Sentinel-3 SRAL Marine User Handbook

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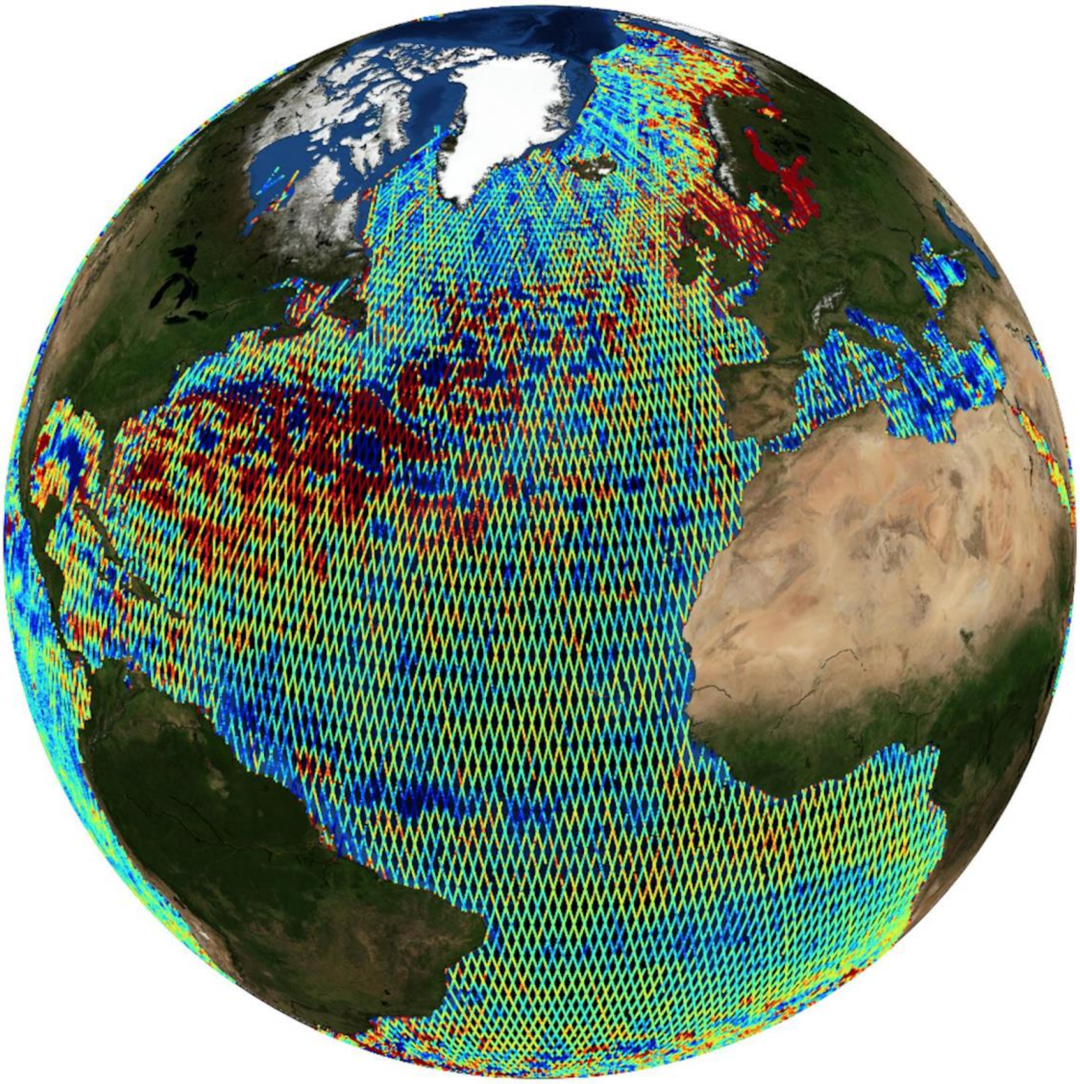

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EUMETSAT
Eumetsat-Allee 1, D-64295 Darmstadt, Germany
Tel: +49 6151 807-7
Fax: +49 6151 807 555
http://www.eumetsat.int

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1 INTRODUCTION

1.1 Purpose

The Sentinel-3 Marine Altimetry Handbook is a user guide that summarises the key information needed to enable a general or specialist end user to get information about Level 1 (L1), Level 2 (L2), Level 2 processed (L2P) and Level 3 (L3) marine altimetry products. The handbook includes information on the components of the altimetry system - the SAR Radar ALtimeter (SRAL), MicroWave Radiometer (MWR) and Precise Orbit Determination (POD) module - the specifics of the measurements techniques used, details on the corrections applied and processing steps taken to derive geophysical variables. The capability of the altimetry system is discussed in the context of its complementarity with, and improvements on, other altimetry missions, with notes on existing limitations. A discussion of file formats, processing tools and data-access routes precedes a presentation of available support resources. Where the detail is not held in the handbook itself, the user is pointed to further (primarily web-based) resources.

1.2 Scope

All current and potential users of the Copernicus Marine Data Stream that are interested in the Sentinel- 3 altimetry products for use in the open-ocean, coastal domain, marine cryosphere and selected inland waters, which currently include the Great lakes, Lake Victoria and the Caspian Sea.

1.3 Document Structure

The document is structured as follows:

- Section 1 General information (this section).
- Section 2 Background information on EUMETSAT, Copernicus and Sentinel-3 mission requirements.
- Section 3 Altimetry context for the Sentinel-3 mission.
- Section 4 Altimetry instrument specifics, including details on the ocean measurement approaches plus and calibration and validation activities
- Section 5 Description of processing approaches and data formats at each product level.
- Section 6 Detailed description of L1, L2 and L2P products available for altimetry.
- Section 7 Explanation of the tools and support options available for downloading, processing and visualise Sentinel-3 altimetry data.

1.4 Applicable Documents

Applicable documents incorporate additional provisions to the source document. A provision may be in the form of requirements, statements, instructions or recommendations.

AD-1 Drinkwater, M., and H. Rebhan, 2007. Sentinel-3: Mission requirements document (MRD). ESA, EOP-SMO/1151/MD-md, (2), 19-22.

AD-2 Donlon, C., 2011. Sentinel-3 Mission Requirements Traceability Document (MRTD). Eur. Space Agency (ESA), Paris, France, Tech. Rep. EOPSM/2184/CD-cd.

1.5 Reference Documents

Reference documents contain additional information related to this document.

RD-1 Chelton, D.B., E.J. Walsh, and J.L. MacArthur, 1989. Pulse Compression and Sea Level Tracking in Satellite Altimetry, 1989. J. Atmos. Oceanic Tech. 6, 407-438.

RD-2 Fu, L.-L., and A. Cazenave (Ed.), 2001. Satellite Altimetry and Earth Sciences, Elsevier (465pp.)

RD-3 Mitchum, G.T., D.W. Hancock, G.S. Hayne, and D.C. Vandemark, 2004. Blooms of sigma(0) in the TOPEX radar altimeter data. J. Atmos Oceanic Tech. 21 (8), 1232-1245.

RD-4 Quartly G.D., T.H. Guymer, and M.A. Srokosz, 1996. The effects of rain on Topex radar altimeter data. J. Atmos. Oceanic Tech. 13, 1209-1229.

RD-5 Gourrion, J., D. Vandemark, S.Bailey, B. Chapron, G.P. Gommenginger, P.G. Challenor, and M.A. Srokosz, 2002. A two-parameter wind speed algorithm for Ku-band altimeters. J. Atmos. Oceanic Tech. 19 (12), 2030-2048.

RD-6 Abdalla, S., 2012. Ku-band radar altimeter surface wind speed algorithm, Mar. Geod. 35(S1), 276-298.

RD-7 Quartly, G.D. et al., 2017. Ensuring that the Sentinel-3A altimeter provides climate-quality data. Proc. of SPIE 2017 (Warsaw, 11-15 Sept. 2017).

RD-8 Passaro, M., P. Cipollini, S. Vignudelli, G.D. Quartly, and H.M. Snaith, 2014. ALES: a multi- mission adaptive sub-waveform retracker for coastal and open ocean altimetry, Remote Sens. Env. 145, 173-189.

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RD-10 Amarouche, L., P. Thibaut, O.-Z. Zanife, J. P. Dumont, P. Vincent, and N. Steunou, 2004. Improving the Jason-1 ground tracking to better account for attitude effects. Mar. Geod., 27 (1-2), 171-197.

RD-11 Bamber, J.L., 1994. Ice-sheet altimeter processing scheme. International Journal of Remote Sensing, 15(4), 925-938.

RD-12 Brown, G.S., 1977. The average impulse response of a rough surface and its applications. IEEE Trans. Ant. Propagat. 25, 67-74.

RD-13 Desjonqueres, J., G. Carayon, N. Steunou, and J. Lambin, 2010. Poseidon-3 radar altimeter: New modes and in-flight performances. Mar. Geod. 33(S1), 57-79.

RD-14 Donlon, C., B. Berruti, A. Buongiorno, M.-H. Ferreira, P. Féménias, J. Frerick, P. Goryl, U. Klein, H. Laur, C. Mavrocordatos, J. Nieke, H. Rebhan, B. Seitz, J. Stroede, R. Sciarra, 2012. The global monitoring for environment and security (GMES) Sentinel-3 mission. Rem. Sens. Env. 120, 37-57.

RD-15 Hayne, G.S., 1980. Radar altimeter mean return waveforms from near-normal incidence ocean surface scattering. IEEE Trans. Ant. Propagat. 28, 687-692.

RD-16 Ijima, B.A., I.L. Harris, C.M. Ho, U.J. Lindqwister, A.J. Mannucci, X. Pi, M.J. Reyes, L.C. Sparks, and B.D. Wilson, 1999. Auto- mated daily process for global ionospheric total electron content maps and satellite ocean altimeter ionospheric calibration based on Global Positioning System data, J. Atmos. Sol.-Terr. Phys., 61, 1205-1218.

RD-17 Kurtz, N.T., N. Galin, and M. Studinger, 2014. An improved CryoSat-2 sea ice freeboard retrieval algorithm through the use of waveform fitting. Cryosphere, 8(4), 1217-1237.
RD-18 Martin-Puig, C., E Leuliette, J Lillibridge, and M Roca, 2016. Evaluating the performance of Jason-2 open-loop and closed-loop tracker modes. J. Atmos. Oceanic Technol. 33 (11), 2277-2288.
RD-19 Raney, R.K., 1998. The delay/Doppler radar altimeter. IEEE Trans. Geosci. Rem. Sens. 36, 1578-1588.
RD-20 Ray, C., C. Martin-Puig, M. P. Clarizia, G. Ruffini, S. Dinardo, C. Gommenginger, and J. Benveniste, 2015. SAR altimeter backscattered waveform model. IEEE Trans. Geosci. Rem. Sens, 53, 911-919.
RD-21 Ray, C., M. Roca, C. Martin-Puig, R. Escola, and A. Garcia, 2015. Amplitude and dilation compensation of the SAR altimeter backscattered power. IEEE Geosci. Rem. Sens, Lett. 12(12), 2473-2476.
RD-22 Sentinel-3 Online Altimetry data product quality reports. https://sentinels.copernicus.eu/web/sentinel/technical-guides/sentinel-3-altimetry/data-quality-reports.
RD-23 Sentinel-3 SRAL/MWR Surface Topography Mission (STM) Level-2 Algorithm Theoretical Basis Document https://sentinel.esa.int/documents/247904/351187/ALT_Level-2_ ADAS.pdf.
RD-24 Tran, N., S. Philipps, J.-C. Poisson, S. Urien, E. Bronner, and N. Picot, 2012. Impact of GDR-D standards on SSB corrections, Aviso, OSTST, available https://www.aviso.altimetry.fr/fileadmin/documents/OSTST/2012/oral/02_friday_28/01_instr_processing_I/01_IP1_Tran.pdf.
RD-25 Walsh, E. J., 1982. Pulse-to-pulse correlation in satellite radar altimeters. Radio Sci., 17, 786-800.
RD-26 Zakharova, E.A., S. Fleury, M. Guerreiro, S. Willmes, F. Rémy, A.V. Kouraev, and G. Heine- mann, G. (2015). Sea ice leads detection using SARAL/AltiKa altimeter. Marine Geodesy, 38(sup1), 522-533.
RD-27 Lorell, J., Colquitt, E., and Anderle, R. J. (1982). Ionospheric correction for SEASAT altimeter height measurement. Journal of Geophysical Research, 87(C5), 3207?3212.
RD-28 Le Roy, Y., Deschaux-Beaume, M., Mavrocordatos, C., and Borde, F. (2010). SRAL, A radar altimeter designed to measure a wide range of surface types. Geoscience and Remote Sensing Symposium, 2009 IEEE International, IGARSS 2009.
RD-29 Wingham, D. (1999). CryoSat mission requirements document, MRD_CS-RS-UCL-SY- 0001, 21 Nov 1999.
RD-30 MacArthur, J. L. (1976). Design of the Seasat-A radar altimeter. Proceedings of the Oceans 1976: IEEE No 76CH1118-90EC, 10B-1-8.

1.6 List of Abbreviations, Acronyms and Symbols

Table of key acronyms and abbreviations.

AGC	Automatic Gain Control

BRAT	Broadview Altimetry Toolbox
CMEMS	Copernicus Marine Environment Monitoring Service
CNES	Centre National d'Etudes Spatiales
DAC	Dynamic Atmosphere Correction
DORIS	Doppler Orbitography by Radiopositioning Integrated by Satellite
DTC	Dry Tropospheric Correction
DPU	Digital Processing Unit
ESA	European Space Agency
EUMETSAT	European Organization for the Exploitation of Meteorological Satellites
GNSS	Global Navigation Satellite System
IBE	Inverse Barometer Effect
ISRO	Indian Space Research Organisation
LRM	Low Rate Mode
LRR	Laser Retro-Reflector
MRD	Mission Requirements Document
MRTD	Mission Requirement Traceability Document
MSS	Mean Sea Surface MWR Microwave Radiometer
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NRT	Near Real-Time
NSAOS	National Satellite Ocean Applications Service
NTC	Non-Time Critical
OLCI	Ocean Land Colour Instrument
PDGS	Payload Data Ground Segment
PLRM	Pseudo-Low Rate Mode
POD	Precision Orbit Determination
PRF	Pulse Repetition Frequency
RFU	Radio Frequency Unit
S3MPC	Sentinel-3 Mission Performance Centre
S3VT	Sentinel-3 Validation Team
SAMOSA	SAR Altimetry MOde Studies and Applications
SAR	Synthetic Aperture Radar
SARM	Synthetic Aperture Radar Mode
SLA	Sea Level Anomaly
SLR	Satellite Laser Ranging
SLSTR	Sea and Land Surface Temperature Radiometer
SNAP	Sentinel Application Platform
SRAL	Synthetic Aperture Radar Altimeter
SSB	Sea State Bias
SWH	Significant Wave Height
SWOT	Surface Water Ocean Topography
STC	Slow Time Critical
TWLE	Total Water Level Envelope
WTC	Wet Tropospheric Correction

2 BACKGROUND

2.1 Copernicus and Sentinels

EUMETSAT provides Earth Observation (EO) data, products and support services to the Copernicus information services and user communities, with a focus on marine, atmosphere and climate. The terrestrial products are produced and distributed by the European Space Agency (ESA).

Copernicus is the European programme for the establishment of a European capacity for EO and monitoring. The programme encompasses space, *in situ* and service components with the space component including the Sentinel satellite missions. Of these, Senetinel-3A was launched in February 2016 with Sentinel-3B due to launch in 2018. Sentinel-3 missions C and D are now being developed.

2.2 Sentinel-3 objectives

Sentinel-3 is a dedicated Copernicus satellite delivering high-quality ocean measurements. In the marine environment, the primary objective of Sentinel-3 is to determine sea-surface topography, sea-surface temperature and ocean-surface colour parameters; offering EO data with global coverage every two days (with two satellites) in support of marine applications, and with near real-time products delivered in less than three hours.

Sentinel-3A was launched in February 2016 with Sentinel-3B due to launch in early 2018; in the longer term the Sentinel-3 mission will have further satellites (Sentinel-3C and Sentinel-3D), extend this global monitoring. Requirements of the Sentinel-3 mission include:

- Sea surface topography (SSH) and, significant wave height (SWH) over the global ocean to an accuracy and precision exceeding that of Envisat RA-2.
- Sea surface temperature (SST) determined globally to an equivalent accuracy and precision as that presently achieved by A/ATSR (i.e. <0.3 K), at a spatial resolution of 1 km.
- Visible and Thermal Infrared radiances (’Ocean Colour’) for oceanic and coastal waters, deter- mined to an equivalent level of accuracy and precision as MERIS data with complete Earth cover- age in two to three days, and co-registered with SST measurements.

For more information, users should consult the specific objectives for the Sentinel-3 missions. These are defined in the Mission Requirements Document (MRD) [AD-1], which is adopted in a traceable format through the Mission Requirements Traceability Document (MRTD) [AD-2]. The Copernicus Marine Environment Monitoring Service (CMEMS) provides regular and systematic core reference information on the state of the physical and biological oceans and regional seas to support marine applications. The products come from both Earth observation data and numerical modelling.

2.3 Disclaimer

The use of these products is granted to every interested user free of charge.

EUMETSAT is very interested in receiving your feedback. Your feedback helps us in improving product quality and maintaining the resources for the EUMETSAT marine services.

2.4 Useful links

Links to internal and external resources and documentation.

