SSC22-V-05

# Scouting for Climate Variables with Small Satellites


Andy Palfreyman, Alex da Silva Curial, Jonathan Rawlinson, Martin Unwin, Sir Martin Sweeting, Serena Donati.
Surrey Satellite Technology Ltd (SSTL), Tycho House 20 Stephenson Road Surrey Research Park,
Guildford GU2 7YE, United Kingdom. apalfreyman@sstl.co.uk

Nazzareno Pierdicca
Sapienza University of Rome,
Piazzale Aldo Moro 5, 00185 Roma, Italy

Estel Cardellach
Institut d'Estudis Espacials de Catalunya (IEEC),
Gran Capità, 2-4 Edifici Nexus, Desp. 201, 08034 Barcelona, Spain

Leila Guerriero
Università di Roma Tor Vergata,
Via Cracovia n.50 - 00133 Roma, Italy

Giuseppe Foti
National Oceanography Centre (NOC) European Way, Southampton SO14 3ZH, United Kingdom.

Emanuele Santi
Institute of Applied Physics,
Consiglio Nazionale delle Ricerche - Piazzale Aldo Moro, 7 - 00185 Roma, Italy.

Paul Blunt
University of Nottingham, University Park, Nottingham, NG7 2RD, United Kingdom.

Kimmo Rautiainen
Finnish Meteorological Institute (FMI), P.O. BOX 503, FI-00101 Helsinki

Jean-Pascal Lejault, Maria Paola Clarizia, Massimiliano Pastena
European Space Agency (ESA),
Keplerlaan 1, 2201 AZ Noordwijk, Netherlands


## ABSTRACT


HydroGNSS is a small satellite mission under the new ESA Scout programme tapping into NewSpace, within ESA's FutureEO programme. The mission will use an innovative GNSS-Reflectometry instrument to collect parameters related to the Essential Climate Variables (ECVs): soil moisture, inundation, freeze/thaw, biomass, ocean wind speed and sea ice extent. GNSS-Reflectometry is a type of bistatic radar utilizing abundant GNSS signals as signals of opportunity, empowering small satellites to provide measurement quality associated with larger satellites.

The HydroGNSS instrument introduces novel measurements compared to its predecessors on UKSA TechDemoSat-1 and NASA CYGNSS missions. These include: the acquisition of Galileo(E1) reflections, and firsts such as dual-polarization, complex 'coherent channel' (amplitude/phase) and second frequency (L5/E5a) acquisitions. These measurements enable HydroGNSS to innovate the L2 products, e.g. improving the ground resolution and soil moisture measurement, as dual-polarized reflections allow the discrimination of vegetation effects from soil moisture.

HydroGNSS will:

- Complement and potentially gap fill other missions sensing soil moisture e.g. ESA's SMOS and NASA's SMAP missions.

- Complement ESA's Biomass mission addressing coverage restrictions over Europe, North and Central America.
- Expand GNSS-Reflectometry techniques.
- Lay the foundations for a future constellation capable of offering continuity in high spatial-temporal resolution observations of the Earth's weather and climate.

## INTRODUCTION

HydroGNSS is the first contracted small satellite mission under ESA's new Earth Observation fast track Scout programme which is a new framework taping into New Space (3 years from KO to launch, cost ≤ 30 M€). The Scout programme is an element in the European Space Agency's FutureEO Earth Science programme, by which ESA aims to 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. Both HydroGNSS satellites (one being optional) are due for launch in 2024.

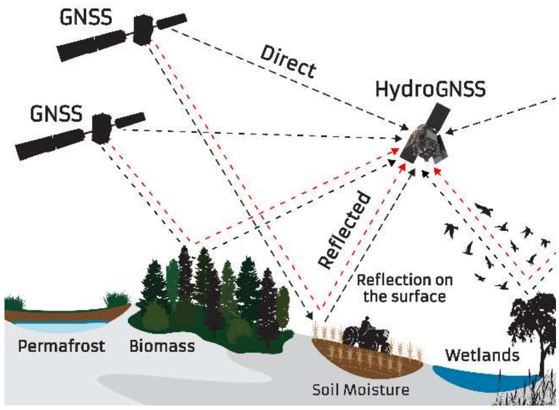


**Figure 1 HydroGNSS uses a bistatic radar concept using GNSS reflected signals for hydrological measurements, targeting soil moisture, freeze / thaw state over permafrost, above ground biomass, soil moisture and wetlands.**

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[1].

