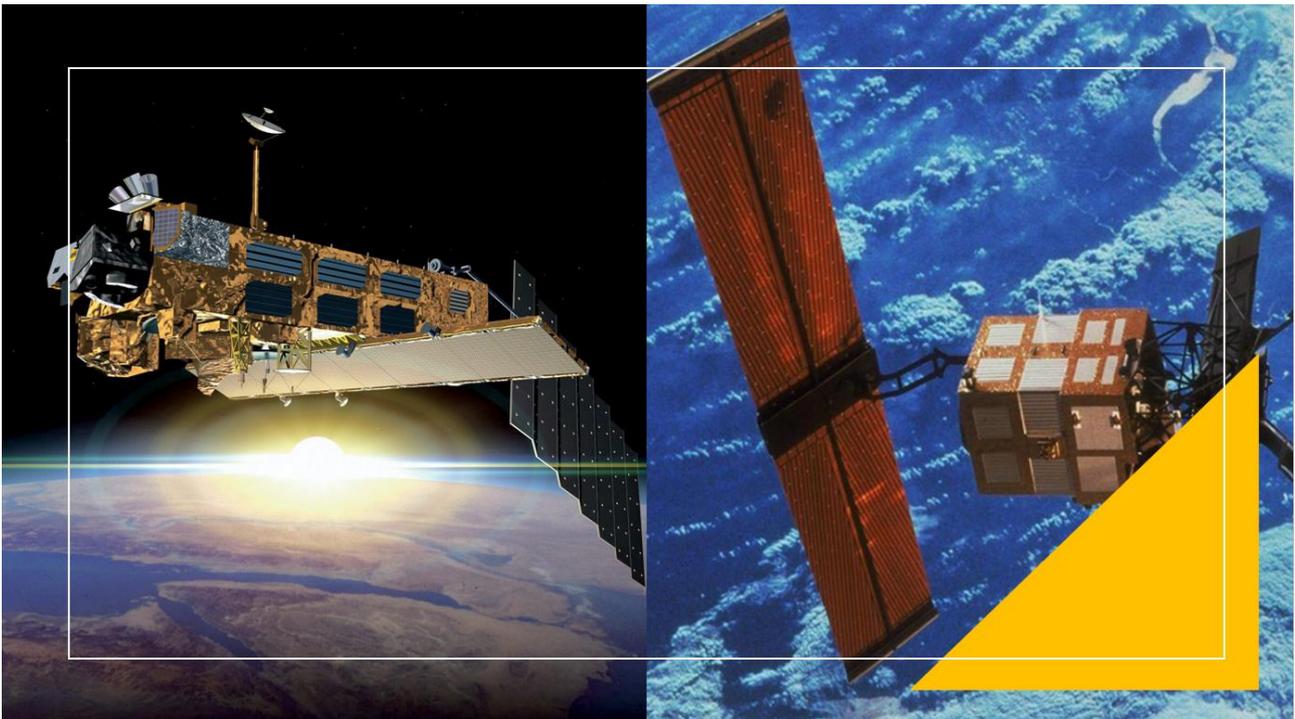




# FDR4ALT



## FDR4ALT Product User Guide



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# 1 Introduction

This document has been written in the frame of the FDR4ALT project, ESA contract N°4000128220/19/I-BG.

## 1.1 The FDR4ALT Project

In the framework of the European Long Term Data Preservation Programme (LTDP+) which aims at generating innovative Earth system data records named Fundamental Data Records (basically Level 1 altimeter and radiometer data) and Thematic Data Records (basically Level 2+ geophysical products), ESA/ESRIN has launched a reprocessing activity of ERS-1, ERS-2 and ENVISAT altimeter and radiometer datasets, called the FDR4ALT project (Fundamental Data Records for Altimetry). A large consortium of thematic experts has been formed to perform these activities which are:

- 1) To define products including the long, harmonized record of uncertainty-quantified observations.
- 2) To define the most appropriate Level 1, Level 2 and Level 2+ processing.
- 3) To reprocess the whole time series according to the predefined processing.
- 4) To validate the different products and provide them to large communities of users focused on the observation of the atmosphere, ocean topography, ocean waves, coastal, hydrology, sea ice, ice sheet regions.

## 1.2 Purpose and scope of this user guide

The FDR4ALT Product User Guide aims at providing a summary of key information needed for users interested in ERS-1, ERS-2 and ENVISAT radiometry and altimetry products, over open ocean, coastal areas, sea-ice, land-ice, inland waters and atmosphere. It gives detailed information about the products delivered to the users.

This User Guide is divided into the following main sections:

- ✓ An introduction dedicated to the role of the European Space Agency and the scope of the ERS-1, ERS-2 and ENVISAT missions.
- ✓ A description of the RA, RA-2 and MWR sensors.
- ✓ An introduction to the radar altimetry principles and the general goals of Level 1 and Level 2.
- ✓ An overview of the FDR4ALT products
- ✓ A dedicated section for each FDR/TDP, providing the content of the products and how to use them.
- ✓ Finally, a helpdesk section providing practical information for users about data access.

## 2 General information

### 2.1 The European Space Agency

The European Space Agency ([ESA](#)) is dedicated to the peaceful exploration and use of space for the benefit of everyone. Established in 1975, ESA is an international organization currently composed of 22 Member States and, for more than 40 years, has promoted European scientific and industrial interests in space. By coordinating the financial and intellectual resources of its members, it can undertake programs and activities far beyond the scope of any single European country.

ESA's programs are designed to find out more about Earth, its immediate space environment, our Solar System and the Universe, as well as to develop satellite-based technologies and services, and to promote European industries. ESA also works closely with space organizations outside Europe.

ESA's purpose shall be to provide for, and to promote, for exclusively peaceful purposes, cooperation among European States in space research and technology and their space applications, with a view to their being used for scientific purposes and for operational space applications systems:

- ✓ by elaborating and implementing a long-term European space policy, by recommending space objectives to the Member States, and by concerting the policies of the Member States with respect to other national and international organizations and institutions.
- ✓ by elaborating and implementing activities and programs in the space field.
- ✓ by coordinating the European space program and national programs, and by integrating the latter progressively and as completely as possible into the European space program, in particular as regards the development of satellite applications.
- ✓ by elaborating and implementing the industrial policy appropriate to its program and by recommending a coherent industrial policy to the Member States.

The ESA Member States currently are Austria, Belgium, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Ireland, Italy, Luxembourg, the Netherlands, Norway, Poland, Portugal, Romania, Spain, Sweden, Switzerland and the United Kingdom. Slovenia and Latvia are Associate Members. Canada takes part in some projects under a cooperation agreement. Bulgaria, Croatia, Cyprus, Malta, Lithuania and Slovakia have cooperation agreements with ESA.

ESA operates on the basis of geographical return, i.e., it invests in each Member State, through industrial contracts for space programs, an amount more or less equivalent to each country's contribution.

### 2.2 The Long-Term Data Preservation Program (LTPD+)

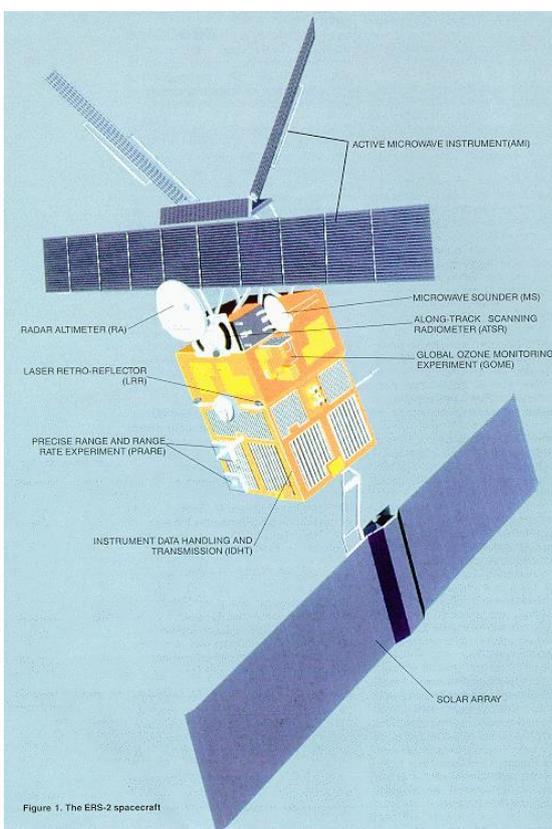
The need for accessing historical Earth Observation (EO) data series has strongly increased in the last ten years, mainly for long term science and environmental monitoring applications. This trend has increased even more in particular for the growing interest on global change monitoring which is driving users to request time-series of data spanning 20 years and more, and due also to the need to support the United Nations Framework Convention on Climate Change (UNFCCC).

Content of EO data archives has extended from a few years to decades and therefore their value as a scientific time-series is continuously increasing. Hence there is a strong need to preserve the EO space data without time constraints and to keep them accessible and exploitable. The preservation of EO space data can be also considered as a responsibility of the Space Agencies or data owners as they constitute a humankind asset.

Main goals of the European EO Long Term Data Preservation Framework are to:

- ✓ Preserve the European, and Canadian, EO space data sets for an unlimited timespan.
- ✓ Ensure and facilitate the accessibility and usability of the preserved data sets respecting the individual entities applicable data policies.
- ✓ Through the adoption of a cooperative and harmonized collective approach among the data owners (LTDP Framework) based on the application of European LTDP Common Guidelines and sustained through cooperative (multi-source) long term funding schemes.
- ✓ Ensure, to the maximum extent, the coherency with the preservation of other non-space based environmental data and international policies.

## 2.3 The ERS missions



The ERS programme was composed of two missions, ERS-1 and ERS-2, which were launched into the same orbit in 1991 and 1995 respectively. The two spacecrafts were designed as identical twins with one important difference – ERS-2 included an extra instrument (GOME) designed to monitor ozone levels in the atmosphere. Following nine years of excellent service, over three times its planned lifetime, the ERS-1 mission ended on 10 March 2000 due to a failure in the on-board attitude control system. Since its launch on 17 July 1991, ERS-1 made 45,000 orbits, acquiring more than 1.5 million individual Synthetic Aperture Radar (SAR) scenes. ESA's ERS-2 satellite followed its predecessor's example, greatly exceeding its three-year life span with 16 years of successful operations. The satellite was safely taken out of service on 5 September 2011, due to low levels of remaining fuel. From its launch on 21 April 1995, ERS-2 made 85,000 orbits, travelling 3.5 billion km. The ERS was the first ESA Earth observation program to provide microwave spectrum-based environmental monitoring. The missions' range of instruments could monitor the land, oceans, and atmosphere, and more specifically sea ice, and many more scientific fields.

Figure 2-1 : Artist view of the ERS-2 satellite with the different instruments.

The payloads consisted of:

- ✓ A SAR (image and wave modes) a Wind Scatterometer (WS),
- ✓ A Radar Altimeter (RA),
- ✓ A Microwave Radiometer (MWR),
- ✓ An Along Track Scanning Radiometer (ATSR),
- ✓ A Precise Range and Range-Rate Equipment (PRARE)
- ✓ Laser Retro-Reflectors (LRR)

- ✓ ERS-2 had an extra spectrometer instrument, GOME, a passive instrument for global monitoring of the ozone content in the atmosphere.

### 2.3.1 Orbit

Both ERS-2 and ERS-1 were in a Sun-synchronous near-polar orbit with an ascending node equatorial crossing at 10:30 Mean Local Solar time, highly inclined to the equator, giving the satellites visibility of all areas of the Earth as the planet rotates beneath their orbits. In a sun-synchronous orbit, the satellite passes over any given point of the planet's surface at the same local solar time. The orbit reference altitude is 780 km and uses a relative high inclination (98.52°). In practice, the orbital altitude of ERS-1 has been changed, by a few kilometers, several times during the four years it has been in orbit. Five orbital patterns have been flown: two had repeat periods of three days but over different ground tracks; for most of the mission, a multi-disciplinary 35-day pattern has been used; and two others had a pattern with a 168-day repeat, offset by half of the track spacing to provide a very dense spatial coverage. Each individual orbit in those patterns lasts approximately 100 min. ERS-1 and ERS-2 were both flying in the same 35-day orbit, over the same ground tracks.

More information about ERS orbits can be found in

- ✓ “ERS-2: A Continuation of the ERS-1 Success” by G. Duchossois and R.Zobl  
<https://earth.esa.int/eogateway/missions/ers/description/>

Parameter	Value
Orbit type	Near-circular, polar, sun-synchronous
Eccentricity	0.001165
Perigee	90°
Inclination	98.52°
Repeat Cycle	3-day, 35-day, 168-day (ERS-1) 3-day, 35-day (ERS-2)
Reference orbit	780 km
Equatorial crossing	10:30 h Mean Local Solar Time
Cycle length	501 orbits / 1002 passes
Ground track separation	104 km at the equator
Ground track deviation	+/- 1km to nominal track

Table 2-1 : ERS missions orbit main characteristics

More detailed information is available from <http://www.deos.tudelft.nl/ers/phases>

### 2.3.2 Mission phases

Name	Start	End	Repeat cycle
Launch	17-Jul-91	-	-
Commissioning Phase, or Phase "A"	25-Jul-91	10-Dec-91	3 days
Roll Tilt Mode validation	12-Dec-91	13-Dec-91	35 days
Ice Phase or Phase "B":	28-Dec-91	01-Apr-92	3 days

<b>Roll Tilt Mode Campaign or Phase "R"</b>	04-Apr-92	14-Apr-92	35 days
<b>Multidisciplinary Phase, or Phase "C"</b>	14-Apr-92	21-Dec-93	35 days
<b>Second Ice Phase, or Phase "D"</b>	23-Dec-93	10-Apr-94	3 days
<b>Geodetic Phase, or Phase "E"</b>	10-Apr-94	28-Sep-94	168 days
<b>Geodetic Phase, or Phase "F"</b>	28-Sep-94	21-Mar-95	168 days
<b>Phase G 2<sup>nd</sup> Multidisciplinary</b>	21-Mar-95	17-Aug-95	35 days
<b>Phase G Tandem</b>	17-Aug-95	02-Jun-96	35 days
<b>Phase G Back-Up</b>	02-Jun-96	10-Mar-00	35 days
<b>End of mission</b>	10-Mar-00	-	-

Table 2-2 : ERS-1 mission phases

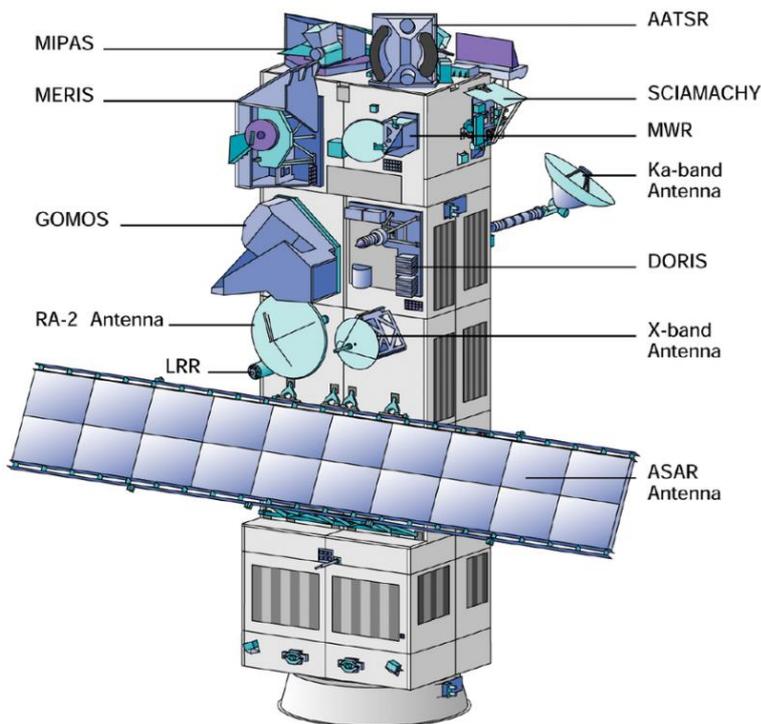
<b>Name</b>	<b>Start</b>	<b>End</b>	<b>Repeat cycle</b>
<b>Launch</b>	21-Apr-95	-	-
<b>Payload switch-on and verification</b>	21-Apr-95	02-May-95	35 days
<b>Commissioning Phase, or Phase "A"</b>	02-May-95	17-Aug-95	35 days
<b>Phase "B": Tandem</b>	17-Aug-95	03-Jun-96	35 days
<b>Phase "B": Multidisciplinary</b>	03-Jun-96	05-Sep-11	35 days
<b>End of Mission</b>	05-Sep-11	-	-

Table 2-3 : ERS-2 mission phases

More information about the ERS missions can be found in:

- ✓ ERS-1 Satellite to ground segment interface specification, ESA document: ER-IS-ESA-GS-0001, 2D issue, Sept 1993

## 2.4 The ENVISAT mission



Launched on 01/03/2002, Envisat (Environmental Satellite) was the follow-on to ERS-1 and ERS-2. Devoted to environmental studies, and climate change in particular, its mission was to observe Earth's atmosphere and surface. Built by ESA, the European Space Agency, ENVISAT was carrying ten complementary instruments for observing parameters ranging from the marine geoid to high-resolution gaseous emissions. From 2002 to October 2010, ENVISAT's orbital period was 35 days, like ERS-2 and some of the ERS-1 phases. As it was integrated in international climate study programmes such as Goos and Godae. ENVISAT thus formed part of the operational era in oceanography, offering near-real-time data access for the first time.

The RA-2 S-band module was definitively lost on 2008/01/18.

To ensure an additional 3-years lifespan, the ENVISAT satellite moved to a new lower orbit on October 22, 2010. From 02 November 2010, for the ENVISAT extension orbit, the ground track changed and consequently the repeat cycle changed: 30 days with 431 orbits per cycle instead of 35 days-501 orbits per cycle.

In April 2012, few weeks after celebrating its ten years of service, ENVISAT has stopped sending data to Earth. ESA declared the end of mission for ENVISAT on May 9th, 2012.

The main objective of the ENVISAT programme was to endow Europe with an enhanced capability for remote sensing observation of Earth from space, with the aim of further increasing the capacity of participating states to take part in the studying and monitoring of the Earth and its environment.

The payloads consisted of:

- ✓ Michelson Interferometer for Passive Atmospheric Sounding (MIPAS)
- ✓ Global Ozone Monitoring by Occultation of Stars (GOMOS)
- ✓ Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY)
- ✓ Medium Resolution Imaging Spectrometer (MERIS)
- ✓ Advanced Along Track Scanning Radiometer (AATSR)
- ✓ Advanced Synthetic Aperture Radar (ASAR)
- ✓ Radar Altimeter 2 (RA-2)
- ✓ Microwave Radiometer (MWR)
- ✓ Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS)
- ✓ Laser Retro-Reflector (LRR)

ENVISAT primary objectives were:

- ✓ To provide for continuity of the observations started with the ERS satellites, including those obtained from radar-based observations.

- ✓ To enhance the ERS mission, notably the ocean and ice mission.
- ✓ To extend the range of parameters observed to meet the need of increasing knowledge of the factors determining the environment.
- ✓ To make a significant contribution to environmental studies, notably in the area of atmospheric chemistry and ocean studies (including marine biology).

These were coupled with two linked secondary objectives:

- ✓ To allow more effective monitoring and management of the Earth's resources.
- ✓ To better understand solid Earth processes.

More information about ENVISAT mission objectives can be found in the ESA webpage <https://earth.esa.int/eogateway/missions/envisat/>

## 2.4.1 Orbit

Many of the choices were examined during the ERS-1 mission preparation and the concept of the multidisciplinary orbit, with a 35-day cycle, evolved. ENVISAT flew this same high-inclination, sun-synchronous, near-circular orbit with the same ground track. The only difference was in the Mean Local Solar Time (MLST) being 10:00 instead of 10:30.

Parameter	Value
<b>Orbit type</b>	Near-circular, polar, sun-synchronous
<b>Eccentricity</b>	0.001165
<b>Perigee</b>	90°
<b>Inclination</b>	98.55°
<b>Repeat Cycle</b>	35 days
<b>Reference orbit</b>	799.8 km
<b>Equatorial crossing</b>	10:00 h Mean Local Solar Time
<b>Cycle length</b>	501 orbits / 1002 passes
<b>Ground track separation</b>	~80 km at the equator
<b>Ground track deviation</b>	+/- 1km to nominal track

Table 2-4 : ENVISAT orbit characteristics

## 2.4.2 Mission phases

Name	Start	End	Repeat cycle
<b>Launch</b>	01-Mar-02	-	-
<b>Launch &amp; early orbit phase, or Phase "0"</b>	01-Mar-02	02-Mar-02	-
<b>Drift phase, or Phase "1"</b>	02-Mar-02	04-Apr-02	-
<b>Nominal phase, or Phase "2"</b>	04-Apr-02	24-Oct-10	35 days
<b>Mission extension phase, or Phase "3"</b>	24-Oct-10	08-Apr-12	30 days
<b>End of mission</b>	08-Apr-12	-	-

Table 2-5 : ENVISAT mission phases

Figure 2-2 shows the ERS-1, ERS-2 and ENVISAT mission phases on the same diagram:

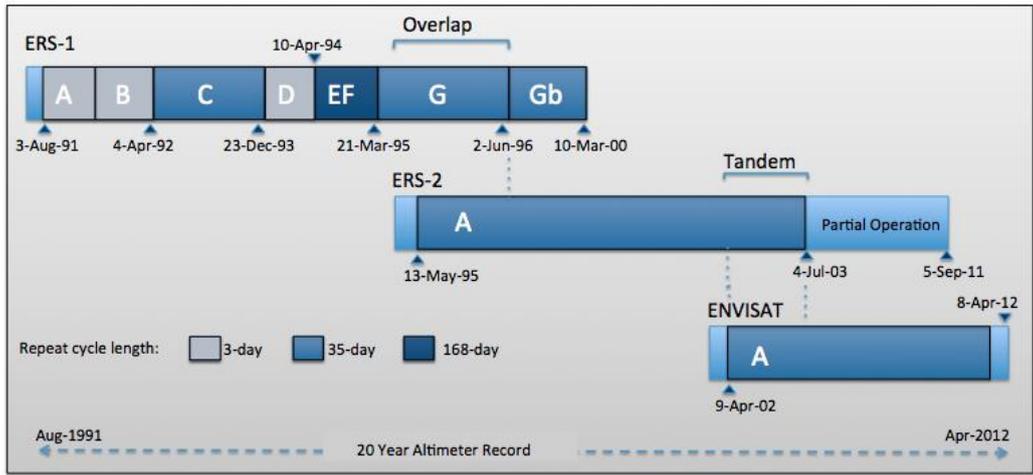


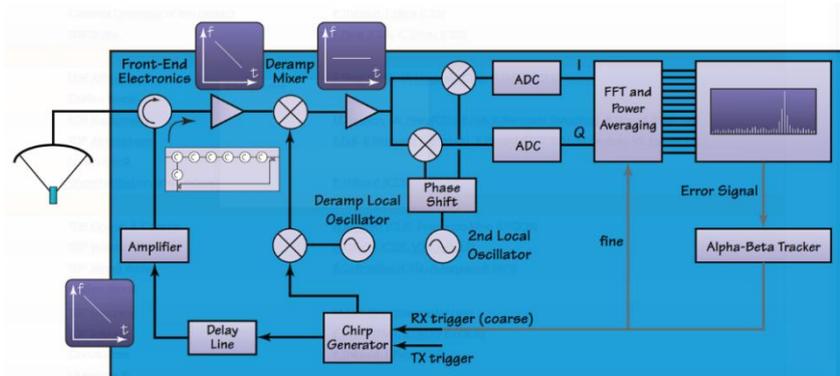
Figure 2-2 : ERS-1, ERS-2 and ENVISAT mission phases



## 3 ERS RA, ENVISAT RA-2 and MWR instruments

### 3.1 RA instrument

#### 3.1.1 Main characteristics



The Radar Altimeter (RA) for ERS-1 and ERS-2 was a Ku-band nadir-pointing pulse radar designed to make precise measurements of the echoes from ocean and ice surfaces. As explained in more details in section 3.1.3, it had two measurement modes, optimized at the time for measurements over ocean and ice, respectively. RA was the first altimeter operating with a centimetric precision and operated in what we call today Low-Resolution Mode (LRM), as opposed to the SAR mode that was successfully tested on-board Cryosat-2, and then used for the Sentinel-3 satellites (see the Sentinel-3 SRAL Land User Handbook for more information). More information about the acquisition in LRM mode can be found in section 4.2.

Parameter	Value
Frequency	13.8 GHz
Pulse duration	20 $\mu$ s
Pulse repetition frequency	1020 Hz
Chirp bandwidth	330 MHz (Ocean Mode) 82.5 MHz (Ice Mode)
Transmitted power	55 W peak
Antenna diameter	1.2 m
Mass	96 kg
DC power	120 W

Table 3-1 : Main technical parameters of the ERS Radar Altimeter (RA)

#### 3.1.2 Tracker

As explained in [Peacock, 1998], under normal tracking conditions, the RA altimeter can operate in one of two modes selected by macro command. These two modes correspond to the two resolution modes of the instrument, high (Ocean) and low (Ice). In Ocean Mode, the waveform is sampled into 64 bins each of width 3.03 ns (equivalent to a range of 0.45 m) and is expected to conform to the Brown model [Brown, 1977]. In Ice Mode, the bin width is increased fourfold to 12.12 ns (1.82 m), thereby allowing tracking over land or other non-ocean surfaces where the signal is less well defined. The arrival of the next echo is predicted by the Parameter Estimation Processor (PEP), which is composed of 3 tracking loops in Ocean Mode: the height tracking loop (HTL) which predicts the time of arrival of the next echo, the slope tracking loop (STL) which tracks the slope of the leading edge of the waveform, and the automatic gain control loop (AGC) which

controls the gain of the receiver. Each of these loops consists of a discriminator which produces an error signal, and a second order low pass filter. The error signals are generated by the Sub-optimal Maximum Likelihood Estimator (SMLE) algorithm, which determines the relevant errors with respect to an ideal echo based on the Brown model [Francis, 1990].

Figure 3-1 shows a simplified representation of the tracking system.

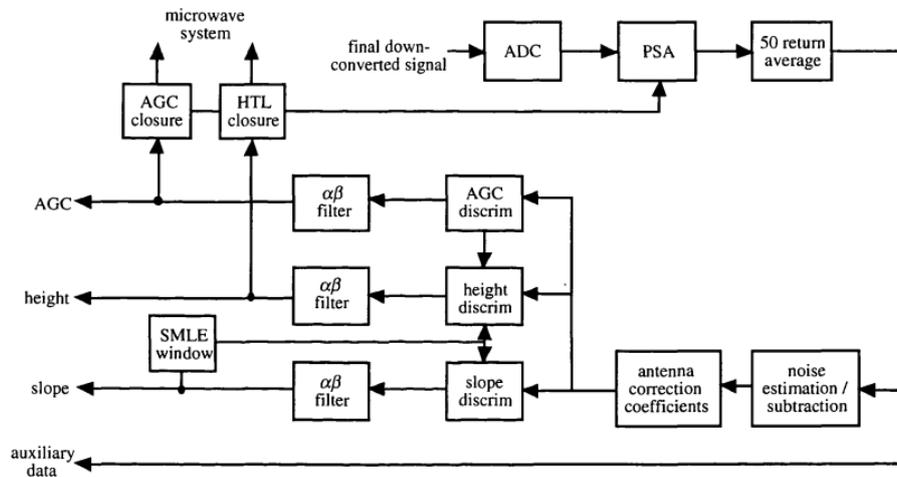


Figure 3-1 : Simplified representation of the ERS tracking system (adapted from Francis [1990]).

Ice Mode operates slightly differently from this, in that it tracks the centre of gravity of the echo rather than the centre of the leading edge [Cudlip and Milnes, 1994]. It does not make use of the STL, and the loops function with slightly different operating parameters.

### 3.1.3 Tracking modes and resolution

As explained above, ERS operated in two possible modes: the “Ocean Mode” and the “Ice Mode”. The radar echoes over ice sheets, particularly the rough surfaces at the continental margins, show much greater variances in shape than oceanic echoes. In order to maximize the data return in those areas, the Ice Mode included different features designed to improve its 'robustness' over ice sheets. The range window width was increased by a factor of four, which also degraded the precision by a similar amount.

Mode	Gate resolution
Ocean	0.4542 m
Ice	1.8169 m

Table 3-2 : Gate resolutions associated with each ERS mode.



ERS-2 Cycle 11

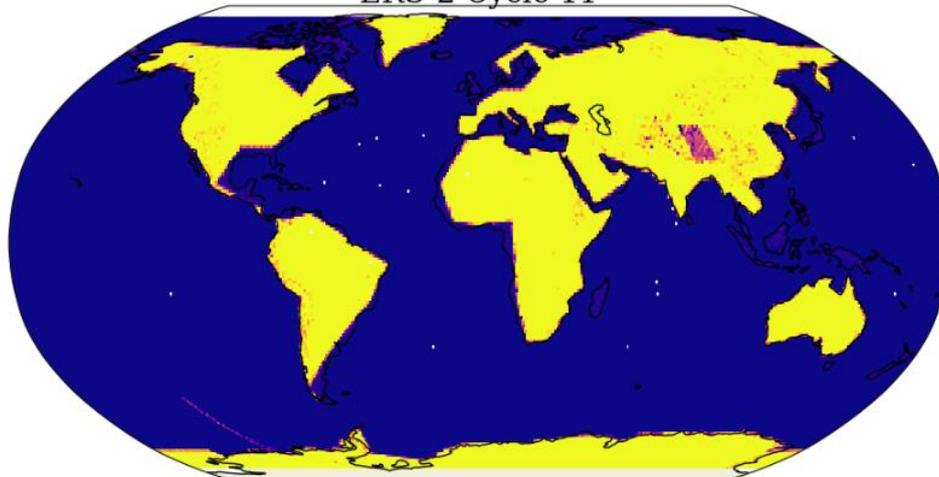


Figure 3-2 : Chirp bandwidth distribution for ERS-2 cycle 11. Yellow represents the ICE mode and Blue represents the OCEAN mode.

### 3.1.4 Internal calibrations

The RA altimeter was able to generate several types of signals useful for calibration and characterisation by disabling the tracking loops and directly controlling the range window instead.

#### Point Target Response (PTR)

The PTR was measured using two different methods:

- ✓ Setting the range window at the effective location of the transmitter, in order to use the transmit signal to generate a Point Target Response (PTR);
- ✓ Slowly sweeping the range window past the effective transmitter location to characterise the entire range window a technique called Scanning Point Target Response (SPTR)

More information about these two types of signals can be found in [Francis, 2000]

#### Low Pass Filter (LPF)

The Low Pass Filter, or intermediate frequency (IF) filter was measured on-board via a measurement of system noise by setting the range window at some intermediate point between the satellite and the Earth, where there is no echo.

### 3.1.5 Instrumental issues

#### 3.1.5.1 ERS-2 Gyroscope system failures (2001)

Throughout its lifetime, ERS-2 suffered several problems with some of the six gyroscopes leading to six different piloting modes in order to ensure the mission continuity.

In 2001, after the failure of several on-board gyro systems, a scheme for flying and controlling the ERS-2 mission without gyros was invented; the "gyro-less" yaw steering mode or the so called "Zero-Gyro Mode" (ZGM). The ERS-2 platform operations were performed in Zero-gyro-mode (ZGM) from June 2001 until March 2002. The Yaw Control Monitoring – Regional operations (YCM-R) piloting was then applied until end of the mission.

