Cryosat-2 Product Handbook

Baseline D 1.0

C2-LI-ACS-ESL-5319

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Document Changelog

Revision	Date	Details of changes
D 1.0	3-APR-2018	Brought up to date for Baseline D.

1 Introduction

1.1 Purpose and Scope of this Product Handbook

This document is intended to give Cryosat-2 data users a concise overview of the Cryosat-2 level-2 (L2) ice and ocean products. This revision of the document has been released to accompany the delivery of Baseline-D Cryosat products. More information about Cryosat product baselines may be found here https://earth.esa.int/web/guest/missions/cryosat/ipf-baseline.

The Baseline-D and later products are in a self-describing netCDF format, and can be read into any program that supports reading netCDF data. This document is intended to help in understanding and using the contents of the products. For a complete list of the contents and structure of the products, see the product format documents:

- CRYOSAT Ground Segment Instrument Processing Facility L1B Products Specification Format CS-RS-ACS-GS-5106
- CRYOSAT Ground Segment Instrument Processing Facility L2 Products Specification Format CS-RS-ACS-GS-5123

A global attribute in the netCDF product named `reference_document` gives the specific product document ID and revision that applies to that product.

1.2 The Cryosat-2 Mission and its characteristics

Cryosat-2 is a four-year radar altimetry mission, launched on 8 April 2010, to monitor variations in the thickness of the Earth's marine ice cover and continental ice sheets. Its primary objective is to measure the extent of thinning Arctic ice due to climate change. However, beyond the core of the mission objective, CryoSat-2 also represents a valuable source of data for the oceanographic community.

The CryoSat-2 satellite replaces the original CryoSat, which was lost due to a launch failure in October 2005. Its main characteristics are summarized in the table below:

Table 1: Satellite main characteristics

Launch	Mission duration	Orbit	Payload	Mass	Dimensions
08 April 2010	Extension until 2017 approved	- Low Earth Orbit - Non Sun-synchronous - Altitude: 730 km - Inclination: 92 degree - Repeat cycle: 369 days (5344 orbits) with 30-day sub-cycle	- **S**AR **I**nterferometric **R**adar **AL**timeter (SIRAL) - DORIS receiver - Laser retro-reflector - 3 Star trackers	720 kg	4.60 m x 2.4 m x 2.2 m

From an altitude of just over 700 km and reaching latitudes of 88°, Cryosat-2 monitors precise changes in the thickness of the polar ice sheets and floating sea ice. The observations made over the four-year lifetime of the mission have provided conclusive evidence of rates at which ice cover may be diminishing.

SIRAL is the primary instrument on-board CryoSat-2 and has extended capabilities to meet the measurement requirements for ice-sheet elevation and sea-ice freeboard.

Derived from the well-known Poseidon ocean altimeter on the Jason satellite, SIRAL is a very compact assembly, weighing just 90 kilograms. It combines three measurement modes to determine the topography of oceans, land and sea ice masses, as well as ice floes and significant elevation transitions, especially between land and ice fields:

- Over the **oceans** and **ice sheet interiors**, Cryosat-2 generally operates like a traditional radar altimeter in **Low Resolution Mode** (so called **LRM**).
- Over **sea ice** and **few oceanographic areas**, coherently transmitted echoes are combined via **Synthetic Aperture Radar Mode** (so called **SAR** processing, to reduce the illuminated surface area. This mode is mainly used to carry out high-resolution measurements of floating sea ice and land ice sheets, enabling the indirect measurement of the sheets' thickness.
- CryoSat's most advanced mode is used around the **ice sheet margins** and over **mountain glaciers**. Here, the altimeter performs **Synthetic Aperture Radar** processing and uses a second antenna as an **interferometer** to determine the across-track angle to the earliest radar returns. This mode (so-called **SIN or SARin** provides the exact surface location being measured when the surface is sloping and can be used to study more contrasted terrains, like the very active areas located at the junction of the ice sheet and the Antarctic continent or Greenland.

The mode of operation is selected from a mask of geographical zones. The mask is updated every two weeks to allow for changes in sea ice extent. The geographical mask is converted into a weekly timeline of instrument commands by the mission planning facility, taking into account the Cryosat-2 reference orbit. An example of the mode mask, downloaded from the ESA website at the URL https://earth.esa.int/web/guest/-/geographical-mode-mask-7107 is shown in Figure 1.

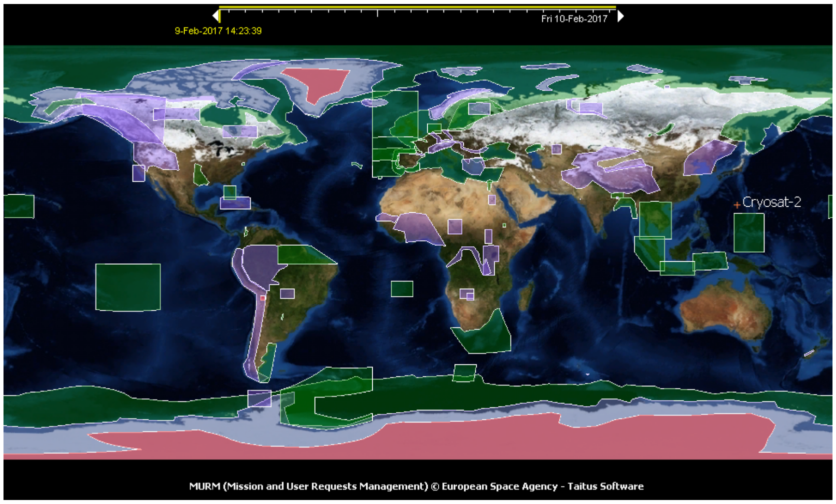


Figure 1: Example mode mask

1.3 Simplified principles of modes of operation

1.3.1 Low Resolution Mode

Conventional radar altimeters operate in pulse-limited mode for which the area of the surface seen by the instrument is limited by the length of the radar pulse transmitted by the altimeter. In CryoSat-2 this mode is often referred to as LRM as the data rate is much lower than for the other measurement modes. In pulse-limited mode radar pulses are sent at intervals of about 500µs (~2000Hz) ensuring that the returning echoes are uncorrelated. Many uncorrelated echoes can be averaged to reduce speckle. This mode of measurement is suitable over the relatively smooth ice sheet interiors or over ocean (red on Figure 1, and also where no other mode is shown).

1.3.2 Synthetic Aperture Radar Mode

The SAR mode (green in Figure 1) is mainly used over relatively flat areas of sea ice. The CryoSat-2 altimeter sends a burst of pulses with an interval of only 50µs (~20,000Hz) partitioning the pulse-limited footprint. Given that the observed surface is in movement relative to the satellite, the echoes received by the radar include a mix of Doppler frequencies corresponding to all surface directions covered by the radar antenna beam, from the front to the back, see Figure 2. In this figure, only 8 beams are shown for clarity (instead of the 64 which are generated) and the divergence angle between them is exaggerated.

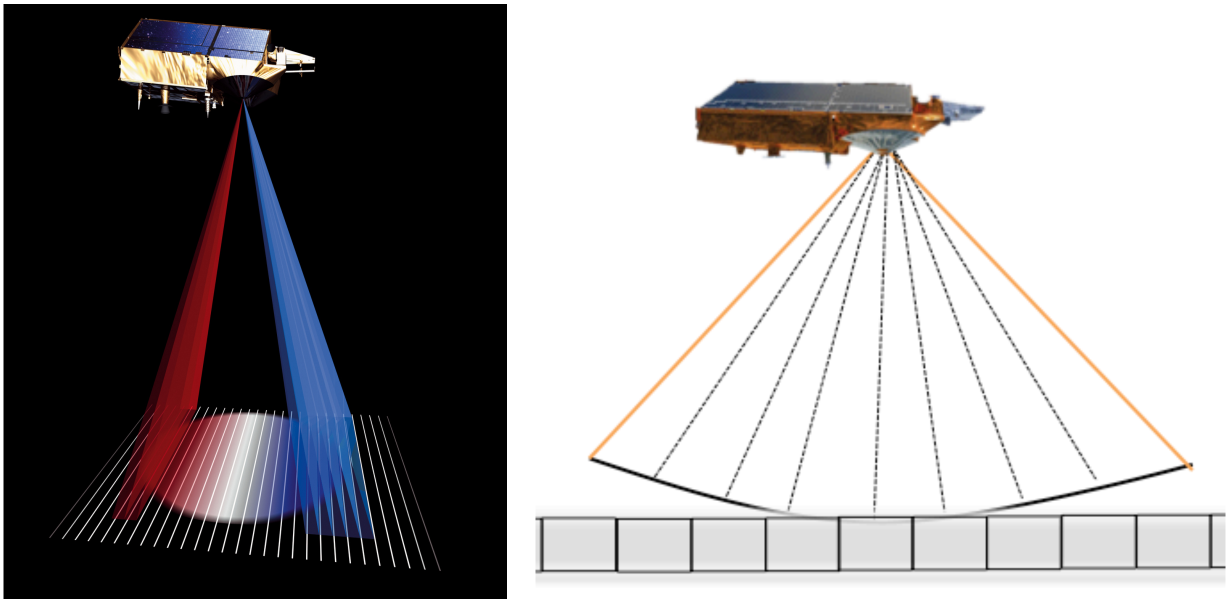


Figure 2: Geometry of measurement for a single burst.

