HydroGNSS: Ocean Surface Wind Speed and Sea Ice Extent Processor L2-OP-SWS

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 L2-SWS 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 Longer-term Roadmap** • **Corresponds to L2-SWS Beta R2**

Contents

List of Applicable Documents

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

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

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

List of Reference Documents

[RD1] Zavorotny, V. U., & Voronovich, A. G.. Scattering of GPS signals from the ocean with wind remote sensing application. IEEE Transactions on Geoscience and Remote Sensing, 38(2), 951-964, 2000.

[RD2] 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.

[RD3] 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/

[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] Gleason, S., Hodgart, S., Sun, Y., Gommenginger, C., Mackin, S., Adjrad, M., & Unwin, M. (2005). Detection and processing of bistatically reflected GPS signals from low earth orbit for the purpose of ocean remote sensing. IEEE Transactions on Geoscience and Remote Sensing, 43(6), 1229-1241.

[RD6] Clarizia, M. P., Ruf, C. S., Jales, P., & Gommenginger, C. (2014). Spaceborne GNSS-R minimum variance wind speed estimator. IEEE transactions on geoscience and remote sensing, 52(11), 6829-6843.

[RD7] Saïd, F., Jelenak, Z., Park, J., & Chang, P. S. (2021). The NOAA track-wise wind retrieval algorithm and product assessment for CyGNSS. IEEE Transactions on Geoscience and Remote Sensing, 60, 1-24.

[RD8] Asgarimehr, M., Zhelavskaya, I., Foti, G., Reich, S., & Wickert, J. (2019). A GNSS-R geophysical model function: Machine learning for wind speed retrievals. IEEE Geoscience and Remote Sensing Letters, 17(8), 1333-1337.

[RD9] Yan, Q., & Huang, W. (2019). Sea ice remote sensing using GNSS-R: A review. Remote Sensing, 11(21), 2565

List of Acronyms

ATBD	Algorithm Theoretical Basis Document
CBRE	Calibrated Bistatic Radar Equation
CyGNSS	Cyclone Global Navigation Satellite System
DDM	Delay-Doppler Map
GMF	Geophysical Model Function
GNSS-R	Global Navigation Satellite System Reflectometry
GSID	GNSS-R Sea Ice Detection
L1	Level-1 data
L2	Level-2 data
LHCP	Left-hand circular polarisation
RHCP	Right-hand circular polarisation
L1B-OP-PX	Level-1 A-posteriori calibration processor
L1B-OP-PX-L	Level-1 A-posteriori calibration processor (Learning Module)
L2-SWS	Level-2 Ocean wind speed and sea-ice extent processor
MSS	Mean Square Slope
PDGS	Payload Data Ground Segment
QC	Quality Control
RFI	Radio-Frequency Interference
Sigma0	Normalised Radar Cross-Section
SNR	Signal-to-Noise Ratio
TDS-1	TechDemoSat-1
U10	Ocean surface windspeed
UK-DMC	United Kingdom - Disaster Monitoring Constellation

1 Purpose of this document

This document describes the NOC Level-2 processing module deployed in the ESA HydroGNSS payload data ground segment (PDGS). Specifically, this details L2-OP-SWS, the processor for retrieval of ocean surface wind speed and sea-ice extent from GPS/Galileo L1/E1 LHCP reflections.

2 Background and Scientific Justification

2.1 Ocean wind speed

Following development by a plurality of research teams around the world, retrieval of wind speed above the ocean surface from GNSS reflected data is now a relatively mature technology. A scattering model of GPS signals over the ocean surface was proposed in [RD1]. A multitude of inversion algorithms to apply this to remote sensing of the ocean surface from spaceborne altitudes have been proposed. Some examples of strategies described in past work are: initial studies based on a handful of ocean-reflected data collected by the UK-DMC mission [RD5], using a significantly larger catalogue collected by TDS-1 [RD2], based on a combination of observables and data from NASA CyGNSS [RD6], using ancillary data to complement GNSS-R sensor data [RD7] and data-driven approaches ingesting multiple parameters from different sources e.g. [RD8].

