HydroGNSS PDGS Product Manual

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1 INTRODUCTION

1.1 SCOPE

This document is the manual for the users of Payload Data Ground Segment products from the ESA Scout-2 HydroGNSS GNSS Reflectometry mission.

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 # (SSTL)	Orig. Rev	Date
AD-1	HydroGNSS Mission Requirements Document	SP#00632438	3.0	26/02/2024
AD-2	Scout-2 HydroGNSS – L1 Algorithm Theoretical Basis Document (ATBD)	SP#00655831	11.0	13/06/2025
AD-3	Soil Moisture Operational Processor ATBD – Sapienza	SP#00649693	2.9 (18)	10/06/2025
AD-4	Freeze/Thaw State ATBD – FMI	SP#00649720	3/1 (18)	08/11/2024
AD-5	Surface Inundation and Coherent Processor ATBD – IEEC/ICE-CSIC	SP#00649719	4.7 (14)	12/11/2024
AD-6	Forest Above Ground Biomass ATBD - IFAC	SP#00655639	1.6 (15)	10/05/2025
AD-7	Ocean Wind Speed and Ice Extent ATBD – NOC	SP#00654815	2.0 (5)	01/12/2023
AD-8	NOC L1b_ext ATBD - NOC	SP#00654816	2.0 (8)	01/12/2023
AD-9	HydroGNSS website, https://www.hydrognss.org/			

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	Cust. Ref. #	Doc #	Revision	Date
RD-1	Network Common Data Form (NetCDF) http://www.unidata.ucar.edu/software/netcdf/			4.8.1	23/08/2021
RD-2	ESA-CCI 1 km/25km Land Cover Map, https://www.esa-landcover-cci.org/,		N/A		
RD-3	NSDIC extent data, https://nsidc.org/data/explore-data		N/A		
RD-4	NOIAA, Coast Proximity Flag, https://catalog.data.gov/dataset/distance-to-nearest-coastline-0-04-degree-grid		N/A		
RD-5	USGS EROS GMTED2010 DEM terrain model, https://www.usgs.gov/centers/eros/science/usgs-eros-archive-digital-elevation-global-multi-resolution-terrain-elevation		N/A		
RD-6	US NGA EGM96 geoid model, https://www.usna.edu/Users/oceano/pguth/md_help/html/egm96.htm		N/A		

1.4 REFERENCE PAPERS

[JAL12] Jales P, "Spaceborne Receiver Design For Scatterometric GNSS Reflectometry.", PhD thesis, University of Surrey, 2012.

[KIN20] L. King, M. Unwin, J. Rawlinson, R. Guida and C. Underwood, "A Topographically-Accurate GNSS-R Reflection Point Predictor for on-Board Operational Processing," IGARSS 2020 - 2020 IEEE International Geoscience and Remote Sensing Symposium, 2020, pp. 6194-6197, doi: 10.1109/IGARSS39084.2020.9324677.

[LYO04] R. Lyons, Understanding Digital Signal Processing, Prentice Hall, 2004 (p541 for Zoom FFT)

[RAU21] K. Rautiainen, D. Comite, J. Cohen, E. Cardellach, M. Unwin and N. Pierdicca, "Freeze-Thaw Detection over High-Latitude Regions by Means of GNSS-R Data," Oct 2021, in IEEE Transactions on Geoscience and Remote Sensing, doi: 10.1109/TGRS.2021.3125315

[SAN20] Santi E., S. Paloscia, S. Pettinato, G. Fontanelli, M.P. Clarizia, D. Comite, L. Dente, L. Guerriero, N. Pierdicca, N. Floury, 2020. "Remote Sensing of Forest Biomass Using GNSS Reflectometry," in IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, DOI: 10.1109/JSTARS.2020.2982993

1.5 ACRONYMS AND ABBREVIATIONS

The following abbreviations are used within this document:

ADC	Analogue to Digital Conversion		MERRByS	Measurement of Earth Reflected Radio-navigation Signals By Satellite
AFS	Attenuated Forward Scattering		MOC	Mission Operations Centre
AGB	Above Ground Biomass		MPS	Mission Planning System
AGC	Automatic Gain Control		NAS	Network Attached Storage
AGSP	Antenna Gain towards Specular Point		NASA	National Aeronautics and Space Administration
ANN	Artificial Neural Network		NBRCS	Normalized Bistatic Radar Cross Section
AOCS	Attitude and Orbit Control Subsystem		NDVI	Normalized Difference Vegetation Index
ATBD	Algorithm Theoretical Basis Document		NDWI	Normalized Difference Water Index
BB	Black Body		NetCDF	Network Common Data Form
C/A	Coarse Acquisition		NORAD	North American Aerospace Defense Command
CCI	Climate Change Initiative		NOC	National Oceanography Centre (UK)
CIC	Cascading Integrator Comb (filter)		NSDIC	National Snow and Ice Data Centre (US)
CRS	Coordinate Reference System		O/S	Operating System
CyGNSS	Cyclone Global Navigation Satellite System		PDGS	Payload Data Ground Segment
DAMP	Dual-Band All Metal Patch antenna		PPS	Pulse Per Second
DC	Digital Conversion		PRN	Pseudo Random Noise (GPS and Galileo satellite identifier)
DDM / DDMR	Delay Doppler Map / DDM Receiver		PVT	Position, Velocity and Time
DEM	Digital Elevation Map		QF	Quality Flag
DFT	Discreet Fourier Transform		RC	Raw Collection
DR	Data Recorder		RD	Receiver Data
DRT	Data Recorder Track		ReSI	Remote Sensing Instrument
DTM	Digital Terrain Model		RF	Radio Frequency
EASE	The Equal-Area Scalable Earth		RFI	Radio Frequency Interference
ECEF	Earth-Centred Earth-Fixed		RHCP	Right-Hand Circularly Polarised
ECVs	Essential Climate Variables		RINEX	Receiver Independent Exchange Format
EIRP	Effective Isotropic Radiated Power		RTP	Real-Time Process

EWOD	Extended Whole Orbit Data		SBPP	SGR Binary Packet Protocol
FAO	Food and Agriculture Organisation of the United Nations		SGR	Space GNSS Receiver
F-AGB	Forest Above Ground Biomass		SGR-ReSI-Z	SGR-Remote Sensing Instrument-ZTC
FDP	Fast Delivery Product		SMAP	Soil Moisture Active Passive (NASA mission)
FFT	Fast Fourier Transform		SMOS	Soil Moisture and Ocean Salinity (ESA mission)
FMI	Finnish Meteorological Institute		SNR	Signal to Noise Ratio
FPGA	Field Programmable Gate Array		SP	Specular Point
FT	Freeze Thaw		SSM	Surface Soil Moisture
GCOS	Global Climate Observing System		SSTL	Surrey Satellite Technology Limited
GIS	Geographic Information System		SV	Space Vehicle (GNSS satellites)
GLDAS	Global Land Data Assimilation System		SVN	Space Vehicle Number
GMF	Geophysical Model Function		TBC	To Be Confirmed
GNSS-R	Global Navigation Satellite System - Reflectometry		TBD	To Be Defined
GL (or GP)	GNSS Positioning Log-files		TDS-1	Technology Demonstration Satellite-1
GSAR	Ground Segment Acceptance Review		TLE	Two-Line Elements
GSID	GNSS-R Sea Ice Detection		TV	Tor Vergata (University of Rome)
HSI	High-Speed Interface		USGS	United States Geological Survey
IEEC	Institut d'Estudis Espacials de Catalunya		VHDL	VHSIC Hardware Description Language
IF	Intermediate Frequency		VHSIC	Very High Speed Integrated Circuit
IFAC	Istituto di Fisica Applicata Nello Carrara		VOD	Vegetation Optical Depth
IGBP	International Geosphere-Biosphere Programme		VRQ	Variable Rate Quantisation
IGS	International GNSS Service		WOD	Whole Orbit Data
L1, L5, E1, E5a	GPS Link-1, Link-5 transmissions, Galileo equivalents in same bands.		WVC	Water Vapour Climatology
L1OP	Level 1 Operational Processor		ZTC	Zoom Transform Correlator (On-board processing algorithm)
L2OP	Level 2 Operational Processor			
LEO	Low Earth Orbit			
LHCP	Left-Hand Circularly Polarised			
LNA	Low Noise Amplifier			

1.6 DEFINITIONS

Ancillary Files – spacecraft log files used by the L1AOP, in conjunction with L0B payload files, to generate L1a metadata. This includes the GL logs, which are actually extracted from the L0B files.

Auxiliary Files – other files, not downloaded from the spacecraft, used to generate mainly L1b metadata, but also some of the L1a metadata. Most of these files are downloaded from the Internet.

Reflectivity - also referred to in the literature as (Fresnel) reflection coefficient, reflectance, equivalent reflectivity, specular reflectivity, and Γ (gamma). See ReflectionCoefficientAtSP in A.4.3.3.3.1.

NRBCS - Normalized Bistatic Radar Cross Section, or σ_0, referred to as Sigma0 in in A.4.3.3.3.1.

2 OVERVIEW

Complementing the well-established series of Earth Explorer research satellite missions, Scout missions are a new component of ESA's Earth Observation FutureEO programme. This new family of small satellites delivers value-added science, either by miniaturising existing space technologies or by demonstrating new observing techniques, at a limited budget and rapid schedule. HydroGNSS is the first Scout mission to emerge from the Scout Programme.

Figure 2-1: HydroGNSS satellites

2.1 HYDROGNSS MISSION SUMMARY

The Scout-2 HydroGNSS mission (referred to as 'HydroGNSS' in this document, or 'the mission') is a scientific mission that takes hydrological measurements over the land. The mission consists of two satellites (Figure 2-1), each approx. 70 kg, flying a GNSS Reflectometry (GNSS-R) instrument in LEO (Low Earth Orbit), providing on-board processed reflections (GNSS Delay Doppler Maps, DDMs) collected near-continuously over the globe. The satellites are designed, built and operated by SSTL. These DDMs are inverted on the ground into hydrological Level 2 products of climate variables delivered to users via a User FTP server. Figure 2-2 illustrates the four terrestrial climate variable targets for HydroGNSS, with secondary measurements taken over the ocean. Science value is increased through the potential of additional satellites or constellation to improve the temporal resolution and global sampling of time-critical variables. See also the video at the bottom of the home page on the HydroGNSS website, AD-9.

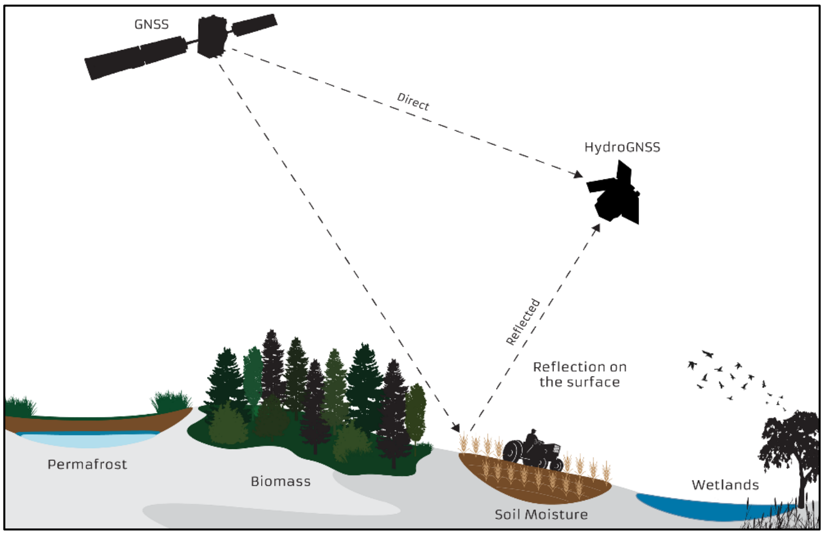

Figure 2-2: HydroGNSS climate variable targets

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 to be flown on the HydroGNSS mission is the

SGR-ReSI-Z instrument. This is a successor to the SGR-ReSI instrument used on TDS-1 and CYGNSS, inheriting its functional capability, but brought onto up-to-date technology to overcome limitations of the earlier instruments. New capabilities include both GPS and Galileo reflection reception, dual polarisation reception, the addition of a coherent channel, and the addition of second frequency (E5a / L5) reflection capability. This offers a unique instrument for delivering observations of four hydrological climate variables, closely related to GCOS-defined Essential Climate Variables (ECVs). These are:

- **Surface Soil Moisture**
- **Inundation state (mapping wetlands and flooding)**
- **Soil Freeze / Thaw state (notably over permafrost)**
- **Forest Above Ground Biomass (F-AGB)**

Secondary products of surface wind speed and sea ice extent are also generated over ocean.

The main goal of the HydroGNSS project is to develop, qualify and validate a space mission that performs the science objectives listed above, and fulfils the following key technical and programmatic requirements:

- Operational system **lifetime of up to 4.5 years.**
- Delivery of **reflectometry EO products** to the scientific community according to ESA's **'free and open' policy**;
- Providing a service to end users with an **availability better than 90%**;
- Demonstration of **novel reflectometry EO techniques**, including **dual polarisation**, a **coherent complex channel** and **dual frequency** (L1/E1 and L5/E5a) from GPS and Galileo signals.
- Development and maturation of the scientific readiness throughout the mission duration to achieve **SRL-7 of the science products at the end of the in-orbit commissioning phase** and **SRL-8 at the end of the nominal mission lifetime** (3 years from launch), with the support of a science End-To-End Simulator (E2ES).

2.2 GNSS REFLECTOMETRY

The GNSS-R technique works in a way that is similar to both existing altimeter and scatterometer radar satellites but eliminates the need for carrying a transmitter on the satellite through using the existing GNSS transmitters for radar sources, i.e. bistatic radar.

The receiver processes the directly received GNSS signals for determining position, velocity and time and the reflected signals for remote sensing as in Figure 2-2. As the receiver moves, the specular point moves with it, starting off ahead of the receiver and slowly passing behind as the receiver overtakes the higher, slower moving GNSS transmitter. The specular point traces out a path over the land/ocean surface which we call its "track". The receiver can process multiple simultaneous reflection tracks, from multiple GNSS-transmitters, across the GPS and Galileo constellations.

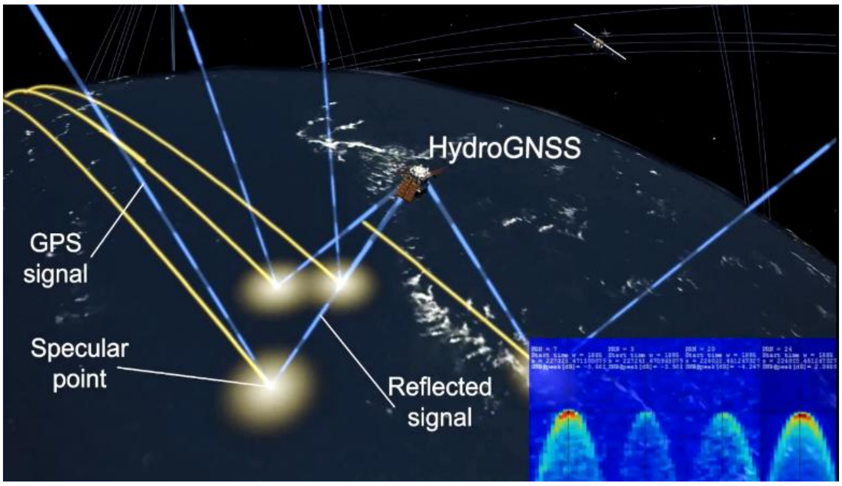

Figure 2-3: GNSS reflectometry

The GNSS-R receiver maps out the received reflections which are sensitive to geophysical characteristics at each reflection specular point, including surface roughness, surface dielectric permittivity, and attenuation from vegetation, if present. The surface roughness causes the reflections from each GNSS transmitter to spread over a glistening zone around the specular reflection point. The receiver recovers the signal power from around the glistening zone through correlation of a replica GNSS signal at a map of delay and Doppler offsets (DDM). These DDM images are then inverted back to a measurement of the surface roughness, such as that caused by wind driven waves.

Over the land, the HydroGNSS mission processes GNSS reflections to recover climate variables including soil moisture content, inundation state, freeze/thaw state, forest above-ground biomass, while over the ocean, sea-ice extent and surface wind speed are measured.

3 HYDROGNSS MISSION

3.1 PLATFORM AND LAUNCH

The HydroGNSS uses the 'SSTL-Micro' platform which is around 47 cm x 47 cm x 70 cm in size, with a mass of about 70 kg, including the payload. It is a highly capable platform, but small enough to maintain the low cost of a future constellation (Figure 3-1). It has dual redundant avionics, 3-axis attitude stabilisation, an X-Band link supporting high-volume data downlinks, up to 200 Mbps, and a propulsion system with 55up to 30 m/s delta-v. In particular this platform offers the HydroGNSS mission near-100% duty cycle, star camera attitude accuracy, and a high data throughput, serving to raise the quality of the science data.

In terms of system budgets, the SSTL-21 offers good margins for the HydroGNSS mission. The orbit average power is 55 watts, and allows for 100% payload operations and scheduled downlinks. The propulsion is used to raise orbit from 510 km altitude launch injection towards 550 km target. Then it is used to phase the two satellites around orbit by 180°, and to allow for collision avoidance manoeuvring during its life. The satellite will naturally re-enter within 25 years due to the low altitude meeting requirements for de-orbit, but remaining propellant may be used to speed up re-entry, or alternatively to extend the mission life if this is requested.

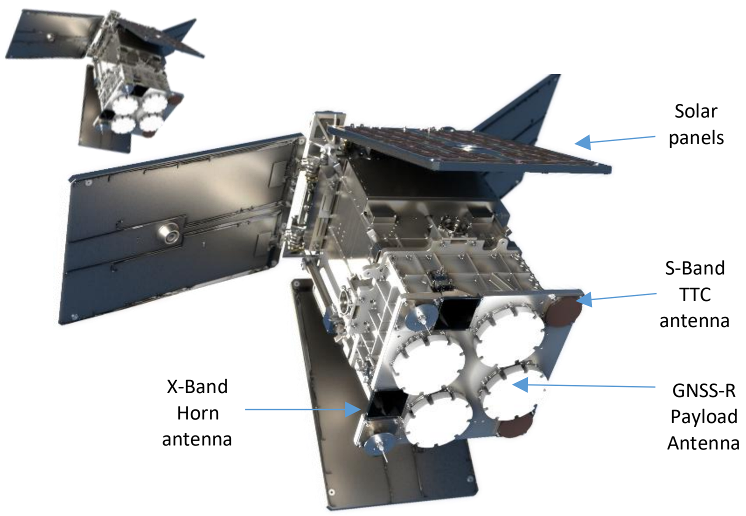

Figure 3-1: HydroGNSS satellites, showing in orbit configuration with deployed solar panels

Figure 3-1 shows the two satellites as configured once in orbit. The GNSS-R nadir antenna is visible, comprising of four dual-patch antennas capable of dual frequency and dual polarization. Not visible in the picture is the single patch antenna that points towards the zenith, and the star cameras that provide a highly accurate knowledge of the satellite pointing.

The GNSS-R payload operates near-continuously night and day, and is not bound to a particular hour angle or ground repeat track, so would be compatible with a number of similar near-polar orbits. Whilst there is a case for 6 am / 6 pm for soil moisture monitoring to match other soil moisture monitoring satellites, a common sun-synchronous orbit (10:30 LTAN, 550 km) has been selected to ensure a timely, and affordable ride-share launch.

3.2 HYDROGNSS MISSION OBJECTIVES

The objectives and requirements for the mission are captured in the Mission Requirements Document [AD-1]. **Error! Reference source not found.Error! Reference source not found.** Table 3-1 shows the primary geophysical measurement objectives for HydroGNSS at Level 2/3 (Product Levels are defined in the next section). These have been selected to address Essential Climate Variables (ECVs) defined by the Global Climate Observing System as variables that critically contribute to the characterisation of the Earth's climate. The spatial resolution of 25 km is typically achieved when signals are diffuse, and shall be considered a threshold. The goal of 1 km refers to the exploitation of the complex signal over flatter surfaces where the reflected signal is more coherent. Temporal resolution is 15 days over 80% of the globe for the two HydroGNSS satellites. This would improve if the number of satellites in the constellation were increased.

ECV	Units	Horizontal Resolution	Uncertainty	Temporal Resolution 80%
Surface Soil Moisture	m^3/m^3	25 km t/r (1 km g/r)	0.08 t/r 0.04 g/r	15 days
Surface Inundation State	Flag	25 km t/r (1 km g/r)	90%	15 days
Freeze/Thaw State	Flag	25 km t/r (1 km g/r)	90%	15 days
Forest Above Ground Biomass	t/ha	25 km t/r (1 km g/r)	<30% error t/r, <20% error, 10 t/ha if < 50 t/ha	15 days

Table 3-1: Targets for primary L2/L3 products (t/r means threshold requirement, g/r is goal requirement)

The HydroGNSS satellites, in a near-polar orbit, will provide coverage over the whole world, but with a denser coverage and a higher repeat rate, especially over the boreal climate regions, and a sparser coverage over equatorial regions.

3.2.1 Secondary Objectives

The four land variables are the primary targets of HydroGNSS, which take precedence over any other measurements, and determine any optimisation of operational settings. Nevertheless, the HydroGNSS mission has been designed to allow continuous operation over all surfaces, as it is recognized that the same GNSS-R Level 1 DDM measurements will be valuable for many other applications.

As a result of TDS-1 and CYGNSS, GNSS-R has been established as a technique for measuring ocean winds. Sea ice can also be measured through observation of transitions from water to ice and ice to water. HydroGNSS has secondary objectives of determining ocean winds to 2 m/s or better for winds up to 20 m/s, and sea ice extent to a classification accuracy of at least 90%.

3.3 HYDROGNSS PRODUCT OUTPUT

The following table shows the products that will be available to users.

Product	File Name	Section
Complete L1 metadata	metadata_L1_merged	9.3, A.6
Soil Moisture Level 2	L2OP-SSM.nc	10.1, A.7.1
Surface Inundation Level 2	L2OP-SI.nc	10.4, A.7.4
Forest Biomass Level 2	L2OP-FB.nc	10.2, A.7.2
Freeze Thaw Level 2	L2OP-FT.nc	10.3, A.7.3
Ocean Surface Wind Speed Level 2	L2OP-SWS.nc	10.5, A.7.5
Ocean Sea Ice Level 2	L2OP-SWS.nc	10.5, A.7.5

Soil Moisture Level 3	L3-SSM.nc	11.1, A.8.1
Forest Biomass Level 3	L3-FB.nc	11.3, A.8.3
Freeze Thaw Level 3	L3-FT.nc	11.2, A.8.2
Raw* DDMs	DDMs.nc	9.1, A.3.2
Raw* Coherent Measurements	CoherentMeasurements.nc	9.1, A.3.2
Raw* Direct Signal Data	directSignalPowerL1E1.nc directSignalPowerL5E5.nc	9.1, A.3.4
Raw* Blackbody Data	blackbodyZenithL1E1.nc	9.1, A.3.3
	blackbodyZenithL5E5.nc	9.1, A.3.3
	blackbodyNadirL1E1LHCP.nc	9.1, A.3.3
	blackbodyNadirL1E1RHCP.nc	9.1, A.3.3
	blackbodyNadirL5E5LHCP.nc	9.1, A.3.3
	blackbodyNadirL5E5RHCP.nc	9.1, A.3.3

Table 3-2: HydroGNSS products summary

* These products are raw from a user perspective, i.e. the data is raw even though the file has been produced from multiple download files.

For further information about HydroGNSS product levels see section 3.4.

3.4 HYDROGNSS PRODUCT LEVELS

The product levels for HydroGNSS are illustrated in Figure 3-2. Data that is captured or generated on the satellite is referred to as Level 0 data. The two HydroGNSS satellites will generate data:

- Level 0a – raw IF sampled continuously by the SGR-ReSI-Z. Due to the large file sizes of level 0a data generated on-board, and the limitations of the payload downlink rate, apart from scheduled captures of 1 to 3 minute bursts, the rest of the level 0a data cannot be downloaded from the satellite.
- Level 0b – compressed DDMs continuously generated using the SGR-ReSI's ZTC processing unit, in compact SSTL format, which are downloaded from the satellite. The DDMs are generated on-board from the level 0a data, for 4 or 5 simultaneous reflection tracks, each of which could be from a GPS or Galileo satellite:
    - GPS L1/L5 - LHCP and RHCP.
    - Galileo E1/E5a – LHCP and RHCP.
    - Coherent channel measurements are included for each DDM channel.
    - The L0b files also include SBPP packets, which are extracted as GL logs. These are used to collate L1a metadata and produce metadata for the small samples of downloaded raw data.

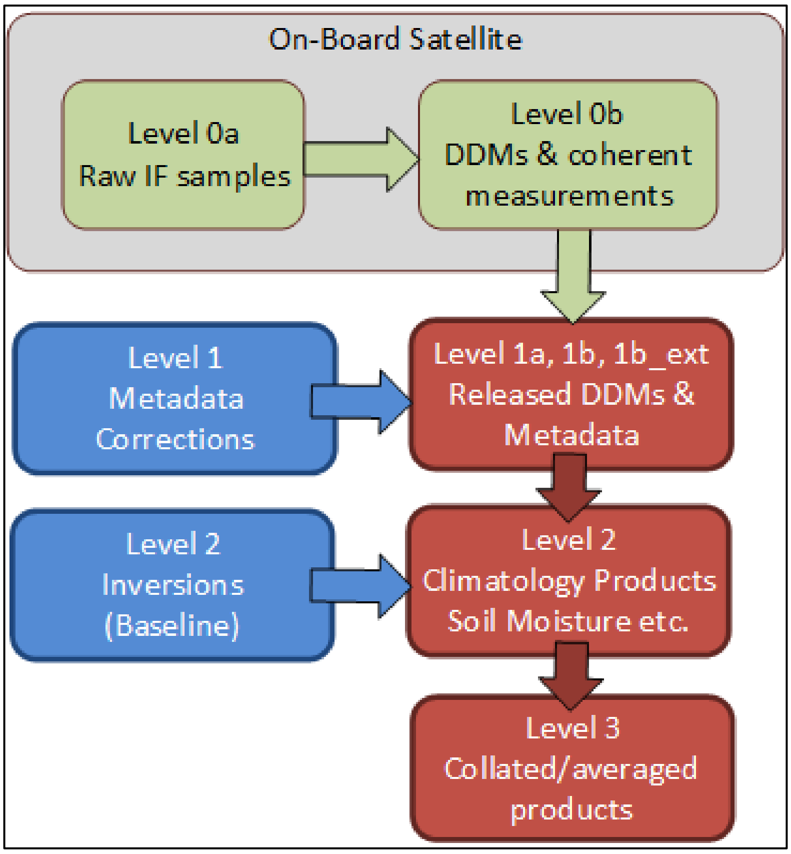

Figure 3-2: HydroGNSS product levels

On the ground the PDGS generates:

- Level 1a – DDMs and coherent measurements in NetCDF format, including collated metadata from GL logs, AOCS logs and thermal EWODs, and gain/noise floor corrections, zenith and nadir black body load measurements, GNSS direct signal measurements, and nadir antenna gain at the specular point using attitude data. The collated metadata should be deterministic, i.e. not depending on specific models or algorithms.
- Level 1b – Level 1b core metadata, i.e. derived corrections, including radiometric corrections, and quality warning flags. The 1b metadata will include corrections based on specific models, and may include versions of the same corrections derived from different models or sources. The L1b metadata also includes derived parameters required by the L2 processors, such as reflectivity (Γ) and bistatic scattering coefficient (σ_o), and direct transmitter power corrections.
- Level1b_ext (NOC) – further calibration corrections, based on *a posteriori* data gathered over oceans, and further quality flags.
- Level1b_ext (IEEC) – coherence coefficient for coherent measurements (CC) and power spread ratio for incoherent measurements (CX).
- L1MergedMetadata – a file combining the L1a, L1b and L1b_ext metadata.
- Level 2 – Trackwise hydrological climate variables derived from inversions of the DDMs, the primary mission objectives:
  - Soil moisture, Inundation/wetlands, Soil freeze/thaw state, Forest Above Ground Biomass
- Additional Level 2 products, as secondary mission objectives:
  - Ocean wind speed, Sea ice extent.
- Level 3 – Gridded Level 2 products, averaged over a time period (day/month(s)), with data merged from the two satellites.

There are some differences in the definition of the products compared to TDS-1 products, as listed in Table 3-3: .

Product	TDS-1/DOT-1	HydroGNSS
Raw IF **sampled data from SGR-ReSI – in orbit.**	Level L0	Level 0A
DDM output from SGR-ReSI in SSTL proprietary format – in orbit.	Level 1A_bin	Level 0B
DDM with collated metadata in NetCDF format	N/A – MERRByS only delivers Level1B in NetCDF	Level 1A
Coherent measurements in NetCDF format	N/A	Level 1A
DDM derived from raw sampled data by on-ground software receiver	Level 1A (SW)	Level 1A (SW)
Derived metadata, include corrected reflectivities	(Level 1B)	Level 1B
***A posteriori* power corrections**	Level 2 CBRE v1.0	Level 1B_ext (NOC)
Coherence coefficient	N/A	L1B_ext CC (IEEC)
Power Spread Ratio	N/A	L1B_ext CX (IEEC)
Soil Moisture L2OP	N/A	Level 2
Freeze Thaw L2OP	N/A	Level 2
Inundation L2OP	N/A	Level 2
Forest Above Ground Biomass L2OP	N/A	Level 2
Ocean Wind Speed, Sea Ice Extent	Level 2, CBRE v1.0	Level 2 (Secondary)

Table 3-3: Comparison of TDS-1/DOT-1 and HydroGNSS product levels

3.5 HYDROGNSS INNOVATIONS

To maintain compatibility with the previous successful TDS-1 and CYGNSS missions, HydroGNSS provides established GNSS-R measurements, based on incoherent Delay Doppler Maps (DDMs) from GPS C/A code at GPS L1 frequency (1.575GHz) at 1 Hz. In addition to these, HydroGNSS provides innovative GNSS-R measurements that have not been available previously:

3.5.1 Galileo Signals

DDMs are generated from Galileo E1, offering up to double the coverage from the same antenna field of view from GPS alone. The Galileo E1 code signals have a wider bandwidth than GPS C/A code signals and longer code lengths, meaning a smaller footprint on the ground, and better rejection of other signals. Both components of Galileo E1 (data and pilot) are used to increase the reflection strength.

3.5.2 Polarisation

DDMs are collected from both Left- and Right-Hand Circular Polarisation (LHCP, RHCP) ports of the antenna. GNSS signals are transmitted in RHCP, but there is a phase change on reflection, so the primary reflections are LHCP, and secondary reflections are RHCP. The ratio of the two polarisations (RR/LR) can help separate soil roughness effects from soil moisture and also can play a role in separation of vegetation from ground reflections.

3.5.3 Coherent complex channel

A channel is added to each Delay Doppler Map (for both polarisations and frequencies, and GPS/Galileo) that aims to capture the coherent amplitude and phase of the signal at the specular reflection point at a higher rate than DDMs. This allows further separation of flat surfaces, and accesses higher resolution than the incoherent DDMs. It gives the flexibility to access longer integrations for weaker signals, and it may also allow retrieval of altimetric measurements under certain conditions.

3.5.4 Second frequency

The ability to sample signals prior to processing on-board will be used to capture both L1/E1 signals, and the wide bandwidth L5/E5 GNSS signals. Models suggest that the wideband signals reflected may be weak but, if proved viable, the rewards would be higher resolution from these signals. As the instrument is reprogrammable, it is planned to exercise E5/L5 on-board processing schemes while the mission is in orbit.

3.5.5 Other Innovations

On HydroGNSS a software-based Automatic Gain Control is used that allows optimal setting of 2-bit sampling, while still allowing a report of the gain control, supporting signal power measurement. Another innovation is that the Delay Doppler Maps are centred within the instrument on the calculated geolocated position of the specular point.

3.6 MEASUREMENT COVERAGE

HydroGNSS comprises of two satellites that will be launched together into a near-polar orbit, at 550 km altitude and 10:30 am LTAN sun-synchronous, and then phased apart by 180 degrees. Simulations indicate a coverage over the Earth in 15 days (84%), assuming a resolution of 0.25° x 0.25° (equivalent to 27 km x 27 km at the equator), and an antenna Field of View of approximately 45°. The revisit time is illustrated in Figure 3-3; the mean revisit time in this orbit at any point on the globe is calculated as less than 3 days. Near the poles, the density of coverage is higher and revisit time lower.