As the returning echoes are correlated, and by treating the whole burst at once, the data processor can separate the echo into 64 strips perpendicular to the track by exploiting the slight frequency shifts caused by the Doppler effect.

Each strip is about 250 m wide and the interval between bursts is arranged so that the satellite moves forward by 80 m each time. Thus, each ground location is looked multiple times (see Figure 3). In this figure, the blue rectangle is the multi-looked footprint.

The strips laid down by successive bursts can therefore be superimposed on each other to create a stack of echoes which are averaged to reduce noise.

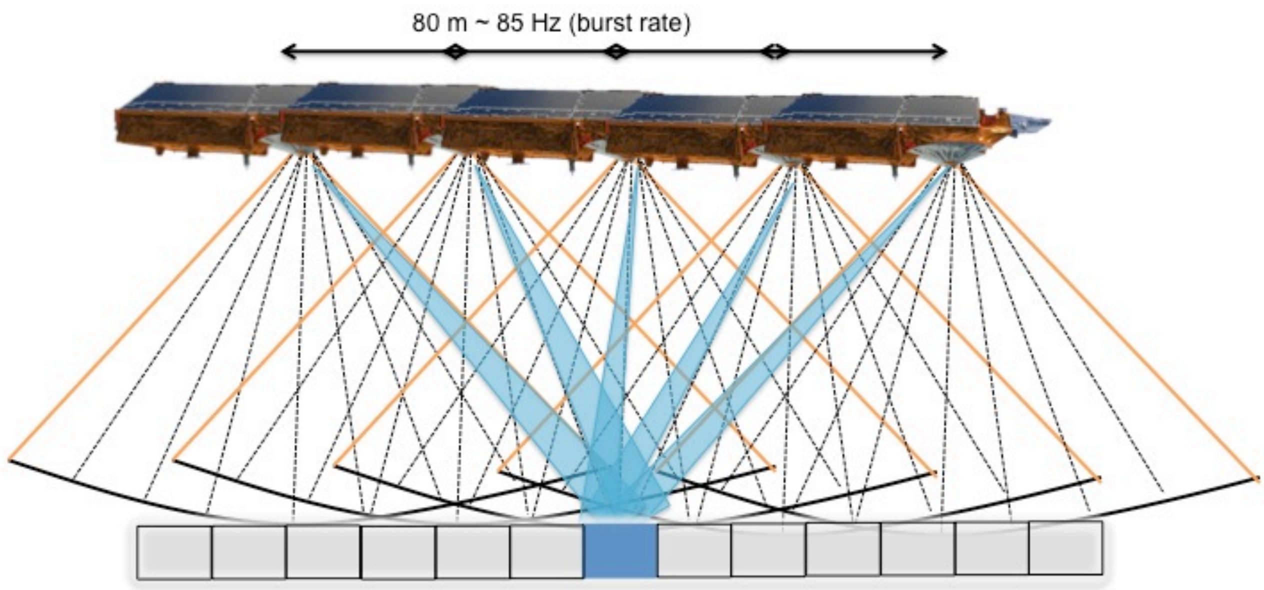


Figure 3: Geometry of multi-looking

1.3.3 SAR Interferometry Mode

SAR interferometry, or SIN or SARIn, mode (purple in Figure 1) is used across ice sheet margins where the ice surface may be sloping. SIRAL has two antennae, mounted about 1m apart, which receive the echo almost simultaneously. If the echo comes from anywhere but directly below the satellite, then there is a difference in the path lengths of the signal travelling to both antennas. By comparing the differing signal phases, the angle of arrival and hence the echo origin can be derived.

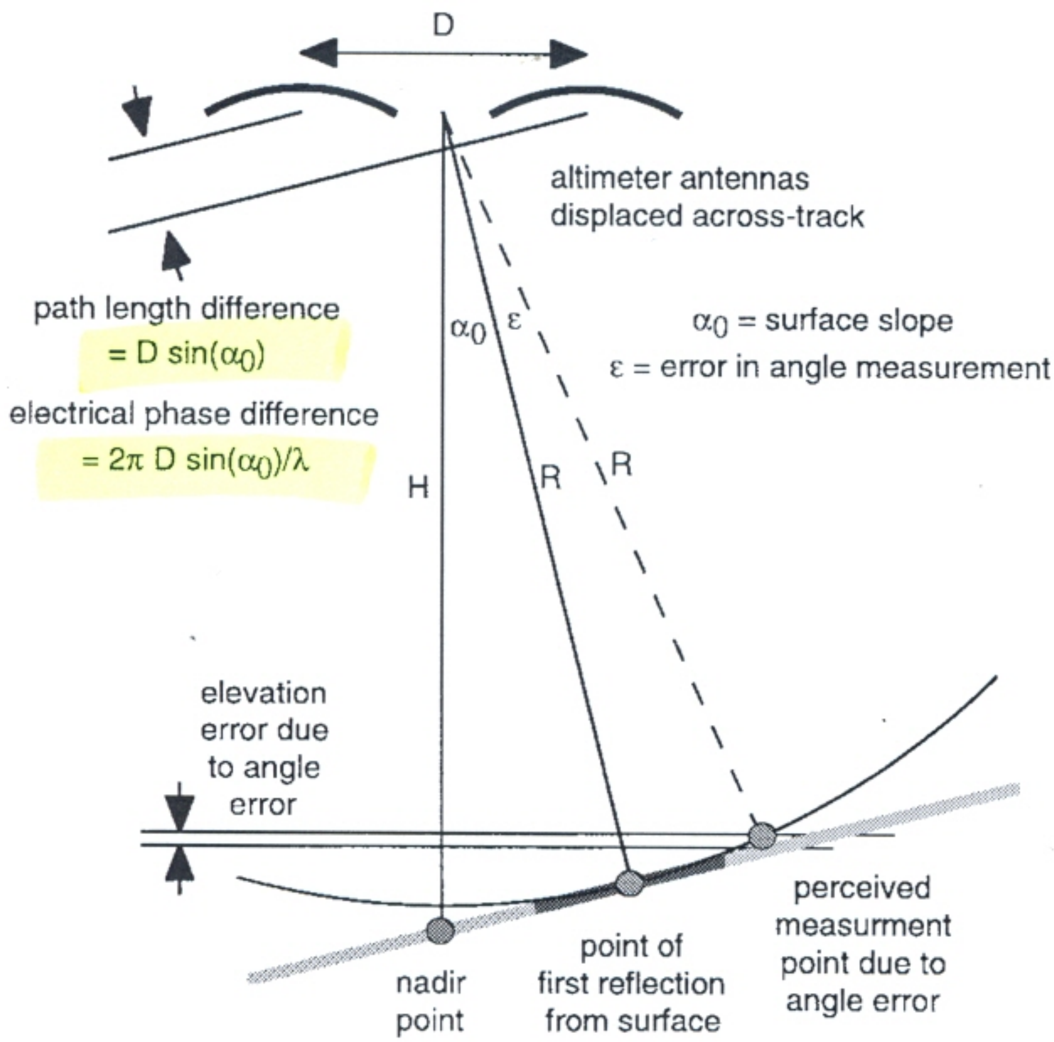


Figure 4: SARin mode across-track angle determination

If one SIRAL receive chain should fail then the instrument can operate in SIN mode with only one channel. This is referred to as SIN degraded mode, or SID. Instead of interferometry method, the slope model intended for LRM mode is used to try to improve the result by estimating the across-track angle. Alongside these operating modes there are specific instrument calibration modes, the pulse response calibration, the receive chain calibration and the interferometric external calibration. Information from these is fed into the higher-level data products and contained in the level-1b data products.

Further general information is given in references 1, 2 and especially 3. An overview of SIRAL is given in reference 15.

