HydroGNSS – DEMONSTRATING HOW SMALL SATELLITES CAN HELP TRACK CLIMATE VARIABLES

Serena Donati[(1)], Martin Unwin[(1)], Pete Garner[(1)], Reynolt De Vos van Steenwijk[(1)], Jonathan Rawlinson[(1)], Andy Palfreyman[(1)], Nazzareno Pierdicca[(2)], Estel Cardellach[(3)], Kimmo Rautiainen[(4)], Leila Guerreiro[(5)], Emanuele Santi[(6)], Giuseppe Foti[(7)], Paul Blunt[(8)], Jean-Pascal Lejault[(9)], Massimiliano Pastena[(10)], Maria Paola Clarizia[(10)].

[(1)] *Surrey Satellite Technology Limited, Tycho House 20 Stephenson Road Surrey Research Park Guildford GU2 7YE UK, Corresponding author: apalfreyman@sstl.co.uk*

[(2)] *Sapienza University of Rome,* IT

[(3)] *Institut d'Estudis Espacials de Catalunya - IEEC,* ES *and Institute of Space Sciences (ICE-CSIC), ES*

[(4)] *Finnish Meteorological Institute, FMI,* IT

[(5)] *Università di Roma Tor Vergata*, IT

[(6)] *Institute of Applied Physics, National Research Council – IFAC CNR,* IT

[(7)] *National Oceanographic Centre,* UK

[(8)] *University of Nottingham, United Kingdom;*

[(9)] *ESA - European Space Agency, The Netherlands,*

[(10)] *ESA - European Space Agency, The Netherlands,*

1 ABSTRACT

HydroGNSS is a small satellite mission under the ESA Scout programme as an element in ESA's FutureEO programme. Using novel GNSS Reflectometry techniques, HydroGNSS will collect several parameters related to the Essential Climate Variables (ECVs): soil moisture, inundation, freeze/thaw, biomass, ocean wind speed and sea ice extent.

Compared to previous GNSS reflectometry missions, HydroGNSS is unique in that it will have new capabilities and features, enabling high coverage and resolution collecting multiple GPS and Galileo reflections simultaneously dual polarisation, dual frequencies(L1/E1 and L5/E5), and collecting, complex (amplitude and phase) 'coherent channel' of the same reflected signals. These will be used to contribute towards the operational recovery of the climate related variables.

HydroGNSS will complement other sensing soil moisture and forest biomass missions such as ESA's SMOS and Biomass, Copernicus Sentinel-1 and NASA's SMAP. The technique of GNSS-Reflectometry will be explored while laying the foundations for a future constellation offering high spatial-temporal resolution observations of the Earth's weather and climate.

This uses GNSS signals of opportunity as sources for bistatic radar; these signals are plentiful and well understood, empower small satellites to punch above their weight and take measurement quality associated with satellites in a larger size and cost category

2 INTRODUCTION

2.1 HydroGNSS ESA Scout Mission

HydroGNSS is the first contracted small satellite mission under the Scout programme as an element in ESA's FutureEO programme, due for launch in 2024. ESA's Scout missions consist of one or several small satellites for rapid prototyping and demonstration of novel Earth observation techniques for Earth science and related non-commercial applications. Scouts demonstrate disruptive sensing

techniques or incremental science, while retaining the potential to be subsequently scaled up in larger missions or implemented in future ESA Earth Observation programmes.
The original submission assumed two HydroGNSS satellites within the required budget of <€30 million. The initial Scout funding is for a single HydroGNSS satellite with the system designed to support a constellation of HydroGNSS satellites.
HydroGNSS uses novel dual frequency, dual polarisation L-Band GNSS Reflectometry to target four hydrological Essential Climate Variables (ECVs) namely: soil moisture, wetlands / inundation, freeze / thaw state and above ground biomass (see Figure 1).

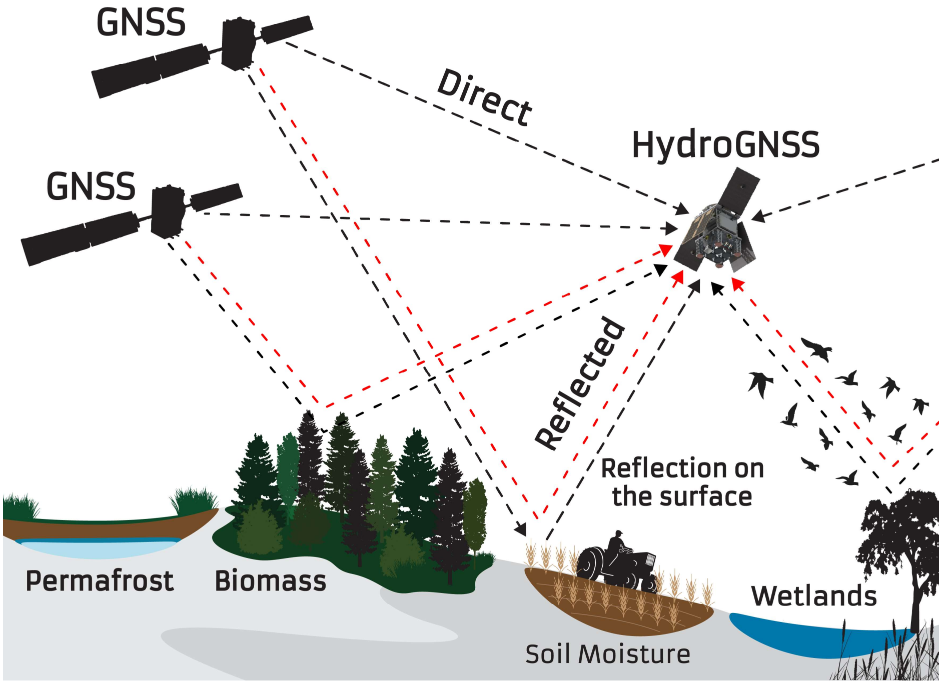

Figure 1 HydroGNSS uses a bistatic radar concept using GNSS reflected signals for hydrological measurements, targeting soil moisture, freeze / thaw state over permafrost, above ground biomass, soil moisture and wetlands.

The satellite is designed to support an on orbit operational life time of 4.5 years. While continuing to explore the technique of GNSS-Reflectometry the mission will lay the foundations for a future constellation offering high spatial-temporal resolution observations of the Earth's weather and climate.
HydroGNSS will complement other missions sensing soil moisture and forest biomass such as ESA's SMOS and Biomass, Copernicus Sentinel-1 and NASA's SMAP missions.
The project also supports the UK National Space Strategy [1] Goal 5 by using space to tackle the global challenge of climate change.