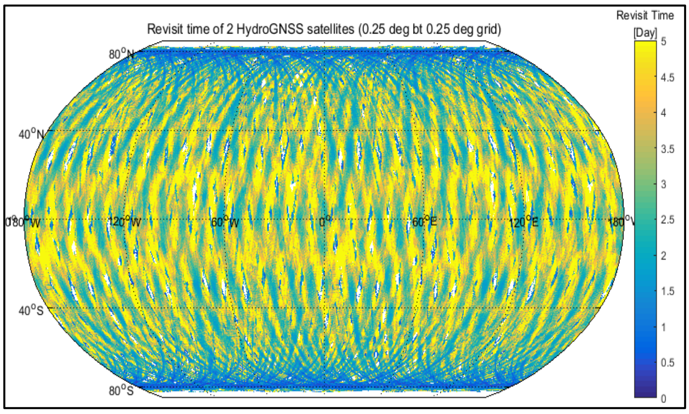

Figure 3-3: Simulated revisit time of 2 HydroGNSS satellites over globe

3.7 CALIBRATION APPROACH

Based on experience from TDS-1 and other missions, achieving good absolute calibrated performance is an important requirement of HydroGNSS. Pre-launch tests were carried out to measure the instrument noise figure, receiver gain and antenna patterns. In orbit, spacecraft attitude, Low Noise Amplifier temperature and direct signal powers are used to apply corrections to GNSS-R measurements. A diagram showing factors affecting calibration is given in Figure 3-4.

1. The receiver RF gain can be estimated using black-body loads from the nadir and zenith LNAs, which allows measurement of the antenna noise. A target in the Antarctic can help verify knowledge stability.

2. The receiving antenna patterns for both satellites are measured accurately prior to launch, while mounted on the flight satellite platforms. The antenna patterns can be verified using long-term data over the ocean.

3. The GNSS transmit powers and antenna patterns (for each GNSS satellite) are determined by the L1BOP-DX-L learning module, at the beginning of the mission and every time there are new GNSS satellites commissioned. Each month L1BOP-DX-L is run to compare the measured transmit power and antenna pattern against previous months data, this is performed using the direct L1/E1 signal data. This allows up-to-date and accurate transmitter powers to be used in calibration method CM1. An alternative calibration mode (CM3) can use the instantaneous transmitted GNSS power for correcting the incident power, see AD-2. Figure 3-4 illustrates the factors affecting measurement of the reflection coefficient at the specular point, including direct powers, antenna patterns, antenna noise.

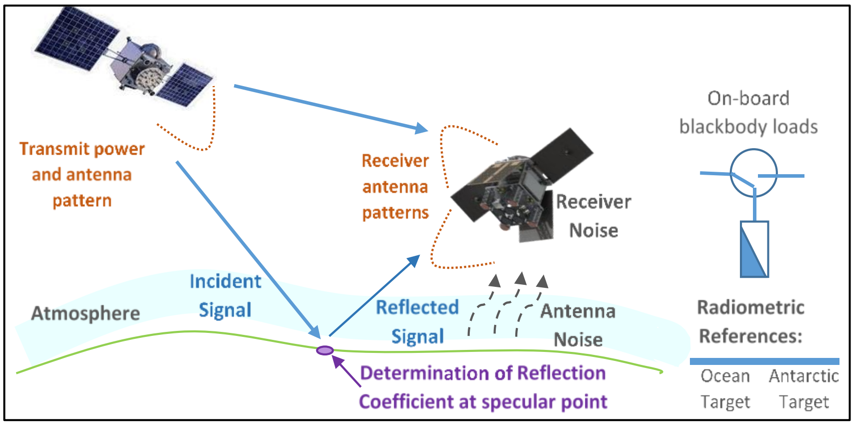

Figure 3-4: Measurement of Reflection Coefficient at Specular Point

4 USER REGISTRATION AND ESA DATA USE POLICY

All HydroGNSS Level 1, Level 2, and Level 3 products (see 3.2) can be downloaded for free for registrants. Users must first register using the form on the HydroGNSS website, AD-9. Users must agree to accept the ESA Data Use Policy and Terms and Conditions: see https://earth.esa.int/eogateway/documents/20142/1564626/ESA-Data-Policy-ESA-PB-EO-2010-54.pdf, and https://earth.esa.int/eogateway/documents/20142/1564626/Terms-and-Conditions-for-the-use-of-ESA-Data.pdf.

Users will then be sent credentials to download the HydroGNSS products from the HydroGNSS User FTP site. The website, AD-9, contains Python and Matlab code samples showing how to download and read the data from the Level 1 and Level 2 NetCDF files.

The HydroGNSS User FTP site will be available to register users on:

Hostname: sftp.hydrognss.org

Protocol: SFTP

Port: 2222

5 THE HYDROGNSS PAYLOAD

5.1 THE PAYLOAD SUBSYSTEM

The HydroGNSS SGR-ReSI-Z payload (Figure 5-1) is an evolution from the SGR-ReSI remote sensing instrument flown on TDS-1 and CYGNSS. Figure 5-1 shows an overview of the payload, comprising nadir and zenith antennas, Low Noise Amplifiers (LNAs) and a Delay Doppler Mapping Receiver (DDMR, also known as SGR-ReSI-Z), and related cabling.

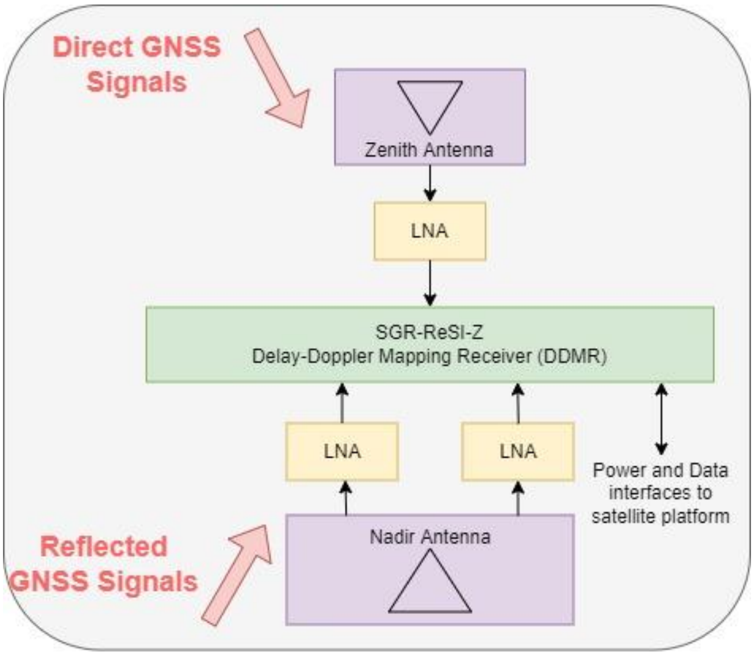

Figure 5-1 HydroGNSS payload elements overview

The zenith antenna is a single element dual frequency (L1/E1, L5/E5a) RHCP patch antenna that is used to track direct GNSS signals. The nadir antenna uses a fixed array of 2 x 2 dual-patch elements, giving a fixed-beam peak boresight gain of 11-12 dBi and low cross-polar reception for each channel, L1 LHCP, RHCP and L5 LHCP and RHCP. This is a lower antenna gain than achieved by TDS-1 at L1 LHCP but is compensated by lower Noise Figures in the LNAs, to give similar expected performance. There are two LNAs to receive LHCP and RHCP nadir reflections respectively and one for the zenith RHCP channel. Each LNA includes cavity filters for both frequencies, temperature sensor, load switch and test ports.

Within the DDMR, two quad channel front-ends are used to collect signals from nadir and zenith channels. A Zynq processor with FPGA is responsible for tracking the GNSS signals and processing the Delay Doppler Maps. A Zoom Transform Correlator (ZTC) block is implemented in VHDL within the Zynq processor, and is driven by the application software running on the Zynq. Reflected signals from the nadir antenna are sampled and processed near-continuously by the DDMR into Delay Doppler Maps. Once collected, the Level 0 data are sent to the data recorder in the satellite platform for later download.

The key instrument performance parameters have been defined that affect Level 1 and Level 2 results, and include GNSS sensitivity, stability and the performance of the signal processing approach used.

5.1.1 Zenith Antenna

The zenith antenna is used to acquire signals directly from the GNSS constellations for the purposes of performing navigation, timing and priming reflectometry channels. Signals from the zenith can also be used to enable calibration of the transmit power from each satellite in the GNSS constellation. The zenith antenna is a single element Dual-band All Metal Patch (DAMP) antenna designed to receive signals at GNSS L1 & L5 bands in both RHCP and LHCP. Due to the small size of the satellite, the zenith antenna had to be mounted within the attach-fitting of the satellite and close to the deployable solar panels, causing perturbations in comparison to the pattern of the stand-alone antenna. The pattern of the antenna was therefore measured using a structural model of the space-facet of the satellite and an Engineering Model zenith antenna identical to flight models. The L1/E1 pattern knowledge is recorded and used in the PDGS, and may be refined in orbit using direct signals. The pattern at L5/E5a is also recorded but is not used within the PDGS in the project baseline. Zenith antenna characteristics are shown in Table 5-1.

Parameter	Specs
Centre Freq	1575.42MHz +/- 10 MHz, (E1 / L1) 1176.45 MHz +/ 10 MHz (E5a / L5)
Feed	Single RHCP feed
Peak Gain	Approx. 7 dBi peak gain at L1, 4 dBi at L5 Higher directionality than standard GNSS antennas, but high efficiency means low elevation satellites are still accessible.

Table 5-1: Characteristics of Zenith Antenna

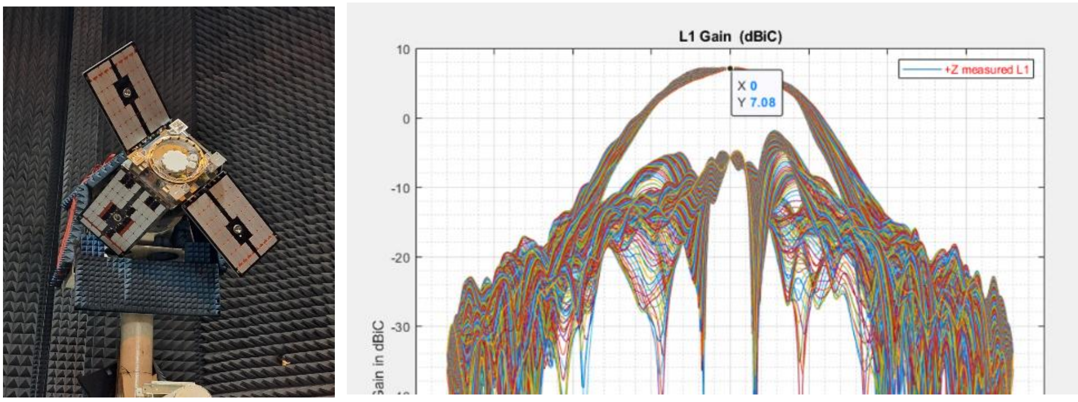

Figure 5-2 left) Antenna Pattern Test at BAe AI Labs, Aug 2024,
Right) Measured Gain of Installed Zenith Antenna at L1/E1 band (Co-and cross polarisation)

5.1.2 Payload Nadir Antenna

The nadir antenna is a fixed array 2 x 2 element DAMP antenna and is used for collecting reflections at L1/E1 and L5/E5a from its LHCP and RHCP ports. The patterns of the stand-alone antennas are affected by the installation on the satellite, so tests have been undertaken to characterise the antenna patterns when mounted on the real flight model satellites. Patterns are recorded and used for processing in the Level 1 processor for correcting reflectivities for antenna gain.

Characteristics of the HydroGNSS nadir antenna are listed in

Channel	FM1 L1 LHCP	FM1 L1 RHCP	FM1 L5 LHCP	FM1 L5 RHCP	FM2 L1 LHCP	FM2 L1 RHCP	FM2 L5 LHCP	FM2 L5 RHCP
Peak Ant Gain dBi	10.8	11.1	11.0	11.3	12.3	12.0	11.5	11.6

Table 5-2.

Parameter	Specs							
Centre Freq	1575.42MHz +/- 10 MHz, (E1 / L1) 1176.45 MHz +/ 10 MHz (E5a / L5)							
Dual Feed	RHCP and LHCP ports							
Peak Gain	Approx 11-12 dBi for each frequency and polarisation (some variation with different ports and antennas)							
Beamwidth	Beamwidth – 6 dB drop at 40° for L1, 53° for L5 (full angles)							
Cross polar rejection	>20 dB at boresight, approximately 12 dB or better across beamwidth							
Channel	FM1 L1 LHCP	FM1 L1 RHCP	FM1 L5 LHCP	FM1 L5 RHCP	FM2 L1 LHCP	FM2 L1 RHCP	FM2 L5 LHCP	FM2 L5 RHCP

Peak Ant Gain dBi	10.8	11.1	11.0	11.3	12.3	12.0	11.5	11.6

Table 5-2: Characteristics of Nadir Antenna (Installed)

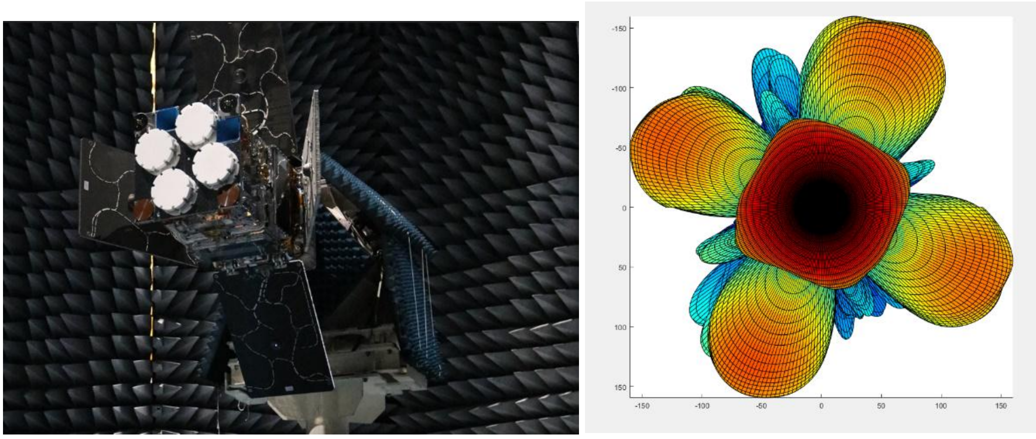

Figure 5-3 (left) FM 1, Antenna Pattern Test at BAe AI Labs, Jan 2025, (Right) Plotted L1/E1 band co-polar pattern

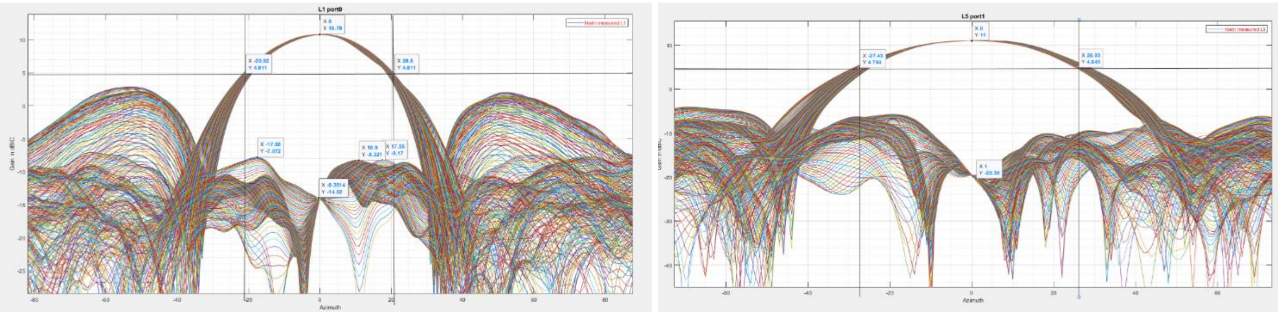

Figure 5-4 Antenna Pattern Test results FM1 Co-and cross polarisation, BAe AI Labs, Aug 2024, (Left) L1/E1 pattern, (right) L5/E5a pattern

5.1.3 LNA Modules

Figure 5-5 HydroGNSS LNA

The LNA (low noise amplifier) module amplifies the received GNSS signals and is key to setting the overall Noise Figure of the receiver Figure 5-5 HydroGNSS LNA. The LNA amplifies both L1/E1 and L5/E5a GNSS signals, whilst filtering out unwanted signals from out of band transmissions. To minimise loss of signal-to-noise power, it is essential to minimise losses in the receiver chain prior to the amplification stage. Three identical LNA Modules are included – one each for the two nadir channels and one for the zenith channel. The LNAs have been characterised, and a summary is given in Table 5-3, including Noise Figures at room temperature (23°C), and NF gradient with temperature.

Parameter	FM1 L1 LHCP	FM1 L1 RHCP	FM1 L5 LHCP	FM1 L5 RHCP	FM2 L1 LHCP	FM2 L1 RHCP	FM2 L5 LHCP	FM2 L5 RHCP
Cable 1 dB	0.25	0.26	0.20	0.21	0.25	0.26	0.20	0.21
Gain R/T dB	29.5	29.8	30.1	29.7	29.7	29.6	29.7	29.9
NF R/T dB	0.97	0.95	1.08	1.12	1.02	1.00	1.15	1.13
NFg dB/°C	0.0044	0.0046	0.0049	0.0040	0.0044	0.0047	0.0047	0.0046

Table 5-3: Characteristics of Nadir LNAs

5.1.4 The Delay Doppler Mapping Receiver (DDMR)

The DDMR implementation on HydroGNSS is named the "SGR-ReSI-Z". This indicates its heritage as a derivative of the SGR-ReSI flown on TDS-1 and CYGNSS but is also based upon the Zynq circuitry that was demonstrated in orbit on the DoT-1 mission.

The DDMR has several functions which are summarised here:

- The DDMR is a GNSS receiver that acquires, tracks and positions in LEO, using direct GNSS signals from a zenith antenna.
- The DDMR can collect the data directly out of the front ends (referred to as raw sampled, uncorrelated, or I/Q data) at the sample clock rate, and store these in an on-board memory storage. This allows the collection of small periods (no more than a few minutes) of nadir and zenith data for later playback on the ground through a software receiver. This raw sample data is sent out over the high-speed interface to the SSTL data recorder (this forms the L0a raw data product).
- Based on its on-board knowledge of its position and the GNSS satellite positions, the DDMR predicts the locations of the GNSS reflections on the Earth's surface, and computes a short-list of reflection specular points, and their expected delay and Doppler shift.
- The DDMR allocates four Delay Doppler Map channels to the most favourable four reflections. Each of these channels uses a VHDL-implemented Zoom-Transform-Correlator (ZTC) to create a Delay Doppler Map of the reflection at both L1 & L5 frequencies for both polarisations received.
- On TDS-1 & CYGNSS, the DDM was centred on the Earth's ellipsoid surface, which meant that over land the location of the reflected signal within the DDM changed and was lost over high altitudes. On HydroGNSS, there is an on-board Digital Elevation Model that is used to centre the DDM near the expected reflection point, ensuring the reflected signal is always captured. The resolution of the on-board DEM is nominally 5 km x 5 km [AD-2].
- The DDM has a grid of pixels with spacing in Delay and Doppler.

  The bit depth is nominally 32 bits in the VHDL, but a variable rate quantisation algorithm (VRQ) has been implemented to reduce this (as per TechDemoSat-1).
- The DDMR primarily operates off GPS satellites using L1 C/A code signals, but also tracks direct Galileo signals, and selects the optimal four reflections signals from both constellations for Delay Doppler Mapping.
- Each reflected signal allocation (e.g. L1C/A and E5a) has two DDM windows allocated – one for LHCP signals and one for RHCP signals
- Each Delay Doppler Map is accompanied by a coherent pixel that coherently integrates amplitude and phase. The nominal duration is 1 ms, so 1000 values of complex output (I&Q) are generated each second. The central pixel and one pixel either side, offset by the pixel delay spacing, are provided.
- Delay-Doppler Maps are collected for both L1/E1 and L5/E5a frequencies, with L5/E5a reflections allocation derived from the L1/E1 direct signal tracking.

5.1.5 Payload Instrument Reflection Processing Configuration

The SSTL ZTC produces two major products, the incoherent DDM and coherent measurements. The nominal configuration settings (compared to CYGNSS) are given below:

Setting	CYGNSS L1	HydroGNSS L1/E1	HydroGNSS L5/E5
DDM Settings			

Incoherent Integration Period	1000	250	250
Coherent integration period	1 ms	4 ms	4 ms
DDM output period	1 Hz (2 Hz over land)	1 Hz	1 Hz
Delay Range of pixels	128 (uncompressed)	52	52
Delay Spacing in samples (and in time equivalent)	4 (249.4 ns)	12 (226.44 ns)	4 (75.48 ns)
Delay Offset (DDM centre)	0	0	0
Doppler range of pixels	20 (uncompressed)	20	20
Doppler Spacing	500 Hz	125 Hz	125 Hz
Coherent Channel Settings			
Coherent Integration Period, Output rate	N/A	4 ms, 250 Hz	4 ms, 250 Hz
Coherent Pixel Sample Points	N/A	3 delay points at DDM spacing	3 delay points at DDM spacing

Table 5-4: ZTC Nominal Configurations

5.1.6 Ancillary data

Alongside the main data products generated by the SGR-ReSI-Z, a number of ancillary data are generated, to assist in the generation of the L1 & L2 data products on the ground. Metadata generated by the SGR-ReSI-Z is added to the data stream in the data headers, adding a small overhead to the data rates for the DDM data captures. Further ancillary data is added in the form of SBPP packets, which are extracted to form the GL log by the L1AOP in the PDGS.

The ancillary data includes:

- GNSS receiver reported position, velocity and time
- Measured direct signal power
- Software & firmware version number(s)
- Configuration of measurements from SGR-ReSI-Z settings
- ZTC status flags
- LNA temperature readings
- DEM height and geoid correction applied on-board in specular point location calculation
- GNSS satellite positions and velocities from broadcast ephemerides
- Specular point positions
- Front-end gain settings
- ADC statistics
- Blackbody DDM readings

Additional ancillary data is obtained from other subsystems on the spacecraft and derived from the science data, i.e. notably the attitude data from AOCS EWODs, and the antenna temperatures from the thermal EWODS. This is extracted by the PDGS to make up the full complement of ancillary data included in the Level 1a metadata.

5.2 L0B - ONBOARD PROCESSING

The SGR-ReSI-Z reflectometry onboard processing flow is summarised below:

5.2.1.1 Reflection Tracking

Reflected GNSS signals are weak and distorted, and so standard GNSS closed loop tracking techniques are not possible. Instead, a geometrically derived estimate of delay and Doppler can be calculated for each reflection within the satellite's footprint in order to prime the Digitally Controlled Oscillators (DCOs) of the DDM co-processor.

Three specific algorithms are required: a) Specular point location calculation, b) Calculation of the delay and Doppler estimates for the specular reflection path. c) Allocation of reflections to processing channels.

5.2.1.2 Specular Point Location

The specular point is the location on the Earth's surface, by the laws of reflection, where the incident and reflection rays have equal angle to the surface normal. Alternatively, the definition is the point on the Earth which has the minimum path-length from transmitter to Earth to receiver. The reflection location is calculated based on an ellipsoidal Earth model adjusted accounting for the Earth's geoid, and over the land, a digital elevation model and an adjustment for the slope (further described in AD-2).

5.2.1.3 Delay and Doppler Determination

For real-time processing the DDM correlators need to be steered to the location of the specular point. This requires the internal replica code delay and carrier frequency (of the chosen offset in the DDM) to match that of the reflection signal. The expected delay and Doppler is calculated given the position and velocities of the transmitter and receiver and the specular point location.

The open-loop reflection tracking scheme runs in the instrument in real-time. The implementation of the tracking is designed to provide the tracking updates to the DDM processor synchronised to the direct signals despite the calculation latency. To do this the receiver, transmitter and specular point locations are updated at a rate of 1 Hz, used to calculate the tracking parameters, which are then extrapolated to provide 10 Hz updates. The updates are applied to each reflection channel's code phase, code rate and carrier frequency.

5.2.1.4 Allocation

The aim of the allocation algorithm is to choose the reflections to track that have the highest signal to noise ratio. This is based on the assumption that a higher signal to noise ratio in the DDM will result in a better estimation of the scattering cross-section of the surface. For the chosen allocation algorithm, the difference in signal to noise ratio between the available reflections is assumed to be dominated by the antenna gain pointed at each.

The reflection channel allocation approach creates a sorted list of reflections, with the 'best' reflections (those with the highest antenna gain) at the top of the list. The allocation algorithm then uses this list to allocate the top reflections (GPS L1 or Galileo E1) to the available reflectometry channels, taking into account which of the antennas has the highest gain towards the reflection.

There are 16 reflection channels available within the instrument, but each has a pair of channels allocated for LHCP and RHCP reception. Initially 8 reflections are targeted, but where a signal is found to support L5 or E5a, then two more channels are allocated to the same reflection in this band. At time of writing, all Galileo satellites broadcast E5 signals but only 50% of GPS satellites transmit L5. This means that if the instrument sees four reflections with dual frequencies, all channels will be used on those reflections, but often, it will be tracking five reflections, two of which will not have L5 signals available or tracked.

5.2.2 DDM Processing

The DDM processing is performed in the Zynq processor and follows the work implemented in TDS-1 described in [JAL12]. The processing approach calculates the Doppler pixels in the frequency domain to reduce the computational complexity. This approach was chosen due to its suitability for implementation in an FPGA. The implementation of this approach is called the Zoom Transform Correlator (ZTC). The diagrammatic representation of this technique is shown in Figure 5-6. The advantage of this approach over that of individual discrete correlators per pixel is that the computational complexity can be reduced as the frequency search reduces to spectrum estimation, for which there are techniques that scale considerably better than with the number of pixels.

Each reflection channel is composed of the processing steps in Figure 5-6. A coarse carrier 'wipe-off' is performed to down-convert such that 0 Hz is the centre of the DDM, corresponding to the carrier frequency (including Doppler shift) of the specular path. This is followed by a set of channels that 'wipe-off' the code, each configured for the delay of a separate DDM row. The result of the coarse carrier wipe-off and code wipe-off leaves a demodulated signal at a small residual range of Doppler frequencies. This contains the full spectrum of Doppler shifts present for the chosen code phase. Performing spectrum estimation on it will return one row of DDM pixels simultaneously.

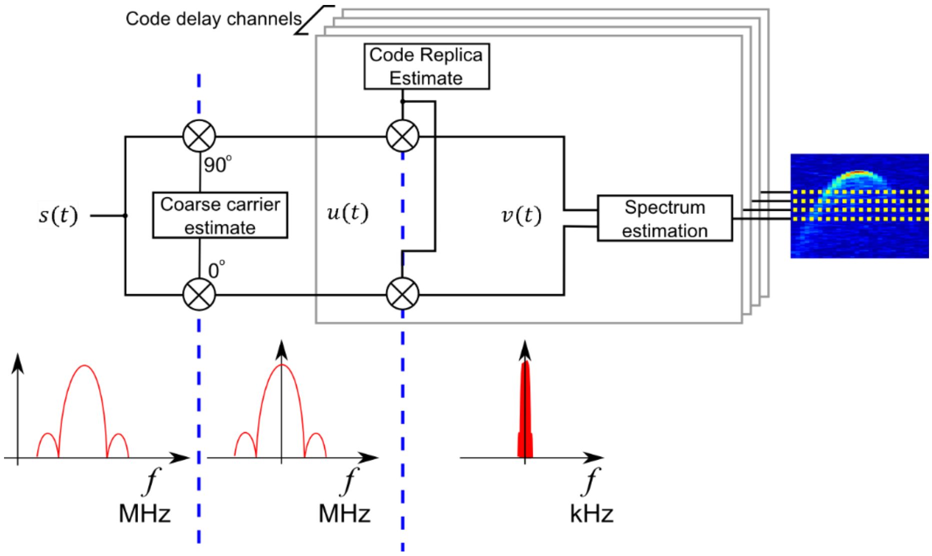

Figure 5-6 Computation of DDM row through process of down-conversion, modulation removal followed by spectrum estimation

The high sample rate used by the instrument means that a very wide range of Dopplers could be covered by each Delay Doppler map (many MHz), whereas the Doppler bandwidth of interest is just 10 kHz, meaning most calculations would be discarded. A way to perform the spectrum estimation over this narrow range is to decimate the signal to a lower sample rate then use a smaller size FFT. In some references this has been called the Zoom FFT [LYO04], hence referred to here as the Zoom Transform Correlator (ZTC). If the pre-decimation filter is constructed efficiently, the total number of operations is reduced. A drawback is that the band of interest will alias with bands at higher frequencies, but with care these alias zone can be placed at nulls in the frequency response, minimising contribution to the measurements of interest (see Figure 5-7).

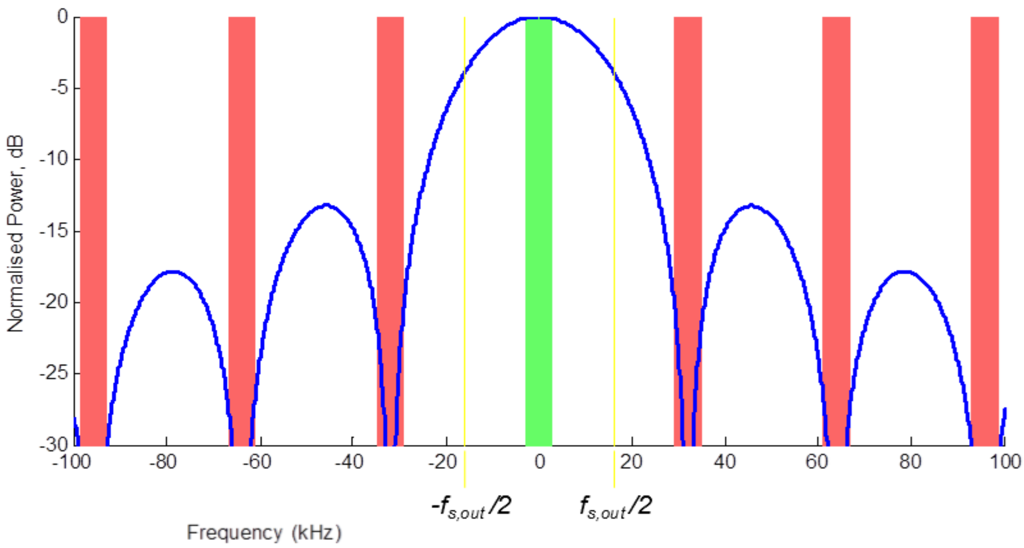

Figure 5-7 The filter response showing post-decimation aliasing.

This decimation greatly reduces the computational complexity of the spectrum estimation. The number of samples to process for a 1 ms coherent integration reduces from 16367 to 32. The discrete Fourier transform is then used with zero-padding, and central pixels are selected. This produces the 'coherent DDM', a number of these are added incoherently (adding $I^2 + Q^2$) to average over multiple looks, or 'incoherent accumulations'. Typically 1000 incoherent accumulations are carried out to produce a new DDM per channel every 1 second, but HydroGNSS has a baseline of using 4 millisecond integrations and 250 incoherent integrations.

5.2.3 Receiver Gain Control

The receiver front-ends are operated in a mode called 'swAGC'– this is where gain is automatically adjusted to an optimal point for 2-bit sampling and fixed for the duration of the measurement (for example 1 second). These adjustments to the gain are recorded, so it is possible to estimate the relative instrument gain from one measurement to the next while still allowing gain to change and match changing incoming powers, using the 2-bit samples at close to the optimal setting. The absolute gain can be determined through measurements taken by calibration loads and used to calibrate relative gains. The nominal switching cadence for the loads are as follows:

- The nadir load switches in once per 10 minutes for a duration of 5 seconds.
- The zenith load switches in once per 100 minutes for a period of 5 seconds

Further description can be found in the L1 processor ATBD [AD-2].

6 HYDROGNSS PDGS OVERVIEW

6.1 SUMMARY OF THE PDGS ALGORITHM PROCESSORS

The Payload Data Ground System (PDGS) components are referred to as processors. For level 1 these are L1OP, level 2 L2OP, and level 3 as L3OP. A summary of these components and the organisation/contractor delivering them is listed in Table 6-1.