### 3.1.5.2 ERS-2 tape recorder failure (2003)

All ERS-2 Low Bit Rate (LBR) instruments were operated on a "global" basis until June 2003. Until then, the on-board recorders were used to record each orbit and the data (real time and playback) was dumped over a predefined set of ground stations (Kiruna-Samijarvi, Maspalomas, Gatineau and Prince Albert). However, on 22 June 2003, a failure in the on-board data storage system led to the mission being re-designed as "real time" only, with LBR data directly relayed to ground at the time of acquisition within the visibility of the ESA ground stations. In order to expand the LBR Near Real Time coverage after the loss of the on-board recorders, a number of additional National Foreign Stations (NFS) were deployed between 2003 and 2011 (end of mission). (Source: ESA website)

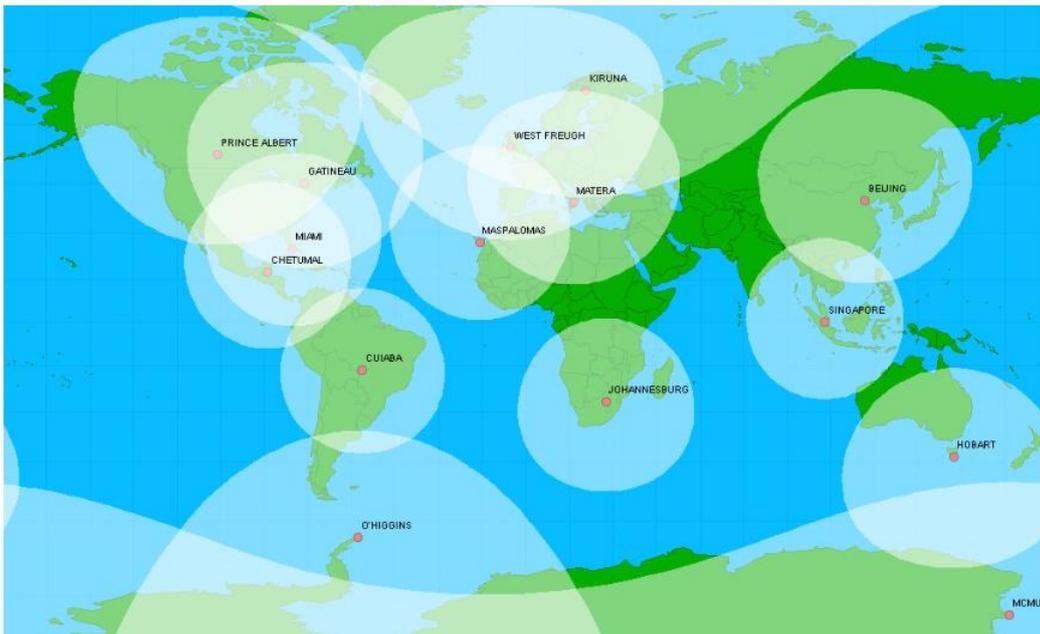
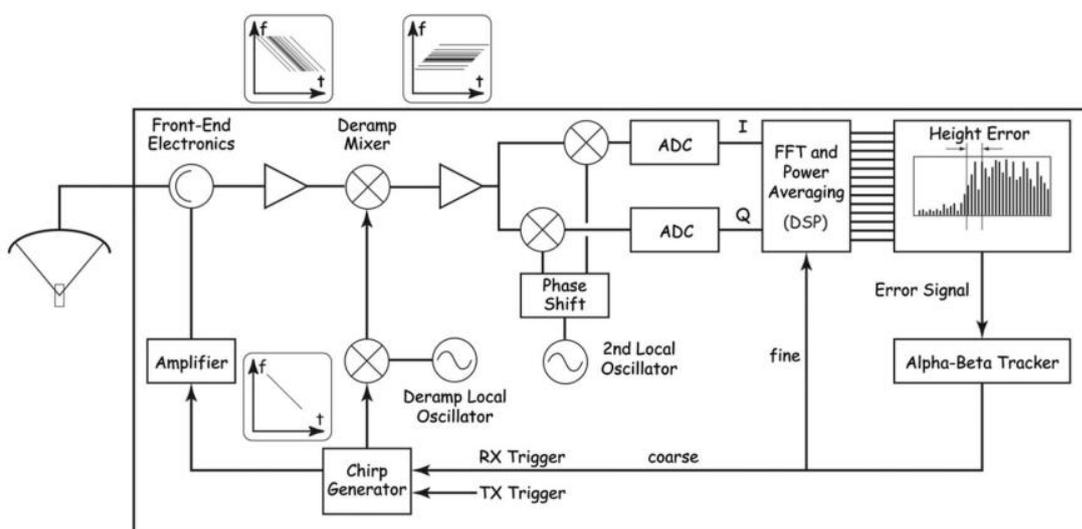


Figure 3-3: Coverage of LBR acquisition stations after tape recorders failure, June 2003 (credits ESA)

## 3.2 RA-2 instrument



The RA-2 instrument was a dual-frequency, nadir-pointing, pulse-limited radar operating at 13.575 GHz (Ku-band) and 3.2 GHz (S-Band) using a single antenna dish and was based on the heritage of the ERS-1 RA. It was designed to operate autonomously and without interruption over all surfaces: ocean, land and ice. RA-2 was the first high-latitude altimeter that aimed at improving the precision of previous altimeters over open oceans (ERS satellites), enhancing operations over ice sheets.

Parameter	Value
Frequency	13.575 GHz (Ku-band) 3.2 GHz (S-band)
Pulse duration	20 $\mu$ s
Pulse repetition frequency	1795 Hz (Ku-band) 449 Hz (S-band)
Chirp bandwidth	320 MHz, 80 MHz, 20MHz (Ku-band) 160 MHz (S-band)
Transmitted power	60 W (Ku-band) 60 W (S-band)
Antenna diameter	1.2 m
Mass	112 kg
DC power	120 W

Table 3-3 : Main technical parameters of RA-2

ERS	TOPEX	RA-2
PRF = 1024	PRF = 4200 Hz	PRF = 1795Hz
Two resolutions: ocean mode of 330 MHz and ice mode of 82.5 MHz	Single resolution of 320 MHz	Three resolutions: 320, 80, 20 MHz
Resolution changes commanded from ground	NA	Autonomous Resolution Selection Logic
Suboptimal MLE	Gating	Onboard Model Free Tracker
64 samples	128 samples	128 (+2 DFT) samples at 16 bits
50 pulses averaged at Ku-band	100 pulses averaged at Ku-band	100 pulses averaged at Ku-band
Single frequency (Ku-band)	Dual frequency for ionospheric correction (Ku- and C-band)	Dual frequency for ionospheric correction (Ku- and S-band)
NA	NA	Individual Echoes (before averaged) at 1.8 kHz with phase information
High-latitude coverage (82°)	Lower latitude coverage (66°)	High-latitude coverage (82°)
Internal calibration commanded from ground with interruption of echo collection		Internal calibration data routinely collected every 1 second without interrupting echo collection

Figure 3-4 : New features of RA-2 with respect to ERS and TOPEX altimeters [Roca et al., 2009]

### 3.2.1 Tracker

To be able to achieve the improved performance, RA-2 had a different tracker philosophy. In contrast to earlier altimeters, a clear distinction was made between the robust collection of accurately quantified radar echo data by the instrument, and the interpretation of these data as meaningful geophysical quantities on ground. This separation reduced the constraints on its optimization. The RA-2 recorded the return echo as a series of 128 samples, in the so-called “range window.” To obtain estimates of surface elevation, it was necessary to maintain the leading edge of the return echo in the range window. The RA-2 measured the power level and time delay. The position, gain, and resolution of the tracking window were updated by the



onboard processor. One of the new features on RA-2 was the MFT (Model Free Tracker) in the onboard signal processor. The MFT was designed to maximize the collection of echoes around the orbit over most surface types. The MFT software was designed to select the highest radar resolution while maintaining an adequate SNR and keeping the leading edge of the radar echoes inside the window. Three range resolutions were available to the Ku channel, related to the three transmitting bandwidths of 320, 80, and 20 MHz, so that the resolution can be adapted over different racking is lost, an automatic procedure restarts operation from detection and acquisition.

### 3.2.2 Tracking modes and resolution

Mode	Gate resolution
High	0.47 m
Medium	1.9 m
Low	7.5 m

Figure 3-5 shows an example of the typical geographical distribution of the bandwidth on one cycle for ENVISAT. The chirp bandwidth switches to 80MHz or 20MHz in areas of high topography variations.

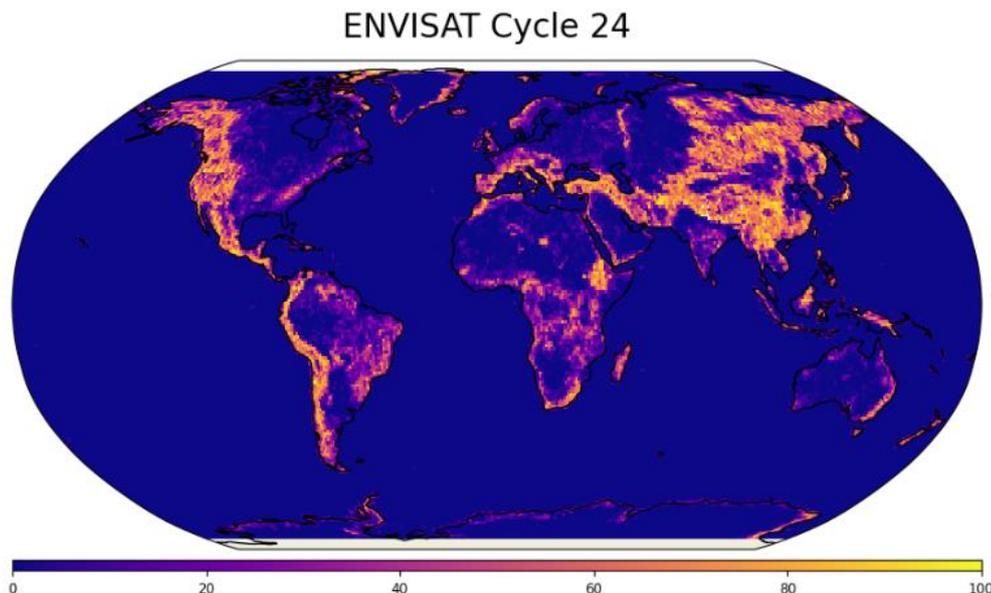


Figure 3-5 : Gridded map of the percentage of points where the chirp bandwidth value is not 320MHz (i.e., where the chirp bandwidth is 80MHz or 20MHz).

### 3.2.3 The DFT samples

Aside from these 128 samples (in comparison to RA's 64 samples), which allowed the observation of a longer waveform trailing edge, the range window included two extra digital samples around the leading-edge position (LEP) to improve the determination of significant wave height.

### 3.2.4 The S-band

Another major innovation of RA-2 with respect to ERS-1/2 was the second channel located in the S-band with a transmit frequency of 3.2 GHz. Indeed, this second frequency is highly sensitive to the ionospheric effects and, when combined with the Ku-band measurements, allowed the estimation of the ionospheric delay for the first time with this technique.

### 3.2.5 Burst mode

The samples collected by the Ku channel are averaged over groups of 100 echoes (25 for the S-Band channel), to reduce speckle noise and data rate. The averages are precisely time tagged and sent to ground via formatted source packets (SPs). These SPs contain 20 average echoes, covering about one second of radar operation (corresponding to the transmission of 2000 Ku-band pulses). The data rate in these conditions is limited to about 68 kb/s. In addition to these averages, the RA-2 had the capability of providing limited bursts of echo sample data at the full PRF rate (IEs). This was achieved by storing full-rate echoes from a single burst in an onboard memory buffer, in parallel to the normal averaging function of the instrument. This operation was commanded from ground.

### 3.2.6 Internal calibrations

#### Point Target Response (PTR)

The Point Target Response (PTR) calibration sequences are performed every 1.114s without any interruption of the echo sample collection. Note that this strategy is different from altimeters of the next generation (Jason-1/2/3) for which dedicated calibration sequences are performed 3 times per repetitive cycle, allowing the retrieval of non-noisy PTR calibrations.

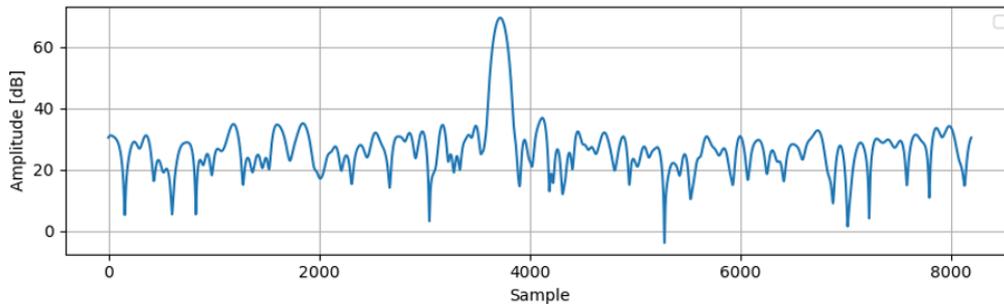


Figure 3-6 : Example of PTR ENVISAT in Ku-band from a single calibration

#### Low Pass Filter (LPF)

The Low Pass Filter, or intermediate frequency (IF) filter, was measured on-board via a dedicated calibration called the IF\_CALIBRATION mode.

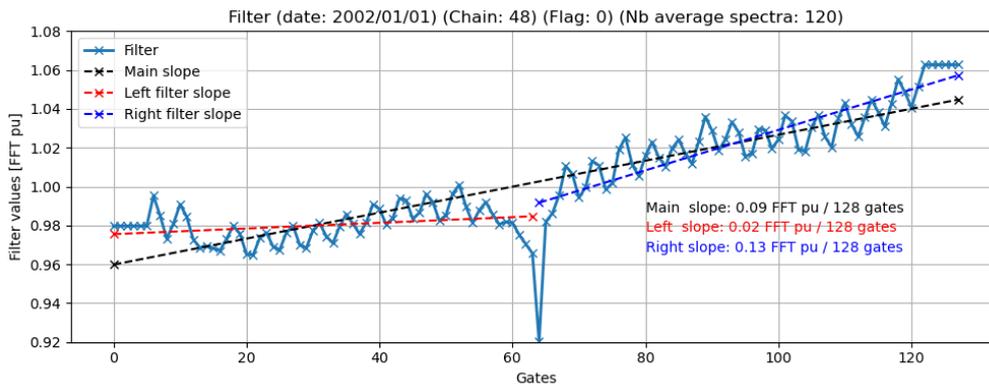


Figure 3-7 :Example of LPF ENVISAT in Ku-band

More information about ENVISAT RA-2 design, tracking and performances can be found in [Roca, 2009]

## 3.2.7 Instrumental issues

### 3.2.7.1 S-band anomaly

During the Commissioning Phase, it has been discovered that the RA-2 data are affected by the so-called S-Band anomaly. The anomaly results in the accumulation of the S-Band echo waveforms ([Laxon, 2002].). It happens randomly after an acquisition sequence and is only stopped by switching the RA-2 altimeter in a Stand-By mode. When this anomaly occurs, the S-Band waveforms are not meaningful. Consequently, all the S-Band parameters and the Dual Frequency ionosphere correction are not reliable. Notably, the S-Band Sigma0 is unrealistically high during these events. Thus, applying a threshold of 5 dB on the (Ku-S) Sigma0 differences is very efficient for detecting the impacted data over ocean. The ratio of flagged measurements over ocean is plotted in Figure 8 of [Laxon, 2002]. A method has been developed to flag the impacted data over all surfaces.

Finally, an algorithm for the S-Band waveform reconstruction has been developed which will enable recovery of data affected by the anomaly. The correction was implemented in the full mission reprocessing V3.0, so this anomaly is not present in the data used for this project. ([Laxon, 2002].; [Ollivier,2014])

### 3.2.7.2 USO drift

On the 1st of February 2006 (12:05:36), at the end of cycle 44, for an unknown reason, a change of behaviour of the USO device occurred. This anomaly, already observed for a short period during cycle 30, created a 5.5m jump on the range parameter and oscillations of about 20-30cm of amplitude at the orbital period. The anomaly became permanent on cycle 46 to 56. On the 1st of March 2007, the USO recovered in a non-anomalous mode. Between cycles 56 and 61, RA2 data were not affected by the anomaly. On the 27th of September 2007 (cycle 62), a new change of behaviour of the Ultra Stable Oscillator (USO) clock frequency occurred. A short break in the anomaly occurred between cycles 63 and 64, followed by another one on the 23rd of January which was permanent over the whole year 2008. The anomaly and associated correction are detailed in [Martini et al, 2003].

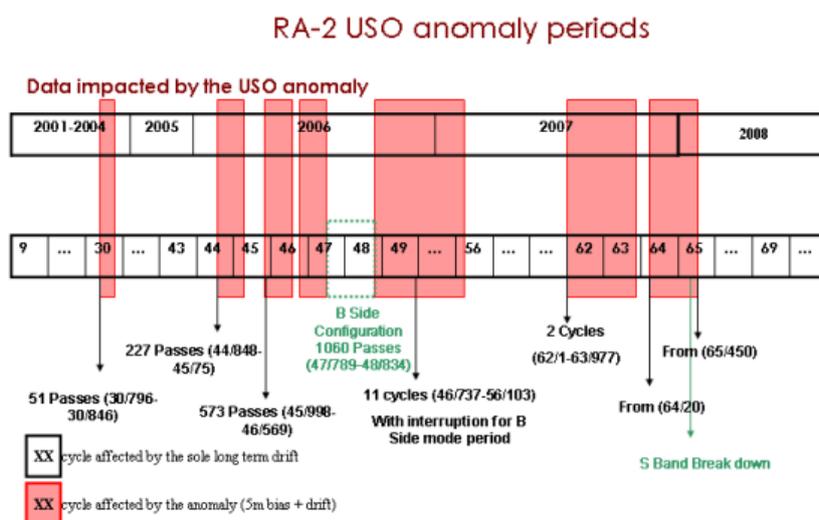


Figure 3-8 : Chronology of USO Correction anomaly

### 3.2.7.3 B-Side Operation and Fixed Chirp Bandwidth

As explained in the ENVISAT Altimetry Level 2 User Manual – V2 : Due to the USO anomaly, it was decided to switch the RA-2 instrument to its B-Side between 15/05/2006 and 21/06/2006 and to operate using fixed Chirp bandwidth on 12-13th May 2006. Before the switch to the B-side operation, on 12th-13th May, a special operation was executed to limit RA-2 Chirp Bandwidth to:

- ✓ 80MHz, starting from 12 May at.15.51.37
- ✓ 20 MHz, starting from 13 May at.03.57.57
- ✓ 320MHz, starting from 13 May at.15.10.17

During cycle 47, the instrument sub-system Radio Frequency Module (RFM) was switched to its B-side on May 15th, 2006, at 14:21:50, orbit 21994. After a few days of promising operations with the RFM B-side, its S-band transmission power dropped on 20th May 2006 at 13:24:57, orbit 22065, making all the S Band related parameters invalid. Due to the loss of the S-Band, the ENVISAT RA-2 instrument was successfully reconfigured to its nominal side (RFSS A-side) and commanded back into Measurement Mode on June 21st, 2006, at 13.20.15.000 UTC time, orbit 22523. Subsequent analysis of the RA-2 data showed expected behavior of the RA-2 parameters but also confirmed the persistence of the abnormal RA-2 Ultra-Stable Oscillator (USO) behavior affecting the Altimetric Range by a few meters.

## 3.3 MWR instrument aboard ERS-1 and ERS-2

### 3.3.1 General description

The satellite ERS-1 (European Remote Sensing-1) carried the ATSR/M (Along Track Scanning Radiometer/Microwave). This instrument is composed of two parts: an InfraRed radiometer (ATSR/IR) built by RAL (Rutherford Appleton Laboratory) and a microwave radiometer (ATSR/MWR) developed by CRPE (Centre de Recherches en physique de l'Environnement). CRPE performed the preliminary studies of the ATSR/MWR and built a breadboard of the radiometer. An engineering model and a flight model were built by MATRA under the responsibility of CRPE.

The ERS-1 microwave radiometer is a two-channel radiometer, with a near nadir viewing. The two selected frequencies (23.8GHz and 36.5GHz) allow a good retrieval of the wet path delay with a good sensitivity to the cloud liquid water content, the 23.8GHz being sensitive mainly to water vapor and 36.5GHz to cloud liquid water content.

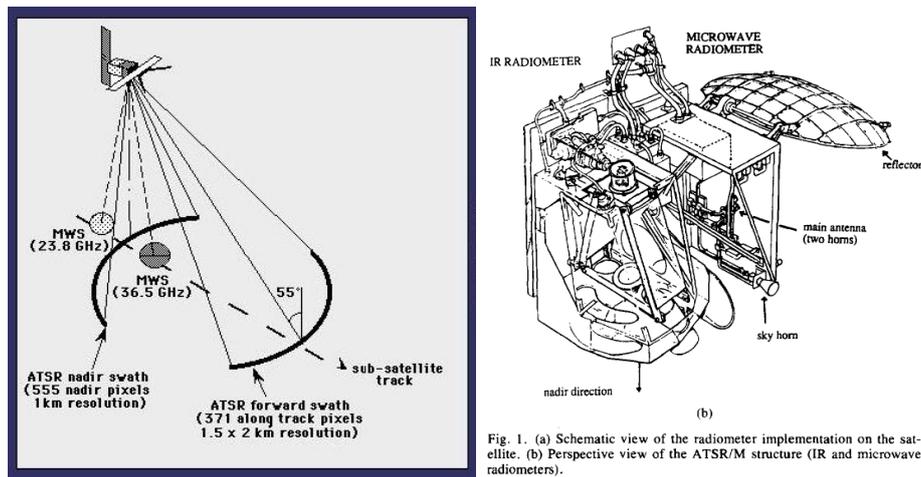


Fig. 1. (a) Schematic view of the radiometer implementation on the satellite. (b) Perspective view of the ATSR/M structure (IR and microwave radiometers).

Figure 3-9 : Left: Footprint geometry of ATSR/IRR and ATSR/MWR (image credit: ESA); Right: Perspective view of the ATSR/M structure (source: [R. Bernard et al,1993])

The microwave radiometer aboard ERS-2 is the follow-on of ERS-1 MWR. It is nominally identical to the hardware on-board ERS-1, but it was provided by a different constructor.

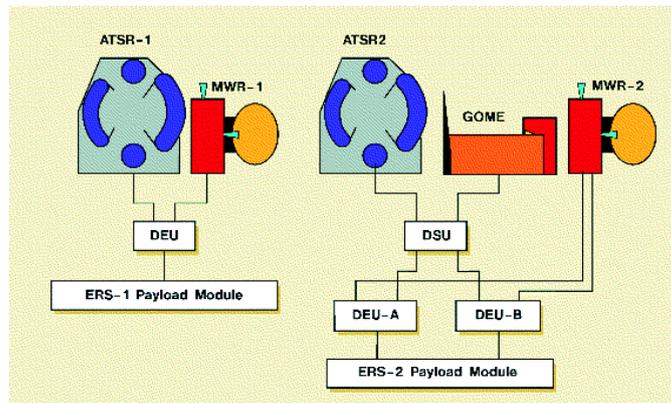


Figure 3-10: Schematic of the configurations of the IRR, MWR and DEU aboard ERS-1 and ERS-2) (source: [Stricker,1995])

Although they are identical in design, there are still small hardware differences that will require a specific calibration. A tandem phase is a good opportunity to intercalibrate two instruments. Indeed, during the tandem phase, both satellites followed the same track but with ERS-2 one day behind ERS-1. The short-time lag between measurements at the same location eliminate long-term ocean variability, the remaining ocean signal being only noise. However, from the radiometer point of view, this time lag is too large to allow a direct comparison of the two instruments because the atmosphere changes a lot over a one-day period. Thus, the differentiation between ERS-1 and ERS-2 contains instrument differences but also atmospheric signal.

### 3.3.2 Viewing geometry

The radiometer is near nadir looking with the 36.5GHz channel looking forward and the 23.8GHz channel looking backward. This means that a co-registration is required in the processing to have the measurements from both channels at the same location. Beam pointing angles and 3db aperture for both channels are provided in Table 3-4 for ERS-1. For ERS-2, beam pointing angles provided incomes from REAPER

configuration files, but no documented source and no information on 3db aperture was found for both channels (Table 3-5).

	Beam Pointing	3dB aperture	3dB footprint
		(deg) Along track (across)	(km) Along track (across)
<b>23.8</b>	1.93	1.52 (1.51)	21.2 (21.2)
<b>36.5</b>	2.5	1.6 (1.37)	22.5 (19.1)

Table 3-4 : ERS-1 ATSR/MWR characteristics [Bernard, 1990]

	Beam Pointing	3dB aperture (deg)	3dB footprint (km)
		Along track (across)	Along track (across)
<b>23.8</b>	1.95°		
<b>36.5</b>	2.53°		

Table 3-5: ERS-2 ATSR-2/MWR characteristics

The time sampling of the MWR is 150ms. In the initial processing, the raw measurements are integrated over a window of 8 measurements (1.2s) to reduce the noise and improve the estimation of the wet tropospheric correction (WTC) in the L2 altimeter processing. For the FDR4ALT project, we intent to keep the raw MWR sampling (~7Hz) in the FDR product and perform the average at 1Hz only at Level 2.

### 3.3.3 Operation mode

This radiometer operates in non-balanced Dicke mode at a switching frequency of 1kHz. During each Dicke cycle, the antenna temperature is compared to the internal hot load. This design allows a lower sensitivity to gain fluctuations than a total power radiometer, but the counterpart is a higher value of the radiometric sensitivity. Indeed, the instrumental noise is averaged only over half the sampling time because the other half is spent looking at the Dicke load.

Internal calibration is performed by switching the receiver connection to a sky horn or to a second internal reference load. A scheme of the internal design is presented in Figure 3-11.



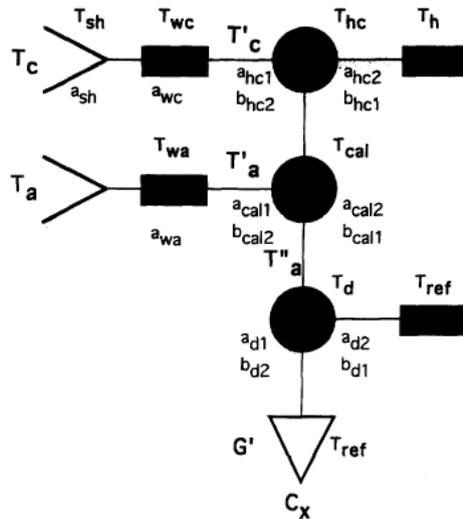


Fig. 2. Scheme of one channel, showing the circulators (circles), the loads (rectangles), the waveguides and horns for the main antenna (temperature  $T_a$ ) and sky horn ( $T_c$ ), and the electronic part (gain  $G'$ ). The output is the radiometric count  $C_x$  ( $x$  being the main antenna or one of the calibration measurements).

Figure 3-11: Radiometric model scheme (source: [R. Bernard et al,1993])

### 3.3.4 Antenna characteristics

To compute the brightness temperature from the antenna temperature, a good knowledge of the antenna patterns is necessary. The antenna patterns of both channels were measured. The integration of the gain distribution over the solid angle of each contributors provided the efficiencies are summarized for both missions in Table 3-6 and Table 3-7.

	Main beam	On-Earth	Sky	satellite	SAR
<b>23.8</b>	0.95	0.013	0.02	0.0138	0.0026
<b>36.5</b>	0.96	0.0105	0.015	0.0109	0.002

Table 3-6 : ERS-1 MWR main and side lobe efficiencies (source [R. Bernard et al,1993])

	Main beam	On-Earth	Sky	Satellite	SAR
<b>23.8</b>	0.91	0.0234	0.037	0.0248	0.0046
<b>36.5</b>	0.94	0.0157	0.0248	0.0164	0.0031

Table 3-7 : ERS-2 MWR main and side lobe efficiencies (source MWR-2 Calibrated instrument – Electrical and Radiometric performance, ER-TN-SAE-MW-0004, issue 1.2, 03-03-1994)

These efficiencies are used to correct the antenna temperature from the sidelobe contributions, coming from different sources such as the Earth, the sky, the satellite that can be seen by the rear lobes and finally the sun (often not considered). For ERS-1, for the first implemented sidelobe correction, the contribution coming from the sun as well as the seasonal variation of the Earth contribution has been considered negligible. Only the variation of the Earth contribution with latitude has been considered. That's why the initial on-Earth sidelobe correction is a look-up table providing a temperature according to the latitude of the measurement only.

### 3.3.5 Instrumental issues

There are several known instrumental issues about ERS-2 MWR.

### 3.3.5.1 Gain drop

In June 1996 (after cycle 12 pass #650), there was a sudden decrease of the gain of the 23.8 GHz channel probably due to the failure of an amplifier. This failure leads to a decrease of the gain by a factor about 10. Despite this issue, the sensitivity of the MWR is still good enough to allow the retrieval of the wet tropospheric correction with a good accuracy.

Two corrections are available for this issue [Dedieu et al, 2004]:.

- ✓ Eymard et al. proposed in 2003 a correction based on the survey of the coldest ocean points.
- ✓ Scharroo et al. proposed in 2004 a new correction taking into account a longer time series.

According to [Dedieu et al, 2004], the correction provided by Scharroo et al. is more accurate than the one first provided by Eymard et al because it uses a longer time series and no linear regression). Thus [Dedieu et al. 2004] recommends to user to use Scharroo correction to correct the 23.8GHz brightness temperature for both the gain drop and the subsequent instrumental drift.

### 3.3.5.2 Failure of the tape recorder

Tape recorders were used to record instrument data globally. After the failure of the ERS-2 tape recorder on 22 June 2003, recording is no longer available, thus only data acquired when the satellite is within the visibility area of one of ESA ground stations are available. The area covered by the mission is thus reduced to Europe, North Atlantic, Arctic and western North America.

## 3.4 MWR instrument aboard ENVISAT

ENVISAT MWR design derives from the radiometer embarked on ERS-1/2. It is a two channels microwave radiometer operating at 23.8Gz and 36.5GHz, with a non-balanced Dicke architecture. The radiometric model is very similar to ERS-1/2 one (Figure 3-12).

Although they have similar design, there are hardware differences that will require a specific calibration. For instance, instrument thermal design has been completely revised and active thermal control was included. Moreover, feed horn design is different to optimize beam efficiency, and the reflector is full aluminium made, hence with very different ohmic losses values [L'Abbate et al.].

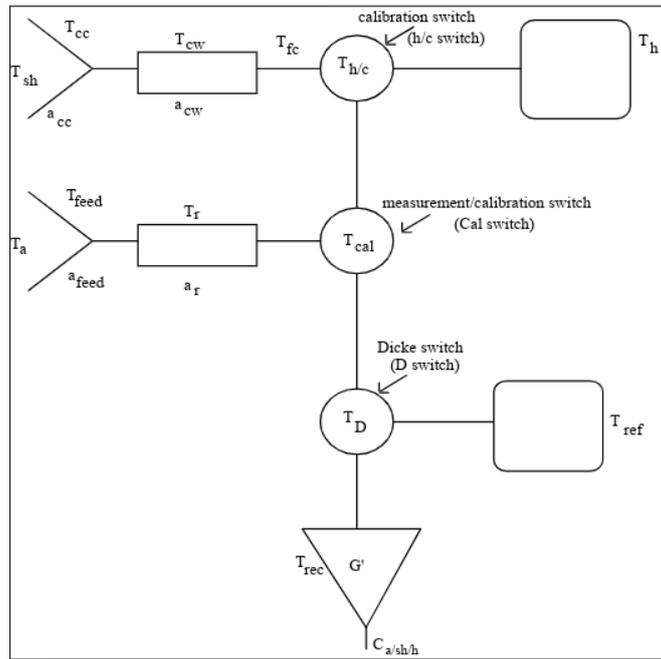


Figure 3-12 : ENVISAT MWR Radiometric model (OP-ID-DOR-MR-0030)

### 3.4.1 Viewing geometry

The radiometer is near nadir looking with the 36.5GHz channel looking forward and the 23.8GHz channel looking backward. This means that a coregistration is required in the processing to have the measurements from both channels at the same location. Beam pointing angles and 3db aperture for both channels are provided in Table 3-8 .