### *Pressing Need for Soil Moisture measurements*

Scientists, meteorologists and others increasingly use global soil moisture measurements from space for: accurate weather forecasting, flood warning services, agriculture, subsidence, permafrost sensing, and climate modelling.

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.

ESA SMOS[2] and NASA SMAP[3, 4] provide soil moisture through passive L-band radiometry, most widely used for soil moisture measurement. Both satellites are past end of design life, with no immediate replacements. Both are large satellites (SMAP had 6 metre antenna, cost ~$1B). There is recognised need for continuity of services.

As shown in Figure 1 HydroGNSS is designed to provide measurements of these parameters by GNSS Reflectometry. A future constellation of 8 HydroGNSS satellites would provide global temporal coverage as SMOS (~3 days), at improved spatial resolution (<25 km).

These measurements can also assist with:

- The UK Net Zero Strategy[5] by monitoring biomass, flooding and providing farmers with information about soil moisture.
- COP26 'Space Enabled Net-Zero' targets by benefiting from monitoring soil moisture in the support of fighting climate change using space–enabled technology, in line with the Ten Point Plan in the UK National Space Strategy [6].

Small satellites such as HydroGNSS can assist in providing for these requirements[7] and the mission fulfils the aims of the ESA Scout programme, retaining the potential to be subsequently scaled up.

## SIGNAL SOURCES

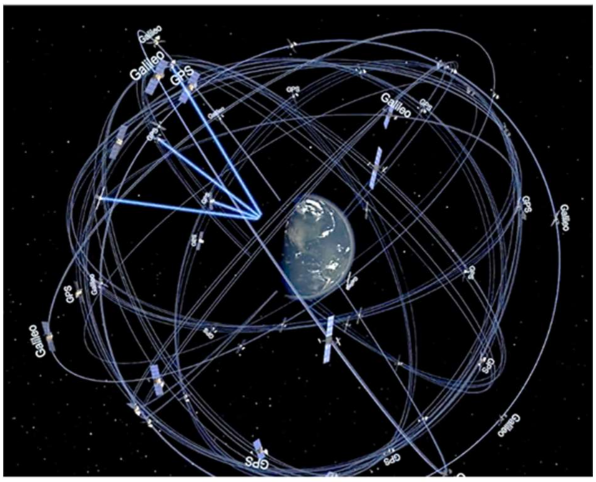


**Figure 2 GPS and Galileo satellites in medium Earth orbit, amongst others, are available as signal sources for GNSS Reflectometry, and reflections are collected by a satellite in Low Earth Orbit [8].**

Global Navigation Satellite Systems (GNSS), such as GPS and Galileo, comprise of dozens of satellites in medium Earth orbit which continually transmit predictable 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 GNSS signals of opportunity for the bistatic radar empower small satellites to take measurement quality associated with satellites above their size category.

Multiple reflections can be simultaneously collected by a single observatory in LEO. GPS and Galileo constellations offer more than 60 sources of L-band signals (see Figure 2). 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 reflection points (see Figure 3).