Abbreviation	Description	Owner
L1AOP	Extracts GL log packets from L0b file, and writes them to a GL log file. Then converts L0b DDM stream in proprietary SSTL format to L1a NetCDF files, and creates metadata directly extracted from the L0b file, and the GL and other spacecraft logs.	SSTL
L1BOP	L1a to L1b, radiometric calibration for the receiver in the HydroGNSS payload, derived metadata including direct signals, and further data from auxiliary files. Also calculates GNSS satellite transmitter power corrections, using zenith antenna measurements of direct signals from the GNSS satellites.	SSTL
L1BOP-DX-L	L1b-Extension (SSTL) learning module, which determines GNSS satellite transmitter characteristics used for calibration methods CM1 and CM3, see section A.4 and AD-2.	SSTL
L1BOP-PX	Use of *a posteriori* data to correct L1/E1 signals for receiver antenna pattern. Then use data to correct for transmit patterns, and generate quality flags.	NOC
L1BOP-PX-L	L1b-Extension (NOC) learning module.	NOC
L1BOP-CX	L1b_ext (IEEC) module, which calculates power spread ratios from incoherent measurements.	IEEC
L1BOP-CC	L1b_ext (IEEC) module, which calculates coherence coefficients from coherent measurements.	IEEC
L1OP-MM	L1a, L1b core, and L1b_ext metadata merge.	SSTL
L2OP-SSM	Generates Soil Moisture from DDMs augmented by coherent measurements and polarisation.	Sapienza (+TV)
L2OP-FT	Calculates Freeze / Thaw state from DDMs.	FMI
L2OP-SI	Calculates Surface Inundation flag from DDMs and coherent measurements for higher resolution.	IEEC
L2OP-FB	Calculates Forest Above Ground Biomass from Artificial Neural Network (ANN) approach from DDMs.	IFAC-CNR
L2OP-SWS	Generates Ocean Surface Wind Speed and Sea Ice Extent from Calibrated Bistatic Radar Equation for ocean, integrated waveforms for ice extent.	NOC
L3OP-FB	Monthly Forest Biomass product, collating L2OP-FB data from the previous 6 months from both HydroGNSS satellites.	IFAC
L3OP-FT	Daily freeze/thaw product, collating L2OP-FT data from both satellites for one day.	FMI
L3OP-SSM	Daily soil moisture product, collating L2OP-SSM data from both satellites for the previous 10 (TBC) days	Sapienza (+TV)

Table 6-1: Summary of L1OP, L2OP and L3OP

6.2 THE PDGS PROCESSING CHAIN

The main PDGS processing chain is depicted in Figure 6-1. The inputs to the main processing chain are the L0b payload data files (incorporating GL logs), AOCS logs and thermal EWODs (Extended Whole Orbit Data) downloaded from the satellite. In addition, orbital elements of the GPS and Galileo satellites, topographic data consisting of global Digital Elevation Maps (DEMs), and on-board antenna parameters are used to generate metadata. The processor modules developed by the Mission Science Partners are shown as pink rectangles in Figure 6-1.

An SSTL L1a processor extracts a GL log from each level 0b data file, and then processes the level 0b DDMs and coherent measurements into a standard level 1a NetCDF format, and generates L1a metadata files collated from GNSS files, GL logs, AOCS logs, and thermal WODs.

An SSTL L1b core processor generates metadata including radiometric corrections based on the black body nadir and zenith sources, and also includes data quality flags, to form a level 1b product. The Specular Point (SP) is calculated on-board. The L1b format allows for the SP to be recalculated on-ground with a high-resolution DEM, i.e. US NGA EGM96 geoid, see RD-6, but the baseline L1b functionality is to is to re-calculate the SP position using GNSS broadcast orbits from RINEX files. The SSTL L1b processor also provides transmitter power corrections based on direct signal measurements.

A NOC L1b_ext processor generates metadata including *a posteriori* GNSS transmitter power corrections and HydroGNSS receiver gain corrections, using calibration data from HydroGNSS ocean data. The NOC L1b processor also generates quality flags.

An IEEC L1b_ext processor provides coherent channel metadata, including the coherence coefficient. A second IEEC L1b_ext processor provides incoherent channel metadata.

The Level 2/3 processors (see sections 10 and 11) generate the climate variables, including soil moisture, freeze/thaw, inundation, forest above ground biomass, ocean wind speed, and sea ice extent.

In addition to the modules shown in Figure 6-1, the PDGS generates discovery data from the L2 products, which are depictions of the climate variables on a global map, in the form of PNG and KML files. The discovery data is displayed on the HydroGNSS website, AD-9, and all L1, L2 and L3 NetCDF products can be downloaded from the User FTP site.

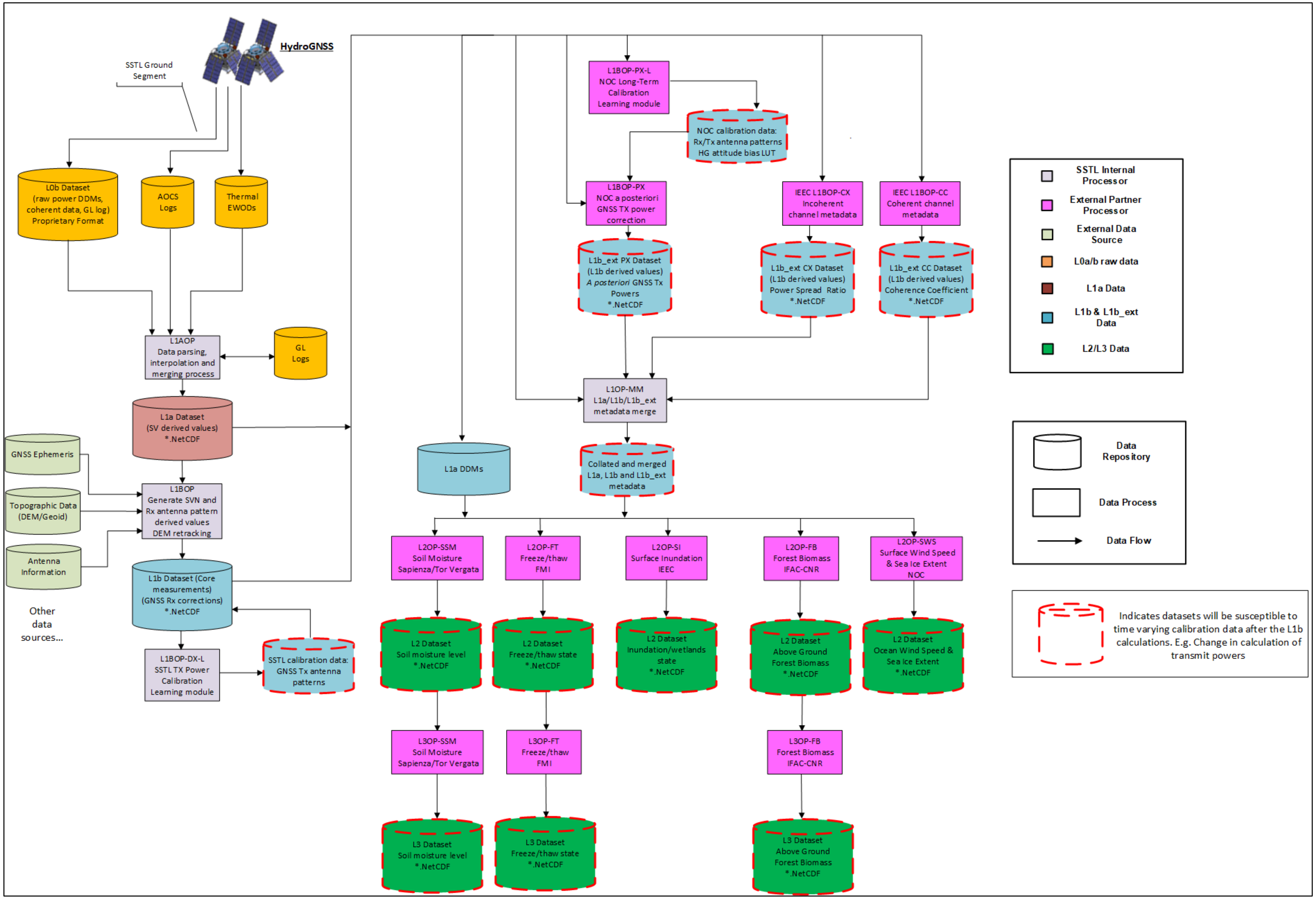

Figure 6-1: PDGS processing chain

7 USER FTP FOLDER STRUCTURE

The HydroGNSS User FTP server holds all L1, L2, and L3 products generated by the HydroGNSS PDGS.

The User FTP has the folders in Figure 7-1 below.

At the top level, there will be the folders:

- HydroGNSS1 – L1 and L2 products for HydroGNSS-1.
- HydroGNSS2 – L1 and L2 products for HydroGNSS-2.
- L3Products – L3 products with merged data from the two satellites, for Freeze Thaw, and Surface Soil Moisture in year-month/day folders, and Forest Biomass in year-month folders.

For further details of the folder structure, see Table 7-2 and Table 7-3.

7.1 L1/L2 DATA SEGMENTATION

L1 and L2 products are split into 6-hour segments and given an identification string based on the centre of this collection period. The format consists of year, month, day and hour, 'yyyy-mm/dd/Hhh'. The time of collection is 3 hours prior and 3 hours after this data identifier.

Data designation **yyyy-MM/dd/Hhh** **Examples:**	**Start time**	**Up-to (excluding)**
2025-06/30/H00	21:00	03:00
2025-06/30/H06	03:00	09:00
2025-06/30/H12	09:00	15:00
2025-06/30/H18	15:00	21:00

Table 7-1 Data segmentation times

There will be three levels of sub-folders for the 6-hour L1/L2 PDGS products on the User FTP, i.e. YYYY-MM\dd\Hhh, where:

- YYYY is the year
- MM is the month number
- dd is the day of the month
- hh is the hour of the data set.

An example would be 2026-03\08\H06.

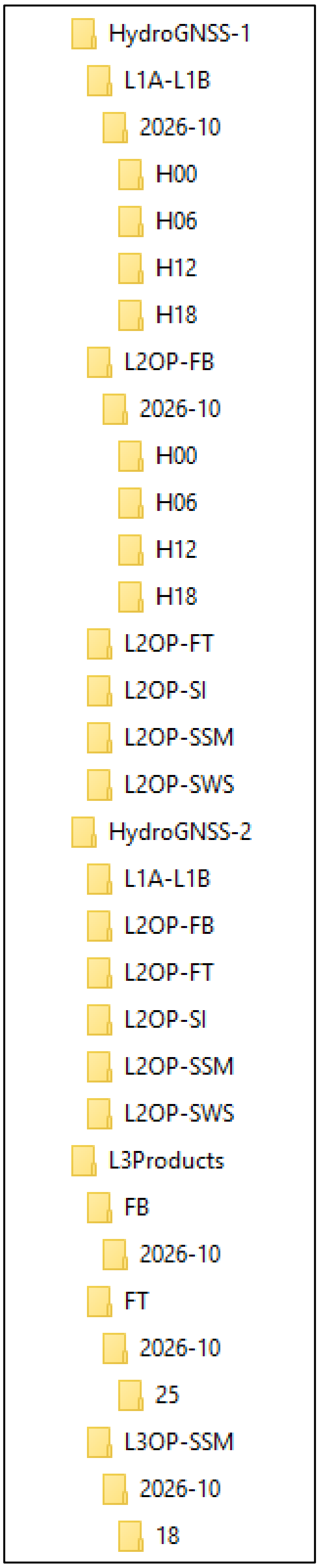

Figure 7-1: User FTP folders

Table 7-2 shows the top-level folder structure on the PDGS data archive, while Table 7-3 lists the sub-folders for each HydroGNSS satellite.

Folder	Description	Sub-folders	Files
HydroGNSS-1	L1 and L2 products for HydroGNSS-1		See Table 7-3
HydroGNSS-2	L1 and L2 products for HydroGNSS-2		See Table 7-3
L3Products	L3 products combining data from the two HydroGNSS satellite.		See Table 7-4

Table 7-2: User FTP top-level folder structure

Folder	Description	Sub-folders	Files
HydroGNSS-n/L1A-L1B	Including SSTL, NOC and IEEC collated and derived metadata, for both L1a and L1b.	yyyy-MM folders, with subfolder for each day, and 6-hourly sub-folders, e.g. 2021-07/20/H06. The four six hourly folders are H00, H06, H12 and H18, each covering a period ±3 hours either side of the labelled hour, e.g. H06 is from 03:00 to 09:00.	blackbodyNadirL1E1LHCP.nc blackbodyNadirL1E1RHCP.nc blackbodyNadirL5E5LHCP.nc blackbodyNadirL5E5RHCP.nc blackbodyZenithL1E1.nc blackbodyZenithL5E5.nc directSignalPowerL1E1.nc directSignalPowerL5E5.nc DDMs.nc CoherentMeasurements.nc metadata_L1_merged.nc (merged L1AOP, L1BOP, L1B_CC, L1B_CX, and L1BOP-PX metadata).
HydroGNSS-n /L2OP-SSM	Soil moisture level.	yyyy-MM/dd/Hhh sub-folders, as for L1A-L1B	L2OP-SSM.nc
HydroGNSS-n /L2OP-FT	Freeze/thaw state.		L2FT.nc
HydroGNSS-n /L2OP-SI	Inundation/wetlands state.		L2OP_SI.nc
HydroGNSS-n /L2OP-FB	Forest Above Ground Biomass.		L2OP-FB.nc
HydroGNSS-n /L2OP-SWS	Ocean wind speed and Sea ice extent.		L2OP_SWS.nc

Table 7-3: User FTP folder structure for each satellite

Folder	Description	Sub-folders	Files
L3Products/FB	Forest Biomass L3 products	yyyy-MM folders, e.g. 2018-08_2018-08.	L3OP-FB.nc
L3Products/FT	Freeze Thaw L3 products.	yyyy-MM folders, with subfolder for each day, e.g. 2018-02/26.	L3OP-FT.nc
L3Products/L3OP-SSM	Surface Soil Moisture L3 products.	yyyy-MM folders, with subfolder for each day, e.g. 2018-02/26.	L3OP-SSM.nc

Table 7-4: User FTP folder structure for L3 products

8 LEVEL 0 DATA FROM THE SPACECRAFT

The Level 0 data that comes from the spacecraft is separated into three types of files, as shown in Figure 8-1.

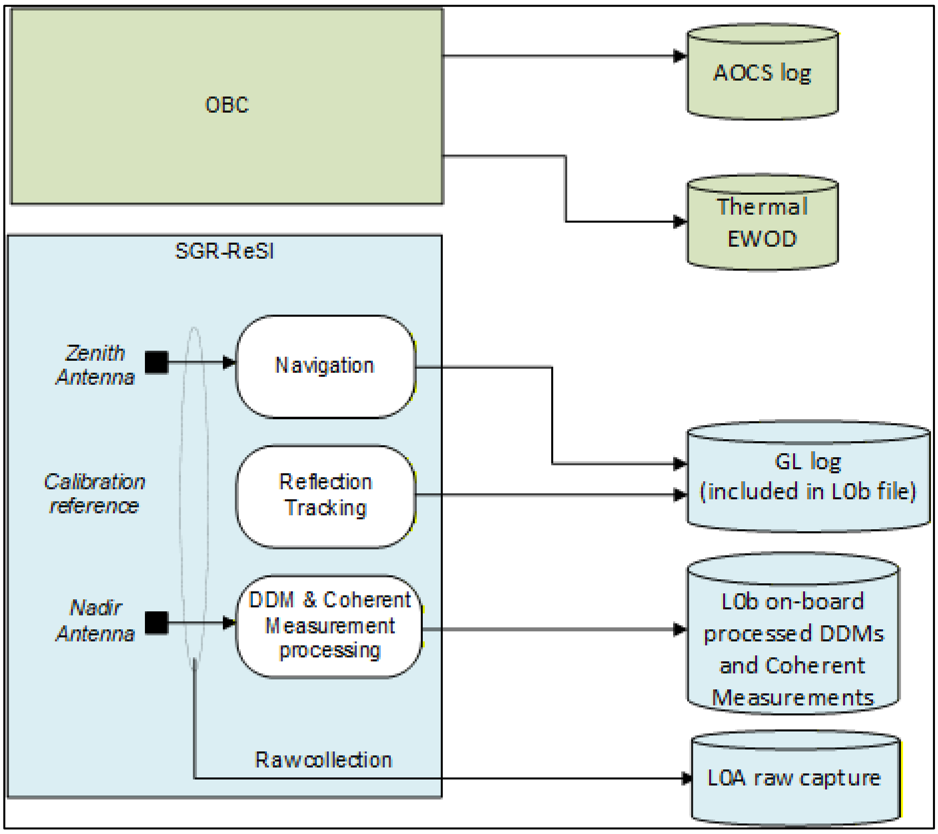

Figure 8-1 GNSS-R data types from the spacecraft

Types of data that come from the SGR-ReSI-Z unit:

- Routinely generated L0b Delay Doppler Maps and Coherent Measurements.
- Payload ancillary data, SBPP (SGR Binary Packet Protocol) file, which is the standard GNSS positioning output, plus special reflectometry status packets – this is referred to as the GL log. The GL log also includes instrument temperatures. For HydroGNSS, the GL log packets are merged into the L0b files, and are extracted by the L1AOP processor module.
- Raw IF L0a data acquisitions.

Platform ancillary data:

- AOCS log, a daily log file containing attitude data, and attitude error information.
- Thermal EWOD (Extended Whole Orbit Data) files, including the antenna temperatures.

8.1 SBPP/GL LOG DATA

Much of the metadata used to accompany the science data is retrieved from the GL log SGR-ReSI-Z telemetry. The full list of GL log data types is large and contains many types of data that are not relevant to reflectometry. The packet types/pages are not relevant to the data products used by the PDGS, so are not listed in this manual. The GL log data used by the PDGS are:

- Front End, PRN and GNSS signal for each ZTC channel.
- HydroGNSS orbit (PVT) data from GNSS signals.
- Black body data from the zenith and the four nadir antennas.
- Signal power and noise estimate per tracking channel.
- Reflectometry tracking lists.
- DEM height, ionospheric correction, geoid correction , and Doppler and delay offsets of reflected signal relative to direct signal.
- RF gain code, and IF coarse and fine gain codes, and bit distribution for each front end.
- Reflection geometry, and GNSS transmitter and specular point position and velocity.
- Temperatures of LNAs and RF front ends.
- GNSS broadcast ephemeris data.

8.2 GNSS-R PAYLOAD DATA

The SGR-ReSI-Z outputs two kinds of GNSS-R files – Level 0a (raw IF sampled) data, and Level 0b (ZTC) data consisting of DDMs and Coherent Measurements, with interspersed GL log packets.

9 LEVEL 1 PROCESSORS/PRODUCTS

See section A.3 for L1a output data formats.

9.1 L0B TO LEVEL 1A DDMS

		Format reference:
Inputs:	L0b on-board processed DDMs in an SSTL proprietary format, including up to 16 DDM/coherent channels.	Section A.2.
	Receiver status, LNA and receiver main board temperatures, and PVT from GL log file (included in L0b data stream)	-
	AOCS WOD data containing satellite attitude	-
	Thermal EWOD containing platform temperatures	-
Outputs:	L1a NetCDF DDM files, DDMs.nc	Section A.3.2.
	L1a NetCDF coherent pixel files, CoherentMeasurements.nc	Section A.3.2.
	L1a metadata file, metadata_1a.nc	Section A.3.1.
	Nadir black body files: • blackbodyNadirL1E1LHCP.nc • blackbodyNadirL1E1RHCP.nc • blackbodyNadirL5E5LHCP.nc • blackbodyNadirL5E5RHCP.nc	Section A.3.3.
	Zenith black body files: • blackbodyZenithE1L1.nc • blackbodyZenithE5L5.nc	Section A.3.3.
	GNSS direct signal files: • directSignalPowerL1E1.nc directSignalPowerL5E5.nc	Section A.3.4

Table 9-1 L0b to L1a processing

The processing flow takes the on-board processed DDMs and converts them into DDM products with synchronised metadata derived from the payload data, thermal EWODs, AOCS LOGS, and SBPP file/GL log. The overview of the data flow is shown in Figure 9-1 and described below. The detailed definitions are provided under the references above.

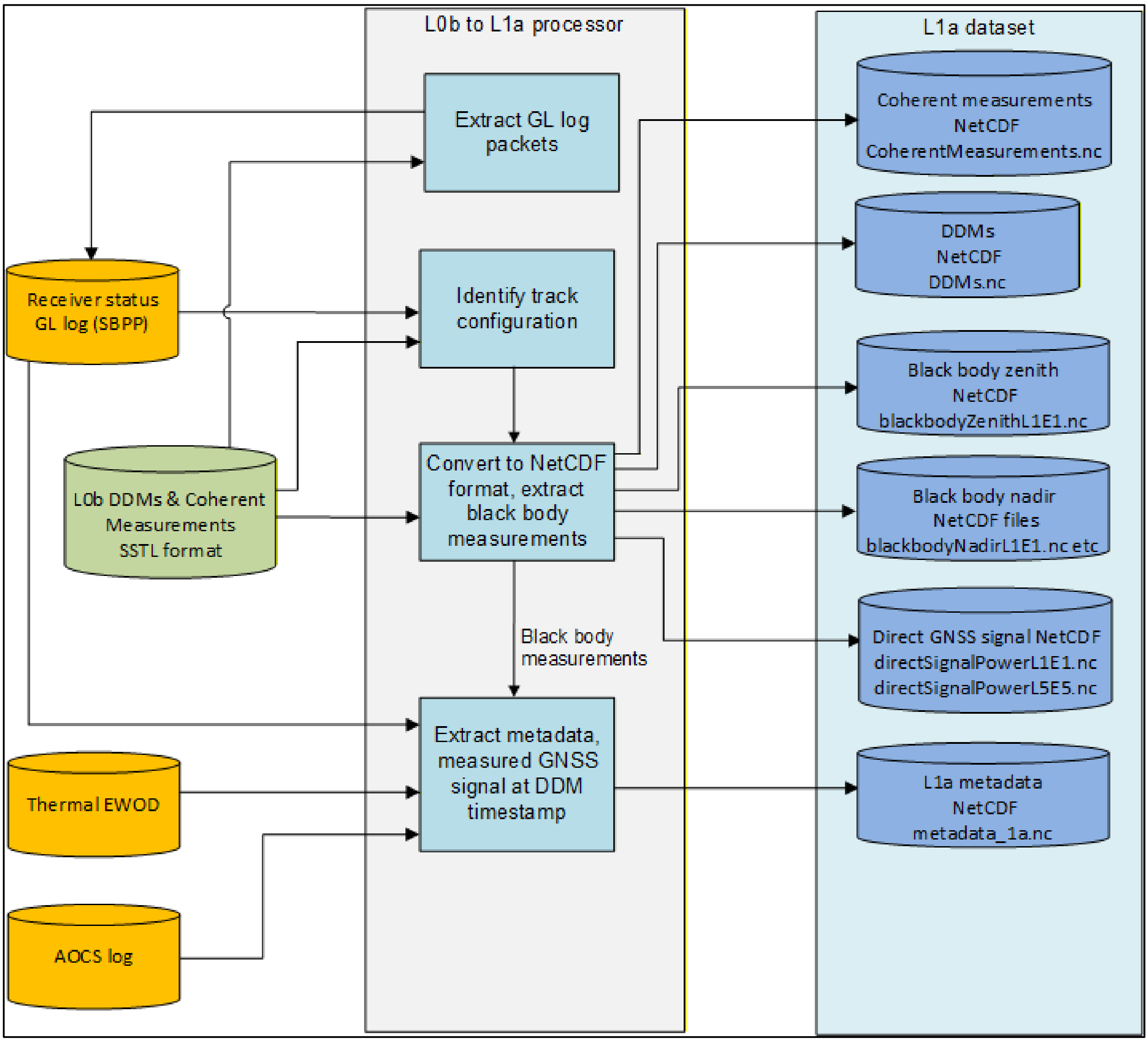

Figure 9-1 L0b to L1a processing flow

Each time the L0b to L1a processor module is run, it operates on a set of L0b data collected in a 6-hourly period, and all the resulting data products are placed in a folder for this 6-hourly period, see Table 7-3 for full details of the folder structure used.

The L0b to L1a processor module takes L0b DDMs downloaded from HydroGNSS. Each DDM is taken in turn and using the L1a DDM Track Headers and GL log data, the data is split into reflections. Each track is a series of DDMs that correspond to the same transmitter PRN and the same receiver processing settings. As the receiver has up to 16 reflection channels, DDMs will be added to 4/5 separate reflections simultaneously. HydroGNSS uses two frequencies for GPS/Galileo satellites, L1/E1 and L5/E5, and two polarisations (LHCP and RHCP). This means we have 16 DDM/ZTC channels. In addition, coherent data is included in each DDM channel. However it may be that the weakest signal, L5/E5 RHCP is not used, which would allow 5 simultaneous reflection tracks to be used. with just three ZTC channels per reflection track. The L1a processor will detect which of these configurations is in use from the Track Headers (see A.2.1), process the L0b data, and construct the L1a products accordingly. For details of the ZTC channel allocation, see AD-2, Appendix 3

Even if both polarisations and both frequencies are in use, some GNSS satellites do not have the L5/E5 signal. A reflection track from one of these satellites will only have two track channels, L1/E1 LHCP and L1/E1 RHCP. This means that at some epochs, there will be 5 or more simultaneous reflections.

A GL log is extracted from the L0b files for each 6-hour period. The DDMs are saved to a NetCDF4 file "***DDMs.nc***, coherent pixels to "***CoherentMeasurements.nc***" and all the metadata (including incoherent and coherent) is stored in the corresponding "***metadata_L1a.nc***". The separation of the data and metadata can reduce time to load and filter the data. Separate NetCDF files for the zenith and nadir antenna blackbody measurements for each signal/frequency combination are derived from the GL log:

- **blackbodyZenithE1L1.nc**
- **blackbodyZenithE5L5.nc**
- **blackbodyNadirL1E1LHCP.nc**
- **blackbodyNadirL1E1RHCP.nc**
- **blackbodyNadirL5E5LHCP.nc**
- **blackbodyNadirL5E5RHCP.nc**

The format of these NetCDF files is described in section A.3.3. Also, direct signal measurements from the GNSS satellites are output to "**directSignalPowerL1E1.nc**" and "**directSignalPowerL5E5.nc**", which are described in A.3.4.

For each DDM the metadata is found and synchronised to the DDM epoch, which is the midpoint between the start and end of the integration. The DDMs are output at 1 reflection per second in the nominal processing configuration, so the metadata is produced for each of these. For example, the receiver position is found from interpolating the lower-rate GL log packet data (the PVT packet was output at 0.1 Hz for TDS-1, but is at 1 Hz for HydroGNSS). Discrete metadata fields cannot be interpolated, so the previous GL log value is used. The coherent measurements are output at 250 Hz, and the timestamps are not synchronised with the DDM timestamps.

Where interpolation is needed, an Akima Spline Interpolation method is used. This is made up from piecewise third-order polynomials. Only data from the next neighbour points is used to determine the coefficients of the interpolation polynomial.

A DDM is discarded from the dataset if any of a number of self-consistency checks fail (between GL log and DDM stream packets). This discards DDMs from L0b datasets for a number of reasons, including if no coincident metadata is available in the GL log file, or if there are gaps in the data downloaded from the spacecraft.

The L1a metadata include:

1. HydroGNSS GNSS receiver reported position, velocity and time (from GL log)
2. HydroGNSS attitude, roll, pitch, yaw data.
3. Temperatures of on-board LNAs, receiver front ends, nadir/zenith antennas.
4. Parameters for each track in the DDM/Coherent Measurements file indicating:
   - Track identifier to correlate with DDM and Coherent Measurement tracks.
   - ZTC channel numbers used for the track
   - Whether it is GPS or Galileo, and the frequency (E1/L1/L5/E5) and polarisation (LHCP/RHCP)used.
   - Whether it was processed on-board or by the L1AOP-SW-RX software receiver in the PDGS. For the products on the User FTP server, this will always be processed on-board.
   - PRN, SVN of the GNSS transmitting satellite for each track.
   - Report of reflection height from on-board DEM/geoid.
   - GNSS satellite broadcast position and velocity in Cartesian ECEF coordinates.
   - Specular point locations generated on-board, as Cartesian ECEF coordinates, and latitude, longitude and height.
5. Status flags, configuration of measurements, direct cross-over flag.

The format is defined in full in section A.3.1.

9.2 L1A TO LEVEL 1B PRODUCTS

		Format reference:
Inputs:	L1a NetCDF DDM files, DDMs.nc	Section A.3.2
	L1a metadata file, metadata_1a.nc	Section A.3.1
	Nadir black body files, blackbodyNadirL1E1LHCP.nc etc.	Section A.3.3
	Zenith black body file, zenithBlackbodyL1E1.nc, etc.	Section A.3.3
	GNSS direct signal file, directSignalPowerL1E1.nc, etc.	Section A.3.4
	Antenna gain maps for looking up the gain of the nadir and zenith receiver antennas, and also the GNSS transmitter.	-
	Radiometric data, i.e. configuration data related to ReSI	-
	GPS transmitter SVN to PRN mapping table	-
	Galileo transmitter SVN to PRN mapping table	-
	Earth topographic map/DEM (USGS EROS GMTED2010) if specular point re-calculated	See RD-5
	Geoid model (US NGA EGM96) if specular point re-calculated	See RD-6
	Land Cover map (ESA-CCI 1 km/25km)	See RD-2
	Snow data from NOAA daily files	-
	Coast proximity from NOAA	-
Outputs:	L1b core metadata file, metadata_1b.nc	Section A.4
	L1b_ext_NOC metadata file: L1B_PX.nc	Section A.5.1
	L1b_ext_IEEC metadata files: L1B_CX.nc, L1B_CC.nc	Section A.5.2

Table 9-2 L1a to L1b processing

The processing flow takes the on-board processed DDMs and converts them into DDM products with synchronised metadata and radiometric calibration products. The overview of the data flow is shown in Figure 9-2, and described below. The detailed definitions are provided under the references above.

There are four components to the L1b processing as described in sections 9.2.1 to 9.2.3.

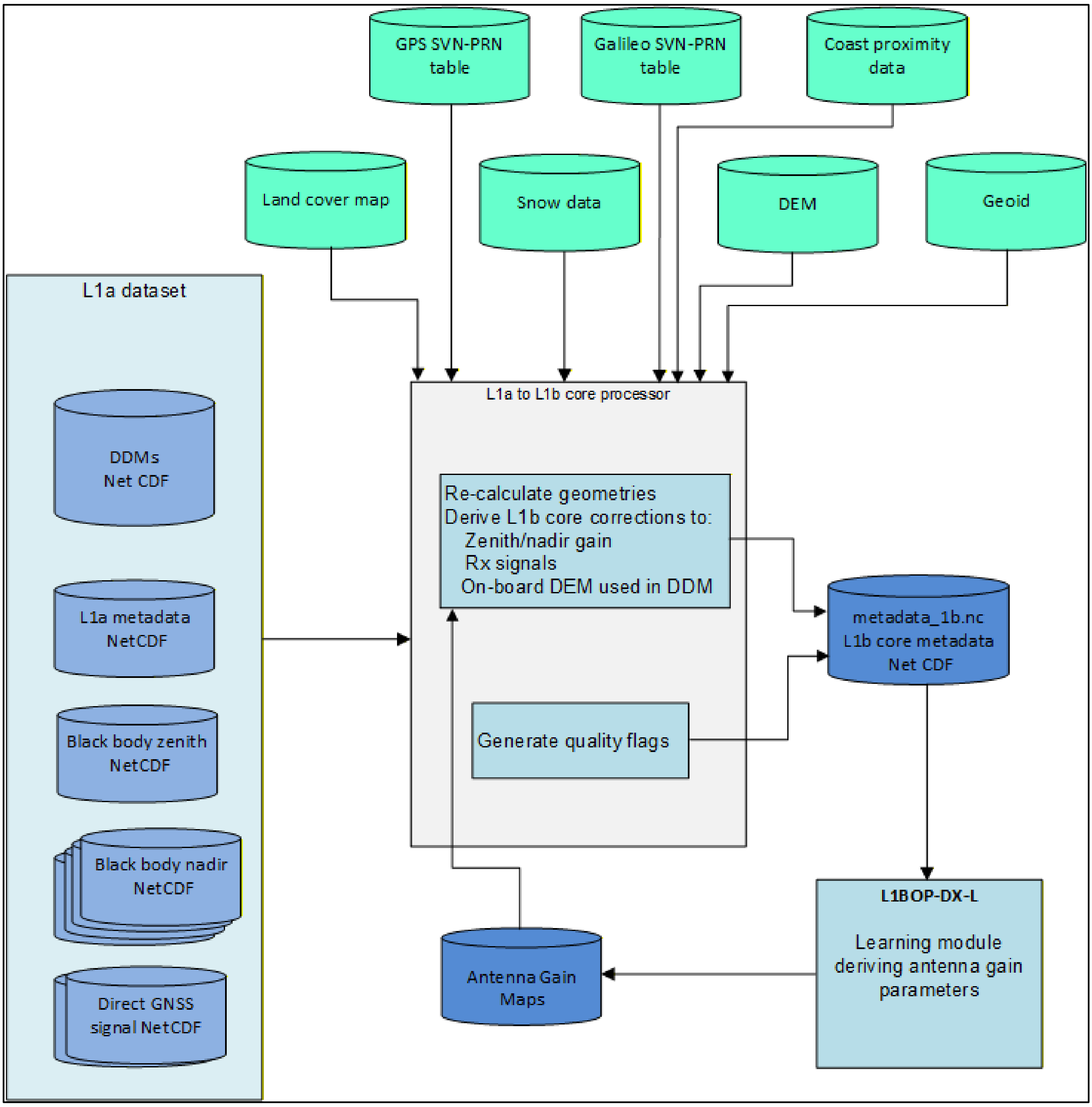

Figure 9-2 L1a to L1b core processing flow

9.2.1 SSTL L1b core processor

The baseline is that the results from the on-board calculations of the specular point location are used, but there is an option to re-calculate the specular point locations at L1b, using transmitter locations determined at the epoch time using ephemeris data from the International GNSS Service (IGS), and the specular point location algorithm which is defined in the L1a/L1b processors ATBD, AD-2.