	Beam Pointing	3dB aperture (deg) Along track (across)	3dB footprint (km) Along track (across)
<b>23.8</b>	1.7188°	1.52° (1.52°)	
<b>36.5</b>	1.827°	1.49° (1.49°)	

Table 3-8: ENVISAT MWR characteristics ([OP-ID-DOR-MR-0030])

### 3.4.2 Operation mode

This radiometer operates in non-balanced Dicke mode at a switching frequency of 1.27kHz. During each Dicke cycle, the antenna temperature is compared to the internal hot load. This design allows a lower sensitivity to gain fluctuations than a total power radiometer, but the counterpart is a higher value of the radiometric sensitivity. Indeed, the instrumental noise is average only over half the sampling time because the other half is spent looking at the Dicke load.

Internal calibration is performed by switching the receiver connection to a sky horn or to a second internal reference load.

### 3.4.3 Antenna characteristics

To compute the brightness temperature from the antenna temperature, a good knowledge of the antenna patterns is necessary. The antenna patterns of both channels were measured. The integration of the gain distribution over the solid angle of each contributors provided the efficiencies summarized in Table 3-9.



Since earth sidelobe efficiencies presented in [Obligis, 2006] clearly suffer from erroneous unit conversion from prototype scale factor to percentage to efficiency. The table was updated to keep the order of magnitude close to ERS ones, as well as to ensure that the sum of efficiencies is close to one. Since we have no further geometry information on the antenna surroundings, the SAR efficiency, which represents the portion solid angle of the antenna pattern occupied by the SAR antenna, is kept to zero.

	Main beam	On-Earth	Sky	satellite	SAR
<b>23.8GHz</b>	0.9388	0.017	0.003973	0.04341	0
<b>36.5GHz</b>	0.9838	0.0084	0.000198	0.00216	0

*Table 3-9: ENVISAT MWR main and side lobe efficiencies after [Obligis, 2006]*



## 4 Radar altimetry backgrounds

### 4.1 General principles

The main objective of radar altimetry is to determine the Earth's surface topography beneath the satellite. This is performed by measuring the time taken for an emitted radar pulse to make the round-trip travel time between the satellite and the surface. Subsequently, radar altimetry is classified as "active remote sensing". Because it operates in the microwave spectrum range, one strong asset of radar altimetry is its ability to operate night and day, and regardless of the meteorological conditions which is extremely valuable to provide continuous and uninterrupted measurements, over all types of surfaces.

Radar altimetry includes three key components:

- ✓ Knowing the satellite location at the time of the measurement
- ✓ Estimating the round-trip time travel of the electromagnetic pulses, between satellite and the Earth surface
- ✓ Correcting for different geophysical effects, that create delays in the radar signal propagation, or biases/errors in the height estimation.

The altitude of a satellite is the satellite's distance between the spacecraft center of gravity (COG), and a reference representing the Earth's surface. As explained in the dedicated ESA webpage (<https://earth.esa.int/eogateway/instruments/doris/description>), the altitude of the ENVISAT and ERS satellites could be accurately estimated thanks to a DORIS instrument.

The electromagnetic pulses are sent by a radar altimeter, namely RA and RA-2 for the ERS and ENVISAT missions. The system transmits radio waves down to the ground through a dedicated antenna. The same antenna also receives the backscattered pulses. Several on-board and on-ground processing are then necessary to estimate the precise travel time of the pulses, which can then be converted into a distance: the so-called altimeter range. This is presented in more details in the following sections 4.2 and 4.3. The section 6.1.7 lists and describes the geophysical effects impacting the altimetry measurements, depending on the surface type.

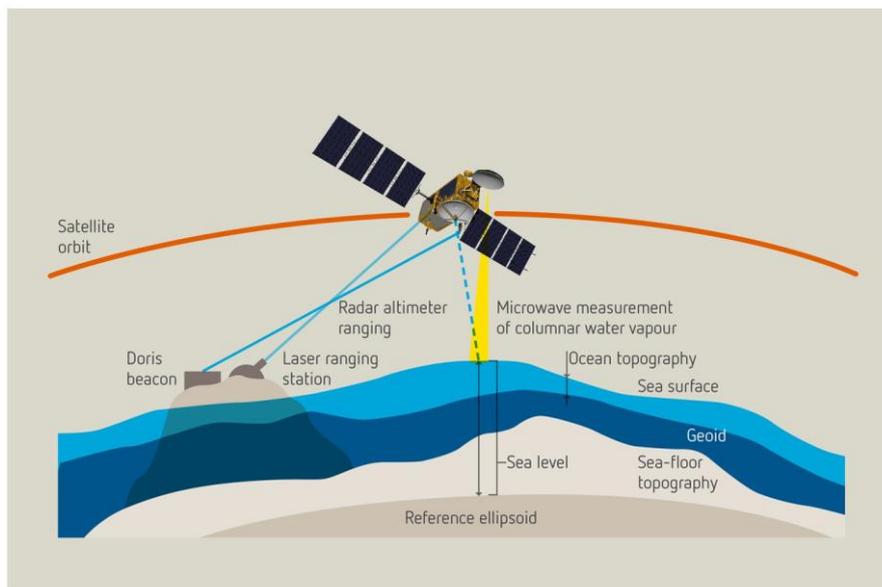


Figure 4-1 : Schematic view of a satellite altimeter, illustrating the measurements taken by the satellite payload, and relationship between main oceanic parameters involved (Credit: Eumetsat)

## 4.2 Level-1 processing radar waveform generation

As explained in sections 3.1 and 3.2, RA emitted 50 Ku-band pulses per 20 Hz radar cycle, versus 100 pulses for RA-2. A deramping technique was applied on-board to each pulse to maximize the Signal-to-Noise Ratio (SNR) and enhance the resolution of the signal. This is done by modulating the frequency of the transmitted signal (i.e. chirping) and mixing it with its replica on board when it is received. This technique is also called “pulse compression” and is commonly used in radar altimetry [Chelton et al., 1989]. The compressed time resolution is inversely proportional to the chirp bandwidth. For ENVISAT, the effective main chirp bandwidth was 320 MHz, resulting in a range gate resolution (or vertical resolution) of 3.125 ns, equivalent to ~46.8 cm when converted to distance. Note that for ERS and ENVISAT, multiple chirp bandwidths were used as explained in sections 3.1.3 and 3.2.2. Several other operations were also applied on-board and all the Ku-band (and S-band for ENVISAT) complex pulses were finally downlinked on-ground.

Figure 4-2 below illustrates the surface sampled (i.e., the footprint) by the radar pulses in LRM, considering a flat surface configuration. Once the pulse hits the surface, the area contributing to the reflected power has an expanding disk shape, that continues to spread into annulus of increasing diameter but constant surface area. For ENVISAT, by considering the whole waveform, the footprint has a diameter of about 15 km when surface is flat. If only the waveform leading edge part is considered (i.e., pulse-limited footprint), the footprint diameter is about 3 km.

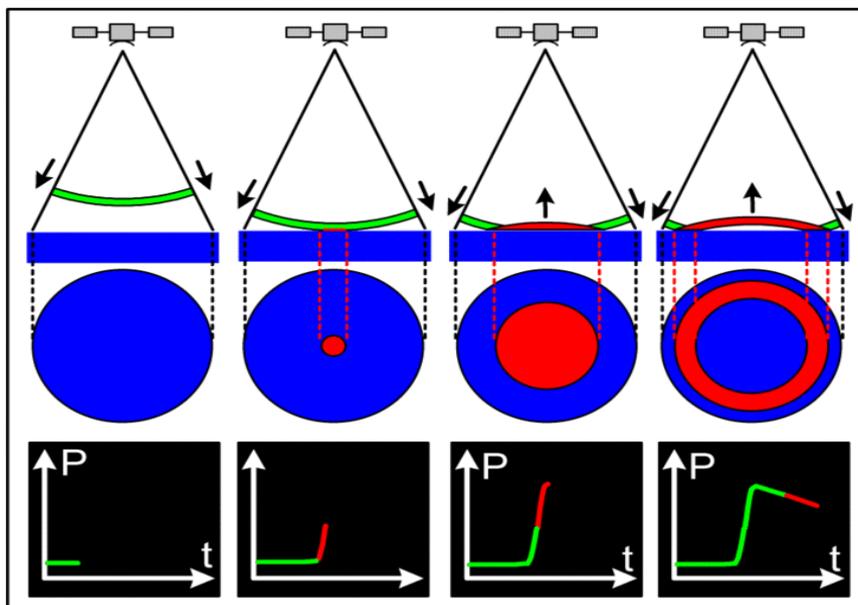


Figure 4-2: Illustration of LRM footprints for different parts of the waveform and considering a flat surface scenario (Credits CNES).

Usually, the individual pulses are emitted at a Pulse Repetition Frequency of about 2 kHz (~1kHz for ERS), so they are uncorrelated. Consecutive complex pulses are aggregated over a radar cycle to build the so-called LRM waveform. This summation reduces the inherent speckle noise affecting the pulses, improving the precision of the geophysical parameters derived from the waveforms during the retracking operation (see section 4.3 ). For LRM altimetry missions operating in Ku-band, the waveforms are usually built over 20 Hz radar cycles, hence lasting ~50 ms. During this time, 100 or 50 uncorrelated pulses (for ENVISAT and ERS respectively) are acquired and aggregated to generate the LRM waveform.

## 4.3 Level-2 processing waveform retracking and geophysical estimations

Geophysical variables are obtained from the on-ground processing by inversion of the on-board radar waveforms -, using a method called “retracking”. The general principle of common retracking algorithms is

to fit a waveform model to the real signal received by the instrument. The inversion (hereafter called estimation procedure) is carried out by minimizing a likelihood function, which characterizes the distance between model and observations. (Brown, 1977; Hayne, 1980).

Over the ocean surface, the different oceanic properties affecting the radar waveforms are well known. Physical models have therefore been established to mathematically describe the waveform shape as a function of these geophysical parameters, namely: the Sea Surface Height (SSH), the Significant Wave Height (SWH) and the backscattering coefficient (Sigma0). For the newly developed “Adaptive Retracker” applied on ENVISAT in the frame of the FDR4ALT project, a fourth geophysical parameter is fitted, called the “pseudo-mss” (mean square slope) [Tourain, 2021] allowing to model different types of waveforms from diffuse waveforms observed over the ocean to peaky waveforms observed over very specular surfaces. Such retracking algorithms, based on a physical formulation of the measured altimetry signal, are classified as “physical retrackers”.

Figure 4-3 below illustrates typical ERS and ENVISAT waveforms measured over ocean with the associated fitted model, used to derive the geophysical parameters. ERS waveforms represent a challenge, as they are shorter (64 range gates) and the reference tracking point is in the middle of the windows, leaving only ~30 useful data points to fit. Furthermore, the number of averaged pulses is lower for ERS (50 versus 100 for ENVISAT) meaning that the speckle noise reduction is lower, making it even harder for a retracker to fit a model.

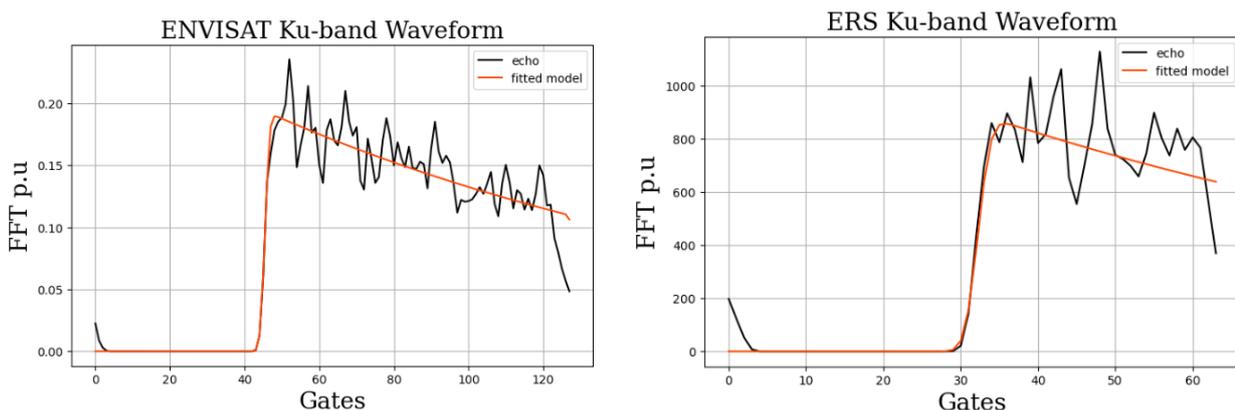


Figure 4-3 : In the left panel, illustration of ENVISAT waveforms over ocean. In the right panel, an example of ERS waveform measured over ocean (black), with a functional fit performed by a physical retracker (red) to estimate the oceanic geophysical parameters.

Over continental and sea ice surfaces, the interactions between the emitted radar signal and the surface are more complex. This is mainly due to surface heterogeneities at the footprint scale, in terms of backscatter properties and/or topography variations. In addition, over snow surfaces the Ku-band radar wave penetrates the snowpack, creating a sub-surface volume scattering signal backscattered to the altimeter. The development of waveform physical models is therefore much more complicated. Consequently, empirical retrackers are generally employed to derive the geophysical parameters from the waveform measured over inland waters, land ice and sea ice, as described in sections 6.4, 6.5 and 6.8.

The estimation of surface topography is the main goal of radar altimetry. As explained in section 4.1, this can be achieved by knowing the satellite altitude, estimating the altimeter range (i.e., satellite-surface distance), and correcting for different geophysical effects. The formulation can be summarized as follow:

$$\text{Surface topography} = \text{satellite altitude} - (\text{altimeter range} + \text{geophysical corrections})$$



The altimeter range can be decomposed into the sum of two parameters, as follow:

$$\text{altimeter range} = \text{tracker range} + \text{epoch}$$

**The tracker range** is a known parameter controlled by the altimeter, using a tracking mode, as seen in sections 3.1.2 and 3.2.1. It is dynamically updated at each 20 Hz radar cycle to adjust the receiving window, so the useful backscattered signal can be captured by the altimeter. The tracker range corresponds to the distance between satellite COG and the reference tracking sample. For ENVISAT, the reference samples are the gate index “45”, and gate index “33” for ERS. The tracker range is usually corrected from all instrumental corrections. More information about the range computation for ENVISAT and ERS are available in section **Erreur ! Source du renvoi introuvable..**

**The epoch parameter**, or retracking point, is estimated during the retracking operation. It corresponds to the waveform leading edge position within the window analysis, relative to the reference tracking sample. The waveform energy at the epoch position is associated with a “mean topography level” of the surface sampled by the altimeter at nadir or Point Of Closest Approach (POCA) in case of a non-flat surface (as occurs over land ice, see section 6.4).

Radar altimetry also allows to derive other geophysical parameters, especially the SWH (significant wave height) that is derived from the **sigma composite** (sigmac) which corresponds to the width of the leading edge of the fitted waveform. More information about the SWH computation can be found in section 6.1.4.

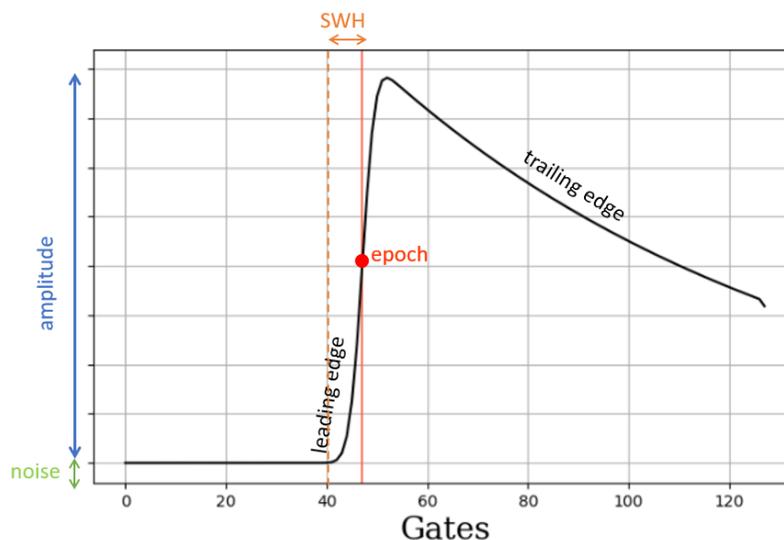


Figure 4-4: Modeled waveform, divided into 128 samples (or range gates). The retracking process attempts to identify the point on the waveform’s leading edge (epoch) that corresponds to the “mean surface level”. The width of the leading edge is identified as the sigma composite that can be converted to a significant wave height value using a dedicated formula.

The different methodologies implemented in the FDR4ALT processing baseline to estimate the altimeter range, SWH and Sigma0 differ depending on the surface as later explained in section 6.1.3. As introduced above, the altimeter range needs to be corrected for different geophysical effects, in particular for several atmospheric delays, and tidal movements. A description of the geophysical corrections applied to the altimeter range, for each product type, is given in section 6.1.7.

# 5 FDR4ALT products overview and conventions

## 5.1 Product types

The FDR4ALT project outcome is represented by 8 different data collections, each of them covering a specific FDR or TDP. Two data collections are FDR (Fundamental Data Record) products:

- ✓ FDR Altimetry
- ✓ FDR Radiometry

The six other data collections are TDP (Thematic Data Products):

- ✓ TDP Land-Ice
- ✓ TDP Sea-Ice
- ✓ TDP Ocean & Coastal Topography
- ✓ TDP Ocean Waves
- ✓ TDP Inland Waters
- ✓ TDP Atmosphere

Each of these 8 different product types has a unique identity and its own DOI, but shares the same format, notations, conventions, and overall general structure. The FDR4ALT project aims at having unified FDRs and TDPs, while respecting the needs of each FDR/TDP to have the most relevant and useful products possible.

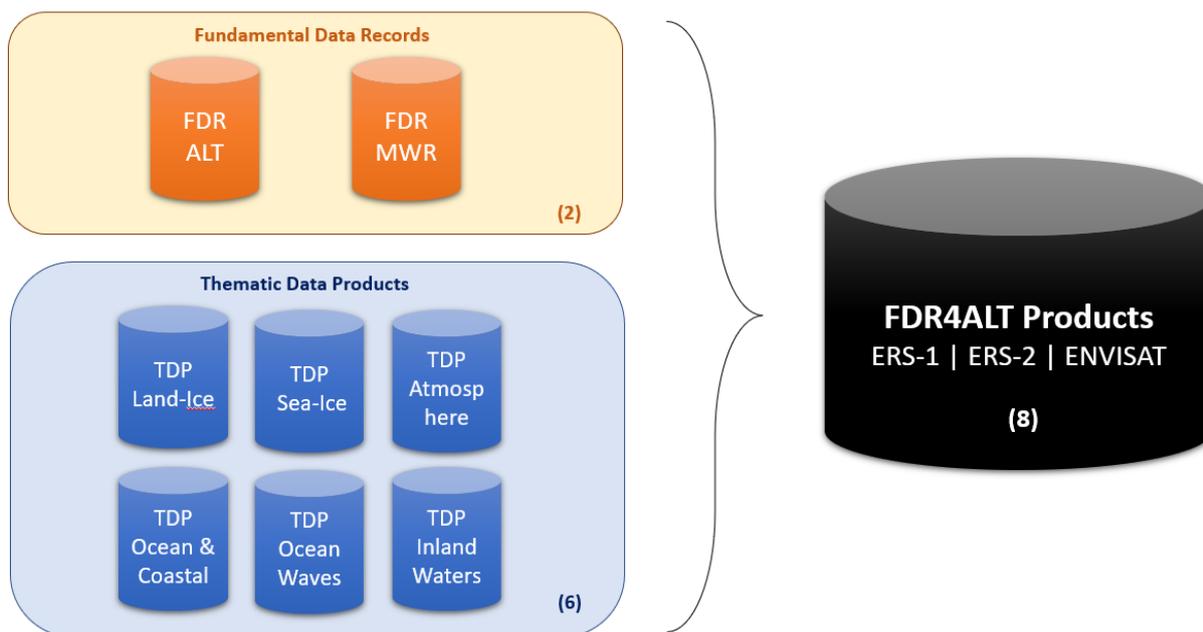


Figure 5-1 : Overview of FDR4ALT product types

## 5.2 FDR and TDP definition

The FDR and TDP do not address the same needs and objectives:



FDRs address spatial agency needs to provide scientific community with robust altimetry mission time series (altimeter and radiometer), including archiving and documentation. This is the first mandatory step to build TDP products for different applications.

TDPs address more specifically the user needs by providing dedicated products with suited geophysical parameters.

It is clear from the previous FDR and TDP descriptions that these definitions are very generic and must be adapted to the specific context of Altimeter and Radiometer records. This will be detailed in each specific section.

## 5.2.1 Fundamental Data Records

In the frame of the Long-Term Data Preservation (LTDP+) program, ESA has established a specific line of action aiming at generating and maintaining Fundamental Data Records. The crucial importance of satellite long term data records has been recognised. The FDR4ALT project is concerned with measurements from altimeter and radiometer instruments. The objective of the FDR4ALT project is to consolidate such products in order to reinforce multi-disciplinary applications and maximize the scientific return of each mission.

FDRs satisfy ESA needs for:

- long term EO data preservation,
- unified and coherent long-term time series,
- quality improvement and valorisation of MWR, RA & RA-2 level 1 products in term of content but also in terms of file format.

## 5.2.2 Thematic Data Products

For the Thematic Data Products, we have collected our understanding of the user needs for the different applications, summarized the context of thematic products in altimetry and radiometry and finally showed how our description of products answers to these needs while respecting the overall picture of the altimetry products.

## 5.3 Product coverage

Figure 5-2 and Figure 5-3 represent the coverage of the FDR4ALT products with respect to the missions' durations.

The FDR4ALT altimetry products cover the whole ENVISAT mission but not the whole ERS-1 and ERS-2 missions as they are based on the REAPER reprocessing that stopped at June 1996 for RA ERS-1 (the altimeter switched off in June 1996 but the mission continued until 2000), and at July 2003 for ERS-2 RA data (failure of the tape recorder, see section 3.1.5.2).

On the other hand, all level-1 radiometry products were recomputed in the frame of the FDR4ALT project, allowing to recover all available data and leading to a more comprehensive coverage for the ERS missions.

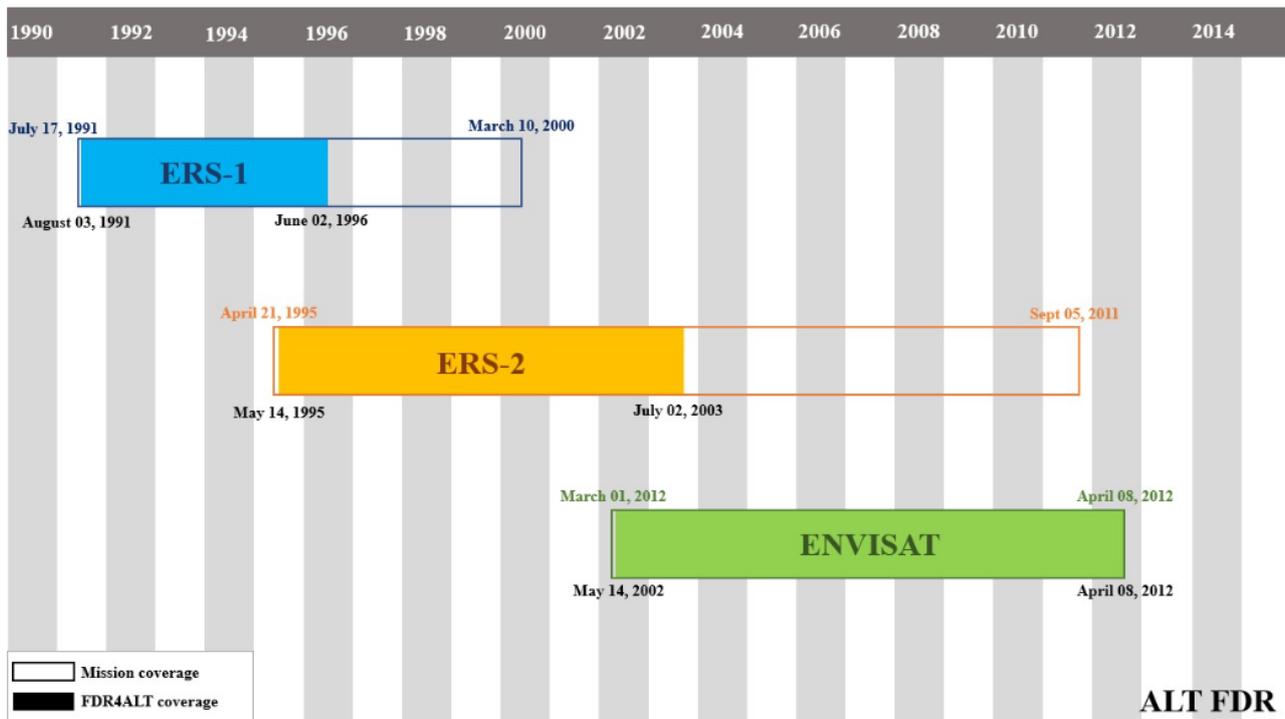


Figure 5-2 : FDR4ALT products coverage for altimetry

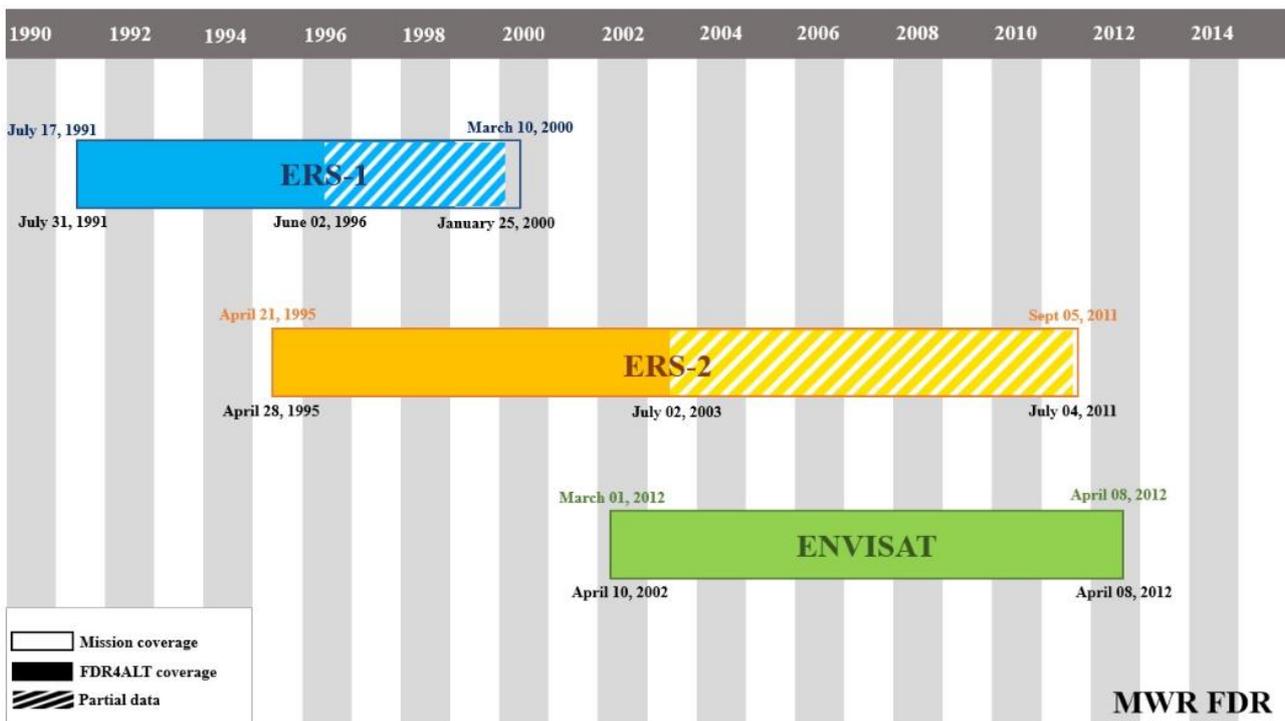


Figure 5-3 : FDR4ALT products coverage for radiometry

## 5.4 Data format

### 5.4.1 File format and CF convention

The NetCDF data format has been chosen to store the FDR4ALT products (one NetCDF file per pass). This format is extremely flexible, self-describing and has been adopted as a de-facto standard for many

operational Earth Observation (EO) systems. What is more, the format follows the Climate and Forecast NetCDF conventions CF-1.8. A NetCDF file specifies dimensions, variables, groups, and attributes, which all have a name by which they are identified.

Section 7 contains information to handle NetCDF files.

## 5.4.2 NetCDF grouping strategy

NetCDF-4 added support for hierarchical groups within NetCDF files. The FDR4ALT project uses the NetCDF-4 grouping strategy. This decision was made to have user-friendly products, by separating the “main” variables from the more “expert” ones. For instance, geophysical corrections are included in the “expert” group, as they are not the main variables of the product, as opposed to e.g. the Sea Level Anomaly or the Significant Wave Height.

	Number of groups (Including sub-groups)	Group names
<b>FDR ALT</b>	ERS: 3	main, expert/ancillary_cal_ptr, expert/ancillary_cal_lpf
	ENVISAT: 6	main, main/Ku, main/S, expert/ancillary_cal_ptr, expert/ancillary_cal_lpf, expert/ancillary_2K
<b>FDR MWR</b>	3	main, expert/ancillary_mwr, expert/ancillary_thermal
<b>TDP Land-Ice</b>	2	main, expert
<b>TDP Sea-Ice</b>	2	main, expert
<b>TDP Ocean &amp; Coastal</b>	4	main, expert (both declined in data_20 and data_01)
<b>TDP Atmosphere</b>	2	main, expert
<b>TDP Inland Water</b>	2	main, expert
<b>TDP Ocean Waves</b>	1	/

Table 5-1 : NetCDF groups available for each FDR4ALT product type

Figure 5-4 displays the content of an example NetCDF file. All FDR4ALT products follow this structure.

Global attributes appear after the file name. Then, for each group, the description of the dataset takes the form:

```
group name {
    dimensions: ...
    variables: ...
    data: ...
}
```

NetCDF dimension declarations appear after the dimensions keyword, NetCDF variables and attributes are defined after the variables keyword, and variable data assignments appear after the data keyword. CDL statements are terminated by a semicolon. Spaces, tabs, and newlines can be used freely to improve readability. Comments in CDL follow the characters ‘//’ on any line.