EUMETSAT Copernicus homepage:
https://www.eumetsat.int/website/home/Satellites/FutureSatellites/CopernicusSatellites/Copernicus
EUMETSAT altimetry homepage:
https://www.eumetsat.int/website/home/Data/CopernicusServices/Sentinel3Services/Altimetry/index.html
EUMETSAT YouTube home:
https://www.youtube.com/channel/UCiN59j5b1fAGnXVzIYFpaMw
Sentinel 3 for oceans:
https://www.youtube.com/watch?v=T9WCWnk_qN4
Sentinel 3 playlist:
https://www.youtube.com/playlist?list=PLbyvawxScNbus9n8rmw0GElhPqrCwcsiD
Altimetry tutorial and toolkit:
http://www.altimetry.info/

2.5 Altimetry product limitations

Information on product status, quality and limitations can be found through the following links:

Sentinel-3A Product Notice - STM L1 Altimetry (NRT, STC and NTC):
http://www.eumetsat.int/website/wcm/idc/idcplg?IdcService=GET_FILE&dDocName=PDF_S3A_PN_STM_L1_ALTIMETRY&RevisionSelectionMethod=LatestReleased&Rendition=Web

Sentinel-3A Product Notice - STM L2 Marine (NRT, STC and NTC):
http://www.eumetsat.int/website/wcm/idc/idcplg?IdcService=GET_FILE&dDocName=PDF_S3A_PN_STM_L2_NRT_STC&RevisionSelectionMethod=LatestReleased&Rendition=Web

2.6 History of product changes

A history of changes to products can be found in the relevant product notice and specification document, which can be found in the *Copernicus>Sentinel-3>Altimetry* section on the following page:
https://www.eumetsat.int/website/home/Data/TechnicalDocuments/index.html

Current and previous Sentinel-3 mission reports can be found via the following link:
https://sentinels.copernicus.eu/web/sentinel/missions/sentinel-3/mission-status

User should also be aware of the recent reprocessing of Level 1B and Level 2 altimetry products, which also has ramifications for the availability of Level 1A and Level 1B-S products. More information can be found at the following link:
https://www.eumetsat.int/website/home/News/DAT_3648215.html

3 SENTINEL-3 AND ALTIMETRY

The Sentinel-3 missions are low earth polar orbiting satellites, operating at an average altitude of 815 km above the Earth's surface with a repeat cycle of 27 days. After launch, Sentinel-3B will initially be placed in a "tandem orbit", occupying the same ground track as Sentinel-3A with a 30 second difference in observations, to enable close inter-calibration of the instruments. Subsequently it will be moved to a position 140^{o} later in its orbit that will mean that the ground tracks of Sentinel-3B and Sentinel-3A are "interleaved", giving a more complete and even sampling of the Earth's surface, so as to better fulfil the monitoring role of the Sentinel missions. They carry three sets of instruments focusing on high-accuracy optical, thermal and altimetry data for marine and land services:

- Optical: OLCI for medium resolution marine and terrestrial optical measurements
- Thermal: Sea and Land Surface Temperature Radiometer (SLSTR) for marine and terrestrial thermal measurements.
- Altimetry: SAR Radar ALtimeter (SRAL) together with the MicroWave Radiometer (MWR) and Precise Orbit Determination (POD) for topography measurements. The handbook is concerned with the latter, altimetry component, and covers applications in the marine domain (open ocean and coastal), across the marine cryosphere and for specific inland water bodies (Great Lakes, Lake Victoria and the Caspian Sea).

3.1 Altimetry; a historical background

In 1992, Topex/Poseidon mission was launched, featuring European and American instrumentation. Topex/Poseidon ended normal operations in early 2006. However, during Topex/Poseidon's lifetime, a number of other satellite altimeters were launch, including: ERS-2 (ESA, launched in 1995), NASA GFO (NASA, 1998), Jason-1 (NASA/CNES, 2001) and Envisat (ESA, 2002). Using these sensors in combination resulted in both an increase in precision of altimetry measurements and a marked reduction in the compromise between temporal and spatial resolution. While all of the aforementioned satellites have ceased operation, six platforms with altimetry capability are currently operational: Jason-2 (NASA/NOAA/CNES/EUMETSAT), Cryosat-2 (ESA), HY-2A (NSOAS), Saral (ISRO/CNES), Sentinel-3A (EUMETSAT) and Jason-3 (NASA/NOAA/CNES/EUMETSAT). In addition, further Sentinel-6/Jason-CS (~2020; EUMETSAT, ESA, NASA with support from CNES) and SWOT (~2021, NASA) missions are planned in the near future. The inclusion of Sentinel-3B completes the current phase of Copernicus' commitment to satellite altimetry (Senintel-3A / Sentinel-3B / Sentinel-6/Jason-CS). Sentinel-3C and 3D will continue this legacy from 2021.

Throughout the development of these platforms, incremental increases in precision have, cumulatively, greatly reduced the errors associated with range and orbit measurements. In addition, increases in both spatial and temporal coverage, as well as faster retrieval of near real-time data has facilitated the use of along-track satellite altimetry data for assimilation into ocean models. Incremental improvements in re-tracking of radar waveforms have allowed us to extract valid signals ever nearer to the coast, facilitated by a step-change in capability under-pinned by the adoption of a Delayed-Doppler / SAR mode (SARM; as opposed to Low Rate Mode, LRM). In addition, improved characterisation of atmospheric effects, better characterisation and removal of tidal signals, and more accurate determination of both the orbit and geoid have all served to improve the precision of the data retrieved.

3.2 Complementarities with other altimetry missions

Technologically, the Sentinel-3A altimetry package is closest to that of the CryoSat satellite series, which pioneered SAR mode altimetry, but only over sea-ice areas, coastal zones and some selected ocean regions. Sentinel-3 pursues the same goals of mesoscale monitoring as had ERS-1, ERS-2 and ENVISAT, including the requirement to cover the high-latitude polar oceans and cryosphere; however, it does not have the same 35-day repeat orbit and ground track as they had occupied.

While single sensor approaches allow for some applications, it is in tandem with other platforms that altimetry provides some of the most useful products. Multi-mission products, such as the L3 SLA and L4 gridded products provided by the SSALTO-DUACS processing and made available through the Copernicus Marine and Environmental Monitoring Service (CMEMS), homogenise data from all currently flying altimeters, including Sentinel-3A. Multi-mission products improve spatial and temporal coverage and, through later processing stages, enable the derivation of key variables such as geostrophic velocities - where a minimum of three sensors are required to derive both components.

In addition, the Radar Altimeter Database System (RADS) offers a database of harmonised, cross- calibrated altimetry records for the primary purpose of studying sea-level.

More information on multi-model products and processing can be found at the following links.

AVISO SSALTO/DUACS Multi-mission processing
https://www.aviso.altimetry.fr/en/data/product-information/information-about-mono-and-multi-mission-processing/ssaltoduacs-multimission-altimeter-products.html

Copernicus Marine and Environmental Monitoring Service
http://marine.copernicus.eu/services-portfolio/access-to-products/

Radar Altimeter Database System
http://rads.tudelft.nl/rads/rads.shtml

4 ALTIMETRY: GEOPHYSICAL VARIABLES, INSTRUMENTS AND PRINCIPLE

4.1 Principles of Altimetry

Throughout this section numerical values are given for pulse duration, antenna beamwidth and repetition frequency, amongst others. However, the reader should be aware that, in practice, these values are not directly applicable to Sentinel-3, and vary slightly from sensor to sensor. The quoted values should, therefore, been seen as relevant, but approximate.

An overview of altimetry missions, techniques, corrections and accuracy can be found in Fu and Cazenave, (2001) [RD-2].

Fundamentally, the goal of altimetry is to determine the height of the Earth's surface directly beneath the altimeter, by accurate measurement of range between the two. This objective can be divided into three key components: knowing precisely where the satellite is at the time of measurement, recording the time for an electromagnetic pulse to travel from spacecraft to surface and back, and having an accurate model or measurement of the factors that delay the propagation of the pulse.

For conventional low rate mode (LRM) altimetry, the altimeter instrument can be considered to emit a rapid series of pulses, each with a duration of 3.125 ns. In practice, the necessary energy content cannot be squeezed into so short a pulse, because the electronics would be affected. Rather, the signal is emitted as a chirp with the same frequency content as the intended pulse (320 MHz) and the reflected signal "deramped" by mixing with an identical chirp to localise the echo of the supposed pulse [RD-1]. On- board software calculates when the echo is expected and sets the timing of the reception window during which it records the pulse amplitude every 3.125 ns. This is the information recorded as a "waveform" [RD-15].

The delay/Doppler processing technique results in two major evolutions in the quality of the altimetric data; on one hand, it allows for a finer along-track resolution; on the other, thanks to the multi-looking we achieve more independent looks of the same scattering surface, and thus this allows for a considerably noise reduction.

The beam-width of the antenna is ∼1.28^{o} (Ku-band), so the electromagnetic pulse irradiates a disk approximately 20 km in radius; however, for a flat marine surface the first returns will come from the sub-satellite point, with later signals corresponding to progressively larger annuli. There will also be an effect of wave height, with reflections from the crest of waves preceding those from the troughs. The result is that the incident narrow width "pulse" will be smeared out by the range of reflecting heights, with the width of the return pulse being the convolution of the original with the probability density function of the reflecting facets (which is related to the significant wave height), as shown in figure 1.

The expected form of the return pulse is given by the convolution of the original pulse, the distribution due to wave height, and the flat surface response (allowing for the contributions from progressively larger annuli) [RD-12]. However, the return echo from a single pulse will vary greatly from this, as it is governed by addition of multiple reflections with random phase.

This effect, known as Rayleigh or fading noise, makes the interpretation of a single waveform impractical. With the translation of the altimeter, these path lengths to reflecting facets decorrelate in ~1/3000 second [RD-25]; thus, for a conventional altimeter, the reflections from successive 2000 Hz pulses are usually independent, and so the effect of this Rayleigh noise can be mitigated by averaging, with typically 100 pulses summed every 1/20s, corresponding to ~300m along-track movement.

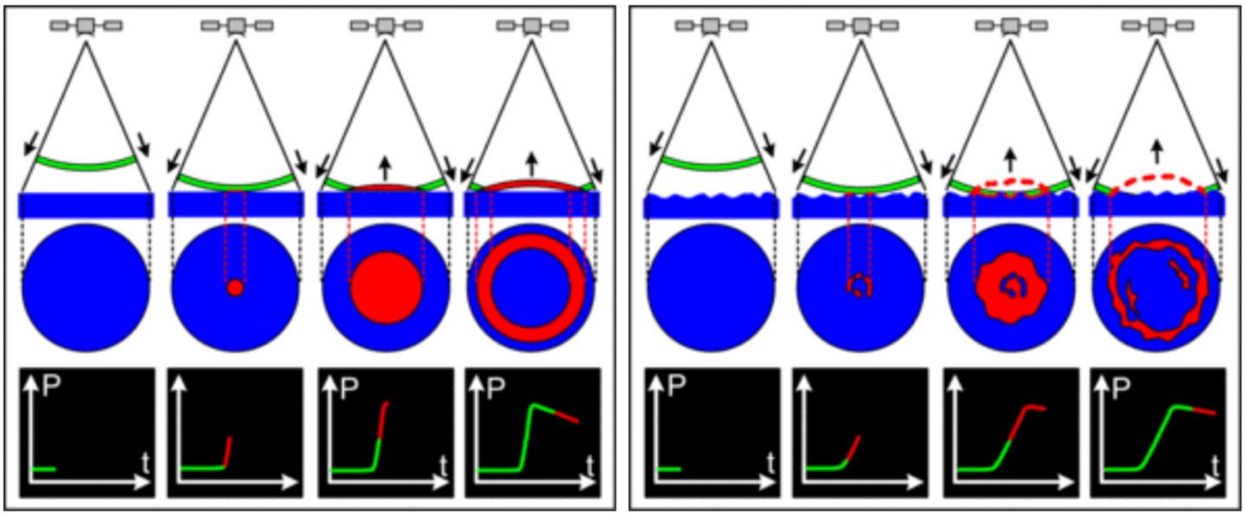

Figure 1: Building a conventional (LRM) waveform. The radar altimeter receives the reflected wave (or echo), which varies in intensity over time. Where the sea surface is flat (left), the amplitude of the reflected wave increases sharply from the moment the leading edge of the radar signal strikes the surface. However, in sea swell or rough seas (right), the wave strikes the crest of one wave and then a series of other crests which cause the amplitude of the reflected wave to increase more gradually. We can derive ocean wave height from the information in this reflected wave, since the slope of the curve representing its amplitude over time is proportional to wave height. (Credit: CNES).

The Sentinel-3 altimeter, SRAL, operates in a more advanced way, using delay-Doppler or SAR (Synthetic Aperture Radar) processing. Throughout this document we will refer to SAR mode, but the term is interchangeable with delay-Doppler. This processing was first developed for Cryosat for its measurements over ice (and later extended to small sample regions of the ocean), but SRAL is the first altimeter to operate in this way globally over all surfaces. There are two key differences to conventional altimetry. Firstly, the return echo is recorded in both range bins (time delay) and in Doppler shift. Although the reflection from directly nadir will have no Doppler shift, those reflections from a little in front of the sub-satellite point will be shifted to a slightly higher frequency and those behind to a lower frequency. Due to the "pulse-to-pulse" coherence and Doppler shift between these reflections, we are able to apply delay/Doppler processing techniques to SAR mode altimetry. As a result, the effective along track resolution is constrained to 300 m along track [RD-19], but remains pulse-limited across track. The resultant footprint is thus far from circular. This shorter along-track footprint allows the potential to look at elevation changes on much smaller scales than hitherto possible, but also crucially, by being able to neglect signal contributions from either before or after the nadir point, it enables altimetry to be applied close to the coast without land reflections contaminating the marine signal. This improvement in localization of echoes means that the same small portion of the sea surface can be measured independently from multiple locations along-track: this "multi-looking" capability leads to a better signal to noise ratio, and thus the ability to detect smaller signals than conventional LRM processing. Secondly, in order to do this SAR processing, it needs multiple coherent returns from the sea surface, so it operates at a much higher pulse repetition frequency (PRF) of 18 kHz so that satellite motion does not lead to significant decorrelation.

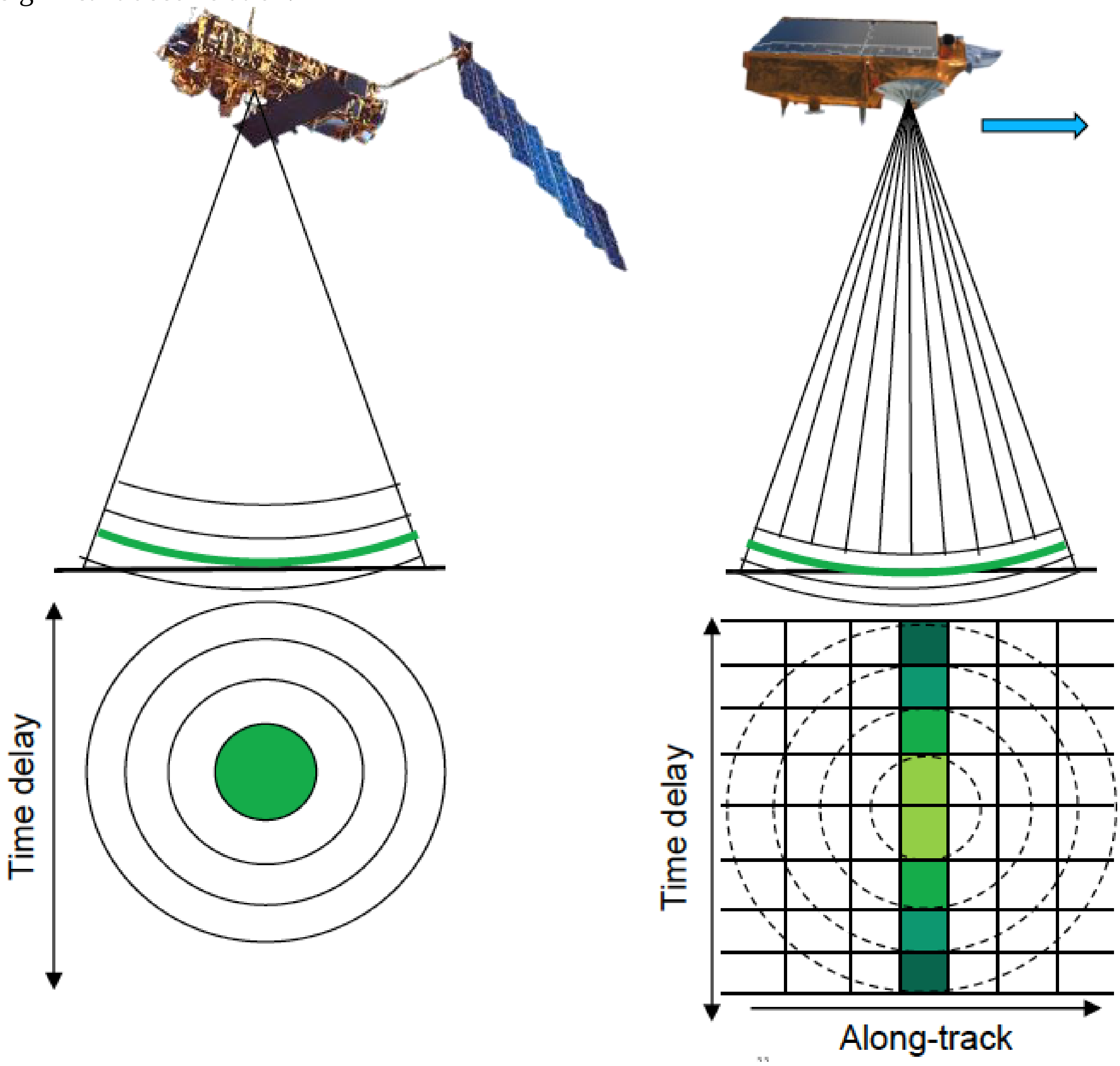

Figure 2: Schematic showing the difference in information recorded by LRM and SARM altimetry. (left) In LRM operation the wave-front from an altimeter propagates spherically, and when it first interacts with the ocean surface (green line) the returned signal is from a small disk, and then at later delays corresponds to wider annuli. (right) In SARM operation, the extra information on Doppler shift further pinpoints the part of the ocean surface giving the radar return. (Credit: Felix Müller).

In order to establish the continuity with previous altimeter datasets, these 18 kHz pulses can be treated in the manner of conventional altimetry processing i.e. neglecting the Doppler information and simply calculating power averages from all of the pulses. As the instrument does not emit a continuous 18 kHz stream of pulses, but rather in bursts of 64 with gaps between, this pseudo low resolution mode (PLRM) processing does not match the performance of a conventional altimeter operating continuously at 2 kHz. However, the results of the PLRM processing are provided in addition to the SAR mode, so that any biases between the two methodologies can be understood.

4.2 Geophysical variables

This section contains more theoretical descriptions of how the Geophysical variables are derived.