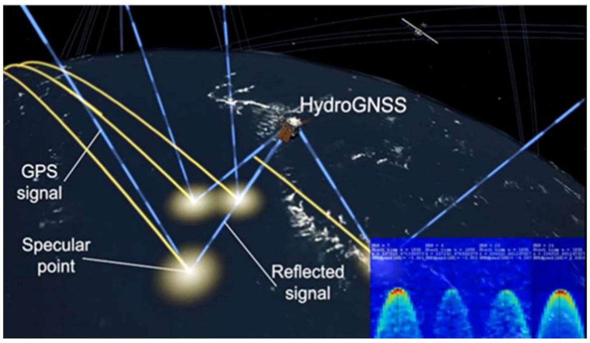


**Figure 3 Each HydroGNSS satellite collects multiple reflections from Low Earth Orbit. Yellow lines indicate accumulated reflection tracks and results are represented as Delay Doppler Maps (DDMs) in bottom right of picture [8].**

These signals of opportunity are by design, deterministic in structure (e.g. code replicas as per Galileo ICD[10] and GPS ICD[11]), from very well described orbits and with signal coverage prescribed to approximately equally illuminate the globe visible beneath them. Information for the transmissions accompanies them such as their orbits.

These characteristics make them ideal for utilization with small satellite sensing missions. They provide large coverage areas signals that can be predicted in advance and thus reliably sensed without having the transmitter under the mission control. The drawback is that areas of interest cannot be specifically targeted if not illuminated by the GNSS-R reflection. The mitigation is being able to track multiple reflections simultaneously.

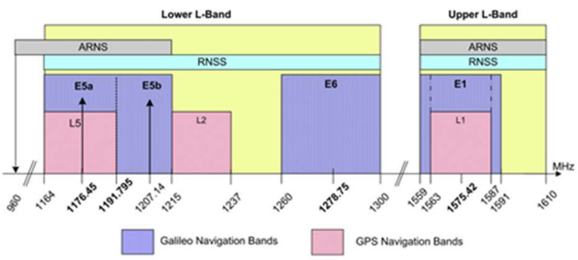


**Figure 4 Galileo / GPS frequency Plan[10]**

The different Galileo signals targeted by HydroGNSS are further described in Table 1. The different signals are expected to provide varying coverage areas due to the bandwidth of the signals. All the signals are transmitted Right-hand Circularly Polarised (RHCP).

**Table 1 GPS,Galileo Signals and Bandwidths used by HydroGNSS**

| Signal | Carrier Frequency (MHz) | Bandwidth to First Nulls (MHz) |
|---|---|---|
| GPS L1 | 1575.42 | 2.046 |
| GPS L5 | 1176.45 | 20.46 |

| | | |
|---|---|---|
| Galileo E1 (B&C) | 1575.42 | 4.092 |
| Galileo E5a | 1176.45 | 20.46 |

Small satellite measurements are thus enabled by atomic clock referenced transmit signals of opportunity, to produce valuable climate parameter measurements, something which would be expensive to achieve with dedicated a signal generator

## THE HYDROGNSS SMALL SATELLITE

The highly capable 'SSTL-21' platform has been selected for HydroGNSS mission, shown in Figure 5. It is the smallest family member of the 'SSTL-Micro' platform. The small size would maintain the low cost of a future constellation.

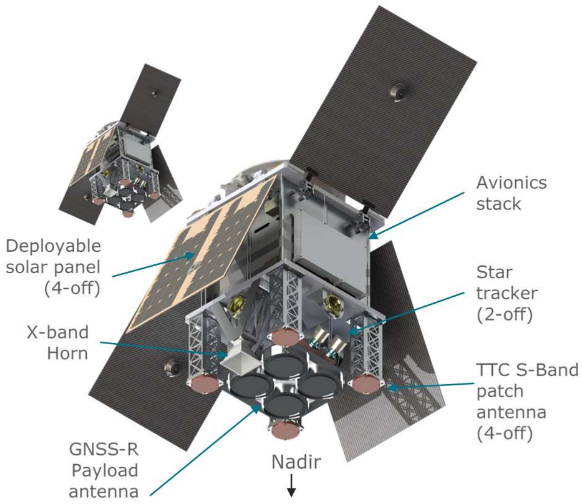


**Figure 5 HydroGNSS satellites, showing in orbit configuration with deployed solar panels. The GNSS-R nadir antenna is visible, comprising of four dual all metal patch antennas capable of dual frequency and dual polarization**

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 during the payload operation.