1.4 SIRAL Characteristics

Radio frequency	13.575 GHz (single frequency Ku-band radar)
Pulse bandwidth	320 MHz (40 MHz for tracking only in SIN)
Pulse Repetition Frequency (PRF)	1.97 kHz in LRM 18.181 kHz in SAR and in SIN; coherent pulse transmission for Doppler processing
Burst mode PRF	Pulses/burst 1970 Hz in LRM, 85.7 Hz in SAR and 21.4 Hz in SIN
	N/A in LRM, 64 in SAR and in SIN
Compressed pulse length	3.125 ns
Pulse duration	44.8 µs
Timing	Regular PRF in LRM, burst mode in SAR and SIN
Samples in echo	128 in LRM and SAR, 512 in SIN
RF peak power	25 W
Antenna size	2 reflectors 1.2 m x 1.1 m, side-by-side
Antenna beamwidth (3 dB)	1.06º (along-track) x 1.1992º (across-track)
Antenna footprint	15 km
Range bin sample	0.2342 m for SAR and SIN, 0.4684 m for LRM
Data rate	60 kbit/s for LRM, 12 Mbit/s in SAR, 2 x 12 Mbit/s in SIN
Instrument mass (with antennas)	90 kg redundant
Instrument power	149 W
Tracking cycle	47.17 ms (not a multiple of PRF)
Burst repetition	11.8 ms (not a multiple of PRF)
Antenna baseline length	1167.6 mm

The along-track sampling resolution in SAR and SIN modes is variable around the orbit. It is, for example, 278 m based on an altitude of 750 km, flat Earth and half power of the azimuth beam. This is then affected by the azimuth hamming weighting function which degrades the resolution. The sampling of the processor is different to the resolution. With the effect of a curved Earth instead of a flat one, then the Doppler cell width on the ground is about 290 m along track; however, it is a function of altitude, so it varies. Including also the beam widening effect of the hamming window applied before the azimuth FFT in the processor, then the effective "resolution" of the beams is widened by a factor of roughly 1.3. So the "resolution" (as opposed to sampling) in the along-track direction is more like 380 meters, but this is plus or minus several percent as the altitude varies.

The width in the across-track direction of the area over which echoes are collected by the antenna (the antenna-limited illuminated area) is approximately equal to 15 km since it can be computed as 2*h*tan(theta/2) being h the altitude and theta=1.2° the antenna beamwidth across-track. The width in the across-track direction of the area illuminated by the leading edge of the pulse until the time the trailing edge first intersects the surface (the pulse-limited illuminated area around the point of closest approach), in case of almost flat surface response, is equal to 2*sqrt(c*h/B), approximately 1.6 km for CryoSat, being B the pulse bandwidth.

For more details, the interested reader may refer to the ESA webpage at

http://www.eoportal.org/directory/pres_CryoSat2EarthExplorerOpportunityMission2.html

1.5 Data Access and Data Processing Tools

Access to Cryosat-2 data is controlled by a registration system. To register, or to download data if already registered, visit ESA 'Earthnet Online' Cryosat-2 portal at:

https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/cryosat

A very useful website is ESA radar altimetry tutorial site, which includes links to tools available for data analysis as well as a general discussion of radar altimetry principles:

http://earth.eo.esa.int/brat/

Beginning with Baseline D, Cryosat-2 L1B and L2 products are produced in standard netCDF formats. For older baselines, a set of API routines to read Cryosat-2 data products is available through ESA 'Earthnet Online' web site under the link under 'Software Routines'. The API libraries have been supplied by UCL and provide ingestion routines written in ANSI C and IDL that can be used to read the L1B and L2 Cryosat-2 products. The download package includes a reference manual and examples.

All Cryosat-2 science products, available on the Cryosat-2 dissemination server (ftp://science-pds.cryosat.esa.int) are processed with the DORIS precise orbits and are generated with a delay of about 30 days after SIRAL acquisition.

2 Data parameters and corrections

Please note that the relevant fields in the data records are referenced by their variable names taken from the Baseline D netCDF products and are presented in `monospaced` font.

2.1 Spacecraft Orbit and Orientation

2.1.1 Drifting orbit and long repeat cycle

The choice of the CryoSat-2 orbit is the result of trade off between the desired high density of crossover point in order to meet the mission requirements and the need to sufficiently cover the south Greenland. For this, the CryoSat-2's orbit has a mean altitude of 717 km and a high inclination of 92°, allowing measurements at high latitudes (up to 88°). This orbit is not-sun-synchronous and drifts through all angles to the Sun in approximately 16 months. Further information is given in reference 4.

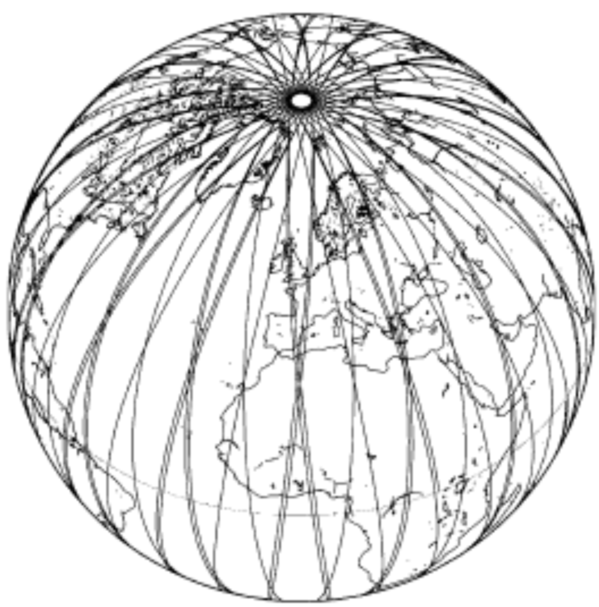


Figure 5: Example of tracks of CryoSat-2's orbit over a three-day period

The repeat cycle for Cryosat-2 orbit should be 369 days, corresponding to 5344 revolutions. **It is however important to note that the Cryosat orbit does not exactly repeat after each cycle**, as it is usually the case for previous ocean-oriented altimetric mission. CryoSat's ascending nodes are repeating from cycle to cycle within few ten meters in order to have equidistant ascending equator crossings in the reference ground track. The descending nodes are however no longer equidistant due to a residual rotation of the eccentricity vector. Even if this issue has been addressed after the Launch and Early Orbit Phase (LEOP), fluctuations up to nearly 4 km can still be observed on the descending node from cycle to cycle.

2.1.2 Orbit processing

In order to measure accurately, the position of the satellite, CryoSat-2 carries some specific equipment:

- DORIS (Doppler Orbit and Radiopositioning Integration by Satellite) is a tracking system carried by CryoSat-2 to detect and measure the Doppler shift on signals broadcast from a network of over 50 radio beacons around the world. These signals are used for orbit determination, down to millimetre level, and are essential for accurately measuring the height of the ice surface. DORIS stands for. The system has been used on previous altimetry missions.
  http://www.aviso.oceanobs.com/en/doris/index.html

- A small laser retro-reflector reflects light back in exactly the direction it came from. A global network of laser tracking stations fire short laser pulses at CryoSat-2 and time the interval before the pulse is reflected back, providing independent reference measurements of CryoSat-2 position. The International Laser Ranging Service (ILRS) provides tracking from its global network of laser ranging stations to support the mission.

The main orbit information for data processing is taken from the DORIS Precise Orbit (POE) or the DORIS Navigator Level-0 Data.

Systematic processing relies on the POE, which becomes available to the Payload Data System around 30 days after acquisition. Near Real Time processing preferably uses the DORIS Navigator level-0 data generated on-board the satellite and downlinked to ground during station visibility.

Orbit formats are described in references 5 and 6.

Precise orbital details used during processing of a given dataset are found in the instrument characterization data file, and the name of the file used during processing is listed in the netCDF global attributes of the product file, see references 12 and 13 for details.

2.1.3 Reference Frame Processing

Knowledge of the precise orientation of the baseline and the two receiving antennas is essential for the success of the mission. CryoSat-2 measures this baseline orientation using the position of the stars in the sky. Three star-trackers are mounted on the support structure for the antennas. Each contains a camera, which take up to five pictures per second. The images are analysed by a built-in computer and compared to a catalogue of star positions.

The CryoSat-2 spacecraft flies in a nose-down attitude inclined at 6 degrees to the positive X axis. The nadir direction is inclined 6 degrees from the negative Z axis. The origin of the satellite reference frame is at the centre of the satellite mounting plane on the launch vehicle. The radar antennas are mounted such that the real beam direction is along the nadir direction.

Full details are given in reference 7.

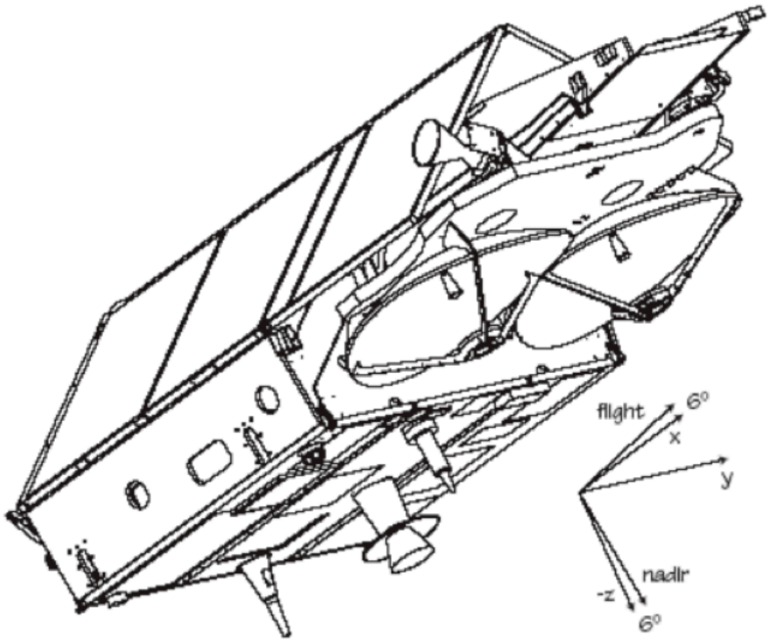


Figure 6: Satellite Reference Frame

This illustration comes from reference 7 and shows CryoSat-2, without its thermal control material. Note that the negative Z axis is shown in order to display the offset to the nadir direction.