Note that for this project, there are no group attributes but only global attributes.



```

netcdf example { ← file name
// global attributes:
:global_attribute_1 = "XXX" ;
:global_attribute_2 = "XXXX" ;
...
group: main {
  dimensions:
  time = XXXX ;
  variables:
  double time(time) ;
  time: FillValue = 9.96920996838687e+36 ;
  time:long_name = "time in UTC" ;
  time:standard_name = "time" ;
  time:calendar = "gregorian" ;
  time:units = "days since 1990-01-01 00:00:00.0" ;
  int latitude(time) ;
  latitude: FillValue = 2147483647 ;
  latitude:standard_name = "latitude" ;
  latitude:units = "degrees north" ;
  latitude:scale_factor = 1.e-06 ;
  latitude:add_offset = 0. ;
  latitude:valid_min = -90000000 ;
  latitude:valid_max = 90000000 ;
  latitude:comment = "Positive latitude is North latitude, negative latitude is South latitude." ;
  int longitude(time) ;
  longitude: FillValue = 2147483647 ;
  longitude:standard_name = "longitude" ;
  longitude:units = "degrees east" ;
  longitude:scale_factor = 1.e-06 ;
  longitude:add_offset = 0. ;
  longitude:valid_min = 0 ;
  longitude:valid_max = 359999999 ;
  longitude:comment = "East longitude relative to Greenwich meridian." ;
} // group main

group: expert {
  dimensions:
  time = XXXX ;
  variables:
  double time(time) ;
  time: FillValue = 9.96920996838687e+36 ;
  time:long_name = "time in UTC" ;
  time:standard_name = "time" ;
  time:calendar = "gregorian" ;
  time:units = "days since 1990-01-01 00:00:00.0" ;
  int latitude_238(time) ;
  latitude_238: FillValue = 2147483647 ;
  latitude_238:standard_name = "latitude of 23.8GHz channel" ;
  latitude_238:units = "degrees north" ;
  latitude_238:scale_factor = 1.e-06 ;
  latitude_238:add_offset = 0. ;
  latitude_238:valid_min = -90000000 ;
  latitude_238:valid_max = 90000000 ;
  latitude_238:comment = "Positive latitude is North latitude, negative latitude is South latitude." ;
  int longitude_238(time) ;
  longitude_238: FillValue = 2147483647 ;
  longitude_238:standard_name = "longitude of 23.8GHz channel" ;
  longitude_238:units = "degrees east" ;
  longitude_238:scale_factor = 1.e-06 ;
  longitude_238:add_offset = 0. ;
  longitude_238:valid_min = 0 ;
  longitude_238:valid_max = 359999999 ;
  longitude_238:comment = "East longitude relative to Greenwich meridian." ;
} // group expert

```

Figure 5-4 : FDR4ALT NetCDF structure with two groups (main and expert)

## 5.5 Conventions

### 5.5.1 Filename

The file naming convention for the FDR4ALT files is the following:

**MMM\_F4A\_BBBBBBBBBB\_LLLLLL\_CCC\_PPPP\_YYYYMMDDTHHmss\_YYYYMMDDTHHmss\_VVV.ZZ**

<b>MMM</b>	Mission ID
<b>BBBBBBBBBB</b>	ESA File Type
<b>CCC</b>	Cycle Number
<b>LLLLLL</b>	Region of interest (Land-Ice TDP only)
<b>PPPP</b>	Pass Number
<b>VVV</b>	Product Version number

The mission ID is ER1, ER2 or EN1 for ERS-1, ERS-2, and ENVISAT respectively.



The start and end date respect the ISO 8601 standard using **YYYYMMDDTHHmms**:

<b>YYYY</b>	Year
<b>MM</b>	Month
<b>DD</b>	Day
<b>HH</b>	Hour
<b>mm</b>	Minutes
<b>ss</b>	Seconds

The ESA File type is a 10 chars string indicating the type of data (FDR or TDP), sensor (ALT or MWR) and surface (only for TDPs):

<b>FDR Altimetry</b>	ALT_FDR__
<b>FDR Radiometry</b>	MWR_FDR__
<b>TDP Sea-ice</b>	ALT_TDP_SI
<b>TDP Land-ice</b>	ALT_TDP_LI
<b>TDP Inland Water</b>	ALT_TDP_IW
<b>TDP Atmosphere</b>	MWR_TDPATM
<b>TDP Ocean Waves</b>	ALT_TDP_WA
<b>TDP Ocean &amp; Coastal Topography</b>	ALT_TDP_OC

Area of interest is used only for two product types:

- For the Land-Ice TDP: it can be either GREENL or ANTARC, if the file contains data from Greenland and Antarctica, respectively.
- For the Sea-Ice TDP: it can be either NORTH\_ or SOUTH\_, if the file contains data from the northern or southern hemisphere, respectively.

Products version number is implemented as VXX, XX being the version number.

The filename extension for NetCDF files is .nc by convention.

## 5.5.2 Products slicing

The FDR4ALT product files are organized according to pass number (half-orbits). So, for instance for ENVISAT, in one cycle during the repetitive 35-day orbit, there are 1002 files.

Note that this choice implied for the project to have ORF (Orbit Revolution File) files (cycle/pass number lists) without any gaps. In the frame of this study, the completeness assessment of existing ORF files has been performed. New ORF files for ERS-2 have been defined to ensure optimal completeness and slicing of the products.

All the FDR4ALT products files are provided pole-to-pole.

## 5.5.3 Time conventions

Times are UTC, referenced to January 1, 1990 00:00:00.00 and implementing the ISO 8601 standard.



For example, 29<sup>th</sup> December 1991 at 01:10:00 UTC will be written “19911229T011000” in the file name and will be written “19911229T011000.000000” in the global attributes *history*, *first\_meas\_time* and *last\_meas\_time*

## 5.6 Data rates

There are different data rates in the FDR4ALT products:

- ✓ High rate of 20 Hz, which is the standard rate for the FDR ALT products
- ✓ Intermediate rate of 5 Hz which is the standard for the L2P ocean wave products
- ✓ Low rate of 1 Hz that is relevant for the Ocean & Coastal TDP
- ✓ Intermediate rate of 7 Hz that is the native rate for the radiometric data
- ✓ Native PRF rate of the RA-2 instrument (1.8 KHz) for the FDR ALT products
- ✓ Calibration rates, specific to the FDR ALT products that store the calibration data.

These different rates are managed using the NetCDF4 groups.

Rate	20 Hz	5 Hz	1 Hz	7 Hz	1.8 KHz	PTR data	LPF data
<b>FDR ALT</b>	X				X	X	X
<b>FDR MWR</b>				X			
<b>TDP Land-Ice</b>	X						
<b>TDP Sea-Ice</b>	X						
<b>TDP Ocean &amp; Coastal</b>	X		X				
<b>TDP Ocean Waves</b>		X	X				
<b>TDP Inland-Water</b>	X						
<b>TDP Atmosphere</b>				X			

Table 5-2 : FDR4ALT products data rates



## 6 FDR4ALT products content

Please note that a complete description of the format of the FDR4ALT products (with all fields attributes) is available in the Products Requirements and Format Specification Document [D-2-02].

### 6.1 Common to all product types

#### 6.1.1 Orbit

New orbit solutions have been developed in recent years for ENVISAT and ERS. The CNES POD team's POE-F solution was compared to the previous one (see the Round Robin Assessment Document [D-2-03]) and was selected for this project to be used in all FDRs and all TDPs except the Sea-Ice TDP. In addition, careful evaluation of the various REAPER v2 solutions has shown that the DEOS solution [Otten, 2019] has the best performance for both ERS-1 and ERS-2 and is recommended to be used as a reference by the POD team. The FDR4ALT project followed this recommendation and therefore the DEOS solution was selected for this project to be used in all FDRs and TDPs except the Sea-Ice TDP.

All TDP and FDR contain the 3 key variables presented in Table 6-1. Hence they are not mentioned again in the sections dedicated to FDR/TDP, for the sake of consistency.

Parameter	Variable name	unit
Latitude	<i>latitude</i>	degrees
Longitude	<i>longitude</i>	degrees
Altitude	<i>altitude</i>	meters

Table 6-1 : Table of variables for satellite location

Please note that the Sea-Ice TDP did not benefit from these new orbit solutions due to project time constraints. Therefore, the orbits used for the Sea-Ice TDP are those of the ENVISAT V3.0 and ERS REAPER projects.

#### 6.1.2 Cycle and pass definition for ERS-2

The ORF gives the definition of cycles and passes. As the FDR4ALT products files are organized according to pass number (half orbits), it was therefore mandatory to have a complete definition of cycles and passes of the three missions. In the frame of this project, no complete ERS-2 ORF was found from previous projects, therefore extra effort was spent to obtain a complete ORF. Fortunately, ERS-2 kept the same repeat cycle throughout the mission lifetime. Dedicated CLS specific tools were used to propagate cycle and pass definition times starting from a reference pass of the REAPER ORF and taking into account the gyro-less mode transition. The file obtained covers the whole ERS-2 mission without any gaps and is provided to the users as an auxiliary data file (format described in the Products Requirements and Format Specification Document [D-2-02]).

#### 6.1.3 Retracker

In the frame of this project, the Adaptive Retracker [Tourain et al., 2021] has been successfully applied to the ENVISAT mission thanks to a new method to average the PTR arrays that are essential for the Adaptive, as they are included directly in the analytical model used to fit the backscattered waveform (see section 6.2.4).

As explained in [Tourain et al., 2021], the main outputs of the Adaptive (Range, SWH and Sigma0) show great improvements compared to the previous reference for retracking oceanic echoes in terms of noise reduction,

reduction of biases and ability to detect events such as rain cells and blooms. It is also very performant on other surfaces such as inland waters and sea-ice, thanks to its ability to retrack peaky echoes.

In the frame of FDR4ALT, the Adaptive was used for the Ocean & Coastal TDP as well as for the Ocean Waves TDP. The Sigma0 Adaptive was also used in the Atmosphere TDP as an input of the processing baseline. The Adaptive shows also promising results for application on other surfaces, but the outcome of the Round Robin exercise selected other retracker for the Sea-Ice TDP, the Land-Ice TDP, and the Inland Waters TDP (Round Robin Assessment Report Document [D-2-03])

Table 6-2 summarizes the retracker used for the main group of each TDP. Note that outputs from other retracker are provided in the expert groups of some of the TDPs. For more information about the content of each TDP, see the dedicated sections below.

More information about the validation of the Adaptive retracker for ENVISAT is available in the Product Validation Report [D-4-02].

Retracker	Ocean & Coastal	Ocean Waves	Sea-Ice	Land-Ice	Inland Waters	Atmosphere (*)
ENVISAT	Adaptive	Adaptive	TFMRA	ICE-1	ICE-1	Adaptive
ERS	MLE3	MLE3	TFMRA	ICE-1	ICE-1	MLE3

Table 6-2 : List of the retracker used for each TDP.

(\*) The Atmosphere TDP does not directly include retracker input as main variables but uses the Sigma0 as input for the wet tropospheric correction computation.

## 6.1.4 Look-up tables

Look-up tables (LUT) have been historically used to compensate for the Gaussian modelling of the PTR in the MLE3/MLE4 Ocean retracker [Thibaut, 2004].

As explained in 6.1.3, the Adaptive retracker was successfully applied to ENVISAT. Thanks to the introduction of the real instrument PTR, no look-up tables are needed anymore to correct for the Gaussian approximation of the PTR for ENVISAT, which is a great improvement. Therefore, no LUT correction needs to be applied to the range computation and the Significant Wave Height (SWH) can be directly derived from the Sigma composite SigmaC such as:

$$SWH = 2 * V_{light} * SigmaC$$

where  $V_{light}$  is the speed of light

For ERS, it should be noted that no look-up tables have been computed for REAPER nor in the frame of this project. Note that for the ENVISAT MLE3, which was the reference for the V3.0 reprocessing, no look-up table was applied on the range as it was quite negligible, but a look-up table was applied for the SWH.

## 6.1.5 Tracker range and instrumental corrections

### 6.1.5.1 ERS-1/2

For ERS, the relative tracker (“tracker range” in the ALT FDR) includes all instrumental corrections. Therefore, a range must be computed as follows:

$$Range = tracker\_range + epoch$$



where epoch is the epoch from the retracker.

### 6.1.5.2 ENVISAT

For ENVISAT, the relative tracker (“tracker range” in the ALT FDR) includes all instrumental corrections except for the doppler correction. Therefore, a range must be computed as follows:

$$\text{Range} = \text{tracker\_range} + \text{epoch} + \text{range\_cor\_doppler}$$

where epoch is the epoch from the retracker.

### 6.1.6 Distance to shoreline from GSHHG

In the FDR4ALT products, the information of distance to shoreline used comes from GSHHG [Wessel et al, 1996]. More information about it can be found here: <https://www.soest.hawaii.edu/pwessel/gshhg/>

### 6.1.7 Geophysical corrections

Among the eight FDR4ALT product types, four of them deliver a key variable derived from the range that has been corrected from geophysical effects.

Each surface had different problematics, and the geophysical corrections to apply differ from one TDP to another. Table 6-3 summarizes all geophysical corrections that have been applied to each TDP.

Geophysical Correction	Ocean & Coastal TDP	Sea-Ice TDP	Land-Ice TDP	Inland Waters TDP
<b>Ionospheric Correction</b>	GIM or NIC09 model	GIM or NIC09 model	GIM or NIC09 model	GIM or NIC09 model
<b>Wet Tropospheric Correction</b>	From ATM TDP (ANN)	ECMWF model	ERA interim	ERA interim
<b>Dry Tropospheric Correction</b>	ERA5 model	ERA5 model	ERA interim	ERA interim
<b>Mean Sea Surface</b>	SIO/CNESCLS15/DTU15	DTU2021 model	/	/
<b>Load Tide</b>	<i>Included in Ocean Tide</i>	<i>Included in Ocean Tide</i>	FES14B model	/
<b>Ocean Tide</b>	FES14B model	FES14B model	FES14B model	/
<b>Internal Tide</b>	Zaron model (HRET8.1, 2019)	/	/	/
<b>Dynamic Atmospheric Correction</b>	TUGO ERA5 model	/	/	/
<b>Inverse Barometer Correction</b>	<i>Included in DAC</i>	ECMWF model	ECMWF model	/
<b>Pole Tide correction</b>	DESAI 2015 (2017 recom.for Mean Pole Location)	Wahr 1985	Wahr 1985	DESAI 2015
<b>Solid Earth Tide Correction</b>	Cartwright / Edden 1973	Cartwright / Edden 1973	Cartwright / Edden 1973	Cartwright / Edden 1973
<b>Mean Dynamic Topography</b>	CLS/CNES 2018	/	/	/

Table 6-3 : List of the geophysical corrections applied to range for each TDP using geophysical corrections.

Please note that the GIM model for the **ionospheric correction** is not available before January 1<sup>st</sup>, 1994. Therefore, for all TDPs, the GIM model has been used for ENVISAT and ERS-2. For ERS-1, the GIM model has been used after 1994, and the NIC09 model has been used before 1994.

### 6.1.8 Uncertainties

In each FDR4ALT product, an uncertainty is associated with each measurement **along-track**. In the following sections, the uncertainty method is briefly described for each FDR/TDP. For more information about the uncertainty computation and how to use it, please refer to the FDR4ALT Uncertainty Characterization Report Document [D-5-02].



## 6.2 ALT FDR

### 6.2.1 Introduction to the thematic

According to section 2.2 and the data preservation objectives, the main goal of the ALT FDR is to provide the scientific community with a well-designed product where all the altimeter-related parameters can be easily found and used for any need, either for studies or for monitoring of the instrumental behaviour of the on-board altimeter at any time and location and throughout the whole lifetime. For that purpose, this section describes the process of generating FDR ALT NetCDF files from different data sources for the ERS-1/-2 and ENVISAT satellites and the use of final products by end-user. Indeed, the starting points of the reprocessing activity were the REAPER products and the V3.0 products respectively for ERS and ENVISAT, which means that no Level 1 was recomputed and that these products were considered of good quality to be directly used as inputs of the ALT FDR.

The ALT FDR addresses level-0 and level-1 altimeter-related variables which mainly consist of providing waveforms and all the instrumental parameters describing the altimeter operating status and configuration through the satellite lifetime. Level-0 refers to the calibration data of the altimeter itself derived from specific in-flight internal calibration sequences, namely CAL1 (known as Point Target Response) and CAL2 (known as Low Pass Filter, LPF) as explained in 3.1.4. Level-1 products provide calibrated radar waveforms and all the altimeter on-board parameters (see 4.2). Most of the level-1 variables comes directly from the last ERS and ENVISAT reprocessing and remained unchanged. Note that same names are used in the ALT FDR products to ensure a clear consistency. Figure 6-1 illustrates the general production scheme of the ALT FDR NetCDF products and is an overview of the multiple data sources handled. In addition to the L0 and L1 mentioned before, the product includes added values and user-friendly parameters as follows:

- ✓ Distance to the shoreline (ERS, ENVISAT)
- ✓ Surface type flag (ERS, ENVISAT)
- ✓ Waveform classification (ERS, ENVISAT)

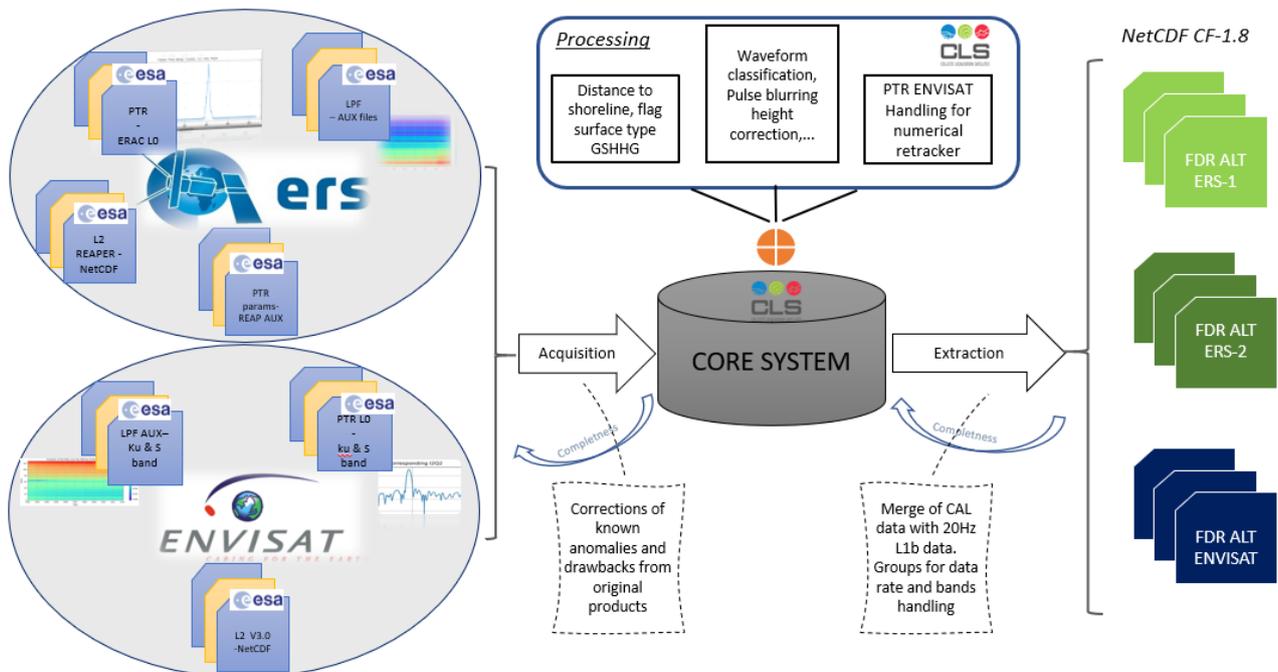


Figure 6-1 : General scheme of the ALT FDR processing chain.

The ALT FDR falls into two different groups of products for ERS and ENVISAT respectively (ERS-1 and ERS-2 being separated but identical in terms of format). Indeed, the NetCDF files are built using groups and subgroups to separate data origin and may be different according to the mission specificities. Note that the ALT FDR is the only FDR4ALT product that has a different format depending on the mission. Therefore, the groups and dimensions are detailed in the following tables:

❖ **For ERS-1 and ERS-2:**

Group	Number of variables	Dimensions
main	59	time, fft_sample_ind_ku
expert/ancillary_cal_ptr	10	time
expert/ancillary_cal_lpf	1	fft_sample_ind_ku

Table 6-4 : Summary table of the ERS ALT FDR product.

The main group contains instrumental parameters from the Ku-band altimeters and the associated quality flags. Also, as described in section 6.2.1, additional user-friendly variables are provided to encourage product use. The expert group contains two subgroups:

- ✓ ancillary\_cal\_ptr: Point Target Response related parameters
- ✓ ancillary\_cal\_lpf: Low Pass Filter array

The following tables list all the variables in the NetCDF file for each group and subgroup:

Main group (20Hz)			
a_agc_coeff	/	power_waveform	count
a_htl_coeff	/	qual_range_cor_net_instr	/
a_stl_coeff	/	qual_wf_bad_le	/
agc	dB	qual_wf_high_peakiness	/
agc_cal_factor	dB	qual_wf_low_peakiness	/
agc_disc_out	count	qual_wf_low_power	/
alt_state_flag	/	qual_wf_low_var	/
alt_state_flag_chirp_type	/	qual_wf_noisy	/
alt_state_flag_lost_track_alarm	/	qual_wf_not_tracking	/
alt_state_flag_lost_track_assert	/	qual_wf_reject	/
alt_state_flag_tracking_surface	/	range_cor_cog	m
alt_state_flag_tracking_type	/	range_cor_doppler	m
altitude	m	range_cor_doppler_slope	m
altitude_rate	m/s	range_cor_net_instr	m
avail_orbit_flag	/	rx_dist_coarse	s
b_agc_coeff	/	rx_dist_fine	s
b_htl_coeff	/	rx_offset	s
b_stl_coeff	/	scaling_factor	dB
distance_to_coast	m	slope	/
fft_sample_ind_ku	count	sptr_jump_corr	s
htl_beta_branch	/	stl_disc_out	/
htl_disc_out	s	surface_type	/
inst_agc_corr	dB	time	days
latitude	degree_north	tracker_range	m
longitude	degree_east	waveform_main_class	/
mcd	/	waveform_main_class_score	/
noise_floor	count	waveform_second_class	/
num_flight_cal_meas	count	waveform_second_class_score	/
p_ref	count	window_delay	s
peakiness	/		

Table 6-5 : ERS table of variables of the main group.

Expert groups	
ancillary_cal_ptr	
counter	/
main_lobe_amplitude_ice	dB
main_lobe_amplitude_ocean	dB
main_lobe_width_ice	dB
main_lobe_width_ocean	dB
n_stack	/
ptr_method	/
time	days
time_delay_ice	ps
time_dealy_ocean	ps
ancillary_cal_lpf	
lpf_ku	count

Table 6-6 : Table of variables of the calibration subgroups from the expert group.

❖ For ENVISAT:

Group	Number of variables	Dimensions
main	43	time, fft_sample_ind_ku ,fft_sample_ind_s , dft_sample_ind_ku
main/Ku	26	time, fft_sample_ind_ku , dft_sample_ind_ku
main/S	15	time, fft_sample_ind_s
expert/ancillary_2K	12	time, fft_sample_ind_ku
expert/ancillary_cal_ptr	2	ind_ptr
expert/ancillary_cal_lpf	1	fft_sample_ind_ku

Table 6-7 : Summary table of the ALT FDR ENVISAT product.

The main group contains two subgroups for Ku and S-band related parameters. The expert group contains three subgroups:

- ✓ ancillary\_cal\_ptr: Point Target Response array for both Ku and S band
- ✓ ancillary\_cal\_lpf: Low Pass Filter array
- ✓ ancillary\_2K: 1.8 KHz data

The following tables list all the variables in the NetCDF file for each group and subgroup:

Main Group (18Hz)		Ku	S
agc	dB	✓	✓
agc_cor	dB	✓	✓
alt_instr_flag_flight_cal	/	✓	✓
chirp_band	/	✓	
chirp_band_qual	/	✓	
flag_loss			✓
flag_waveform_dft	/	✓	✓
flight_cal_numval	/	✓	
mcd_flag_anomaly	/		✓
open_sea_ice_flag	/	✓	
peakiness	count	✓	✓
power_waveform	fft power unti	✓	✓
range_cor_doppler	m	✓	✓
range_cor_doppler_slope	m	✓	✓
range_cor_doppler_path	m	✓	✓
range_cor_doppler_path_diff	m	✓	
range_cor_net_instr	m	✓	✓
rx_delay_coarse	count	✓	
rx_delay_fine	count	✓	
scaling_factor	dB	✓	✓
sig0_cor_calibration	dB	✓	✓
tracker_range	m	✓	✓
tracker_range_qual	/	✓	
waveform_dft	count	✓	
waveform_main_class	/	✓	
waveform_main_class_score	/	✓	
waveform_second_class	/	✓	
waveform_second_class_score	/	✓	

Table 6-8 : ENVISAT table of variables of the subgroups Ku and S of the main group



Main group (18Hz)	
agc_noise_power	dB
alt_instr_flag_chain_id	/
alt_instr_flag_ptr_band_id	/
alt_instr_flag_red_error	/
altitude	m
altitude_rate	m/s
avail_orbit_flag	/
dft_sample_ind_ku	/
distance_to_coast	m
fault_id	/
fft_sample_ind_ku	/
fft_sample_ind_s	/
flag_cal_selection	/
flag_man_plane	/
flag_man_pres	/
flag_uso_anomaly	/
flag_uso_qual	/
instr_mode_id_db	/
instr_mode_id_sp	/
latitude	degree_north
longitude	degree_east
mcd_flag_agc_fault_id	/
mcd_flag_fault_id	/
mcd_flag_obdh	/
mcd_flag_orb_state_rest	/
mcd_flag_packet_length	/
mcd_flag_proc_error	/
mcd_flag_rx_delay_fault_id	/
mcd_flag_uso	/
mcd_flag_waveform_fault_id	/
noise_power	count
nominal_tracking	/
off_nadir_angle_pf	/
offset_tracking	count
offset_tracking_flag	/
p_ref	dB
range_cor_cog	m
range_cor_uso	m
seq_count	/
surface_type	/
time	days
uso_clock_smoothed	s
waveform_fault_id	/

Expert groups	
ancillary_2K (2kHz)	
agc	dB
altitude	m
altitude_rate	m/s
db_conf_flag	/
ind_meas_18hz	degree_north
latitude	degree_east
longitude	fft power unit
power_waveform	count
power_waveform_phase	radian
scaling_factor	dB
time	days
tracker_range	m
ancillary_cal_lpf	
lpf_ku	count
ancillary_cal_ptr	
ptr_ku	count
ptr_s	count

Table 6-9 : ENVISAT tables of variables of the main group (at root) and expert subgroups.

## 6.2.2 Uncertainty

In the frame of this project and as explained in 6.1.8, it is provided along-track uncertainties characterization within each type of product. By principle the radar waveform is built on-board, making a “bottom-up” approach a real challenge when it comes to characterize the altimeter signal uncertainties. As a result, the ALT FDR does not provide a true uncertainty of the waveform itself. However, a shape classification algorithm (see the Detailed Processing Model [D-2-01]) was developed for both ERS and ENVISAT and comes with a set of two score indicators, hence two scalar values for each FDR record within the NetCDF ‘main/Ku’ group. The variables are named “waveform\_main\_class\_score” and “waveform\_second\_class\_score” respectively for

the most likely class score and the second most likely class score. It can be seen also as a performance indicator of the neural network algorithm in predicting waveform shape classes (see the Product Validation Report [D-4-02] for more details on the waveform classification outputs). Also, more information about this score parameter can be found in the FDR4ALT Uncertainty Characterization Report Document [D-5-02] and to go further with the altimeter waveform characterization please refer to the FDR4ALT Uncertainty Characterization Definition Document [D-5-01].

### 6.2.3 Waveform classification (ENVISAT & ERS)

For this project, a dedicated neural network-based algorithm was developed and implemented in order to classify both ERS-1 and ERS-2 waveforms' shape. The same principles and methods already used in the ENVISAT/RA-2 classification [Poisson, 2018] have been used to ensure consistency between all the missions. The waveform classification is a new parameter that was not in the REAPER nor in the ENVISAT V3.0 products and that is very useful for all TDPs. For more information, one should refer to the Detail Processing Model document [D-2-01] and the Product Validation Report Document [D-4-02] where the algorithm and results are fully developed and explained.

0	1	2	3	4	5	6	7	8
9	10	11	12	13	14	15	16	17
18	19	20						

Table 6-10 : List of possible classes as output of the neural network algorithm for waveform shape classification. Applicable to both ERS and ENVISAT missions.

Here is a brief description of each class sketch:

- ✓ **Class 1:** Brownian echoes, mainly found in open ocean
- ✓ **Class 2:** Peaky echoes, mainly encountered over narrow rivers, small lakes (smaller than the altimeter footprint) and water leads in sea ice regions
- ✓ **Class 3:** Several peaks, corresponds to multiple reflection in the footprint, encountered over land or heterogeneous areas
- ✓ **Class 4:** Strong peak with a very low trailing edge, corresponds to high reflective surfaces, often encountered on sea ice, most of the time over First Year Ice (FYI)
- ✓ **Class 5:** Brownian shape with a peak on the trailing edge, mainly found in coastal areas where the altimeter is close to the coast and a "bright point" is present in the footprint (but not at nadir)
- ✓ **Class 6:** Brownian shape with a peak on the leading edge or Brownian shape with a sharp trailing edge. Can be encountered over sea ice.
- ✓ **Class 7:** Brownian shape with a flat or increasing trailing edge. Can be found in rain cells or over land ice
- ✓ **Class 8:** Peaky echo shifted at the end of the analysis window, mainly found on hydrology and land
- ✓ **Class 9:** Very disturbed echoes.
- ✓ **Class 10:** Brownian shape with a high thermal noise level mainly found on land, land ice and sometimes on very heavy rain event
- ✓ **Class 11:** Double leading edge, can be encountered over land

- ✓ **Class 12:** shifted Brownian, can be found over land ice and hydrology (big lake with a non-optimal tracker command)
- ✓ **Class 13:** Brownian shape with a noisy leading edge
- ✓ **Class 14:** Volume-Brownian echo shape
- ✓ **Class 15:** Linear rise, can be found over land
- ✓ **Class 16:** Right-shifted Brownian echo
- ✓ **Class 17:** Brownian echo with breakage in leading edge
- ✓ **Class 18:** Linear decrease, can be found over land
- ✓ **Class 19:** Small energy step before leading edge
- ✓ **Class 20:** Peaky return before Brownian echo

## 6.2.4 Calibrations (ENVISAT & ERS)

### ✓ Point Target Response

As introduced in 3.2.6, the PTR characterizes the impulse response (IR) of the radar altimeter and allows to monitor range and power drift over time that are critical for long-term studies such as GMSL (Global Mean Sea Level). In the frame of this project, averaged PTR have also been computed from raw PTR (Level-0) to improve the performance of the new numerical Adaptive retracker over ocean, that use such a signal as input of the waveform modelling. This specific PTR averaging has been done for both Ku and S-band PTR and the algorithm is fully detailed in the Details Processing Model [D-2-01]. Scientific validation is available in the Round Robin Assessment Report Document [D-2-03] and in the Product Validation Report Document [D-4-02]. In the ENVISAT NetCDF files, one PTR array for each bandwidth is provided as *ptr\_ku ptr\_s variables*. By doing so, consistence is ensured because these exact PTR arrays have been used as inputs to the Adaptive retracker described in section 6.1.3.