2.2 Importance of Hydrological Knowledge and the HydroGNSS Mission Objectives

The World Meteorological Organisation states: "*Global hydrological conditions of floods and droughts as well as potential conflicts in water use are some of the greatest challenges and threats facing the world's population. Some 20 million people are at risk from flooding with the associated damage costing nearly US$80 billion; this could rise to 50 million people affected in just 15 years time, according to the World Resources Institute.*" [2]. Furthermore, water is a natural resource vital to climate, weather, and life on Earth, and unforeseen global variability in hydrology poses one of the greatest threats to the world's population [3].
Water manifests itself in or on the land in different ways, for example, moisture in the ground, wetlands and rivers, snow and ice, and vegetation. Global knowledge of land water content and state importance in its different forms define the HydroGNSS primary mission objectives to measure, using reflected GNSS Signals:

- **Soil Moisture**– 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. This knowledge is needed for weather forecasting, hydrology, agricultural analysis, and wide scale flood prediction.
- **Inundation / Wetlands**– including use of the coherent channel to achieve higher resolution. Better vegetation penetration and higher resolution may be possible using second frequency reflections. This knowledge is important as the fragile water-dependent ecosystems in wetlands, often hidden under forest canopies, can also turn into sources of methane, whilst elsewhere an over-supply of water can lead to inundation and destructive flooding.
- **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 coherent channel. The freeze / thaw state affects the surface radiation balance and the exchange rates of latent heat and carbon with the atmospheric boundary layer, and acts as a tracer for sub-surface permafrost behaviour in high latitudes.
- Forest Above Ground **Biomass**– using attenuation of signals in combination with knowledge of underlying surface and soil moisture characteristics. This knowledge feeds into the understanding of carbon stock in forests and a sink in the carbon dioxide cycle, and also has a coupling to biodiversity.

Secondary Mission Objectives (these do not drive instrument, mission development and operations):

- To measure **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, and inland water bodies).

The four aspects of hydrology: soil moisture, inundation / wetlands, soil freeze / thaw and above ground biomass, are four aspects of the hydrology ECVs, as identified by the Global Climate Observing System, GCOS [4]. ECVs are defined in association with the United Nations Framework Convention on Climate Change (UNFCC), the Intergovernmental Panel on Climate Change (IPCC) and the World Meteorological Organization (WMO) in order to help understand and predict climate change, to guide mitigation measures, and to assess risks. Specific committees and programmes address the need for measurements of soil moisture (including freeze / thaw and inundation states), permafrost and biomass, while wetlands are among the targets of the Climate Change Initiative (CCI) Land Cover, and play a role as a primary source for greenhouse gases. Increasingly complex and accurate models are used to characterise and forecast hydrological processes: Earth System Models (ESMs) are used for climate, and Numerical Weather Prediction (NWP) models for weather forecasting. These models have a requirement for hydrological observational data to be assimilated to ensure correspondence with the complexity of the real world.

These measurements can also assist with the UK Net Zero Strategy [5] by monitoring Biomass, flooding and providing farmers with information about soil moisture.

2.3 Uniqueness and Complementarity

HydroGNSS fits well into the context of current and future institutional EO missions and addresses shortcomings and demonstrates how small rapid satellites can assist in adding valuable measurements to track climate variables.

As illustrated in Figure 2, HydroGNSS offers to augment current capabilities through additional density of measurements, adding new synergic ECV observations that extend from current sensing techniques, offering timely continuity over a potential gap in L-band missions, reaching geographic areas not covered by Biomass, and demonstrates a low-cost small satellite approach that is sustainable for the future.

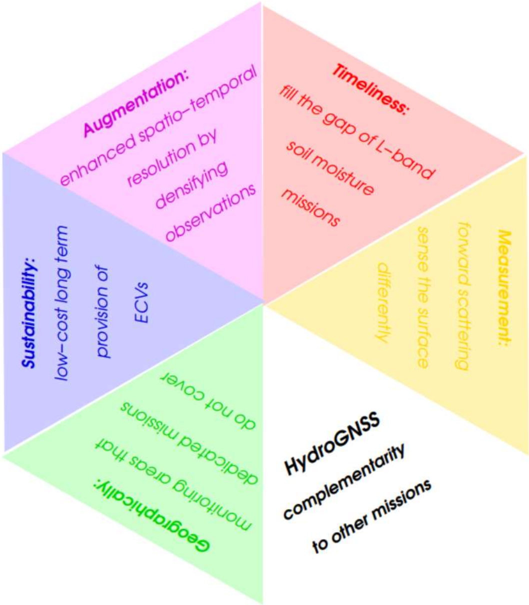

Figure 2 Uniqueness and complementary of ESA Scout HydroGNSS

SMOS [6] and SMAP [7,8] 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.

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).

Six small HydroGNSS satellites would be expected 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. Using techniques compatible with small satellites, HydroGNSS offers medium to high resolution proving the value of small satellites.

3 THE ESA SCOUT HYDROGNSS MISSION

The mission architecture comprises the satellite payload, satellite platform, control and downlink ground segment, and the payload data ground segment (including Level 2 processors and data dissemination).

3.1 The HydroGNSS Satellite

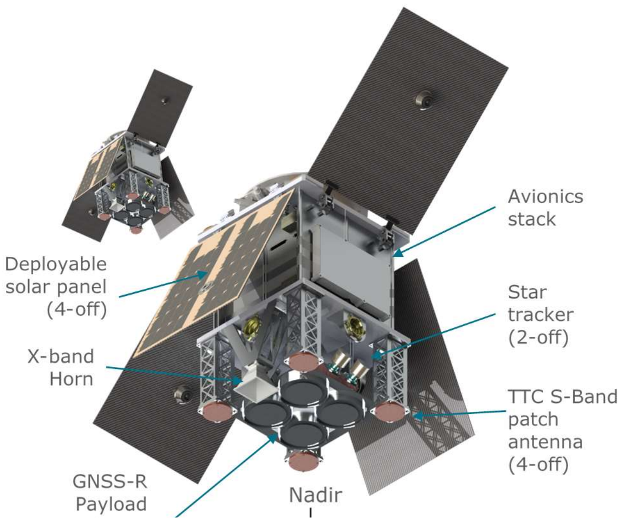

Figure 3 Two HydroGNSS satellites, showing in orbit configuration with deployed solar panels. The GNSS-R nadir antenna is visible, comprising of four patch excited cup antennas capable of dual frequency and dual polarization.