Level-2 and level-1b products use a Cryosat-2 processing reference frame (not the satellite reference frame) to describe the interferometric antenna baseline `inter_base_vec_20_ku` and real antenna boresight (real beam) direction vectors `beam_dir_vec_20_ku`. This reference frame has its origin at the satellite centre of mass (CoM). CryoSat-2's CoM is colocated with its centre of gravity (CoG) and has been designed so that the CoM corresponds to the centre of the single, spherical fuel tank. The fuel is gaseous nitrogen, which uniformly fills the tank. CryoSat-2 has no moving parts. Consequently the centre of mass will not move during the satellite lifetime. Overall design concerns are given in reference 4.

The X axis is directed from the frame origin and is parallel with the normal incidence to the reference ellipsoid. The Y axis is in the plane defined by the X axis and the spacecraft velocity vector V. It is determined by

$Y = (V - X (X . V)) / | V - X (X . V) |$ (Equation 2.1)

The remaining axis is determined by $Z = Y \times X$ (Equation 2.2)

All reference frames used during processing are described in detail in reference 20.

In other words, the antenna baseline and real beam vectors are defined in the Cryosat-2 processing reference frame (CoG, X, Y, Z) orthonormal but left-handed, where X is the unit vector pointing to nadir in the "along-track' plan defined by the COG and the velocity vector, and Y is the unit vector almost in the same direction as the velocity vector.

The interferometric baseline vector and the real beam vector components are normalized to make a unit vector and scaled by one million to get integer components in micrometres. These components are measured by the star trackers angles on board. In the perfect situation, the baseline vector is [0;0;-1000000] and the beam vector is [1000000;0;0].

Since one vector element is nominally one unit and the angles are very small, the roll, pitch, and yaw angles of the antenna bench in the Cryosat-2 processing reference frame can be approximated with :

roll = + (baseline_vector_x) in microrad, where roll is relative to axis Y defined above.

yaw = - (baseline_vector_y) in microrad, where yaw is relative to axis X defined above.

pitch = - (beam_vector_y) in microrad, where pitch is relative to axis Z defined above.

These angles are presented in the variables `off_nadir_roll_angle_str_20_ku`, `off_nadir_pitch_angle_str_20_ku`, `off_nadir_yaw_angle_str_20_ku`, at a resolution of 0.1 microdegrees and with all applicable corrections and biases applied.

Positive/negative roll corresponds to right antenna down/up respectively.

Positive/negative yaw corresponds to spacecraft nose on the right/left respectively.

Positive/negative pitch corresponds to spacecraft nose down/up respectively.

In order to look at Earth, the satellite turns one revolution in inertial space for each revolution that it makes around the Earth. Since a revolution around the Earth takes roughly 6000 seconds, the rotation rate is about 360 degrees / 6000 seconds, or about 0.06 degrees per second. It is mainly the pitch which must turn in inertial space to follow the Earth. Therefore, if there is a timing error in a datation or a calculation, one can expect pitch, in particular, to be affected by an amount of order 0.06 degrees/sec times whatever is the delta time.

The SIN phase difference waveforms in L1B data `ph_diff_waveform_20_ku` **do include** a phase difference bias `instr_ext_ph_cor_20_ku`, which accounts for the roll fixed bias component only, but **do not include** the roll variable component, which can be extracted in the product itself according to the above formula and should be used, as shown below, to correct the inferred angle.

The variable roll `off_nadir_roll_angle_str_20_ku` can be applied to the inferred angle as a variable correction. The inferred angle alpha is obtained from the retracked SIN L1B phase difference waveform `ph_diff_waveform_20_ku` with: alpha [rad] = lambda * retrack_PD / (2*pi*baseline), where retrack_PD is the retracked phase difference in radians, baseline = 1.1676 m and lambda = 0.022084 m

Then the variable roll correction can be applied to the inferred angle with : alpha - roll.

Note that the phase difference values `ph_diff_waveform_20_ku` are provided between –pi and +pi microradians. A positive/negative phase difference (and across-track inferred angle) corresponds to a signal coming from the right/left hand side of the observer sitting on the antenna bench with its dorsal spine aligned with the nadir direction and looking forward in the along-track flight direction.

The mispointing angle is the angle between the antenna pointing, i.e. the direction of the actual beam, and the nadir direction. Nominally this should be zero degree.

2.2 Spacecraft Time and Location

2.2.1 Reference Ellipsoid

Satellite altimeter height measurements are usually referenced to an ellipsoid, a simple mathematical figure that describes a rough approximation of the geoid. The geoid is the shape that would have the sea surface under the single influence of Earths's gravitation and without any signature associated to the ocean circulation and tide effects. For CryoSat, the reference ellipsoid is WGS84, defined by the National Geospatial Intelligence Agency of the USA. This can be explored online at

https://www1.nga.mil/ProductsServices/GeodesyandGeophysics/Worldgeodeticsystem/Pages/default.aspx

2.2.2 Some Basic Altimetry Terms

Basic terms used in the Cryosat-2 mission are (see Fig 2.3):

Range: the one-way distance from the satellite to the sensed surface below.

Altitude: the distance of the satellite centre of mass above the reference ellipsoid.

Corrections: Values to be subtracted to the *Range* in order to avoid undesirable effects due to the delay of the echo propagation through the atmosphere layers, the temporally subsampled high frequency geophysical signals and the instrumental noise.

Height: Difference between the *Altitude* and the corrected *Range*, i.e. the instantaneous elevation of the surface observed above the reference ellipsoid.

Mean Sea Surface: Temporal average of the sea *Height* over a given period which contains both the signature of marine geoid and of the sea elevation due to the mean oceanic circulation.

Sea Height Anomaly: Difference between the *Height* and the *Mean Sea Surface* corresponding to the variable component of the instantaneous elevation.

Mean Dynamic Topography: Difference between the *Mean Sea Surface* and the *Geoid,* corresponding the surface signature of the single mean oceanic circulation.

Absolute Dynamic topography: *Mean Dynamic Topography* plus *Sea Height Anomaly* (or equivalently *Height* minus *Geoid*) containing the surface signature of both the mean circulation and transient oceanographic processes.

Note that most radar altimeters observe the surface at nadir, but Cryosat-2 can observe off-nadir when it operates in SARin mode. If the observation is off-nadir then the latitude and longitude of the actual observed point observed is provided in the data products.

At level 1b, only the engineering corrections (including the USO), the Doppler corrections and the centre-of-mass offset (explained in sections 2.2.6, 2.3.7 and 2.4.1) are applied to the range measurement (given as a time delay `window_del_20_ku`). The altitude is given as `alt_20_ku`.

At level 2, the atmospheric and tidal corrections (explained in sections 2.5 and 2.6) are also applied to the range before it is used to compute height. The heights presented in the L2 products are contained in variables that have the string '`height`' in the name, e.g. `height_1_20_ku`.

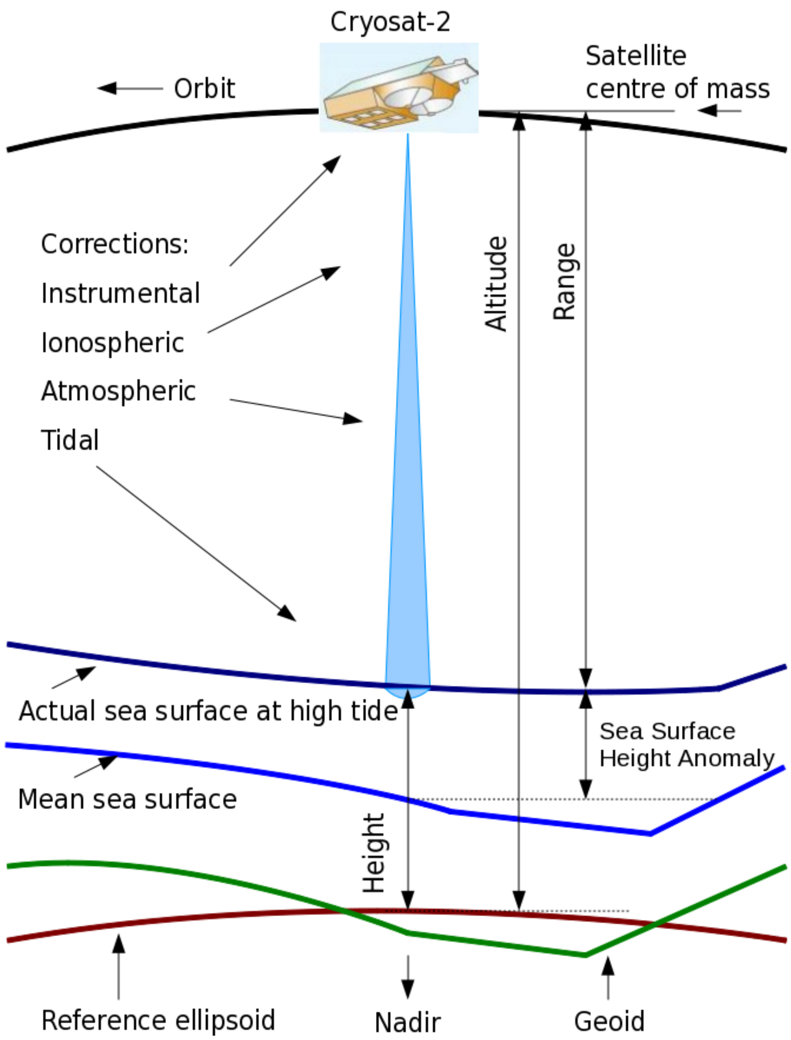


Figure 7: Basic altimetry terms and applicable corrections over open ocean

2.2.1 Geoid and Mean Sea Surface

In the level-2 data product, values of the geoid (over land and land ice) or alternatively of the mean sea surface (MSS over open ocean or closed sea) are spatially interpolated at the ground track locations. The models used are EGM96 (geoid) `geoid_20_ku` and UCL13 (mean sea surface MSS) `mean_sea_surf_sea_ice_20_ku`.

