the signal within the DDM is affected by the elevation of the specular point; there was no correction for this in the SGR-ReSI used on TDS-1 and CYGNSS, but there will be a topographic correction on-board the HydroGNSS instrument. Over the ocean, it may be beneficial to correct using the geoid or sea-height model. Higher resolution corrections to the geometry can be made on the ground and, though not essential for most GNSS-R applications, the satellite's orbit can be improved using Precise Orbit Determination.

Flag Parameters: Other parameters that affect the quality of measurements supplied to users include flags (direct code cross-overs, anomaly detection, coastal proximity, interference detection, ice detection).

New Observables: New observables for HydroGNSS include Galileo DDMs, coherent channels, cross polarisation measurements. These will all require approaches developed to characterise, determine and apply corrections.

The different stages of the mission are shown in Figure 6-2, and how they interact with the end-to-end simulator, Data levels, and correction / processing data-bases. Three levels of correction databases are anticipated – those for Level 1A data (instrument related), those for Level1B data (derived corrections), and those for the Level 2 / Level 3 algorithms (potentially large geographic look-up databases depending on parameters).

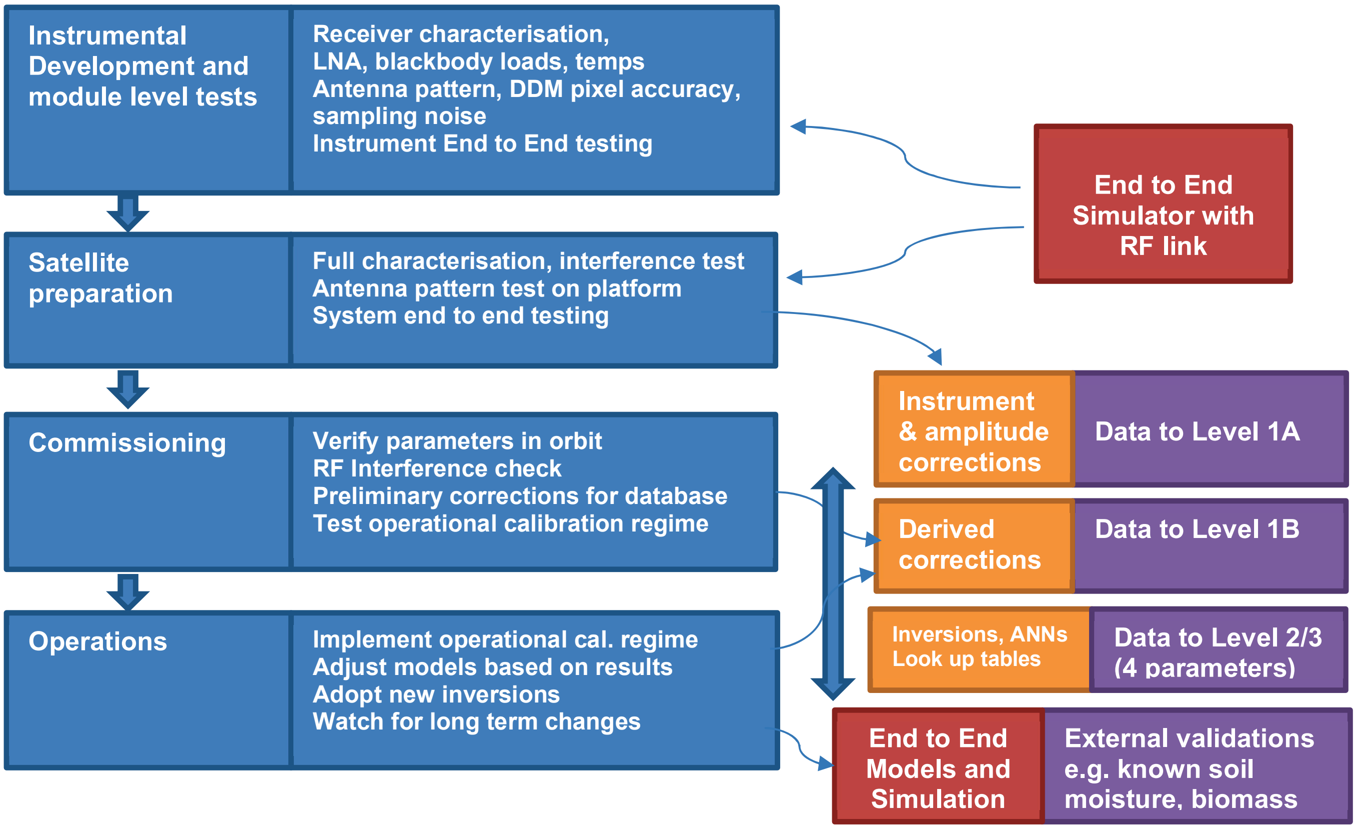

Figure 6-2. Stages in Mission and Calibration Interactions (Orange boxes show calibration databases)

Reference	Requirement
MRD-310	An error budget shall be developed with the support of an End to End simulator, incorporating estimates for contributors towards uncertainties in parameters that affect the ECV-related products.
MRD-320	There shall be a method for measuring the Instrument Noise and Gain dominant contributors, in order to allow recovery of the received signal power at the instrument antennas.
MRD-330	The Low Noise Amplifier (LNA) characteristics over temperature and over the measurement frequency range shall be available.