The platform that has been selected for HydroGNSS is the ‘SSTL-21’, which is the smallest family member of the ‘SSTL-Micro’ platform. This is a highly capable platform, but small enough to maintain the low cost of a future constellation, see Figure 3.

To best support the mission aims and objectives, over geographically diverse targets the platform is chosen to offer the HydroGNSS mission 100% duty cycle to allow payload operation continuously. The satellite also supports a large data store and a high data throughput to support the data volumes generated with these 24/7 payload operation.

The satellite has precise attitude knowledge supported by the inclusion of star cameras, these support identification of the reflected

signal RX antenna pierce angle and thus antenna gain witnessed.
The SSTL-Micro platform, incorporates many features advantageous to a GNSS reflectometry mission. The ESA Scout HydroGNSS platform offers:

- **Dual redundant** SSTL Core avionics to support mission lifetime availability and reliability
- Mission **configurability** → software can be updated in-orbit, including on the Science Payload
- Deployable solar arrays → flexibility to support **100% Science Payload duty cycle** at different orbit LTAN
- An efficient battery regulated power bus running at 12V, suitable for a small satellite
- High rate Science Payload data **downlink @ 200 Mbps**
- On-board payload data **storage of up to 500 GBytes**
- **Xenon propulsion system** to support constellation phasing, altitude correction and collision avoidance firings
- 3-axis stabilised AOCS subsystem
    - Capability to **slew to a specific target of interest**
    - Capability to dynamically track the Ground Station during downlinks
- 45 cm x 45 cm x 70 cm in size, and a mass of approximately 65kg.

In these ways, and others, the small satellite platform will serve to provide high quality science data.

3.2 Orbit and Launch

The ESA Scout HydroGNSS selected orbit is currently a sun-synchronous orbit with a nominal altitude of 550 km and10:30 LTAN.

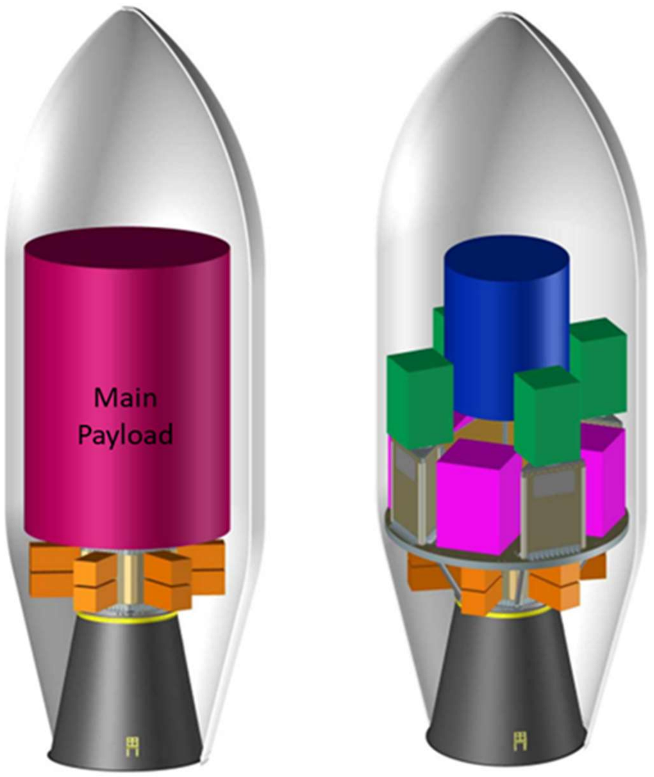

Figure 4 Supported possible Piggyback configuration and Rideshare configuration

This orbit has been selected to ensure a timely, and good value launch. The GNSS-R payload operates night and day, and is not bound to a particular hour angle or ground repeat track, so it could be put into a number of similar near-polar orbits.
The Arianespace Vega-C SSMS is selected for HydroGNSS launch but the HydroGNSS satellite is compatible with several other launcher options should an alternative launch need to be considered. The HydroGNSS satellite is flexible in supporting both "Piggyback" and "Rideshare" launch configurations as shown in Figure 4.
The chosen Arianespace launcher would give a good opportunity to launch a multiple HydroGNSS satellites, should this be required, leveraging the advantage of small satellites with increased coverage and resilience of supply through constellations.

3.3 Science Instrument

Global Navigation Satellite Systems (GNSS), such as GPS and Galileo, comprise of dozens of satellites in Medium Earth orbit which continually transmit low power L-Band microwave navigation

signals towards the Earth. These signals reflect back, carrying the geophysical imprint of the surface. GNSS Reflectometry (GNSS-R) is a technique to collect these reflections, in this case from low Earth orbit (LEO) in order to sense geophysical properties of the Earth's surface [9]. These transmitted signals form the transmit signals in the bistatic radar that the science instrument employs.
This use of signals of opportunity for the bistatic radar empower small satellites to punch above their weight and take measurement quality associated with satellites above their size category.

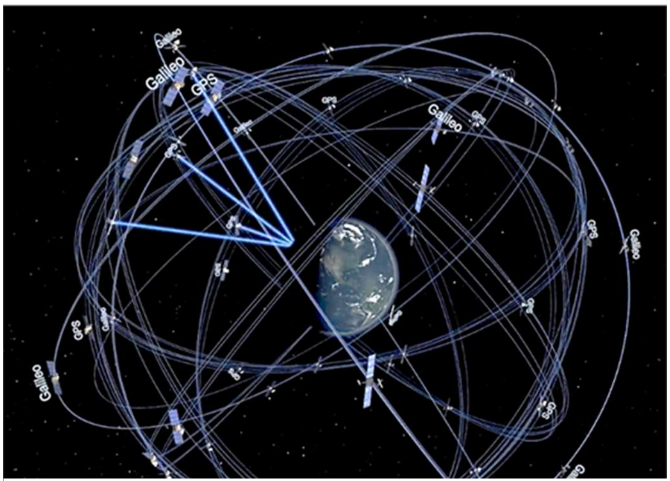

Figure 5 GPS and Galileo satellites in Medium Earth Orbit, amongst others, are available as signal sources for GNSS Reflectometry, and reflections are collected by a satellite in Low Earth Orbit [24].