Ocean wind speed products are a secondary objective of the ESA HydroGNSS mission. To this end, the NOC CBRE algorithm, a relatively simple independent algorithm originally designed for TDS-1 has been selected as the baseline inversion strategy for ocean winds. Using TDS-1 data, the algorithm achieves a wind retrieval performance in line with the HydroGNSS mission requirements.

2.2 Sea ice extent

Previous studies focusing on the analysis of reflected ocean data collected by the TechDemoSat-1 mission have shown that integrated delay waveforms have a markedly different signature for reflections over sea-ice when compared to the open ocean, due to the higher reflectivity and different scattering mechanism over sea-ice. Reflected signal waveforms associated with the presence of sea-ice typically show a sharper peak than returns scattered over sea water.

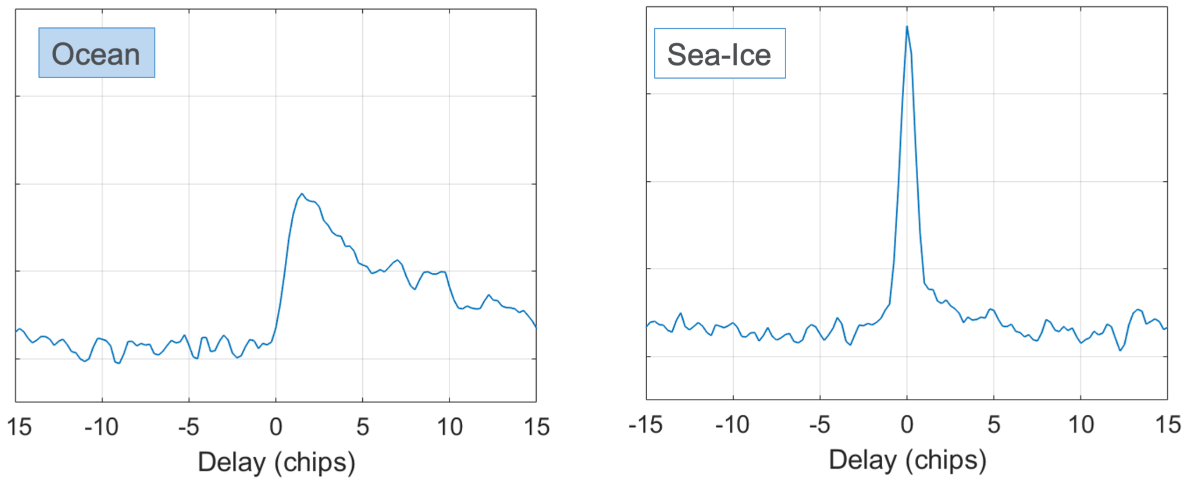

Figure 1 - Integrated delay waveform from ocean (left) and sea-ice (right)

Several methods for retrieval of presence of sea-ice have been proposed, a review of such strategies is presented in [RD9].

The NOC GSID algorithm is the baseline strategy to deliver HydroGNSS sea ice extent secondary products. The method is based on analysis of the shape (slope) and kurtosis of the integrated delay waveform, see more details below.

3 Algorithm Description

Figure 2 illustrates the flow diagram of the ocean wind speed and sea-ice extent processor.