By using the knowledge of the satellite's position, velocity and attitude the antenna gain is determined. The antenna gain is found from a look-up table stored in the Antenna Gain Map file. Using this file and the provided metadata, the antenna gain away from the specular ray is calculated. The receiver antenna gain pointed towards the specular point is provided in the metadata.

The on-board DEM and geoid may be replaced with the values from higher resolution maps held on the PDGS server, but this is not in the baseline functionality.

The level 1b metadata includes (see the ATBD, AD-2, for full details):

1. GNSS ephemerides (Re-use of those detected on-board or read from RGS RINEX files.)
2. Specular point locations – the L1b metadata includes the SP locations calculated on-board.
3. Nadir Antenna Gain towards Specular Point (AGSP).
4. Reflection Incident angle, i.e. the incidence angle of the specular point of the reflection. This is the angle between the Transmitter to Specular point ray and the surface normal.
5. Delay and Doppler offset of the peak found in the bounded box.
6. Correction for any on-board topographic delay offset if using on-ground higher resolution DEM/geoid.
7. Instrument gain and noise figure correction.
8. Measurement of signal to noise ratio of reflected signals.
9. Measured reflected signal power (corrected for noise and gain).
10. Measured cross-polarised signal power (corrected for noise and gain).
11. Antenna gain nadir towards SP (AGSP).
12. Corrected reflected signal power density propagated to specular point, using an estimate of the power at the GNSS transmitter.
13. Best estimated GNSS incident power density at specular point.
14. For three calibration models, CM1, CM2 (in the NOC L1b_ext), and CM3, defined in the L1 ATBD, AD-2:
    a. Estimated EIRP at the GNSS transmitter.
    b. Reflection coefficient at specular point (for land and ice surfaces), see 4.1.3.2 of AD-2.
    c. Sigma0 bistatic normalised radar cross-section at specular point (for ocean surfaces), see 4.1.3.3 of AD-2.
15. The surface area of the specular point region used to calculate Sigma0 (for ocean surfaces), see 4.1.3.3 of AD-2.
16. Reflected signal coherence measurement.
17. Information and quality flags, see 4.1.4 of AD-2 for details.
    a. DirectSignalInDDM
    b. Noise Kurtosis.
    c. Atmospheric attenuation.
    d. Land/sea flag.
    e. Coast proximity flag.
    f. Land type flag.
    g. Low SNR flag.
    h. Very low SNR flag.
    i. Low overall quality flag.

The SSTL L1b metadata also contains the items:

1. Updated power towards specular point from GNSS transmitter
2. Updated GNSS transmitter EIRP, CM3

3. Updated reflection coefficient, CM3
4. Updated Sigma0, CM3
5. Attenuation from atmosphere/ionosphere

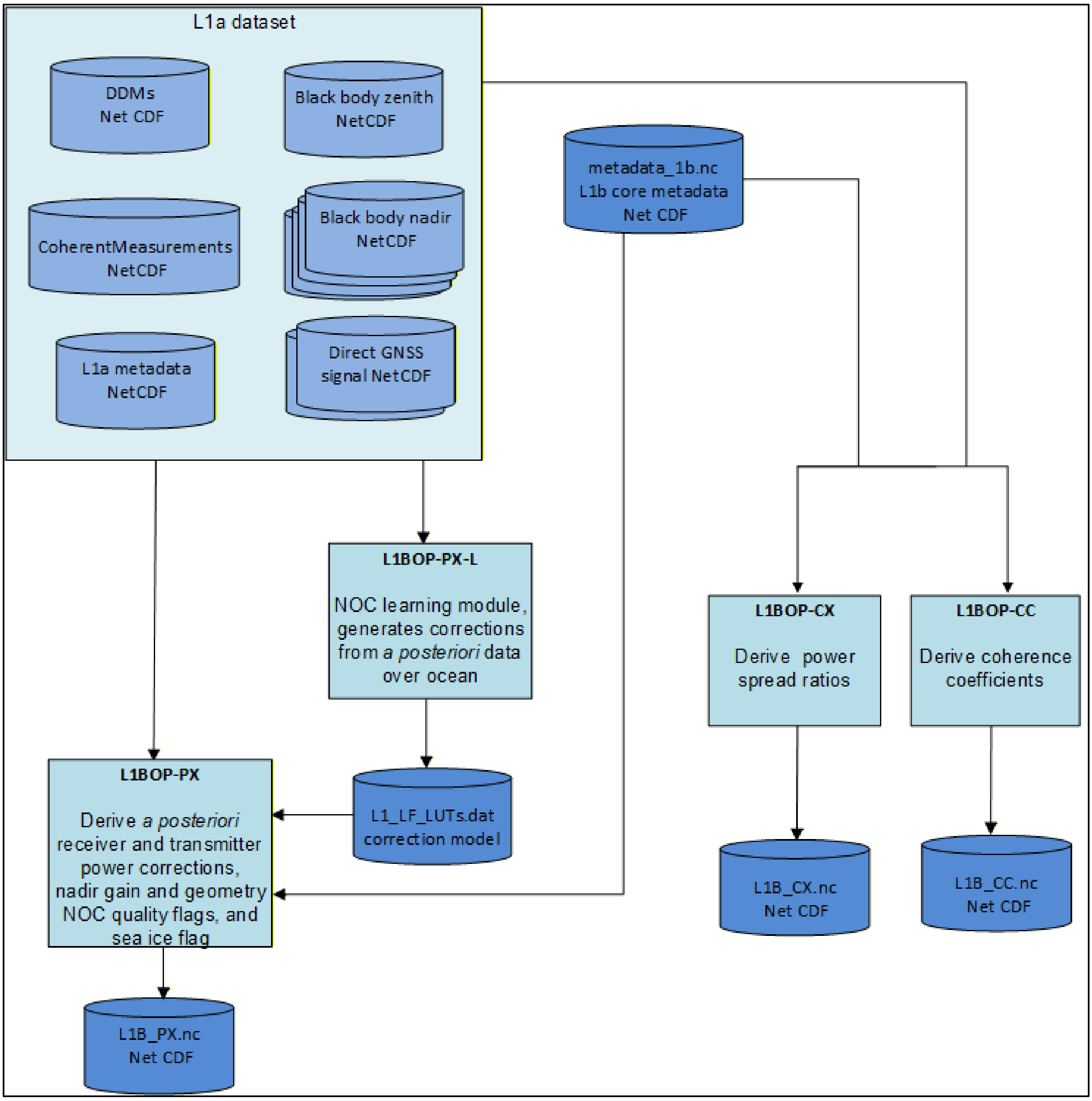

Figure 9-3 L1b_ext processing flow

9.2.2 NOC L1b_ext processor

The NOC L1b correction learning module generates and routinely updates a calibration data set, using *a posteriori* data over the ocean and associated metadata. This dataset is used to generate L1b_ext_NOC metadata including *a posteriori* corrections:

- GNSS satellite transmitter power corrections over land, ice and sea. Transmitter-end corrections are defined as a function of off-pointing angle.
- Reflection coefficient calculated using calibration method 2.
- Sigma-0, plus the assumed reflection area for the sigma-0, calculation using calibration method 2.

The L1b_ext_NOC metadata data also includes flags to indicate:

- The likely presence of RF interference – all surfaces
- The likely presence of a correlator anomaly – all surfaces
- The likely presence of ice – ocean surfaces >45 degrees N/S
- QC pass flag

The L1b_ext_NOC processor is initially applicable for L1/E1 reflected signals LHCP, but with placeholder provision for newer signals (L1/E1 RHCP, L5/E5 LHCP and RHCP). See L1B-OP_PX ATBD, AD-7, for full details, and A.5.1 for data format.

9.2.3 IEEC L1b_ext processors

The IEEC L1BOP-CC processor generates a metadata file containing Coherence Coefficients, and the L1BOP-CX module generates Coherency and Power Spread Ratios, see IEEC ATBD, AD-5 for full details, and A.5.2 and A.5.3 for data formats.

9.3 MERGED LEVEL 1 METADATA

The L1OP-MM processor will merge all L1a, L1b and L1b_ext metadata into a single file, metadata_L1_merged.nc, for ease of use by the L2 processors, and the HydroGNSS data users. See section A.6. Since the NOC and IEEC L1b_ext modules will expect merged L1a and L1b as input, the L1 merge module L1OP-MM is run twice, once after the L1BOP, and then again after the L1b_ext modules, so that the L2 modules can input a complete merged L1 metadata set. Only the final merged L1 metadata file is uploaded to the User FTP server.

10 LEVEL 1 MERGED TO LEVEL 2 PROCESSORS/PRODUCTS

10.1 L2OP-SSM - L1MERGED TO L2 SURFACE SOIL MOISTURE (SAPIENZA/TOR VERGATA)

This module generates the estimates of Surface Soil Moisture (SSM) from Level 1b (calibrated) products and auxiliary files. See AD-3 for full details of the L2OP-SSM processor.

10.1.1 Inputs

The inputs of the L2OP-SSM processor are listed below.

10.1.1.1 HydroGNSS L1Merged data

The following data from the L1Merged product are used:

- Time tag
- Calibrated DDM’s (e.g. signal at the antenna port in power units, as a function of delay and Doppler with noise power removed)
- Estimated noise power (at the antenna port)
- Estimated SNR
- Latitude and longitude of the specular point. It should be computed considering the mean elevation of the Earth surface using a DEM
- Incidence angle at the specular point. It should be computed considering the mean elevation of the Earth surface
- Quality flags
- Estimated degree of coherence (from complex signal or DDM)
- Transmitter identification (PRN)

- Frequency band and signal modulation ID
- Peak ("equivalent") reflectivity
- Normalized Bistatic Cross Section (NBRCS)
- Transmitter and receiver position and velocity (in ECEF)
- Processing parameters (integration times, DDM size, etc)

10.1.1.2 Auxiliary data

Auxiliary data to be collocated with HydroGNSS data are required in the Equal-Area Scalable Earth (EASE) grid version 2 coordinate reference system (EASE-Grid 2.0). The Equal-Area Scalable Earth (EASE) Grids are intended to be versatile formats for global-scale gridded data, including remotely sensed data. Data can be expressed as a digital array with one of many possible grid resolutions, which are defined in relation to one of four possible projections: Northern / Southern Hemispheres (Lambert's equal-area, azimuthal), temperate zones (cylindrical, equal-area), or global (cylindrical, equal-area) (see https://nsidc.org/ease/ease-grid-projection-gt). As for the grid space (resolution) the baseline value is D= 25 km. Finer resolution could be considered at a later stage of the project. We can distinguish between "static" data, i.e., updated on a long temporal scale (say months or years), and "dynamic" time-variant data, i.e., available within a time difference order of a few days or weeks from HydroGNSS overpass. The selection of static or dynamic data will depend on the availability and reliability of available products at the time of HydroGNSS operations. Auxiliary data needed for L2 processing are:

- Digital Terrain Model (DTM). Digital Elevation Model (DEM) of the surface with respect to the WGS84 ellipsoid at a resolution better than 1 km and elevation standard deviation, mean slope and slope standard deviation within a resolution cell of 6 km or better.
- Vegetation Optical Depth (VOD) at a resolution of 6 km or better or any other quantity that can act as a proxy of the VOD. A dynamic, almost real-time, dataset set is highly recommended. Depending on the availability of satellite products at the time of the HydroGNSS launch it can be provided by difference sources, among which:
  - SMAP and VOD WVC products
  - If SMAP data is not available, NDVI and NDWI from MODIS are used.
  - CCI biomass data
- Soil small scale roughness (surface height standard deviation) has not been used as reliable values are not available, and the AFS parameter is deemed not suitable as now only available from CyGNSS in the tropical latitude range.
- Land use map. It shall include water bodies (river, lakes), forest, urban areas, etc. This is the CCI land cover map.
- Soil texture and soil porosity maps, e.g., Global Land Data Assimilation System (GLDAS), is not used in the baseline version of the L2OP-SSM.
- Freeze/thaw data from L2OP-FT outputs was considered, but the coverage from only two satellites was thought to be too sparse to be of practical benefit for SSM L2 products, so it has not been implemented.

10.1.2 Outputs

The level 2 product is delivered in NetCDF format and contains:

- The SSM estimates.
- The geolocation information.
- Flags to indicate the expected quality of the estimates.

10.2 L2OP-FB - L1 MERGED TO L2 FOREST ABOVE GROUND BIOMASS (IFAC-CNR)

10.2.1 Introduction

The Forest Above Ground Biomass (F-AGB) L2OP-FB processor uses an Artificial Neural Network (ANN) approach.

The IFAC-CNR F-AGB processor (L2OP-FB) will process L1Merged data into a Level 2 product of F-AGB at global scale. The F-AGB retrieval from HydroGNSS L1Merged data is carried out by an algorithm based on Artificial Neural Networks (ANN). The core algorithm is an outcome of the research carried out during GNSS Overland (ESA n.4000120299/17/NL/AF/hh), Ecology (ESA 4000130560/20/NL/FF/gp) and SCOUT (ESA AO/1-9901/19/NL/CT). The core algorithm has been refined and updated with respect to the one described in Santi et al. 2020 [SAN20] and has been re-engineered for this application. See AD-6**Error! Reference source not found.** for full details of the L2OP-FB processor.

10.2.2 Processor module description

The main steps of the processing are summarised in the flowchart of Figure 10-1. The processor is composed of a “training” and a “test” module. The “training” module is executed offline only once to define the ANN structure for the given problem. Training also includes a peculiar algorithm for iteratively defining the best ANN architecture in terms of neurons, hidden layers, and transfer function (Santi et al. 2021).

The ANN configuration defined by the training, including transfer function type, number of neurons and hidden layers, coefficients for weights and biases, is stored in a config file that is then loaded by the “test” module that represents the operational processor. Considering the impossibility to realize unsupervised training, the L2OP-FB processor will include the “test” module, which loads the ANN parameters and applies the ANN to the input data, but not the “training” module. The ANN configuration file to be read by the “test” module will be part of the deliverables. The training set will be defined locally at IFAC: it might also contain L1Merged data from the previous steps in the processing chain.

In the “test” module, L1b and ancillary data are loaded and (if needed) aggregated at the target/goal resolution. QF are also screened. Then the ANN is loaded from the Matfile and the “per pixel” inversion based on ANN is carried out to generate the F-AGB output map. The map is then checked for anomalies and uncertainties as described in section 10.2.4. Optionally a validation of the result could be included here, depending on the SAG outcomes.

Then the final F-AGB map is outputted by the system in NetCDF and KML formats: the map will be generated every six months. The best option for processing will be assessed based on computational cost and retrieval accuracy. Two possibilities are foreseen: estimating F-AGB for each input dataset and then temporally averaging the obtained values on the six months period to generate the output map or averaging on the six months period the HydroGNSS observables before inputting the algorithm. Along with the map, quality check of results, flag anomalies and output uncertainty figures will be also produced. The assessment of the anomalies will be mainly based on outliers and quality flags in the input data. The uncertainties will be assessed mainly based on the F-AGB range for which the retrieval is feasible, however validation against some datasets that can be suggested during SAG could be also implemented.

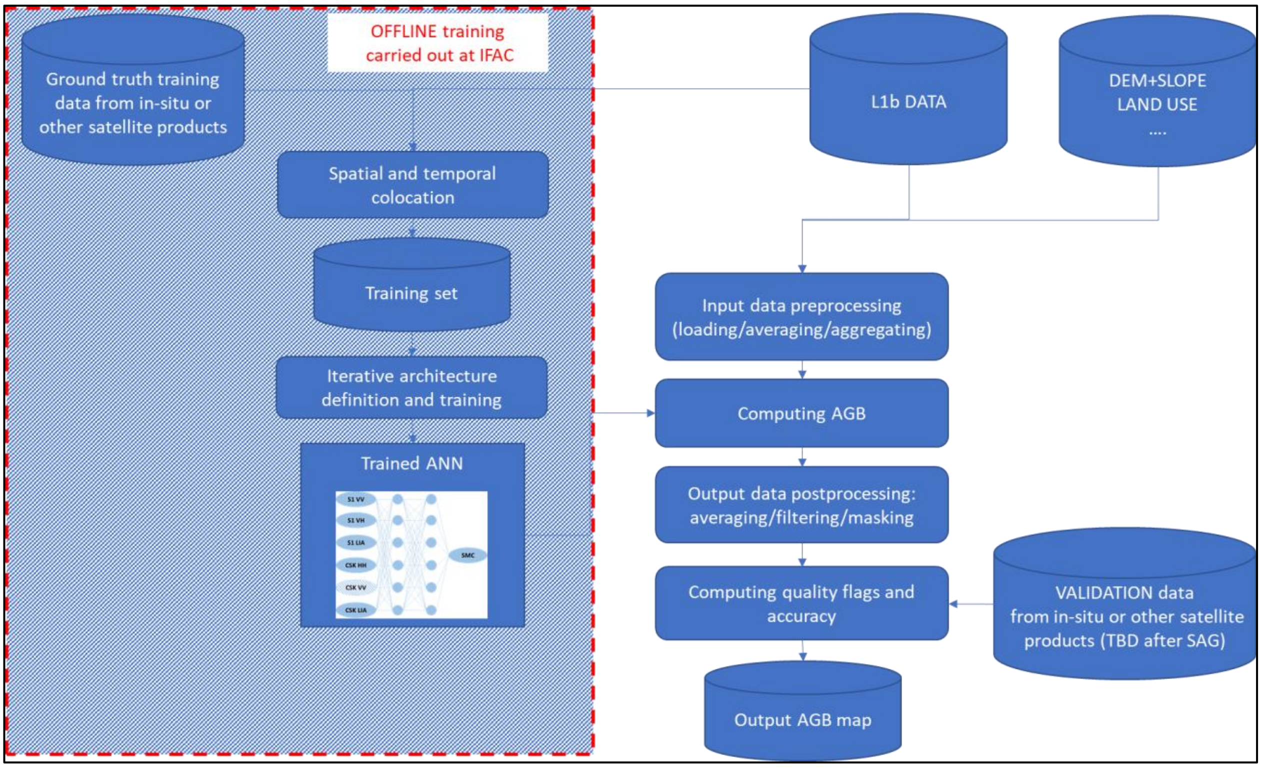

Figure 10-1: The main steps of the processing to generate the L2OP FB product

10.2.3 Inputs

The algorithm will require as inputs the following:

- HydroGNSS observables at L1b processing level, including elevation angle (NetCDF format)
- Global DEM at the same resolution of the output AGB map (target 25 Km, goal 1 Km): suggested GTOPO30 but other sources are also fine (NetCDF/tiff or other formats)
- Land cover/land use map from ESA CCI (Net CDF or original tiff format)
- Configuration file containing the ANN parameters (mat file).

To compute the QC and uncertainty, ancillary validation data may be necessary. This has to be assessed at SAG, alternatively, computation could be made offline at IFAC based on the reference data available.

10.2.4 Outputs

The algorithm output is:

- AGB map at target/goal resolution (NetCDF format)
- Quality flag indicating good or poor quality for each specular point.
- AGB uncertainty figure for each specular point. The uncertainty values range between 0% (maximum uncertainty – AGB value not reliable at all) and 100% (minimum uncertainty – AGB maximum reliability).

10.3 L2OP-FT - L1MERGED TO L2 FREEZE/THAW STATE (FMI)

The initial implementation is expected to use a simple threshold-based soil freeze and thaw detection as validated using TDS-1 reflectivity values and is reported in [RAU21]. The data is first gridded onto the conventional EASE-2 grid scheme. To deal with a limited amount of available reflectivity, spatial averaging is performed over the EASE-2 grid, which is composed of 720 x 720 pixels having dimension equal to 25 x 25 km. The gridding procedure is developed performing a daily average over each grid cell. Land class distribution and the topography information over the observed area (footprint of the measurement) are taken into account when averaging the data. The HydroGNSS footprint is defined according to the provided antenna pattern and based on estimated roughness on target area. All observations having incidence angles below 35° are included.

The detection relies on defining pixel-wise thresholds for determing whether the observed reflectivity is estimated to origin from frozen or thaw soil conditions. For this purpose, pixel-wise reference reflectivities were first determined for frozen and thaw soils: an average of all available February observations can be selected for frozen ground reference, and an average of all available July-August observations for thaw ground reference. The threshold value to categorize the gridded TDS-1 reflectivity data either to frozen or thaw soil can be set to the middle of the two references. Hence, the soil state is considered frozen if data is closer to the frozen ground reference than to the thaw ground reference. If limited data is available, additional temporal averaging can be applied to achieve daily gridded reflectivities, e.g. using 30-day running mean or Kalman filtering. Areas having limited observable contrast (threshold to be defined) between thaw and frozen ground reference can be excluded. Some of the gaps are expected due to open water bodies - data will be discarded if the open water fraction within the footprint is too high (threshold TBD). A rough estimate of the footprint of the illuminated area for the observations is required – provisionally a circle having a 5 km radius from the given middle point (which coincides with the corresponding specular point). This resolution value is expected to be optimised with more research, potentially making dynamic use of the coherent channel information.

More details on the L2OP-FT implementation are contained in the ATBD (AD-4).

10.3.1 Inputs

10.3.1.1 HydroGNSS data

L1Merged data needed for L2OP FT processor:

- Reflection coefficient at the specular point: <ReflectionCoefficientAtSP>.
- Specular point location – which is a track on ground, length depending on the integration time: <SpecularPointLat>, <SpecularPointLon>
- Incidence angle: <SPIncidenceAngle>
- Reflection coefficient: <ReflectionCoefficientAtSP>
- Near real-time snow extent – to better estimate the effect of snow cover, and also to define the best periods for reference ground conditions.

10.3.1.2 Auxiliary Data

Auxiliary data used:

- Topography or elevation map on the globe (static data, using look-up table) for data gridding.
- Land cover data (static data, using look-up table) for data gridding.
- Near real-time air temperature data (i.e. ECMWF NRT data) for removal of obvious errors during summer period, and for defining the best periods for reference ground conditions.

10.3.2 Outputs

Output data is provided in EASE-2 polar projection at 25 km x 25 km resolution. The output data consists of:

- FT data in 2 level binary format: value at specular point is either thaw or frozen. Additionally, non-data values are given.
- FT data error estimation.

10.4 L2OP-SI - L1MERGED TO L2 INUNDATION/WETLANDS (IEEC)

The objective of the L2OP-SI processor is to assign an inundation flag based on the coherence indicators and external scene information. After some training with CYGNSS and TDS-1 data, a set of thresholds (for different geographical regions, topography and land cover characteristics) was used to associate the coherence indicators to flooded or non-flooded conditions, as well as its uncertainty levels. The quality flags flow down from L1Merged data. See AD-5 for full details of the L2OP-SI processor.

10.4.1 Inputs

- Level L1a power DDMs
- Level L1a coherent channel data
- L1b CC Metadata – coherence coefficients ad normalised amplitude (at 40 ms)
- L1b CX metadata – power spread ratio, reflectivity (at 1 second).
- External (auxiliary) data about the scene: topography, and land cover.

10.4.2 Outputs

- High resolution - Inundation flag (40 ms) and water probability, with its uncertainty and quality flags.
- Low resolution - Inundation flag (at 1Hz) and water probability, with its uncertainty and quality.

10.5 L2OP-SWS - L1MERGED TO L2 OCEAN SURFACE WIND SPEED AND SEA ICE EXTENT (NOC)

See AD-7 for full details of the L2OP-SWS processor.

10.5.1 Inputs

- DDMs
- L1Merged metadata
- Sigma0 (output of L1B-OP-PX processor)
- Quality Control Flags (output of L1B-OP-PX processor)

10.5.2 Ocean Wind speed

Ocean surface wind speed is retrieved using a geophysical model function (GMF) based on the estimated Sigma0 values from the L1B-OP-PX processing module. The ocean surface wind speed GMF follows a two-factor exponential equation of the form: Sigma0=A*exp(Bx) + C*exp(Dx) +E. Where x is the estimated wind speed, and A, B, C, D, and E are parameters controlling the relationship between Sigma0 and wind speed. These parameters are determined through calibration relative to a reference dataset.

10.5.3 Sea Ice Extent

The NOC GNSS-R Sea Ice Detection (GSID) algorithm is based on the characteristics of the DDM, which have a markedly different signature for reflections over sea-ice and the open ocean, due to the higher reflectivity and different scattering mechanism over ice, sea-ice can be identified in integrated delay waveforms as having a sharper peak than oceanic returns. Threshold values for three parameters describing the peak of the integrated delay waveforms are used to determine the presence of sea-ice. These values are optimised separately for each hemisphere due in part to the different characteristics of sea-ice over the North and South hemispheres.

10.5.4 Outputs

The following variables are output by the processor on a record-by-record basis

- Ocean surface wind speed
- Sea ice extent
- Quality flag

11 LEVEL 3 PRODUCTS

11.1 L3 SSM

Data from HydroGNSS-1 and HydroGNSS-2 is gridded and averaged over a rolling three-day period to produce a level 3 surface soil moisture product. See AD-3 for further details and A.8.1 for data format.

11.2 L3 FT

Data from HydroGNSS-1 and HydroGNSS-2 is gridded and averaged over a rolling ten-day period to produce a level 3 freeze/thaw product. See AD-4 for further details and A.8.2 for data format.

11.3 L3 FB

Data from HydroGNSS-1 and HydroGNSS-2 is gridded and averaged over a rolling (TBD) six-month period to produce a level 3 forest biomass product. See AD-6 for further details and A.8.3 for data format.

APPENDIX A. PRODUCT FORMATS

A.1 File format

As with MERRByS, Level 1a, 1b, L1b_ext, Level 2, and Level 3 products are provided in NetCDF4 format, v4.8.1.

NetCDF is a set of software libraries and data formats that provide for a self-describing and machine-independent way of sharing array-orientated scientific data. There are a number of software applications and libraries that are available for reading this format. The project homepage is hosted by the Unidata program at UCAR (RD-1). SSTL use the following two Java tools:

- Panoply from https://www.giss.nasa.gov/tools/panoply/
- toolsUI from https://docs.unidata.ucar.edu/netcdf-java/current/userguide/toolsui_ref.html

A.1.1 Time format

Times are represented in the SGR-ReSI-Z receiver using GPS weeks and seconds. The metadata is calculated by converting the time to UTC with the applicable GPS-UTC offset. Since 1st January 2017, GPS to UTC offset has been 18 seconds, but this is likely to change by the start of, and during the HydroGNSS mission, on June 30th or Dec 31st if/when UTC leap seconds are introduced.

The ground processing represents time using the "DateTime" .net class. This represents time as an integer number of 100 ns ticks. This is relevant as it provides the precision limit of the timestamps. This format loses some of the precision of the GPS weeks and seconds, but has the convenience of representing the time without the GPS 1 week roll-over.

Time is then stored into the NetCDF4 files in the Matlab native format of, number of days from January 0, 0000.

A.1.2 Data use license

All HydroGNSS L1, L2, and L3 products have the same data use license. The wording of the ***`License`*** field is:

> Data Use Policy and Terms and Conditions: see https://earth.esa.int/eogateway/documents/20142/1564626/ESA-Data-Policy-ESA-PB-EO-2010-54.pdf, and https://earth.esa.int/eogateway/documents/20142/1564626/Terms-and-Conditions-for-the-use-of-ESA-Data.pdf

A.2 Level 0b (ZTC) data – DDMs and coherent measurements

NB. The channels referred to in this section are ZTC channels, of which there are up to four for each reflection track. As there are nominally four reflections at any time, this means there are up to 16 ZTC channels, numbered 1 to 16. These channels are not related to the platform telemetry channels in any way.

These products are generated on-board the satellite and contain the Delay Doppler Maps and coherent measurements obtained with the Zoom Transform Correlator (ZTC) processing algorithm.

To optimise the format for low data rate output, the file format is split into three types of packet:

- The DDM Track Header, which specifies the configuration of the DDM channel. This is output at the start of the stream, before each DDM channel, and then following a change in configuration to any of the DDM channels such as:
    - PRN number being tracked in the ZTC channel.
    - The signal used, i.e. E1/L1/E5/L5.
    - The polarisation used, LHCP/RHCP.
- The DDM packet, consisting of a DDM header and DDM pixels, which is output following each incoherent integration period.
- The Coherent Track Header, which specifies the configuration of the coherent channel. This is output at the start of the stream, before each Coherent channel, and then following a change in configuration to the associated DDM channel.

- The Coherent Measurement packet, with a group of N pixels, nominally 3, for each timestamp, at a much greater frequency – (250Hz) than the DDM data (1Hz).

These three components are illustrated in Figure 11-1.

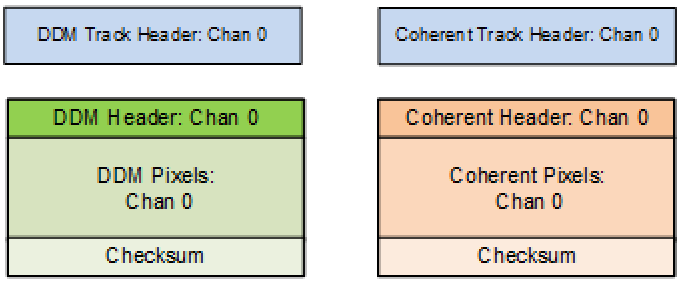

Figure 11-1: DDM file format components

An example stream structure is shown in Figure 11-2. The DDM Track Header is output at the start of the stream and is then followed by DDM Packet, and a Coherent Track Header and Coherent packet. In this example, part way through the file the SGR has changed a tracking parameter, so a new DDM Track Header is stored preceding the next DDM channel, and a new Coherent Track Header is stored before the associated Coherent channel. As an example this would occur on reallocation of the hardware channel to a different GNSS transmitter's specular point. The thick black outlines indicate the packet boundaries. Note that in Figure 11-2, it is assumed that DDM and coherent data have been gathered for four GNSS satellite tracks, on two frequencies and two polarisations, making a total of 16 ZTC channels in the ZTC data stream. The L1AOP processor also supports other configurations, such as just L1/E1 LHCP, or L1/E1 LHCP/RHCP and L5/E5 LHCP.