Multiple reflections can be simultaneously collected by a single observatory in LEO. GPS and Galileo constellations alone offer more than 60 sources of L-band signals (see Figure 5).The observations made are of forward scattered reflections i.e. implementing a bistatic radar geometry. The observations are usually captured in the form of Delay Doppler Maps (DDMs), where incoming signals are correlated with the on-board code replicas and integrated incoherently. The HydroGNSS instrument can give measurements from four simultaneous specular point reflections (see Figure 6).

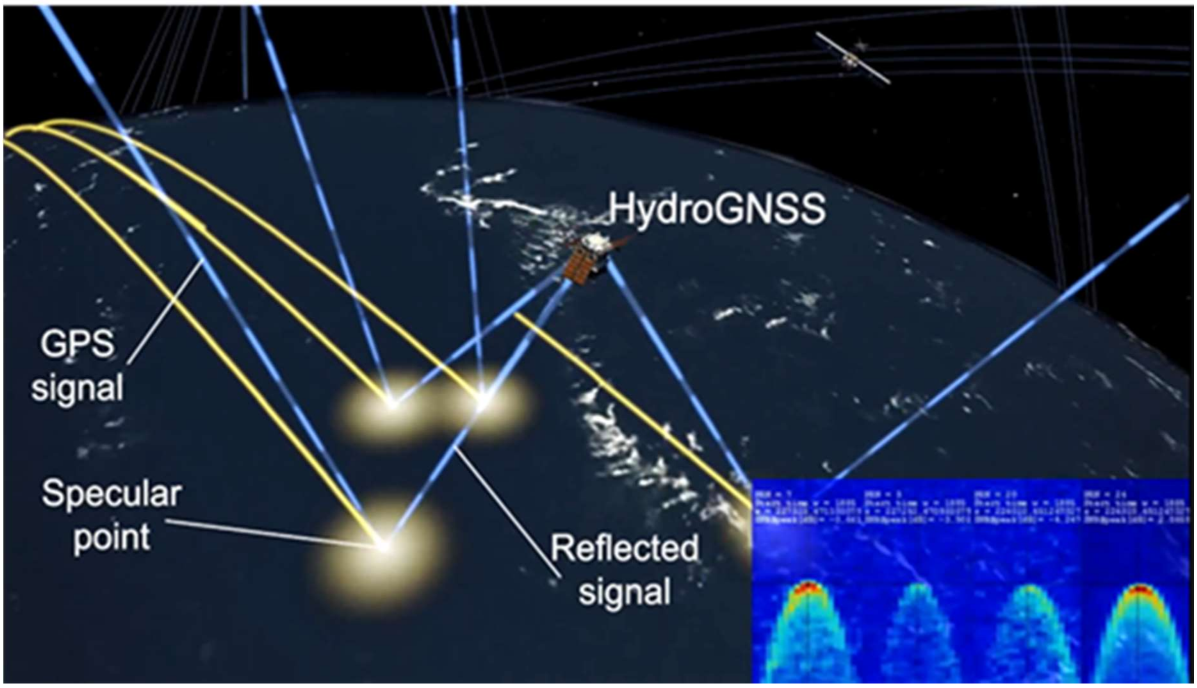

Figure 6 Each HydroGNSS satellite collects multiple reflections from Low Earth Orbit. Yellow lines indicate accumulated reflection tracks and results are represented as Delay Doppler Maps (DDMs) in bottom right of picture [24].

The science instrument on-board the HydroGNSS spacecraft is a development of that flown on the UKSA TechDemoSat-1 and NASA CYGNSS missions. Compared to previous GNSS reflectometry missions, HydroGNSS is unique in that it will have new capabilities and features providing a total of 8 reflection measurements for a single GNSS spectral point, contrasted to the one on previous missions. With dual polarisation, coherent channels and dual-frequency, enabling high coverage and resolution by allowing for additional types of reflectometry measurements, see Figure 7, ultimately aimed at addressing the required ECV parameter aims of the mission. These new features will also benefit the broad range of secondary products. For example, the coherent channel might enable precise sea ice, inland water bodies and calm coastal waters altimetry [10-13].

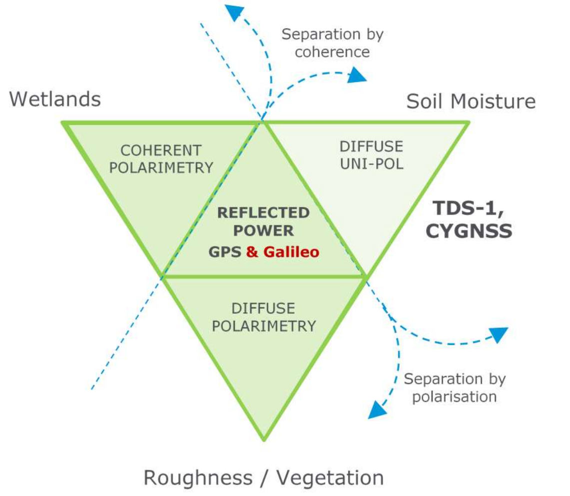

Figure 7 New Measurements on HydroGNSS compared to TDS-1 and CYGNSS. Top right of triangle shows extent of measurement from TDS-1 and CYGNSS, restricted to diffuse, unipolar measurements from GPS. Top left and bottom triangles are added with coherent channel, polarimetric and Galileo measurements

As shown in Figure 8, the instrument nadir facet antenna uses 2 x 2 array of metal patches to implement an optimised dual frequency (L1/E1 and L5/E5) / dual polarisation receive antenna to facilitate these novel measurements.

The instrument is then able to collect multiple GPS and Galileo reflections simultaneously at dual polarisation and at dual frequencies, using this antenna. This antenna gives a gain of around 14 dBi at L1/E1, with a good cross-polar performance at both frequencies, and takes a physical area of about 32 cm x 32 cm on the spacecraft. The antenna is thus suited to both GNSS reflectometry, by providing a gain sufficient to target weak reflections, and being used on a small spacecraft.

The low noise amplifier uses a similar approach to those on CYGNSS including a cavity filter, temperature sensor, load switch and test ports. The load switches give access to black body loads that give reference noise measurements.