EGM96 can be explored more fully at http://cddis.nasa.gov/926/egm96/egm96.html.

UCL13 is a hybrid global model compiled from CryoSat sea-surface height measurements above 60 degrees north and the CLS2011 MSS (http://www.aviso.oceanobs.com/index.php?id=1615) below 50 degrees North. Between those two latitudes, a linear blend is performed between the models. The purpose of the model is to provide better accuracy in the Arctic ocean. Model details are also given in section 2.8.1 and reference 8.

2.2.2 Sea Surface Height Anomaly

Sea surface height anomaly (SSHA) is the difference between the long-term average sea surface height, i.e. the MSS, and the ocean height actually observed by the satellite. This must be determined in order to accurately calculate the sea ice freeboard. At level 2, the SSHA is found by comparing the ocean height with the UCL13 MSS to get the ocean height anomaly `ssha_20_ku`, and then using linear interpolation to get the SSHA `ssha_interp_20_ku`. The SSHA quality flag gives the RMS of the residuals of the linear fit `ssha_interp_rms_20_ku`. Technically another MSS may be chosen if desired, as choice is configurable. Model details are also given in section 2.8.1 and reference 8.

2.2.3 Freeboard

Sea ice freeboard `freeboard_20_ku` is the height by which an ice floe extends above the sea surface. Level 2 data includes climatological snow depth `snow_depth_20_ku` and density values `snow_density_20_ku` for each record. The snow depth values are extracted from a static climatology, UCL04, and can be used to adjust the freeboard estimate to account for snow load. Note that the freeboard can possibly be negative if there is heavy snow load on thin ice. There is a separate climatology file for each month of the year, which provides snow depth values for the Arctic region. No climatology for the Antarctic region is available. Snow density is provided as a single global constant average. The current value is 400 kg/m3. Model details are also given in section 2.8.1 and reference 8.

2.2.4 Timestamps

In LRM, the timestamp `time_20_ku` for each measurement dataset record is the time at which the middle of the averaged group of pulses impacts the ground. In SAR and SIN modes, it is the time at which the satellite overflies the surface sample location.

2.2.5 Latitude, Longitude and Altitude

The latitude `lat_20_ku`, longitude `lon_20_ku` and altitude `alt_20_ku` measurements are those interpolated from the orbit at the exact time recorded in the timestamp. All of them are measured from the reference ellipsoid at nadir to the satellite centre of gravity.

2.2.6 DORIS Ultra Stable Oscillator Drift

The DORIS USO drift `uso_cor_20_ku` is required to accurately convert the SIRAL altimeter time and range counts into UTC time tag and range delay measurements. SIRAL derives all its radar frequencies from the DORIS Ultra Stable Oscillator whose frequency, in terms of deviations from nominal value (one measurement every 24 hours), is made available in a DORIS Level 1b product, which is an incremental file. This is described in reference 6.

The USO correction is applied to the window delay at L1b. The correction applied is given in terms of range at L2 as `uso_cor_applied_20_ku`.

2.2.7 Satellite Velocity Vector

The satellite velocity vector `sat_vel_vec_20_ku` is given in the International Terrestrial Reference Frame (ITRF), which is defined and maintained by the International Earth Rotation Service (IERS). See their online presence at

http://www.iers.org/IERS/EN/Science/science.html

2.2.8 Reference Orbit

Two phases have been included in the Cryosat-2 Reference Orbit File because during the period between launch and June 2010 the Cryosat-2 cycle was not consistent due to continuous orbital manoeuvres which needed to be performed in order to obtain a stable orbit. These manoeuvres were planned as part of the Commissioning Phase activities. From July 2010 onwards, a stable orbit was maintained and consequently there are Phase 1 in the Reference Orbit File, which includes the period between launch in April 2010 to June 2010, and Phase 2 which includes the period from July 2010 onwards.

Initially, the Reference Orbit File used until October 2011 was incorrect such that it only contained Phase 1 and as a result all data products with validity up until October 2011 currently contain the wrong cycle number and length which does not correspond with the actual data and is the cause of the discrepancy observed by the users. In early October 2011, the Orbit Scenario File was updated with the two phases described above. One can notice that the orbit parameters have changed in October 2011. This is corrected in all processing baselines from B onwards.

Please note that data between launch and July 2010 will not be reprocessed as it has been decided that at this early stage of the mission the data were of little scientific use due to the manoeuvers.

2.2.9 Ground Tracks

The scope of this section is to explain the retrieval and analysis of Cryosat-2 orbits and ground tracks files. The main interest of this analysis is to investigate the differences in the ground tracks when using different predictions of the orbit. Information and description about available files can be found on the ESA Cryosat-2 web pages.

The following information is extracted from this website:

The Reference Orbit file contains information on the orbits over a full repetition cycle (369 days), generated at the start of every orbital repetition cycle.

The Reference Ground Track file is generated from the Reference Orbit file.

The Predicted Orbit file is a high accuracy orbit prediction, generated closer to the time of the overpass. It is generated every day, and contains one Orbit State Vector (OSV) per orbit, located at (or very near to) the Ascending Node. The coverage is for 30 days starting at the generation time.

As a result, the orbits for a given day can be evaluated from the Reference Orbit file or from 30 different Predicted Orbit files which all contain that day, but with increasingly accurate predictions.

The following paragraphs show the differences among these predictions, and furthermore set a documented example of how the information can be extracted and analysed.

In particular, the Reference Ground Tracks are analysed, the Reference Orbit and Predicted Orbit files are compared and the differences among 30 consequent ground tracks, retrieved from the predicted orbits, are assessed.

All the mentioned files can be retrieved from the FTP server:

FTP server: ftp://calval-pds.cryosat.esa.int Username: ground Password: tracks

Upon connection to the FTP server, the following data structure can be observed:

- 3 Reference Orbit files, one per year (2010, 2011, 2012, etc.)
- Predicted Orbit files, about 30 files per month
- Ground Tracks, available on a monthly or yearly basis and with three different sampling steps (2, 10 or 60 seconds)
- Software folder, which contains the necessary tools to generate ground tracks from the orbit files and other functionalities.

The Ground Tracks file is a simple .txt file. For January 2012, this file contains all the reference ground tracks from 01 January 2012 to 31 January 2012 sampled every 10 seconds.

In order to compare Reference Orbits and Predicted Orbits for 2012, the following files can be retrieved from the FTP server:

CS_OPER_MPL_ORBREF_20110617T070122_20120619T224135_0001.EEF

CS_OPER_MPL_ORBPRE_20120102T092520_20120201T092520_0001.EEF

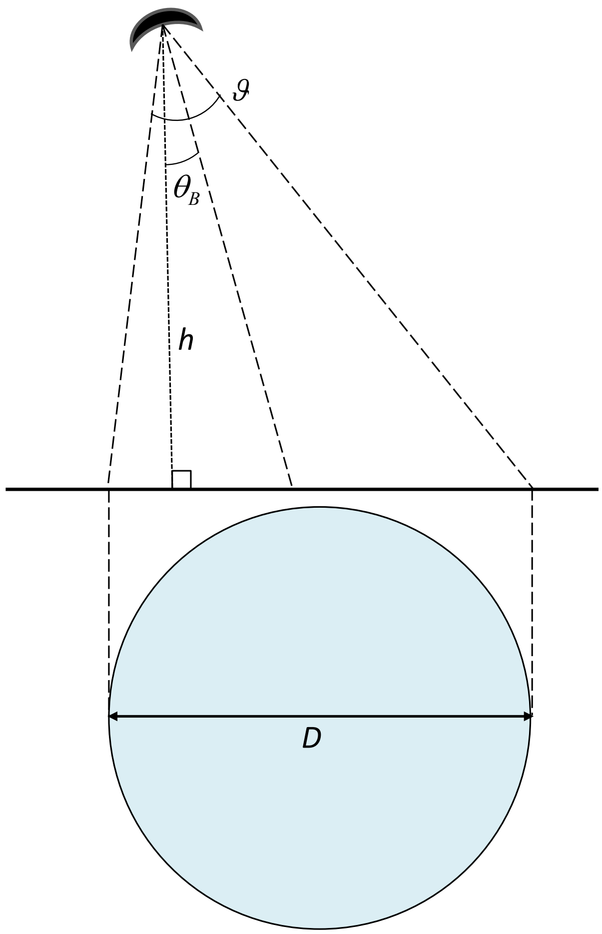
The Reference Orbits span from 17 June 2011 to 19 June 2012.