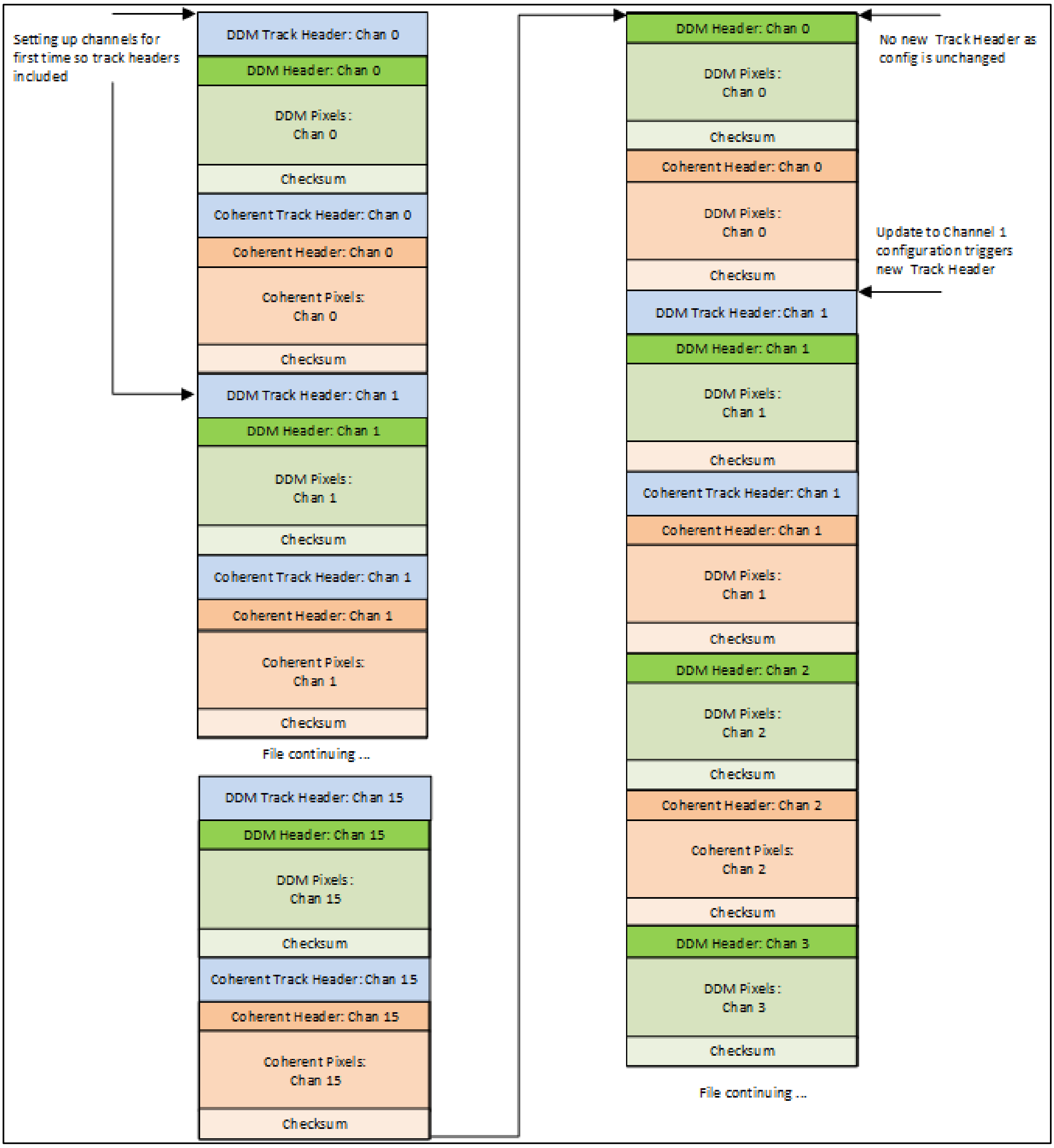

Figure 11-2: Example ZTC file with 16 DDM/coherent channels

A.2.1 Track Header

The Track Header contains all the necessary information that relates to the configuration of the DDM/Coherent processing. At the start of the file stream and in the circumstance that any item in the Track Header changes, a new header is output in the data stream as a prefix to the DDM/Coherent header. This is put into the file stream preceding the DDM/Coherent Packet. A track header is output for each channel.

The timestamp fields contain the GPS Weeks and Seconds at the last PPS prior to the reconfiguration that caused the generation of the track header. This is to allow the configuration described in the track header to be directly related back to the GL log telemetry (such as the PVT solution) by referencing all data to the last PPS.

A.2.2 DDM Packet

The DDM Packet contains the DDM pixel data with a compact header to relate it to the configuration provided in the DDM Track Header.

A.2.3 Coherent Packet

The Coherent Packet contains the Coherent measurement pixel data with a Coherent Track Header to relate it to the configuration provided in the DDM Track Header. The pixel data is output at 16 (or 32) bits per pixel, in groups consisting of a timestamp, and N pixel values, where N is nominally 3, and each pixel consisting of an I and Q value.

A.2.4 Black body loads

The nadir antenna captures black body measurements in five second bursts, nominally once every 10 minutes, and the zenith antenna makes black body measurement for five seconds, once every 100 minutes. During these five second bursts, the black body measurements replace the data in the raw DDM, so there is a brief gap in the DDM. In addition, during the transition between gathering DDM and black body data, there will be a few measurements that are marked as invalid in the DDM. There are separate black body measurements on each frequency and each polarisation, but the black body data is the same in each reflection track. The nadir black body data is written to a separate file for each frequency/polarisation combination. When the zenith load is switched into the DDM, it sits in the nadir DDM stream. There is only L1/E1 RHCP data for the zenith load.

During L1a processing, the black body data is extracted from the DDM and written into its own files, blackbodyNadirL1E1LHCP.nc, blackbodyNadirL1E1RHCP.nc, blackbodyNadirL5E5LHCP.nc, blackbodyNadirL5E5RHCP.nc, and blackbodyZenithL1E1.nc, blackbodyZenithL5E5.nc,as shown in Figure 7-1.

A.3 Level 1a

A.3.1 L1a metadata

File format:	NetCDF4
Filename	/L1A_L1B/yyyy-MM/Hhh/**metadata_L1a.nc**

A.3.1.1 Structure

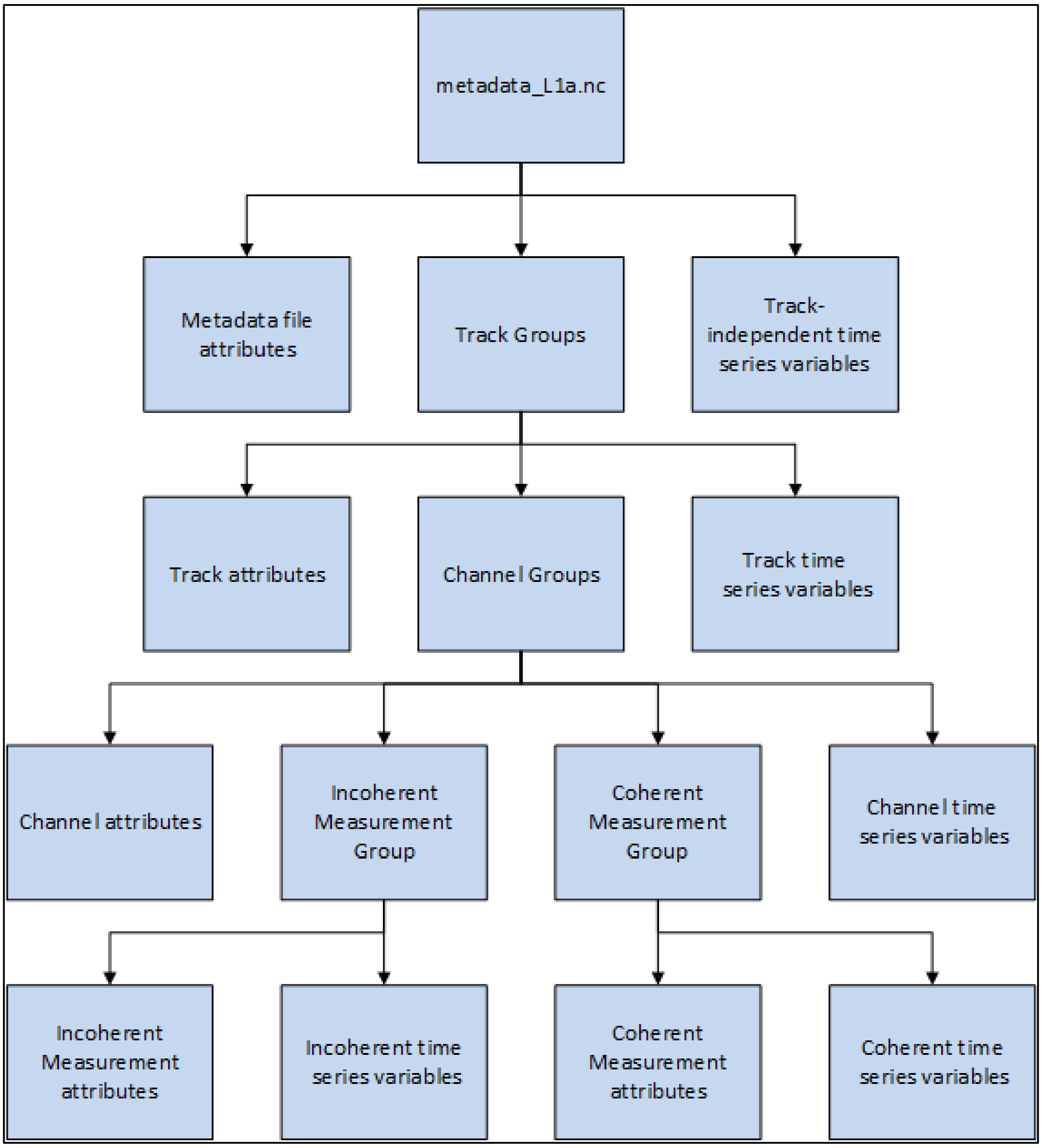

Figure 11-3 L1a metadata structure

As shown in Figure 11-3, the L1a metadata file consists of a set of attributes, some time series variable for the DDM as a whole, and then a track group for each reflection track. The track group also has its own attributes and time series parameters, and then a channel group for up to four channels, which have data for the L1/E1 LHCP, L1/E1 RHCP, L5/E5 LHCP, L5/E5 RHCP channels. The L1a metadata contains all values directly obtained from the payload and platform ancillary data.

<L1aMetadata>
  <Attributes>
  <Variables>
  <Track Groups>
    <Track Attributes>

```
<Track Variables>
<Channel Groups>
  <Channel Attributes>
  <Channel Variables>
  <Incoherent Measurement Group
        <Incoherent Measurement Attributes>
        <Incoherent Measurement Variables>
  <Coherent Measurement Group
        <Coherent Measurement Attributes>
        <Coherent Measurement Variables>
```

NB. On the User FTP site, the L1a metadata is contained in the file metadata_L1_merged.nc, which also includes the L1b and L1b_ext metadata.

A.3.1.2 Attributes

<***Name***>: “HydroGNSS-1 L1a metadata file” or “HydroGNSS-2 L1a metadata file”

<L1a_date_created>

Current time when the L1a metadata file was created, e.g. "2022-03-30T08:30:32".

<***License***>

The license that applies to the contents of the file, see A.1.2.

<***FileIDCode***>

The ID of the L1a metadata file, i.e. yyyy-MM/dd/Hhh, e.g. 2024-08/18/H06

<***DataTag***>

A tag to label the current processing run, to be copied over to the L1b and L1 merged metadata and the L2 products. This is set to <dataset path>_<current timestamp>, e.g. “2024-08/18/H06_30/03/2022 08:30:17”.

<***SourceConstellation***>

The name of the satellite constellation of the source data. This is set to HYDROGNSS.

<***SourceNumber***>

The identification number of the source data, i.e. the satellite number within the constellation, starting at 1, or always 1 if there is only one satellite. This will be 1 or 2 for HydroGNSS.

<***ProcessingType***>

Tag specifying whether the data was processed into DDMs on-board or on the ground. Several ground reprocessing types are defined, as the strings:

{`“Onboard”, “ReplayInHardwareOnGround”, “SWROnGround”, “Ground3”, “Ground4”, “Ground5”`}

<***L1a_ProcessorVersion***>

The version number of the L1a processor used to generate the synchronised L1a metadata.

<***FPGAVersion***>

The version of the FGPA firmware used by the ZTC processor, for DDMs processed on-board. This is output as a float, e.g. 1.2, where 1 is the major version, and 2 the minor version.

<***SoftwareReceiverVersion***>

The version of the L1a(SW) receiver processor, for L0a raw IF acquisitions.

<***IncoherentMeasurementFrequency***>

The frequency of the incoherent measurement time series in the DDM and metadata in Hz. As for MERRByS, the incoherent time sequences for HydroGNSS are expected to be at a frequency of 1 Hz.

<***GpsUTCOffset***>

The offset between UTC and GPS time. At the start of the file [seconds]. This is the number of seconds that GPS time is ahead of UTC.

<***FirstTimeStamp***>

The first timestamp in the data array in the file. UTC timestamp.

<***LastTimeStamp***>

The last timestamp in the data array in the file. UTC timestamp.

A.3.1.3 Variables

Each data array consists of an array of <***ReceiverMetaDataPerEpoch***> structures. These contain all the time-varying parameters that are in common across all the L1a tracks.

<***IntegrationMidPointTime***>

The UTC timestamp of the DDM integration mid-point, expressed as the number of days from January 0, 0000. This is the epoch for which all the receiver data is referred to, as it is corresponds to the centre of the integration time for the DDM. This field provides the key that relates it to entries in the TrackMetaData files.

<IntegrationMidPointTimeGPSWeeks>

The start time of the DDM integration. The number of GPS weeks since the GPS epoch of the start of 6th January 1980.

<IntegrationMidPointTimeGPSSeconds>

The start time of the DDM integration as GPS seconds, the number of seconds into the GPS week.

<IntegrationStartTime>

The UTC timestamp of the start of the DDM integration, expressed as the number of 100-nanosecond intervals that have elapsed since 12:00:00 midnight, January 1, 0001.

<IntegrationEndTime>

The UTC timestamp of the end of the DDM integration, in the same units as ***IntegrationStartTime***.

<ClockStatus>

The status of the receiver clock knowledge as an integer value:
{ 0:Uncorrected,1:SignalOnlyCorrection,2:CorrectionFromFix,3:CorrectionFromFixWithUTC }

<ClockErrorRate>

The clock error rate as measured from the navigation solution. Expressed as equivalent frequency difference from the nominal GPS L1 carrier centre frequency [Hz]

e.g. For the GPS L1 carrier frequency of 1.57542 GHz, a sampling frequency offset of 1 ppm in the receiver TCXO would produce a 'nominal' GPS L1 carrier at a higher frequency by 1574.42 Hz.

The value of this field, ClockErrorRate, would then be 1574.42 Hz.

<***PositionFixValidity***>

The validity of the receiver position/velocity fix:

[=0] No Navigation
[=1] 2D Fix
[=2] 3D Fix

<ReceiverPositionX, ReceiverPositionY, ReceiverPositionZ>

The receiver position at the time: IntegrationMidPointTime. This is represented in the ECEF WGS-84 coordinate frame [m]. The receiver position is output from the SGR-ReSI-Z at 1 Hz and captured in the on-board GL log.

NB. For MERRByS it was necessary to perform a spline interpolation on the 0.1 Hz SGR-ReSi data in in the GL log. For HydroGNSS this is unnecessary as the data is at 1 Hz in the GL log. This applies also to the ReceiverVelocity, ReceiverPositionSource and GDOP.

<ReceiverVelocityX, ReceiverVelocityY, ReceiverVelocityZ>

The receiver velocity at the time: IntegrationMidPointTime. This is represented in the ECEF WGS-84 coordinate frame [m/s]. The receiver velocity is output from the SGR-ReSI-Z at 1 Hz and captured in the onboard GL log

<ReceiverSubSatLatitude>

The receiver sub-satellite point latitude in degrees at the time: IntegrationMidPointTime.

<ReceiverSubSatLongitude>

The receiver sub-satellite point latitude in degrees at the time: IntegrationMidPointTime.

<ReceiverPositionSource>

The source of the receiver position as an integer value: {0:Predicted,1:Measured}.

If the receiver position is calculated on-board then the epoch is tagged as *Measured*. Otherwise if an orbital mode, i.e. TLE, has been propagated to this time then the tag is *Predicted*.

<GDOP>

The Geometric Dilution of Precision provides an indicator of the uncertainty magnification of the position fix due to geometric alignment of the GPS satellites. A lower GDOP indicates a more accurate solution, but if the GDOP rises above a threshold, the user should be cautious.

<TimeDiffToClosestPVT>

The time difference between the DDM integrationMidPoint time and the closest receiver PVT solution. Positive indicates DDM is after the closest PVT. Units [seconds]

<AttitudeRoll, AttitudePitch, AttitudeYaw>

The Roll, Pitch, Yaw [degrees], derived from the AOCS log from the satellite. Satellite attitude is the alignment of the satellite body relative to the orbit-defined axes. The attitude terms, roll, pitch and yaw are defined as right-handed rotations about the three orbit-defined axes. Further details are provided in AD-2.

<AttitudeUncertaintyRoll, AttitudeUncertaintyPitch, AttitudeUncertaintyYaw>

Satellite attitude uncertainty: Roll, Pitch, Yaw [degrees]. The attitude provided has an uncertainty in its estimation. The uncertainty varies during the orbit as different attitude sensors become available. This field provides our best guess at the attitude uncertainty in each of the roll, pitch and yaw rotations. The magnitude of the attitude uncertainty depends on the sensors used during that part of the orbit. On HydroGNSS the platform attitude sensors are sun-sensors, star trackers and magnetometers. During the eclipse the sun-sensors are not available, and the attitude is estimated by the star trackers and magnetometers and so this is flagged by the *InEclipse* flag. The AttitudeUncertainty is not a measured value, it will be provided as a configuration parameter for the L1a processor.

<***StarTrackerBlindingFlag***>

Set to 1 if the star tracker camera is blinded, 0 otherwise.

<AttitudeSource>

Satellite attitude source as an integer: {"0:OnboardFromReSIStatus,1:Platform,2:NominalAttitudeAssumed,3:GPSAttitude}.

This is the data source used for the attitude field:

OnboardFromReSIStatus: - The attitude that was provided to the receiver from the AOCS function onboard the satellite.
Platform: - The attitude that has been recorded by the AOCS system; this is the nominal setting.
NominalAttitudeAssumed: - The attitude has been assumed as Roll, Pitch, Yaw of 0,0,0 as no other sources available
GPSAttitude: - The attitude has been calculated from the phase measurements provided by multiple zenith GNSS antennas.

<InEclipse>

This integer flag specifies if the receiver is eclipsed from the Sun by the Earth, {0:Sunlit,1:InEclipse} This is provided as the `AttitudeUncertainty` field depends on whether the sun sensors are available. The source of the flag is the negated value of the platform's AOCS system Sun Sensor Active flag. This flag is only valid when the attitude source is '*Platform'.*

<InternalTemperatures0, InternalTemperatures1, InternalTemperatures2, InternalTemperatures3, InternalTemperatures4, InternalTemperatures5, InternalTemperatures6>

Temperatures of the LNAs, receiver front ends, and antennas:

- *InternalTemperatures0*- LHCP nadir LNA
- *InternalTemperatures1*- RHCP nadir LNA
- *InternalTemperatures2*- zenith LNA
- *InternalTemperatures3*- receiver front end 0
- *InternalTemperatures4*- receiver front end 1
- *InternalTemperatures5*- zenith antenna
- *InternalTemperatures6*- nadir antenna

The LNA and receiver front end temperatures come from the GL log data, the antenna temperatures from the thermal WOD. For further details of these temperatures, see AD-2, 3.2.3.

<ActiveTracks>

A list of the track IDs that are active/idle at this epoch.
ActiveTracks is actually 8 separate variables, *ActiveTracks0, ActiveTracks1, ActiveTracks2, ActiveTracks3, ActiveTracks4, ActiveTracks5, ActiveTracks6, ActiveTracks7*. For HydroGNSS there will nominally be 4 simultaneous tracks at any point. However, depending on the geometry of the GNSS satellite orbits at any point, there may be less than 4 reflections at some epochs. However, some of the GPS satellites only broadcast on the L1 frequency, so reflection tracks from these satellites will use only two ZTC channels. With a total of 16 ZTC channels, this means that it is theoretically possible to have up to 8 simultaneous reflections at any epoch. At any epoch with less than 8 reflections, any unused ActiveTracks variable is set to -1 at that epoch.

<NumberOfTracks>

The number of tracks captured at this epoch. This will nominally be 4, but up to 8 is possible at any epoch.

<***RxTemperature***>

The receiver noise temperature estimate for the channel, L1/E1 LHCP. From Friis cascade of noise temperature including look-up function for the LNA Noise Figure at the measured physical temperature [K].

<ADCPercentagePositiveZenith>

Measure of DC bias in the samples from the zenith front-end. See definition in **Error! Reference source not found.**.

<ADCPercentageMagnitudeZenith>

The percentage of the samples that set the 'mag' bit in the 2-bit quantised zenith RF samples. See definition in AD-4.

<NadirLHCPBlackBodySwitchStatus>

False if nadir LHCP LNA is in DDM data mode, true if in black body mode.

<NadirRHCPBlackBodySwitchStatus>

False if nadir RHCP LNA is in DDM data mode, true if in black body mode.

<ZenithRHCPBlackBodySwitchStatus>

False if zenith RHCP LNA is in DDM data mode, true if in black body mode.

A.3.1.4 Track groups

Group Name	Track number e.g. ‘000000’, ‘000001’, ‘000002’…

Each group corresponds to a reflection track. The group structure consists of attributes (as a header) and then arrays of variables, one for each DDM in the track. The attributes contain all the settings and information that remain constant over the length of the track. The Track Variable arrays contain an entry for each DDM frame in the corresponding **DDMs.nc** file.

The metadata for each time-step in the track can be combined with the timestamps from the ***<Variables>*** to get the information that is common across tracks, such as the receiver position.

In addition each track contains up to 4 channel groups, depending on how many polarisations and frequencies are in use.

A.3.1.4.1 Track attributes

<***TrackID***>

The identification number of the track.

<***DataTag***>

This is an identification text tag that could be used to specify any additional information about the modes that the satellite was running in, currently unused, and left blank.

<***TrackIDOrbit***>

An additional identification number of the track, used for the E2ES only. This is intended to identify tracks unambiguously, when the E2ES simulator generates datasets for periods longer than six hours, for which the PDGS would restart the TrackID at 0 every six hours, resulting in different tracks having the same TrackID. When the PDGS processes real HydroGNSS payload data **TrackIDOrbit** is not be included in L1a, L1b, L1 merged metadata or any of the L2 products. However when the L1a metadata is generated by the E2ES, **TrackIDOrbit** is included in the L1 metadata, and is then be copied over into L1b and L1 merged metadata, and all the L2 products.

<***ReflectionChannelNumberList***>

Array of the nadir front end numbers included in this track. The nadir front end numbers are in the range from 0 to 3:

0: Nadir_L1E1_LHCP, 1: Nadir_L1E1_RHCP, 2: Nadir_L5E5_LHCP, 3: Nadir_L5E5_RHCP

<***MasterNavChannelNumber***>

Channel number of the navigation correlators used to track the direct signal which corresponds to the reflection channel. Numbering starts from 1, and is a different parameter to the ZTC channel number.

<***GNSSConstellation***>, <***GNSSConstellation_units***>

The constellation of the GNSS satellite, as an integer, {GPS=0, Galileo=2}. NB the software allows for Glonass=1, but this option is not used for HydroGNSS.

<***PRN***>

The transmitter satellite Pseudo Random Noise code identifier. Numbering starts from 1. These numbers are reused, so are only unique at one point in time.

<***SVN***>

The transmitter Satellite Vehicle Number identifier. A unique number given to each GNSS satellite.

<***GnssBlock***>, <***GnssBlock_units***>

The GNSS block as an integer.

Units are a string giving the value decoding for <GNSSBlock> “0:Unknown, 1:BlockI, 2:BlockII, 3:BlockIIA, 4:BlockIIR, 5:BlockIIR_A, 6:BlockIIR_B, 7:BlockIIR_M, 8:BlockIIF, 9:BlockIII, 10:IOV, 11:FOC1-2, 12:FOC3-22, 13:FOC23-34” These all relate to GPS (1 to 9) or Galileo (10- to 13) satellite manufacturing batches.

<***AllocationMode***>, <***AllocationMode_units***>

The receiver mode used for allocating potential reflections to the reflection channels, as an integer, { 0:Manual, 1:Auto, 2:Unknown}

A.3.1.4.2 Track variables

<***IntegrationMidPointTime***>

`IntegrationMidPointTime` is the mid-point between the start and the end of the DDM’s integration, The UTC timestamp of the DDM integration mid-point, expressed as the number of days from January 0, 0000. All the following fields are referenced to this time.

<***GNSSBroadcastPositionX***>, <***GNSSBroadcastPositionY***>, <***GNSSBroadcastPositionZ***>

Transmitter position at the time of reception of the signals at the receiver. The transmitter corresponds to the <PRN> from the header. The position is extracted from the GL log, but there is an option to obtain this from RINEX files.

Units: [m]

<***GNSSBroadcastVelocityX***>, <***GNSSBroadcastVelocityY***>, <***GNSSBroadcastVelocityZ***>

Transmitter velocity at the time of reception of the signals at the receiver. The transmitter corresponds to the <PRN> from the header. The velocity is extracted from the GL log, but there is an option to obtain this from RINEX files.

Units: [m/s]

<OnBoardReflectionHeight>

The reflection SP height, calculated from the specular point position in the GL log.

<OnBoardDemHeight>

The DEM height in metres at the specular point from the GL log.

<OnBoardGeoidHeight>

The geoid height in metres at the specular point from the GL log.

<OnBoardSpecularPointPositionX>, <OnBoardSpecularPointPositionY>, <OnBoardSpecularPointPositionZ>

The specular point location at the time of the reflection ECEF WGS-84 [m], as calculated on-board the satellite, and extracted from the GL log. There is an option to re-calculate this in L1AOP, but this is only used for test purposes.

<OnBoardSpecularPointLat>, <OnBoardSpecularPointLon>

The latitude and longitude of the specular point at the time of the reflection [degrees, degrees], as calculated from the specular point coordinates used on board the satellite. There is an option to calculate this in L1AOP, for test purposes.

<OnBoardDelayReferencedToDirectGeom>

The delay, calculated geometrically, between reception of the direct signal and reception of the reflected signal as calculated on board. This value is used on-board to move the DDM to pick up the specular point at the crosshairs, hence on the ground, it can be used to reference the delay of the central pixel.

Units: [ns]

<OnboardAtmosphericDelayL1E1>

The additional delay to the L1 and E1 signals due to ionospheric effects. Note that the delay due to tropospheric effects has not been implemented as this is considered to be negligible. This term includes both the downwards and reflected paths of the signal. The total expected delay can be calculated for the L1 and E1 signals by adding the atmospheric delay term to the geometric delay term <OnboardDelayReferencedToDirect>.

Units: [ns]

<OnboardAtmosphericDelayL5E5>

The additional delay to the L5 and E5 signals due to ionospheric effects. Note that the delay due to tropospheric effects has not been implemented as this is considered to be negligible. This term includes both the downwards and reflected paths of the signal. The total expected delay can be calculated for the L5 and E5 signals by adding the atmospheric delay term to the geometric delay term <OnboardDelayReferencedToDirect>.

Units: [ns]

A.3.1.4.3 Channel groups

Group Name	Channel<front end number>, where <front end number> is 0 to 3: 0: Nadir_L1E1_LHCP, 1: Nadir_L1E1_RHCP, 2: Nadir_L5E5_LHCP, 3: Nadir_L5E5_RHCP

Each track contains up to four ZTC channels for the 4 possible frequency/polarisation combinations.

A.3.1.4.4 Channel attributes

<***ChannelID***>

The channel number, 1 - 16.

<***TrackID***>

The identification number of the track which this channel is a part of.

<***SignalFrequency***>

The signal frequency being processed in this channel, as a string:

{ "NO_SIGNAL", "GPS_L1", "GALILEO_E1", "GPS_L5", "GALILEO_E5"}

<***SignalPolarisation***>

The signal polarisation being processed in this channel, as a string:

{ "LHCP", "RHCP" }

<***TrackingMode***>, <***TrackingMode_units***>

The tracking mode that is being used to steer the ZTC processor as an integer:

{1:DirectSignalOverride, 2:OpenLoopReflection }

DirectSignalOverride: Slaves the DDM window to the location of the direct signal

OpenLoopReflection: Open loop tracking of the specular point

<***FrontEnd***>, <***FrontEnd_units***>

The radio front-end source processed in this track, as an integer:

For HydroGNSS: {

0: Nadir_L1E1_LHCP,
1: Nadir_L1E1_RHCP,
2: Nadir_L5E5_LHCP,
3: Nadir_L5E5_RHCP,

4: Zenith_L1E1_RHCP,
5: Zenith_L1E1_LHCP (N/A),
6: Zenith_L5E5_RHCP,
7: Zenith_L5E5_LHCP (N/A)

}

<***SamplingFrequency***>

Sampling frequency of the front-end. This is the nominal frequency without correction from the GPS time standard [Hz].

HydroGNSS uses a sampling frequency of 53 MHz, TBC.

<***FrontEndGainMode***>, <***FrontEndGainMode_units***>

The gain control mode being used on the front-end being processed in the track as an integer:

{0:FixedGain, 1:AutoUnmonitored, 2:AutomaticMonitored}

FixedGain: Gain fixed to the value in <FrontEndGainControlSetting>

AutoUnmonitored: Gain controlled by the front-end internal Automatic Gain Control, gain not monitored.

AutomaticMonitored: Gain controlled by the receiver application, gain setting monitored and reported in <FrontEndGainControlSetting>

<***FrontEndGainControlSetting***>

The gain setting of the programmable gain section of the RF front-end - Valid if <FrontEndGainMode> = FixedGain or AutomaticMonitored

Units are nominally dB, although this is not a calibrated dB scale.

<***LNASwitchStatus***>

LNA signal source. Antenna or internal ambient black-body (BB) source as an integer, see *LNASwitchStatus_units.*

Note that DDMs that are from the internal BB reference source are split into a separate file.

<***LNASwitchStatus_units***>

{ 0:Antenna, 1:Reference}

<***NumberOfZTCChannelReallocations***>

The number of times a new DDM Track Header arrived for this front end during the course of this reflection track, after the track was started.

A.3.1.4.5 Channel variables

<***IntegrationMidPointTime***>

IntegrationMidPointTime is the mid-point between the start and the end of the DDM incoherent measurement's integration. Any other fields that may be added (currently there are none) will be referenced to this time.

A.3.1.4.6 Incoherent Measurement group

Group Name	Incoherent

Each group corresponds to the incoherent measurements within a channel. The group structure consists of attributes (as a header) and then arrays of variables. The attributes contain all the settings and information that remain constant over the length of the track, while the variables are the time varying parameters.

A.3.1.4.6.1 Incoherent Measurement attributes

<***DelayResolution***>

Incoherent DDM pixel spacing [ns]

<***CodeDelaySpacingSamplesBetweenPixels***>

The delay between pixels in the delay axis of the DDM, which is specified in front-end samples

Units are [samples between pixels]

Values are 1 - 12.

<***DopplerResolution***>

The difference in frequency between pixels in the Doppler axis of the DDM

Units: [Hz]

<***IncoherentIntegrations***>

The number of coherent integrations that were added together incoherently to produce the DDMs in the track.

Typically 1000.

<***NumberOfDelayPixels***>

The number of delay pixels processed

<***NumberOfDopplerPixels***>

The number of delay pixels processed

<***TrackingOffsetDelayNs***>

This field is the offset of the targeted open-loop tracking point from the 1st DDM row.

See AD-2 for a description of recovering the targeted pixel.

Units: [ns]

<***TrackingOffsetDelayInPixels***>

This field is the offset of the targeted open-loop tracking point from the 1st DDM row.

See AD-2 for a description of recovering the targeted pixel.

Units: [pixels]

<***TrackingOffsetDopplerHz***>

The offset of the open-loop tracking point from the central DDM column

See AD-2 for a description of recovering the targeted pixel.

Units: [Hz]

<***TrackingOffsetDopplerInPixels***>

The offset of the open-loop tracking point from the central DDM column

See AD-2 for a description of recovering the targeted pixel.

Units: [pixels]

A.3.1.4.6.2 Incoherent Measurement variables

<***IntegrationMidPointTime***>

`IntegrationMidPointTime` is the mid-point between the start and the end of the incoherent DDM's integration. All the following fields are referenced to this time.

<ADCPercentagePositive>

Measure of DC bias in the samples from the receiver front-end. See definition in AD-2.

<ADCOffset>

Measure of DC bias in the front-end calculated by (sum over samples) / (number of samples) of the 2-bit quantised RF samples. See definition in AD-2.

Units: [ADC Least Significant Bits]

<ADCPercentageMagnitude>

The percentage of the samples that set the 'mag' bit in the 2-bit quantised RF samples. See definition in AD-2.

Units: [%]

<DDMOutputNumericalScaling>

The scaling applied to the 16-bit DDM variables. This corresponds to the value of the maximum DDM pixel before scaling to 65535 for the 16-bit storage range.

<FrontEndRFGainCode>

The front-end RF gain manual control code.

<FrontEndIFCoarseGainCode>

The front-end Intermediate Frequency coarse gain value manual control code.

<FrontEndIFFineGainCode>

Front-end Intermediate Frequency fine gain value manual control code.

A.3.1.4.7 Coherent Measurement group

Group Name	Coherent

Each group corresponds to the coherent measurements within a channel. The group structure consists of attributes (as a header) and then arrays of variables. The attributes contain all the settings and information that remain constant over the length of the track, while the variables are the time varying parameters.