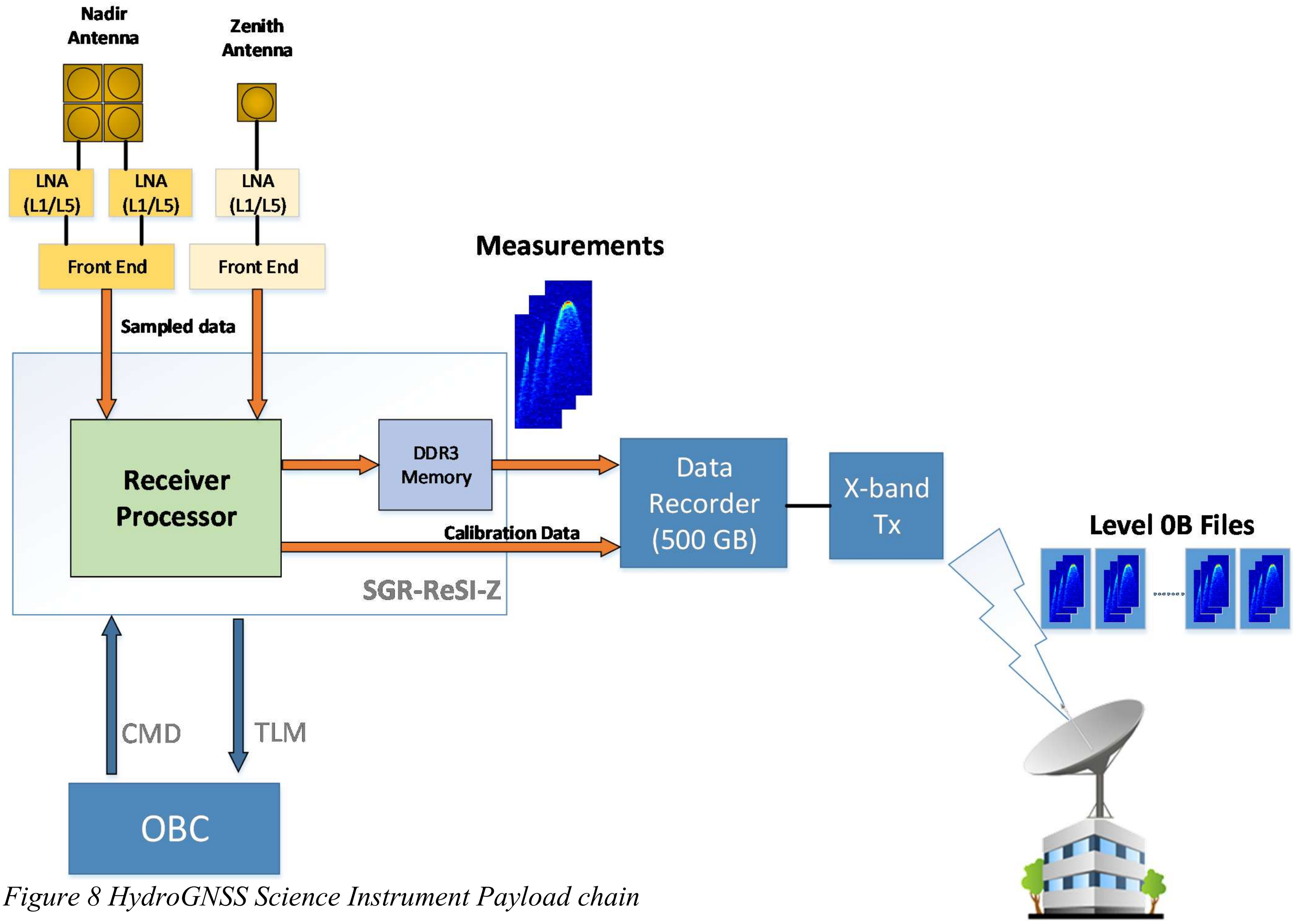

Figure 8 HydroGNSS Science Instrument Payload chain

The central science instrument unit, SGR-ReSI-Z, is a Delay Doppler Mapping Receiver tracking the direct GNSS signals through the Zenith Antenna and processing the reflected signals for the Nadir Antenna into Delay Doppler Maps.
The Science Instrument signal processor uses open loop predictions to target position of the reflections at each specular point and collect measurements in the form of Delay Doppler Maps (DDMs). HydroGNSS will use a Digital Elevation Model to target the position of the specular point position over land [14]. This DEM is essential for successfully tracking the specular point of a reflection as it travels over the land whose altitude varies for a simpler global model.
This Digital Elevation Model has been designed with two aims to enable small satellite operation:

- Algorithms designed to be implemented on resources available on a small satellite.
- Increase reflection prediction accuracy to reduce required DDM size to capture the specular point an thus reduce the data downlink requirements

The Science Payload can be run in two main data acquisition modes:
Normal operations for routine (DDM) Capture Mode:

- The receiver computes a real-time geometrical tracking to centre the measurements on the reflection, an on-board DEM is used for this purpose.
- There is an allocation algorithm that selects the best reflections to track.
- The inphase and quadrature (I/Q) components of the peak signal are stored at high sampling rate (baseline sampling 250 Hz), the so called 'coherent channel'.
- The full complex DDMs are further integrated incoherently to generate the power DDM measurements (baseline integration 1 second).
- These measurements are stored on-board and downloaded in file to the Ground Station.

Raw Data Sampling Mode (in addition to the normal operations tasks):

- Data is captured in raw sampling mode for dedicated debugging operations.
- Short raw captures can be used for calibration campaigns, especially during Commissioning before the start of service.
- Data rates are 100 times higher in this mode, so only targeted short capture durations can be supported in this mode.

Once collected, the Level 0A (Raw Data) and Level 0B (DDMs and coherent channel) data are sent to the onboard data recorder in the satellite platform for later download. This large capacity data storage and high rate X-band downlink allow acquisition the Delay Doppler Maps and simultaneously that of targeted raw sampled captures for scientific development activities.

3.4 HydroGNSS Mission Architecture

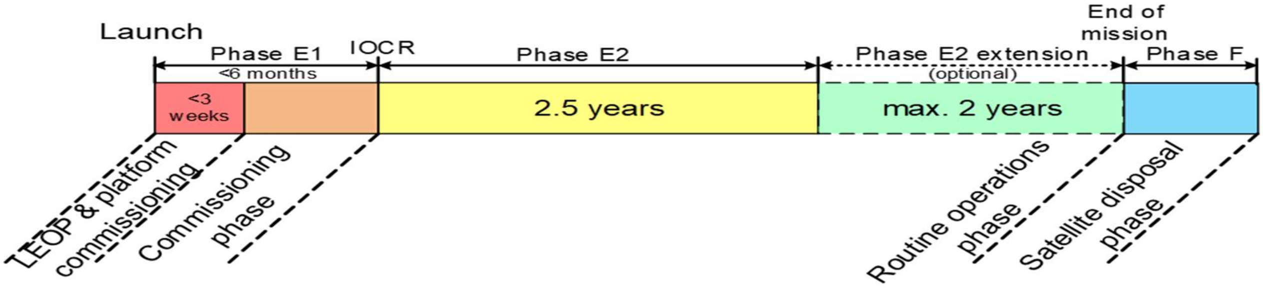

Figure 9 HydroGNSS satellite timeline

A HydroGNSS satellite timeline is shown in Figure 9. After launch, the satellite(s) will be commissioned using the Guildford ground station and any required orbit manoeuvres such as orbit phasing or altitude correction and any resultant from tip-off from the launch vehicle undertaken.