The Predicted Orbits span from 02 January 2012 to 01 February 2012

The time sampling of the Reference Orbits file is 100 minutes, therefore only one OSV is given for each orbit (100 minutes is approximately the orbit period) for the local ascending node. The orbit files content is fully described in the Cryosat-2 ground system Mission Files Format Specifications (pages 9-27). There, the time, number of orbit and state vector are stored. The X, Y and Z coordinates can be used to calculate the Orbit Height $H = (X*X + Y*Y + Z*Z)^{1/2} - R_{equator}$

The differences on X, Y and Z coordinates, comparing the reference and the predicted orbits, in percentage, are always < 5%.

All the information to calculate the ground tracks from the orbit files is in the document:



"CRYOSAT-2: TRANSPONDER PASS TOOLS - FILE TRANSFER DOCUMENT" from EOCFI-FTD-004_1_5.zip

Starting with a Reference Orbit or Predicted Orbit file, the executable function returns the ground track points (at a temporal sampling defined in Time Step) which are contained in the area defined in Zone Database, for a given set of orbits or for a given time interval.

The ground track samples retrieved from the oldest predicted orbit (one month before) and the ground track samples retrieved from the newest predicted orbit (one day before) can be a bit different. This difference mainly depends on the time or distance from the last orbit maneuver. The spatial difference between the tracks cannot be calculated as the simple distance between two samples of the different ground tracks, because there is a time delay which turns into a spatial shift. However, the across-track distance can be easily calculated with some geometry. Nominally, the across-track distance never exceeds 1km and rarely exceeds 500m in polar areas.

2.2.10 Illuminated Areas

2.2.10.1 Beam-limited footprint

The beam-limited illuminated area is defined as the whole area on the Earth surface on which a beam echo is collected. It depends mainly on the antenna illumination pattern, as a consequence it does not vary with the acquisition mode. It can be described by its widths in the along-track direction and in the across-track direction, that depend on the antenna pattern. Being $\boldsymbol{\vartheta}$ the antenna beam width at -3 dB, $\boldsymbol{\theta_B}$ the angle of the central beam direction with respect to the nadir and h the altitude of the satellite, the width of the beam-limited footprint results in$\boldsymbol{D} = \boldsymbol{h} \cdot \tan(\boldsymbol{\theta_B} + \boldsymbol{\vartheta}/\mathbf{2}) - \boldsymbol{h} \cdot \tan(\boldsymbol{\theta_B} - \boldsymbol{\vartheta}/\mathbf{2})$ where the flat Earth approximation is used.

Considering an altitude of 730 km, $\boldsymbol{\vartheta}$ = 1.06 degrees and $\boldsymbol{\theta_B}$ = 0 degrees along track, while $\boldsymbol{\vartheta}$ = 1.1992 degrees and $\boldsymbol{\theta_B}$ = 0 degrees across track, the beam-limited illuminated area for SIRAL can be decomposed in:

- width of the beam-limited area along track approximately equal to 13.5 km
- width of the beam-limited area across track approximately equal to 15.3 km

Both the along and across beam-limited areas are not constant but are dependent on the orbit characteristics and therefore they change with latitude. The width of the beam-limited area along track varies between 13.2 and 14.0 km while the beam-limited area across track varies between 14.9 and 15.8 km.

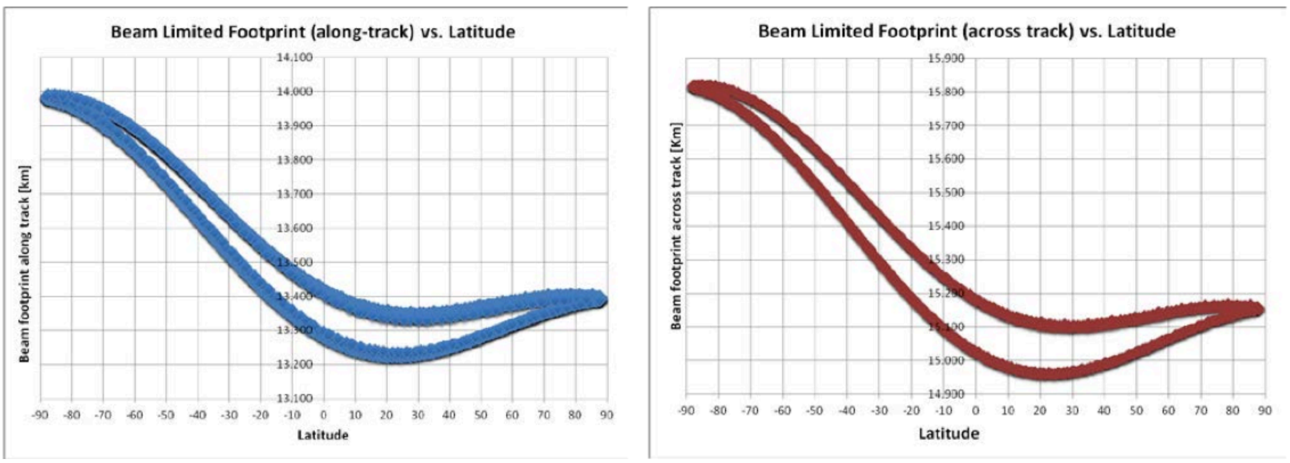


Figure 8: Variation of footprint with latitude

2.2.10.2 Pulse-limited footprint

The pulse-limited illuminated area is defined as the illuminated area on ground around the point of closest approach and it corresponds to the area illuminated by the leading edge of the pulse until the time the trailing edge first intersects the surface.

For LRM, the pulse-limited footprint depends only on the compressed pulse duration, since LRM acquisition has only one independent variable (the time delay).

The Doppler beam formation in SAR and SIN modes allows discriminating the direction of arrival of the echoes in the along-track direction, so that a pulse-Doppler footprint can be defined. This is due to the fact that in SAR and SIN modes there are two independent variables, the along-track position and the across-track position, related to time delay.

The width of the illuminated area for LRM and SAR/SIN modes is defined below using the flat Earth approximation and assuming a quasi-flat ground surface.

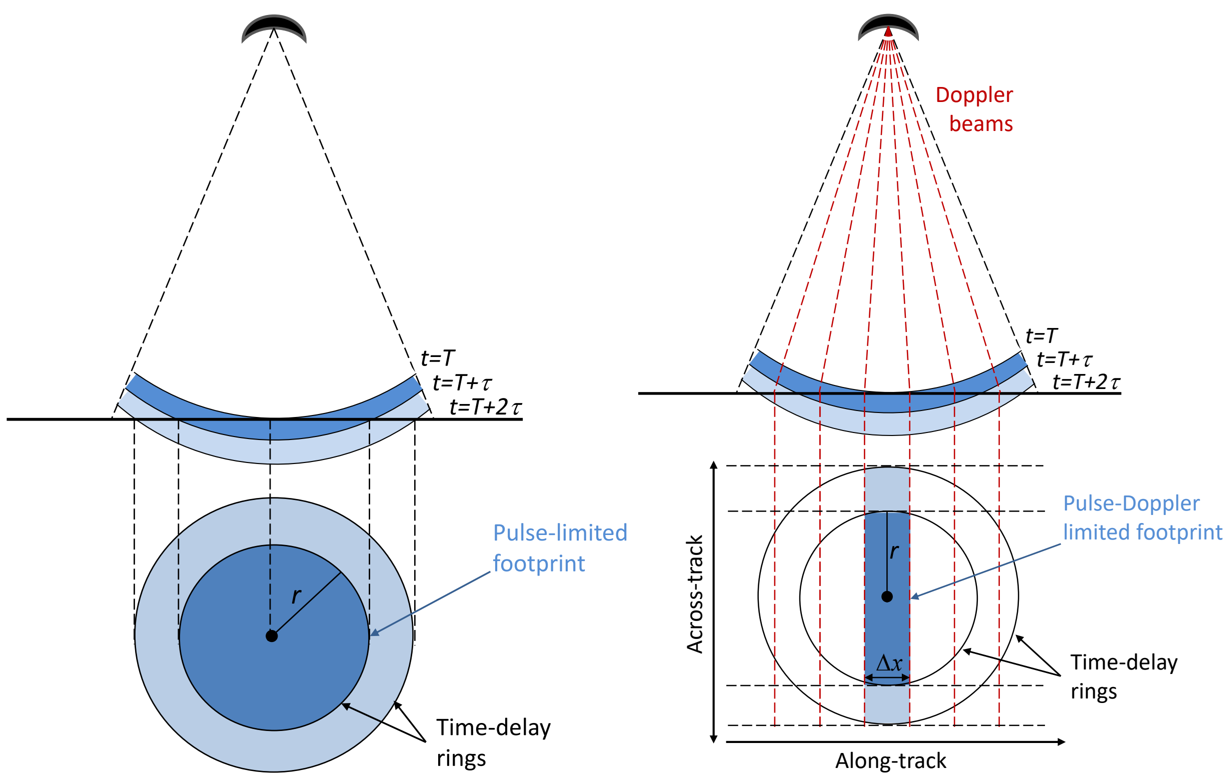
2.2.10.3 Pulse-limited footprint for LRM

In conventional altimeter acquisition, such as LRM, the area around the closest approach point is fully illuminated when the rear of the pulse reaches the Earth surface. The pulse-limited illuminated area can therefore be approximated as a circular area with radius equal to:

$$r = \sqrt{h \cdot c \cdot \tau} = \sqrt{h \cdot \frac{c}{B}}$$

where c denotes the speed of light, h=730km is the altitude of the satellite and the compressed pulse length is $\tau = 1/B$ with B being the pulse bandwidth.