4.2.1 Sea surface height

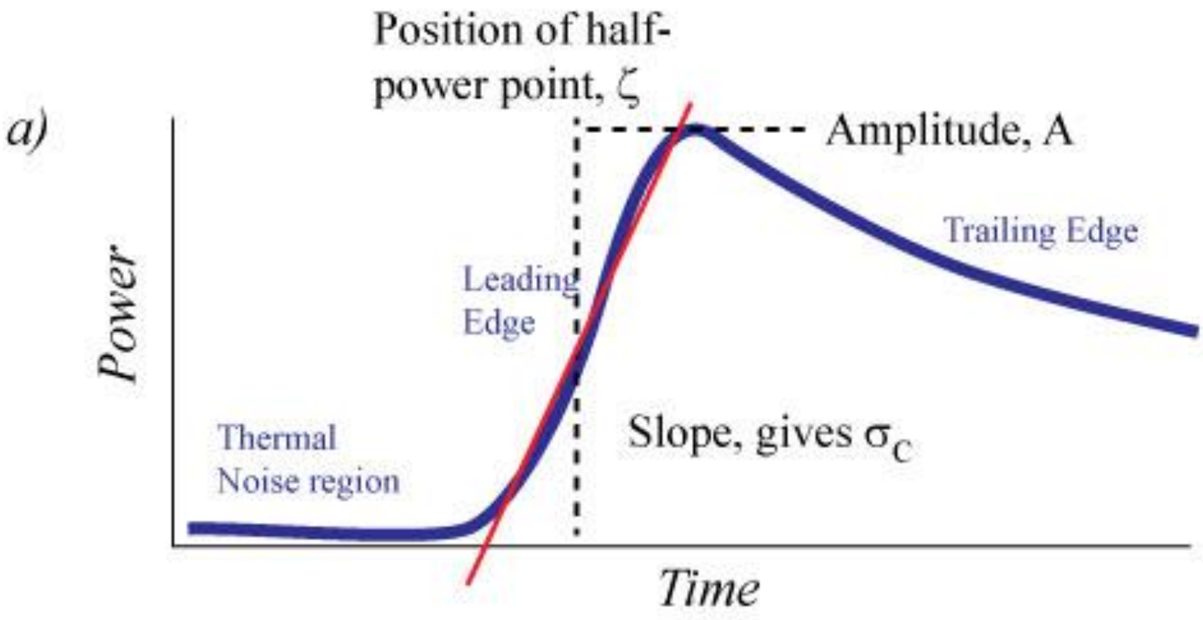

Figure 3: Schematic of an LRM waveform over the ocean.

For LRM (and PLRM) processing the expected shape of the waveform is given by;

$$P(t) = \mathrm{PDF}(t) * \mathrm{PTR}(t) * \mathrm{FSR}(t) \qquad (1)$$

where "∗" means convolution, PDF is the probability distribution function of reflecting facets (typically represented by a Gaussian with S.D. = SWH/4), PTR is the Point Target Response i.e. the shape of the emitted pulse, and FSR is the Flat Surface Response.

The waveform shape, illustrated in figure 3, is thus a copy of the error function (erf), with position (ζ), amplitude (A) and leading-edge slope (σ_c), with a well-defined tapering off on the right-hand side due to antenna beamwidth (θ_o) and mispointing angle (ψ) and a low level of additive thermal noise (T_n) throughout. The formal derivation (taken from Amarouche et al., (2004) [RD-10]) is:

$$P(\zeta, A, \sigma_c, t) \quad = \quad Aexp(-\nu_1)[1 + erf(u_1)] \quad - \quad (A/2)exp(-\nu_2)[1 + erf(u_2)] \quad + \quad T_n \qquad (2)$$

where;

$$u_1 = \frac{t - \tau - \alpha_1 \sigma_c^2}{\sqrt{2}\sigma_c} \quad , \quad \nu_1 = \alpha_1 (t - \alpha_1 \sigma_c^2 / 2) \quad , \quad \alpha_1 = \delta - \beta^2 / 8 \tag{3}$$

$$u_2 = \frac{t - \tau - \alpha_2 \sigma_c^2}{\sqrt{2}\sigma_c} \quad , \quad \nu_2 = \alpha_2 (t - \alpha_2 \sigma_c^2 / 2) \quad , \quad \alpha_2 = \delta \tag{4}$$

$$\mathrm{erf}(x) = \frac{2}{\sqrt{(\pi)}} \int_0^x e^{-t^2} dt \tag{5}$$

For a given open ocean waveform, the key parameters, ζ, σ_c and A are determined by minimising the sum of squares of the differences between model and data. This fitting may be done using a weighted or unweighted sum, with the minimization over 3 or more unknowns achieved by an iterative technique.

$$\beta = \frac{4}{\gamma} \left[\frac{c}{k} \right]^{1/2} sin(2\psi) \quad , \quad \delta = \frac{4}{\gamma} \frac{c}{k} cos(2\psi) \quad , \quad \gamma = \frac{sin^2 \theta}{2ln2} \quad , \quad \zeta = c\tau/2 \tag{6}$$

[The full model, detailed in RD-10, was designed to accommodate significant values for the mispointing ($\psi > 0.3^o$), with this descriptor being the 4th free parameter for the model fit.] As part of the data structure, fields are supplied giving the number of iterations needed for convergence, and the resultant error of the fit; these may be used as part of the quality control procedures to ignore waveforms that did not conform well to the expected shape over the ocean.

For SAR processing, the model for the expected shape of the waveform encompasses variations in both time and Doppler shift:

$$P(t, \Delta f) = \mathrm{PDF}(t) * \mathrm{PTR}(t, \Delta f) * * \mathrm{FSR}(t, \Delta f) \tag{7}$$

The shape of the pulse at zero Doppler shift has a steeper leading edge than that for LRM processing, and thus its location can be determined more precisely. For SRAL, the fitted model is SAMOSA 2.5 [RD-20, RD-21]. Examples of actual waveforms for ocean and ice in both PLRM and SAR mode are shown in figure 4 and figure 5, respectively.

Although the effective pulse width and the width of the sampling bins are 3.125 ns, corresponding to a 2-way travel distance of 46.875 cm, by having a good physical model of the interaction with the sea surface, the aim is to localise this return to within 2 cm. This is not possible for 20 Hz waveforms due to the effect of the Rayleigh noise, but with suitable averaging along-track this can be achieved.

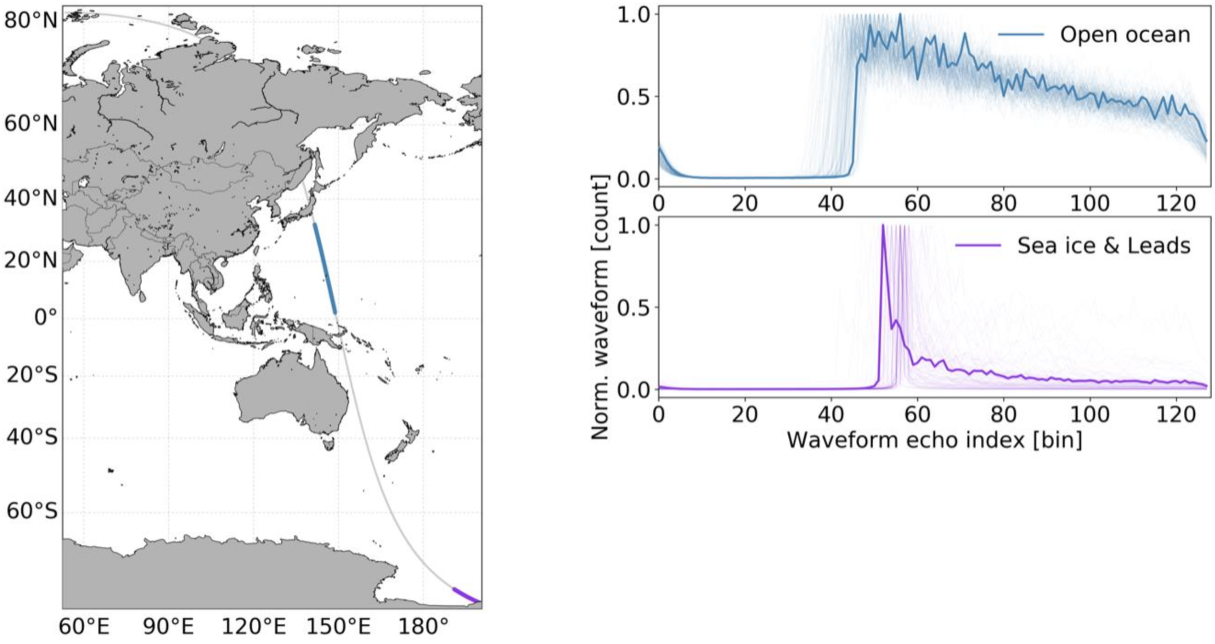

Figure 4: Examples of PLRM waveforms extracted from a Sentinel-3 SRAL Level 2 enhanced product. The map on the left shows the overpass for relative orbit 23. Coloured points and lines refer to the relevant classification of the extracted waveform as open ocean (blue) or sea-ice/lead (purple). Grey map points are still associated with waveforms, but not represented in the right-hand panels. The right-hand panels show the differences in waveforms for these locations, with the bold line showing a single indicative example. (Credit: EUMETSAT).

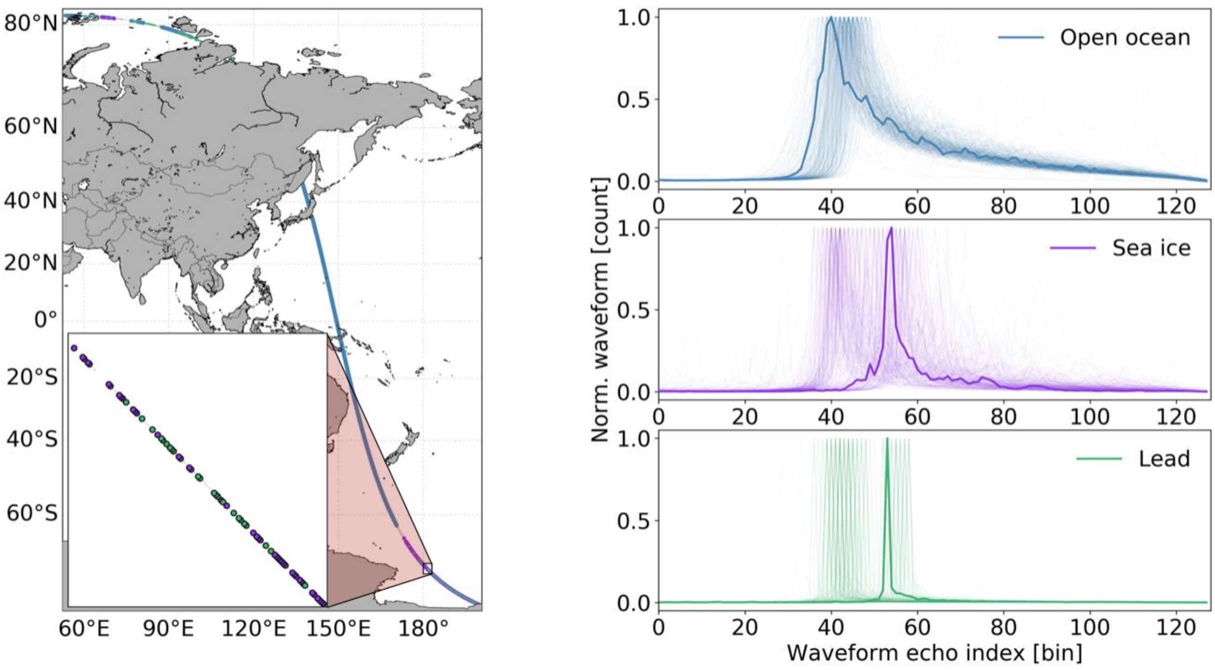

Figure 5: As in figure 4, but for 20 Hz SAR_Ku mode. In this case grey points show uncategorised waveforms (e.g. the surface class is indeterminate). The in- set map shows the complex transition between sea-ice (purple) and lead (green) waveforms. (Credit: EUMETSAT).

The range from satellite to sea surface is approximated by half the round-trip time of the signal divided by the speed of light in a vacuum. To get an accurate sea surface elevation the difference between satellite orbit height and range needs to be corrected for various propagation delays due to the Earth's atmosphere, viz:

$$\text{sea surface elevation} = \text{orbit height} - (\text{range} + \text{DTC} + \text{WTC} + \text{iono} + \text{SSB}) \tag{8}$$

where, DTC is the Dry Tropospheric Correction; an adjustment for the retardation of the radio waves by the atmosphere. This is simply calculated from the mass of the atmospheric column, characterised by a meteorological model's value for the atmospheric pressure at the surface. [For the data provided in Near Real-Time, the model used in the ECMWF Operational forecast; for data with a few days latency, the values from the ECMWF Operational analysis are preferred, as they include observations.] WTC is the Wet Tropospheric Correction, which compensates for the extra delay due to water vapour and liquid water in the atmospheric path. This value may be obtained from the on-board radiometer or from the ECMWF model (as for DTC). The Ionospheric Correction is represented by *iono*, which corrects for the reduction in phase velocity caused by free electrons within the ionosphere. This effect is frequency dependent, so one correction ('dual-frequency') is developed from the difference in delay at the altimeter's Ku- and C-band, whilst another ('GIM') is based on the NASA/JPL Global Ionospheric Model [RD-16].

The last of these important corrections is the sea state bias (SSB), which is not a propagation delay, but the difference between the median height of reflecting points on the sea surface and the mean of the whole surface. This term includes any skewness of the sea surface, the electromagnetic bias that describes the differential reflectivity of wave crests and troughs, and any tracker bias (which is an error associated with the processing of the waveforms). The overall correction sea state bias differs from one altimeter to another, and is usually given as a multiple of SWH, with the proportion itself parameterised as a weakly-varying function of SWH and altimeter-derived wind speed. For Sentinel-3 there is currently no bespoke SSB model; instead, it is recommended that users apply that for Jason-2, which is represented by a non-parametric lookup table as a function of SWH and wind speed [RD-24].

The above calculation yields a sea surface elevation relative to the reference ellipsoid, which is the datum for observation of satellite dynamics. To obtain an oceanographically meaningful value it is necessary to subtract the geoid (an equipotential of the gravity field that conforms to the level of a homogeneous motionless ocean). Alternatively, the mean sea surface (MSS) is removed (which corresponds to the geoid plus the mean absolute dynamic topography. For example, the Total Water Level Envelope (TWLE) is the real physical height of the sea surface at a point, with all atmospheric and instrumental corrections applied:

$$\text{TWLE} = \text{orbit height} - (\text{range} + \text{DTC} + \text{WTC} + \text{iono} + \text{SSB}) - \text{MSS} \tag{9}$$

This definition includes the result of a number of oceanographic processes, and is useful for the examination of extreme sea levels when many different causes may coincide. This may be particularly relevant when a low-pressure system (causing raising of water levels), and possibly associated with wave set-up, coincides with high tides in a particular region.

For a number of other applications, such as long-term sea level trends or the study of currents associated with mesoscale features, it is essential to model and remove the tides and the ocean's response to changes in atmospheric pressure. For example, the sea level anomaly (SLA) is defined by:

$$\text{SLA} = \text{orbit height - (range} + \text{DTC} + \text{WTC} + \text{iono} + \text{SSB) - MSS - DAC - tides} \tag{10}$$

where DAC is the Dynamic Atmospheric Correction, and includes both the static response (also known as the Inverse Barometer Effect, IBE) and changes associated with the ocean's response to the recent history of sea level pressure and winds. Again, this correction is determined from a model, using meteorological reanalyses as input. The response of the Earth to the gravitational disruption of the moon and sun is complicated, with effects on the ocean and the Earth, with each having multiple harmonics. Normally, the "tides" value to be removed is the sum of one solution for each of Ocean tide, Loading tide, Earth tide and Pole tide.

4.2.2 Significant wave height

The approach to estimating significant wave height (SWH) is very different for the two models. For LRM operation it is only the leading edge of the waveform that is sensitive to the value of SWH. The difference in delay for reflections from wave crests and wave troughs affects the slope of the leading edge of the waveform, σ_c. This measure includes both the width of the original pulse and the std. dev. of the delays associated with reflecting facets, $2\sigma_h/c$ (where c is the speed of EM waves). As the standard deviation of surface elevation is equivalent to one quarter of the SWH, the wave height can be determined via equation 11.

$$SWH^2 = 4c^2(\sigma_c^2 - \sigma_p^2) \tag{11}$$

At very low wave heights, the effect of fading noise on the waveform-fitting may return values of σ_c less than the original pulse width, σ_p. The resultant negative values for SWH^2 are not necessarily more erroneous than other values with measurement noise, and may often be successfully used.

For altimeters operating in SAR mode, both the leading edge and the trailing edge of the waveform are affected by changes in SWH, with the SAMOSA 2.5 model using both these parts of the waveform to determine the SWH value [RD-20, RD-21].

4.2.3 Wind speed over ocean surface

The amplitude of the fitted waveform gives a measure of the strength of backscatter of the surface. After corrections for atmospheric attenuation, range of the satellite from the surface, antenna gain, any mispointing issues, the fitted amplitude (A) is used to infer the normalised radar cross-section at 0^o incidence, σ^o. This represents a physical property of the surface, and over the ocean it varies inversely with the mean square slope, a measure of the sea surface roughness. Consequently, algorithms have been developed relating σ^o to u_{10}, the wind speed at 10 m above the surface (a standard meteorological convention). Although some inversion algorithms combine information from σ^o and SWH [RD-5], the standard algorithm for SRAL is based on Abdalla et al. (2012) [RD-6]. *[Note there is generally poor absolute calibration of*

σ^o*, so the values from different instruments need at least a bias adjustment to enable a common conversion to wind speed.]*.

4.2.4 Quality Control flags for marine data

The mathematical model used to fit waveforms over the ocean (either PLRM or SARM) assumes the surface to be homogeneous and diffusely scattering. If patches within the instantaneous footprint have apparently different surface properties (typically either real changes in mean square slope due to patches of mineral oil or biogenic oil [RD-3] or apparent changes due to attenuation by rain [RD-4] then the waveform shape will not conform to the expected model. Other causes of error are nearby higher surface elevations (land or icebergs) that lead to power in the waveform ahead of or on the leading edge. However, the waveform retracking procedure may provide "best estimates" that are erroneous.