Since no numerical retracker has been applied to ERS waveforms, only derived scalar parameters (recovered from auxiliary OLC files from REAPER) are included in the ERS products.

### ✓ Low Pass Filter

Ku-band arrays are provided in the ALT FDR NetCDF files as a single array per track file (*lpf\_ku*) and for both missions for expert use.

## 6.2.5 Range correction (ERS, ENVISAT)

### ✓ Internal Path Delay correction (ENVISAT)

The internal path delay correction is part of the correction applied to the range and comes directly from the PTR itself. Recomputed PTR signals have been used to perform the Adaptive retracker, but it has been decided to keep the internal path delay correction unchanged and so to use the one from the ENVISAT V3.0 reprocessing. This choice was made after Cal/Val investigations on GMSL over ocean and coastal regions as part of the Ocean & Coastal TDP. For more information, please refer to Product Validation Report Document [D-4-02].

### ✓ Range net instrumental correction (ERS)

As mentioned by REAPER, *range\_cor\_net\_instr* is wrongly set to 0 instead of default values in case of bad PTR correction, causing potential and significant range bias. A new dedicated flag called "*qual\_range\_cor\_net\_instr*" related to the instrumental variable "*range\_cor\_net\_instr*" is now available and is defined as follows:

If  $range\_cor\_net\_instr = 0$ , then  $qual\_range\_cor\_net\_instr = 1$

## 6.2.6 Redondant Side B (ENVISAT)

As mentioned in 3.2.7.3, the RA-2 altimeter switched to Side B during 1 month between May 15th 2006 and June 16th 2006. To help users to filter these data, a new flag ( $alt\_instr\_flag\_chain\_id$ ) is available in the NetCDF files.

## 6.2.7 Bandwidth

As explained in sections 3.1.3 and 3.2.2, the bandwidth (and gate resolution) is not constant for ERS and ENVISAT.

Users must use the field “ $alt\_state\_flag\_chirp\_state$ ” for ERS to identify the bandwidth used (0=Ocean mode 330MHz and 1= Ice Mode 85MHz).

For ENVISAT, the variable “ $chirp\_band$ ” indicates the bandwidth used (0=320MHz, 1=80MHz, 1=20MHz).

## 6.2.8 Offset tracking flag and reference Abscissa (ENVISAT)

According to Table 6-11, a new flag named «  $offset\_tracking\_flag$  » is available in the ALT FDR NetCDF to characterize the tracking offset scenario depending on the  $offset\_tracking$  value:

If  $offset_{tracking} = -4608$ , then  $offset\_tracking\_flag = 0$ .

Indeed, the reference gate of the range tracker is not constant. This is an important point to consider while performing any retracking of the echoes. The abscissa reference gate can be recovered using a variable in the ALT FDR products, called “ $offset\_tracking$ ” and the following formula:

$$Reference\ Abscissa = 63 + \frac{offset\_tracking}{256} * \frac{Bandwidth}{320000000}$$

With Bandwidth, the chirp bandwidth of the instrument in Hz. Note that for most of the data, the reference abscissa value is 45.

For cycles 14, 15 and 20, shifted waveform can be observed as illustrated in Figure 6-2 (right panel). Non-shifted waveforms from cycle 21 are displayed in Figure 6-2 (left panel) for comparison.

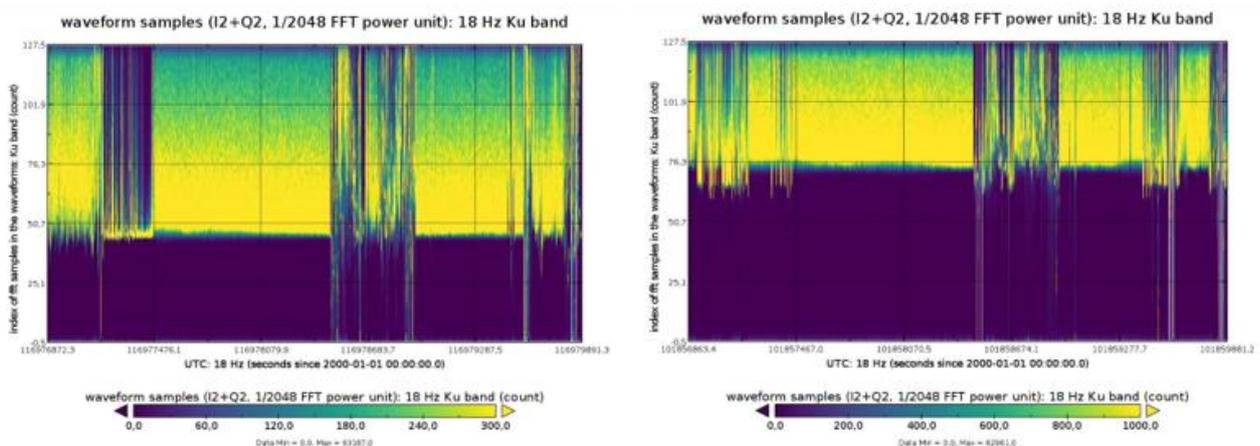


Figure 6-2 : Left plot shows waveforms from cycle 21 pass 1 with nominal abscissa reference gate (equal to 45). Right plot shows waveforms from cycle 15 pass 1 with a shifted abscissa reference gate.

## 6.2.9 DFT samples

In addition to the 128 gates, ENVISAT Ku-band waveforms have 2 additional samples, created by an interpolation during on-board processing in order to improve the sampling of the leading edge of the waveform. Nominally, they correspond to gates 44.5 and 45.5 (indexes 45 & 47 to the 130-gates array).

In the ENVISAT ALT FDR, the corresponding fields are the following:

- ✓ power\_waveform: the 128-gates waveform
- ✓ power\_waveform\_dft: the 2 extra samples index
- ✓ flag\_waveform\_dft: scenario flag (0: nominal, 1: not nominal)

If the variable “flag\_waveform\_dft” is set to “0”, then the two samples are located to gates 44.5 and 45.5. If it is set to “1”, then the two samples are located to other gates that are then given by the field “power\_waveform\_dft”

## 6.2.10 Improvements compared to the previous reprocessing

The FDR4ALT project aimed at providing improvements and evolutions in comparison to previous reprocessing for both missions:

- ❖ Baseline V3.0 for ENVISAT:  
<https://earth.esa.int/eogateway/documents/20142/37627/ENVISAT-RA-2-Level-2-Product-Handbook.pdf>
- ❖ REAPER reprocessing for ERS-1/-2:  
<https://earth.esa.int/eogateway/documents/20142/37627/reaper-product-handbook-for-ers-altimetry-reprocessed-products.pdf>

In a general aspect, the ALT FDR provides (by definition of FDR) all the altimeter-related parameter in a single product, easy-to-use, including calibration data that are usually available in auxiliary files. This is a notable improvement in itself for the users.

### 6.2.10.1 ERS-1 & 2

Correction of drawbacks from REAPER:

- ✓ 20Hz time tags jump
- ✓ Negative waveform values due to numerical overflow
- ✓ PTR correction management issue in the sum of all the range corrections
- ✓ A new pulse blurring correction (see Sea Ice TDP in 6.5)

Also, calibration data (arrays and scalars) were recovered and provide as useful information to user to better characterize the altimeter waveform:

- ✓ IF mask arrays, known as LPF (from Level-0)
- ✓ OLC PTR scalar parameters, characterizing the IR of the radar altimeter (from Level-0)

Additional parameters can be found as:

- ✓ A new surface classification flag based on GSHHG.
- ✓ The distance to the nearest shoreline based on the GSHHG coastline.
- ✓ A new waveform classification algorithm based on neural network.

## 6.2.10.2 ENVISAT

As for ERS, the project aimed to bring some evolutions as follows:

- ✓ A new flag for waveform DFT scenario
- ✓ A new waveform classification algorithm based on neural network.
- ✓ A surface classification flag based on GSHHG.
- ✓ The distance to the nearest shoreline based on the GSHHG coastline.

Also, calibration data (arrays and scalars) were recovered and provide an useful information to user to better characterize the altimeter waveform:

- ✓ IF mask arrays, known as LPF (from Level 0)
- ✓ PTR array (recomputed)

For more information and details, please refer to the Product Validation Report Document [D-4-02]

## 6.2.11 How to use the Altimetry FDR

Each ALT file contains the core FDR product (within the *main* NetCDF group), together with a set of supplementary parameters (within the *expert* group) that may be of use to the more experienced altimetry user.

Within the *main* group, the user will find all the Level 1 data coming from previous reprocessing (REAPER and V3.0 respectively for ERS and ENVISAT), together with auxiliary parameters that will be useful for filtering the data, such as the surface type classification, the waveform shape classification, and flags. Table 6-11 describes all the new or corrected variables brought by the FDR4ALT project.

Description	Output fields name	Type	ERS	ENVISAT
Distance to coastline (GSHHG)	<i>distance_to_coast</i> <i>surface_type</i>	scalar	✓	✓
Waveform Classification	<i>waveform_main_class</i> <i>waveform_main_class_score</i> <i>waveform_second_class</i> <i>waveform_second_class_score</i>	scalar scalar scalar scalar	✓	✓
Offset Tracking	<i>offset_tracking_flag</i>	scalar		✓
PTR	<i>ptr_ku</i> <i>ptr_s</i>	array		✓
OLC PTR	<i>main_lobe_width[..]</i>	scalar	✓	
LPF	<i>lpf_ku</i>	array	✓	✓
Time jump	<i>time</i>	scalar	✓	
Negative waveforms	<i>power_waveform</i>	array	✓	
Flag waveform DFT	<i>flag_waveform_dft</i>	array		✓
Range correction	<i>qual_range_cor_net_instr</i>	scalar	✓	
B chain flag	<i>alt_instr_flag_chain_id</i>	scalar		✓

Table 6-11 : Summary table of the new ALT FDR variables

Note that 1Hz original variables have been duplicated at 20Hz. The next sections focus on some of the variables listed in the above table in order to provide useful insights to users.

## 6.2.12 Useful comments

### ✓ SPTR jump correction (ERS)

This correction has not been revised in the frame of this project and could be looked at in future reprocessing activities according to [Francis, 2000] drawbacks in term of data gaps and availability over ice mode. This correction is applied at L1b (variable *ptr\_jump\_corr* in the product) and L1b *mcd* flag provides the following information: 0 indicates SPTR jumps correction valid and 1 indicates invalid.

### ✓ Not tracking waveform (ERS)

For ERS, there are periodic waveforms that peak every 1200 20Hz measurements. There is a specific flag coming from the REAPER products allowing to remove these bad waveforms. The flag is available in the ALT FDR NetCDF as *qual\_wf\_not\_tracking*. This flag has been used systematically to produce the TDPs.

### ✓ Pulse blurring (ERS)

No blurring correction is available in the ALT FDR product as it was applied at the TDP level and only over Sea Ice. Please refer to 6.5.5 for more information about the pulse blurring correction on ERS.

### ✓ Orbit degraded file (ERS)

As explained in the REAPER User handbook [Brookley, 2014] ), the REAPER project provided ASCII files (*e1\_flag.dat* and *e2\_flag.dat*) for the convenience of users who wish to filter out data that may be of poor quality due to orbital manoeuvres or anomalous PTR correction behaviour

## 6.3 MWR FDR

### 6.3.1 Introduction to the thematic

The MWR Fundamental Data Record addresses Level 1 information required for the processing of TDPs, when MWR-derived information is required. The MWR FDR product contains calibrated TOA (Top of the Atmosphere) brightness temperatures at 23.8 GHz and 36.5 GHz. The first channel is sensitive to the presence of water vapor in the atmosphere, the second to the presence of liquid water in clouds. The raw MWR measurement (called antenna temperature) is the sum of different contributions from space, surface (ocean, land or ice) and atmosphere for the on-Earth part (see Figure 6-3), but also directly from the sky or the satellite by the sidelobes and back lobes. The parameter retrieved is the brightness temperature, which represents the emission received within the 2.5 Half Power Beam Width (2.5  $\theta_{3dB}$ ).

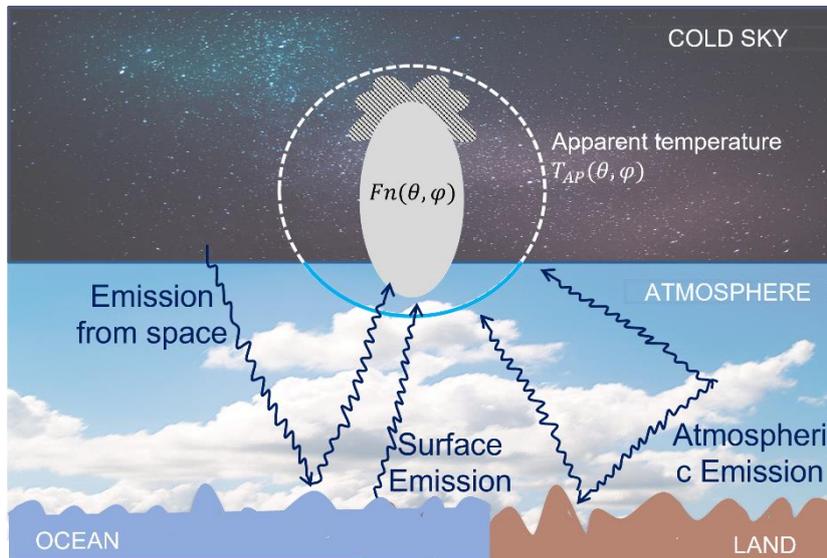


Figure 6-3: Main components of brightness temperatures

## 6.3.2 Variables

The MWR FDR product is composed of three groups:

- **main group** contains the main parameters of the MWR, such as the brightness temperatures, associated uncertainties, quality flag.
- **expert / ancillary\_mwr group** is dedicated to experts, and contains intermediate parameters that may be required for reprocessing, such as non-coregistered antenna and brightness temperatures, calibration parameters.
- **expert / ancillary\_thermal group** contains all the internal instrument temperatures.

Main group (7 Hz)	
tb_238	K
tb_365	K
tb_238_uncertainty	K
tb_365_uncertainty	K
tb_238_qual	/
tb_365_qual	/
tb_238_bias_adjusted	K
tb_365_bias_adjusted	K
distance_to_coast	K
surface_type_flag	K
rad_retrieval_quality_flag	/
surface_type_flag	/

Table 6-12 : MWR FDR: main group variables

Expert/ancillary_mwr group (7 Hz)	
lat_238	degrees
lat_365	degrees
lon_238	degrees
lon_365	degrees
ta_238	K
ta_365	K
tb_238	K
tb_365	K
tb_238_qual	/
tb_365_qual	/
gain_238	mV/K
gain_365	mV/K
residual_temperature_238	K
residual_temperature_365	K

Expert/ancillary_thermal group (7 Hz)	
reflector_temperature	K
skyhorn_feed_temperature	K
feedhorn_temperature_238	K
feedhorn_temperature_365	K
skyhorn_wg_temperature_238	K
skyhorn_wg_temperature_365	K
feedhorn_wg_temperature_238	K
feedhorn_wg_temperature_365	K
hccal_switch_temperature_238	K
hccal_switch_temperature_365	K
cal_switch_temperature_238	K
cal_switch_temperature_365	K
dicke_switch_temperature_238	K
dicke_switch_temperature_365	K
hot_load_temperature_238	K
hot_load_temperature_365	K

Table 6-13 : MWR FDR: expert groups variables

### 6.3.3 Uncertainty

The uncertainty for the MWR FDR product is provided as a single value for each FDR record within the NetCDF ‘main’ group, with variables named “tb\_238\_uncertainty” and “tb\_365\_uncertainty” which provide an estimate of the total uncertainty associated with any given brightness temperature. The uncertainty itself is computed in a bottom-up approach, using the radiometer transfer model and the laws of uncertainty propagation. In the context of this project, a list of potential contributions has been identified. Not all identified sources of uncertainties have been accounted for in the uncertainty values provided, only those we consider to be the most significant.. All details can be found in the Uncertainty Characterisation Definition Document [D-6-01] and in the Uncertainty Characterisation Report Document [D-6-02].

### 6.3.4 Improvements compared to the previous reprocessing

Several improvements have been brought by the FDR4ALT project for the three missions. The main ones are listed here.

#### 6.3.4.1 ENVISAT

1. **Radiometer transfer model:** The radiometer transfer model has been corrected for several assumptions, and/or mistakes in the equations. Some of these errors were previously partially compensated by updating the coefficients in the transfer model. After the correction, more realistic values are used for the retrieval of the brightness temperatures. These updates, along with the sidelobe correction, improve the strong ascending/descending signal observed when comparing measurements with simulations over ocean (Figure 6-4).



2. **Sidelobe correction:** In the previous reprocessing, the efficiencies for the on-Earth sidelobe contribution were quite strange, looking rather like a typo due to the scale factor in the auxiliary file. The efficiency for this contributor has been reviewed and corrected to have a sum closer to 1.
3. **Sidelobe correction:** the on-Earth correction maps have been updated, with a revised antenna pattern for ENVISAT antenna, a correction grid with a better resolution.
4. **Drift correction:** the 36.5 GHz gain drift is a well-known issue in ENVISAT product. Analyses have shown that the “drift” observed on the 36.5 GHz brightness temperatures was not due to the gain drift which is correctly accounted for through the calibration processing. It seems more likely that the drift is not just a drift, but a sequence of jumps and small drifts due to instrumental issues (Figure 6-5). The main cause of the drift at the end of the mission seems due to the evolution of internal temperatures which is not accounted for through the radiometric model.
5. **Data rate:** In FDR4ALT, the original MWR sampling (150ms) is kept to enhance the resolution of the product and to allow fine tuning of the algorithms near the coast. The calibrations create data gaps of 900ms every 38.4s in the TB timeseries. The first antenna reading after a calibration is discarded in the processing.
6. **Intercalibration:** Intercalibration is achieved by tuning of the radiometer transfer model, and satellite sidelobe efficiency, using Sentinel-3 as a target. We used methods similar to the S3 in-flight calibration methods, the so-called vicarious calibrations.

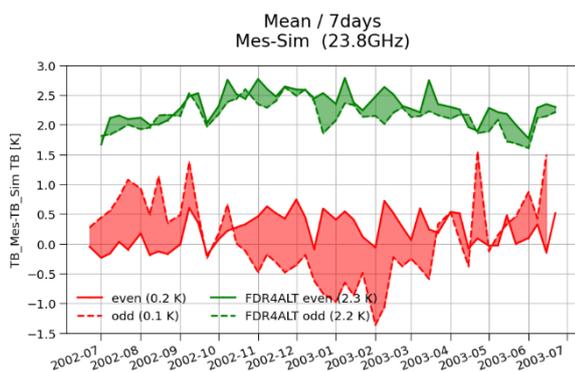


Figure 6-4 : Difference of measured and simulated brightness temperatures for ocean measurements for ENVISAT (23.8GHz)

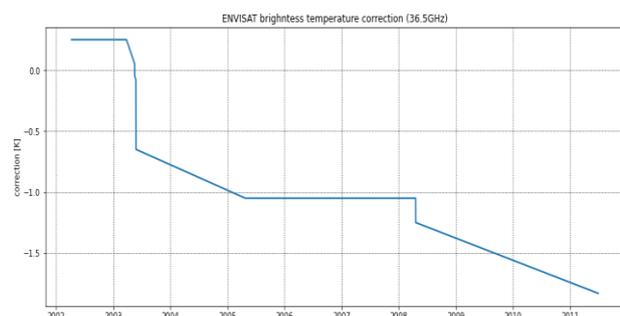


Figure 6-5: Correction for ENVISAT 36.5GHz brightness temperature

### 6.3.4.2 ERS-2

1. **Radiometer Transfer model:** REAPER ground prototype was modified to use the losses/isolations coefficients as direct input and perform the computation (and convert it from dB to linear in ERS-2 case) inside the processor instead of reading precomputed coefficient. Like Sentinel3 processing, to correctly account for the instrument thermal behaviour, the characterisation coefficients need to be interpolated according to the temperature. As it required a huge code modification, only the most impacting coefficient (i.e., the skyhorn transmission) was interpolated. For further improvement, the other coefficients varying with temperature should also be interpolated.
2. **Gain drop:** After the calibration, it appeared that the gain drop correction was no more suited. We implemented a new gain drop correction (see Figure 33), inspired by the one described by [Scharroo et al] but with some modifications:

- a. The drift correction was removed because no drift was observed on the 1996-2001 period,
  - b. Since the level of TB changed after the calibration, the coefficients were updated.
  - c. The correction is applied on antenna temperatures (TA) instead of TB.
  - d. Since the temperature of no change is lower (280), we chose to force the correction to 0 if the antenna temperature is superior to 280.
3. **Failure of the tape recorder:** After REAPER and EMIR projects, efforts for gap filling have been continued by the LTDP program, new data have been found and can be reprocessed. A great amount of work was dedicated to recover as much as possible all auxiliary data needed for processing this period. Thanks to these efforts, FDR4ALT project will reprocess for the first time the data covering tape recorder failure period.
  4. **Data rate:** In FDR4ALT, the MWR original sampling (150ms) is kept to enhance the resolution of the product and allow fine tuning algorithms near the coast. The calibrations create data gaps of 900ms every 38.4s in TB timeseries. The first antenna measure after a calibration is discarded in the processing.
  5. **Intercalibration:** Intercalibration is achieved by tuning of the radiometer transfer model, and satellite sidelobe efficiency, using Sentinel-3 as a target. We used methods similar to the S3 in-flight calibration methods to do that, the so-called vicarious calibrations.

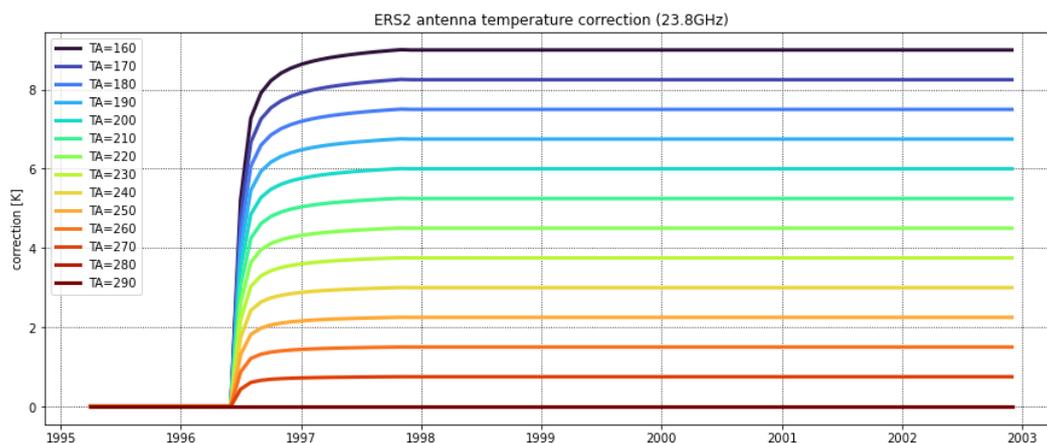


Figure 6-6 : Correction for ERS-2 23.8GHz antenna temperature as function of antenna temperature.

### 6.3.4.3 ERS-1

1. **Radiometer Transfer model:** REAPER ground prototype was modified to use the losses/isolations coefficients as direct input and perform the computation (and convert it from dB to linear in ERS-2 case) inside the processor instead of reading precomputed coefficient. Like Sentinel3 processing, to correctly account for the instrument thermal behaviour, the characterisation coefficients need to be interpolated according to the temperature. As it required a huge code modification, only the most impacting coefficient (i.e., the skyhorn transmission) was interpolated. For further improvement, the other coefficients varying with temperature should also be interpolated.
2. **Calibration processing:** In FDR4ALT reprocessing, the calibration processing was modified to perform an averaging of the nearest calibrations around the actual measurement. The filtering of erroneous values of resistance that was not correctly implemented in REAPER ground prototype was corrected in the prototype used for FDR4ALT. It allows to replace anomalous brightness temperature with

correct ones. In addition to the code correction, a filtering of spurious gain values was added before running the averaging to avoid strong contaminations in general. The Figure 6-7 illustrates the previous gain estimation (linear fit) in red, and the new averaging method (dark blue) for two consecutive orbits.

3. **Sidelobe correction:** The digitized antenna patterns of ERS-1 were found to be quite similar to Sentinel3 measured one. We found it was better to use a well-known antenna pattern of Sentinel3A instead of ENVISAT one which is not well documented nor digitized. The earth sidelobe correction can be computed directly from S3A sidelobe correction maps: a set of seasonal high-resolution grids (0.2°) of TB of S3A convolved with the 4pi antenna pattern of S3A. The enhanced grid resolution will allow to improve the data quality in coastal areas.
4. **Data rate:** In FDR4ALT, the MWR original sampling (150ms) is kept to enhance the resolution of the product and allow fine tuning algorithms near the coast. The calibrations create data gaps of 900ms every 38.4s in TB timeseries. The first antenna measure after a calibration is discarded in the processing.
5. **Intercalibration:** Intercalibration is achieved by tuning the radiometer transfer model, and the satellite sidelobe efficiency using Sentinel-3 as a target. We used methods similar to the S3 in-flight calibration methods to do that, the so-called vicarious calibrations.

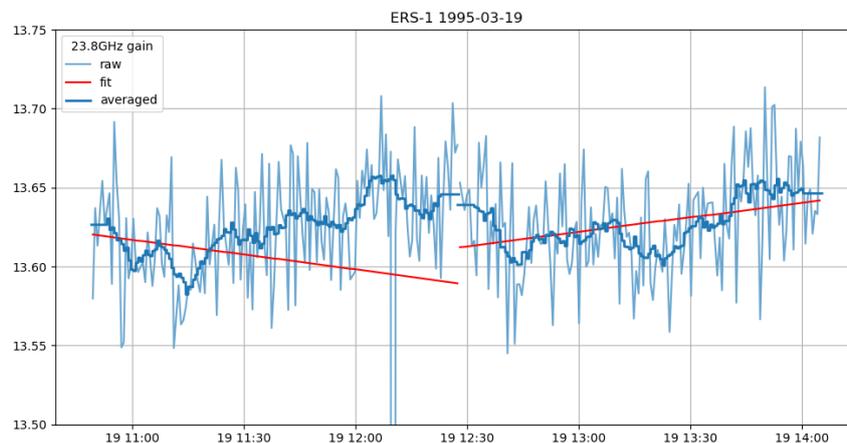


Figure 6-7 : Example of gain computation processing over 2 consecutive orbits of ERS-1

More information about these significant improvements can be found in the Product Validation Report [D-4-02] and in the Round Robin Assessment Report Document [D-2-03]. A peer-reviewed publication documenting the excellent performances of the FDR MWR is also planned to be written in 2023.

### 6.3.5 How to use the Radiometry FDR

#### main group

Brightness temperatures are provided in the main group of the FDR product with both channels co-registered. Indeed, ERS-1/2 and ENVISAT MWRs have two channels, pointing at near-nadir incidence (close to 2°), with one channel pointing forward (36.5GHz) and the other pointing backward (23.8GHz). The reference for the co-registration is the 36.5 GHz.

The calibrations create data gaps of 900ms every 38.4s in TB timeseries. The first antenna measure after a calibration is discarded in the processing.

## 6.3.6 Known limitations

Although FDR4ALT project allowed to homogenize the processing and address many issues, some points have still room for improvement in future versions:

### ERS

- ✓ The dynamic computation of leakage temperature in radiometric model instead of using a constant value impacts the TB up to 2.5K with possible orbital dependency.
- ✓ The reflector temperature derived from S3 can be improved by considering seasonal variations and drift along the mission life (as observed on all other internal temperatures of ERS-2)
- ✓ We recommend evaluating the quality and representativeness of the skyhorn sidelobe correction, for instance checking if there is ascending/descending effect and update it accordingly.

### ENVISAT

- ✓ We recommend evaluating the quality and representativeness of the skyhorn sidelobe correction, for instance checking if there is an ascending/descending effect and update it accordingly.
- ✓ Study the drift at the end of the mission related to temperature to assess if a set of parameters varying with temperature can be found.

## 6.4 Land-Ice TDP

### 6.4.1 Introduction to the thematic

Land ice surfaces comprise ice sheets, ice shelves, glaciers, and polar ice caps, each having different and varying surface characteristics. The Land Ice TDP focuses specifically on the ice sheets of Greenland and Antarctica, aiming to develop consistent ice sheet elevation records. Nonetheless, across these vast ice masses, the ice topography and snowpack properties vary considerably, creating a substantial measurement challenge.

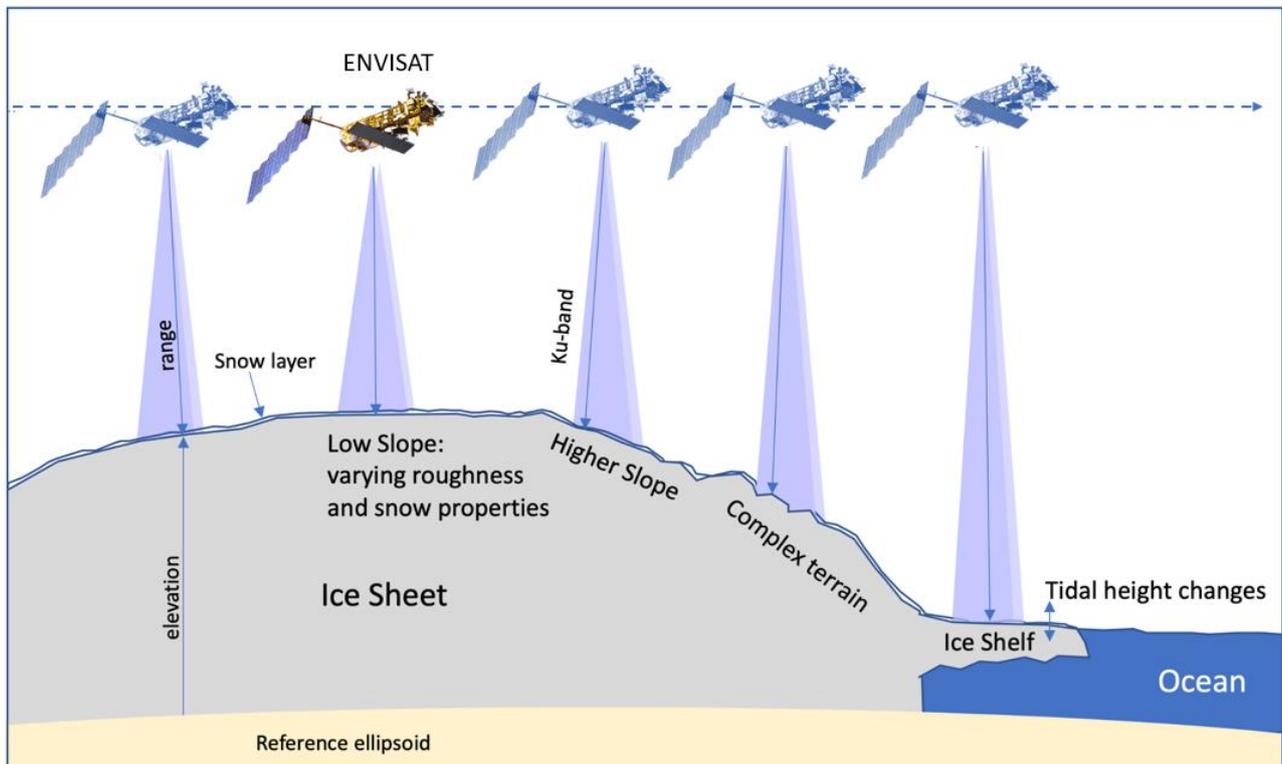


Figure 6-8 :Schematic representation of the land-ice variations in terms of topography, slope, snow/ice properties and oceanic tides (credits MSSL)

Over land ice, the basic principles of altimetry remain the same. Surface elevation is measured by calculating the time that a radar wave takes to travel from the altimeter to the reflecting ice surface and back. The waveform retracking is complicated by the fact that over land ice there may be varying topography, roughness, and snow and ice properties within the radar footprint, meaning that the returned waveform rarely matches that expected from an idealised surface. Specifically, these factors can all add noise, or fundamentally alter the number and the shape of the waveform's leading and trailing edges.