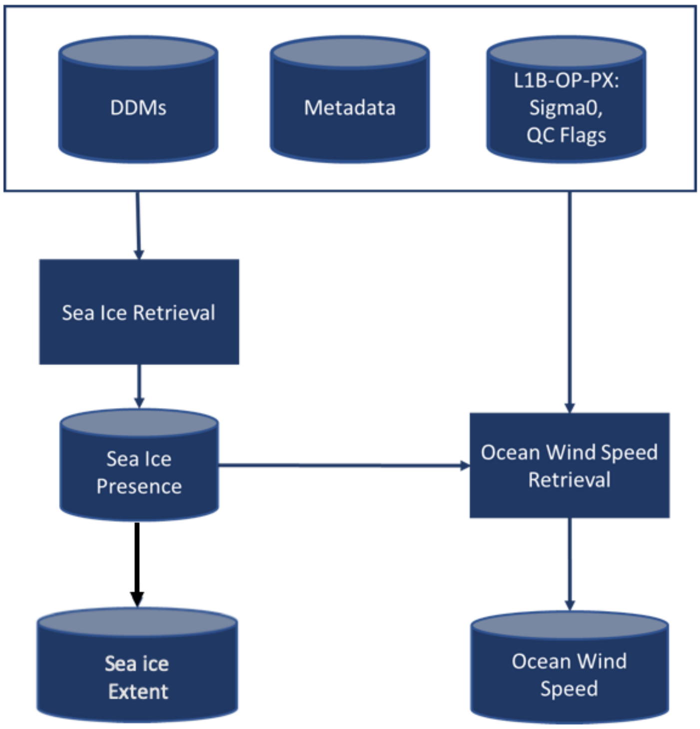

Figure 2 Overview of the L2-OP-SWS processor

3.1 Input

- GPS/Galileo L1/E1 LHCP DDM data
- L1a metadata including:
  - SP position
- Receiver-end correction term (output of L1B-OP-PX processor)
- Transmitter-end correction term (output of L1B-OP-PX processor)
- RFI and Correlator Anomaly Flags (output of L1B-OP-PX processor)

3.2 Applicability

The L2-SWS processor has been designed, implemented and tested using GPS L1 LHCP ocean-reflected data (integrated power DDM) from UK TechDemoSat-1 [RD2]. Some initial investigations have been carried out using Galileo E1 LHCP ocean reflected data collected by SSTL DoT-1 [RD3]. Applicability of a similar inversion strategy to other measurement types (e.g. L5/E5, RHCP) is expected to depend on quality of such reflected signals and may become the subject of future work in the longer-term.

3.3 Sea Ice Extent

The NOC GSID algorithm is a single-sensor GNSS-R algorithm based on analysis of the integrated delay waveform. The likely presence of sea-ice within the nadir antenna footprint is determined by examining the characteristics of the DDM, with the first step consisting in integrating the DDM along the Doppler component to derive the integrated delay waveform. The algorithm then applies a thresholding mechanism based on three parameters that are associated with the sharpness of the integrated delay waveform peak. If all three parameters exceed their threshold values, sea-ice is determined as being present. These threshold values are determined through an optimisation process based on reference sea-ice datasets (NSIDC). The threshold values have been optimised for each hemisphere independently, due in part to the different characteristics of sea-ice over the North and South hemispheres [RD4].

Sea-ice presence is estimated over the ocean at latitudes above 45°N and below 45°S, provided the specular point is located at least 25 km away from the coast to mitigate the risk of potential contamination from land. In the latitudinal band comprised between 45°S and 45°N regular presence of sea-ice is not expected and thus the output is set to 0 (no sea-ice). The sea-ice flag is set to NaN if any of the quality control flags produced by the L1B-OP-PX processing module is set (correlator anomalies, RFI) as no determination can be made. Using TDS-1 data, the classification accuracy of the sea-ice extent algorithm has been found to be better than (or equal to) 90%, in line with HydroGNSS mission requirements.

3.4 Ocean Wind Speed

As from the GNSS-R bistatic radar model described in [RD1], the normalized radar cross-section (Sigma0) is linked to forward-scattered GNSS power, and decreases as MSS increases. Retrieval of ocean wind speed is based on the assumption that the mean square slope (MSS) of the ocean surface is a proxy to the wind stress over the surface.

Surface wind speed is retrieved from Sigma0 derived using a similar method as the L1B-OP-PX processing module (see relevant ATBD), albeit derivation of received power is based on a different SNR estimation method aiming to reduce variance of signal power.

3.4.1 SNR estimation

SNR is estimated as the ratio of the average signal power in an area dynamically located around the peak of the DDM and the average noise power measured in a noise box in the signal-free area of the DDM (noise box as defined in L1B-OP-PX, see relevant ATBD).

The baseline size of the signal area, as determined for TDS-1, is a DDM area of four delay bins and three Doppler bins (1 chip and 1500 Hz respectively), dynamically positioned to include the peak.

As these settings were optimised for reflected GPS signals collected by TDS-1, further refinement may be required for Galileo reflections received by HydroGNSS.

3.4.2 Peak detection

The wind speed strategy includes a DDM peak detection scheme to mitigate potential variability of the peak location in the DDM. Peak detection is based on the application of a median filter and subsequent extraction of the local maxima in DDM space.