If working with the high-frequency 20 Hz data, the parameters to check are the number of iterations to convergence and the goodness of fit. This may also be combined with an outlier detector that flags any points for which range, SWH or σ^o differ markedly, from say, a 7-point running median.

If working with the 1 Hz data, there is useful summary data, providing the number of 20 Hz estimates used to form the 1 Hz mean of range, SWH and σ^o, and also the std. dev. of those values used. If the std. dev. exceeds some threshold then it is likely that one or more samples contributing to the mean were corrupted. In the 1 Hz data, there are also flags warning when the altimeter is i) near to land, ii) in a region with significant rain, and iii) whether ice is believed to be present. It is left to the user, according to their intended application, to choose how stringently to discard possible suspect data.

4.2.5 Ice parameters

Continuous ice floe within the instrument footprint will give a flat surface response similar to that over the ocean, and thus similar shaped waveforms. The main difference is that ice floes are much better reflectors of Ku-band radar that the ocean surface, so the signal strength, described by σ^o, is often 10 dB or greater than that over the ocean. The reflections from ice floes can be processed in a similar manner to give the elevation of the surface of the ice.

However, there is also a dedicated retracker to process SAR mode sea-ice waveforms, which models the waveform shape by several separate parts: the leading edge is modelled by a Gaussian, with an exponential function for decay of the trailing edge. The key geophysical parameters produced by this model are the range and the backscatter coefficient [RD-23]. Note: loosely packed snow lying on the ice does not give a sharp interface with the atmosphere, so the reflecting surface is taken to be the top of the compact ice.

When leads (gaps of clear water or thinly frozen ice) exist between the ice floes then very different waveforms may be generated. With minimal wind roughening or swell, the surfaces within the leads are glassy, providing a very strong specular reflection when the altimeter passes directly overhead [RD-26]. Waveforms within LRM or PLRM are "peaky", with almost all the power concentrated in only a few bins of the waveform (figure 4), and the SAR waveforms for leads are also more “peaky” than those for ocean (figure 5). The information gained from retracking these waveforms is the level of the water within the leads. Firstly, this gives a sea surface height for comparison with open ocean values and for study of dynamic circulation. Secondly, it provides a reference for the measures of sea-ice elevation. The difference between the height of the top of the ice and of the water is termed "freeboard", and may be used to calculate the ice thickness (by making assumptions about the density of ice, which can vary with age, and of whether there is snow loading depressing the ice surface). The current implementation for Sentinel-3A is described in [RD-23].

4.3 Instrumentation

The Sentinel-3A altimetry system consists of three components; The SAR radar altimeter (SRAL), microwave radiometer (MWR) and precise orbit determination system (POD). Each of these is discussed below, but the user is also referred to [RD-14] for more information.

4.3.1 Sentinel-3 Ku/C SAR Radar Altimeter (SRAL)

SRAL [RD-28] is a fully redundant dual-frequency (Ku and C-band), nadir-looking, radar altimeter that employs SAR altimetry technologies inherited from the CryoSat [RD-29] and Jason altimeter missions. SRAL emits narrow pulses (or more precisely chirps) and records their reflected echoes from the Earth’s surface. It is a dual-frequency instrument, operating at both 13.6 GHz (Ku-band) and 5.4 GHz (C- band). For the start of the mission it was operated in Low Resolution Mode (LRM), but after the first few 27-day cycles, it has operated exclusively in SAR mode. The SAR altimeter approach increases the measurement accuracy and along track resolution when compared to conventional altimetry products, providing measurements with high spatial resolution (300 m along-track).

SRAL contains the following sub-systems:

- A Satellite Management Unit for instrument commanding and monitoring.
- A Data Handling and Mass Memory Unit for payload data handling.
- A Radio Frequency Unit (RFU) comprised of Solid State Power Amplifiers in Ku and C bands, diplexers used to route signals in the transmit or receive chains, a signal demodulation and “der- amp” system, and gain controlled amplifiers to slave the echo level.
- A Digital Processing Unit (DPU) that manages all communication interfaces between the satellite platform (telemetry and tele- commands), a chirp generator, full sequencing of the instrument, received signal sampling and all elements of the required for tracking.

SRAL is fully redundant, containing two identical DPU and RFU systems. Table 1 contains a summary of key SRAL design elements. The SRAL antenna is consists of a parabolic reflector which focusses an incident signal to a C band and Ku band feedhorn, placed at a focal distance of 430 mm. SRAL transmits alternate transmission of Ku band (13.575GHz, bandwidth=350MHz) and C band (5.41 GHz, bandwidth=320 MHz) signals. The minimum gains for the Ku band and C band are 41.5 dB and 31.6dB, respectively. The C band is used to correct range delay due to the varying density of electrons in the ionosphere. Meteorological data and models are used to correct for the dry troposphere [RD-2]. Wet tropospheric correction requires accurate determination of atmospheric water vapour content, which is provided by the Microwave Radiometer (discussed in section 4.3.2). SRAL emits a linearly frequency-modulated pulse (chirp) with pulse compression, carried out on-board using the deramp technique [RD-30]. An on-board Ultra-Stable Oscillator generates a 10 MHz signal, which serves the SRAL instrument, and also serves the on-board navigation system. SRAL is capable of operating in two radar modes; LRM and SAR Mode.

Parameter	Ku band	C band
Frequency	13.575 GHz	5.41 GHz
Bandwidth	350 MHz (320 used)	320 MHz (290 used)
Antenna footprint	18.2 km	48.4 km
Radius of 1st resolution cell	823 m	865 m
Low Resolution Mode (LRM) Pulse repetition frequency (PRF)	1924 Hz	274.8 Hz
LRM Tracking Modes	closed and open loop	closed and open loop
Synthetic Aperture Radar (SAR) mode SAR (PRF)	17,825 Hz	
SAR along track resolution	291 m (Orbit height 795 km) to 306 m (Orbit height 833 km)	
SAR across track resolution	> 2 km depending on Hs	
Doppler bandwidth	15,055 Hz	
Tracking modes	closed and open loop	
Antenna size	1.2 m diameter, focal length 0.43 m	

Table 1: Technical specifications of the SRAL instrument [RD-14].

In LRM, SRAL operates as a conventional pulse-limited altimeter with regular transmitting and receiving sequences, at a Pulse Repetition Frequency (PRF) of 1920 Hz. Patterns of six Ku-band pulses preceded by one C-band pulse, are used to ensure measurements for the ionospheric bias correction [RD-27. The echo received from each pulse is sampled on 128 points corresponding to a 60 m range window. C and Ku-band echoes are accumulated separately over a 50 ms cycle of the radar cycle (i.e. 84 Ku-band pulses and 14 C-band pulses accumulated over that cycle).

In SAR Mode, SRAL emits 64 pulses at a PRF of 17.9 kHz, with one C-band pulse preceding the burst and one following it (see figure 6). The burst cycle duration is approximately 12.5 ms so that a four-burst cycle is equal to the LRM cycle of 50 ms. The echo received from each pulse is sampled on 128 complex points. The interval between the bursts is adjusted by the on-board tracker.

SRAL operates in one of two on-board tracking modes, open and closed loop. Autonomous closed loop tracking of range and gain may be used where the altimeter range window is autonomously positioned based on-board NRT analysis of previous SRAL waveforms [RD-28]. Open loop tracking mode is available where the altimeter range window is positioned using a-priori knowledge of the surface height stored on-board the instrument in a one-dimensional along-track Digital Elevation Model (DEM). Open and closed loop modes are discussed more fully in section 4.3.5.

4.3.2 Microwave Radiometer (MWR)

Atmospheric attenuation caused by the wet troposphere is the cause of significant altimeter range-delay errors. Correcting for these, particularly over the coastal zone, where land-sea water vapour gradients are complex, requires information on atmospheric water vapour content, with a degree of horizontal resolution that NWP models cannot provide. The MWR provides measurements of atmospheric water vapour and liquid water content to allow for these corrections to be made during ground station processing.

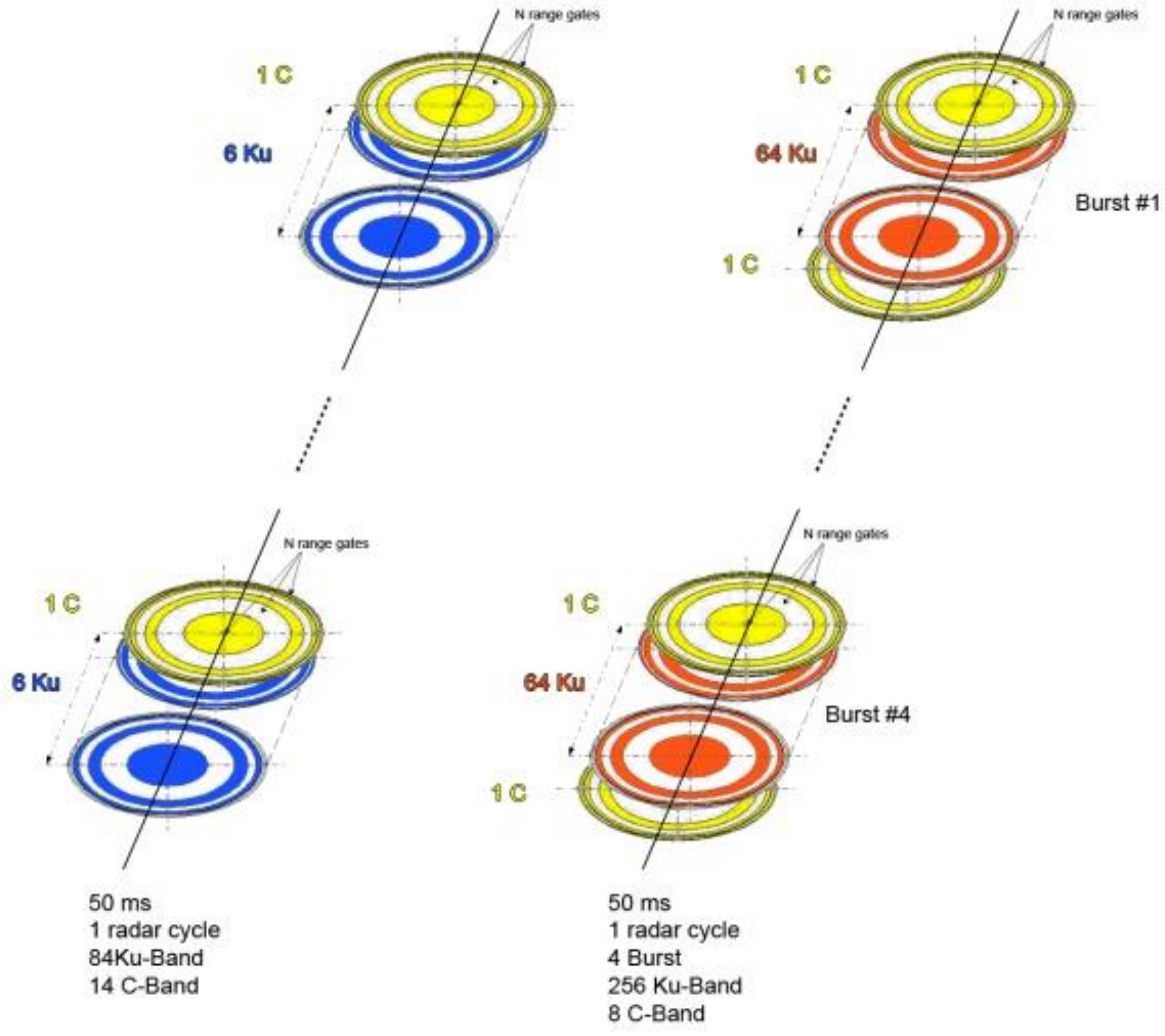

Figure 6: LRM radar cycle transmitting pattern (left) and SAR radar cycle trans- mitting pattern (right). LRM radar cycles contain 96 pulses (84 Ku-band and 14 C-band) structured in transmitting sequences of 1 C - 6 Ku pulses. SAR radar cycles contain four bursts, each of these bursts structured in transmitting sequences of 1 C - 64 Ku -1 C pulses. (Credit: Thales Alenia Spazio).

The MWR (figure 7) is a two-channel passive microwave system, whose footprint is governed by the frequencies used and the size of the antenna. Following the heritage of ERS-1, ERS-2 & Envisat it operates at 23.8 GHz (where there is strong emission/absorption by atmospheric water vapour) and at 36.5 GHz to record the presence of atmospheric liquid water. By using feed horns that are not directly on the boresight of the antenna, the 24 km diameter footprint of the 23.8 GHz is located 28 km in front of the sub-satellite point and the 18.5 km diameter footprint of the 36.5 GHz is 27 km behind nadir. Thus, the time series of brightness channels at the two frequencies have to be shifted to match the spatial locations of the altimeter measurements.

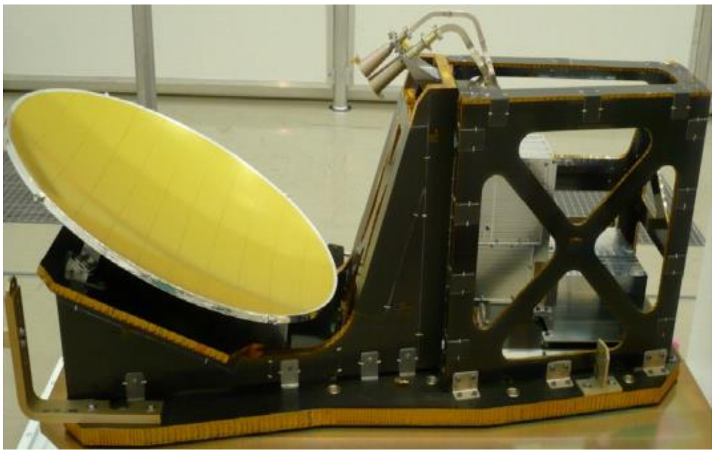

Figure 7: Photo of the MWR antenna plus 2 feed horns

These brightness temperatures are used with a radiative transfer model to infer the amount of water vapour and liquid water in the sub-satellite atmospheric column, and thus to calculate the WTC (correction to range) and the atmospheric attenuation (correction to σ^o). Table 2 contains a summary of MWR instrument specifications.

Centre frequency	23.8 GHz	36.5 GHz
Bandwidth	200 MHz	200 MHz
Integration time (typical)	152.88 ms	152.88 ms
Polarization	Linear	Linear
Main antenna (reflector) size (projected diameter)	0.6	
Calibration	Noise injection Dicke radiometer configuration with a separate sky horn viewing deep space (cold reference at 50% and 100% noise injection). Dedicated instrument calibration temperature sensors	
Noise figure (at 25 C)	<4.4 dB (main path)	<5.1 dB (main path)
Radiometric sensitivity (main path, NIR mode)	0.29 K	0.34 K
Radiometric accuracy	< 3 K	< 3 K
Radiometric stability	0.6 K	0.6 K

Table 2: Technical specifications of the MWR instrument [RD-14].

4.4 Precise Orbit Determination package (POD)

SRAL requires high accuracy radial orbit detection to meet its operational requirements (see section 6.2). The POD package consists of three measurement systems that serve this purpose; the Global Navigation by Satellite System (GNSS), Doppler Orbitography by Radiopositioning Integrated by Satellite (DORIS), and a Laser RetroReflector (LRR).

GNSS uses the information from the global array of existing GPS and GLONASS satellites (which are in a much higher orbit) to determine the position of the satellite in 3-D, within the established inertial reference system. Sentinel-3B will also us the European Galileo system. The GNSS system performs the following functions:

- Sensor and data for the S-3 Attitude and Orbit Control Sub-system.
- Data for POD required for the topography mission.
- Real time orbit information support to SRAL tracking.

Each Sentinel-3 satellite employs two GNSS units in a redundant configuration, with each unit able to concurrently track up to 8 GNSS satellites. The GNSS receiver provides real-time on-board positions to within an accuracy of ~3 m, correcting for ionospheric attenuation by simultaneously monitoring GOPS signals at two frequencies (1160 MHz and 1590 MHz). Ground station processing reduces the altitude errors to < 8 cm (in NRT mode, less than 3 hours), and < 2 cm (un STC mode, less than 48 hours - see section 5.1.6 for information on product latency.).

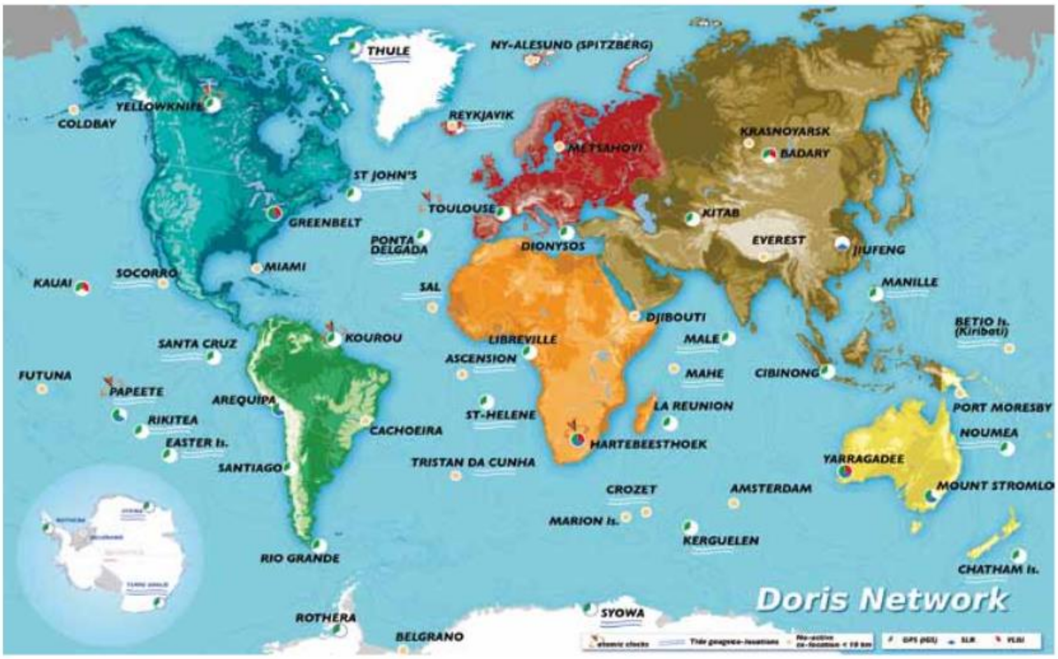

Figure 8: Distribution of DORIS beacons.