MRD-340	The nadir antenna gain knowledge shall be determinable in the direction of a reflection to sufficient accuracy to fit within the error budget (defined in MRD-310) for the antenna gain knowledge for AGSP, at least in E1/L1 band. The antenna shall also be characterised in both polarisations and both frequency bands as applicable.
MRD-350	The zenith antenna gain knowledge shall be determinable in the direction of the GNSS direct transmitted signal to sufficient accuracy to fit within the error budget defined in MRD-310, at least in E1/L1 band. The antenna shall also be characterised in both polarisations and both frequency bands as applicable.

7 USER SERVICE REQUIREMENTS

Payload data received from the satellites will be processed by the Payload Data Ground Segment (PDGS). Level 1B data will be derived from Level 0B Delay Doppler Maps collected on-board the satellite.

Normally Level 2 and 3 products are directly derived from Level 1 products using established L2 Operational Processors. On occasion, a new L1OP or L2OP will mean that a new version of Level 2 / 3 products will be re-processed from historical Level 1 data. New processing versions will add tags to the data for traceability.

Reference	Requirement
MRD-360	Level 1A, Level 1B, Level 2, Level 3 product format shall be NetCDF.
MRD-370	Updated Level 2 / Level 3 products using processors refined during the mission lifetime shall be anticipated, requiring reprocessing of back catalogue.
MRD-380	Level 1B, Level 2 and Level 3 data shall be released to users via a portal on a full “free and open” basis in accordance with ESA’s policy.
MRD-390	Discounting planned outages, e.g. for SAG-approved experimentation, instrument upgrades, and planned maintenance (including orbit maintenance) the service availability shall be higher than 90%.

8 VALIDATION AND MISSION SUCCESS CRITERIA

Preliminary validation of the ECV-related parameters will take place early in the mission during commissioning phase. Level 2 HydroGNSS products will be gathered and verified against independent measurements from in situ, other satellite, and / or modelled sources. Mission success is measured against scientific readiness levels defined in [AD-03], i.e SRL-7 after commissioning, and achievement of SRL-8 by the end of the mission duration.

