HydroGNSS: A-Posteriori L1 Calibration Processors

L1B-OP-PX(-L)

Algorithm Theoretical Basis Document

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Document History		
Version	**Date**	**Description**
0	**07/12/2021**	• **First draft**
1	**16/05/2022**	• **Corresponds to L1B-PX and L1B-PX-L Alpha**
1.1	**16/12/2022**	• **Added placeholders for Background and Scientific justification, Validation Plan and Roadmap**
2.0	**01/12/2023**	• **Added Document History** • **Added Background and Scientific justification** • **Added Calibration and Validation Plan** • **Added Roadmap** • **Corresponds to L1B-PX and L1B-PX-L Beta R2**

Contents

List of Applicable Documents

[AD1] HydroGNSS PDGS Algorithm ICD, ref. 00637207, v7.0, 30/03/2022

[AD2] SRD Science Team Annex, ref. 00635466, v3.0, 01/10/2021

[AD3] Scout-2 HydroGNSS Mission Requirement Document, ref. 00632438, v2.0, 08/09/2021

[AD4] Scout-2 HydroGNSS L1 Algorithm Theoretical Baseline Document (ATBD), ref. 00655831, v8.0, 27/01/2023

[AD5] MERRByS Product Manual - GNSS Reflectometry on TDS-1 with the SGR-ReSI, ref. 0248366, revision 007, 04/12/2019

Reference Documents

[RD1] Foti, G., Gommenginger, C., Jales, P., Unwin, M., Shaw, A., Robertson, C. and Rosello, J., "Spaceborne GNSS reflectometry for ocean winds: First results from the UK TechDemoSat-1 mission," Geophysical Research Letters, 42(13), pp.5435-5441, 2015.

[RD2] Foti, G., Gommenginger C., Unwin M., Jales P. and Rosello, J., "Preliminary analyses and early validation of calibrated spaceborne GNSS-R data from the UK TechDemoSat-1 mission for ocean wind retrieval, "Ocean Scatterometry, GNSS+R2017, Ann Arbor, USA, 24 May 2017, https://www.gnssr2017.org/images/Wednesday_afternoon/

[RD3] Foti, G., Gommenginger, C., TechDemoSat-1 Exploitation Campaign
For Future Sea State Monitoring (RFP ESA-IPL-PEO-FF-ah-LE-2015-377), Technical Note 2b: Validation Activities and Consolidation of Inversion Algorithm, December 2017

[RD4] Hammond, M. L., Foti, G., Rawlinson, J., Gommenginger, C., Srokosz, M., King, L., ... & Roselló, J. (2020). First assessment of geophysical sensitivities from spaceborne Galileo and BeiDou GNSS-reflectometry data collected by the UK TechDemoSat-1 Mission. Remote Sensing, 12(18), 2927

[RD5] Steigenberger, P., Thölert, S., & Montenbruck, O. (2019). Flex power on GPS block IIR-M and IIF. GPS Solutions, 23(1), 1-12.

[RD6] Hajj, G. A., & Zuffada, C. (2003). Theoretical description of a bistatic system for ocean altimetry using the GPS signal. Radio Science, 38(5), 10-1.

[RD7] Wang, T., Ruf, C. S., Block, B., McKague, D. S., & Gleason, S. (2018). Design and performance of a GPS constellation power monitor system for improved CYGNSS L1B calibration. IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing, 12(1), 26-36.

[RD8] Wang, T., Ruf, C., Gleason, S., McKague, D., O'Brien, A., & Block, B. (2020, September). Monitoring GPS EIRP for CYGNSS level 1 calibration. In IGARSS 2020-2020 IEEE International Geoscience and Remote Sensing Symposium (pp. 6293-6296). IEEE.

List of Acronyms

ADC	Analog-to-Digital Converter
AGSP	Antenna Gain in the Specular Point direction
C-BRE	Calibrated Bistatic Radar Equation
CM1/2/3	Calibration Method 1/2/3
DDM	Delay-Doppler Map
GNSS-R	Global Navigation Satellite System Reflectometry
GPS	Global Positioning System
GRFI	GNSS-R Radio Frequency Interference Detection
GSID	GNSS-R Sea Ice Detection
L1	Level 1 data
NRP	Normalised Receiver Power
REC	Receiver-End Correction
RFI	Radio Frequency Interference
Rx	Receiver
SNR	Signal-to-Noise Ratio
SP	Specular Point
SVN	Space Vehicle Number
TCAD	TDS-1 Correlator Anomaly Detection
TDS-1	TechDemoSat-1
TEC	Transmitter-End Correction
Tx	Transmitter

1 Purpose of This Document

This document provides a description of the background, scientific justification, algorithms, initial in-orbit calibration/validation plan and future roadmap (long-term goal) of the NOC Level 1 processing modules deployed in the ground segment of the ESA HydroGNSS mission.