A.3.1.4.7.1 Coherent Measurement attributes

<***CoherentIntegrationTime***>

Coherent integration time [ms]

<***NumberOfPixelsInMeasurementGroup***>

The number of coherent pixel values for each `CoherentIntegrationTime`.

<***OutputBitsPerPixel***>

Either 16 (default) or 32, the bit size of the I and Q signed integer values.

<***CurrentSpacingBetweenCoherentPixels***>

The delay spacing between each pixel in a measurement group.

<***SamplingFrequencyHz***>

The nominal sampling frequency in Hz.

<***TrackingOffsetDelayNs***>

Offset of the channel delay from the open-loop estimate, relative to the central coherent pixel.

<***TrackingOffsetDopplerHz***>

Offset of the channel Doppler from the open-loop estimate, relative to the central coherent pixel.

A.3.2 L1a DDM/CoherentMeasurements files

File Format:	NetCDF4
Bit depth:	16 bits per pixel

A ***DDM.nc*** *file* stores the pixel data for each DDM and separates these into tracks as NetCDF groups. The groups and variable structures correspond exactly to those in the ***metadata_L1a.nc*** file. A ***CoherentMeasurements.nc*** *file* stores the coherent measurement pixel data and also separates these into tracks as NetCDF groups. The groups and variable structures correspond exactly to those in the ***metadata_L1a.nc*** file. The combination of these three files make up the complete L1a data, with separation of DDM, Coherent Measurement, and metadata.

The DDMs and CoherentMeasurements files contain attributes specifying the data source and for each track, a group containing a 3-dimensional array for the incoherent DDM storage in the DDMs file, and a group containing the coherent pixels in the CoherentMeasurements file.

A.3.2.1 Structure

As shown in Figure 11-4, the DDM file consists of a set of attributes, and a track group for each reflection track. The track group also has its own time series parameters, and then channel groups for up to four channels, which have data for the L1/E1 LHCP, L1/E1 RHCP, L5/E5 LHCP, L5/E5 RHCP channels, and a group for the incoherent measurements.

```
<DDMs>
  <Attributes>
  <Track Groups>
    <Track Variables>
    <Channel Groups>
      <Incoherent Measurement Group>
            <Incoherent Measurement Variables>
```

The CoherentMeasurements file is structured similarly but with a Coherent Measurement group instead of the Incoherent Measurement group:

```
<CoherentMeasurements>
  <Attributes>
  <Track Groups>
    <Track Variables>
    <Channel Groups>
      <Coherent Measurement Group>
            <Coherent Measurement Variables>
```

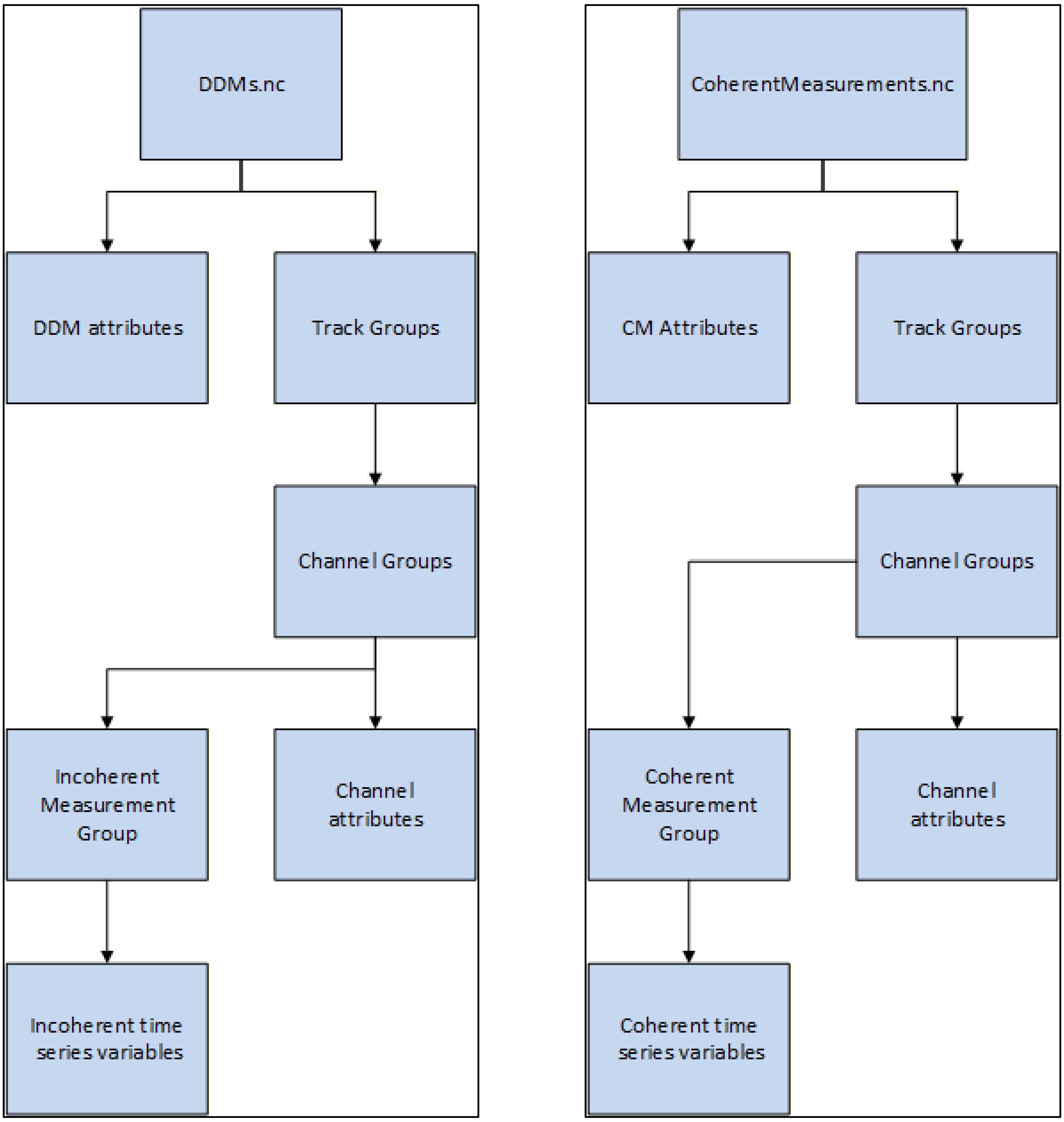

Figure 11-4 DDM structure

A.3.2.2 Attributes

<Name>

A string specifying the name of the data type, e.g. "HydroGNSS-1 L1a DDM File" or "HydroGNSS-1 L1a Coherent Measurements File".

<date_created>

The date and time that the file was created. In the format, "yyyy-mm-ddThh:mm:ss"

<***License***>

The license that applies to the contents of the file, see A.1.2.

<FileIDCode>

A string specifying the name of the data. This allows matching up of the DDM.nc and CoherentMeasurements.nc files to the corresponding metadata_L1_merged.nc file.

e.g. 2026-01/27/H18

<***L1a_ProcessorVersion***>

The version number of the L1a core processor used to generate the DDM and CoherentMeasurements files.

A.3.2.3 Track groups

Group Name	Track number e.g. ‘000000’, ‘000001’, ‘000002’…

Each track is encapsulated in a group. The groups correspond exactly to those in metadata_L1_merged.nc file.

A.3.2.3.1 Channel groups

Group Name	Channel number, 1 to 16

Each track contains up to four ZTC channels for the 4 possible frequency/polarisation combinations.

A.3.2.3.1.1 Channel attributes

<***ChannelID***>

The channel number, 1 - 16.

<***TrackID***>

The identification number of the track which this channel is a part of.

A.3.2.3.1.2 Incoherent measurement variables

<Delay>

An array of pixel indexes. Nominally 0 to 127.

<Doppler>

An array of pixel indexes. Nominally -10, -9, -8, -7 … 0 … 7, 8, 9

<IntegrationMidPointTime>

`IntegrationMidPointTime` is the mid-point between the start and the end of the DDM incoherent measurement’s integration. All the following fields are referenced to this time. NB the time step for the coherent measurements is one second.

<DDM>

Dimensions: Delay, Doppler, `IntegrationMidPointTime`

Each frame in DDM data, with time <`IntegrationMidPointTime`>, has a corresponding entry in the metadata file.

The DDMs are stored as images of the normalised pixel power. The normalisation rescales the maximum pixel of the DDM as output by the receiver's ZTC processing to the maximum for the 16-bit depth stored in the variable. The original DDM pixel scaling can be restored by performing the following operation:

```
(Restored DDM pixel) = (<DDM> pixel) / 65535
```

A.3.2.3.1.3 Coherent measurement variables

<CoherentIntegrationMidPointTime>

`CoherentIntegrationMidPointTime` is the mid-point between the start and the end of the coherent measurement's integration. All the following fields are referenced to this time. NB the time step for the coherent measurements is 4 ms.

For each `CoherentIntegrationMidPointTime`, the coherent measurement consists of:

The following two arrays, with length NumberOfPixelsInMeasurementGroup, see A.3.1.4.7.1. Nominally the array length is 3, and there is a central pixel plus one pixel either side, offset in delay by ±CurrentSpacingBetweenCoherentPixels:

Pixel 0: Central pixel delay – CurrentSpacingBetweenCoherentPixels, see A.3.1.4.7.1.

Pixel 1: Central pixel

Pixel 2: Central pixel delay + CurrentSpacingBetweenCoherentPixels

<***IValues***>

Array of `I` signed integers, each of OutputBitsPerPixel bits, see A.3.1.4.7.1. Nominally 16 bits.

<***QValues***>

Array of `Q` signed integers, each of OutputBitsPerPixel bits, see A.3.1.4.7.1. Nominally 16 bits.

<***InstantaneousPower***>

This has been removed to save on storage. It can easily be calculated for each pixel value as:

$$P = I^2 + Q^2$$

A.3.3 L1a Blackbody files

File Format:	NetCDF4
Filename	/L1A_L1B/yyyy-MM/Hhh/blackbodyNadirL1E1LHCP.nc, blackbodyNadirL1E1RHCP.nc, blackbodyNadirL5E5LHCP.nc, blackbodyNadirL5E5RHCP.nc
Filename	/L1A_L1B/yyyy-MM/Hhh/blackbodyZenithL1E1.nc, blackbodyZenithL5E5.nc

The receiver switches the LNA to the internal blackbody load periodically. In the ground processing, the resulting 'blackbody DDMs' are extracted to separate files, for nadir and zenith antennas. The resulting files are ***blackbodyNadirL1E1LHCP.nc*** etc.

These files follow the same definitions for many of the fields as the ***metadata_L1a.nc*** file. However all attributes and variables are at the file level, as this data is not specific to any reflection track.

The following parameters are given:

A.3.3.1 Attributes

<Name>

HydroGNSS L1a blackbodyNadirL1E1LHCP.nc, blackbodyNadirL1E1RHCP.nc, blackbodyNadirL5E5LHCP.nc, blackbodyNadirL5E5RHCP.nc, blackbodyZenithL1E1.nc, blackbodyZenithL5E5.nc

As per ***metadata_L1a.nc***

<date_created>, <License>, <FileIDCode>, <SourceConstellation>, <SourceNumber>, <L1a_ProcessorVersion>

Attributes not in the L1a metadata:

<BlackbodyType>

{0:Nadir, 1:Zenith}

A.3.3.2 Variables

The following variables are provided as a time series of variable ***<DateTime>.***

<IntegrationMidPointTime>, <ConfigurationNumber>,<ReflectionChannelNumber>, <FrontEnd>, <SamplingFrequency>, <FrontEndGainMode>, <FrontEndGainControlSetting>, <CoherentIntegrationTime>, <DelayResolution>, <CodeDelaySpacingSamplesBetweenPixels>, <DopplerResolution>, <IncoherentIntegrations>, <NumberOfDelayPixels>, <NumberOfDopplerPixels>, <TrackingOffsetDelayNs>, <TrackingOffsetDelayInPixels>, <TrackingOffsetDopplerHz>, <TrackingOffsetDopplerInPixels>, <PRN>, <LNATemperature>, <ADCPercentagePositive>, <ADCOffset>, <ADCPercentageMagnitude>, <DDMOutputNumericalScaling>, < DDMPixelValueNoiseWholeDDM>, <FrontEndIFCoarseGainCode>, <FrontEndIFFineGainCode>, <FrontEndRFGainCode>, <InternalTemperatures0>, <InternalTemperatures0>, <InternalTemperatures1>, <InternalTemperatures2>,<InternalTemperatures3>, <InternalTemperatures4>, <InternalTemperatures5>, <InternalTemperatures6>, <ReceiverPositionX>, <ReceiverPositionY>, <ReceiverPositionZ>, <Delay>, <Doppler>, <DDM>

Variables as per ***metadata_L1a.nc*** and ***DDMs.nc except:***

< DDMPixelValueNoiseWholeDDM>

The mean of all pixel values in power counts.

A.3.4 L1a direct signal files

File Format:	NetCDF4
Filename	/L1A_L1B/yyyy-MM/Hhh/directSignalPowerL1E1.nc /L1A_L1B/yyyy-MM/Hhh/directSignalPowerL5E5.nc

The receiver tracks the direct signals during normal operations. The power measurements from these are extracted and provided in ***directSignalPowerL1E1.nc*** and ***directSignalPowerL5E5.nc***.

A.3.4.1 Attributes

<License>

<Name>: HydroGNSS L1a directSignalPower File

<SourceConstellation>, <SourceNumber>, <L1aProcessor_Version>, <StartTime>, <StopTime>

A.3.4.2 Variables

The following variables are provided as a time series of variable ***<DateTime>.***

<DateTime>, <PRN>, <SVN>, <GnssBlock>, <FEGainMode>, <ADCPercentageMagnitude>, <ADCPercentagePositive>, <FrontEndRFGainCode>, <FrontEndIFCoarseGainCode>, <FrontEndIFFineGainCode>, <InEclipse>, <ReceiverPositionX>, <ReceiverPositionY>, <ReceiverPositionZ>, <ReceiverVelocityX>, <ReceiverVelocityY>, <ReceiverVelocityZ>, <TransmitterPositionX>, <TransmitterPositionY>, <TransmitterPositionZ>, <TransmitterVelocityX>, <TransmitterVelocityY>, <TransmitterVelocityZ>, <AttitudeRoll>, <AttitudePitch>, <AttitudeYaw>, <InternalTemperatures0>, <InternalTemperatures0>, <InternalTemperatures1>, <InternalTemperatures2>,<InternalTemperatures3>, <InternalTemperatures4>, <InternalTemperatures5>, <InternalTemperatures6>

These are terms are not defined further specifically for the DirectSignalPower file as they match the definitions given for the equivalent variables in the other (nadir) metadata files. Additional parameters descriptions are provided below:

<RxToTxAzimuthInDegrees>, <RxToTxElevationInDegrees> are defined as the angles to the GNSS transmitter (rather than specular point) from the receiver. The antenna transformation for the zenith antenna is $-Z_B$ (upward pointing).

Units: [degrees]

<***ReceiverGainTowardsTx***>

The zenith antenna gain towards the transmitter GNSS satellite.

Units: [dBi]

<TxToRxAzimuthInDegrees> , <TxToRxElevationInDegrees > is defined as the angles to the receiver from the GNSS transmitter, calculated considering the transmitter attitude. The antenna is downward pointing.

Units: [degrees]

<**TxYaw**>

Transmitter nominal yaw angle defined from 0 to 360 degrees. The transmitter corresponds to the <SVN> from the header. Modified yaw behaviour is flagged in the <**ModifiedYawSteeringFlag**>.

Units: [degrees]

<***ModifiedYawSteeringFlag***>

Related to the <**TxYaw**>, this flag indicates when the tracked transmitter <SVN> is estimated to be in a non-nominal yaw scenario, 1: Modified Yaw Steering, non-nominal yaw behaviour expected 0: Nominal Yaw Steering.

Units: [bool]

<TransmitterGainTowardsRx>

The GNSS satellite transmitter antenna gain pointed in the direction of the HydroGNSS zenith antenna, from the GNSS antenna gain map.

Units: [dBi]

<SystemGainCorrected>

Estimate of the system gain at the epoch of the zenith power measurement. This is generated using the closest zenith blackbody measurement, corrected for temperature and AGC variation. When a system gain cannot be calculated, from the black body measurement, a predetermined estimate of the system gain is stated, in which case the ***< SystemGainEstimateFlag>*** flag is raised.

Units: [dB]

<SystemGainTempCompensation>

System gain temperature correction term for translating the zenith blackbody system gain measurement to the instance of the DDM measurement.

Units: [dB]

<SystemGainAGCCompensation>

System gain correction term for translating the blackbody system gain measurement to the instance of the DDM measurement. The parameter reports the difference between the receiver zenith front-end AGC setting at DDM measurement and the AGC setting at the closest blackbody measurement.

Units: [dB]

<ReceiverGainSetting>

Receiver zenith IF gain setting in dB required to maintain the output near the 2-bit optimal sampling region. The parameter is the sum of the intermediate frequency look up values, converted to dB using the datasheet front-end gain determination table. Front-end gain can be modelled by

$$G_{AGC} = 12+0.97*\mathit{RFGainsetting} + \mathbf{ReceiverGainSetting},$$

where the *RFGainSetting* is by default set at step 15.

Units: [dB]

<***SystemGainEstimateFlag***>

Flag raised when an estimate of system gain is used for L1B calculations, 1 = estimate, 0 = calculated from BB or ExtRef.

<AntennaTemperature>

The zenith antenna noise temperature measured from a correlator noise channel (of the zenith receiver) and last set of zenith blackbody DDMs. See **Error! Reference source not found.**.

Units: [Kelvin]

<***RxTemperature***>

The zenith receiver noise temperature estimate for each channel. From Friis cascade of noise temperature including look-up function for the LNA Noise Figure at the measured physical temperature.

Units: [Kelvin]

< SignalPower> and ***< NoisePower>*** are double values in power counts.

Units: [Counts]

<***CalibratedPowerAtAntennaPort***> The power of the signal at the antenna output port, corrected for signal noise.

Units: [dBW]

<***EIRPtoReceiverModelled***>

An estimate of the Effective Isotropic Radiated Power (EIRP) at GNSS transmitter towards the specular point, using the CM1 calibration method detailed in **Error! Reference source not found.**. The value will be set to NaN if this calibration method is not available for this GNSS frequency and polarisation.

<***EIRPtoReceiverMeasured***>

An estimate of the Effective Isotropic Radiated Power (EIRP) at GNSS transmitter towards the specular point, using the CM3 *a posteriori* calibration method detailed in **Error! Reference source not found.**. The value will be set to NaN if this calibration method is not available for this GNSS frequency and polarisation.

Units: [dBW]

A.4 Level 1b core metadata

File format:	NetCDF4
Filename	/L1A_L1B/yyyy-MM/Hhh/**metadata_L1b.nc**

A.4.1 Structure

As shown in Figure 11-5, the L1b metadata file consists of a set of attributes, and then a track group for each reflection track. The track group also has its own attributes and time series parameters, and then a channel group for up to four channels, which have data for the L1/E1 LHCP, L1/E1 RHCP, L5/E5 LHCP, L5/E5 RHCP channels. The L1b metadata contains data derived from sources on the ground (rather than from the satellite), and data derived from this including direct radiometric corrections.

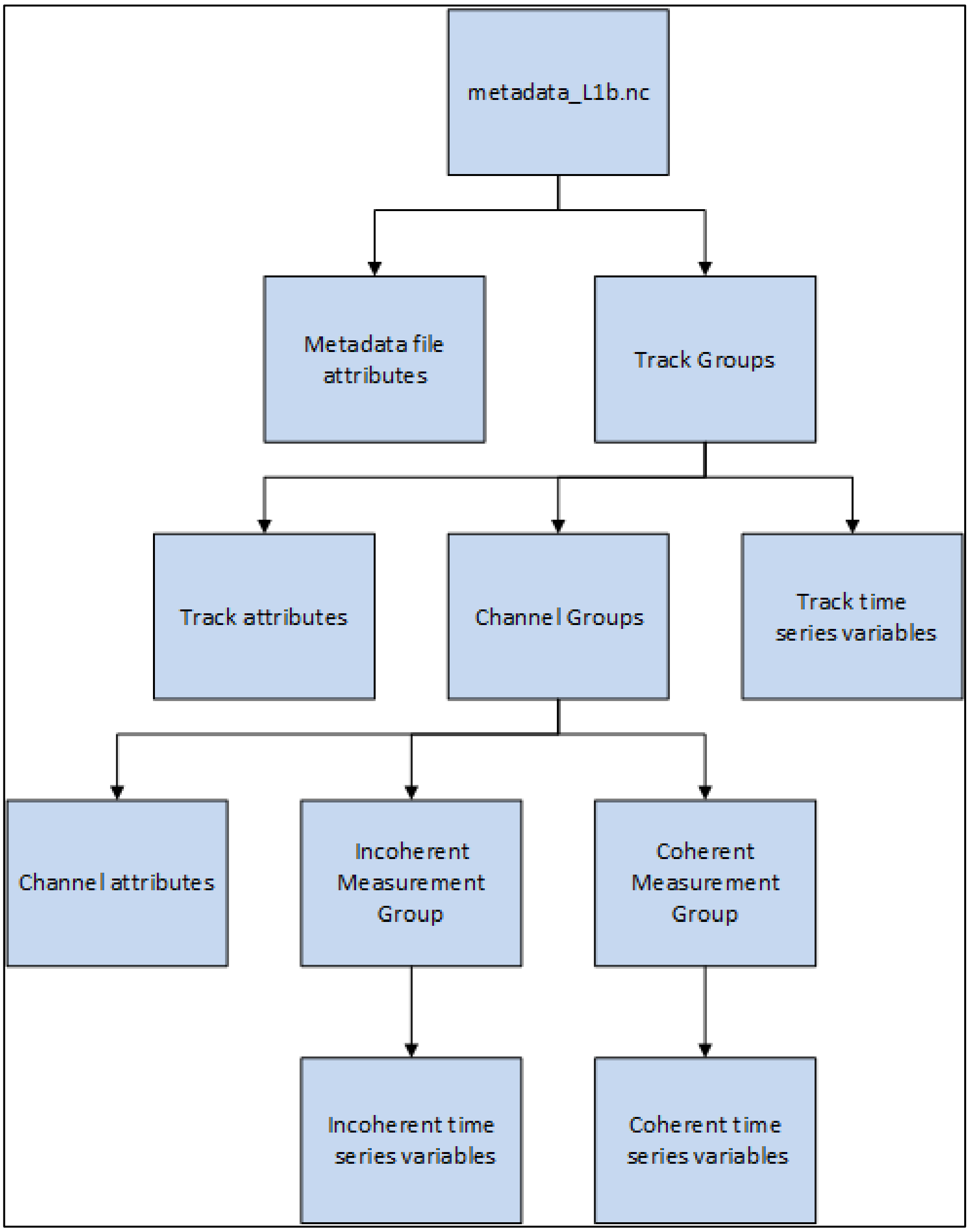

Figure 11-5 L1b metadata structure

```
<L1bMetadata>
  <Attributes>
  <Track Groups>
    <Track Attributes>
    <Track Variables>
    <Channel Groups>
      <Channel Attributes>
      <Channel Variables>
      <Incoherent Measurement Group
            <Incoherent Measurement Variables>
      <Coherent Measurement Group
            <Coherent Measurement Variables>
```

NB. On the User FTP site, the L1b metadata is contained in the file metadata_L1_merged.nc, which also includes the L1a and L1b_ext metadata.

A.4.2 Attributes

<*Name*>: "HydroGNSS-1 L1b metadata file" or "HydroGNSS-2 L1b metadata file".

<*L1b_date_created*>

Current time when the L1b metadata file was created , e.g. "2022-03-30T08:30:32".

<***License***>

The license that applies to the contents of the file, see A.1.2.

<***FileIDCode***>

The ID number of the L1b metadata file, i.e. yyyy-MM/dd/Hhh, e.g. 2024-08/18/H06

<***DataTag***>

A tag to label the current processing run, copied over from the L1a metadata. This is set to <dataset path>_<current timestamp>, e.g. "2018-08/18/H06_30/03/2022 08:30:17".

<***L1b_ProcessorVersion***>

The version number of the L1b core processor used to generate the synchronised L1b metadata.

<***L1a_ProcessorVersion***>

The version number of the L1a core processor used to generate the input L1a products used by the L1b processor.

<***BoundingBoxDelay***>

The size of the bounding box, delay dimension, used for the peak search in ms.

<***BoundingBoxDoppler***>

The size of the bounding box, doppler dimension, used for the peak search in Hz.

<***SizeOfNoiseCorners***>

The size of the corner of the DDM to be used as noise pixels. Two corners are used, each described be an equal number of doppler and delay pixels.

<***NumberOfNoiseDDMs***>

Number of DDMs to be used to gather noise pixels. DDMs before and after the current DDM are used up to the total number specified here.

<***LowAGSPThreshold***>

The threshold below which the antenna gain towards the specular point is considered low, indicating that the data related to this specular point may be of low quality.

<***LowSNRThreshold***>

The threshold below which the signal to noise ratio is considered, indicating that the data related to this specular point may be of low quality.

<***VeryLowSNRThreshold***>

The threshold below which the signal to noise ratio is considered to be very low, indicating that the data related to this specular point is unlikely to be useable.

<***HighIncidenceAngleThreshold***>

The threshold above which the incidence angle is considered to be high, and the data related to this specular point may not be useable.

<***HighNoiseKurtosisThreshold***>

The threshold above which the noise kurtosis is considered to be high, and the data related to this specular point may not be useable.

A.4.3 Track groups

A.4.3.1 Track attributes

<***TrackID***>

The identification number of the track.

<***TrackIDOrbit***>

An additional identification number of the track, used for the E2ES only. This is intended to identify tracks unambiguously, when the E2ES simulator generates datasets for periods longer than six hours, for which the PDGS would restart the TrackID at 0 every six hours, resulting in different tracks having the same TrackID. When the PDGS processes real payload data **TrackIDOrbit** is not included in L1a, L1b, L1 merged metadata or any of the L2 products. However when the L1a metadata is generated by the E2ES, **TrackIDOrbit** is included in the L1 metadata, and is then be copied over into L1b and L1 merged metadata, and all the L2 products.

<***ReflectionChannelNumberList***>

Array of the nadir front end numbers included in this track. The nadir front end numbers are in the range from 0 to 3:

0: Nadir_L1E1_LHCP, 1: Nadir_L1E1_RHCP, 2: Nadir_L5E5_LHCP, 3: Nadir_L5E5_RHCP

A.4.3.2 Track variables

<***IntegrationMidPointTime***>

IntegrationMidPointTime is the mid-point between the start and the end of the DDM's integration. All the following fields are referenced to this time.

<***TransmitterPositionX***>, <***TransmitterPositionY***>, <***TransmitterPositionZ***>

Transmitter position at the time of reception of the signals at the receiver. The transmitter corresponds to the <PRN> from the header. The position is re-calculated from the RINEX broadcast ephemeris file retrieved on the ground from the International GNSS Service (IGS).

Units: [m]

<***TransmitterVelocity***>, <***TransmitterVelocityY***>, <***TransmitterVelocityZ***>

Transmitter velocity at the time of reception of the signals at the receiver. The transmitter corresponds to the <PRN> from the header. The velocity is re-calculated from the RINEX broadcast ephemeris file retrieved on the ground from the International GNSS Service (IGS).

Units: [m/s]

<TxAzimuthTowardsRx>, ***<TxElevationTowardsRx>***

The piercing angles of the transmit antenna pattern <PRN> in the direction of the HydroGNSS zenith receiver. The azimuth angle is defined as -180 to 180 degrees, with 0 at boresight. Elevation is 0 to 90 degrees, with 0 at boresight.

Units: [degrees]

<TxAzimuthTowardsSP>, ***<TxElevationTowardsSP>***

The piercing angles of the transmit antenna pattern <PRN> in the direction of the specular point. The azimuth angle is defined as -180 to 180 degrees, with 0 at boresight. Elevation is 0 to 90 degrees, with 0 at boresight.

Units: [degrees]

<GNSSTransmitterYaw>

Transmitter nominal yaw angle defined from 0 to 360 degrees. The transmitter corresponds to the <PRN> from the header. Modified yaw behaviour is flagged in the <ModifiedYawSteeringFlag>.

Units: [degrees]

<SpecularPointPositionX>, <SpecularPointPositionY>, <SpecularPointPositionZ>

The specular point location at the time of the reflection ECEF WGS-84 [m], this is copied from the on-board specular point in the L1a metadata.

<SpecularPointLat>, <SpecularPointLon>

The latitude and longitude of the specular point at the time of the reflection [degrees, degrees]. This is re-calculated using the RINEX transmitter orbit data

<ReflectionHeight>

The specular point height relative to the WGS 84 ellipsoid, based on the detailed on-ground DEM/geoid models.
Units: [m]

<DelayReferencedToDirectGeom>

The delay, calculated geometrically, between the direct signal and the reflected signal is recalculated during level 1B processing.

Units: [ns]

<AtmosphericDelayL1E1>

The additional delay to the L1 and E1 signals due to ionospheric effects. Note that the delay due to tropospheric effects has not been implemented as this is considered to be negligible. This term includes both the downwards and reflected paths of the signal. The total expected delay can be calculated be calculated for the L1 and E1 signals be adding the atmospheric delay term to the geometric delay term <DelayReferencedToDirect>. Note that this will be an exact replica of the OnboardAtmosphericDelayL1E1 but is included in case future developments include more accurate processing of this variable.

Units: [ns]

<AtmosphericDelayL5E5>

The additional delay to the L5 and E5 signals due to ionospheric effects. Note that the delay due to tropospheric effects has not been implemented as this is considered to be negligible. This term includes both the downwards and reflected paths of the signal. The total expected delay can be calculated be for the L5 and E5 signals be adding the atmospheric delay term to the geometric delay term <DelayReferencedToDirect>. Note that this will be an exact replica of the OnboardAtmosphericDelayL5E5 but is included in case future developments include more accurate processing of this variable.

Units: [ns]

<SpecularPathRangeOffset>

This field provides a per DDM correction to the delay tracking point to allow correct location of the targeted specular point location, if necessary. See L1a/L1b ATBD, AD-2.

Units: [ns]

<SPIncidenceAngle>

This field is the incidence angle of the reflection. This is the angle between the transmitter to specular point ray and the surface normal. The surface normal is calculated for the WGS-84 ellipsoid.

Units: [degrees]

<***SPSlopeAlphaAngle***>
Elevation angle (alpha) of the 2D topographical slope at the specular point, the elevation and aspect of the slope are used to calculate the SP displacement parameters (<SPSlopeRangeDisplacement>, <SPSlopeSPDisplacementX> and <SPSlopeSPDisplacementY>). Alpha defines the angle of the slope from the X-Y plane. The algorithm is defined in **Error! Reference source not found.**.
Units: [Degrees]

<***SPSlopeAspectAngle***>
Aspect angle (beta) of the 2D topographical slope at the specular point, the elevation and aspect of the slope are used to calculate the SP displacement parameters (<SPSlopeRangeDisplacement>, <SPSlopeSPDisplacementX> and <SPSlopeSPDisplacementY>). Beta defines the azimuth of the slope as an anticlockwise angle from the reflection plane (from +z direction). The algorithm is defined in **Error! Reference source not found.**.
Units: [Degrees]

<***SPSlopeRangeDisplacement***>
Estimated error in range due to the 2D topographical slope of the region around the specular point, as defined in **Error! Reference source not found.**.
Units: [m]

<***SPSlopeSPDisplacementX***>
Estimated error in the X coordinate of the specular point due to the 2D topographical slope at the specular point, as defined in **Error! Reference source not found.**.
Units: [m]

<***SPSlopeSPDisplacementY***>
Estimated error in the Y coordinate of the specular point due to the 2D topographical slope at the specular point, as defined in **Error! Reference source not found.**.
Units: [m]

<SPElevationORF>

Elevation is the angle between the Receiver to Specular point vector and the orbit radial vector, $\mathbf{z}_O$, as defined in the L1a/L1b ATBD, AD-2.

e.g. elevation of 90 degrees is towards receiver nadir.

Units: [degrees]

<SPAzimuthORF>

The azimuth angle of the Specular point to Receiver vector in the receiver's orbit reference frame. The azimuth angle is from the $\mathbf{x}_O$ axis towards the $\mathbf{y}_O$ axis. This is defined in L1a/L1b ATBD, AD-2.

Units: [degrees]

<SPElevationARF>

Elevation is the angle between the Specular point to Receiver vector and the antenna boresight vector, $\mathbf{z}_A$, as defined in AD-2.

e.g. elevation of 90 degrees is towards antenna boresight.