#### **Surface roughness/topography effect**

In practice, over diffuse reflecting surfaces, the topography measured by radar altimeters is estimated at the point where the satellite-surface distance is the shortest: the so-called Point Of Closest Approach (POCA). Over a flat area this point is located at nadir but is shifted in case of a tilted surface or irregular relief. This effect is called the "slope-induced error" in the literature (Brenner et al., 1983).

Over land ice, a process of "echo relocation" is therefore needed to estimate the surface elevation at its corresponding echoing point on-ground (Figure 6-9). Without such a correction, the topography can be

strongly biased, from meters (within the ice sheet interior) to dozens of meters (across parts of the ice sheet margin).

In addition, the surface roughness, from centimetre to kilometre scales, acts on the waveform shape from leading to trailing edge. In combination with the volume scattering effect, described below, this further complicates the estimation of an accurate topography corresponding to the snow/air interface. Finally, over complex terrain in the ice sheet margins, it is common to have multiple peaks in the waveform, which also complicates the retracking operation, and can create ambiguities in the POCA determination.

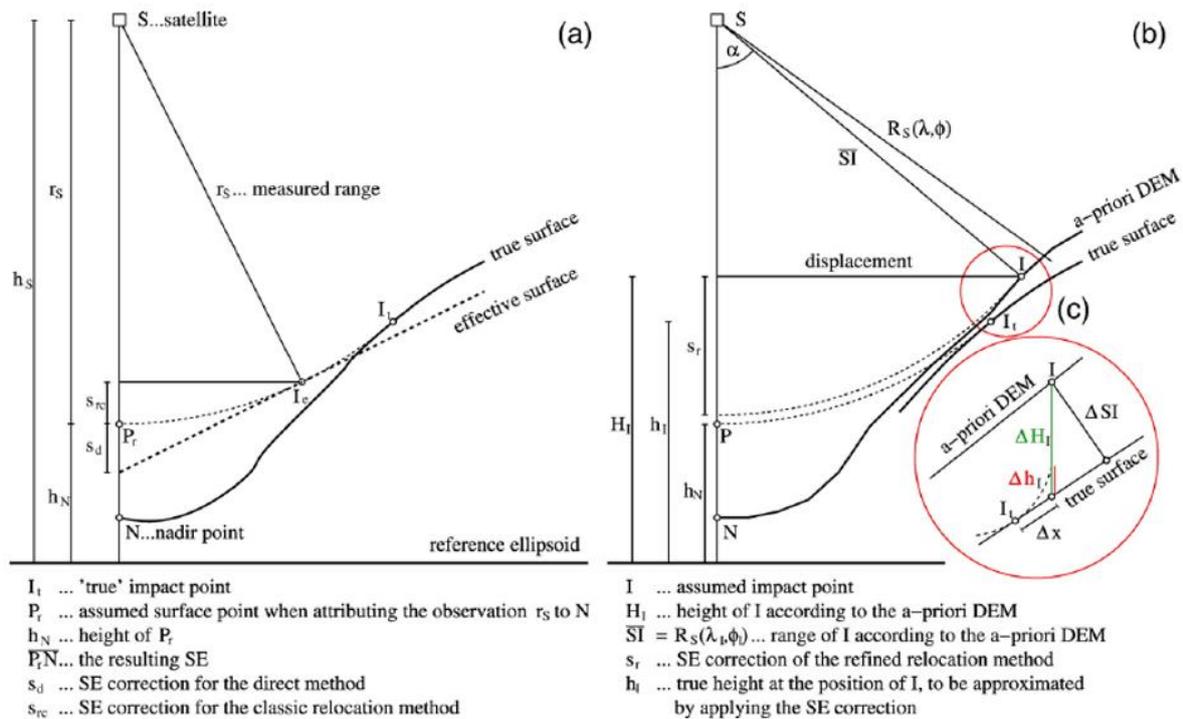


Figure 6-9 : Geometry of slope correction for the direct and classic relocation methods (a) and for a refined approach which utilises surface elevations from a Digital Elevation Model (b), from Roemer et al. [2007].

### Volume scattering effect

As the Ku-band radar wave penetrates the snowpack, the backscattered energy measured by the altimeter comes from both the surface that comprises the snow/air interface, and also from within the snowpack: the so-called "volume scattering" signal. The returned waveform can therefore be expressed as the sum of surface and sub-surface contributions. The sub-surface signal has two origins: the reflections from the snowpack's internal layers (Rott et al., 1993) and the snow grain scattering (Ridley & Partington, 1988). The altimeter signal is also attenuated by absorption loss within the snowpack. The sub-surface waveform is sensitive to snowpack properties, which are variable in time and space. Scientific surveys demonstrate that these properties are mainly: snowpack stratification, snowpack temperature, snow grain size and snow density (Rémy and Parouty, 2009). The degree of penetration affects both the shape of the leading and trailing edges.

## 6.4.2 Variables

Main group (20Hz)	
surface_elevation	meters
surface_elevation_uncertainty	meters
surface_type	/
waveform_class	/
reference_elevation	meters
sigma0	dB

Expert Group (20Hz)			
int_path_cor	meters	latitude	degrees
inv_bar_cor	meters	longitude	degrees
iono_cor_gim	meters	distance_nadir_poca_roemer	meters
load_tide_fes14b	meters	ice_sheet_elevation_model	meters
load_tide_got4v10	meters	time	seconds
mod_dry_tropo_cor	meters	range_ice1	meters
mod_wet_tropo_cor	meters	range_tfmra	meters
ocean_tide_fes14b	meters	retracking_ice1_qual	/
ocean_tide_got4v10	meters	retracking_tfmra_qual	/
ocean_tide_fes14	meters	sigma0_ice1	dB
pole_tide	meters	sigma0_tfmra	dB
solid_earth_tide	meters	waveform_class	/
range_cor_uso	meters	waveform_class_score	/
range_cor_doppler	meters	width_leading_edge_ice2	1/seconds
range_cor_doppler_slope	meters	slope_first_trailing_edge_ice2	1/seconds
ice_sheet_elevation_ice1_roemer	meters	slope_second_trailing_edge_ice2	1/seconds
ice_sheet_elevation_correction_poca	meters	altitude	meters
ice_sheet_lat_poca	degrees	chirp_band	/
ice_sheet_lon_poca	degrees	epoch_tfmra	meters
ice_sheet_qual_relocation	/	amplitude_tfmra	fft p.u

Table 6-14 : List of all the variables included in the Land-Ice TDP

## 6.4.3 Geographical coverage

For each half-orbit, the land-Ice TDP provides to users two files corresponding covering either the Antarctic region or Greenland (see section 5.5.1). This allows users to choose one or the other depending on their interest.

## 6.4.4 Relocation algorithm

One of the key steps within a land ice Level-2 processing chain is the relocation algorithm, which aims to identify the location on the ice surface contributing to the leading edge of the echo; usually assumed to be the Point of Closest Approach (POCA). This is required because when radar altimeters acquire data over the undulating topography of ice sheets, POCA diverges from nadir. In the case of a linear slope, the echoing

position is offset laterally in proportion to the magnitude of the slope, and in the direction of maximum gradient. Depending on the gradient of the slope, the lateral relocation can be of the order of kilometres and the corresponding vertical adjustment can be tens of meters. Over more complex, undulating topography, however, the Point of Closest Approach, is impacted by not only the linear slope, but also topographic highs within the beam limited footprint. Hence methods have been developed that relocate based upon the topography within the beam footprint (e.g. Roemer et al., 2007). Here, we implement an approach based upon the Roemer et al. (2007) algorithm. Following the POCA strict definition, the relocation algorithm determines its location by searching the DEM point at the closest range to the satellite. If the on-ground distance between nadir and POCA is greater than 8 km a warning flag is raised (~8 km is the ground distance corresponding to antenna aperture at -3dB). Over Antarctica, the DEM employed for the relocation is the mosaic REMA v1.0, 200 m resolution [Howat et al., 2021]. Over Greenland it is the mosaic ArcticDEM v3.0, 500 m resolution [Porter et al., 2018].

## 6.4.5 Uncertainty

The uncertainty for the Land Ice Thematic Data Product is provided as a single value for each TDP record within the NetCDF 'main' group. The variable is named "surface\_elevation\_uncertainty" and provides an estimate of the overall uncertainty associated with each given elevation measurement. The uncertainty itself is computed using a top-down approach, based upon an empirical parameterisation of elevation differences relative to airborne reference data. Specifically, uncertainty is parameterised as a function of surface slope. This is motivated by the knowledge that measurement accuracy degrades as a function of ice sheet surface slope, due to the challenges of retracking waveforms and identifying the correct echoing point over increasingly complex ice sheet terrain. The empirical relationship used to compute the TDP uncertainty parameter is computed through comparison to contemporaneous Operation IceBridge and pre-IceBridge airborne laser altimeter reference data, with the comparison performed separately for each mission. For further details relating to the computation of uncertainty, please refer to the Uncertainty Characterization Definition Document [D-5-01] and the Uncertainty Characterization Report [D-5-02].

## 6.4.6 Improvements compared to the previous reprocessing

The FDR4ALT Land Ice processing offers a number of improvements, in terms of both the Level-2 and Level-2+ algorithms that have been implemented. At Level-2, the main improvement comes from the use of a more sophisticated relocation approach, which has the purpose of correcting for the influence of topographic undulations on the location of the echoing point. Whereas past products often assume a linear slope across the beam footprint, here we use a high-resolution Digital Elevation Model to identify the Point of Closest Approach (Roemer et al., 2007). This is particularly important in coastal regions, where complex, non-linear topography contravenes an assumption of linear surface slope.

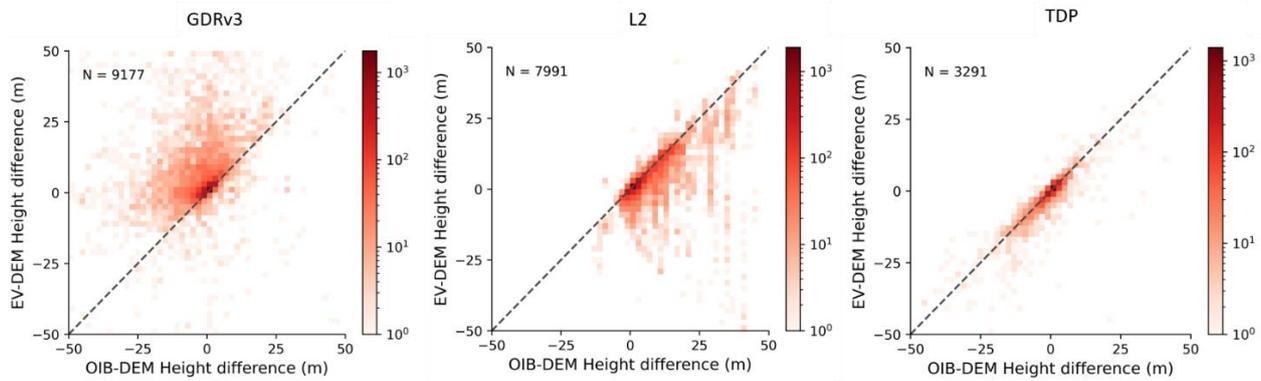


Figure 6-10 : Differences to airborne reference data for ENVISAT GDR version 3 (left), the equivalent FDR4ALT L2 product (centre), and the FDR4ALT TDP (right). In all cases, an auxiliary Digital Elevation Model has been used to remove the large-scale elevation signal.

In addition to the improved Level-2 processing, the subsequent Level-2+ TDP processor is designed to produce a more consistent, quality assured product to ease use for the non-expert user. The principal enhancement within the TDP processing is to account for the across track drift of the satellite, so as to generate consistent, geolocated elevation measurements at fixed nodes along the reference ground track. This, in essence, reduces the topographically induced variance in elevation measurements, and thereby makes it easier for the user to analyse temporal changes in ice sheet elevation. Additionally, enhanced quality control has been performed to remove erroneous records, so that the TDP provides users with a more quality assured product.

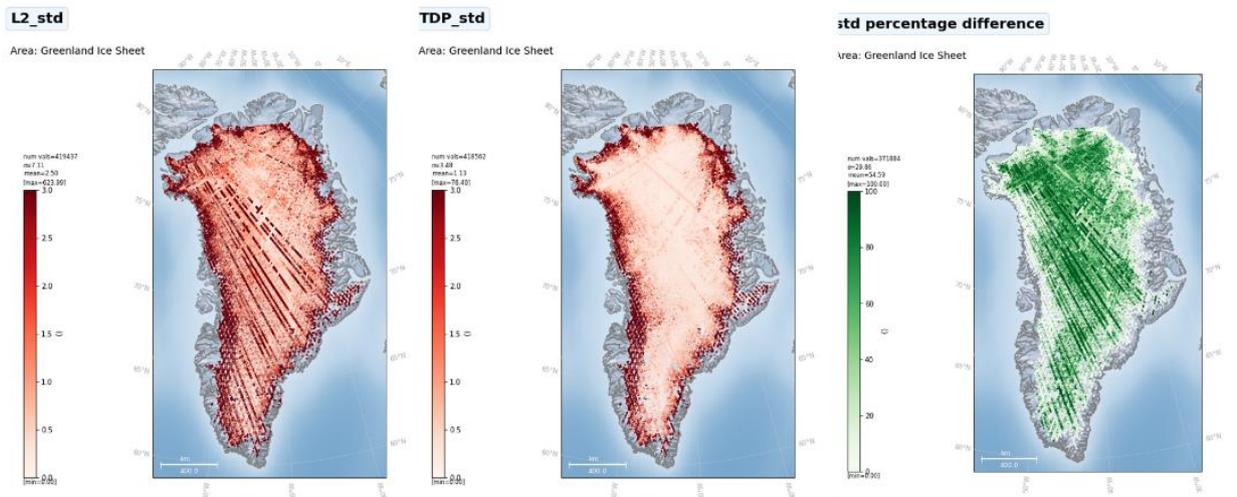


Figure 6-11 : Assessment of the internal stability of the ENVISAT Land Ice TDP for tracks over the Greenland Ice Sheet. Each panel shows the temporal standard deviation for the Level-2 product (left), the TDP product (centre) and the percentage improvement in the standard deviation along each track (right).

Finally, the TDP also includes several new parameters that were not available in past products, and which are designed to further aid the use of the product by a wide range of users. Specifically, the following new fields are provided; (1) an estimate of the uncertainty associated with each measurement, (2) a categorisation of the waveform type (based upon a Neural Network classifier), and (3) a reference elevation for each measurement (based upon an auxiliary high-resolution DEM). Full details of the performance of the TDP can be found within the Product Validation Report document [D-4-02].

### 6.4.7 How to use the Land-Ice TDP



The principal uses of the Land Ice TDP are to generate estimates of ice sheet surface elevation, elevation change and, ultimately, ice sheet mass balance. Each TDP file contains the core TDP product (within the *main* NetCDF group), together with a set of supplementary parameters (within the *expert* group) that may be of use to the more experienced altimetry user. Within the *main* group, the user will find estimates of ice sheet elevation and associated uncertainties, together with auxiliary parameters that will be useful for filtering the data, such as the surface type classification and the waveform shape classification. By analysing data from this *main* group for multiple ground tracks and orbital cycles, the user can derive estimates of ice sheet elevation and elevation change for any ice sheet region of interest. Within the *expert* group, the user will find the full range of parameters normally found within a standard Level-2 product. This allows the more experienced user greater flexibility to replace geophysical corrections, correct for the orbital drift using an alternative approach, or to make use of additional fields that are not included in the TDP *main* group.

## 6.4.8 Known limitations

**ERS-1 geodetic phase sampling.** The TDP processing is specifically designed to provide the user with a consistent elevation dataset, which is sampled at the same ground locations through time, thus facilitating the computation and analysis of ice sheet elevation change. Such a configuration is optimally suited to orbits that have a regular, relatively short repeat period, such as the 35-day repeat maintained by ERS-2 and ENVISAT. For ERS-1, the situation is more complex, due to the varying cadence of the repeat cycle that was operated throughout the mission (Table 2-2). Whilst the majority of the mission was operated with a 3-day or 35-day repeat, which is well-suited to the TDP method, the geodetic phases that operated for an 11-month period between April 1994 and March 1995 had a much longer repeat of 168 days. These phases were specifically designed to provide a dense coverage of ground tracks rather than frequent repeat sampling and therefore, by definition, cannot be used to generate a regularly sampled (~monthly) product along a consistent set of reference ground tracks (as is the purpose of the TDP processing). Hence, although the full ERS-1 Level-2 elevation data from the geodetic phases are provided in the *expert* group, there is no corresponding L2+ value in the *main* group, due to the absence of a regularly sampled ground track.

**Occasional level-2 elevation anomalies.** Within the Level-2 product ingested by the TDP processing, there are occasional cycles (~ 1 cycle per mission) where a few (~ 10%) tracks exhibit either a systematic bias or an anomalous long term trend in elevation, of the order of several metres. Such a signal is geophysically implausible, and so these artefacts are removed from the TDP product (*main* group) during the quality assurance process; however, it should be noted that they are still present within the *expert* group that includes the Level-2 input parameters.

## 6.5 Sea-Ice TDP

### 6.5.1 Introduction to the thematic

The main measurement over sea ice is the radar freeboard, defined as “the height of the radar scattering horizon from sea ice floes, relatively to the height of the local sea surface observed within the leads”. Radar freeboard is an important parameter for climate studies as, when combined with snow thickness and snow and ice densities, it can be further processed into Sea Ice Thickness (SIT), which is also part of the FDR4ALT products. It must be noted that “radar freeboard” differs from “sea ice freeboard”, depending upon the speed propagation reduction of the radar wave within the snow and the penetration depth. For the snow depth we use the modified Warren 99 climatology for Arctic and the LEGOS ASD climatology for Antarctic. The speed reduction into the snow depth is taken into account, but we make the hypothesis that the radar fully penetrates the snow, down to the snow/ice interface.

Figure 6-12 illustrates the process of estimating the radar freeboard from radar altimetry measurements, with representation of the main geophysical parameters involved:

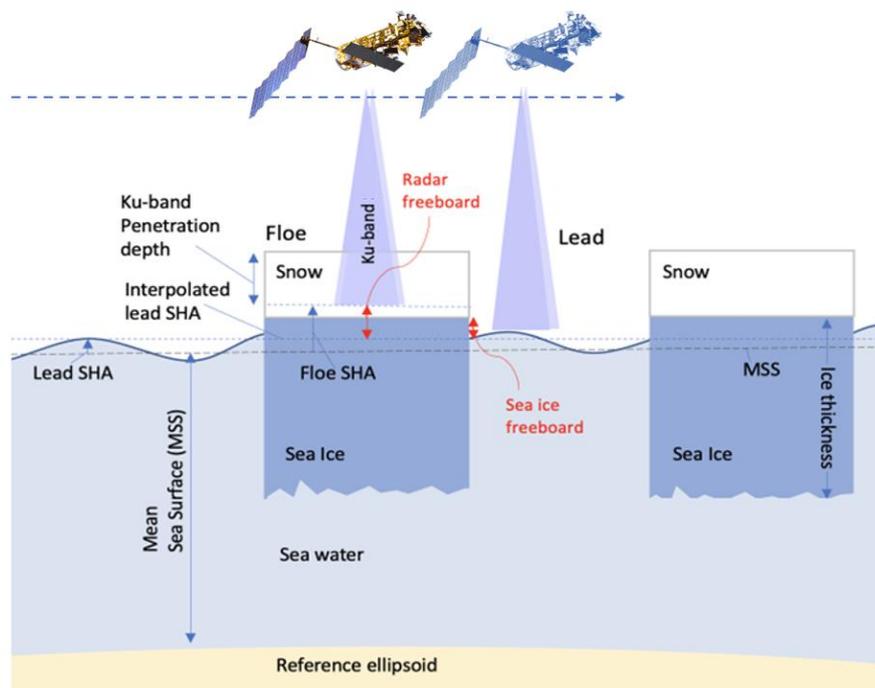


Figure 6-12: Schematic representation of the sea ice radar freeboard derived from altimetry measurements, with the main geophysical parameters involved: the sea ice floes elevations and an interpolated sea elevation of the surrounded leads.

The first problematic for altimetry over sea ice is to distinguish between reflections from open ocean, sea ice floes and sea ice leads. This is a complex task considering the relatively small size of the sea ice leads compared to the altimeter footprint extent. Nonetheless, sea ice leads and sea ice floes have different backscattering properties: while the reflections from sea ice leads are in general highly specular, those from sea ice floes tend to be more diffuse, depending on the snow properties. This is illustrated by Figure 6-13 showing example of waveform shapes measured over sea ice. Thus, the sea ice surface classification can be made by analyzing the characteristics of the waveforms. Different approaches exist for that purpose; the Sea Ice TDP uses the waveform pulse peakiness (PP) which is the ration between the maximum power of the waveform and the mean power. For ENVISAT with the typical 0.1 and 0.3 threshold values:  $PP < 0.1$  are considered as floes and  $PP > 0.3$  are considered as leads. For ERS1 and ERS2 we compute these threshold in

order to keep the same leads and floes ratio as for ENVISAT. We've got the following thresholds: 0.1328 and 0.2838.

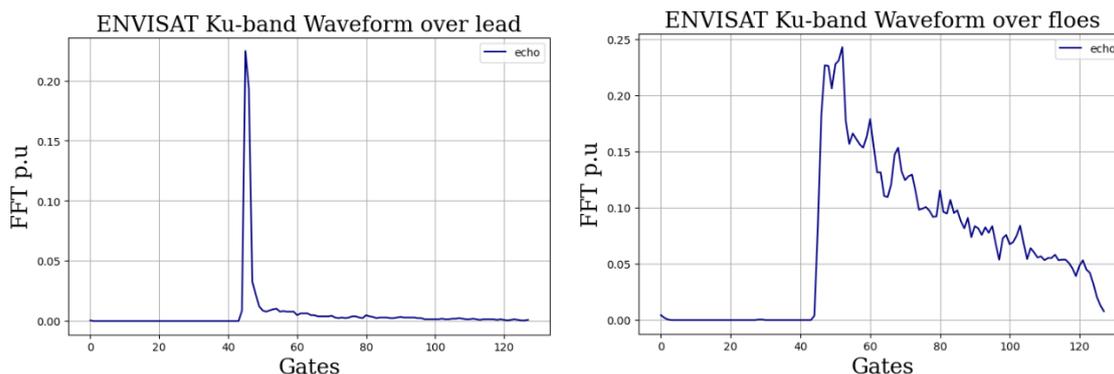


Figure 6-13: Typical ENVISAT waveform shapes over sea-ice leads and floes.

Waveform retracking has also another challenge, due to heterogenous nature of the sea ice surface at the footprint scale. Over sea ice floes, the surface roughness can also vary from centimetre to decametre scales, for example due to the presence of pressure ridges. All these effects act on the waveform shape, from leading to trailing edge.

## 6.5.2 Variables

Main group (20Hz)			
radar_freeboard	meters	sea_level_anomaly_uncertainty	meters
sea_ice_freeboard	meters	snow_depth	meters
sea_ice_thickness	meters	sea_ice_type	/
radar_freeboard_uncertainty	meters	surface_type	/
sea_ice_freeboard_uncertainty	meters	measurement_status	/
sea_ice_thickness_uncertainty	meters	mean_sea_surface	meters
surface_height	meters	sea_ice_concentration	percent
sea_level_anomaly	meters		

Expert Group (20Hz)	
dry_tropospheric_correction	meters
wet_tropospheric_correction	meters
inverse_barometric_total_correction	meters
ionospheric_correction	meters
ocean_tide_correction	meters
ocean_tide_non_equilibrium_correction	meters
solid_earth_tide_correction	meters
pole_tide_correction	meters
sea_ice_type_rad_alti	/

Table 6-15 : List of all the variables included in the Sea-Ice TDP

## 6.5.3 Geographical and temporal coverage



The Sea-Ice TDP only provides winter periods, i.e., October to June for the Arctic, and May to November for the Antarctic.

For each half-orbit, the Sea-Ice TDP provides to users two files corresponding covering either the Antarctic region or the Arctic region (see section 5.5.1). This allows users to choose one or the other depending on their interest.

## 6.5.4 Freeboard calibration

To ensure a consistent timeseries between the different satellites, a multi-parameter neural network approach is used to calibrate the older satellite with a newer satellite. This means calibrating ENVISAT with CryoSat-2 (CryoSat-2 not included in the Sea Ice TDP), ERS-2 with ENVISAT, and finally ERS-1 with ERS-2. The calibration makes use of the mission overlap periods and is trained on the discrepancies observed between the altimeter measurements and a set of parameters characterizing the sea ice state. For the calibration, the overlap period along-track radar freeboard estimates are gridded into monthly grids that in addition contain parameters describing surface roughness and other sea ice variables, using the newer radar freeboard as reference. These are used to train a neural network, which is then applied to the along-track data to obtain the corrected radar freeboards. The procedure is detailed in [Bocquet et al., 2022].

## 6.5.5 ERS pulse blurring

One of the challenges of ERS for sea-ice is a feature called ERS RA “pulse blurring”. Pulse blurring frequently occurs in the vicinity of targets causing strong peaky waveform (in this case leads in sea ice) and it has an effect on the retracked range that needs to be corrected. The parameter used to derive the pulse blurring correction in the literature (‘height tracking loop error estimate’) is present in the REAPER SGDR product (under name ‘htl\_disc\_out’) and permits to reproduce the deblurring procedure as described by [Peacock, 2004].

Indeed there is a strong correlation between the tracker dynamics and the height error signal, and thus a correction function using the tracker error signal was applied to the elevation measurements. This function and its application are detailed in [Bocquet et al., 2022].

## 6.5.6 Uncertainty

Uncertainties are provided in the Sea Ice TDP for each value where applicable in the along-track data, named with “\_uncertainty” ending. The uncertainties are estimated with a bottom-up approach based on the dominant sources of uncertainty.

First there are the uncertainties present during along-track processing. For the Sea Ice TDP three sources are considered: two random uncertainties: speckle noise and the sea level anomaly measurement accuracy, and third linked with retracker choices, surface roughness and snow radar signal penetration. In addition, for the gridding phase, other input variable uncertainties are considered in grid cell level averages.

Uncertainty propagation for the radar freeboard correction is done through a Monte Carlo approach for this grid cell level, and from its results the uncertainties can be estimated. For a thorough explanation see the Uncertainty Characterization Report document [D-5-02] and [Bocquet et al., 2022].

## 6.5.7 Improvements compared to the previous reprocessing

The current product is very innovative as before the FDR4ALT project, monthly or along-track sea-ice thickness products from ERS-1 and ERS-2 did not exist. The only ERS based estimates of sea-ice thickness were the winter thickness estimate from [Laxon et al, 2003] averaged over ERS-1 and ERS-2 missions. Now

with this Sea-Ice TDP are provided **the first time series of sea-ice estimates ever provided for ERS-1 and ERS-2**.

Moreover, until now, only few ENVISAT monthly maps have been distributed from a handful of labs and institutes (LEGOS, AWI, UCL and ESA SI-CCI) but none from official distribution and never along-tracks.

The provided time series of ERS-1, ERS-2 and ENVISAT is continuous and homogeneous over two decades (even three when considering the CryoSat-2 used for ENVISAT calibration)

Concerning the sea\_ice\_type, both ERS-1 and ERS-2 flags are now in line with the ENVISAT flag (reprocessing v3.0 version). The 3-state flags (0= open-ocean, 1= sea-ice, 2= not evaluated) became a 6-state flags (0= open-ocean, 1= first-year ice, 2= wet ice, 3= multi-year ice, 4= ambiguous / mixture of type, 5= not evaluated) with a finer description of the sea-ice type.

Please refer to the Product Validation Report [D-4-02] for more information on the strengths and weaknesses of the Sea-Ice TDP to assess fitness for a particular purpose.

### 6.5.8 How to use the Sea-Ice TDP

The Sea-Ice TDP provides the main sea ice related geophysical parameters, along with associated uncertainties within the main group variables.

It is possible for the users to e.g., test their own snow depths in sea ice thickness calculations with the provided radar freeboard, or e.g., grid and calculate sea ice volumes with the provided sea ice thickness and concentration.

### 6.5.9 In the expert group, variables contributing to the sea ice calculations are provided. Known limitations

Sea-Ice TDP products have been processed from ERS REAPER and from ENVISAT v3.0 reprocessing and did not benefit from the improvement brought at level-1 by the ALT FDR, such as the new orbits or the ERS time-tag correction. However, because the ice freeboard is derived from the difference between two level anomalies, the sea level anomaly and the level anomaly over floes, the impacts of the orbit, atmospheric and tide corrections are negligible. The retracker outputs are unchanged since the waveforms remain the same. The new corrections and the updated altitude (for ERS-1 and ERS-2) have a very light impact. For instance for ENVISAT the median difference between the freeboard computed from v3 and from the new FDR is of 0mm+-12mm before calibration and of 2mm+-14mm after calibration over one month of data (April 2011). For ERS-2 the difference before calibration is of 0mm+-12mm (we cannot compare after calibration as we did not do it with the FDR4ALT FDR data).

## 6.6 Ocean and Coastal Topography TDP

### 6.6.1 Introduction to the thematic

The specific requirements of Ocean & Coastal Topography TDP depend on the applications for which the end users will use the products. One of the main goals of the FDR4ALT project is to build an improved sea level data record from the ERS-1, ERS-2 and ENVISAT missions. For that purpose, scientific community studies and recommendations have been reviewed for all the corrections applied to calculate the sea-level (the orbit computation, the atmospheric corrections derived from model, the oceanic and internal tidal corrections, pole tide correction, ...). In some cases, several algorithms (instrumental parameters, the radiometer wet tropospheric correction, the sea-state bias, ...) have been developed within the project to improve these Level 2 altimetry data (mono-mission along-track data).

Note that multi-mission sea level L2P products at 1Hz are available on AVISO (ERS-1, ERS-2 and ENVISAT included) [see link below]. This L2P product, in its 2018 reprocessing version, benefited from ESA Sea Level CCI project [Quarty,2017]. It was followed by the L2P 2021 reprocessing, as part of the SALP (Service d'Altimétrie et de Localisation Précise) project supported by CNES (Centre National d'Etudes Spatiales) and of the Sentinel-3 Marine Altimetry L2P-L3 Service (operated under an EUMETSAT contract).

The FDR4ALT Ocean and Coastal Topography TDP includes both 1Hz and 20Hz resolution datasets to address climate and/or coastal areas studies. They also include point-to-point validation flags. The different solutions that compose the sea level variable are orbit, range, mean sea surface and corrections applied to the range (sea state bias, ionospheric, wet tropospheric, dry tropospheric, dynamical atmospheric, ocean tide, internal tide, pole tide and solid earth tide corrections). The objective here was to find the best compromise so that each sea level component has the best quality both in coastal and open ocean areas and is suitable for climate studies. This section aims at providing all key elements to use the final products.