3.4.3 Ocean Windspeed GMF

The empirical Sigma0-to-U_{10} geophysical model function (GMF) applied by the algorithm follows a two-factor exponential form:

$$U_{10} = Ae^{B\sigma^0} + Ce^{D\sigma^0} + E$$

where U_{10} is the estimated wind speed, and A, B, C, D, and E are fitted parameters derived from training wind data from ASCAT in the range 0 – 20 m/s. [RD3]

The approach provides estimates of surface wind speed over the global ocean, provided the specular point is located at least 25 km away from the coast to mitigate potential land-related effects. No wind speed is output (NaN) if any of the quality control flags produced by the L1B-OP-PX processing module is set (correlator anomalies, RFI) or sea-ice presence is detected by the sea-ice module. Target wind retrieval performance is an average accuracy better than (or equal to) 2 m/s for wind speeds up to 20 m/s. Validation against scatterometer wind data (ASCAT) has shown that TDS-1 winds based on the NOC CBRE approach achieve a level of performance that matches HydroGNSS mission requirements (Figure 3).

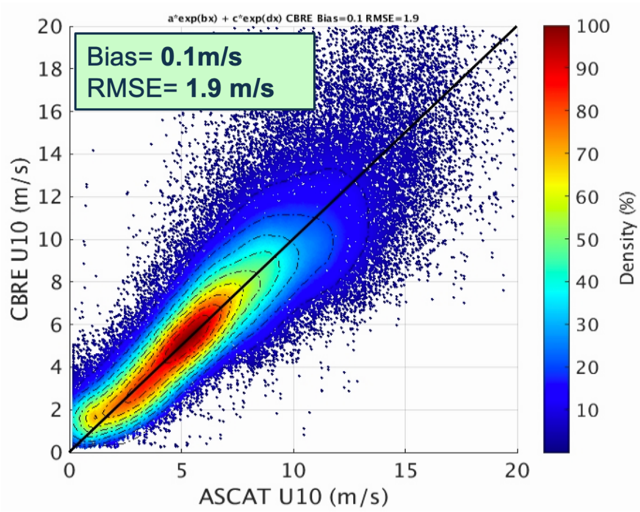

Figure 3 – TechDemoSat-1, NOC CBRE wind retrieval validation

3.5 Output

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

- Sea ice extent
    - Units: Boolean (unitless)
    - Range: ocean=0, presence of sea-ice=1

- Ocean surface wind speed
    - Units: [m/s]
    - Range: 0-20 (NaN outside of the validity range, or if QC fails)

4 Calibration and Validation plan

Calibration of the ocean wind algorithm has been carried out using data from TDS-1 and training data from the ASCAT scatterometer constellation. Validation has been carried out against ASCAT and model output from ECMWF ERA-5.

Calibration of the sea-ice algorithm has been performed using data from TDS-1 and training data from NSIDC. Validation has been carried out against sea-ice data from ECMWF ERA-5.

Further (re)calibration and validation steps following the launch of HydroGNSS include:

- Collection of initial HydroGNSS ocean-reflected GPS/Galileo L1/E1 LHCP dataset (uncalibrated DDM and L1 metadata)
- Collocation with reference ocean and sea-ice data (e.g. ECMWF ERA-5, NSIDC)
- Review of wind algorithm, including re-training the GMF using collocated training data (e.g. ASCAT, ECMWF ERA-5)
- Review of sea-ice algorithm, including re-tuning parameters using collocated sea-ice data (e.g. NSIDC, Eumetsat OSI SAF)
- Preliminary assessment of HydroGNSS wind and sea-ice products.

5 Longer-term Roadmap

As a longer-term goal, potential future activities carrying significant scientific value to further advance GNSS-R ocean remote sensing and/or the NOC L2-SWS processor currently include:

- Developing a refined inversion strategy for high winds (over 20 m/s)
  - Investigating potential of AI-based inversion methods (including multi-sensor approaches)
  - Investigating opportunities for complementarity with other technologies (scatterometry, radiometry, altimetry)
- Examining GNSS-R applicability in the coastal area
- Comparing GNSS-R winds with other satellite products (e.g. SMOS, SMAP, Ku-band scatterometers)
- Developing methods for additional GNSS-R products (e.g. waves, precipitation)
- Investigating novel inversion approaches for the exploitation of the enhanced HydroGNSS hardware capability (L5/E5, RHCP)