The inclusion of star cameras supports the satellite precise attitude knowledge, these support identification of the reflected signal's observatory antenna incident angle and thus the receiving antenna gain witnessed by the reflection.

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 SSTL-21 satellite platform will serve to provide high quality science data.

## REMOTE SENSING INSTRUMENT (RESI)

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 witnessed at the Nadir Antenna into Delay Doppler Maps (DDMs).

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 DDMs, this open loop tracking is enabled by the stability and predictability of the GNSS transmit signals used as the signal of opportunity.

HydroGNSS will use a Digital Elevation Model[12] to target the position of the specular point position over land [12]. This DEM is essential for successfully tracking the specular point of a reflection as it travels over the land whose altitude varies from a simpler global model and could move the reflection point outside the DDM created.

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 reliably capture the specular point and 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 in-phase 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.

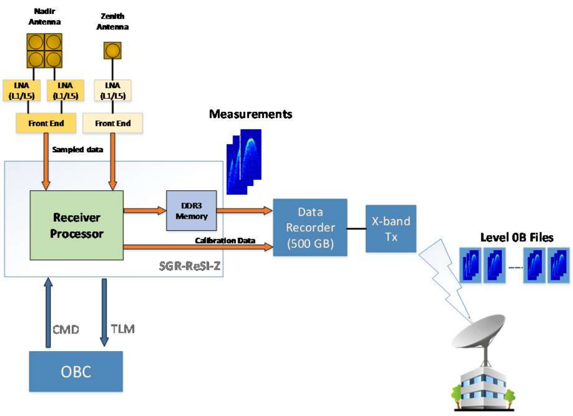


**Figure 6 HydroGNSS Science Instrument Payload Chain**

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 of the Delay Doppler Maps and simultaneously that of targeted raw sampled captures for scientific development activities.

## HYDROGNSS MISSION OBJECTIVES

The primary mission objectives are to measure, using reflected GNSS Signals GCOS Defined ECV parameters[13]:

- **Soil Moisture**– including the novel 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 introduced 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. There is much evidence of GNSS-R capabilities in sensing inundation and wetlands even in the presence of vegetation[14-15].
- **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. It was demonstrated that the increase of reflectivity between frozen and thawed states modelled according to the SMAP F/T product is observable in GNSS-R data[16].
- 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:

- 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, chlorophyll-a, ice concentration, snow water equivalent, sea ice thickness, and inland water bodies).

The outline definition of the data products to meet these objectives 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 Payload Data Ground Segment (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.

## CONCLUSIONS

ESA Scout HydroGNSS shows the potential of small satellites to provide valuable scientific data and by utilizing plentiful high quality transmit GNSS signals-of-opportunity.

Inherently small satellites such as HydroGNSS offer a route to constellations giving low latency, low repeat time measurements, with accompanying low launch costs and ready route to constellation management.

GNSS reflectometry can provide valuable inputs to Earth System Models (ESMs) and Numerical Weather Prediction (NWP) models. Future constellations benefit from resilience through multiple satellites.

The ESA Scout programme is supporting a novel Earth observation technique for Earth science and demonstrating disruptive sensing techniques and incremental science, providing the potential to be subsequently scaled up in larger missions or implemented in future ESA Earth Observation programmes.

## REFERENCES

1 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. [34] 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.

2 SMOS Mission Background https://earth.esa.int/eogateway/missions/smos/description

3 SMAP Mission description https://smap.jpl.nasa.gov/mission/description/

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

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

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

7 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.

8 HydroGNSS Smallsat Mission Animation, SSTLTV, YouTube, 2020 https://youtu.be/30pemNtyBVA

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 Galileo Open Service Signal in Space Interface Control Document v2.0. https://www.euspa.europa.eu/newsroom/news/updated-galileo-os-sis-icd-now-available

11 GPS ICD https://www.gps.gov/technical/icwg/

12 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

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

14 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.

15 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.

16 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.