These include both the L1B-OP-PX module estimating sigma0, gamma and deriving data quality flags from uncalibrated L1 DDM data and associated L1 metadata; and the L1B-OP-PX-L, the learning module required to derive calibration corrections associated with effects including viewing geometry, GNSS source, transmitter antenna pattern, nadir receiver antenna patterns, and temporal variability of direct GNSS power.

2 Background and Scientific Justification

GNSS signals reflected off the surface of the Earth have been shown to be affected by a plurality of factors including the characteristics of the GNSS source and of the GNSS-R receiving instrumentation. In particular, uncertainties in knowledge of transmitter and receiver antenna gains and variability of available direct power have been shown to directly affect performance of the geophysical inversion process. Several GNSS-R calibration approaches are found in the literature, based on models (e.g. HydroGNSS CM1), direct GNSS power received on the ground [e.g. RD7], in-flight measurements of direct power, or a combination of these [e.g. RD8].

The underlying mechanism of the NOC GNSS-R signal calibration processor (L1B-PX and L1B-PX-L) is based on long-term (~weeks) accumulation of in-flight ocean-reflected GNSS-R signatures. This method has shown some merit when applied to data collected by the TechDemoSat-1 mission, and has been selected as the baseline of Calibration Method 2 (CM2) of the HydroGNSS mission [AD1][AD2].

Please see scientific justification at sub-module level in the relevant paragraphs below.

3 Algorithm Description

The L1B-OP-PX processor (Figure 1) corrects for receiver antenna patterns and GNSS transmitter power using an a-posteriori process estimated using ocean-reflected data in the L1B learning module (L1B-OP-PX-L), and implements a data quality control process and flagging algorithm. The inputs consist of uncalibrated Delay Doppler Maps (DDMs) and associated L1a metadata. The output parameters include data quality control flags, calibration correction factors (TEC, REC) being applied, calibrated Sigma0 (CM2) and calibrated Gamma (CM2).

The L1B-OP-PX processor comprises a number of sub-algorithms: (i) DDM signal to noise ratio (SNR) estimation, (ii) Radiometric calibration, (iii) Transmitter End Correction (TEC), (iv) Receiver End Correction (REC), and (v) Quality control flagging. A brief overview of each of these sub-algorithms follows:

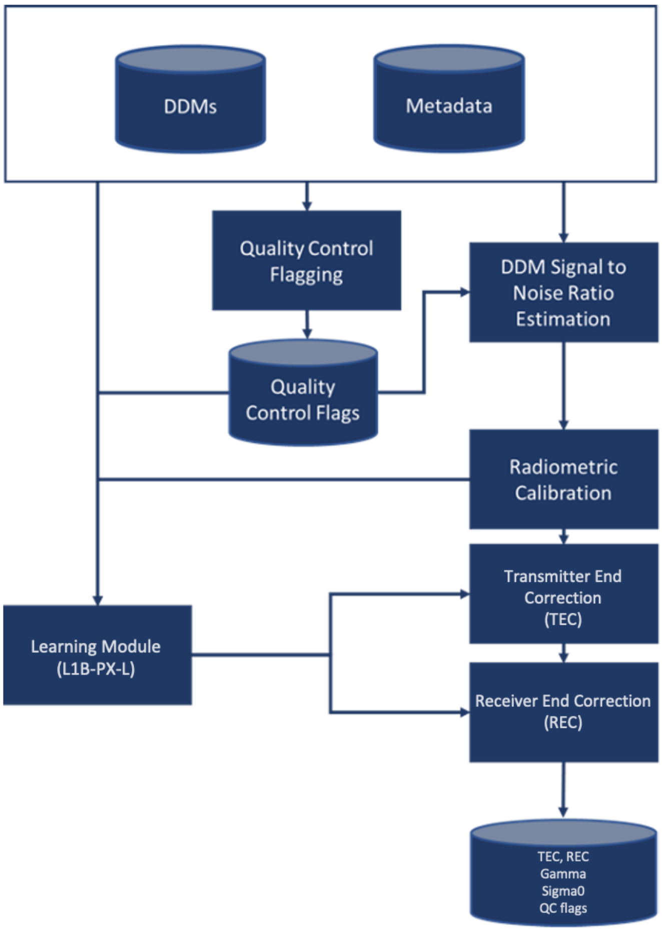

Figure 1 Overview of the L1B-OP-PX and L1B-OP-PX-L processing chain

3.1 Applicability

The L1B-OP-PX processor has been designed, implemented and tested using GPS L1 LHCP ocean reflected data (integrated power DDM) from UK TechDemoSat-1. Some initial tests have been carried out using Galileo E1 LHCP ocean reflected data collected by SSTL DoT-1 [RD4]. It is assumed that this method may be applicable to reflected signals over other surfaces typically containing a higher coherent component. Applicability of a similar calibration strategy to other frequencies and polarisations (L5/E5, RHCP) is expected to depend on quality and quantity of available ocean reflections. These aspects may become the subject of future investigations (long-term) once sufficient in-orbit data volumes become available.

3.2 Input

- L1/E1 GPS/Galileo LHCP DDMs
- L1a metadata including:
    - Acquisition Time
    - Transmitter SVN
    - Transmitter position and velocity
    - Receiver position and velocity
    - Specular point position
    - Nadir antenna gain at the specular point
    - Nadir antenna noise temperature
    - Nadir LNA physical temperature

3.3 Submodules

3.3.1 Signal-to-Noise Ratio Estimation

This module estimates the Signal-to-Noise ratio (SNR) from integrated power DDM data. Signal power is estimated from the peak pixel in the DDM, similar to the approach adopted by current version of HydroGNSS Calibration Methods 1 and 3 (CM1 and CM3). Noise power is estimated by computing the average power of DDM pixels in a 'noise box' typically included in the signal-free DDM area. The default size of this box, as determined for TDS-1, is all Doppler frequency bins and the first four delay (1 chip) bins of the signal-free area. As these settings were optimised for reflected GPS L1 LHCP signals collected by TDS-1, some further optimisation may be required for Galileo signals received by HydroGNSS.

3.3.2 Radiometric Calibration

This algorithm is designed to derive absolute received power following the approach described in [AD4][AD5]. Inputs comprise SNR estimated from the DDM (see above), and L1 metadata including physical temperature of the nadir low noise amplifier (LNA) and nadir antenna noise temperature.

The output of the radiometric calibration module is measured received power (P_r), please see details of model and derivation in [AD4][AD5].

Note: The current version of the Radiometric Calibration modules assumes a ratio of implementation losses (L_N/L_S) equal to 1 dB.

3.3.3 Sigma0

Estimation of the normalised radar cross-section (Sigma0) is based on the bistatic formulation:

$$P_r = \sigma^0 \, \frac{\lambda^2 \, P_t \, G_t \, G_r \, A_S}{(4\pi)^3 \, R_r^2 \, R_t^2} \qquad \text{(eq. 1)}$$

Where P_r is the received power, P_t is the transmitted power, G_t is the transmitter antenna gain, G_r is the nadir receiver antenna gain, R_r is the specular point-to-receiver distance, R_t is the transmitter-to-specular point distance, A_s is the size of the scattering area, and λ is the carrier wavelength.

Following the approach found in [RD6], the scattering area A_s is assumed to be corresponding to the area of the 1st iso-delay ellipse, having size:

$$A_S = \pi \, \frac{1}{\sin \varepsilon} \left(\frac{R_r R_t \, T_c \, c}{R_r + R_t} \right) \qquad \text{(eq. 2)}$$

Where ε is the grazing angle (defined as 90° - incidence angle), T_c is the chip time duration, c is the speed of light, R_r is the specular point-to-receiver distance and R_t is the transmitter-to-specular point distance.

In addition to the L1a information required during the radiometric calibration process to estimate measured received power, L1a metadata used by the L1-OP-PX(-L) processors to estimate Sigma0 also include receiver position, transmitter position, and specular point position.