Following platform and payload commissioning, the payloads will be operated continuously for the 2.5 year lifetime with the potential of a 2 year life extension. At the end of the mission will fulfil the Agency's Space Debris Mitigation Policy by allowing the satellites to de-orbit.
The short flexible on orbit lifetime allows for an optimised small satellite to rapidly fulfil scientific aims.

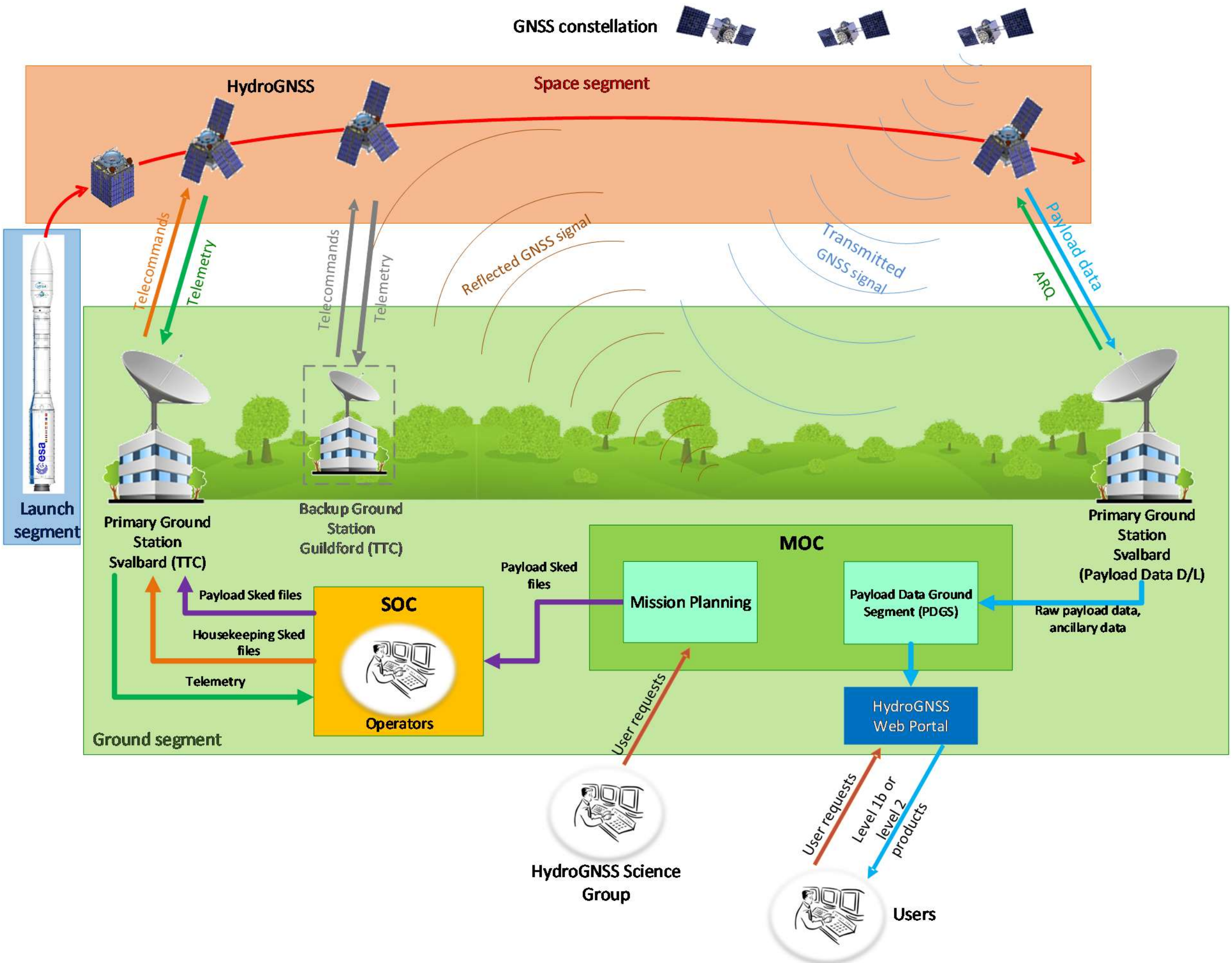

Figure 10 Mission architecture and operations overview for HydroGNSS, including launch, telemetry and telecommand via Guildford, operational reflectometry collection, and data download via ground station at Svalbard, data processing and delivery of Level 1 and 2,

The ground segment makes use of the KSATlite Ground Station in Svalbard for both telemetry, telecommand and control link as well as payload downlink, where the high latitude frequent passes could be an enabler for fast data availability for future weather applications. SSTL's and Viasat-RTE ground stations in Guildford are available as backup.
Once collected, the downlinked data is processed by the SSTL's hosted Payload Data Ground Segment (PDGS), which processes the data into different levels of products. Figure 11 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 be delivered using the industry standard NetCDF and will be made available at Level 1A and 1B, together with appropriate metadata, including calibration parameters.
During the mission inversions will be deployed to allow access to Level 2 products. These Level 2 inversions may evolve, and be refined and updated during the mission as the scientific understanding of the new measurements improves.