For SIRAL, the pulse-limited illuminated area is about 2.15 km^2, corresponding to a width of the area approximately equal to 1.65 km. It has the same width in both the along-track and the across-track directions since in LRM there is only one independent variable, that is the time delay.



2.2.10.4 Pulse-Doppler-limited footprint for SAR and SIN modes

In SAR/SIN acquisition modes, the processor allows to sharpen the area of the pulse in the along-track direction. As stated before, the Doppler beam formation in SAR/SIN mode allows to discriminate the direction of arrival of the echoes in the along-track direction in addition to the measure of the time delay. This way the illuminated area width is defined independently in both independent directions, the along-track and the across-track directions.

In the across-track direction, the illuminated area width for SIRAL is defined as the pulse-limited width in LRM. However, in the along-track direction, the illuminated area width for SIRAL is defined as the sharpened beam-limited area. The pulse-Doppler-limited area for SAR/SIN can be approximated by a rectangle area given by the pulse-limited area width across track and by the sharpened beam-limited area width along track.

Since the band of Doppler frequencies that is unambiguously sampled by the PRF goes from –PRF/2 to +PRF/2, and 64 different sharpened beams are equally spaced in the Doppler domain, the width of the sharpened beam-limited area results in

$$\Delta x = h \frac{\lambda}{2\,v} \frac{PRF}{64}$$

where h is the altitude of the satellite, λ is the wavelength, v is the velocity of the spacecraft and PRF is the Pulse Repetition Frequency.

For CryoSat, the pulse-limited area width in the across track direction is approximately equal to 1.65 km while the sharpened beam-limited area width in the along-track direction is approximately equal to 305 m, which in turn corresponds to an along-track resolution approximately equal to 401 m, using flat Earth approximation. Hence, the pulse-Doppler-limited area for SAR/SIN is about 0.5 km^2.

2.3 Instrument Corrections and Noise

Error components can be characterised according to their time dependence as follows:

A bias error is a residual fixed offset error, which is stable throughout the mission by definition. Biases are assumed to have a uniform distribution.

A drift error is a variation due to ageing, or other effects, which appears as a slow change with time, having no periodic character, with the possibility of discrete steps.

A harmonic error varies periodically, where the period is typically of the order of the orbital or half orbital period but may be much smaller or much longer. The error has a mean of zero.

A random error varies in an unpredictable manner, relatively quickly in relation to an orbital period, in which there is no correlation between successive realisations. These errors can be assumed as having a Gaussian distribution with zero mean and given standard deviation.

Instrument corrections are derived from characterisation and calibration data. The altimeter electronic system introduces fixed biases that can be determined during ground calibration. Perturbations due to e.g. differential heating around the orbit, cause cyclic and long-term drift, and during the mission are estimated using data from periodic on-board calibrations. The internal path delay correction is a combination of both a fixed part and frequent calibrations. The internal path delay is computed using a specific calibration called CAL1, which is performed about 10 times per week, and performed for each SIRAL mode. Physically the path delay is the same for LRM and SAR modes. However LRM data are processed on board where a small shift is added equal to 1/64 range bin ≈ 7mm. So the LRM path delay is different from the SAR one, it is actually smaller by 1/64 range gate: this does compensate the shift introduced by the LRM on-board processor. The values are provided in the L1B products. However, the L1B product contains in addition another component of the path delay relative to the waveguides, which is a constant value, measured before launch and common to all modes.

Both antennae need separate correction for instrument effects on range `instr_cor_range_rx_20_ku` and `instr_cor_range_tx_rx_20_ku` and on gain `instr_cor_gain_rx_20_ku` and `instr_cor_gain_tx_rx_20_ku`.

2.3.1 Automatic Gain Control

CryoSat-2 uses automatic gain control (AGC), where information about the previous signal level is used to adjust the gain in anticipation of the next. The aim is to keep the signal level as constant as possible. The actual setting of the on-board receiver attenuator at the observation time is what is recorded in the data `agc_ch1_20_ku` and `agc_ch2_20_ku`. The AGC is constant within the radar cycle.

2.3.2 Signal Phase Corrections

Signal phase corrections are split into internal and external types, internal for the electronic system and external for antenna subsystem and waveguide effects. Signal phase is used in SIN mode only. The corrections are derived from in-flight calibration data. The internal phase correction `instr_int_ph_cor_20_ku` is the internal phase correction computed from the CAL-4 packets during the azimuth impulse response amplitude (SIN only). It is set from the latest available CAL-4 packet. The external phase correction `instr_ext_ph_cor_20_ku` is an external phase correction taken from the IPF database file (SIN mode only) to be added to the internal phase correction term. This is the temperature-averaged component of external inter-channel phase difference derived from phase difference sensitive antenna subsystem, waveguides and instrument waveguide switches. It does not contain internal instrument temperature dependent effects of calibration coupler and duplexer, which are dealt with by the CAL-4 signal and its subsequent processing and is reported in the internal phase correction parameter.

2.3.3 Phase Slope Correction

Across the whole bandwidth there is a constant change in phase difference. Some of this was measured before launch; the rest is calibrated at 1Hz. Both measurements are combined to give the phase slope correction `ph_slope_cor_20_ku`. Since the highest data rate is 20Hz, the closest correction value in time to that of the sample is the one used.

2.3.4 Hamming Weighting Function for SAR Azimuth FFT

A hamming window of length N=”number of echoes in burst” (always 64 for SAR and SIN) is generated once at the beginning of the SAR processing, and applied in azimuth direction, to all samples of all echoes of every burst at the very beginning of the beam-forming step.

The windowing process is performed with the following parameters from the processor configuration file:

- Apply_Azimuth_Hamming: which defines whether or not apply the window.
- Azimuth_Hamming_c1 and Azimuth_Hamming_c2: which are used to change the shape of the window
  - H(x) = c1 + c2 (cos((πx/N) – (π/2)))2
- In the IPF1 processor release VK 1.0 (February 2012) the above parameters are set to:
  - Apply_Azimuth_Hamming: on
  - Azimuth_Hamming_c1: 0.08
  - Azimuth_Hamming_c2: 0.92

for both SAR and SIN specialized processors. When the hamming window is applied, the power is not compensated by any factor. See below the azimuth impulse response of a CAL1 SAR burst, with and without hamming window (zero-padding = 64).