3.3.4 Gamma

Estimation of the surface reflectivity (Gamma) is based on the bistatic formulation:

$$P_r = \Gamma \frac{\lambda^2 P_t G_t G_r}{(4\pi)^2 (R_r + R_t)^2} \qquad (\text{eq. } 3)$$

Where P_r is the received power, P_t is the transmitted power, G_t is the transmitter antenna gain, G_r is the nadir receiver antenna gain, R_r is the specular point-to-receiver distance, R_t is the transmitter-to-specular point distance, and λ is the carrier wavelength. Similar to the Sigma0 estimation module, additional L1a information required by the Gamma estimation module include the positions of receiver, transmitter and specular point.

Note: The current version of the NOC calibration processors assumes a nominal GNSS transmitter EIRP of 27.2 dBW. This value corresponds to the average EIRP reported by CM3 over one week of HydroGNSS test data (based on August 2018 TDS-1 data).

3.3.5 Transmitter-End Calibration (TEC)

Global Navigation Satellite System (GNSS) satellites are known to have variable transmitted power levels depending on design and manufacturer. In addition to that, available direct power at the specular point depends on viewing geometry and transmitter antenna gain pattern. Direct power levels have been shown to be characterised by temporal variability on a wide range of timescales, due to a plurality of factors including hardware ageing and programmed operational changes. Using long-term averages estimated from ocean reflected data, a posteriori corrections for some of these effects (low-frequency) are estimated by the TEC sub-algorithm.

The TEC correction factors are estimated by the L1B-OP-PX-L learning module using nominal Sigma0 estimates over the global ocean, provided these are free of correlator anomalies, Radio Frequency Interference (RFI), and sea-ice (see below further details on quality control algorithms). Quality-controlled data are segregated by the geometry of the specular point (elevation) relative to the transmitter antenna. For each of these geometric subdivisions and for each transmitter, biases are calculated as the difference between the average Sigma0 relative to the bin minus the global-ocean average Sigma0. By iterating through all geometry/SVN bins, a first-order calibration look-up table is derived.

Following this step, a further correction step addressing temporal variability of available direct power is carried out. Ocean reflections over the sea-ice free zone are segmented by time of collection, individual transmitter (SVN) and GNSS block. The baseline time window duration currently being applied is 2 months, although a long-term goal is to revise this depending on instrument sampling capability and quality of ocean-reflected data. The resulting TEC calibration look up tables are then applied in the L1B-OP-PX module for each record, for a given transmitter and acquisition time.

3.3.6 Receiver-End Calibration (REC)

The REC sub-module is designed to mitigate discrepancies between in-flight nadir antenna gain pattern and pre-launch antenna gain estimates measured on-ground. Biases are estimated by the L1B-OP-PX-L learning module using available TEC-corrected Sigma0 estimates over the global ocean, provided these are free of correlator anomalies, RFI, and sea-ice (see below for further details on data quality flagging). Quality controlled data are split by location of the specular point relative to the nadir antenna (elevation and azimuth) in the orbit reference frame. For each bin, offsets are computed as the average TEC-corrected Sigma0 relative to the bin minus the global average ocean TEC-corrected Sigma0. A REC calibration look-up table is thus derived for application in the L1B-OP-PX module.

3.3.7 Data Quality Control

Data quality control and flagging mechanisms included in the NOC L1B-OP-PX(-L) processors comprise: GNSS-R Radio Frequency Interference Detection (GFRI), TDS-1-type Correlator Anomaly Detection (TCAD), and GNSS-R Sea-Ice Detection (GSID). Details of the GSID submodule are provided in the L2-OP-SWS ATBD.

3.3.7.1 GNSS-R Radio Frequency Interference Detection (GFRI)

Inspection of TDS-1 L1 data has revealed the presence of contaminated data most likely associated with radio-frequency interference (RFI) events. This contamination typically manifested itself in DDM space as anomalous power 'bands' concentrated around multiple (and variable) Doppler frequency ranges. By integrating along the delay component, such anomalies correspond to a series of power peaks in the waveform. The RFI detection approach (GRFI) is based on detection and identification of such power peaks, other than the single peak typical of ocean-reflected signals. The detection algorithm is supported by a thresholding mechanism to mitigate the potential impact of secondary peaks. If RFI is determined to be present, the flag is set to 1, otherwise the flag is set to 0.