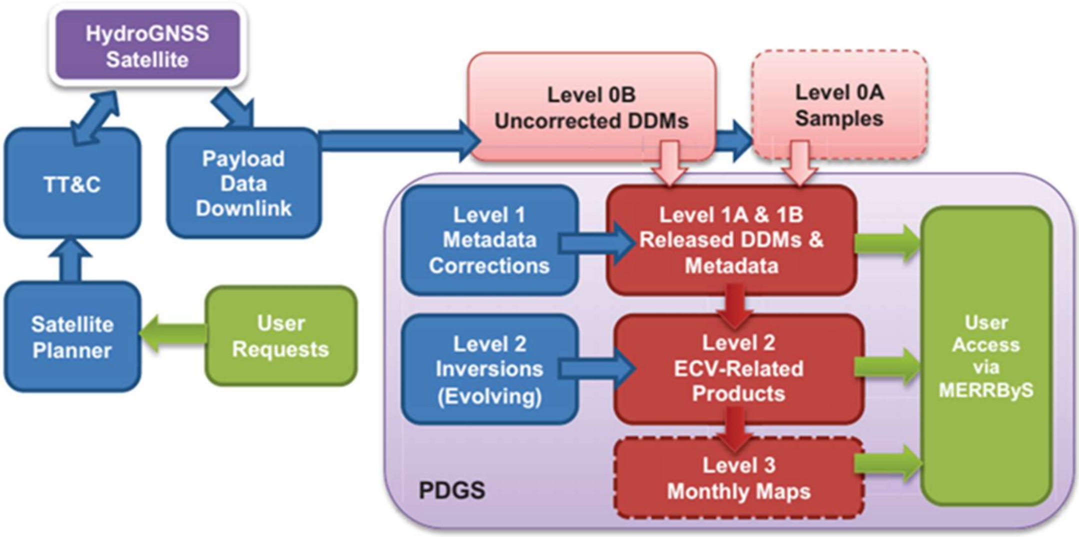

Figure 11 HydroGNSS Ground Segment & Products

The outline definition of the productions shown in Figure 11 are:

- Level 1 data comprises of GNSS DDMs and coherent channel measurements, and will be made available with sufficient metadata for calibration and recovery of surface reflection coefficients at the specular reflection points.
- Level 2 operational processors, supplied to the PDGS by the missions scientific partners, will allow the operational recovery of the climate related variables, i.e., soil moisture, inundation, freeze/thaw and biomass, ocean wind speed and sea ice extent, represented along individual reflected measurement tracks.
- Level 3 is mapped versions of the Essential Climate Variables. These could be Level 2 products plotted directly on a map, or a mapped product combining measurements from multiple tracks and satellites.

The products will be shared publically with registered users over the web using a similar platform to "MERRByS" that shared the TechDemoSat-1 data. The planned delivery of reflectometry EO products to the scientific community will be based upon ESA's 'free and open' policy.

4 HYDROGNSS PRIMARY MISSION OBJECTIVES

The HydroGNSS mission objectives and science are discussed in greater detail in [15] a summary is included here of the primary mission objectives.

4.1 Soil Moisture

Table 1 GCOS-Defined ECV Requirement Soil Moisture: Surface Soil Moisture [4]

ECV	Units	GCOS Resolution target	GCOS Uncertainty target	Ground Coverage Frequency
Surface Soil Moisture	m^3/m^3	1-25 km	0.04 m^3/m^3	Daily

The capability of GNSS-R for deriving soil moisture measurements is based upon well-known mechanisms. Specular reflectivity is directly related to soil permittivity, which has a good sensitivity at L-Band GNSS sensing frequencies. Reflectivity is also inversely related to roughness and vegetation optical depth, which is the opposite to backscatter radar, a fact which further highlights the complementarity between GNSS-R and monostatic radar.

HydroGNSS will provide Surface Soil Moisture as a Level 2 product at each location to an expected uncertainty of better than 0.08 m3/m3, and resolution 25 km or better (requirement). Global maps of Surface Soil Moisture will be provided 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 with two satellites every 15 days.

4.2 Inundation / Wetlands

Table 2 GCOS-Defined ECV Requirement Soil Moisture Surface Inundation [4]

ECV	Units	GCOS Resolution target	GCOS Uncertainty target	Ground Coverage Frequency
Surface Inundation	Flag	1-25 km	90% classification accuracy	Daily

There is much evidence of GNSS-R capabilities in sensing inundation and wetlands even in the presence of vegetation [16-17].

Bi-static forward scattered signals are strong and coherent over calm water and easy to be detected. The long GNSS L-Band signal wavelengths (~19 cm), whilst partially attenuated by thick vegetation canopies, have better penetration than C-band radar, and can show up strong reflecting surfaces, especially because of the forward scattering geometry in GNSS-R observations.

HydroGNSS will provide as a Level 2 product a flag at each location indicating whether the land surface is inundated or not, with a classification accuracy expected of at least 90% and resolution of 25 km or better. Global maps of Inundation/Wetlands will be provided 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 with two satellites every 15 days.

4.3 Above Ground Biomass (AGB)

Table 3 GCOS-Defined ECV Requirement AGB [4]

ECV	Units	GCOS Resolution target	GCOS Uncertainty target	Ground Coverage Frequency
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

There is growing evidence that above-ground biomass (AGB) can also be retrieved from GNSS-R measurements. The mechanism is that the vegetation attenuates the soil-reflected signals due to absorption and scattering phenomena. This generates an inverse correlation of the signal with respect to biomass, with a sensitivity that does not saturate as is usual for L-band backscatter when biomass is greater than 150 ton/ha [18-22].

HydroGNSS is expected to provide global maps of Above Ground Biomass every 6 months. HydroGNSS will provide an Above Ground Forest Biomass Level 2 product at each location to an expected uncertainty of: 30% or 10 t/ha for biomass values < 50 t/ha, resolution of 25 km or better. The Biomass measurement limit is expected at 250-350 t/h.

4.4 Soil Freeze/Thaw and Permafrost

Table 4 GCOS-Defined ECV Requirement Soil Moisture Freeze/Thaw and Permafrost [4]

ECV	Units	GCOS Resolution target	GCOS Uncertainty target	Ground Coverage Frequency
Freeze/Thaw	Flag	1-25 km	90% classification accuracy	Daily

Because of its depth, the state of permafrost cannot be measured directly by GNSS-R, but the active layer freeze / thaw state above can be sensed, and this provides a valuable input into permafrost models. Frozen soil has a much lower permittivity with respect to thawed soil, thus surface-reflected signal diminishes in frozen conditions. The reflectivity measured is less directly related to subsurface temperature than is the case for measurements made by microwave radiometers.

It was demonstrated in [23] that the increase of reflectivity between frozen and thawed states modelled according to the SMAP F/T product is observable in GNSS-R data.