(Link L2P AVISO

[https://www.aviso.altimetry.fr/fileadmin/documents/data/tools/hdbk\\_L2P\\_all\\_missions\\_except\\_S3.pdf](https://www.aviso.altimetry.fr/fileadmin/documents/data/tools/hdbk_L2P_all_missions_except_S3.pdf))

### 6.6.2 Variables

All the variables for this TDP are listed in Table 6-16. In order to allow the user to compute his own sea surface height, the corrections used to compute the "sea\_level\_anomaly" variable are provided in the expert group. This allows great flexibility to the expert user for computing the raw sea surface height.

The Ocean and Coastal Topography TDP product is composed of two resolution groups, at 1Hz and 20Hz. With the exception of the ERS-1 and ERS-2 20Hz *sea\_state\_bias*, all values have been directly computed at 1Hz or 20Hz time stamps with associated latitude and longitude.

<b>Main group data_20 (20Hz) and data_01 (1Hz)</b>	
sea_level_anomaly	meters
inter_mission_bias	meters
validation_flag	/
distance_to_coast	meters
meso_scale_uncertainty	meters
short_scale_uncertainty	meters

Expert Group			
		data_01 (1Hz)	data_20 (20Hz)
surface_type	/	X	X
altitude	meters	X	X
range	meters	X	X
sea_state_bias	meters	X	X
ionospheric_correction	meters	X	X
high_frequency_adjustment	meters		X
range_ssb_hfa	meters	X	
wet_tropospheric_correction	meters	X	X
dry_tropospheric_correction	meters	X	X
dynamic_atmospheric_correction	meters	X	X
ocean_tide_height	meters	X	X
ocean_tide_height_model_type	/	X	X
internal_tide	meters	X	X
pole_tide	meters	X	X
solid_earth_tide	meters	X	X

Table 6-16 : List of all the variables included in the Ocean & Coastal Topography TDP

### 6.6.2.1 Sea level anomaly and validation flag

The “*sea\_level\_anomaly*” variable is provided as orbit (=altitude) minus range measurement (altimetric corrections applied) minus mean sea surface. The *sea\_level\_anomaly* components are all described in the following sections. Altimetric corrections can be instrumental errors, environmental perturbations (wet tropospheric, dry tropospheric and ionospheric effects), the ocean sea state influence (sea state bias), the tide influence (ocean tide, internal tide, earth tide and pole tide) and atmospheric pressure (combined atmospheric correction: high frequency fluctuations of the sea surface topography and inverted barometer height correction). The provided variable includes SLA estimations for all available telemetry records. Note that it has to be associated to the provided “*validation\_flag*” variable in order to select valid data only.

Note that a dedicated processing to coastal zones has been applied for coastal distances below 200 km.

The “*validation\_flag*” variable can take 3 values: “0” indicates a rejected status, meaning the users are advised not to use it in their analyses; “1” indicates a validated point during the validation process over ocean; “2” indicates a validated point during the validation process over coastal area. The validation procedures are described in FDR4ALT Detailed Processing Model Document [D-2-01].

### 6.6.2.2 Distance to coast (main group) and surface type (expert group)

The “*distance\_to\_coast*” and “*surface\_type*” variables are derived from GSHHG. See part 6.1.6 for more details.



### 6.6.2.3 Inter mission bias

The “*inter\_mission\_bias*” variable allows to consider global biases between the missions, with respect to ENVISAT. It is set to 0 for ENVISAT, -13.22cm for ERS-2 and 14.01cm for ERS-1. Users are advised that these *inter\_mission* biases are already applied in the “*sea\_level\_anomaly*” variable of the products.

### 6.6.2.4 Precise Orbit Determination

The “altitude” variable is provided with POE-F CNES POD team solution for ENVISAT and the REAPER DEOS solution for ERS-1 and ERS-2 missions (see part 6.1.1 for more details).

### 6.6.2.5 Range, sea state bias and high frequency adjustment

#### ERS-1/2

ERS MLE3 range values are copied from the 1Hz and 20Hz REAPER products. No high frequency adjustment or new sea state bias solution have been computed. REAPER sea state bias solution, available at 1Hz, is reused. Note that as it is only available at 1Hz, FDR4ALT ocean and coastal TDP 20Hz values of this corrected solution are derived by interpolating the 1Hz values to 20Hz time stamps.

#### ENVISAT

For ENVISAT, the adaptive retracker outputs have been used as explained in section 6.1.3. Range values are provided at 20Hz, and a compression is done for 1Hz values (see section 6.6.4.1). Sea state bias corrections have been developed as regular three-dimensional look-up table against SWH, WS and ERA5 mean wave period (T02) with a non-parametric estimation technique applied to the Adaptive retracker outputs. WS value is computed with Collard’s 2D-algorithm [Collard, 2005] as for the Jason and Sentinel-6 missions after biasing ENVISAT sigma0. Sea state bias correction is then computed at each 20Hz location through a trilinear interpolation, for each (SWH, WS, T02) triplet. A high-frequency adjustment (HFA) term is then also applied on 20Hz SSH data [Tran, 2019]. HFA is an additional correction that reduces the high-frequency noise in SSH correlated to the high-frequency noise in SWH following the approach developed by Zaron and Decarvalho [Zaron,2016]. It is computed from 20Hz SWH data.

Note that the Adaptive retracker have been processed with a null skewness but it is compensated by the sea-state bias that has been computed specifically in the frame of this TDP.

### 6.6.2.6 Reference surfaces

The “*sea\_level\_anomaly*” variable is the sea level measurement anomaly to the reference mean sea surface.

**Mean sea surface** represents the mean sea level distance above the reference ellipsoid (WGS84). The solution provided is a hybrid CNES/CLS/DTU solution that has been developed to take advantage of each most recent solutions in specific areas. This MSS results from the combination of 3 different reference MSSs over the ocean:

- The SIO MSS [ref] is used in the open ocean.
- The CNES\_CLS15 [ref] MSS used on coastal areas (<30km from the coast) and for the Antarctic region.
- The DTU15 MSS [Andersen,2016] used in Arctic regions (latitude> 80 N).

The Mean Sea Surface Combined SIO/CNES\_CLS2015/DTU15 model [DOI 10.24400/527896/a01-2021.004] was produced by SSALTO/DUACS and distributed by AVISO+ (<https://www.aviso.altimetry.fr/>) with support from CNES, in collaboration with SIO and DTU.

**Mean dynamic topography** model is computed from satellite altimetry data from a variety of missions. It corresponds to mean geostrophic currents and its change. The solution provided in this TDP is the CNES/CLS18 solution, computed over the 1993-2012 20 years referencing time period mean profile.

### 6.6.2.7 Geophysical corrections

The corrections below have been applied to range measurements in the “*sea\_level\_anomaly*” variable.

**Ionospheric correction**, caused by the presence of electrically charged particles in the atmosphere. GIM (Global Ionosphere Map) is provided for ENVISAT and ERS2 missions. For ERS1 mission, GIM is provided from cycle 106 onwards, NIC09 (NOAA Ionosphere Climatology) is provided for the beginning of the mission (until cycle 105 included).

**Wet tropospheric correction**, due to the presence of water vapor in the atmosphere. Wet tropospheric correction from FDR4ALT project radiometer reprocessing is provided. For coastal processing, an additional editing step is used, and the Wet tropospheric correction is flagged if its value is not appropriate. For more details, see section 7.2.13 of the FDR4ALT Detailed Processing Model Document [D-2-01].

**Dry tropospheric correction**, due to the dry neutral gases in the atmosphere. Dry tropospheric correction from ERA 5 pressures model is provided courtesy of ECMWF.

**Dynamical Atmospheric Correction** allows considering the dynamic response of the ocean to atmospheric forcing for high frequencies. The solution provided in the “*dynamical\_atmospheric\_correction*” variable includes the inverted barometer correction and high frequencies from TUGO model, using ERA5 pressures in courtesy of ECMWF and CNES/CLS/LEGOS. [Carrere, 2020] for ENVISAT and ERS2 whole missions. In case of ERS1, this solution is only available from cycle 64 onwards, so that the same solution as the one provided in REAPER V2 datasets has been reused until cycle 63 included.

**Geocentric Ocean Tide** = Ocean Tide + Load Tide + Non Equilibrium Long-Period Tide. The geocentric tide values are computed with diurnal and semi diurnal ocean and load tide values predicted by the fes2014b model (with courtesy of LEGOS/NOVELTIS/CLS/CNES). It includes load tides, the equilibrium and non-equilibrium long-period ocean tide. In some cases, regional solutions are provided in this TDP, see part 6.6.3 for more details).

**Internal tide correction**, due to the internal tides surface signatures. The solution provided in the “*internal\_tide\_correction*” variable includes the 4 main barotropic tide frequencies [M2, K1, S2, O1] from Zaron2019/HRet8.1 model. [Zaron, 2019]

**Solid earth tide correction** represents the water surface height amplitude due to elastic response to tidal potential. The provided solution is based on Cartwright and Edden [1973] corrected tables of tidal harmonics. The same correction was already available in the ENVISAT V3.0 and REAPER V2 products at 1Hz and have been reused in expert/data\_01 group. The FDR4ALT product using the same model but updated directly at 20Hz as concerned the expert/data\_20 group.

**Pole tide correction**, due to earth rotation is based in Desai-2015, following the IERS2017 recommendation for mean pole location [Desai, 2015] [Desai, 2017].

### 6.6.2.8 Uncertainty

Uncertainties values are provided at large-, meso- and small-scales in the Ocean and Coastal Thematic Data Product. Large scale uncertainty is provided in each NetCDF file as a global attribute. Uncertainty values are provided over ocean at each data record for meso-scales and small-scales. They are deduced from a method based on Power Spectral Density (PSD) applied to ocean data. Note that no uncertainty value is provided for coastal distance below 50km.

Users must be aware that the uncertainty field must be associated to the field “*sea\_level\_anomaly*” in the product (main group). If a user computes another sea level anomaly (using the expert group for example), the uncertainty provided in this TDP will not be applicable anymore.

For more details about uncertainties, see the FDR4ALT Uncertainty Characterization Report.

### 6.6.3 Coastal areas

Coastal areas have been defined as areas up to a distance of 200km from the coast (using the GSHHG coastline). A dedicated processing has been applied for these areas, following the “X-track” processing as described in the Detailed Processing Model Document [D-2-01].

ENVISAT and ERS-2 missions have been checked thoroughly with coastal processing chain, which is tailored for the determination of coherent coastal altimetry time series. The validation of the outputs of the coastal processing chain includes the generation of these time series (level-3 information which is *not* part of the Ocean & Coastal TDP) which is used to assess performance of the altimetry data with respect to tide gauges. The particular orbital characteristics of ERS-1 (which has 7 phases, unlike ERS-2 which has only one) make using the coastal processing chain cumbersome, and the length of the validation time series too short for being meaningful. It was decided not to apply the coastal processing to ERS-1 data, and instead leave the ocean data as it is. This means that the Wet Tropospheric Correction has no coastal flags for ERS-1, and that data is still available as close to the coast as possible, but only as part of the project's Ocean processing. In short, the ERS-1 product represents only the Ocean TDP.

### 6.6.4 Data Compression

#### 6.6.4.1 Range, SWH and sigma0 compression

For ENVISAT, 20 Hz values of Adaptive retracker outputs are used for SSH estimations. 1Hz range estimations are deduced from 20Hz range values - compressed to 1Hz - following the same compression method as the one used for ENVISAT v3.0. An additional variable is available in the TDP product, taking advantage of the noise reduction at 20Hz from the use of the HFA correction: the *range\_ssb\_hfa* variable (1Hz data\_01 group only) is computed by directly compress the (range + ssb + hfa) at 20Hz values.

For ERS, no new retracker solution has been used in the frame of this project. The corresponding variables provided at 1Hz are copied from REAPER data at 1Hz and no new compression is needed.

#### 6.6.4.2 Wet tropospheric compression

Data compression is necessary to deduce 1Hz Wet Tropospheric Correction values from 7Hz native radiometer resolution. As a first step, brightness temperatures are interpolated to 1Hz data points, using a selection among land fraction and MWR reprocessing validity flag. Note that a dedicated to coastal zone area process is implemented during this step. Wet tropospheric correction is then computed from these brightness temperature values at 1Hz.

### 6.6.5 How to use the Ocean & Coastal TDP

1. A complete sea surface height anomaly is provided in the product. Users are advised to use the provided validation flag in addition to the sea\_level\_anomaly variable to select only valuable points (see part 6.6.2.1 for details on how to use the “validation\_flag” variable).
2. Note that main/data\_01 and expert/data\_01 subgroups (respectively main/data\_20 and expert/data\_20) are using the same time dimensions. Time values are only available in the main subgroups.
3. As sea\_level\_anomaly is computed as altitude – range – ( $\sum_{i=1}^n correction$ ) – mss, users are advised to uncorrect sea level anomaly as follow:

$$\begin{aligned}
 new\_SLA = & main/data\_xx/sea\_level\_anomaly \\
 & + expert/data\_xx/correction\_to\_uncorrect \\
 & - new\_correction\_to\_apply
 \end{aligned}$$

Please note that in that case, the provided validation\_flag will not take into account the validity status of the studied new correction.

4. Caution about range, sea state bias and range ssb hfa use at 1Hz:

In case of ENVISAT, a high frequency adjustment correction is available at 20Hz. Note that this correction is applicable to range measurements at 20Hz resolution directly and is correlated to the provided sea\_state\_bias. A dedicated 1Hz variable (“range\_ssb\_hfa”) has been computed at 1Hz, from the compression of (range + sea\_state\_bias + high\_frequency\_adjustment) 20Hz values (see part 6.6.4). Note that sea state bias correction is then included in the “range\_ssb\_hfa” variable at 1Hz and users are advised to consider correction\_to\_uncorrect = (range\_ssb\_hfa) and new\_correction\_to\_apply = (range – new\_ssb) in case of sea state bias studies.

Sea\_level\_anomaly in ENVISAT 1Hz solution is provided as below:

altitude of satellite (/expert/data\_01/altitude) – **Ku band corrected with ssb and hfa ocean altimeter range (/expert/data\_01/range\_ssb\_hfa)** – altimeter ionospheric correction on Ku band (/expert/data\_01/ionospheric\_correction) – radiometer wet tropospheric correction (/expert/data\_01/wet\_tropospheric\_correction) – model dry tropospheric correction (/expert/data\_01/dry\_tropospheric\_correction) – dynamic atmospheric correction (/expert/data\_01/dynamic\_atmospheric\_correction) – geocentric ocean tide height (/expert/data\_01/ocean\_tide\_height) – internal tide (/expert/data\_01/internal\_tide) – geocentric pole tide height (/expert/data\_01/pole\_tide) – solid earth tide height (/expert/data\_01/solid\_earth\_tide) – mean sea surface (/expert/data\_01/mean\_sea\_surface) – inter mission bias (/expert/data\_01/inter\_mission\_bias).

## 6.6.6 Known limitations

### **Wet Tropospheric Correction over coastal areas**

For consistency reasons, we use the new radiometer product of this project to calculate the Wet Tropospheric Correction. However, because of the presence of land, the radiometer gives unrealistic values near the coast. This behaviour is usual, and many approaches to correct it have been made. The best one is the GPD+ correction algorithm by [Fernandes et al. 2015]. The calculation of the GPD+ correction requires the use of the new FDR4ALT radiometer correction and scheduling conflicts were unavoidable. We chose to use the *edited* radiometer correction for calculation of the coastal sea level anomaly, at the price of losing

points near the coast. The calculation of a revised GPD+ wet tropospheric correction based on the FDR4ALT radiometry product should be used to improve the coastal data.

### **Wet Tropospheric Correction over open ocean (ENVISAT)**

During the 7Hz to 1Hz compression, the flagging strategy of radiometer reprocessing output data points leads to small data gaps around radiometer calibration events. It is then propagated in 20Hz dataset. This could be corrected in future versions thanks to a modification of the compression algorithm.

### **Ionospheric correction (ENVISAT)**

From the beginning of the mission to cycle 64, ENVISAT band S telemetry is available and allows to compute a dual-frequencies ionospheric correction. Such a solution needs to be analysed w.r.t the use of the Adaptive retracker over Ku band consistency with S-band value of range and sea state bias.

### **SSB (ERS-1, ERS-2)**

For the reasons described in section 6.6.2.5, the products at high-rate includes SSB that has been interpolated from the 1-Hz values, for ERS-1 and ERS-2. However, we know that the data quality is much better when the SSB is calculated directly at 20Hz, not by interpolation, as it is a quantity depending directly to the altimetry range. For ENVISAT, the SSB is recalculated directly at 20Hz, so the quality is optimum.

## **6.7 Ocean Waves TDP**

### **6.7.1 Introduction to the thematic**

Ocean waves are the most variable part of the ocean. From altimetry, it is estimated for two purposes:

- ✓ Significant Wave Height description for better ocean characterisation and assimilation in Marine Weather Forecast Systems, or climate problems such as increased subduction effects near coasts.
- ✓ Significant Wave Height and sea state effect as a pollution for altimetric Sea Level Height

In both cases, it is important to get the most accurate estimate possible, as close to the coasts as possible, and with the best understanding of noise.

The FDR4ALT project integrates a global effort to enhance the future wave products assimilated by users. By now, 1Hz products have been used, but user surveys have shown that users are willing for better along track resolution, better coastal approach, and uncertainty value associated with the data.

### **6.7.2 Variables**

All variables from the Ocean Waves TDP are given at 5 Hz.

<b>Main group (5Hz)</b>	
swh_adjusted	meters
swh_adjusted_filtered	meters
swh_bias_adjusted	meters
swh_uncertainty	meters

*Table 6-17 : List of the variables included in the Ocean Waves TDP*



### 6.7.3 Uncertainty

Users need filtered data to avoid noise but also want to have the highest resolution possible. The uncertainty provided in the Ocean Waves TDP is higher when the filter removes more signal. It enables to isolate a contamination of data due to the coherence of sea state in cases of large swell conditions. Therefore, the uncertainty is to be associated with the `swh_adjusted_filtered` variable. It is computed as the standard deviation of the residual between the filtered and the unfiltered signal within a moving window of 50 km.

The idea is to define the spectral signature of wave groups removed by the EMD filter as an uncertainty on L3 SWH data.

For more details, see the Uncertainty Characterization Definition Document [D-5-01] and the Uncertainty Characterization Report document [D-5-02].

### 6.7.4 Retracking

The Ocean Waves TDP benefited from the application of the Adaptive retracker on ENVISAT (see section 6.1.3 for more details), which allowed a significant noise reduction of the SWH, the most impacted of the four estimated parameters. Thanks to the introduction of the instrument's true PTR, look-up tables are no longer needed and the SWH is therefore naturally unbiased.

For ERS-1 and ERS-2, no new retracker was developed as part of this project. Therefore, the SWH used is the REAPER SWH estimated from the MLE3 retracker.

### 6.7.5 Improvements compared to the previous reprocessing

Thanks to the Adaptive retracker and the application of the High-Frequency Adjustment (HFA), the FDR4ALT ENVISAT data show drastic improvements compared to the previous ENVISAT baseline V3.0:

- ✓ More accurate
- ✓ Less biased (no Look-Up Tables needed)
- ✓ Less noisy
- ✓ Better resolution (5Hz)
- ✓ Better approach to the coast
- ✓ Associated uncertainty

Compared to the REAPER solution, the FDR4ALT ERS-1 and ERS-2 data show the following improvements:

- ✓ Better resolution (5Hz)
- ✓ Associated uncertainty
- ✓ Calibration with ENVISAT

More information and comparisons can be found in the Round Robin Assessment Report Document [D-2-03] and in the Product Validation Report Document [D-4-02]

### 6.7.6 How to use the Ocean Waves TDP

The Ocean Waves TDP is the only FDR4ALT product that does not use grouping in the NetCDF files: it consists of only 4 variables.

Two fields of the FDR4ALT Ocean Waves TDP contain SWH values:

- ✓ `swh_adjusted`
- ✓ `swh_adjusted_filtered`

The first one contains swh after flagging for invalid data is applied. The second one contains the result of the `swh_adjusted` field once filtered with the EMD filtering method.

For ERS missions, one can add the `swh_bias_adjusted` field to the `swh_adjusted` and `swh_adjusted_filtered` data to recover the original data (ERS-1/-2 products are calibrated to be consistent with ENVISAT data). For ENVISAT, the `swh_bias_adjusted` field contains zero values.

Finally, the `swh_uncertainty` field is to be used in association with `swh_adjusted_filtered` data as it is computed from the residual between `swh_adjusted` and `swh_adjusted_filtered` data.

## 6.7.7 Known limitations

ERS-1 and ERS-2 Level 2 SWH noise level is significantly higher than ENVISAT one. This comes from the different retracking used (Adaptive for ENVISAT data and MLE3 for ERS) and the absence of High-Frequency Adjustment processing for ERS-1/2 data.

Because of these differences, the EMD filter is less efficient on ERS data. This is visible from the spectral analysis presented in the FDR4ALT Product Validation Report Document [D-4-02]

### Cycles 14/15/20 (ENVISAT)

As explained in section 6.2.8, waveforms were shifted for the second half of cycle 14, the first half of cycle 15 and during cycle 20. The Adaptive seems to perform well on these cycles, these measurements show abnormal behavior only for the Ocean Waves TDP. Users should be advised that these data have not been edited in the final time series. Note that the Ocean & Coastal TDP was not impacted by these data.

## 6.8 Inland Waters TDP

### 6.8.1 Introduction to the thematic

Over inland waters, the principle of altimetry is similar to that over other surfaces: radio pulses are emitted, and the backscattered energy is monitored as a function of time (Figure 6-14). As explained in sections 4.2 and 4.3, Level 1 processing provides the waveforms, from which information such as the distance in between the satellite and the reflecting surface (range), the amplitude of the backscattered signal (Sigma-0), etc. is derived by means of retracking algorithms.

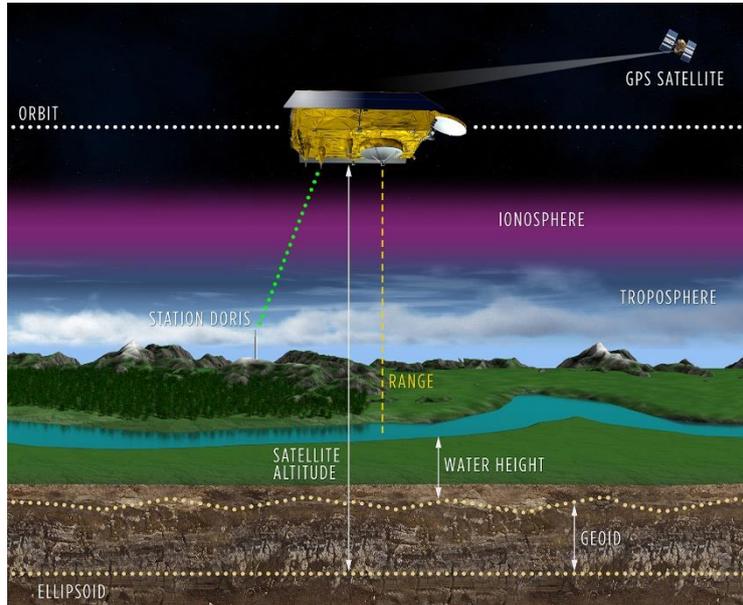


Figure 6-14. Key principles for Inland Water estimation (Credits CNES/Mira Production/Aviso)

The specificities of the inland water surfaces induce different waveform shapes depending on the characteristics of the water bodies (their size, surface roughness, surrounding other echogenic targets...). As presented in “[How to use altimetry for hydrology](#)”, over small targets the echo is very peaky while it has a more ocean-like shape over large lakes (Figure 6-15)

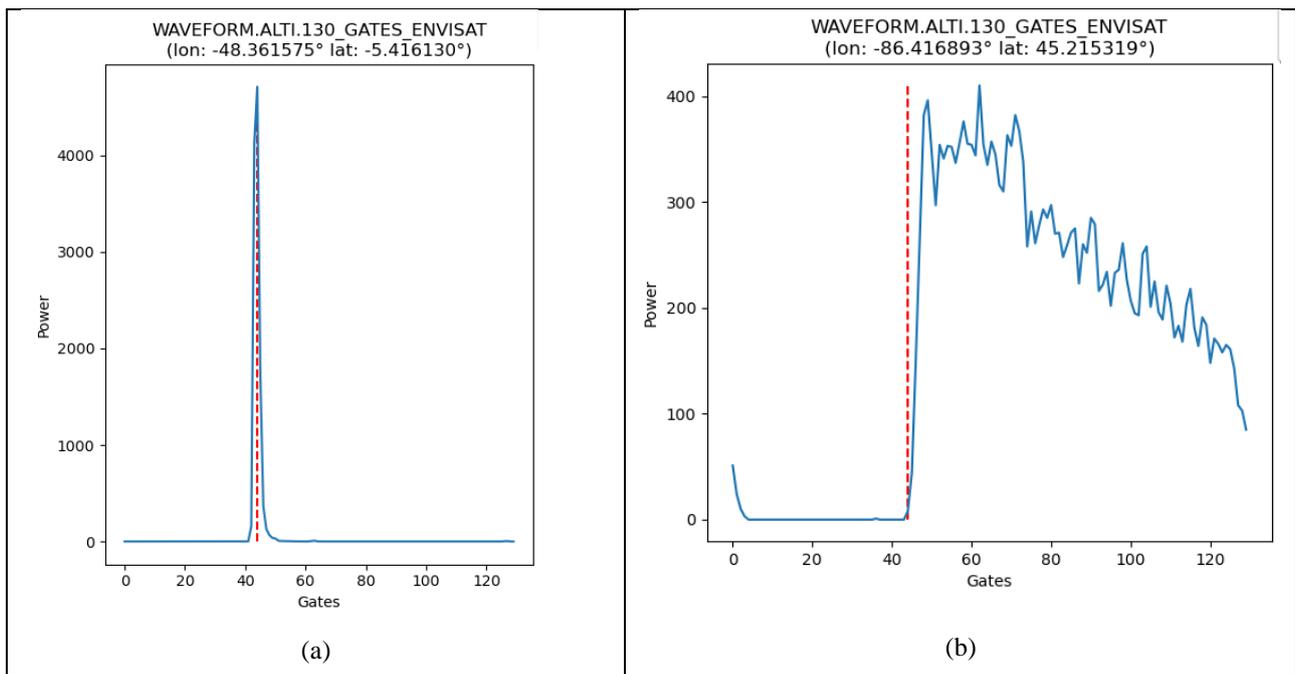


Figure 6-15. Waveforms over inland waters. On the left (a), peaky waveform over Araguaia Rive. On the right (b), ocean-like waveform over Michigan Lake.

The main estimated parameter from altimetry measurements is the Water Surface Height (WSH). It is computed using the following formula:

$$WSH = \text{satellite altitude} - \text{altimeter range} - \text{corrections} - \text{geoid}$$

- ✓ **Satellite altitude:** Altitude of satellite centre of mass above the reference ellipsoid
- ✓ **Altimeter range** is estimated through the waveform retracking operation.
- ✓ **Corrections:** atmospheric and geophysical corrections that need to be applied to the altimeter range to get precise water level heights. (Section 6.8.3)
- ✓ **Geoid** is the shape that the ocean surface would take under the influence of the Earth's gravity, including gravitational attraction and Earth's rotation, in the absence of other influences such as winds and tides.

## 6.8.2 Variables

Main group (20Hz)	
wsh_above_ellipsoid	meters
wsh_quality_flag	/
wsh_uncertainty	centimeters
geoid	meters
land_water_occurrence	/
surface_type	/

Expert Group (20Hz)			
waveform_class	/	range_tfmra	meters
altitude	meters	range_ice3	meters
sigma0_mle4	dB	range_adaptive	meters
sigma0_ice1	dB	dry_tropospheric_correction	meters
sigma0_tfmra	dB	wet_tropospheric_correction	meters
sigma0_ice3	dB	ionospheric_correction	meters
sigma0_adaptive	dB	pole_tide_correction	meters
range_mle4	meters	solid_earth_tide_correction	meters
range_ice1	meters		

Figure 6-16 : List of all the variables included in the Inland Waters TDP

## 6.8.3 Geophysical corrections

**Dry tropospheric correction:** due to the dry neutral gases in the atmosphere. The dry tropospheric correction from the ERA Interim model is provided courtesy of ECMWF and considers the surface elevation measured at the target altitude.

**Wet tropospheric correction:** due to the presence of water vapor in the atmosphere. The wet tropospheric correction from the ERA Interim model is provided courtesy of ECMWF and considers the surface elevation measured at the target altitude.

**Ionospheric correction:** caused by the presence of electrically charged particles in the atmosphere. GIM (Global Ionosphere Map) is provided for ENVISAT and ERS-2 missions. For ERS-1 mission, NIC09 (NOAA Ionosphere Climatology) is provided before 01/01/1994 followed by GIM.

**Solid Earth tide correction:** Water Surface height amplitude due to elastic response to tidal potential. Based on [Cartwright and Edden, 1973] Corrected tables of tidal harmonics.



**Pole tide correction:** due to Earth's rotation, based on [Desai, 2015].

## 6.8.4 Geoid

The **geoid** corresponds to the shape of the Earth's surface under the influence of gravity. The geoid provided in the TDP IW is the Earth Gravitational Model EGM 2008

## 6.8.5 Quality flag

The **quality flag** is based on the waveform classification and is described in the Detailed Processing Model Document ([D-2-01]). Four levels of measurement quality are indicated: good, medium, bad and no data. These are quality indicators and are important for the correct use of inland water data.

## 6.8.6 Uncertainty

The uncertainty for inland water targets is based on a bottom-up approach. The uncertainties of the Inland Water Thematic Data Product (IW TDP) are estimated by summing all uncertainties from each component of water surface height: atmospheric and geophysical corrections and orbit-range component as described in the Uncertainty Characterization Definition document [D-5-01] and in the Uncertainty Characterization Report document [D-5-02].

## 6.8.7 Retracking

Water Surface Height provided in the main group is estimated using the ICE1 retracking range as it offers better performance on the hydro targets in most cases compared to the other retrackers. For expert users, interested in a specific water body, the range from other retrackers (MLE4; ICE3, ADAPTIVE, TFMRA) is provided in the expert group.

## 6.8.8 Improvements compared to the previous reprocessing

The main advantage for the hydrological community is the availability of a product dedicated exclusively to inland waters for users who are not necessarily altimetry experts. It includes a quality flag of the measurement as well as the associated uncertainty. Additionally, the product contains external and useful information concerning the type of surface based on GLWD3 (Global Lakes and Wetlands Database), as well as the occurrence of water during the 1984-2015 period, based on GSWE (Global Surface Water Explorer).

Moreover, thanks to the use of the NetCDF format and its features, particularly the use of groups, the information for expert altimetry users is also available. This information includes the different components used to estimate the water height such as the geophysical corrections, the range from the existing retrackers or the waveform classification.

## 6.8.9 How to use the Inland Waters TDP

The Water Surface Height Level 2 is provided in the main group of the product. The quality flag per measurement is important in selecting valuable points. These values can then be used to calculate Level 3 data. More information on the timeseries estimated on precise targets can be found in the

For expert users, the NetCDF file contains also the range from other retrackers as well as the values of the geophysical corrections used to estimate the Water Surface Height. Expert users have the possibility to replace some values in the equation above allowing a different estimation for a specific target.

## 6.8.10 Known limitations

Inland water measurements may be contaminated by water bodies near the intended target or by the surrounding land. Therefore, the user should be careful with inland water measurements. Filtering on the estimation of Level 3 timeseries is highly recommended. Some timeseries over specific targets of different types (lakes, rivers, wetlands) and their comparison with external datasets are indicated the Product Validation Report Document ([D-4-02]).