3.3.7.2 TDS-1-type Correlator Anomaly Detection (TCAD)

During the validation and test phases of the NOC GNSS-R data processor, a non-negligible proportion of DDM data collected by the TechDemoSat-1 (TDS-1) mission were identified as being anomalous, characterised by 'bands' of unrealistically high power present at certain correlation delay, across a wide range of Doppler frequencies, which potentially leads to large errors in the SNR estimation process. These data anomalies are thought to be linked to errors in the on-board signal correlation process. The NOC TCAD algorithm scans individual waveforms at each Doppler bin, and following derivation it detects and identifies unrealistic steps in the waveform using a threshold mechanism. The algorithm has been tuned using ocean-reflected data. If the likely presence of an on-board correlator anomaly is detected the flag is set to 1, otherwise it is set to 0.

3.4 Output

The following parameters are output by the NOC L1-OP-PX processor, on a record-by-record basis:

- Quality control flags
  - RFI
    - Units: Boolean (unitless)
    - Range: no RFI=0, RFI detected=1
  - Correlator anomalies
    - Units: Boolean (unitless)
    - Range: no correlator anomaly=0, correlator anomaly detected=1
  - Sea ice presence
    - Units: Boolean (unitless)
    - Range: ocean=0, presence of sea-ice detected=1
- Receiver-end correction (REC)
  - Units: dB
- Transmitter-end correction (TEC)
  - Units: dB
- Sigma0 (CM2)
  - Units: dB
- Gamma (CM2)
  - Units: dB

3.5 Calibration window

Based on the experience from TDS-1 (intermittent operations, 4 channels) the learning function module L1B-OP-PX-L is expected to required ~2 months of in-orbit data for the algorithm to provide sufficiently accurate estimates of the REC/TEC calibration factors related to GPS sources. HydroGNSS may provide a higher sampling capability and thus possibly enable shorter windows (< 1 month).

3.6 Calibration update frequency

Re-training of the L1B-OP-PX-L module currently envisages a calibration update frequency of 30 days, which proved adequate to tackle effects deriving from non-high-frequency variability of direct GNSS power seen in TDS-1 collections. Assuming sufficient new L1a data of adequate quality are available and processing time does not become an obstacle, the update frequency may be revisited and more frequent calibration updates may be scheduled based e.g. on a sliding window of past data.

3.7 Scheduling and Processing time

Following the L1-OP-PX-L training phase, computational cost of the L1B-OP-PX module is expected be able to derive quality flags and apply the relevant calibration terms in a near-real time fashion as soon as new L1a data become available.

3.8 Flex-power events

GPS flex-power modes [RD5] are high-frequency and/or regional events that are not directly addressed by the current calibration strategy based on global ocean-reflected data collected by the nadir channel.

4 Calibration and Validation

The L1B-OP-PX and L1B-OP-PX-L processors have been calibrated and validated using data collected by the TechDemoSat-1 mission. Once HydroGNSS is in orbit the calibration/validation plan further includes:

- Collection of a sufficiently large ocean-reflected GPS/Galileo L1/E1 LHCP global dataset (uncalibrated DDM and L1 metadata)
- Collocation of initial HydroGNSS collections with ocean verification data (e.g. ECMWF ERA-5)
- Assessment and characterisation of algorithm performance at a range of given surface conditions (U10, waves, etc) on a global scale.
- Algorithm review, including preliminary re-tuning of internal parameters

5 Longer-term Roadmap

As a longer-term goal, potential future activities carrying significant scientific value for the advancement of GNSS-R calibration technology currently include:

- Optimisation of calibration window and re-calibration frequency (requires long-term assessment of in-orbit L1/E1 LHCP ocean-reflected data quality and volume, and impact on calibration performance).
- Development of additional calibration steps to address transmitter azimuthal geometry dependence (requires modelling of GNSS yaw-steering mode, computation of the azimuth angle of the specular point in the transmitter antenna frame, etc)
- Evaluate feasibility of extension to other frequencies/polarisations (L1/E1 RHCP, L5/E5 LHCP, L5/E5 RHCP) (requires assessment of HydroGNSS ocean-reflected received power, and sampling capability of the instrument)
- Assessing performance of ocean-derived correction factors over predominantly coherent targets
- Assessing performance of quality flagging over land (RFI, correlator anomalies), develop adaptations and improvements
- Assessing residual sensitivity to receiver parameters (IF gain, bit distribution, physical temperatures, self-interference, etc), and possible ways to mitigate these.
- Development and integration of a step detection mechanism to identify operational changes of direct power (flex-power events)
- Development of a novel calibration strategy combining received power data collected by nadir and zenith channels to mitigate a wider variability range of direct power, including flex-power events.