HydroGNSS shall provide as a Level 2 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 a resolution of 25 km or better. HydroGNSS shall provide global maps of Freeze/Thaw state with a temporal update according to the number of. HydroGNSS satellites deployed One HydroGNSS satellite is estimated to cover 80% of the globe every 30 days, two satellites every 15 days

5 CONCLUSIONS

ESA Scout HydroGNSS shows the potential of small satellites to provide valuable scientific data and by using transmit signals-of-opportunity the value and quality of the measurements is shown to match that of much larger satellites. Small satellites such as HydroGNSS offer a route to constellations giving low latency, low repeat time measurements providing valuable inputs to Earth System Models (ESMs) and Numerical Weather Prediction (NWP) models and resilience through multiple satellites. The ESA Scout programme is supporting a novel Earth observation technique for Earth science and demonstrate disruptive sensing techniques or incremental science, providing the potential to be subsequently scaled up in larger missions or implemented in future ESA Earth Observation programmes.

6 REFERENCES

[1] UK National Space Strategy https://www.gov.uk/government/publications/national-space-strategy

[2] HydroSOS - https://public.wmo.int/en/our-mandate/what-we-do/application-services/hydrosos

[3] Jenkins A., Dixon, H., Barlow, V., Smith, K., Cullmann, J., Berod, D., Kim, H., Schwab, M., Roberto Silva Vara, L., "*HydroSOS – The Hydrological Status and Outlook System*", *WMO Bulletin* Vol 69(1) 2020.

[4] GCOS, Essential Climate Variables Factsheets. Retrieved June 2021, from https://gcos.wmo.int/en/essential-climate-variables

[5] UK Net Zero Strategy: Build Back Greener https://www.gov.uk/government/publications/net-zero-strategy

[6] SMOS Mission Background https://earth.esa.int/eogateway/missions/smos/description

[7] SMAP Mission description https://smap.jpl.nasa.gov/mission/description/

[8] SMAP Handbook, 178_SMAP_Handbook_FINAL_1_JULY_2014_Web.pdf, https://smap.jpl.nasa.gov/mission/description/

[9] Zavorotny, V., Gleason, S., Cardellach, E., and Camps, A. "*Tutorial on Remote Sensing Using GNSS Bistatic Radar of Opportunity,*" IEEE Geoscience and Remote Sensing Magazine, pp. 8-45, 2014, doi:10.1109/MGRS.2014.2374220

[10] W. Li et al., “First spaceborne phase altimetry over sea ice using TechDemoSat-1 GNSS-R signals”, in Geophysical Research Letters, 44, 8369– 8376, 2017, doi:10.1002/2017GL074513
[11] E. Cardellach et al., "GNSS Transpolar Earth Reflectometry exploriNg System (G-TERN): Mission Concept," in IEEE Access, vol. 6, pp. 13980-14018, 2018, doi: 10.1109/ACCESS.2018.2814072.
[12] Li, W., et al., “Lake level and surface topography measured with spaceborne GNSS-Reflectometry from CYGNSS mission: Example for the Lake Qinghai”. Geophysical Research Letters, 45, 13,332– 13,341, 2018, https://doi.org/10.1029/2018GL080976
[13] E. Cardellach et al., "First Precise Spaceborne Sea Surface Altimetry With GNSS Reflected Signals," in IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 13, pp. 102-112, 2020, doi: 10.1109/JSTARS.2019.2952694.
[14] King,L., Unwin,M., Rawlinson,J., Guida,R., Underwood,C., *Towards a Topographically-Accurate Reflection Point Prediction Algorithm for Operational Spaceborne GNSS Reflectometry—Development and Verification*, https://www.mdpi.com/2072-4292/13/5/1031
[15] M. J. Unwin et al., "*An Introduction to the HydroGNSS GNSS Reflectometry Remote Sensing Mission*," in IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, vol. 14, pp. 6987-6999, 2021, doi: 10.1109/JSTARS.2021.3089550.
[16] Nghiem, S. V., Zuffada, C., Shah, R., Chew, C., Lowe, S. T., Mannucci, A. J., Cardellach, E., Brakenridge, G. R., Geller, G., and Rosenqvist, A., “Wetland monitoring with Global Navigation Satellite System reflectometry,” Earth and Space Science, 4, 16– 39, 2017, doi:10.1002/2016EA000194.
[17] Rodriguez-Alvarez, N., Podest, E., Jensen, K., and McDonald, K., Classifying Inundation in a Tropical Wetlands Complex with GNSS-R. Remote Sensing, 11(9), 2019.
[18] Egido, A., S. Paloscia, Motte E., L. Guerriero, N. Pierdicca, M. Caparrini, E. Santi, G. Fontanelli, and N. Floury, “*Airborne GNSS-R polarimetric Measurements for Soil Moisture and Above Ground Biomass Estimation*.” IEEE Journal of Selected Topics in Applied Geoscience and Remote Sensing, vol. 7, no. 5, pp. 1522-1532, May 2014, doi: 10.1109/JSTARS.2014.2322854.
[19] Zribi, M., Motte, E., Baghdadi, N., Baup, F., Dayau, S., et al., “*Potential Applications of GNSS-R observations over agricultural areas: results from the GLORI airborne campaign*.” Remote Sensing, MDPI 10 (8): 17, 2018 doi:10.3390/rs10081245.hal-01914977
[20] Santi, E., Paloscia, S., S. Pettinato, G. Fontanelli, M.P. Clarizia, L. Guerriero, and N. Pierdicca. 2019. “*Remote Sensing of Forest Biomass Using GNSS Reflectometry.” Journal of Selected Topics in Applied Earth Observations and Remote Sensing*. doi:10.1109/JSTARS.2020.2982993.
[21] Carreno-Luengo, H., Luzi, G., and Crosetto, M., “*Above-Ground Biomass Retrieval over Tropical Forests: A Novel GNSS-R Approach with CYGNSS,” Remote Sens., 1368, 2020*, doi:https://doi.org/10.3390/rs12091368
[22] Santi, E., Paloscia, S., Pettinato, S., Fontanelli, G., Clarizia, M., Guerriero, L., and Pierdicca, N., “*Forest biomass monitoring at local and global scale by using GNSS Reflectometry*,” Jour. Sel. Top. on Appl. Earth Obs. and Rem. Sens, Vol. 13, pp. 2351-2368, 2020.
[23] Chew, C., Lowe, S., Parazoo, N., Esterhuizen, S., Oveisgharan, S., Podest, E., Freedman, A., “SMAP radar receiver measures land surface freeze/thaw state through capture of forward-scattered L-band signals,” Remote Sensing of Environment, 198, 333-344, Sept. 2017.
[24] HydroGNSS Smallsat Mission Animation, SSTLTV, YouTube, 2020 https://youtu.be/30pemNtyBVA