Regarding the uncertainties, the values provided are based on a statistical method, and some variation between targets, especially small ones, is to be expected.

## 6.9 Atmosphere TDP

### 6.9.1 Introduction to the thematic

The Atmosphere TDPs produced in the context of the FDR4ALT project comprise *Total Column Water Vapour* (TCWV), *Cloud Liquid Water Path* (LWP), *Atmospheric Attenuation of the altimeter backscattering coefficient at Ku-band* (AttKu), and *Wet Tropospheric Correction* (WTC), retrieved from observations of the Microwave Radiometer (MWR) instruments flown on-board the ERS-1, and ERS-2, and ENVISAT satellites.

Long-term observations of trends in TCWV and sea surface height (SSH) are essential for understanding impacts and risks of Climate Change. The Global Climate Observing System (GCOS) has thus identified at an early stage both TCWV and SSH as atmosphere and ocean essential climate variables (ECVs). More recently, the cloud water path (liquid and ice) has also been defined as an additional Atmospheric ECV, underpinning the importance of the TCWV and LWP generated in the context of FDR4ALT Atmospheric TDP.

The largest source of uncertainty for SSH estimates from radar altimetry is caused by the path delay of the radar signal due to the highly variable atmospheric humidity. In fact, the spatial and temporal variability of water vapour is such that an instantaneous estimation and correction of its impact on altimeter measurements is needed, the so-called wet tropospheric correction (WTC), which is also provided by FDR4ALT.

Atmospheric TDPs are produced using two different processing streams: the standard operational products (“OPERA”) are derived using an artificial neural network approach (ANN) and are included in the “main” group of the FDR4ALT Atmospheric TDP files. Additionally, 1DVAR-based retrievals are provided through the “expert” group of the Atmospheric TDPs. Both methods exploit the sensitivity of the observations in the two MWR channels at 23 and 36 GHz to the varying atmospheric content in TCWV and LWP. An example of the 1DVAR “expert” TCWV product is shown in Figure 6-17.

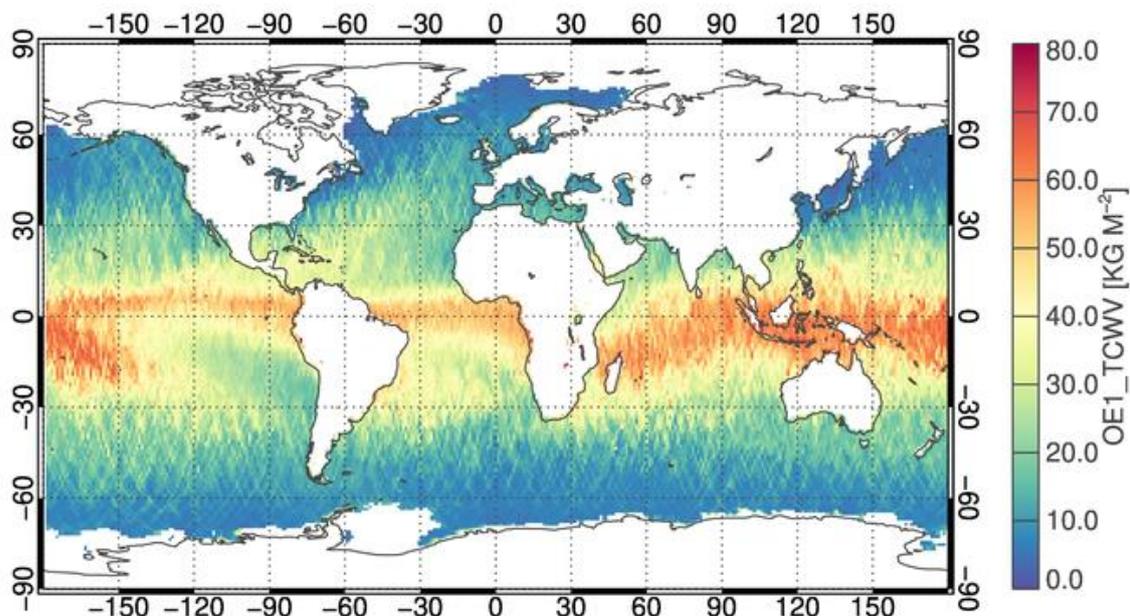


Figure 6-17 – Average atmospheric total column water vapour content for the period from 13.1.2013 to 16.2.2013 on a 1°x1° grid as derived by applying 1DVAR to ENVISAT MWR observations.

## 6.9.2 Variables

Main group (7 Hz)	
rad_water_vapor	kg/m <sup>2</sup>
rad_water_vapor_uncertainty	kg/m <sup>2</sup>
rad_liquid_water	kg/m <sup>2</sup>
rad_liquid_water_uncertainty	kg/m <sup>2</sup>
rad_wet_tropo_corr	meters
rad_wet_tropo_corr_uncertainty	meters
rad_attenuation_ku	dB
rad_attenuation_ku_uncertainty	dB
rad_retrieval_quality_flag	/
surface_type_flag	/
solar_zenith_angle	degree
day_night_flag	/

Expert group (7 Hz)	
rad_water_vapor_1DVAR	kg/m <sup>2</sup>
rad_water_vapor_uncertainty_1DVAR	kg/m <sup>2</sup>
rad_water_vapor_prior_1DVAR	kg/m <sup>2</sup>
rad_liquid_water_1DVAR	kg/m <sup>2</sup>
rad_liquid_water_uncertainty_1DVAR	kg/m <sup>2</sup>
rad_wet_tropo_corr_1DVAR	meters
rad_wet_tropo_corr_uncertainty_1DVAR	meters
rad_attenuation_ku_1DVAR	dB
rad_attenuation_ku_uncertainty_1DVAR	dB
rad_retrieval_quality_flag_1DVAR	/
day_night_flag_1DVAR	/
rad_cost_1DVAR	/

## 6.9.3 Uncertainty

### 6.9.3.1 ANN retrieval (main group)

Uncertainties for ANN (Artificial Neural Network) retrieval are not provided in the FDR4ALT product. During this study, a lot of work was done on the MWR FDR: the Level 1 processing was improved but also the brightness temperatures uncertainties have been estimated for the first time for ERS and ENVISAT missions. Unfortunately, we did not have the time to pursue the effort up to the Level 2.

### 6.9.3.2 1D-VAR retrieval (expert group)

The FDR4ALT 1D-VAR retrieval scheme (“expert” group) directly assigns an uncertainty value to each individual TCWV and LWP retrieval. Through uncertainty propagation, uncertainties are also assigned to each WTC and ATT\_KU retrieval, which are derived in a follow-on step from the two formers. The availability of such uncertainty estimates taking all potential error sources explicitly into account allows for the identification of retrievals that meet application-specific quality requirements.

1D-VAR finds an optimal solution for a vector of variables (here TCWV and LWP) given the observations (top-of-atmosphere brightness temperatures), a forward model relating variables and observations, and a set of other parameters that describe the prior knowledge before the observations are incorporated.

Uncertainties associated with the retrieval of the atmospheric TDPs result from three different sources:

- ✓ Uncertainties associated with the observations, for example due to calibration uncertainties or noise.
- ✓ Uncertainties associated with the ancillary background data required for the retrieval.
- ✓ Uncertainties associated with the simplifications of the implemented forward model.

Please refer to the “Uncertainties Characterization Report” (Appendix A -FDR4ALT deliverables) for more information on how uncertainties for the Atmospheric TDPs are calculated.

## 6.9.4 Improvements compared to the previous reprocessing

The current product has improved over to the previous reprocessing through the following measures:

- ✓ L0 to L1B processing has been improved, leading to more accurate parameters. This concerns especially the ENVISAT observations.
- ✓ Many data gaps in the underlying L0 data archive have been filled, leading to a better temporal coverage of the FDR4Alt time series. This concerns in particular the ERS-2 observations.
- ✓ The L2 operational retrieval has been improved. Neural network retrieval has been updated, contributing to better performance. The FDR4ALT reprocessing proposes also an additional correction based on the 1D-VAR approach.
- ✓ Several aspects of the 1D-VAR retrieval have been improved, contributing to further increase product accuracy and coverage. This concerns for example a completely revised approach to the bias correction of TOA brightness temperatures.

Please refer to the “Product Validation Report” (Appendix A -FDR4ALT deliverables) for more information on the strengths and weaknesses of each Atmospheric TDP and fitness for a particular purpose.

## 6.9.5 How to use the Atmosphere TDP

There are two main application areas of the Atmospheric TDP:

- ✓ WTC retrievals can be used to correct concomitantly acquired altimeter observations over the ice-free global ocean, thus contributing to the provision of SSH retrievals meeting GCOS accuracy requirements.
- ✓ TCWV retrievals can be used to study the occurrence and temporal evolution of regional or global atmospheric moisture patterns. This is preferably done by generating Level-3 products, for example monthly means for 2°×2° grid cells.

Unless a specific user-self-defined quality flag is employed, it is recommended to apply the quality flag provided in the “expert” group (“rad\_retrieval\_quality\_flag\_1DVAR”) to avoid retrievals affected by land contamination, sea ice or heavy precipitation.

## 6.9.6 Known limitations

Uncertainties for ANN retrieval are not provided in the FDR4ALT product.

The 1D-VAR wet tropospheric correction and auxiliary products are not provided for a small percentage of the total dataset:

- ERS-1
  - Number of processed L1B files: 49 067.
  - Number of OPERA L2 files: 49 067.
  - Number of 1D-VAR L2 files: 48 202 (equiv. ca. 1.8 % product reduction).
- ERS-2:
  - Number of processed L1B files: 150 481.
  - Number of OPERA L2 files: 150 481.
  - Number of 1D-VAR L2 files: 148 918 (equiv. ca. 1.0 % product reduction).
- ENVISAT:
  - Number of processed L1B files: 101 154.
  - Number of OPERA L2 files: 101 154.
  - Number of 1D-VAR L2 files: 99 361 (equiv. ca. 1.8 % product reduction).

# 7 Helpdesk

## 7.1 Access to FDR4ALT products

The FDR4ALT products are available at this address:

*[Here we will put all the information necessary to access the products]*

## 7.2 Contacts

Pierre Féménias : <a href="mailto:pierre.femenias@esa.int">pierre.femenias@esa.int</a>	ESA technical officer
Fanny Piras: <a href="mailto:fpiras@groupcls.com">fpiras@groupcls.com</a>	CLS Project Manager

## 7.3 Useful links

### **About ESA and the ENVISAT and ERS missions:**

- ✓ ESA website: <http://www.esa.int>
- ✓ ERS Online <https://earth.esa.int/eogateway/missions/ers>
- ✓ ENVISAT Online <https://earth.esa.int/eogateway/missions/envisat>
- ✓ The LTDP+ Program: <https://earth.esa.int/eogateway/missions/heritage-missions>

### **More about the FDR4ALT project:**

- ✓ The FDR4ALT website <https://www.fdr4alt.org/>

### **NetCDF documentation**

- ✓ How to access NetCDF files using Python:
  - With NETCDF4: <https://unidata.github.io/netcdf4-python/>
  - With XARRAY: <https://docs.xarray.dev/en/stable/user-guide/io.html>
- ✓ How to see the content of the NetCDF file using the Linux command **ncdump**:  
[http://www.bic.mni.mcgill.ca/users/sean/Docs/netcdf/guide.txn\\_79.html](http://www.bic.mni.mcgill.ca/users/sean/Docs/netcdf/guide.txn_79.html)

## 8 Bibliography

- Andersen, O. (s.d.). The DTU15 MSS (Mean Sea Surface) and DTU15LAT (Lowest Astronomical Tide) reference surface. *ESA Living Planet Symposium 2016 - Prague, Czech Republic*, .  
[http://lps16.esa.int/page\\_session189.php#1579p](http://lps16.esa.int/page_session189.php#1579p).
- Aublanc, J. (2022). Sentinel-3 SRAL Land User Handbook.
- Bocquet, M. (2022). Arctic sea ice radar freeboard retrieval from ERS-2 using altimetry: Toward sea ice thickness observation from 1995 to 2021. *EGUsphere [preprint]*.
- Brenner, A. (1983). Slope induced errors in radar altimetry over continental ice sheets. *J. Geophys. Res*, *88(C3)*, 1617-1623.
- Brockley, D. (2014). *REAPER--Product handbook for ERS Altimetry reprocessed products*.
- Brown, G. (1977). The average impulse response of a rough surface and its applications. *IEEE Transactions on Antennas and Propagation* *25(1)*, 67–74.
- Carrere, L. (2020). Using ERA5 to improve the Dynamic Atmospheric Correction for altimetry. *OSTST 2020*.
- Collard, F. (2005). Algorithmes de vent et période moyenne des vagues JASON à base de réseaux de neurones. *Boost Technologies BO-021-CLS-0407-RF*, 33 pp.
- Cudlip, W. a. (1994). Overview of altimeter data processing at the U.K. Earth Observation Data Centre. *Int. J. Remote Sens.*, *15*, 871-887.
- D., C. (1989). Pulse Compression and Sea Level Tracking in Satellite Altimetry. *J. Atmos. Oceanic Technol.*, *6*, 407–438, [https://doi.org/10.1175/1520-0426\(1989\)006<0407:PCASLT>2.0.CO;2](https://doi.org/10.1175/1520-0426(1989)006<0407:PCASLT>2.0.CO;2).
- Desai, S. (2015). Revisiting the pole tide for and from satellite altimetry. *J. Geod.*, *89(12)*, 1233- 1243. doi: 10.1007/s00190-015-0848-7.
- Duchossois, G., & Zobl, R. (s.d.). ERS-2: A continuation of the ERS-1 success.
- ENVISAT-1/MWR Specific Interface Control Document. (2000). *OP-ID-DOR-MR-0030 iss 2A*.
- (1993). *ERS-1 Satellite to ground segment interface specification, ESA document ER-IS-ESA-GS-0001*. second issue.
- Francis, C. (1990). *RA Data Chains Rep. ER-IS-ESA-GS-0001*. Noordwijk: ESTEC.
- Francis, R. (2000). *Identification and correction of clock asymmetry in the ERS-1 and ERS-2 radar altimeters*.
- G.Hayne. (1980). *IEEE Trans. Antennas Propag*, vol. AP-28, no. 5, pp. 687–692.
- Hayne, G. (1980). *IEEE Trans. Antennas Propag.*, ol. AP-28, no. 5, pp. 687–692, Sep. 1980.
- Howat, I. M. (2019). The Reference Elevation Model of Antarctica. *The Cryosphere*, *13(2)*, 664-674.
- L'Abbate, M. (s.d.). ENVISAT-1 MWR, In flight fonctionnal and performances.
- Laxon. (2002). *ENVISAT RA-2: S-BAND PERFORMANCE*. Noordwijk: PProceedings of the ENVISAT Calibration Worskshop.
- M., D. (2004). Final Report on activities performed in 2002-2004 on the ER2/MWR survey. *1.0*.

- Martini, A. (2003). *Envisat RA-2 Range instrumental correction: USO clock period variation and associated auxiliary file*. Technical Note ENVI-GSEG-EOPG-TN-03-0009.
- MWR-2 Calibrated instrument – Electrical and Radiometric performance, ER-TN-SAE-MW-0004, iss 1.2, 03-03-1994 . (s.d.).
- N.Stricker. (1995). ATSR-2: The Evolution in its Design from ERS-1 to ERS-2. *ESA Bulletin No 83*, 32-37.
- Obligis, E. (2006). First Three Years of the Microwave Radiometer aboard Envisat : In-Flight Calibration, Processing and Validation of the Geophysical Products. *J.Atmos. Ocean. Technol. vol. 23 no6*, 802-814.
- Ollivier, A. (2014). *Envisat RA-2/MWR ocean data validation and cross-calibration activities. Yearly report 2010*. CLS DOS/NT/12.021.
- Otten, M., & Visser, P. (2019). *ERS Orbit Validation Report*. DOPS-SYS-TN-101-OPS-GN.
- Peacock, N. R. (1998). Arctic sea ice and ocean topography from satellite altimetry. *Doctoral thesis (PhD), UCL (University College London)*.
- Poisson, J. (2018). Development of an ENVISAT Altimetry Processor Providing Sea Level Continuity Between Open Ocean and Arctic Leads.
- Porter, C. (2018). *ArcitcDEM, Version 3*. <https://doi.org/10.7910/DVN/OHHUKH>: Harvard Dataverse, V1.
- Pujol, M. I. (2018). Gauging the improvement of recent mean sea surface models: A new approach for identifying and quantifying their errors. *Journal of Geophysical Research: Oceans*, 123. .
- Quarty, G. (2017). A new phase in the production of quality-controlled sea level data. *Earth Syst. Sci. Data, vol. 9, Is. 2*, 557-572 <https://doi.org/10.5194/essd-9-557-201>.
- R.Bernard. (199). The Microwave Radiometer Aboard ERS-1 : Part 1-Characteristics and Performances. vol. 31, no. 6.
- R.Bernard. (1993). The Microwave Radiometer Aboard ERS-1 : Part 1-Characteristics and Performances. vol. 31, no. 6.
- Rémy, F., & Parouty, S. (2009). Antarctic ice sheet and radar altimetry : a review. *Remote Sensing* , 1(4), 1212-1239.
- Ridley, J. (1988). A model of satellite radar altimeter return from ice sheets. *Remote Sensing*, 9(4), 601-624.
- Ries, J. C., & Desai, S. (2017). AGU Fall Meeting Abstracts. Update to the conventional model for rotational deformation. <https://ui.adsabs.harvard.edu/abs/2017AGUFM.G14A..07R>.
- Roca, M. (2009). The EnviSat RA-2 Instrument Design and Tracking Performance. *IEEE Transactions on Geoscience and Remote Sensing*.
- Roemer, S. (2007). Roemer, S., Legrésy, B., Hor Refined analysis of radar altimetry data applied to the region of the subglacial Lake Vostok/Antarctica. *Remote sensing of environment*, 106(3), 269-284.
- Rott, H. (1993). Active and passive microwave signatures of Antarctic firn by means of field measurements and satellite data. *Annals of Glaciology*,17, 337-343.
- Tourain, C., & Piras, F. (2021). Benefits of the Adaptive Algorithm for Retracking Altimeter Nadir Echoes: Results From Simulations and CFOSAT/SWIM Observations. *IEEE TRANSACTIONS ON GEOSCIENCE AND REMOTE SENSING*, ol. 59, no. 12, pp. 9927-9940, Dec. 2021, doi: 10.1109/TGRS.2021.3064236.

- Tran, T. (s.d.). Assessing the effects of sea-state related errors on the precision of high-rate Jason-3 altimeter sea level data. *Advances in Space Research/Special issue "25 years of Progress in Radar Altimetry" Volume 68 Issue 2*, 963-077.
- Wessel, P., & Smith, W. H. (1996). A Global Self-consistent, Hierarchical, High-resolution Shoreline Database. *J.Geophys. Res* 101, 8741-87-43.
- Zaron, E. D. (2019). Baroclinic tidal sea level from exact repeat mission altimetry,. *Journal of Physical Oceanography*, 49(1), 193-210.
- Zaron, E. D., & Decarvalho, R. (2016). Identification and reduction of retracker-related noise in altimeter derived sea surface height measurements. *J.Atmos. Ocean. Technol.* 33(1), 201-210.

## Appendix A - FDR4ALT deliverables

The table below lists all FDR4ALT deliverables with their respective ID number and confidentiality level.

Document	ID	Confidentiality Level
<b>Products Requirements &amp; Format Specifications Document</b>	[D-1-01] [D-2-02]	Public
<b>Roadmap &amp; Product Summary Document</b>	[D-1-02]	Project Internal
<b>Data Requirements Document</b>	[D-1-03]	Project Internal
<b>System Maturity Matrix</b>	[D-1-04]	Project Internal
<b>Examples of products</b>	[D-1-05]	Project Internal
<b>Review Procedure Document</b>	[D-1-06]	Project Internal
<b>Review Data Package</b>	[D-1-07]	Project Internal
<b>Phase 1 Review Report Document</b>	[D-1-08]	Project Internal
<b>Detailed Processing Model Document</b>	[D-2-01]	Public
<b>Round Robin Assessment Report Document</b>	[D-2-03]	Public
<b>Data Production Status Report</b>	[D-3-01]	Project Internal
<b>Final Output Dataset</b>	[D-3-01]	Public
<b>Product Validation Plan</b>	[D-4-01]	Project Internal
<b>Product Validation Report : FDR</b>	[D-4-02a]	Public
<b>Product Validation Report : Sea-Ice TDP</b>	[D-4-02b]	Public
<b>Product Validation Report: Land-Ice TDP</b>	[D-4-02c]	Public
<b>Product Validation Report : Ocean Waves TDP</b>	[D-4-02d]	Public
<b>Product Validation Report : Ocean &amp; Coastal TDP</b>	[D-4-02e]	Public
<b>Product Validation Report: Inland Waters TDP</b>	[D-4-02f]	Public
<b>Product Validation Report: Atmosphere TDP</b>	[D-4-02g]	Public
<b>Uncertainty Characterization Definition Document</b>	[D-5-01]	Project Internal
<b>Uncertainty Characterization Report</b>	[D-5-02]	Public
<b>Product User Guide</b>	[D-5-03]	Public
<b>Completeness Report ALT</b>	[D-7-01]	Public
<b>Completeness Report MWR</b>	[D-7-02]	Public

Table 8-1 : List of FDR4ALT deliverables

# Appendix B - System Maturity Matrix

Maturity	SOFTWARE READINESS	METADATA	USER DOCUMENTATION
1	Conceptual development	None	Limited scientific description of the methodology available from PI
2	Research grade code	Research grade	Comprehensive scientific descriptions of the methodology, report on limited validation, and limited product user guide available from PI ; paper on methodology is submitted for peer-review
3	Research code with partially applied standards ; code contains header and comments, and a README file ; PI affirms portability, numerical reproducibility and no security problems	Standards defined or identified; sufficient to use and understand the data and extract discovery metadata	Score 2 + paper on methodology published; comprehensive validation report available from PI and a paper on validation is submitted; comprehensive user guide is available from PI; Limited description of operations concept available from PI
4	Score 3 + draft software installation/user manual available; 3rd party affirms portability and numerical reproducibility ; passes data providers security review	Score 3 + standards systematically applied; meets international standards for the dataset; enhanced discovery metadata; limited location level metadata	Score 3 + comprehensive scientific description available from data provider; report on inter comparison available from PI; paper on validation published; user guide available from data provider; comprehensive description of operations concept available from PI
5	Score 4 + operational code following standards ; actions to achieve full compliance are defined ; software installation/user manual complete ; 3rd party installs the code operationally	Score 4 + fully compliant with standards; complete discovery metadata ; complete location level metadata	Score 4 + comprehensive scientific description maintained by data provider; report on data assessment results exists; user guide is regularly updated with updates on product and validation; description on practical implementation is available from data provider
6	Score 5 + fully compliant with standards; Turnkey System	Score 5 + regularly updated	Score 5 + journal papers on product updates are and more comprehensive validation and validation of quantitative uncertainty estimates are published; operations concept regularly updated

1&2	Research Capability (RC)
3&4	Initial Operations Capability (IOC)
5&6	Full Operations Capability (FOC)

Maturity	UNCERTAINTY CHARACTERIZATION	PUBLIC ACCESS, FEEDBACK, UPDATE	USAGE
1	None	Restricted availability from PI	None
2	Standard uncertainty nomenclature is identified or defined; limited validation done; limited information on uncertainty available	Data available from PI, feedback through scientific exchange, irregular updates by PI	Research: Benefits for applications identified. DSS : Potential benefits identified
3	Score 2 + standard nomenclature applied; validation extended to full product data coverage, comprehensive information on uncertainty available; methods for automated monitoring defined	Data and documentation publicly available from PI, feedback through scientific exchange, irregular updates by PI	Research: Benefits for applications demonstrated. DSS : Use occurring and benefits emerging
4	Score 3 + procedure to establish SI traceability are defined; (inter) comparison against corresponding CDRs (other methods, models, etc); quantitative estimates of uncertainty provided within the product characterising more or less uncertain data points; automated monitoring partially implemented	Data record and documentation available from data provider and under data provider's version control; Data provider establishes feedback mechanism; regular updates by PI	Score 3 + Research: Citations on product usage in occurring. DSS : societal and economical benefits discussed
5	Score 4 + SI traceability partly established; data provider participated in one international data assesment; comprehensive validation of the quantitative uncertainty estimates; automated quality monitoring fully implemented (all production levels)	Score 4 + source code archived by Data Provider; feedback mechanism and international data quality assessment are considered in periodic data record updates by Data Provider	Score 4 + Research: product becomes reference for certain applications. DSS : Societal and economic benefits are demonstrated
6	Score 4 + SI traceability partly established; data provider participated in one international data assesment and incorporating feedbacks into the product development cycle; temporal and spatial error covariance quantified; Automated monitoring in place with results feedback to other accessible information, e.g metadata or documentation.	Score 5 + source code available to the public and capability for continuous data privisons established (ICDR)	Score 5 + Research: Product and its applications becomes references in multiple research field. DSS : Influence on decision and policy making demonstrated

Figure 8-1 : System Maturity Matrix for the FDR4ALT project. The green represents the status at the end of the project.

## Appendix C - Acronyms

<b>AATSR</b>	Advanced Along-Track Scanning Radiometer
<b>AEM</b>	Airborne electromagnetic
<b>AIR</b>	AIRWAVES2
<b>ALT</b>	Altimetry
<b>AMSR-E</b>	Advanced Microwave Scanning Radiometer - Earth Observing System sensor
<b>AMSU-A</b>	Advanced Microwave Sounding Unit-A
<b>ANN</b>	Artificial Neural Network
<b>AVISO</b>	Archivage, Validation et Interprétation des données des Satellites Océanographiques
<b>ASSIST</b>	Arctic Shipborne Sea Ice Standardization Tool
<b>ATM</b>	Airborne Topographic Mapper
<b>BDHI</b>	Base de datos Hidrologica integrada
<b>BGEP</b>	Beaufort Gyre Exploration Project
<b>CAL</b>	Calibration
<b>CCI</b>	Climate Change Initiative
<b>CFOSAT</b>	Chinese-French Oceanic SATellite
<b>CDS</b>	Copernicus Data Service
<b>CDL</b>	Common Data Language
<b>CLS</b>	Collecte Localisation Satellite
<b>CMEMS</b>	Copernicus Marine Environment Monitoring Service
<b>CMSAF</b>	Climate Monitoring Satellite Application Facility
<b>CNES</b>	Centre National des Etudes Spatiales
<b>CRREL</b>	Cold Regions Research and Engineering Laboratory
<b>DAHITI</b>	Database for Hydrological Time Series of Inland Waters
<b>DGA</b>	Dirección General de Aguas
<b>DFT</b>	Discrete Fourier Transform
<b>ENVISAT</b>	ENVironment SATellite
<b>EMD</b>	Empirical mode decomposition
<b>EO</b>	Earth Observation
<b>EPS</b>	European Polar System
<b>ERA</b>	ECMWF Re-Analysis
<b>ERS</b>	European Remote-Sensing Satellite
<b>ESA</b>	European Space Agency
<b>ESTEC</b>	European Space Research and Technology Centre
<b>FCDR</b>	Fundamental Climate Data Record
<b>FDR</b>	Fundamental Data Records
<b>FIDUCEO</b>	Fidelity and uncertainty in climate data records from Earth Observations
<b>FMR</b>	Full Mission Reprocessing
<b>FYI</b>	First Year Ice
<b>GEWEX</b>	Global Energy and Water Exchanges
<b>GFO</b>	Geosat Follow-On
<b>GIEMS</b>	Global Inundation Extent from Multi-Satellites
<b>GMSL</b>	Global Mean Sea Level
<b>GNSS</b>	Global Navigation Satellite System
<b>GPM</b>	Global Precipitation Measurement
<b>GRDC</b>	Global Runoff Data Centre
<b>G-REALM</b>	Global Reservoir And Lake Monitor
<b>G-VAP</b>	GEWEX Water Vapour Assessment
<b>HYBAM</b>	HYdro-géochimie du Bassin AMazonien

<b>ICARE</b>	
<b>IGM</b>	Instituto Geografico Militar
<b>IGN</b>	Instituto Geografico Nacional
<b>IMB</b>	Ice Mass Balance
<b>INA</b>	Instituto Nacional de Agua
<b>ISRO</b>	Indian Space Research Organisation
<b>IRPI</b>	Istituto di Ricerca per la Protezione Idrogeologia
<b>IWMI</b>	International Water Management Institute
<b>LEGOS</b>	Laboratoire d'Etudes en Géophysique et Océanographie Spatiales
<b>LIDAR</b>	Ligth Detection And Ranging
<b>LTAN</b>	Local time of the ascending node
<b>LWP</b>	Liquid Water Path
<b>MAC</b>	Multisensor Advanced Climatology
<b>MEAS-SIM</b>	Measure-Simulation
<b>MQE</b>	Mean Quadratic Error
<b>MSSH</b>	Mean Sea Surface Height
<b>MWR</b>	Microwave Radiometer
<b>NASA</b>	National Aeronautics and Space Administration
<b>NE</b>	North East
<b>NN</b>	Neural Network
<b>NPI</b>	Norwegian Polar institute
<b>NWP</b>	Numerical Weather Prediction
<b>NOAA</b>	National Oceanic and Atmospheric Administration
<b>OIB</b>	Operation Ice Bridge
<b>OLC</b>	Open Loop Calibration
<b>ORF</b>	Orbit Revolution File
<b>OSTST</b>	Oceanography Surface Topography Science Team
<b>POSTEL</b>	Pôle d'Observation des Surfaces continentales par TELEdetection
<b>PRF</b>	Pulse Repetition Frequency
<b>PTR</b>	Point Target Response
<b>RD</b>	Reference Document
<b>REAPER</b>	Reprocessing of Altimeter Products for ERS
<b>RM</b>	Review Meeting
<b>RSS</b>	Remote Sensing System
<b>SALP</b>	Service d'Altimétrie et de Localisation Précise
<b>SARAL</b>	Satellite with Argos and Altika
<b>SLA</b>	Sea Level Anomaly
<b>SCICEX</b>	Submarine Arctic Science Program
<b>SGDR</b>	Sensor Geophysical Data Record
<b>SHOA</b>	Servicio Hidrografico y Oceanografico de la Armada
<b>SSB</b>	Sea State Bias
<b>SSH</b>	Sea Surface Height
<b>SSM/I</b>	Special sensor microwave/imager
<b>SST</b>	Sea Surface Temperature
<b>SWH</b>	Significant Wave Height
<b>SWIM</b>	Surface Waves Investigation and Monitoring instrument
<b>TAC</b>	Thematic Assembly Center
<b>TB</b>	Température de Brillance (Brightness Temperature)
<b>TDP</b>	Thematic Data Products
<b>TDS</b>	Test Data Set
<b>TFMRA</b>	Threshold First-Maximum Retracker Algorithm
<b>TMR</b>	Topex Microwave Radiometer

<b>TP</b>	Topex/Poseidon
<b>TCWV</b>	Total column water vapour
<b>VCC</b>	Vicarious calibration
<b>VS</b>	Virtual Station
<b>ULS</b>	Upward Looking Sonar
<b>USA</b>	United States of America
<b>USDA</b>	United States Department of Agriculture
<b>WHALES</b>	Wave Height Adaptive Leading Edge Subwaveform
<b>WTC</b>	Wet Tropospheric Correction
<b>WSH</b>	Water Surface Height