Units: [degrees]

<SPAzimuthARF>

The azimuth angle of the Specular point to Receiver vector in the receiver's antenna reference frame. In the antenna reference frame has azimuth angle from the $\mathbf{X}_A$ axis towards the $\mathbf{Y}_A$ axis. This is defined in AD-2.

e.g. If attitude is [0,0,0] roll, pitch, yaw then azimuth 0 is in the velocity direction. Positive azimuth is clockwise when viewed from above.

Units: [degrees]

<HighIncidenceAngle>

Data quality flag is true if the incidence angle is higher than a configurable threshold and false otherwise.

<***LandType***>

This is derived from the ESA CCI Land Cover Map, see RD-2. This is a global NetCDF dataset in 30 arcsecond steps in latitude and longitude. Each point along the reflection track is assigned an integer value based on the CCI land cover map values, i.e.

No_data=0,
Cropland_rainfed=10,
Cropland_rainfed_herbaceous_cover=11,
Cropland_rainfed_tree_or_chrub_cover=12,
Cropland_irrigated=20, Mosaic_cropland=30,
Mosaic_natural_vegetation=40,
Tree_broadleaved_evergreen_closed_to_open=50,
Tree_broadleaved_deciduous_closed_to_open=60,
Tree_broadleaved_deciduous_closed=61, Tree_broadleaved_deciduous_open=62,
Tree_needleleavedleaved_evergreen_closed_to_open=70, Tree_needleleaved_evergreen_closed=71,
Tree_needleleaved_evergreen_open=72,
Tree_needleleaved_deciduous_closed_to_open=80,
Tree_needleleaved_deciduous_closed=81,
Tree_needleleaved_deciduous_open=82, Tree_mixed=90,
Mosaic_tree_and_shrub=100,
Mosaic_herbaceous=110,
Shrubland=120,
Shrubland_evergreen=121,
Shrubland_deciduous=122,
Grassland=130,
Lichens_and_mosses=140,
Sparse_vegetation=150,
Sparse_tree=151,
Sparse_shrub=152,
Sparse_herbaceous=153,
Tree_cover_flooded_fresh_or_brackish_water=160,
Tree_cover_flooded_saline_water=170,
Shrub_or_herbaceous_cover_flooded=180,
Urban=190, Bare_areas=200,
Bare_areas_consolidated=201,
Bare_areas_unconsolidated=202,
Water=210,
Snow_and_ice=220

<***SnowIceCover***>

Data retrieved from NSIDC, see RD-3. Values are :

outside_coverage_area = 0
open_water = 1
land_without_snow = 2
sea_ice_or_lake_ice = 3
snow_covered_land = 4

<***CoastProximity***>

Data retrieved from NOAA, see RD-4. This is the distance of the specular point from the coast, in km. The value is negative if the specular point is over land, and positive if it is over the sea.

A.4.3.3 Channel groups

Group Name	Channel number, 1 to 16

Each track contains up to four channels for the 4 possible frequency/polarisation combinations.

A.4.3.3.1 Channel attributes

<***ChannelID***>

The channel number, 1 - 16. The channels are as defined for L1a metadata, see A.3.1.4.3.

<***TrackID***>

The identification number of the track which this channel is a part of.

A.4.3.3.2 Channel variables

A.4.3.3.3 Incoherent measurement group

A.4.3.3.3.1 Incoherent measurement variables

<***IntegrationMidPointTime***>

`IntegrationMidPointTime` is the mid-point between the start and the end of the DDM incoherent measurement's integration. All the following fields are referenced to this time.

<AntennaGainTowardsSpecularPoint>

The antenna gain pointed at the specular point is provided in this field. The antenna gain for the specular point is calculated by transforming the specular point to receiver vector into the Orbit Reference Frame using the receiver position and velocity, then using the receiver attitude it is transformed into the Satellite Body Frame, then using the Antenna Boresight vector into the Antenna Reference Frame. The azimuth and elevation of this vector is then used to index into an antenna gain look-up table.

The look-up table was determined from measuring the antenna on an antenna test range on the ground before launch. The table is in 1°x1° steps and will be available from the HydroGNSS web portal.

These steps are defined in more detail in section AD-2.

Units: [dB]

<AntennaGainRangeMin>, <AntennaGainRangeMax>

The antenna gain pointed at the specular point is a function of the receiver attitude. The attitude determination has an inherent uncertainty, so this is propagated through to a range of antenna gains. The uncertainty value used is a rough estimate and varies during the orbit, depending on the combination of sun-sensors or magnetometers being used. The attitude uncertainty is provided in variables *<AttitudeUncertaintyRoll>*, *<AttitudeUncertaintyPitch>*, *AttitudeUncertaintyYaw>*. The minimum and maximum gain values are found by taking the attitude and multiplying by every combination of the uncertainties scaled by [-1,0,1]. There is poor understanding of the uncertainty values, but this is still useful to understand the rate of gain change of the antenna pattern.

Units: [dB]

<DDMPixelValueNoise>

A simple, rough estimate of the DDM noise. The pixel value at 0 Hz Doppler and the 1st delay row of the DDM. Being based on one-pixel it has a higher variance in comparison to the noise box approach. This noise measure was in the original MERRByS data release and has been kept for backward compatibility.

Units: [Power counts]

<NoiseRows>

The noise rows are calculated from the top of the DDM down to a configurable number of rows above the tracking point. This is a constant value for all DDM's in this dataset. However, for TDS-1, a variable number of rows was used, and this processing path is still available. See below.

For TDS-1 the noise rows are specified in the following way: A noise box is defined in the region above the reflection in the DDM. This area is above the Earth's surface, so measures the DDM noise, without reflections. This field gives the variable number of rows used for the noise box. The onboard DDM processing always aligns the tracking of the specular point with the quasi-spherical Earth model. Therefore when there is significant land elevation, the specular point moves to smaller delays in the DDM processing window. The noise box is scaled according to surface altitude which is found from a topographic map and corrected for incidence angle. This variable noise box size ensures that land reflections do not corrupt the noise measurement.

If the number of rows specified is 0, then there were no complete DDM rows predicted to be free of reflections. In that case an attempt to retrieve the noise could be obtained from ***<MeanNoiseHighDoppler>***. The noise box limits to 1 row, which means a measure still appears in ***<MeanNoise>*** and ***<NoiseKurtosis>*** (although these could potentially include ground reflections).

<MeanNoise>

The mean pixel value of all the noise pixels gathered from the noise rows and corners of the current DDM and those before and after as specified by ***<NoiseRows>***.

Units: [Power counts]

<NoiseKurtosis>

The sample excess Kurtosis of the noise box pixels.

<MeanNoiseHighDoppler>

The mean pixel value at the 1st delay row, 1st and last Doppler cells only. This can be useful when operating over high altitude regions. The specular point is above the top of the DDM and there are no complete rows for a noise box, <*NoiseBoxRows*> is set to 0. The high Doppler pixels will have less land corruption, but based on only two pixels, will have a higher variance.

Units: [Power counts]

<DDMMaxPixelBounded>

Peak pixel value found within the bounded region of the DDM. This value is used as the peak signal value for the DDMSNRAtPeakSingleDDM, MeasuredReflectedSignalPower and subsequent measurements.

Units: [Power counts]

<***DDMSNRAtPeakSingleDDM***>

This field provides the SNR of the peak/maximum DDM pixel from within the bounding box. The peak DDM pixel is from one DDM and one pixel, without any additional averaging.

For the SNR's noise estimate, <`MeanNoise`> is used. However when there are insufficient DDM rows available for noise estimation, (so <`NoiseRows`> = 0) then <`MeanNoiseHighDoppler`> is used instead.

The peak SNR is calculated:

SNR = 10*log10((PeakPixel / NoiseEstimate) - 1)

See A.3.1.4.2 for definitions of `MeanNoise, NoiseRows, and MeanNoiseHighDoppler.`

Units [dB]

<***MeasuredReflectedSignalPower***>

The power of the signal reflected from the AGSP and received by the nadir antenna, corrected for noise and receiver antenna gain. This is calculated using the maximum DDM pixel value from within the bounding box.

Units: [dBW]

<***MeasuredDirectSignalPower***>

The power of the signal received by the zenith antenna direct from the GNSS satellite, corrected for noise and receiver antenna gain.

Units: [dBW]

<***EIRP***>

An estimate of the Effective Isotropic Radiated Power (EIRP) at GNSS transmitter towards the specular point, using the best available calibration method from CM1, CM2, or CM3.

<***EIRP_CM1***>

An estimate of the Effective Isotropic Radiated Power (EIRP) at GNSS transmitter towards the specular point, using the the CM1 calibration method using the model detailed in AD-2. The value will be set to NaN if this calibration method is not available for this GNSS frequency and polarisation.

<***EIRP_CM2***>

An estimate of the Effective Isotropic Radiated Power (EIRP) at GNSS transmitter towards the specular point, using the the CM2 direct calibration method detailed in AD-8. The value will be set to NaN if this calibration method is not available for this GNSS frequency and polarisation.

<***EIRP_CM3***>

An estimate of the Effective Isotropic Radiated Power (EIRP) at GNSS transmitter towards the specular point, using the the CM3 *a posteriori* calibration method detailed in AD-2. The value will be set to NaN if this calibration method is not available for this GNSS frequency and polarisation.

Units: [dBW]

<***ReflectionCoefficientAtSP***>

Reflection coefficient at the specular point, calculated over sea and land, using the best available calibration method from CM1, CM2, or CM3.

<***ReflectionCoefficientAtSP_CM1***>

An estimate of the reflection coefficient at the specular point, using the peak power value from within the bounding box. The CM1 calibration method using the model detailed in AD-2 is used. The value will be set to NaN if this calibration method is not available for this GNSS frequency and polarisation.

<***ReflectionCoefficientAtSP_CM2***>

An estimate of the reflection coefficient at the specular point, using the CM2 direct calibration method detailed in AD-8. The value will be set to NaN if this calibration method is not available for this GNSS frequency and polarisation.

<***ReflectionCoefficientAtSP_CM3***>

An estimate of the reflection coefficient at the specular point, using the peak power value from within the bounding box. The CM3 *a posteriori* calibration method detailed in AD-2. The value will be set to NaN if this calibration method is not available for this GNSS frequency and polarisation.

Units: [dB]

<***ReflectionCoefficientUnbounded***>

Reflection coefficient at the specular point, calculated using the peak power value found in the whole DDM.

<***Sigma0***>

The bistatic normalised radar cross-section at the specular point (along with the assumed surface area used for the sigma-0 calculation), calculated over sea and land, using the best available calibration method from CM1, CM2, or CM3.

<***Sigma0_CM1***>

An estimate of sigma-0, using the CM1 calibration method using the model detailed in AD-2. The value will be set to NaN if this calibration method is not available for this GNSS frequency and polarisation.

<***Sigma0_CM2***>

An estimate of sigma-0, using the CM2 direct calibration method detailed in AD-8. The value will be set to NaN if this calibration method is not available for this GNSS frequency and polarisation.

<***Sigma0_CM3***>

An estimate of sigma-0, using the CM3 *a posteriori* calibration method detailed in AD-2. The value will be set to NaN if this calibration method is not available for this GNSS frequency and polarisation.

Units: [m^2/m^2]

<***Sigma0Area***>

The area of the specular point region used to calculate Sigma0.

Units: [m^2]

<SystemGainBBNadir>

System gain measurement using the nadir blackbody in nominal conditions. In the absence of a blackbody measurement the system gain estimate from the external reference site will be provided (***<SystemGainExternalReference>***). When a system gain cannot be calculated, from the black body or external reference measurement, a predetermined estimate of the system gain is stated, in which case the ***<SystemGainSourceFlagNadir>*** and ***<LowOverallQuality>*** flags are raised.

Units: [dB]

<SystemGainBBCompNadir>

System gain correction term for translating the blackbody system gain measurement to the instance of the DDM measurement. The parameter reports the difference between the receiver nadir front-end AGC setting at DDM measurement and the AGC setting at the closest blackbody measurement.

Units: [dB]

<SystemGainAGCCompNadir>

System gain correction term for translating the blackbody system gain measurement to the instance of the DDM measurement. The parameter reports the difference between the receiver nadir front-end AGC setting at DDM measurement and the AGC setting at the closest blackbody measurement.

Units: [dB]

<ReceiverFrontEndGainSettingNadir>

Receiver nadir IF gain setting in dB required to maintain the output near the 2-bit optimal sampling region. The parameter is the sum of the intermediate frequency look up values (Coarse IF and Fine IF), converted to dB using the datasheet front-end gain determination table. Front-end gain can be modelled by

G_{AGC} = 12+0.97**RFGainsetting* + ***ReceiverGainSetting***,

where the *RFGainSetting* is by default set at step 15.

Units: [dB]

<AntennaTemperatureNadir>

The nadir antenna noise temperature measured from the DDM noise ***<MeanNoise>*** and last set of nadir blackbody DDMs. See **Error! Reference source not found.**.

Units: [Kelvin]

<AntennaTemperatureExternalReference>
The nadir antenna noise temperature measured from the DDM noise ***<MeanNoise>*** over a specific target location. An average of the noise for each pass of the site is used to provide an estimate of the antenna temperature for every epoch of the track, within a set validity period. See **Error! Reference source not found.**.

When the processing is not performed (data not available over the target location for example) the parameter will take a NaN value.

Units: [Kelvin]

<SystemGainExternalReference>

The system gain measured from the DDM noise ***<MeanNoise>*** over a specific target location. An average of the noise for each pass of the site is used to provide an estimate of the system gain for every epoch of the track, within a set validity period. See **Error! Reference source not found.**.

When the processing is not performed (data not available over the target location for example) the parameter will take a NaN value.

<***SystemGainSourceFlagNadir***>

Flag raised when an estimate of system gain is used for L1B calculations, 1 = estimate, 0 = calculated from BB or ExtRef.

<***RxTemperatureNadir***>

The nadir receiver noise temperature estimate for each channel. From Friis cascade of noise temperature including look-up function for the LNA Noise Figure at the measured physical temperature.

Units: [Kelvin]

<GnssTransmitterGainTowardsSP>

The GNSS satellite transmitter antenna gain pointed in the direction of the secular point, from the GNSS antenna gain map.

Units: [dBi]

<***DirectSignalInDDM***>

This flag provides an indication for one source of potentially poor quality data. If set to true (1) then the reflected signal being processed is separated from the direct signal by a delay and Doppler that is within the DDM processing window.

Due to the limited length of the GPS L1 C/A (Coarse Acquisition) code signal, it will repeat every 1023 chips. Due to the chipping rate of 1.023 Mbps, this means the signal will be ambiguous over 1 ms periods during the travel time. The direct signal and the reflected signal can therefore appear in the same signal space potentially corrupting the reflected measurement. For orbit altitudes of less than 600 km there could be three geometries where the direct signal interferes with the reflected signal, assuming there is sufficient gain in the back-lobe of the nadir antenna. This flag is relevant to both polarisations of the signal.

The Galileo E1 signals have a code length of 4096 chips, which is 4 ms in duration or approx. 1200 km spatial ambiguity. This means that no geometry can cause direct signal interference while the orbit altitude is less than 600 km (maximum range difference is when signal originates from overhead, causing a 2 x height difference between direct and reflected paths).

The GPS and Galileo L5/E5 signals have ten times the chipping rate and ten times the primary code length compared to C/A code (i.e. 10 Mbps, 10230 chips), so are expected to have the same 1 ms ambiguity as GPS L1 C/A code signals. This may be avoided, however, if the secondary codes are used to extend the code repetition time to 10 or 20 ms.

<***LowAGSP***>

Quality flag to indicate that the AGSP is below a configurable threshold.

<***LowSNR***>

Quality flag to indicate that the SNR is below a configurable threshold.

<***VeryLowSNR***>

Quality flag to indicate that the SNR is below a (lower) configurable threshold.

<***HighNoiseKurtosis***>

Quality flag to indicate that the Kurtosis of noise is above a configurable threshold.

<***LowOverallQuality***>

Low quality summary flag composed of a bitwise **or** of ***VeryLowSNR***, ***LowAGSP***, and TBD other flags. Flag not set (value = zero) means the data is of good quality. When the flag is set (value= 1) then the quality is poor.

A.4.3.3.4 Coherent measurement group

There is currently no L1b coherent metadata.

A.5 Level1b_ext

A.5.1 NOC L1b_ext

File format:	NetCDF4
Filename	/L1A_L1B/yyyy-MM/Hhh/**L1B_PX.nc**

The structure of the NOC L1b_ext metadata file will follow the same pattern as the L1a, L1b metadata files described in A.3.1, A.4.1.

NB. On the User FTP site, the L1b_ext metadata is contained in the file metadata_L1_merged.nc, which also includes the L1a and L1b metadata.

A.5.1.1 Attributes

<***License***>

The license that applies to the contents of the file, see A.1.2.

<***L1B_PX_date_created***>

The date and time at which processing started.

<***SourceConstellation***>

HydroGNSS.

<***L1B_PX_ProcessorVersion***>

The version number of the NOC L1b_ext processor used to generate the synchronised NOC L1b_ext metadata.

<***L1b_ProcessorVersion***>

The version number of the L1b core processor used to generate the L1b metadata used by the L1b_ext_NOC processor.

<***L1a_ProcessorVersion***>

The version number of the L1a core processor used to generate the input L1a products used by the L1b_ext_NOC processor.

<***FirstTimeStamp***>

Start of the dataset.

<***LastTimeStamp***>

End of the dataset.

A.5.1.1.1 Channel attributes

<***ChannelID***>

The ZTC channel number, 1 - 16.

<***TrackID***>

The identification number of the track which this channel is a part of.

A.5.1.1.1.1 Incoherent Measurement Variables

(1D Dimension "DateTime")

<***SI_flag***>

Boolean flag, set to 1 if sea ice detected, or 0 if sea ice was not detected.

<***Sigma0_CM2***>

An estimate of Sigma0, bistatic normalised radar cross-section at the specular point, is provided following radiometric calibration steps and the application of the <*TransmitterEndCorrection*> & <*ReceiverEndCorrection*> in the L1OB-PX processor. There is no output (NaN) if any of the quality control flags are set (see <*CAFlag*>,<*RFIFlag*>) or if the specular point is over land.

Units: dB (arbitrary offset)

<***ReflectionCoefficientAtSP_CM2***>

An estimate of the reflection coefficient at the specular point from the same process as Sigma0_CM2.

Units: dB (arbitrary offset)

<***TEC***> & <***REC***>

Two correction parameters are output by the L1BOP-PX processor. The first correction is called the Transmitter-End Correction (TEC) and addresses power variations across different GPS transmitters. The second correction is known as the Receiver-End Correction (REC) and aims at mitigating inaccuracies in antenna pattern knowledge on-board HydroGNSS. There is no output (NaN) if any of the quality control flags are set (see <*CAFlag*>, <*RFIFlag*>).

Units: dB (arbitrary offset)

<***QC_pass_flag***>

Quality control Boolean flag, set to 0 if CA_Flag and RFI_Flag are both zero, or 1 if CA_Flag and/or RFI_Flag are set to 1.

<***RFI_flag***>

Radio Frequency Interference (RFI) has the potential to contaminate DDM data and thus bias the geophysical retrieval process. Inspection of TDS-1 data has revealed that some RFI is typically represented by "bands" of strong correlated power spanning all delays at certain Doppler frequencies within the DDM, a similar representation is expected on HydroGNSS. In order to exclude such contaminated samples from the record, the detection algorithm makes a decision based on the presence of these characteristic "bands" within the DDM. If RFI is determined to be present, the flag is set to 1, otherwise the flag is set to 0.

Units: Boolean (unitless)

Range: no RFI=0, presence of RFI=1

<***CA_flag***>

Some DDMs within the TDS-1 record were marked by a single strong "band" of high power at a given delay spanning all Doppler frequencies, believed to be associated with infrequent glitches in the correlation process. Similar to the presence of RFI, the presence of such anomalies may contaminate DDM data, lead to erroneous signal estimation and thus bias the geophysical retrieval algorithm. The correlator anomalies sub-algorithm identifies these effects by their characteristic signature in the DDM. If correlator anomalies are detected the flag is set to 1, otherwise it is set to 0.

Units: Boolean (unitless)

Range: no correlator anomaly=0, presence of correlator anomaly=1

A.5.2 IEEC Incoherent Data L1b_ext

File format:		NetCDF4
Filename		/L1A_L1B/yyyy-MM/Hhh/**L1B_CX.nc**

The structure of the IEEC L1b_ext metadata file will follow the same pattern as the L1a and L1b metadata files described in A.3.1, and A.4.1.

A.5.2.1 Attributes

<***Name*** >

The description of the L1b_ext CX file.

<***License***>

The license that applies to the contents of the file, see A.1.2.

<***L1B_CX_date_created***>

The date when the CX file was created.

<***License***>

The license that applies to the contents of the file, see A.1.2.

<***L1B_CX_Creator***>

The developer of the IEEC CX processor.

<L1B_CX_ProcessorName>

The name of the IEEC CX processor.

<L1B_CX_ProcessorVersion>

The version number of the IEEC CX processor.

<L1B_CX_CreationTime>

Current time when CX file was created.

<L1B_CX_comment>

A brief description of the IEEC L1b_ext processor.

<***L1Merge_ProcessorVersion***>

The version number of the L1Merge processor used to generate the input L1Merge metadata file used by the L1b_ext_IEEC processor.

<***L1b_ProcessorVersion***>

The version number of the L1b core processor used to generate the L1b metadata used by the L1b_ext_IEEC processor.

<***L1a_ProcessorVersion***>

The version number of the L1a core processor used to generate the input L1a products used by the L1b_ext_IEEC processor.

A.5.2.1.1 Channel attributes

<***ChannelID***>

The ZTC channel number, 1 - 16.

<***TrackID***>

The identification number of the track which this channel is a part of.

A.5.2.1.1.1 Incoherent Measurement Variables

<***PowerSpreadRatio***>

The power spread ratio, at 1 Hz.

<Coherency>

Coherence flag for PSR products, set to zero when the PSR below 2 and set to one otherwise.

<DDMPeakOffsetDistance>

Quality indicator of the PSR and Coherence Flag that warns of actual distance (in delay-Doppler cells) between the actual DDM peak and the nominal specular point delay-Doppler cell location. This can be an indicator that the <PowerSpreadRatio> and the <Coherency> products being produced corresponded to conditions over topographic features away from the specular point (so, not related to the coordinates of the reflection, as provided in the metadata). The distance is computed in delay-Doppler pixel units, therefore, if DeltaDelay is the number of delay-lags between the nominal specular point cell and the cell with maximum power, and DeltaDoppler is the number of Doppler slices between the nominal specular point cell and the cell with maximum power, the <DDMPeakOffsetDistance> = sqrt(DeltaDelay*DeltaDelay + DeltaDoppler*DeltaDoppler).

As illustrated in Figure 11-6, values of <DDMPeakOffsetDistance> larger than 3 could indicate that the power spread ratio has been computed over areas that barely cover the specular point. If <DDMPeakOffsetDistance> is larger than 13, then the <PowerSpreadRatio> and the <Coherency> products correspond to an area on the surface that does not cover the nominal specular point. See, for example, Case A in Figure 11-6, where the blue zone does not cover the red (nominal) specular point, at a distance of 14 cells.

<DDMPeakQualityFlags>

Quality flag for the PSR and Coherence products. When this flag is zero, the <PowerSpreadRatio> is not computed but set to zero, and neither the <PowerSpreadRatio> nor the <Coherency> products have physical meaning. They need to be disregarded.

The reason is that the <PowerSpreadRatio> is computed across a subset of cells of 7 Delay lags x 11 Doppler slices around the power peak value, but sometimes the peak power is located in a delay-Doppler cell close to the edge of the DDM. Then, part of the required subset of cells is not covered by the measured DDM. Any power spread ratio values computed in an incomplete set would have a value which is not comparable to the rest, so it is set to zero and the <DDMPeakQualityFlags>, too.

Figure 11-6 illustrates three examples. In white the original HydroGNSS DDM cells; in red the cell that corresponds to the nominal specular point; in blue the subset of cells used to compute the <PowerSpreadRatio>; in green three different examples where the peak power could be located. In case A, the subset of cells required to compute the power spread ratio is complete, so the <DDMPeakQualityFlags>=1. In cases B and C, the subset is not complete, so the <PowerSpreadRatio> cannot be computed, it is instead set to zero, and the flag DDMPeakQualityFlags>=0.

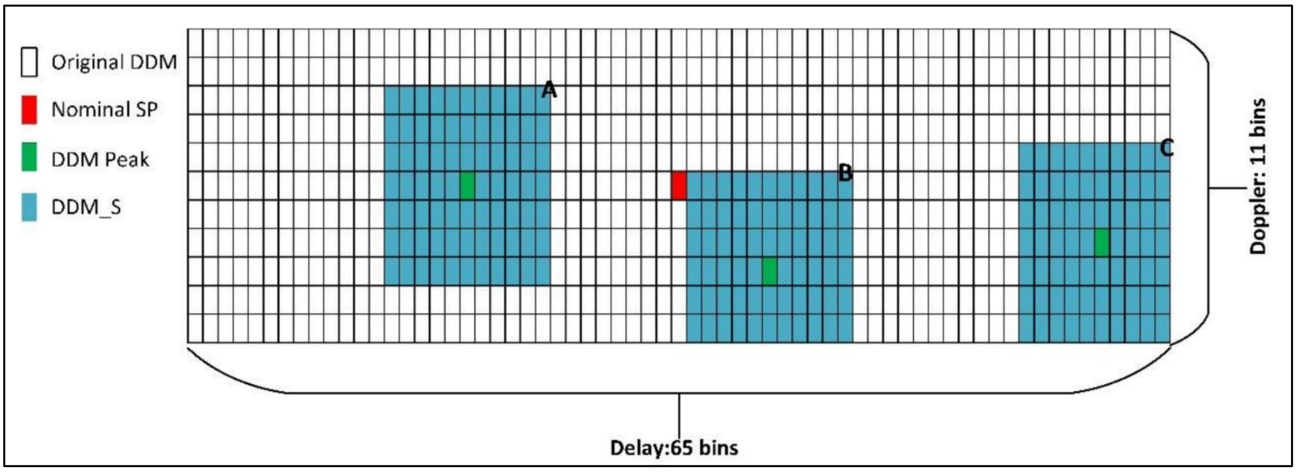

Figure 11-6: PowerSpreadRatio Calculation DDM Cell Subset Examples

A.5.3 ***IEEC Coherent Data L1b_ext***

File format:	NetCDF4
Filename	/L1A_L1B/yyyy-MM/Hhh/**L1B_CC.nc**

The structure of the IEEC L1b_ext metadata file will follow the same pattern as the L1a and L1b metadata files described in A.3.1, and A.4.1.

A.5.3.1 Attributes

<***Name***>

The name of the L1b_ext file

<***License***>

The license that applies to the contents of the file, see A.1.2.

<***L1B_CC_date_created***>

The date when the IECC CC file was created.

<***License***>

The license that applies to the contents of the file, see A.1.2.

<***L1B_CC_Creator***>

The developer of the IEEC CC processor.

<L1B_CC_ProcessorVersion>

The version number of the IEEC CC processor

<L1B_CC_comment>

A brief description of the IEEC L1b_ext processor

<***L1b_ProcessorVersion***>

The version number of the L1b core processor used to generate the L1b metadata used by the L1b_ext_IEEC processor.

<***L1a_ProcessorVersion***>

The version number of the L1a core processor used to generate the input L1a products used by the L1b_ext_IEEC processor.

A.5.3.1.1 Channel attributes

<***ChannelID***>

The ZTC channel number, 1 - 16.

<***TrackID***>

The identification number of the track which this channel is a part of.

A.5.3.1.1.1 Coherent Measurement Variables

Al these variables are at 25 Hz except where indicated.

<***PercentageCoherenceCoefficient***>

Percentage Coherence Coefficient (1 Hz) is defined the percentage of Coherence Coefficient above threshold 0.6 in time batches that correspond to the incoherence integration in the power DDMs.

<***Time_CoherentInt***>

The time of each Coherence Coefficient.

<***WF_CoherenceFlag***>

Coherence flag for complex measurement, set to zero when the Coherence Coefficient below 0.6 and set to one otherwise.

<***Latitudes_CoherentInt***>

The Latitude of each Coherence Coefficient.

<***Longitudes_CoherentInt***>

The Longitude of each Coherence Coefficient.

<***Incidence_CoherentInt***>

The Incidence angle of each Coherence Coefficient.

<***CoherenceCoefficient***>

Amplitude of the integrated coherence coefficient calculated from the coherence measurement, at one measurement every 40 ms, i.e. 25 Hz. This is a measure of the coherence of the reflected signal, varying from 0 for reflections from an extremely rough surface, to 1 for a completely smooth surface, such as a totally still lake.

<HighSamplingRateReflectivity>

High Sampling Rate Reflectivity is derived from the fitted function between the normalized amplitude of coherence measurement and **<***ReflectionCoefficientAtSP***>**, at one measurement every 40 ms, i.e. 25 Hz. This is a measure of the reflectivity of the reflected signal. .

<NormalizedAmplitude>

Normalized Amplitude is derived from the amplitude of the coherence measurement normalized by coherence coefficient, at one measurement every 40 ms, i.e. 25 Hz. This is a measure of the power of the reflected signal, varying from 0 for reflections from an extremely rough surface, to 1 for a completely smooth surface, such as a totally still lake.

A.6 L1a/L1b/L1b_ext merged metadata file

File format:	NetCDF4
Filename	/L1A_L1B/yyyy-MM/Hhh/**metadata_L1_merged.nc**

The L1Merged file combines all attributes in the L1a, L1b, CX, CC and PX metadata files with no repetition of any items. There is also an L1Merge_ProcessorVersion, and L1Merge_date_created for the L1Merge product.

A.7 Level 2

A.7.1 Soil Moisture

A.7.1.1 Attributes

<***Name***>**:**

Set to ‘HydroGNSS Soil Moisture’

< ***ProductCreationTime***>

Current time when the file was created, e.g. "2022-03-30T08:30:32".

<***License***>

The license that applies to the contents of the file. Set to “Accredit to Sapienza University of Rome”

<***FileName***>

The name of the L2G product file. Set to “L2OP-SSM.nc”.

<***DataTag***>

A tag to label the current processing run, to be copied over to the L1b and L1 merged metadata and the L2G products. This is currently set to <dataset path>_<current timestamp>, e.g. “2018-08/18/H06_30/03/2022 08:30:17”.

<***SourceConstellation***>

The name of the satellite constellation of the source data. This will be set to “HYDROGNSS”.

<***Program***>

Set to “European Space Agency Scout Program”

<***ProcessingLevel***>

Tag specifying the processing level, set to 2G

<***L2_ProcessorName***>

The name of the L2OP processor. Set to “Soil Moisture Algorithm from Reflectometry (SMART)”

<***L2_ProcessorVersion***>

The version number of the L2OP_SSM processor used. It set to vX, where X=1, 2, 3, etc. Taken from OutputProduct.Version.

<***L2_ProcessorCreator***>

The developer of the L2OP processor. Set to “Sapienza University of Rome”.

<***FirstTimeStamp***>

The first timestamp in the data array in the file. UTC timestamp.

<***LastTimeStamp***>

The last timestamp in the data array in the file. UTC timestamp.

<L1a_date_created>

Time and date when the L1A dataset was created

<***L1a_ProcessorVersion***>

The version number of the L1a processor used to generate the input.

<L1b_date_created>

Time and date when the L1B dataset was created

<***L1b_ProcessorVersion***>

The version number of the L1b processor used to generate the input.

<L1B_CX_date_created>

Time and date when the CX dataset was created

<L1B_CX_ProcessorVersion>

The version of the CX processor used

<L1B_CC_date_created>

Time and date when the CC dataset was created

<L1B_CC_ProcessorVersion>

The version of the CX processor used

<L1B_PX_date_created>

Time and date when the PX dataset was created

<L1B_PX_ProcessorVersion>

The version of the PX processor used

<L1Merge_ProcessorVersion>

The L1 merge processor version used

<L1Merge_date_created>

Time and date when the L1Merge dataset was created.

<***SMAPDataFiles***>

List of SMAP file paths used.

<***MODISDataFiles***>

List of MODIS file paths used, empty if MODIS data was not used.

<***GridResolution***>

The grid resolution in km of the L2G product

<***AlgorithmCoefficientsFile***>

The file path of the algorithm coefficients file.

<***SMAPDataFiles***>

List of SMAP file paths used.

<***LanduseFile***>

File path of the land use file used.

< ***BiomassFile***>

File path of the AGB file used.

< ***DEMElevationFile***>

File path of the DEM elevation file used.