DORIS is flown on the Sentinel-3 missions to ensure POD accuracy and robustness. DORIS uses the signals permanently emitted by dedicated DORIS beacons on the ground in order to localise the satellite, delivering real time orbital accuracy to within 1cm. The array of beacons makes use of many small islands (see figure 8) to achieve global coverage.

LRR is a passive device, simply containing seven corner cubes at different orientations (see figure 9), each of which will reflect a laser beam back in exactly the direction from which it came. A number of Satellite Laser Ranging (SLR) stations throughout the world maintain a programme of measurements of range to selected satellites by recording transit times for pulses of light at 532 nm and/or 694 nm.

The majority of stations are in the northern hemisphere, although some of the most useful observations come from Yarragadee in Australia, as it loses very few nights observing due to cloud cover. LRR provides ranging to within an accuracy of < 2 cm.

Since no single instrument provides a continuous record of satellite location at a high enough accuracy, the orbit information supplied in the data files is generated by a physical model of the forces acting on the satellite (including solar radiation pressure and weak atmospheric drag) with a detailed description of the Earth’s gravity field (including components that vary with time in response to the seasonality in the movement of water due to the hydrological cycle, glacier melt and the seasonal changes in transpiration of large forests.

Figure 9: Photo of the Laser RetroReflector array

4.4.1 Operation Modes

Sentinel-3A has two operational modes: LRM and SAR mode. However, as only one operational mode can be used at a given time and as we have the ability to emulate LRM from SAR mode thanks to the reduced SAR mode technique, which results into pseudo-LRM, the mission advisory group and community recommended that Sentinel-3A would operate all over the globe in SAR mode only. This decision was latterly approved by the EU. Currently, it is planned that the SRAL instrument on Sentinel- 3B operate similarly, after a short initialisation phase where LRM mode will be operated for test purposes only.

4.4.2 Tracking modes: Closed Loop and Open Loop

For each pulse emitted, there is a need to anticipate when the radar echo will return and devote the recording time to that period in detail. This means that on-board the satellite, there has to be control over the positioning of the reception window, which for SRAL is 128 waveform bins, each of duration 3.125 ns, giving a total width of 60m. There is some simple predictive software on-board (known as a $\alpha - \beta$ tracker which uses the immediate history of leading edge position to forecast where it should subsequently be, and adjust the positional delay accordingly. This system, using only current altimetry data is termed "closed loop" and has been used on many previous altimeters. However, near the coast, early returns from neighbouring land may confuse the $\alpha - \beta$ tracker, leading to it preferentially recording the echoes from land. As many of the key concerns about sea level rise and changes in current are pertinent in the coastal zone, Sentinel-3 adopts a system to mitigate this problem.

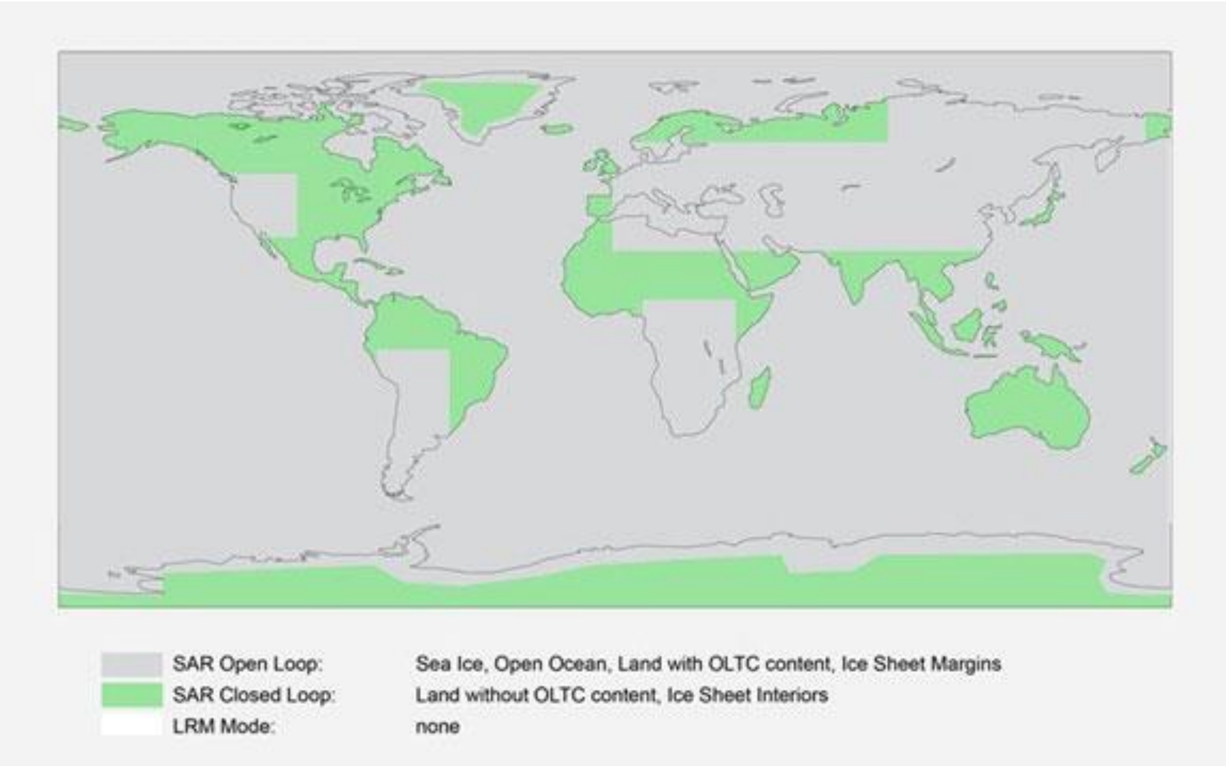

Figure 10: Geographical overview of the use of open and closed modes of operation for retracking.

Instead, Sentinel-3 operates in "open loop" mode over all ocean surfaces and some land surfaces (see figure 10). In this mode extra information, namely the interpolated predictions from a detailed DEM (digital elevation model) are also used in the fixing of the reception window. Such a mode was first pioneered on Jason-2, where it reduced acquisition time from ~2 s to ~0.5 s [RD-9], which can improve the quality of sea surface height data in the coastal zone; in the open ocean, the switch between open and closed mode affected the range information from Jason-2 by only a few centimetres, but made significant differences to the higher order statistics of SWH [RD-13, RD-18]. This is not done globally because over some land surface the current knowledge about elevation on the Sentinel-3A tracks is not reliable to within the necessary tolerance of the on-board tracker. As well as in the coastal zone, open loop operation should be of benefit for measuring water levels in mountain lakes, because the on-board tracker can be commanded to have the reception window at the expected level of the lake.

Parameter	Value
Orbit type	sun-synchronous
Eccentricity	0.001148
Perigee	90.00^o
Inclination	98.65^o
Revisit	27 days (to exact point), 4(2*) days (primary sub-orbit)
Reference orbit	814.5 km
Equatorial crossing	10:00 h Mean Local Solar time (descending pass)
Cycle length	385 orbits
Period	6059 s
Ground track separation	104(52*) km at the Equator

Table 3: Sentinel-3A orbital characteristics. *values factor in S3B.

Open loop operation was also expected to be useful for the margins of the ice sheets, so the initial mode mask for S-3A was set to that around the edges of Greenland and Antarctica. However, in the first year of operation there was poor recovery of radar echoes in these climatically important regions, so the mode masks there has been changed to closed loop, whilst further investigations are performed. Figure 10 shows a map of the current mode mask.

4.4.3 Coverage

Sentinel-3A is in a sun-synchronous orbit with a mean altitude of 815 km, completing 385 orbits (i.e. 770 pole-to-pole tracks) in exactly 27 days. This means that neighbouring tracks run parallel 0.93^o apart (which is 104 km track separation at the Equator). As SRAL is not a swath instrument, a full 27-day cycle is needed for complete coverage, but there is a 4-day sub-cycle giving roughly even global coverage.

When Sentinel-3B is launched it will initially be in a "tandem phase" for close calibration with Sentinel-3A, but will subsequently be moved to a set of tracks interleaving those of Sentinel-3A to give a denser pattern of coverage. Sentinel-3B will retain the orbital characteristics of Sentinel-3A, but $\pm 140^o$ out of phase, as shown in figure 11.

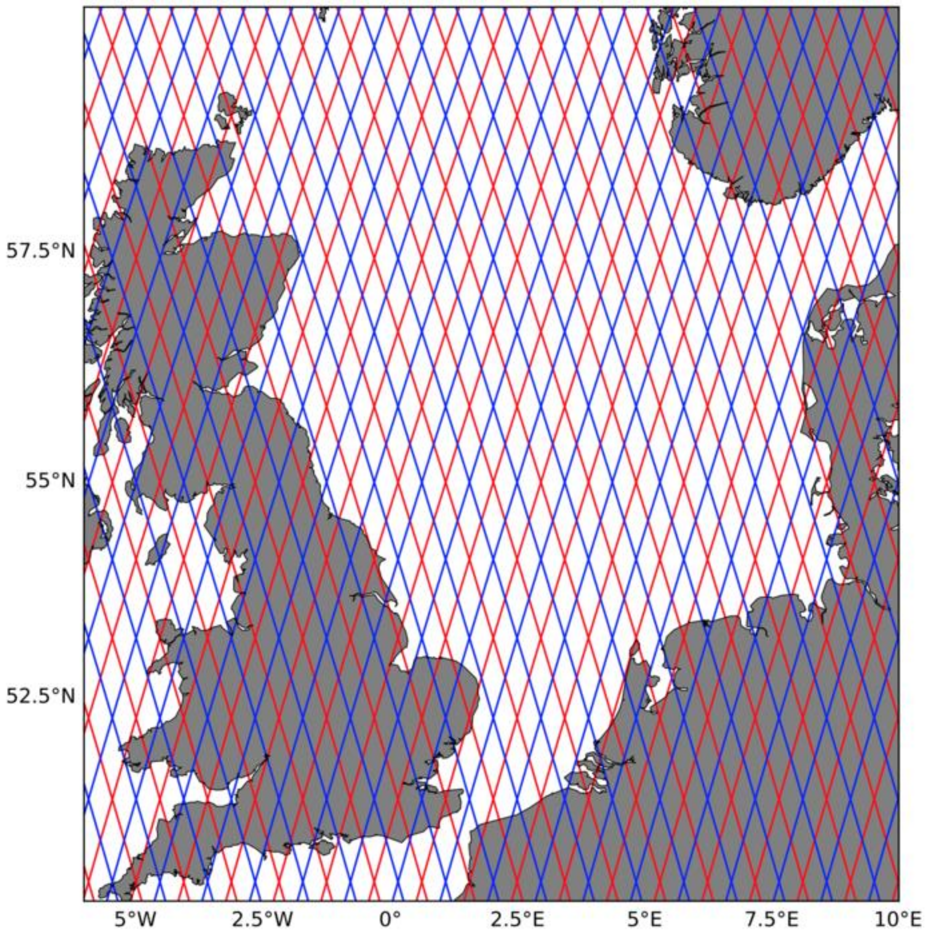

Figure 11: Example coverage of Sentinel-3A (red) and Sentinel-3B (blue) over the UK.

4.5 Calibration and validation activities

Assessment of instrument performance, determination of calibration coefficients and the validation of products are carried out by a large number of scientific research groups. Many of these are members of the Sentinel-3 Validation Team (S3VT), which has subgroups focussing on SRAL, SLSTR, OLCI and Synergy products, and which typically meets once per year providing an important forum for disseminating independent research results. The Sentinel-3 Mission Performance Centre (S3MPC) is a group specifically funded to examine the data on a regular basis reporting promptly on the quality of each cycle of data, and providing recommendations on changes to the processing. This section summarises some of the research findings by the S3MPC.

There are a wide range of calibration/validation activities, ranging from those internal to the instrument to tests for self-consistency of products, and to validation against independent data. More information on these activities can be found in [RD-7].

4.5.1 On-board calibrations

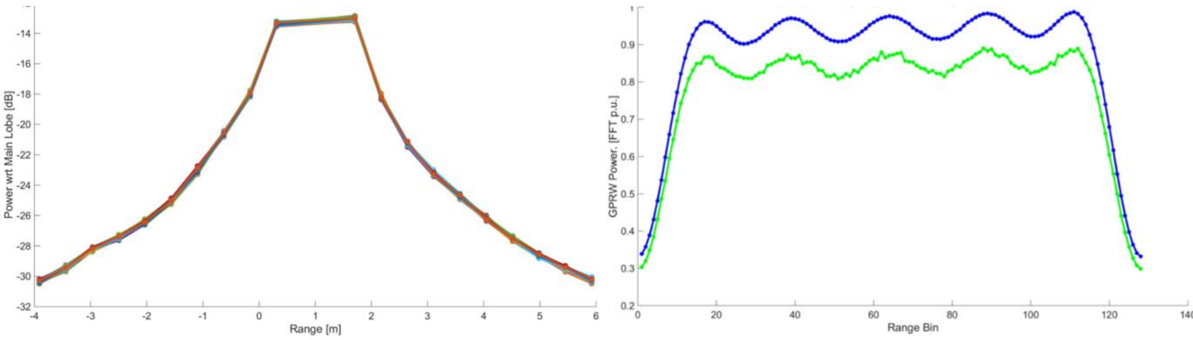

Figure 12: Illustration of the two internal calibration modes for SRAL. (left) CAL1 shows the sidelobe intensities in the Point Target Response. (right) CAL2 shows the shape of the System Transfer Function. (Images produced by isard-SAT.)

The SRAL instrument has two calibration modes. CAL1 sends a reduced amplitude pulse direct from transmitter to receiver chain to examine the characteristics of the pulse, especially the level of the side- lobes, and their positioning. Changes in the intensity of the emitted signal have to be recorded and used to adjust the calculation of σ^o; changes in the position of the main lobe could, if not corrected for, lead to erroneous values for global mean sea level rise. The CAL2 mode records the system transfer function, which is a distortion of the instrument waveforms due to the actual instrument response. To achieve the original echo shape, this effect needs to be corrected for. The CAL2 response is the same for both LRM and SARM, but different at the 2 frequencies, Ku- and C-band (see figure 12). There is also monitoring of the Ultra Stable Oscillator (USO) which governs the chirp generation, the timing of pulses and controls the acquisition time for the echo. Thus, knowledge of its precise value is critical to the determination of altimeter range, such that any unmonitored drift could be misinterpreted as a global change in sea level.

The MWR uses a noise-injection diode as a reference for its records of brightness temperature. The temperature of these diodes (one for each of the MWR channels) is monitored several times per day, along with the gain (the proportionality constant linking observations to temperatures).

4.5.2 Consistency checks

The SRAL and MWR data are regularly compared with their previous records (to detect any effect of changes in processing or to monitor long-term changes in instrument characteristics). For example, the probability distribution functions of SWH, σ^o and wind speed are compiled for every 27-day cycle, with the mean and standard deviation assessed on a daily basis. Similarly, the MWR brightness temperatures are monitored over hot and cold reference targets (see Figure 13). For these analyses, multiple other radiometers are also considered in order to discern whether the changes noted for the Sentinel-3 MWR are consistent with variations in the reference as recorded by other instruments.

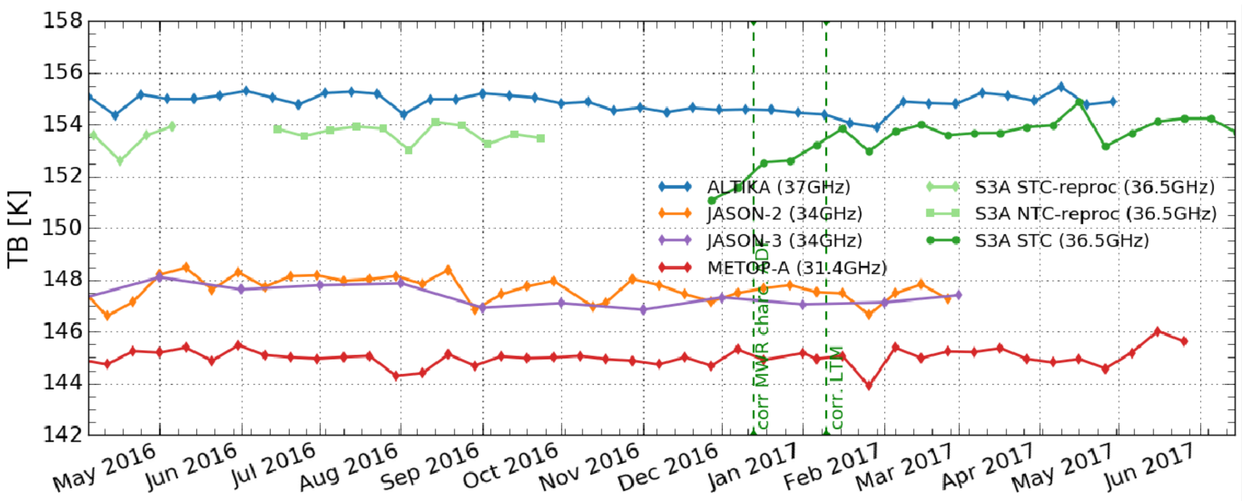

Figure 13: Illustration of the time series of the vicarious cold reference temperatures observed over the reference site for the 36.5 GHz channel. (Image produced by M.L. Frery, CLS.)

Furthermore, some validation is achieved by comparing with other sensors, although divergent behaviour does not necessarily indicate which is in error. For example, gridded maps of SLA and SWH are routinely compared with those from Jason-3 (albeit that this does not cover the same latitudinal extent). As many satellite and other sources of data are regularly assimilated into numerical weather models, these can also be used as a reference to identify regional errors. Not only are the wind and wave data from SRAL compared with ECMWF output, but also the correction terms from the radiometer can be compared too.