Soil moisture and biomass datasets derived from in-situ measurements, models and climatology are available at a global scale and they can be used as reference data for calibrating and validating the algorithms for retrieving the ECVs from the HydroGNSS acquisitions. The International soil moisture network (ISMN - Dorigo et al. 2011) is an international cooperation supported by the Earth Observation Programme of the European Space Agency (ESA), aimed at establishing and maintaining a global database of in-situ soil moisture measurements. It comes from a combined effort of the Global Energy and Water Exchanges Project (GEWEX), the Committee on Earth Observation Satellites (CEOS), the Global Climate Observing System - Terrestrial Observation Panel for Climate (GCOS-TOPC), the Group of Earth Observation (GEO), and the Global Terrestrial Network on Hydrology (GTN-H). ISMN collects and organizes in situ measurements coming from the most part of soil moisture measuring stations all around the word. Despite some inhomogeneities in reliability and maintenance, it has been and is currently used as the primary source of reference data for the cal/val of EO SM products, such as the SMOS and SMAP SM products. SMOS and SMAP products are good candidates for Level 2 product validation campaigns, as used to generate and validate the SM products from CYGNSS, though there is a risk associated with SMAP or its concurrent SMOS data availability if they were to cease operations in the near future.

The HydroGNSS Freeze / Thaw state can be validated against the ISMN database, and Freeze Thaw state is captured in SMOS and SMAP measurements, and the site of Sodankylä in Finland is a test site for SMOS, used during the HydroGNSS consolidation study may also be used for validation.

The Yucatan lake in Louisiana, USA is a suitable target for validation over wetlands, as it is used as a test site for NISAR. Another potential site is the Can Gio mangrove wetland reserve in Vietnam that has been used as a target for densely forested wetland sensing experimentation in comparison with CYGNSS measurements.

Direct measurements of biomass variables are limited to certain test areas around the world and other datasets mainly come from Earth Observations combined with models. A significant part of the data available is historical and time invariant, and may not capture the forest dynamics, for example preparatory P-Band and L-Band polarimetric airborne SAR activities of the BIOMASS P-Band SAR mission (AfriSAR, AfriScat, TROPISAR, TROPIScat, BioSAR). Other biomass datasets are derived from conventional ground-based and LIDAR techniques.

The in-situ SM networks belonging to ISMN and other soil moisture networks that provide also soil temperature measurements in boreal areas can be used within this scope, as for SMAP and SMOS cal/val activities, for example cite the Alaska stations belonging to SNOTEL and SCAN networks, the Kenaston and BERMS networks managed by ECC Canada, the Sodankylä network (Ikonen et al. 2016) and the Cherskii, Samoylova and Tiksi stations in Siberia.

Reference	Requirement
MRD-410	All primary ECV-related parameters shall achieve preliminary validation by IOCR to achieve SRL 7.
MRD-420	New EO techniques shall be demonstrated in orbit as preliminary Level 1B products by IOCR: • GPS and Galileo DDMs at L1/E1 • Coherent complex channel • Dual-polarised DDM collection • GPS and Galileo DDMs at L5/E5
MRD-430	The HydroGNSS Level 2 / Level 3 Surface Soil Moisture products will be validated against in situ (e.g. ISMN) and/or other Earth Observation sources (SMOS/SMAP/ASCAT) – uncertainty and resolution shall be assessed.

MRD-440	The HydroGNSS Level 2 / Level 3 Inundation/Wetlands products will be validated against known permanent water bodies, and against Copernicus Emergency Management Service flood monitoring products. Uncertainty and resolution shall be assessed.
MRD-450	The HydroGNSS Level 2 / Level 3 Freeze/Thaw products will be validated against in orbit (SMOS, SMAP), in situ (e.g. ISMN) and/or model sources (GEOS-5, ERA-5). Uncertainty and resolution shall be assessed.
MRD-460	The HydroGNSS Level 2 / Level 3 Above Ground Biomass products will be validated against in situ (e.g. Biomass Cal/Val sites) and/or Earth Observation sources (Biomass product). Uncertainty and resolution shall be assessed.
MRD-470	Secondary objective: The Level 2 / Level 3 HydroGNSS ocean Wind Speed and Ice Extent products will be validated against models (e.g. ERA-5, NSIDC) and/or Earth Observation sources (e.g. ASCAT). Uncertainty and resolution will be assessed. This objective shall not drive mission implementation.

These requirements are an indication of the steps to achieve a preliminary validation. It is anticipated that following the IOCR further more extensive validation activities will be undertaken under the supervision of the Science Advisory Group during the mission's operational phase as new signals types are made available to the research community.