< ***DEMSlopeFile***>

File path of the DEM slope file used.

< ***DEMRMSHeightFile***>

File path of the DEM RMS height file used.

< ***DEMRMSSlopeFile***>

File path of the DEM RMS slope file used.

< ***GeostrataFile***>

File path of the Geostrata file used.

< ***GeostrataSEFile***>

File path of the Geostrata SE file used.

< ***SeaMaskFile***>

File path of the sea mask file used.

A.7.1.2 Track attributes

< ***TopLeftColumn***>

< ***TopLeftRow***>

A.7.1.3 Track variables

<***ObservationMidPointTime***>

The mean timestamp (integrationMidPointTime) of the reflections averaged over the grid cell. Number of days from January 0, 0000. Taken from OutputProduct.PointTime .

Unit ‘days’; type: ‘double’; description: “Mean timestamp of the product’

<Variable Attribute>= The mean timestamp (integrationMidPointTime) of the reflections averaged over the grid cell. Number of days from January 0, 0000.

<***ObservationUTCMidPointTime***>

The mean UTC timestamp of the reflections averaged over the grid cell. Taken from OutputProduct.UTCTime

Unit ‘UTC time’; type: ‘string’; description: “Mean timestamp of the product in UTC’

<Variable Attribute>= The mean UTC timestamp of the reflections averaged over the grid cell

<***GridResolution***>

The resolution of the grid cell where the reflections are averaged. Get from OutputProduct.Resolution

Unit ‘km'; type: double; description: “Resolution of the cell grid where the specular point observables were averaged” <Variable Attribute>= The resolution of the grid cell where the reflections are averaged.

<***DataLatitude***>

Mean latitude of the reflection specular points aggregated within the grid cell. Taken from OutputProduct.SPlatitude.

Unit “deg”; type: double; description: “mean longitude of observables”

<Variable Attribute>= Mean latitude of the reflection specular points aggregated within the grid cell.

<***DataLongitude***>

Mean longitude of the reflection specular points aggregated within the grid cell. Taken from OutputProduct.SPlongitude.

Unit “deg”; type: double; description: “mean longitude of observables”

<Variable Attribute>= Mean longitude of the reflection specular points aggregated within the grid cell.

<***SoilMoisture***>

Soil moisture estimate. Taken from OutputProduct.SM

Unit “100*m^3/m^3 or %”; type: double; description: surface volumetric soil moisture’.

<Variable Attribute>= Soil moisture estimate

<***SoilMoistureMap***>

Mapped soil moisture estimate.

<***NumIntegratedSPs_LHCP***>

<***NumIntegratedSPs_RHCP***>

Number of aggregated observations in the grid cell.

Unit “count”; type: uint16; description: “mean longitude of observables”.

<Variable Attribute>= Number of aggregated observations in the grid cell.

<***Uncertainty***>

Uncertainty of the product.

Unit “dB”; type: double; description: “radiometric resolution of L1B observable computed as

10*log10(1+std/mean), where std and mean are the standard deviation and mean values of the reflectivity in linear unit of the specular points averaged within the grid cell”. <Variable Attribute>= Uncertainty of the product.

<***SSMQuality***>

Quality flags. Taken from OutputProduct.Quality
Unit: “bits’; type uint8; description ‘8 bits Quality flags
#1' <Variable Attribute>= Quality flags.

<***Reflectivity_LHCP_dB***>

Mean LHCP Reflectivity in the grid cell. Reflectivity in linear unit is averaged first and then converted into dB.

<***Reflectivity_RHCP_dB***>

Mean RHCP Reflectivity in the grid cell. Reflectivity in linear unit is averaged first and then converted into dB.

<***AboveGroundBiomass***>

Above ground biomass from the CCI product averaged within the grid cell. Taken from OutputProduct.agb_class_EASE25 unit: “ton/ha”; type: double; description “Mean CCI agb in the aggregation area”

<Variable Attribute>= Above ground biomass from the CCI product averaged within the grid cell.

<***DEM_elevation***>

Mean surface elevation within the grid cell. Taken from OutputProduct.DEM_elevation_EASE25

Unit: “meters”; type double; description “Mean 1km DEM elevation within the grid cell”

<Variable Attribute>= Mean surface elevation within the grid cell

<***LandUseLandCover***>

Most probable land use / land cover class within the grid cell

<***DEM_slope***>

Mean GMTED 1km DEM slope within of the grid cell

<***Signal***>

GNSS signal and polarization used in the retrieval algorithm. Taken from OutputProduct.Signal

Unit: N/A, type: string; description “GNSS signal processed”

<Variable Attribute>=GNSS signal and polarization used in the retrieval algorithm

A.7.2 Forest Above Ground Biomass

Produces a NetCDF file and a KMZ file.

A.7.2.1 Attributes

<***Name***>

'HydroGNSS Forest Biomass'

<***Product_description***>

Description of the product

<***Algorithm_description***>:

Description of the algorithm

<***Product_creation_time***>

Current time when the file was created, e.g. "2022-03-30T08:30:32".

<***L1a_date_created***>

Date when the L1a dataset was generated.

<***L1a_ProcessorVersion***>

The version of the L1a processor used

<***L1b_date_created***>

Date when the L1b dataset was generated.

<***L1b_Processor_Version***>

The version of the L1b processor used

<***L1B_CX_date_created***>

Time and date when the CX dataset was created

<***L1B_CX_ProcessorVersion***>

The version of the CX processor used

<***L1B_CC_date_created***>

Time and date when the CC dataset was created

<***L1B_CC_ProcessorVersion***>

The version of the CX processor used

<***L1B_PX_date_created***>

Time and date when the PX dataset was created

<***L1B_PX_ProcessorVersion***>

The version of the PX processor used

<***L1Merge_ProcessorVersion***>

The L1 merge processor version used

<***L1Merge_date_created***>

Time and date when the L1Merged dataset was created

<***SourceConstellation***>

The name of the satellite constellation of the source data. This will be set to "HYDROGNSS".

<***SourceNumber***>

HydroGNSS satellite ID, either 1 or 2.

<*FileName*>

The name of the L2 product file. Set to “L2OP-FB.nc”.

<*License*>

The license that applies to the contents of the file. Set to “Accredit to Sapienza University of Rome”

<*FileIDCode*>

As for L1a/L1b, e.g. 2018-08/03/H12.

<*Program*>

Set to “European Space Agency Scout Program”

<*Processing_Level*>

Tag specifying the processing level. It is set to L2.

<*L2_ProcessorName*>

The name of the L2OP processor. Set to “Soil Moisture Algorithm from Reflectometry (SMART)”

<*L2_ProcessorVersion*>

The version number of the L1a processor used. It set to vX, where X=1, 2, 3, etc. Taken from OutputProduct.Version.

<*L2_ProcessorCreator*>

The developer of the L2OP processor. Set to “Sapienza University of Rome”.

<*FirstTimeStamp*>

The first timestamp in the data array in the file. UTC timestamp.

<*LastTimeStamp*>

The last timestamp in the data array in the file. UTC timestamp.

<*ProjectionType*>

Reference coordinate projection of the gridded data.

<*GridResolution*>

Blank, as track-wise product

<*TimeResolution*>

Blank, as track-wise product

A.7.2.2 Track Variables

<*AGB*>

Forest Above Ground Biomass

<*IntegrationMidPointTime*>

Timestamp from the L1 data.

<*LandCover*>

Land Cover Classes (from ESA CCI)

<*OnboardLatitudes*>

Subsatellite latitudes.

*<**OnboardLongitudes**>*

Subsatellite longitudes

*<**SpecularPointLatitudes**>*

Specular point latitudes.

*<**SpecularPointLongitudes**>*

Specular point longitudes

*<**Quality_Flag**>*

Quality flag for each AGB value at SP: 0 (good retrieval) and 1 (bad retrieval).

*<**Uncertainty_Flag**>*

Track uncertainty flag (range from 0% - not reliable at all, to 100% - fully reliable) - repeated for each SP.

*<**IntegrationMidPointTime**>*

Timestamp of each point in the track.

A.7.3 Freeze/Thaw State

A.7.3.1 Attributes

<*Name*>

HydroGNSS F/T L2 product

<*Product_creation_time*>

Current time when the file was created, e.g. "2022-03-30T08:30:32

<*License*>

ESA license

<*L2_Processor_Name*>

A tag to label the current processing run, to be copied over to the L1b and L1 merged metadata and the L2G products. This is currently set to <dataset path>_<current timestamp>, e.g. “2018-08/18/H06_30/03/2022 08:30:17”.

<*L2_ProcessorVersion*>

The version of the L1a processor used

<*L2_ProcessorCreator*>

Finnish Meteorological Institute

<*L1a_date_created*>

Time and date when the L1A dataset was created.

<*L1a_ProcessorVersion*>

The version of the L1a processor used

<*L1b_date_created*>

Time and date when the L1B dataset was created.

<***L1b_ProcessorVersion***>

The version of the L1b processor used

<***L1B_CX_date_created***>

Time and date when the CX dataset was created

<***L1B_CX_ProcessorVersion***>

The version of the CX processor used

<***L1B_CC_date_created***>

Time and date when the CC dataset was created

<***L1B_CC_ProcessorVersion***>

The version of the CX processor used

<***L1B_PX_date_created***>

Time and date when the PX dataset was created

<***L1B_PX_ProcessorVersion***>

The version of the PX processor used

<***L1Merge_ProcessorVersion***>

The L1 merge processor version used

<***L1Merge_date_created***>

Time and date when the L1Merged dataset was created

<***L2_ProcessorVersion***>

The version of the L2OP-FT processor.

<***FileIDCode***>

As for L1a/L1b, e.g. 2018-08/03/H12.

<***SourceConstellation***>

The name of the satellite constellation of the source data. This will be set to “HYDROGNSS”.

<***SourceNumber***>

HydroGNSS satellite ID, either 1 or 2.

A.7.3.2 Track Dimensions

FTTrack

A.7.3.3 Track Variables

<***IntegrationMidPointTime***>

Timestamp from L1 data.

<***SpecularPointLat***>

Specular Point Latitude.

<***SpecularPointLon***>

Specular Point Longitude.

<***FreezeThawState***>

Soil freeze and thaw state derived from E1/L1 channel. Possible values are:

1 – thaw
3 – frozen
255 – no data
2 – currently not used, reserved for partially frozen/unknown state

<***LowOverallQuality***>

Low overall L1b data quality flag for E1/L1 channel

<***LowAGSP***>

Low AGSP quality flag for E1/L1 channel.

<***LowSNR***>

Low SNR quality flag for E1/L1 channel.

<***VeryLowSNR***>

Very low SNR quality flag for E1/L1 channel.

<***LowAGSPChannelL5E5***>

Level 1B quality flag carried through.

<***FreezeThawStateChannelL5E5***>

Soil freeze and thaw state derived from E5/L5 channel, with the same possible values as *FreezeThawState*.

<***LowOverallQualityChannelL5E5***>

Low overall L1b data quality flag for E5/L5 channel.

<***LowSNRChannelL5E5*** >

Low SNR quality flag for E5/L5 channel.

<***VeryLowSNRChannelL5E5*** >

Very low SNR quality flag for E5/L5 channel.

A.7.4 Surface Inundation (Low-Resolution and High-Resolution Products)

A.7.4.1 Attributes

<***date_created***>

Current time when the file was created, e.g. "2022-03-30T08:30:32".

<***L1Merge_ProcessorVersion***>

The L1 merge processor version

<***L1Merge_date_created***>

Time and date when the L1Merged dataset was created

<***License***>

ESA license

<***FileIDCode***>

Time and date folders of the input data file

<***DataTag***>

A tag to label the current processing run, to be copied over to the L1b and L1 merged metadata and the L2G products. This is currently set to <dataset path>_<current timestamp>, e.g. “2018-08/18/H06_30/03/2022 08:30:17”.

<***SourceConstellation***>

The name of the satellite constellation of the source data. This will be set to “HYDROGNSS”.

<***SourceNumber***>

HydroGNSS satellite ID, either 1 or 2

<***Processing Type***>

Tag specifying whether the data was processed into DDMs on-board or on the ground.

<***L1a_ProcessorVersion***>

The version of the L1a processor used

<***L1a_date_created***>

Time and date when the L1A dataset was created

<***FPGAVersion***>

The FPGA version from the L1 metadata.

<***SoftwareReceiverVersion***>

The version from the L1 metadata.

<***IncoherentMeasurementFrequency***>

The frequency of incoherent measurements from the L1 metadata, in Hz.

<***GpsUTCOffset***>

The GPS to UTC offset from the L1 metadata, in seconds.

<***FirstTimeStamp***>

The first timestamp in the data array in the file. UTC timestamp.

<***LastTimeStamp***>

The last timestamp in the data array in the file. UTC timestamp.

<***L1b_date_created***>

Time and date when the L1B dataset was created

<***L1b_ProcessorVersion***>

The version of the L1a processor used

<***Name***>

“HydroGNSS Surface Inundation using power DDM observables”.

<***BoundingBoxDelay***>

The size of the bounding box, delay dimension, in ms, from L1 metadata.

<***BoundingBoxDoppler***>

The size of the bounding box, doppler dimension, in Hz, from L1 metadata.

<***SizeOfNoiseCorners***>

The size of the corner of the DDM to be used as noise pixels, from L1 metadata.

<***NumberOfNoiseDDMs***>

Number of DDMs to be used to gather noise pixels, from L1 metadata.

<***LowAGSPThreshold***>

The threshold below which the antenna gain towards the specular point is considered low, from L1 metadata.

<***LowSNRThreshold***>

The threshold below which the signal to noise ratio is considered, from L1 metadata.

<***VeryLowSNRThreshold***>

The threshold below which the signal to noise ratio is considered to be very low, from L1 metadata.

<***HighIncidenceAngleThreshold***>

The threshold above which the incidence angle is considered to be high, from L1 metadata.

<***HighNoiseKurtosisThreshold***>

The threshold above which the noise kurtosis is considered to be high, from L1 metadata.

<***L1B_CX_date_created***>

Time and date when the CX dataset was created

<***L1B_CX_Comment***>

A brief description of the IEEC CX processor.

<***L1B_CX_Creator***>

Institute of Space Sciences (ICE-CSIC, IEEC)

<***L1B_CX_ProcessorName***>

HydroGNSS-IEEC_L1B-CX

<***L1B_CX_ProcessorVersion***>

The version of the CX processor used

<***L1B_CC_date_created***>

Time and date when the CC dataset was created

<***L1B_CC_Comment***>

A brief description of the IEEC CC processor.

<***L1B_CC_Creator***>

Institute of Space Sciences (ICE-CSIC, IEEC)

<***L1B_CC_ProcessorName***>

HydroGNSS-IEEC_L1B-CC

<***L1B_CC_ProcessorVersion***>

The version of the CX processor used

<***L1B_PX_date_created***>

Time and date when the PX dataset was created

<***L1B_PX_ProcessorVersion***>

The version of the PX processor used

<***L2OP_SI_Comment***>

A brief description of the IEEC L2OP-SI processor.

<***L2OP_SI_CreationTime***>

Time and date when the L2OP-SI dataset was created

<***L2OP_SI_Creator***>

Institute of Space Sciences (ICE-CSIC, IEEC)

<***L2OP_SI_ProcessorName***>

HydroGNSS-IEEC_L2OP_SI.

<***L2OP_SI_ProcessorVersion***>

The version of the L2OP-SI processor used

<***L2OP_SI_RFModelVersion***>

The version of the Random Forest model used.

A.7.4.2 Track Groups

There are no attributes or variables associated with the track

A.7.4.2.1 High_Resolution Group

Contains data obtained from the coherent channel which is available at high resolution

A.7.4.2.1.1 Dimensions

<***DelayAxis***>

UNLIMITED

<***DopplerAxis***>

UNLIMITED

A.7.4.2.1.2 Variables

< ***Time_CoherentInt***>

The timestamps of the specular points.

<***WaterFlagCoherent***>

Water flag, 0:Land, 1:Water at each specular point

<***WaterProbabilityCoherent***>

Water Probability Coherent at each specular point

<***Longitudes_CoherentInt***>

Longitudes of specular points

< ***Latitudes_CoherentInt*** >

Latitudes of specular points

A.7.4.2.2 Low_Resolution Group

Contains data obtained from the incoherent channel which is available at low resolution.

A.7.4.2.2.1 Dimensions

<***DateTimeTrack***>

UNLIMITED

A.7.4.2.2.2 Variables

<***IntegrationMidPointTime***>

IntegrationMidPointTime is the mid-point between the start and the end of the DDM's integration. All the following fields are referenced to this time.

<***SpecularPointLat***>

The latitude of the specular point at the time of the reflection [degrees, degrees

<***SpecularPointLon***>

The longitude of the specular point at the time of the reflection [degrees, degrees

<***DDMPeakOffsetDistance***>

Quality indicator of the PSR and Coherence Flag that warns of actual distance (in delay-Doppler cells) between the actual DDM peak and the nominal specular point delay-Doppler cell location, from L1 CX metadata.

<***DDMPeakQualityFlags***>

Quality flag for the PSR and Coherence products, , from L1 CX metadata.

<***WaterFlagIncoherent***>

Water Flag Incoherent, 0:Land,1:Water

<***WaterProbabilityIncoherent***>

Water Probability Incoherent.

<***SIOverallQualityFlags***>

SI Overall Quality Flags.

A.7.5 Ocean Surface Wind Speed and Sea Ice Extent

A.7.5.1 Attributes

<***Name***>

"NOC HydroGNSS L2-SWS".

<***date_created***>

Current time when the file was created, e.g. "2022-03-30T08:30:32".

<***FileIDCode***>

Time and date folders of the input data file

<***DataTag***>

A tag to label the current processing run, to be copied over to the L1b and L1 merged metadata and the L2G products. This is currently set to <dataset path>_<current timestamp>, e.g. "2018-08/18/H06_30/03/2022 08:30:17".

<***SourceConstellation***>

The name of the satellite constellation of the source data. This will be set to "HYDROGNSS".

<***AlgorithmVersion***>

L2OP-SWS processor version.

<***L1a_date_created***>

Date when the L1a dataset was generated.

<***metadata_L1a_ProcessorVersion***>

L1a processor version.

<***L1b_date_created***>

Date when the L1b dataset was generated.

<***metadata_L1b_ProcessorVersion***>

L1b processor version.

<***L1b_Processor_Version***>

The version of the L1b processor used

<***L1B_CX_date_created***>

Time and date when the CX dataset was created

<***L1B_CX_ProcessorVersion***>

The version of the CX processor used

<***L1B_CC_date_created***>

Time and date when the CC dataset was created

<***L1B_CC_ProcessorVersion***>

The version of the CX processor used

<***L1B_PX_date_created***>

Time and date when the PX dataset was created

<***L1B_PX_ProcessorVersion***>

The version of the PX processor used

<***L1Merge_ProcessorVersion***>

The L1 merge processor version used

<***L1Merge_date_created***>

Time and date when the L1Merged dataset was created

<***FirstTimeStamp***>

The first timestamp in the data array in the file. UTC timestamp.

<***LastTimeStamp***>

The last timestamp in the data array in the file. UTC timestamp.

<***License***>

The license, as in L1 metadata.

A.7.5.2 Variables

(1D Dimension "DateTime")

<IntegrationMidPointTime>

Time stamp from the L1Merged metadata

<QC_pass_flag>

Quality control Boolean flag, set to 0 if CA_Flag and RFI_Flag are both zero, or 1 if CA_Flag and/or RFI_Flag are set to 1, from PX metadata.

<SpecularPointLat, SpecularPointLat>

From the L1MergedMetadata.

<U10>

As in the Incoherent group, see below.

<SI>

As in the Incoherent group, see below.

A.7.5.2.1 Incoherent group

(1D Dimension "DateTime")

<U10>

Ocean surface wind speed. The L2OP-SWS processor retrieves ocean wind speeds based on the signal-to-noise ratio of the DDM, which is then radiometrically calibrated, and further corrected.

(see <*TransmitterEndCorrection*> & <*ReceiverEndCorrection*> parameters). Ocean wind speed is estimated through a Geophysical Model Function (GMF) that will be trained using collocated scatterometer or reference model data in the range 0 – 20 m/s. On that account, wind speeds exceeding 20 m/s are set to NaN. Wind speeds are being estimated over the global ocean, provided the specular point is located at least 25 km away from the closest coast to avoid potential land-related effects. No wind speed is output (NaN) if any of the quality control flags are set (see <*CAFlag*>, <RFIFlag>, <*SeaIceFlag*>).

Units: [m/s]

Range: 0 – 20

<SI>

Sea-Ice flag. The L2OP-SWS processor identifies and filters signals incoming from surfaces including sea-ice, which would otherwise bias ocean wind speed retrievals. In order to determine sea-ice presence no ancillary data are used, instead sea-ice is independently determined from the GNSS-R waveform itself. The DDM is integrated across all Doppler bins to produce an integrated delay waveform. The shape of the integrated delay waveform is then characterised and compared against pre-determined thresholds to identify possible presence of sea ice (flag set to 1). The sea-ice flagging module is only enabled at latitudes exceeding ±45° with remaining latitudes routinely set to 0 (no sea-ice). The sea-ice flag is set to NaN for L1b data that fail data quality control as no determination can be made.

Units: Boolean (unitless)

Range: ocean=0, presence of sea-ice=1

A.8 Level 3

A.8.1 Soil Moisture

A.8.1.1 Attributes

<***Name***>:

Set to ‘HydroGNSS Soil Moisture’

<***SourceConstellation***>

The name of the satellite constellation of the source data. This will be set to ‘HYDROGNSS’.

<***Program***>

Set to ‘European Space Agency Scout Program’

<***ProcessingLevel***>

Tag specifying the processing level. It set to 3.

<***L2_ProcessorName***>

The name of the L2 processor. Set to 'Soil Moisture Algorithm from ReflecTometry (SMART)'

<***L2_ProcessorVersion***>

The version number of the L2/L3 processor used. It is set to vX, where X=1, 2, 3, etc. Taken from OutputProduct.Version.

<***L2_ProcessorCreator***>

The developer of the L2 processor. Set to “Sapienza University of Rome”.

<***ProjectionType***>

Reference coordinate projection of the gridded data. Set to ‘EASE grid v2’

<***License***>

The license that applies to the contents of the file. Set to “Accredit to Sapienza University of Rome”

<***NameOfSatellites***>

"HydroGNSS-1,HydroGNSS-2".

<***NumberOfSatellites***>

2.

<***FileName***>

The name of the L3 product file, L3OP-SSM.nc.

<***ProductCreationTime***>

Current time when the file was created, e.g. "2022-03-30T08:30:32".

<***FirstTimeStamp***>

The first timestamp in the data array in the file. UTC timestamp.

<***LastTimeStamp***>

The last timestamp in the data array in the file. UTC timestamp.

<***L1a_ProcessorVersion***>

L1a processor version.

<***L1b_ProcessorVersion***>

L1b processor version.

<***NumberOfMaps***>

No of maps in the output dataset.

<***NumberOfTracks***>

Number of L1 tracks used to generate the dataset.

<***GridResolution***>

Grid resolution of the map

<***TimeResolution***>

Time resolution of the output

<***LanduseFile***>

Path of the land cover file used.

<***BiomassFile***>

Path of the AGB file used.

<***DEMFile***>

Path of the DEM file used.

<***AFSFile***>

Path of the AFS file used.

<***GammaFile***>

Path of the gamma file used.

A.8.1.2 Dimensions

<***NumberOfPoints***>

Get from OutputProduct.NumRetrievals

<***NumberOfColumns***>

Number of columns of the gridded product. Get from OutputProduct.GridColumns

<***NumberOfRows***>

Number of rows of the gridded product. Get from OutputProduct.Gridrows.

A.8.1.3 Variables

<***MeanObservationTime***>

The mean timestamp (*integrationMidPointTime*) of the reflections averaged over the grid cell. Number of days from

January 0, 0000. Taken from OutputProduct.PointTime

Unit “days”; type: double; description: “Mean timestamp of the product’

<Variable Attribute>= The mean timestamp (`integrationMidPointTime`) of the reflections averaged over the grid cell. Number of days from January 0, 0000.

<***MeanObservationUTCTime***>

The mean UTC timestamp of the reflections averaged over the grid cell. Taken from OutputProduct.UTCTime

Unit “UTC time”; type: string; description: “Mean timestamp of the product in UTC”

<Variable Attribute>= The mean UTC timestamp of the reflections averaged over the grid cell

<***DataMeanLatitude***>

Mean latitude of the reflection specular points aggregated within the grid cell. Taken from OutputProduct.SPlatitude.

Unit 'deg'; type: double; description: 'mean longitude of observables'

<Variable Attribute>= Mean latitude of the reflection specular points aggregated within the grid cell.

<***DataMeanLongitude***>

Mean longitude of the reflection specular points aggregated within the grid cell. Taken from OutputProduct.SPlongitude.

Unit 'deg'; type: double; description: 'mean longitude of observables'

<Variable Attribute>= Mean longitude of the reflection specular points aggregated within the grid cell.

<***SoilMoisture***>

Soil moisture estimate. Taken from OutputProduct.SM

Unit '100*m^3/m^3 or %'; type: double; description: surface volumetric soil moisture’.

<Variable Attribute>= Soil moisture estimate

<***SoilMoistureMap***>

Soil moisture estimate over a grid according to the *`ProjectionType`* and *`GridResolution`*. The map is

limited to the geographical area covered by the product. Taken from

OutputProduct.Grid_SM Unit '100*m^3/m^3 or %'; type: double; description: ‘gridded surface volumetric soil moisture’.

<Variable Attribute>= Soil moisture estimate over a grid according to the *`ProjectionType`* and *`GridResolution`*. The map is limited to the geographical area covered by the product

<***NumIntegratedSP_LHCP***>

Number of aggregated LHCP observations in the grid cell.

<***NumIntegratedSP_RHCP***>

Number of aggregated RHCP observations in the grid cell.

<***Uncertainty***>

Uncertainty of the product.

Unit 'dB'; type: double; description: 'radiometric resolution of L1B observable computed as

10*log10(1+std/mean), where std and mean are the standard deviation and mean values of the reflectivity in linear unit of the specular points averaged within the grid cell'. <Variable Attribute>= Uncertainty of the product.

<***SSMQuality***>
Quality flags. Taken from OutputProduct.Quality
Unit: "bits'; type uint8; description '8 bits Quality flags
#1' <Variable Attribute>= Quality flags.

<***Reflectivity_LHCP_dB***>

Mean LHCP L1B reflectivity of the reflection specular points aggregated within the grid cell.

Unit: "dB"; type double; description: 'Reflectivity in linear unit is averaged first and then converted into dB' <Variable Attribute>= Mean L1B reflectivity of the reflection specular points aggregated within the grid cell.

<***Reflectivity_RHCP_dB***>

Mean RHCP L1B reflectivity of the reflection specular points aggregated within the grid cell.

Unit: "dB"; type double; description: 'Reflectivity in linear unit is averaged first and then converted into dB' <Variable Attribute>= Mean L1B reflectivity of the reflection specular points aggregated within the grid cell.

<***AboveGroundBiomass***>

Above ground biomass from the CCI product averaged within the grid cell. Taken from OutputProduct.agb_class_EASE25

unit: "ton/ha"; type: double; description 'mean CCI agb in the aggregation area'

<Variable Attribute>= Above ground biomass from the CCI product averaged within the grid cell.

<***DEM_elevation***>

Mean surface elevation within the grid cell. Taken from OutputProduct.DEM_elevation_EASE25

Unit: "meters"; type double; description "Mean GMTED 1km DEM elevation within the grid cell"

<Variable Attribute>= Mean surface elevation within the grid cell

<***DEM_slope***>

Mean surface elevation GMTED 1km DEM slope of the grid cell.

<***Signal***>

GNSS signal and polarization used in the retrieval algorithm. Taken from OutputProduct.Signal unit: Unit: "N/A", type: string; description "GNSS signal processed"

<Variable Attribute>=GNSS signal and polarization used in the retrieval algorithm

A.8.2 Freeze Thaw

A.8.2.1 Attributes

<***Name***>**:**

Name of the product

<***Product_creation_time***>

Current time when the file was created, e.g. "2022-03-30T08:30:32".

<***License***>

The license that applies to the contents of the file, as in the L1 metadata.

<***File_Name***>

The name of the L3 product file, e.g. L3FT20180818.nc.

<***L3_ProcessorName***>

The name of the L3 processor. Set to “HydroGNSS L3 Soil freeze and thaw processor'

<***L3_ProcessorVersion***>

The version number of the L3processor used.

<***L3_ProcessorCreator***>

The developer of the L3 processor. Set to “Finnish Meteorological Institute”.

<***ProjectionType***>

Reference coordinate projection of the gridded data. Set to ‘EASE-2’.

<***Grid_Resolution***>

The grid resolution in km.

<***L1a_ProcessorVersion***>

The version of the L1a processor used.

<***L1b_ProcessorVersion***>

The version of the L1b processor used.

<***L1b_Date_Created***>

Date when the L1B dataset was created.

<***SourceConstellation***>

The name of the satellite constellation of the source data. This will be set to ‘HYDROGNSS’.

<***Satellites***>

The number of satellites in the constellation.

A.8.2.2 Dimensions

<***x***>

X coordinate dimension.

<***y***>

Y coordinate of dimension.

A.8.2.3 Variables

<***crs***>

Coordinate reference system (CRS) Definition:

<***grid_mapping_name***>

<***false_easting***>

<***false_northing***>

<***latitude_of_projection_origin***>

<***longitude_of_projection_origin***>

<***long_name***>

<***longitude_of_prime_meridian***>

<***semi_major_axis***>

<***inverse_flattening***>

<***spatial_ref***>

<***GeoTransform***>

<***x***>

X coordinate of projection

<***y***>

Coordinate of projection

<***date***>

Date stamp for the soil freeze and thaw data expressed as the number of days from January 0, 0000.

<***FreezeThawState***>

Soil freeze/thaw state derived from E1/L1 channel.

<***QualityFlag***>

Quality/Uncertainty Flag for E1/L1 channel soil freeze/thaw estimate in each grid cell.

<***dnum***>

Number of days since last E1/L1 channel observation (in each grid cell).

<***FreezeThawStateChannelL5E5***>

Soil freeze and thaw state derived from E5/L5 channel.

<***QualityFlagChannelL5E5***>

Quality/Uncertainty Flag for E5/L5 channel soil freeze/thaw estimate in each grid cell.

<***dnumChannelL5E5***>

Number of days since last E5/L5 channel observation (in each grid cell).

A.8.3 Forest Biomass

A.8.3.1 Attributes

<***Name***>

Set to ‘HydroGNSS Forest Biomass’

<***Product__description***>

Product description.

<***Algorithm_description***>

Algorithm description.

<***Product_creation_time***>

Current time when the file was created, e.g. "2022-03-30T08:30:32".

<***License***>

The license that applies to the contents of the file.

<***FileName***>

The name of the L3 product file, L3OP-FB.nc.

<***SourceConstellation***>

The name of the satellite constellation of the source data. This will be set to 'HYDROGNSS'.

<***Program***>

Set to 'European Space Agency Scout Program'

<***ProcessingLevel***>

Tag specifying the processing level. It is set to 3.

<***L2_ProcessorName***>

The name of the L2 processor. Set to 'Forest Biomass Processor'

<***L2_ProcessorVersion***>

The version number of the L2 processor used.

<***L3_ProcessorVersion***>

The version number of the L3 processor used.

<***L3_ProcessorCreator***>

The developer of the L3 processor. Set to "CNR-IFAC".

<***FirstTimeStamp***>

The first timestamp in the data array in the file. UTC timestamp.

<***LastTimeStamp***>

The last timestamp in the data array in the file. UTC timestamp.

<***ProjectionType***>

Reference coordinate projection of the gridded data. Set to 'EASE grid v2.0'

<***GridResolution***>

<***TimeResolution***>

A.8.3.2 Dimensions

A.8.3.3 Variables

<***LandCover***>

Land Cover Classes (from ESA CCI).

A.8.3.3.1 Coordinates group

<***Latitudes***>

Matrix of EASE Grid 25 km Latitudes.

<***Longitudes***>

Matrix of EASE Grid 25 km Longitudes.

A.8.3.3.2 L3 group

<***AGB***>

AGB L3 map gridded on EASE Grid at 25 km with data acquired between 18-Aug-2018 and 18-Aug-2018: range 0-1000 t/ha, invalid data=\'NaN\'.

A.8.3.3.3 Flags group

<***Quality_Flag***>

Quality flag for each pixel, values 0 (good retrieval) and 1 (bad retrieval).

<***Uncertainty_Flag***>

Track uncertainty flag (range from 0% - not reliable at all, to 100% - fully reliable)