4.5.3 Direct Comparisons

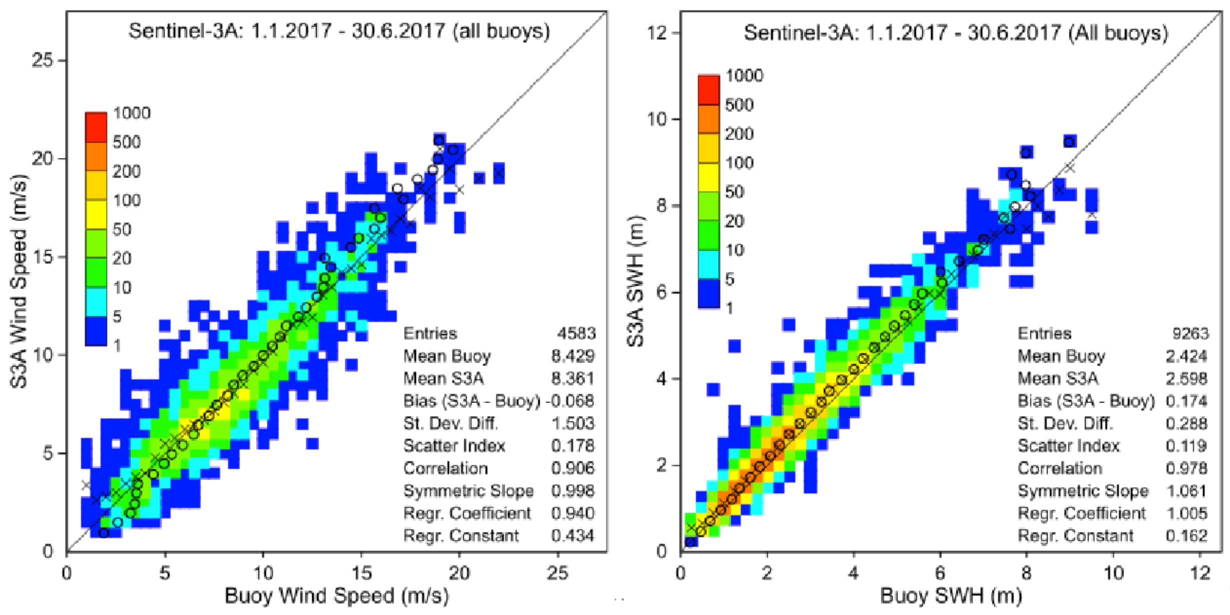

Figure 14: Scatterplots comparing in situ measurements from buoys, ships and other platforms to records from SRAL. (left) Significant Wave Height. (right) Wind Speed. (Images produced by S. Abdalla, ECMWF.)

The wind speed and wave data produced by SRAL are regularly compared with collocated measurements from a network of meteorological buoys. Typically, the standard deviation of the differences is around 1.5 ms $^{-1}$ for u_{10} and 0.3 m for SWH.

Validation of the range measurement is performed over well-constrained surface that have been accurately surveyed by GPS. One validation site is Gavdos (south of Crete) where a radar transponder (active reflector) has been placed on a Sentinel-3A track. The second site is the Mediterranean south-west of Corsica, which has already been surveyed for previous altimetry missions. The third site is Lake Issyk-kul, the second largest mountain lake, which is crossed by two Sentinel-3A tracks, and provides a water surface free from significant waves (and thus no sea state bias).

4.5.4 Validation over Sea-Ice

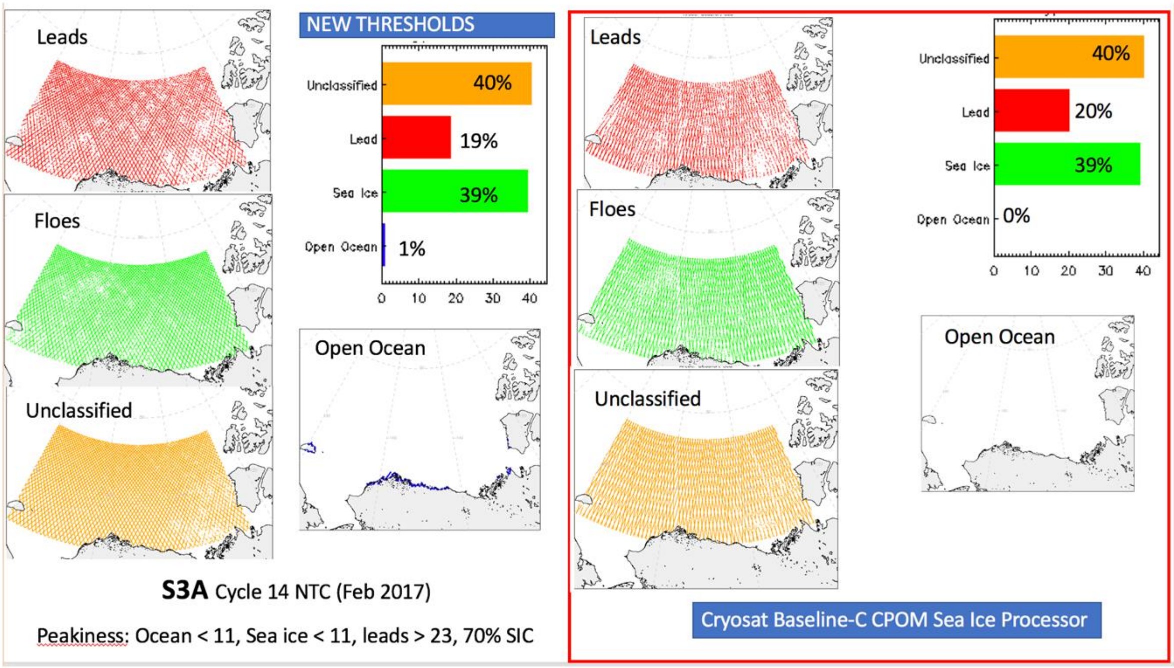

Figure 15: Comparison of waveform classification for Sentinel-3A (left) and Cryosat-2 (right) for February 2017. Note the track orientations are different due to the satellites different orbit inclinations. [Image produced by UCL/U. of Leeds.]

The SRAL data need separate validation over sea-ice, because the different waveform shapes have necessitated different retrackers and editing criteria. Gathering sufficient *in situ* data for a validation is challenging, thus most effort at the moment concerns the discrimination of leads within the ice floes. Validation activities in the cryosphere make use of dedicated research aircraft flights as part of Operation IceBridge, comparisons with ice floe detection by near-coincident SAR imagery, and evaluation of the statistics on percentage of leads in comparison to those from the SAR altimeter on Cryosat [RD-17].

Figure 15 shows the separate classification of waveforms received by both Sentinel-3A and Cryosat for a section of the Arctic during February 2017. As some of the processing options for Sentinel-3A and Cryosat differ, it was necessary to tune a few of the thresholds in the classification procedure in order to get a similar correspondence of the different classes. Further assessment of this classification, by comparison with S-1 SAR imagery will be performed for boreal winter 2017/2018. Waveforms identified as 'leads' may then be further processed to give sea surface height (SSH) in the Arctic, and enable studies of freshwater storage and changes in circulation (REF: Giles et al). Waveforms identified as 'floes' represent a measure of the top of the ice. These can be references to an expected SSH (from interpolation of the records from leads) to give the freeboard. By assuming values for the ice density and the depth of the snow layer, the thickness of the ice may be inferred. Reliable records for Arctic SSH and freeboard should be available in the datasets produced in 2018 onwards.

5 PROCESSING LEVELS AND SCHEMES

5.1 Processing levels

There are different data products associated with the three levels of processing of altimeter data:

- Level 0 is the raw telemetered data, dated and with initial geolocation.
- Level 1 is the Level 0 data corrected for instrument and geometric effects. This may be broken into multiple steps, with associated products, e.g. Level 1A, Level 1B-S, and Level 1B.
- Level 2 is the Level 1B data corrected for geophysical effects.

A flow chart showing the progress through each processing level is shown in figure 16.

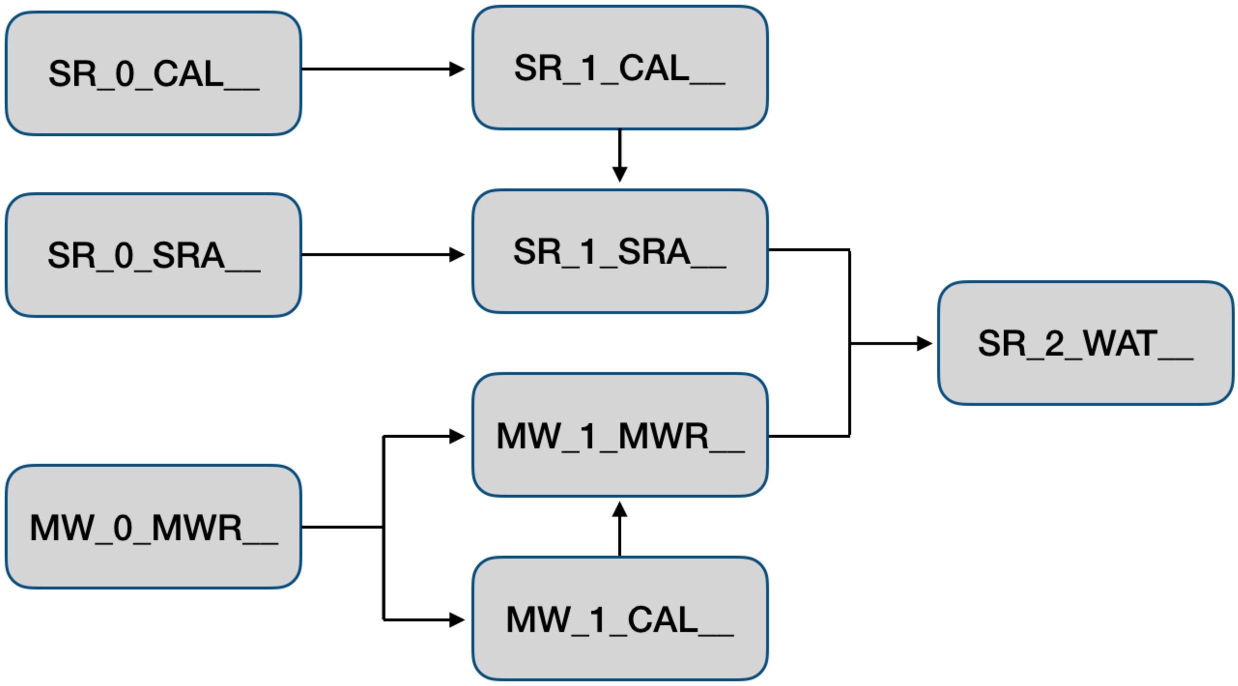

Figure 16: SRAL processing chain. The Level 1 scientific products (SR_1_SRA) and Level 2 marine scientific products (SR_2_WAT) are available to users. The Level 0 scientific products (SR_0_SRA), the SRAL calibration products (SR_0_CAL and SR_1_CAL) and the MWR products (MW_0_MWR, MW_1_MWR and MW_1_CAL), are not available to users and are considered only as an input to the relevant processing chains.

More information on these processing levels can be found in the following sections, along with discussions of the steps performed in each chain.

5.1.1 Level 0

The input data for Level 0 processing is the Instrument Source Packet (ISP). The ISP contains raw data expressed in instrument engineering units, which are not in international system (SI) units. The first function of the Level 0 processing chain is to extract and decode the raw ISP data and convert it to SI units. The second function of the Level 0 processing chain is to correct the date and time of the measurements and to locate these measurements on the Earth (satellite position and measurement location on the Earth's surface). Thirdly, the Level 0 processing chain prepares Level 0 calibration parameters for use in the Level 1 processing chain. Level 0 products are not made available to the community.

5.1.2 Level 1

The input data for Level 1 processing are the Level 0 products. The main function of the Level 1 processing chain is to calculate the tracker range, the sigma0 scaling factor and the Level 1 waveforms, applying instrumental corrections to all of them. The Level 1 processing chain outputs three types of products: Level 1A, Level 1BS and Level 1B products.

- Level 1A products contain geolocated bursts of echoes with all instrument delay calibrations applied. *Note: Gain calibrations are supplied in Level 1A products, but they have not yet been applied (see section 5.2.1).*
- Level 1B-S products contain SAR-processed and fully calibrated high-resolution complex echoes, arranged in stacks after saint range correction, but prior to echo multi-look.
- Level 1B products contain geolocated, multi-looked, and fully calibrated high-resolution power echoes.

5.1.3 Level 2

The input data for Level 2 processing are the Level 1B products. The first function of the Level 2 pro- cessing chain is to apply different re-tracking algorithms to the Level 1B waveforms to calculate the final altimeter range, backscatter coefficient, wind speed over the ocean and SWH. There are different types of re-tracking algorithms, which are used according to the type of waveforms that are being re-tracked (ocean, ice, sea-ice). The second function of the Level 2 processing chain is to compute and apply all geophysical corrections to the measurements. Examples of geophysical corrections are corrections for tides and establishing the reference surface used (e.g. the geoid).

The Level 2 processing chain requires the following inputs (which are exploited as shown in figure 17):

- Level 1B SRAL product
- Level 1B MWR product

5.1.4 Level 2P products

The Level 2P ("Processed") products are along-track products that contain time, sea level anomaly, information of validity of the data and all corrections which were necessary to compute the sea level anomaly (range, orbital altitude, environmental and geophysical corrections). These products contain only marine surfaces. They have a homogenized format and content for all altimeter missions. Note that the variable inter-mission-bias can be different between Level 2P NRT/STC and Level 2P NTC data. Level 2P products are the input data for the Level 3 production. Note that the sea level anomaly considered in Sentinel-3 Level 2P products is always based on Synthetic Aperture Radar (or if not avail- able on Low Resolution Mode) data, but never on Pseudo LRM data. *[Note: NRT, STC, NTC refer to near real-time, slow time critical and non-time critical data latencies, respectively. The logic under- pinning this terminology is discussed below.]* The Level 2P products are processed by the Sentinel- 3 Level 2P/Level 3 Marine Altimetry Service (CNES/CLS), under a EUMETSAT contract framework. The products are available through AVISO+ (all latencies), and EUMETCAST (NRT/STC). In the future data will be also available through CODA and the Data Centre (UMARF) under a EUMETSAT contract framework funded by the EUROPEAN UNION. For any further information on Level 2P please refer to https://www.eumetsat.int/website/home/News/DAT_3525999.html?lang=EN&pState=1.

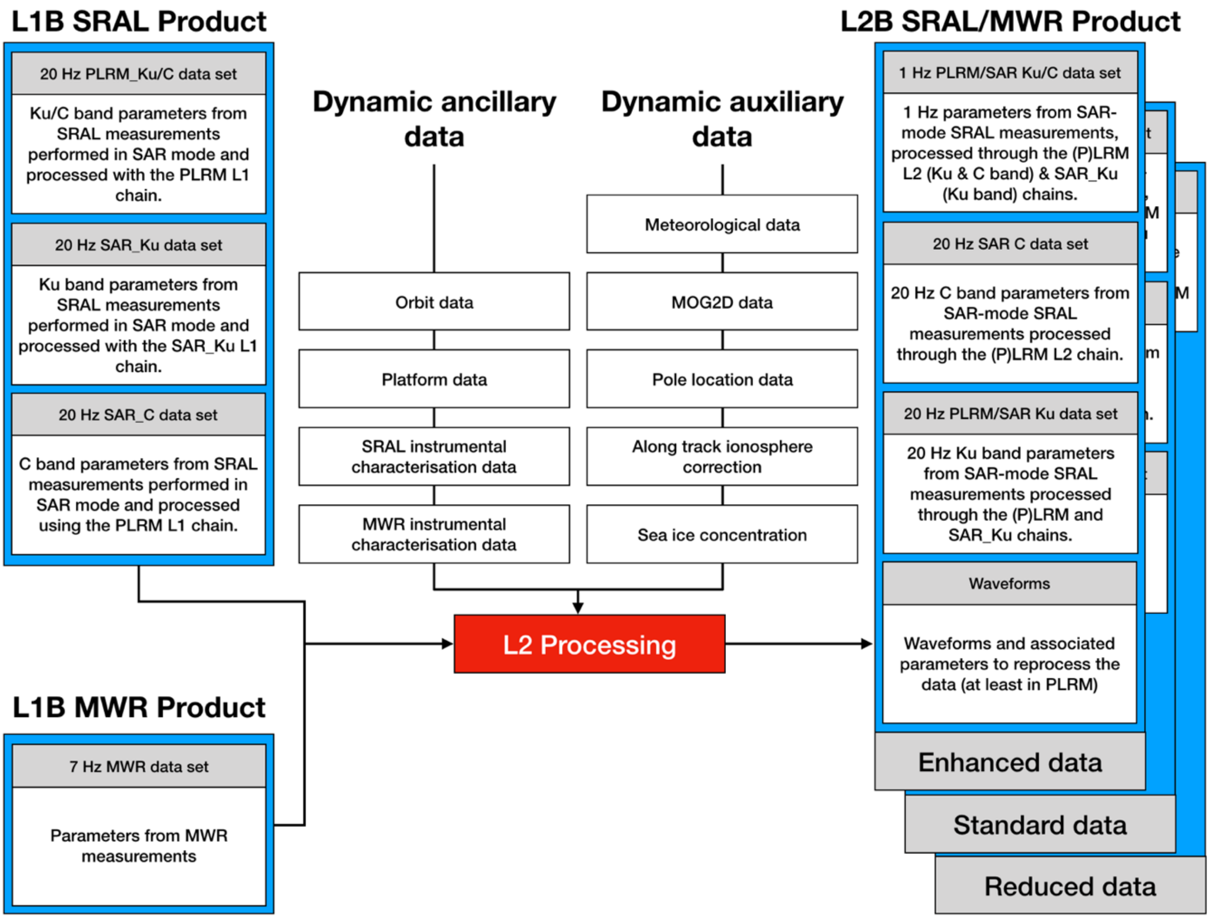

Figure 17: SRAL Level 2 processing inputs and outputs.

5.1.5 Level 3 product links

Level 3 along-track products ingest data from multiple altimetry missions, and, as such, fall beyond the scope of this document. Although no discussion of Level 3 products will be presented here, multi- mission products hold great relevance for many users, and more information on them can be found via the following resources:

- AVISO SSALTO/DUACS Multi-mission processing
- Copernicus Marine and Environmental Monitoring Service (CMEMS)

Product	*Latency*	*Improvements*	*Usage*
NRT	<3 hours		• marine meteorology • ocean-atmosphere gas transfer studies • ocean forecasting
STC	<48 hours	Consolidation of auxiliary and ancillary data during the available STC processing time-window allows for a more robust restitution of orbital data, resulting in lower measurement errors than in the NRT product.	• geophysical studies • operational oceanography • ocean forecasting
NTC	~ 1 month	Incorporating further auxiliary/ancillary data allows for more precise orbit determination and lower errors than in the STC product.	• geophysical studies • operational oceanography • climatology

Table 4: Product latency types, with associated improvements and usages.

5.1.6 Latency

Latency refers to the delay between the time of data acquisition and the availability of a product at a given level. Longer latency allows for the incorporation of additional auxiliary and ancillary data that allows, for example, for improved determination of the orbit, the platform or wet and dry tropospheric correction. Consequently, there is invariably there is a trade-off between timeliness and final accuracy of the product at each level. Additionally, some Level 2 parameters depend on additional auxiliary and ancillary, and so are not available at shorter latencies. There are three levels of latency for Sentinel-3 altimetry products:

- Near Real-Time (NRT): delivered less than 3 hours after data acquisition.
- Slow Time Critical (STC): delivered within 48 hours after data acquisition.
- Non-Time Critical (NTC): delivered within typically 1 month after data acquisition.

The improvements made to products at each level of latency, and their level of use is summarised in table 4. The latency at which each product level is available, and the access platforms for these products, is summarised in table 5.

Product	*EUMETCAST*	*CODA*	*Data Archive*
Level 1A	–	STC, NTC	STC, NTC
Level 1B-S	–	STC, NTC	STC, NTC
Level 1B	NRT, STC	NRT, STC, NTC	NRT, STC, NTC
Level 2	NRT, STC	NRT ,STC, NTC	NRT, STC, NTC

Table 5: Overview of product availability by latency, and where the data can be accessed. Product Dissemination Units

Sentinel-3 User Products are disseminated in Product Dissemination Units (PDU), in order to ease the online dissemination and data handling. Users should also note that the PDUs for NRT, STC and NTC products differ in coverage. Offline product chains, i.e. those associated with the STC and NTC chains, deliver products in half-orbit PDUs; e.g. one file contains one half orbit for each product, irrespective of level. In the original product definitions, PDUs for NRT products were set at 'dump', a full orbit per file. In the new definitions, this has subsequently been refined such that NRT products are delivered in 10 minute stripes. More details on PDU definitions can be found in the in the Sentinel-3 Payload Data Ground Segment Products Definition Document.

5.2 Processing schemes

5.2.1 Level 0 processing steps

During the Level 0 processing, the satellite sends all data measured to the ground stations in the form of Instrument Source Packets (ISP). The data in ISPs are categorised as either a science or a calibration product and packaged according to their type:

- TM_ACQ: telemetry packets generated during acquisition mode
- TM_CAL1: telemetry packets generated during CAL1 calibration mode
- TM_CAL2: telemetry packets generated during CAL2 calibration mode
- TM_ECHO_LRM: telemetry packets generated during LRM tracking mode
- TM_ECHO_SAR: telemetry packets generated during SAR tracking mode

The Level 0 processor also translates the packaged data from engineering units (as transmitted in the ISP) into SI units for further processing. Although date and preliminary geolocation is applied to the Level 0 science products, this requires correction in the Level 1 processing stage. Level 0 CAL1 products (L0_CAL1_LRM_IQ, L0_CAL1_SAR) are used to characterise instrument delay in the Level 1 processor. Level 0 CAL2 products (L0_CAL2_SAR) are used to characterise instrument gain.

5.2.2 Level 1 processing steps

Note: The following sections, and parts of section 6, discuss the processing steps and products that are relevant to the Level 1 processor. The reader should be aware that, while discussion of the LRM processor is presented, during normal operating procedure Sentinel-3 operates exclusively in high resolution SAR mode for the Ku band. Discussions of LRM are retained as Sentinel-3B (and presumably C and D) will, post-launch, operate temporarily in LRM mode during their pre-operational phase. It is also possible that any of the Sentinel-3 satellite series may revert to LRM mode in the case of an operational disturbance to SAR mode. Text concerning LRM mode is presented as grey text to underline this point. The PLRM mode is now used for processing the C band.

There are three Level 1 processing chains:

- Level 1 SAR_Ku processing chain. This computes and applies the main corrections for a SAR mode processing for the Ku band.
- Level 1 LRM processing chain. This is a conventional altimetry processing chain and all algorithms involved are similar to the algorithms applied to other conventional altimetry missions such as Envisat or Jason-2. **As Sentinel-3A operates exclusively in SAR mode, LRM is not routinely used**
- Level 1 PLRM processing chain. This is very similar to Level 1 LRM processing chain algorithms but applied to Level 0 SAR input data. In the PLRM chain, a new algorithm is used to convert SAR Ku band waveforms to LRM-like waveforms, as well as process SAR C band waveforms.

Figure 18, and figure 19 show the respective processing steps for the Level 1 PLRM and SAR_Ku chains. More information on each step of the Level 1 processing stages for each chain can be found in the Sentinel-3 Altimetry technical guide, here. Note that the Level 1 outputs are processor dependant. More information on the products generated via each chain is given in the **SENTINEL-3 ALTIMETRY PRODUCT AND FILE TYPES** section of this document.

At Level 1, all calibration corrections are applied or supplied. This is performed as follows:

- Internal instrument calibrations (CAL1) depend on the Level 0 CAL1 parameters for the relevant mode (LRM or SAR_Ku). In the SAR_Ku processing chain, the calibration is performed prior to the generation of Level 1A products (figure 19).
- Gain profile range window calibrations (CAL2) depend on the Level 0 CAL2 parameters. In the SAR_Ku processing chain, the calibration is performed prior to the generation of Level 1A products.

- Automatic Gain Control (AGC) correction tables calibrations. These are generated in the Level 1 CAL1 routines. In the SAR_Ku processing chain, the AGC calibration is applied prior to the generation of Level 1A products.

Figure 18 and figure 19 show when the various calibrations are supplied and applied.

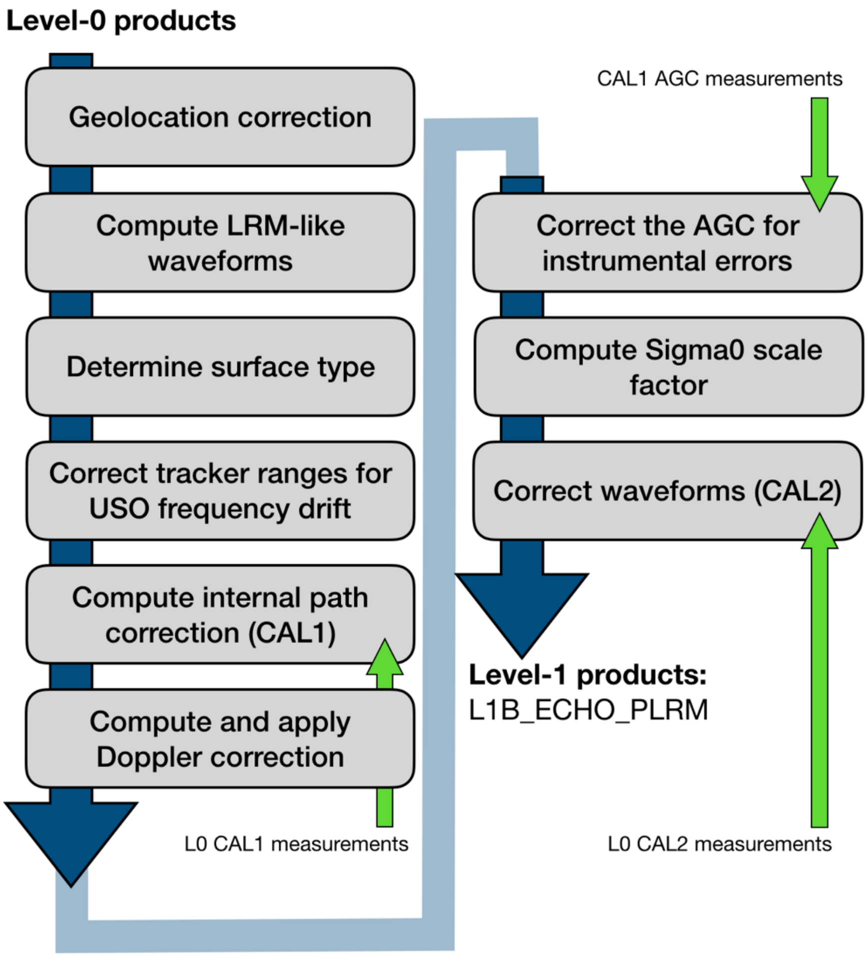

Figure 18: Level 1 processing steps for the PLRM chain.

5.2.3 Level 2 processing steps

The Level 2 processor performs 3 tasks:

- Stage 1: Computing time-derived geophysical/environmental parameters
- Stage 2: Performing re-tracking and compute physical parameters
- Stage 3: Computing Level 2 altimeter/radiometer geophysical processing

The approach to retracking and computing physical parameters (Stage 2) differs, depending on which mode (LRM or SAR_Ku) has been used in the Level 1 processor. The processes undertaken in each step of the chain and shown in figure 20.

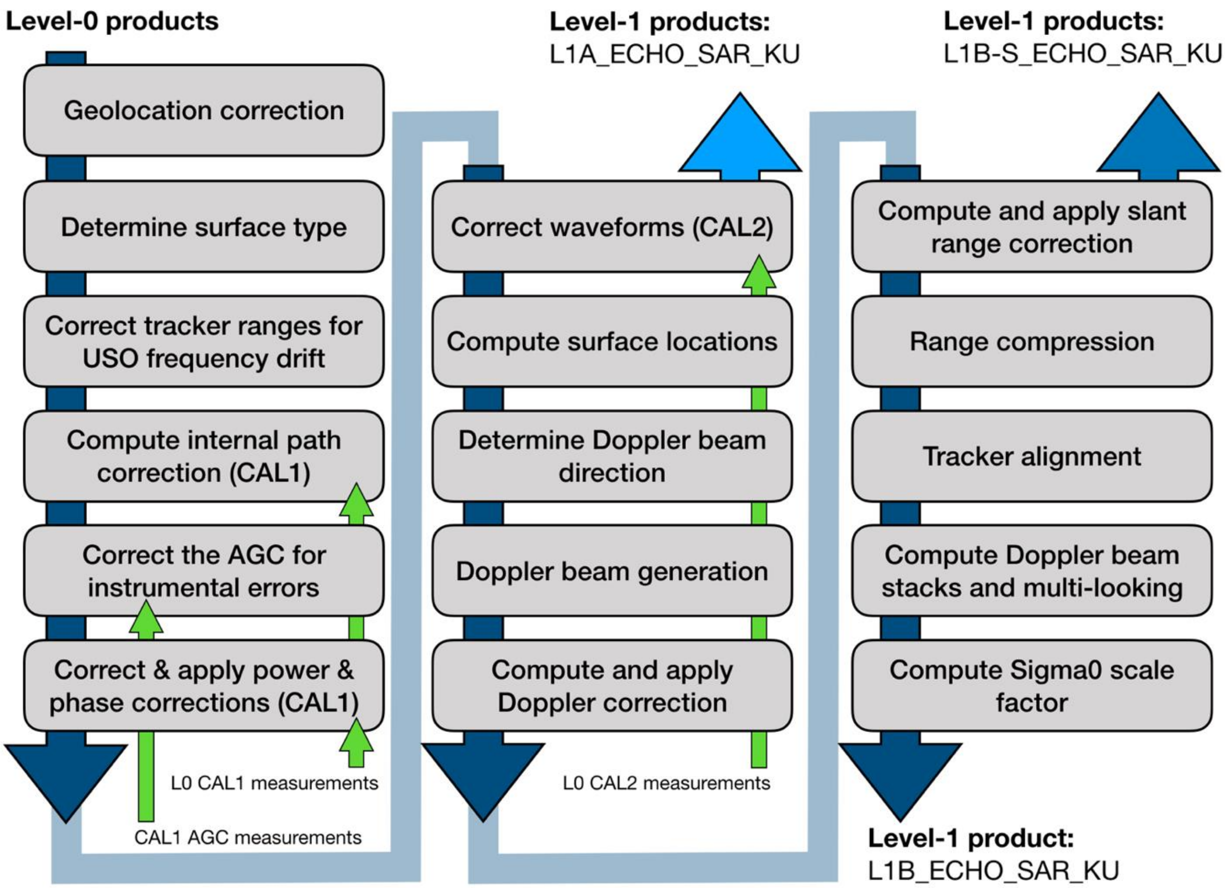

Figure 19: Level 1 processing steps for the SAR_Ku chain.

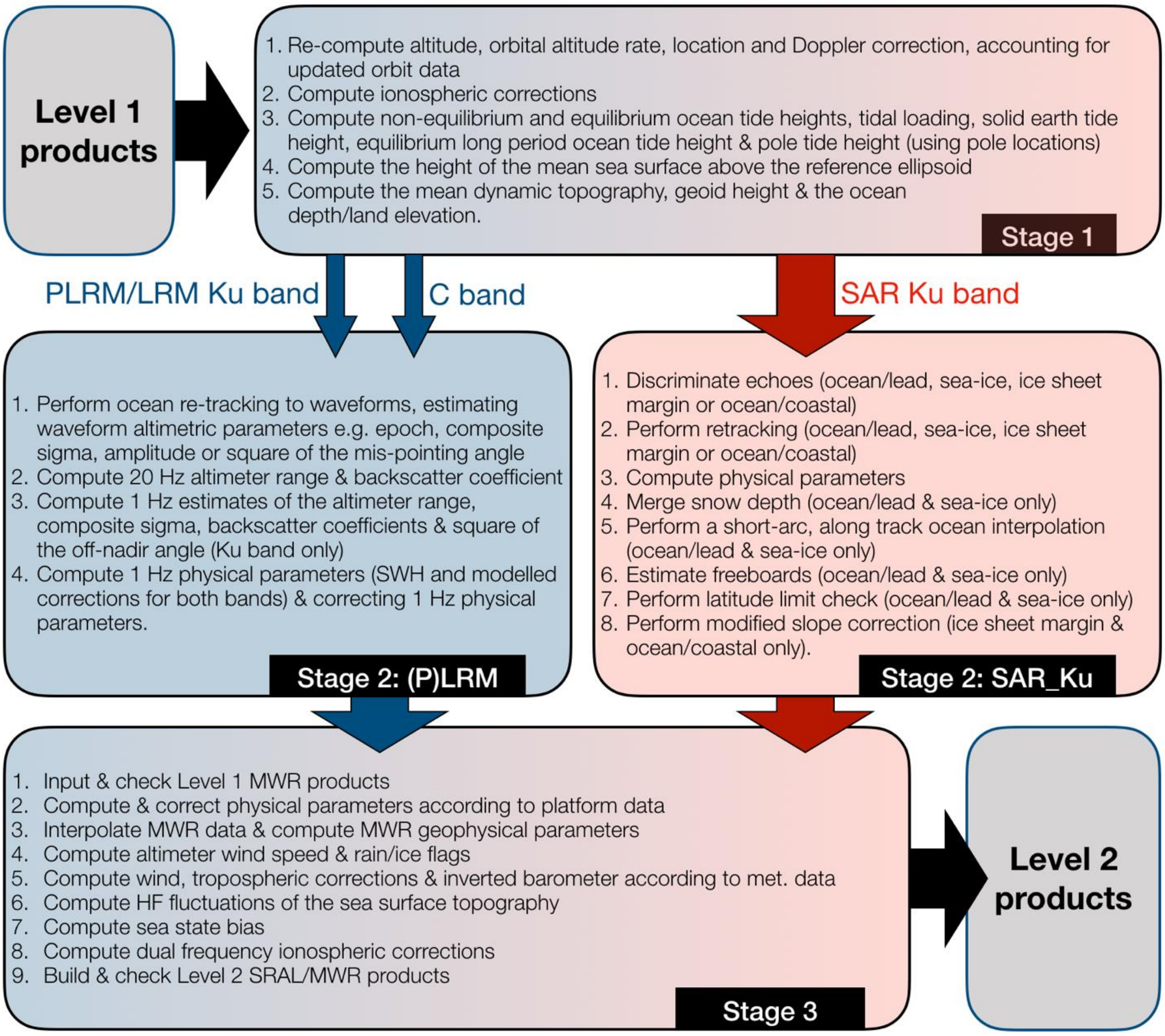

Figure 20: Level 2 processing steps.

6 SENTINEL-3 ALTIMETRY PRODUCT AND FILE TYPES

6.1 Product Levels

6.1.1 Level 0

No Level 0 products are distributed.

6.1.2 Level 1

Five Level 1 products are distributed:

- **L1B_ECHO_SAR_Ku**: L1 Tracking measurements in SAR mode - Ku band (20 Hz)
- **L1B-S_ECHO_SAR_Ku**: L1 Tracking measurements in SAR mode - Ku band (20 Hz)
- **L1A_ECHO_SAR_Ku**: L1 Tracking measurements in SAR mode - Ku band (20 Hz)
- **L1B_ECHO_LRM**: L1 Tracking measurements in LRM mode - (20 Hz Ku and C bands)
- **L1B_ECHO_PLRM**: L1 Tracking measurements in pseudo-LRM mode - (20 Hz Ku and C bands)

Level 1A products contain geolocated bursts of echoes with all calibrations applied. Level 1BS products contain fully SAR-processed and calibrated high-resolution complex echoes arranged in stacks after range correction and prior to echo multi-look. Level 1B products contain geolocated and fully calibrated multi-looked high-resolution power echoes. Figure 18 and figure 19 show the points in the Level 1 processing chain where these products are generated for the LRM, PLRM and SAR_Ku processing chain, respectively. Level 1A, Level 1BS and Level 1B products are collected together, and are made available separately according to a file naming convention outlined later in the File naming section. Each product contains a directory with an *"xdfumanifest.xml"* file and a *"measurement.nc"* file. A description of the format and function of these files can be found in the Data Formats section, below.

Note: while LRM variables may appear to be present in the netCDF Level 1B products, the variables themselves are typically empty as SRAL operates exclusively in SAR mode. See section 5.2.2.

6.1.3 Level 2

A single Level 2 product is distributed. This contains the outputs from both the Level 2 SAR_Ku and LRM processing branches (figure 20), organised into separate Reduced, Standard and Enhanced files, which contain:

- Reduced: Low resolution (1 Hz) measurements, with corrections and flags.
- Standard: Low (1 Hz) and high (20 Hz) resolution measurements, with corrections and flags.

- Enhanced: As in standard mode, but also including the waveforms.

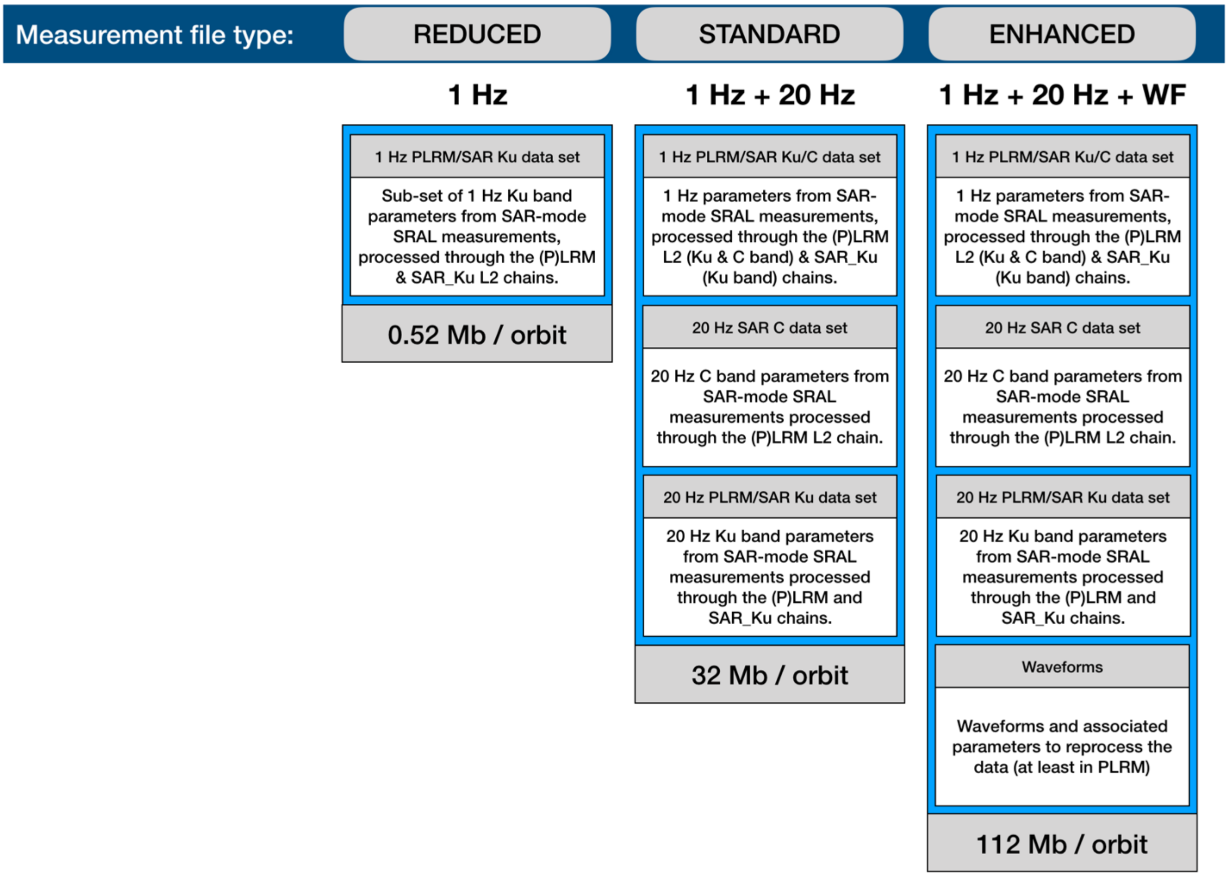

Figure 21: Level 2 SRAL product manifest.

Each file contains the geophysical variables that correspond to the relevant frequency. Figure 21 presents an overview of the contents of each product, and their approximate size per file. The three products are contained within three individual netCDF files with the zipped Level 2 product directory.

6.1.4 Level 2P

Level 2P products are currently disseminated by [AVISO+](). A thorough description of the processing stages used in the development of these products, and the file structure of the eventual product can be found in the [AVISO L2P Product Handbook](). Plans to make these products available through EUMETCast and CODA are currently under consideration.

6.2 Latency and Level 2 product accuracy

As discussed in section 5.1.6, Level 2 altimetry products are made available according to the level of urgency that is required, the level of processing that needs to be undertaken, and the availability of auxiliary and ancillary data to allow for more precise orbital determination. Table 6 describes the acceptable level of error altimeter height estimation at each product latency (NRT, STC and NTC).

Parameter	NRT	NRT	STC	STC	NTC	NTC
	Requirement	Goal	Requirement	Goal	Requirement	Goal
Range Noise (cm)	3.0	2.0	3.0	2.0	3.0	2.0
Sea State bias (cm)	5.0	2.0	3.0	2.0	2.0	1.4
Ionosphere (cm)	3.0	2.0	1.4	1.0	1.0	0.7
Dry Troposphere (cm)	3.0	2.0	1.4	1.0	1.4	1.0
Wet Troposphere (cm)	4.0	3.0	2.0	1.4	1.0	1.0
RSS Range Error (cm)	8.3	6.0	5.0	3.5	4.1	2.9
Radial Orbit Error (cm)	10.0	8.0	4.0	3.0	3.0	2.0
RSS SSH Error (cm)	13.0	10.0	6.5	4.6	5.1	3.5

Table 6: Major error terms for altimeter height estimation. All data in this table are derived using a 1 Hz integration time and a 2 m Hs. (Reference: ESA)

6.3 Data formats

6.3.1 The SAFE format

Sentinel-3 altimetry data products are distributed using a SENTINEL-specific variation of the Standard Archive Format for Europe (SAFE) format specification. All the information relevant to the product is gathered into a single package. Inside this package, the specific objects containing measurement data are encoded in NetCDF format, and are referenced via a xdfumanifest.xml file.

The SENTINEL-SAFE format has been designed to act as a common format for archiving and conveying data within ESA Earth Observation archiving facilities. SENTINEL-SAFE is based on the XML Formatted Data Units (XFDU) standard under development by the Consultative Committee for Space Data Systems (CCSDS). SENTINEL-SAFE is a profile of XFDU, and it restricts the XFDU specifications for specific utilisation in the EO domain, providing semantics in the same domain to improve interoperability between ground segment facilities.

6.3.2 NetCDF

SRAL products are supplied in the NetCDF format (version 4). The NetCDF format is extremely flexible, self-describing and has been adopted as a de-facto standard for many operational oceanography systems. For practicality, the files follow Climate and Forecast NetCDF convention (CF-1.4) metadata standards.

A NetCDF file contains named dimensions, variables and attributes. These components can be used together to capture the meaning of data and relationships between data fields in an array-oriented data set.

A dimension may be used to represent a real physical dimension, for example, time. A dimension might also be used to index other quantities, for example, waveforms index.

Variables are used to store the majority of data in a NetCDF file. A variable represents an array of values of the same type. A scalar value is treated as a zero-dimensional array. A variable has a name, a data type and a shape described by its list of dimensions, specified when the variable is created. A variable may also have associated attributes which may be added, deleted or changed after the variable is created.

NetCDF attributes are used to store information about the data (ancillary data or metadata) and are similar in many ways to the information stored in data dictionaries and schema in conventional database systems. Most attributes provide information about a specific variable. These are identified by the name of that variable, together with the name of the attribute.

Below is an example of the header from a "reduced" Level 2 product. The output was generated using the 'ncdump' tool, with the '-h' option to only display header information. The output has been truncated.

```
netcdf reduced_measurement (
dimensions:
time_01 = 1784 ;
variables:
double time_01(time_01) ;
  time_01:long_name = "UTC: 1 Hz" ;
  time_01:units = "seconds since 2000-01-01 00:00:00.0" ;
 time_01:standard_name = "time" ;
  time_01:calendar = "gregorian" ;
short UTC_day_01(time_01) ;
  UTC_day_01:long_name = "day UTC : 1 Hz" ;
  UTC_day_01:units = "days since 2000-01-01 00:00:00.0" ;
double UTC_sec_01(time_01) ;
  UTC_sec_01:long_name = "Second in the day UTC : 1 Hz" ;
  UTC_sec_01:units = "seconds in the day" ;
int lat_01(time_01) ;
  lat_01:long_name = "latitude : 1 Hz" ;
  lat_01:units = "degrees_north" ;
  lat_01:standard_name = "latitude" ;
  lat_01:add_offset = 0. ;
  lat_01:scale_factor = 1.e-06 ;
  lat_01:comment = "Positive latitude is North latitude, negative latitude is South latitude" ;
int lon_01(time_01) ;
  lon_01:long_name = "longitude : 1 Hz" ;
  lon_01:units = "degrees_east" ;
  lon_01:standard_name = "longitude" ;
  lon_01:add_offset = 0. ;
  lon_01:scale_factor = 1.e-06 ;
  lon_01:comment = "East longitude relative to Greenwhich meridian" ;
byte surf_type_01(time_01) ;
  surf_type_01:_FillValue = 127b ;
```

 surf_type_01:long_name = "surface type : 1 Hz" ;
 surf_type_01:flag_values = 0b, 1b, 2b, 3b ;
 surf_type_01:flag_meanings = "ocean_or_semi_enclosed_sea ....
....
.... *(a significant number of other variables)*
.... // global attributes:
....
....end of file

6.4 File naming

The SRAL/MWR Level 2 product file name is defined according to the following convention:

MMM_SS_L_TTTTTTT_yyyymmddThhmmss_YYYYMMDDTHHMMSS__YYYYMMDDTHHMMSS_<instance ID>_GGG_<class id>.<extension>

- **MMM**: mission ID: (e.g. S3A for SENTINEL-3A mission, S3B for SENTINEL-3B mission, S3_ for both SENTINEL-3A and SENTINEL-3B missions).
- **SS**: data source for the instrument data (e.g. SR for SRAL, DO for DORIS, MW for MWR and GN for GNSS) or the data consumer of the auxiliary data (e.g. AX for multi instrument auxiliary data).
- **L**: processing level: one digit or one underscore "_" (e.g.: "2" for Level 2 products, "1" for Level 1 products, "0" for Level 0 products or underscore "_" if processing level is not applicable).
- **TTTTTTT**: data type ID:
    - Level 2 SRAL data: "LAN____" for Land products and "WAT____" for water products.
    - Level 1A SRAL data: "SRA_A__" for SAR Ku products.
    - Level 1BS SRAL data: "SRA_BS_" for SAR Ku products.
    - Level 1B SRAL data: "SRA____" for LRM, SAR Ku and SAR C products and "CAL____" for calibration products.
    - The last 2 digits suffix indicates "AX" for an auxiliary data and "BW" for a browse product.
- **yyyymmddThhmmss**: Data Start time.
- **YYYYMMDDTHHMMSS**: Data Stop time.
- **YYYYMMDDTHHMMSS**: the creation date of the product
- **<instance ID>**: DDD_CCC_LLL_____, either upper-case letters or digits or underscores "_".
    - DDDD: orbit duration Sensing data time interval in seconds.
    - CCC: cycle number at the start sensing time of the product.
    - LLL: relative orbit number within the cycle at the start sensing time of the product.
    - 4 underscores "_".
- **GGG**: product generating centre: three characters (e.g. "LN3" for Land Surface Topography Mission Processing and Archiving Centre and "MAR" for Marine Processing and Archiving Centre).

- **<class id>**: platform, eight characters, either upper-case letters or digits or underscores: P_XX_NNN, where:
  - P = one upper-case letter indicating the platform (e.g. O for operational, F for reference, D for development, R for reprocessing or one underscore"_" if not relevant).
  - XX = two upper-case letters/digits indicating the timeliness of the processing workflow (e.g. NR for NRT, ST for STC, NT for NTC or two underscores"__" if not relevant).
  - NNN: three letters/digits. Free text for indicating the baseline collection (001, 002,... .) or data usage(e.g. test, GSV, etc.) or three underscores"_" if not relevant.
- **<extension>**: the adopted filename extension is "SEN3"

7 HELPDESK, PRODUCT DISSEMINATION AND TOOLS

7.1 Helpdesk

The EUMETSAT User Helpdesk is available to all users during standard office hours. The service provides support on data access and product usage and application. All user requests on the EUMETSAT OLCI Marine data products should be directed to the EUMETSAT Help Desk ops@eumetsat.int.

7.2 Data access routes

EUMETSAT provides data access through a number of routes, depending on your preferred delivery route and the latency of the data that's needed. The central catalogue in the first tier / row of figure 22 and table 7 lists all EUMETSAT missions (Meteosat, Metop, and Jason-2) in addition to the Copernicus Sentinel-3 marine and atmosphere products.

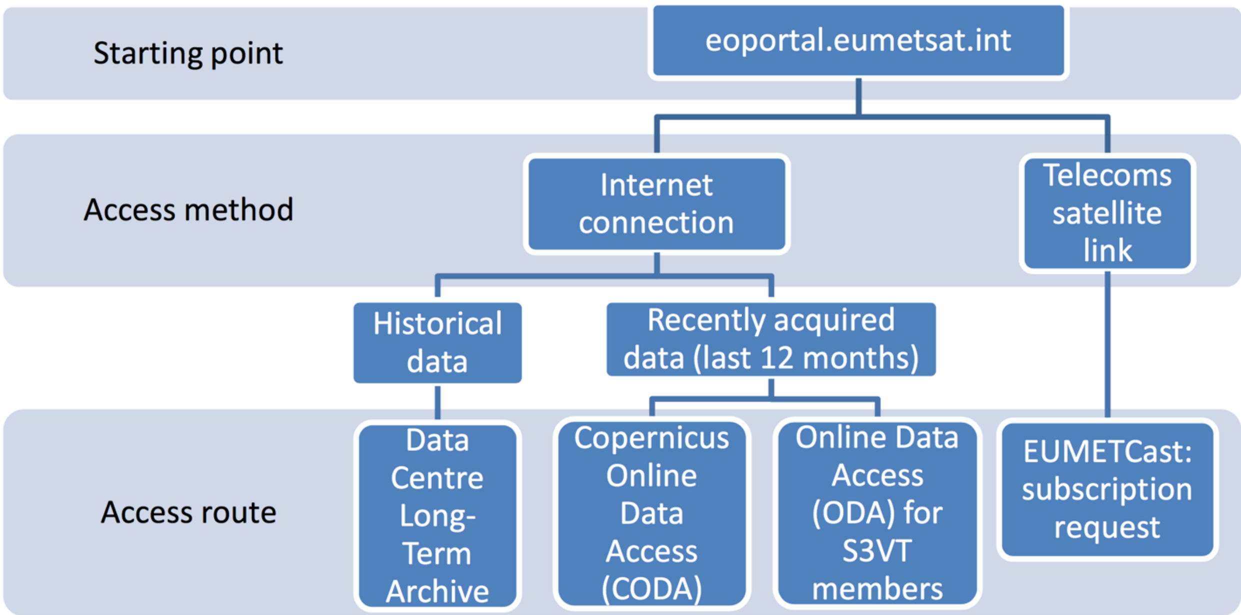

Figure 22: Data access routes.

Additional data access may, in the future, be available through the Global Telecommunication System (GTS), the World Meteorological Organisation telecommunications system for the dissemination of data streams and products that are relevant to weather applications.

7.3 Data coverage

Sentinel-3 marine altimetry products cover the open ocean, coastal domain, land within 10km of coast, the marine cryosphere. Further coverage for the Great Lakes, Caspian and Lake Victoria is planned for imminent inclusion.

	EUMETCast EUMETCast	Multi service push dissemination system based on multicast technology, which is transported to the user via satellite (EUMETCast Satellite, with coverage over Europe, the Middle-East and Africa).
	CODA coda.eumetsat.int	Download service offers all the recently acquired Sentinel-3 marine and atmospheric products through a rolling dataset that (at a maximum) will span 12 months.
	Data centre long term archive Data centre	Ordering application that enables users to browse and select products, from EUMETSAT's long-term archive, including the Copernicus Sentinel-3 marine and atmospheric products.

Table 7: Data access route descriptions

7.4 Software tools

7.4.1 Broadview Radar Altimetry Toolbox

The Broadview Radar Altimetry Toolbox (BRAT) is a tool designed to read all altimetry products, ranging from Sensor Geophysical Data Record to gridded merged data, from official data centres, and from ERS- 1/2, Topex/Poseidon, Geosat Follow-On (GFO), Jason-1, Envisat, Jason-2, Cryosat-2 and Sentinel-3. It is additionally able to perform some data processing operations. The package, which is available in Linux, Windows and MacOS flavours operates via a GUI that also enables the display of all the aforementioned products, either ingested or derived. More information on BRAT, including in depth tutorials on altimetry approaches, can be found here: Radar altimetry tutorial and toolbox. As of August 2017, the current version is v.4.1.0.

7.4.2 Dedop[3]

Prior to the incorporation of Delayed-Doppler (or SAR) mode into altimetry, beginning with CryoSat-2, a clear division existed between Level 1B and Level 2 processing stages. However, with Delayed- Doppler/SAR modes this is not the case, necessitating the development of new tools to cater for the intrinsic link between the re-tracking of waveforms at L1b and retrieval of geophysical variables at L2. The DeDop^3 toolbox was developed to fill this gap. DeDop^3 is an open-source, Python-based, command-line driven toolkit that supports the exploration of this subtle link between these two processing stages. More information on the DeDop^3 package, including installation instructions and binaries for Linux/Windows/MacOS, can be found here: DeDop^3 Tool Documentation.

7.4.3 Radar Altimetry Database System

The Radar Altimeter Database System (RADS) is a DEOS' effort to establish a harmonised, validated and cross-calibrated sea level data base from satellite altimeter data. It operates within the framework of the Netherlands Earth Observation NETwork NEONET, an internet facility, funded by the Dutch government (BCRS and SRON) for exploitation of remote-sensing expertise and data. The RADS database server is accessible through BRAT, directly, facilitating access to cross-calibrate sea-level data. More information on RADS can be found here: Radar Altimeter Database System.