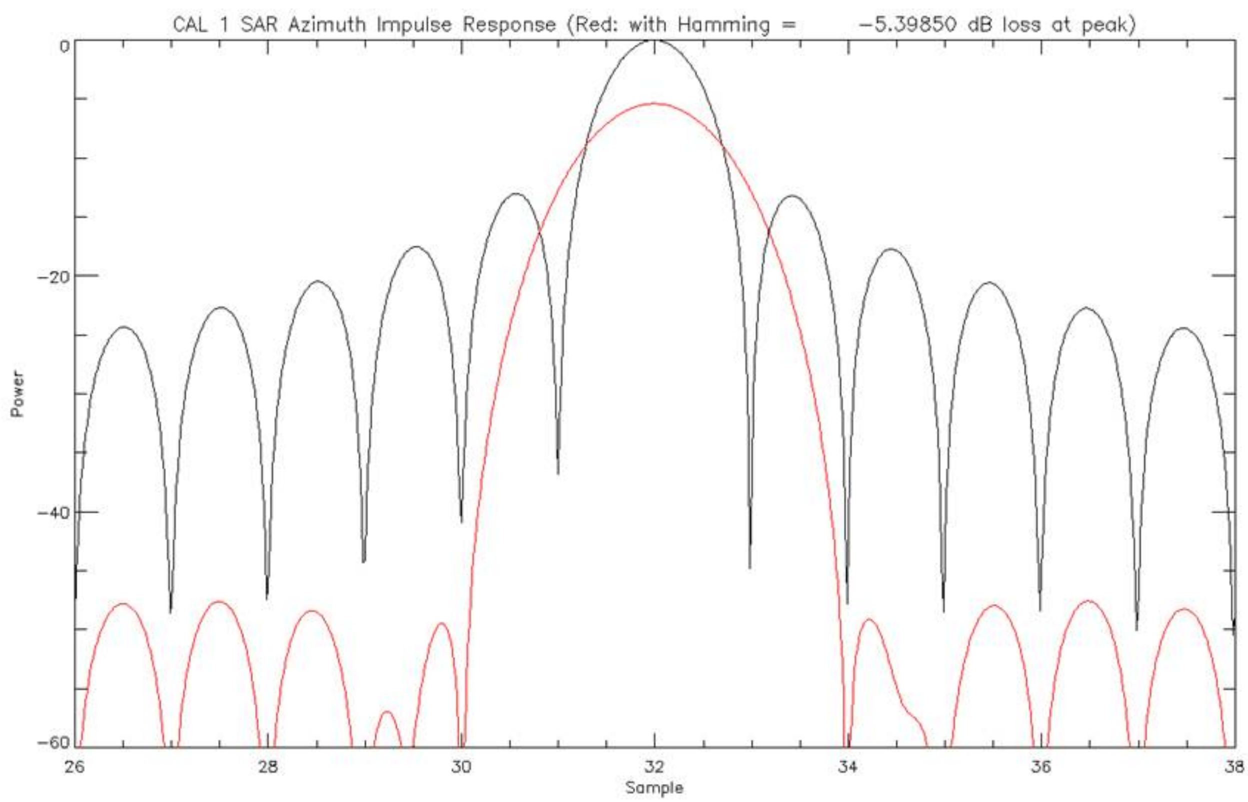


Figure 9: Comparison of AIR with and without Hamming window

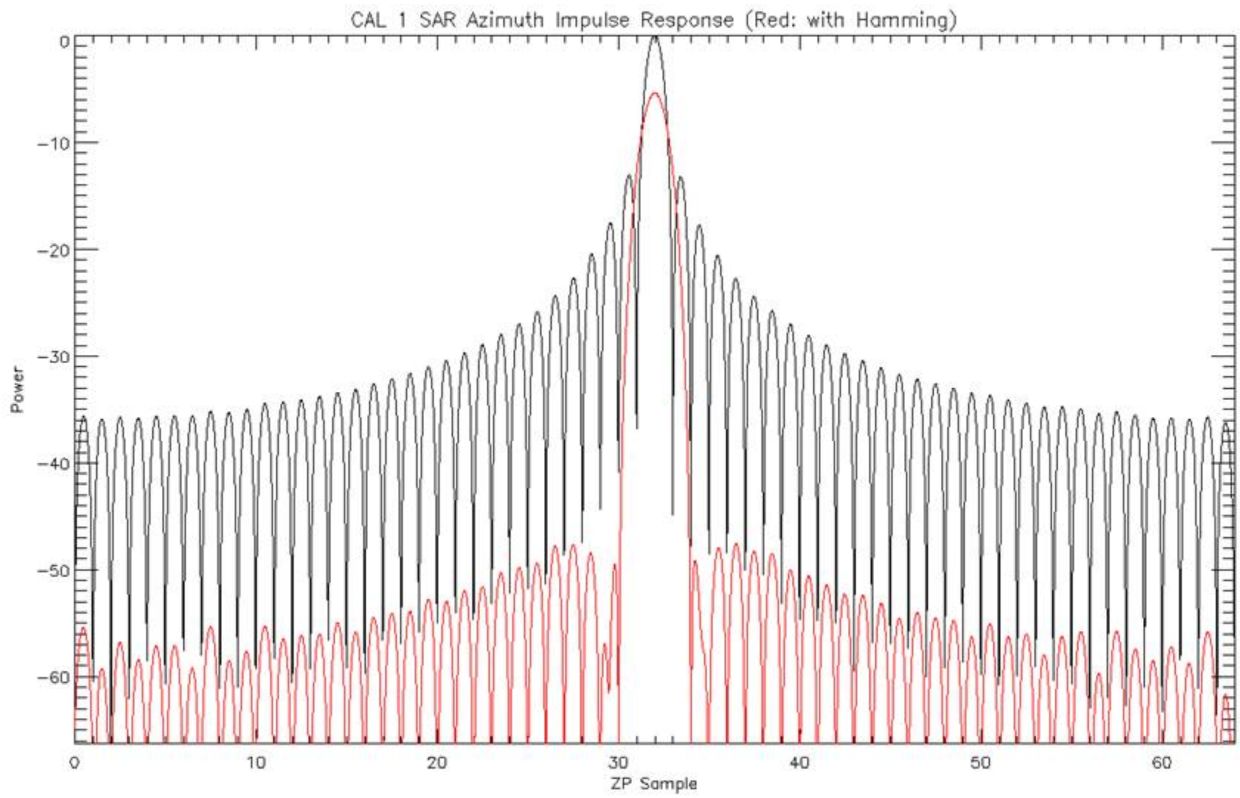


Figure 10: Comparison of AIR with and without Hamming window (full range)

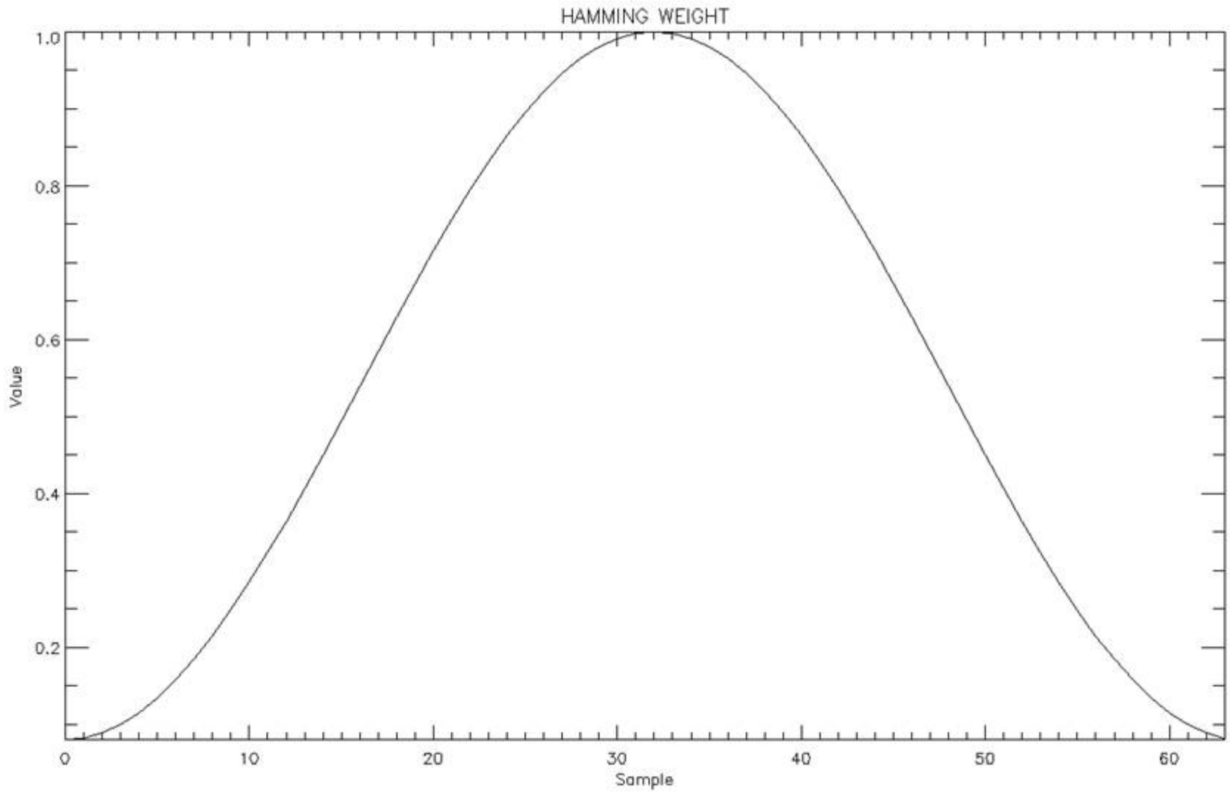


Figure 11: Hamming weighting function

The main beam widening factor is about 1.5 so the azimuth resolution is decreased. The peak power decrease is about 5.4 dB but this should not have any impact on the L2 data. The weighting function aim is to reduce the side lobes. This always has the side effects of increasing the main beam width (which means a loss in resolution), and decreasing the main beam power level. There are several weighting functions. Hamming has the characteristic of making the first side lobes very low, reduced by about -42 dB. Hamming is currently used in the processor, in azimuth processing before beam forming (64 beams are created from each burst of 64 waveforms), but this could be changed in the future, if a more suitable one is recommended. It is needed for specular surfaces where the nadir echo is very strong, and beams pointing off nadir contain a strong energy from nadir, which is the clutter in this case. This can be seen in the following four figures for sea ice, showing how the nadir clutter, removed by windowing, can impact the L1B waveform shape and mainly the leading edge.

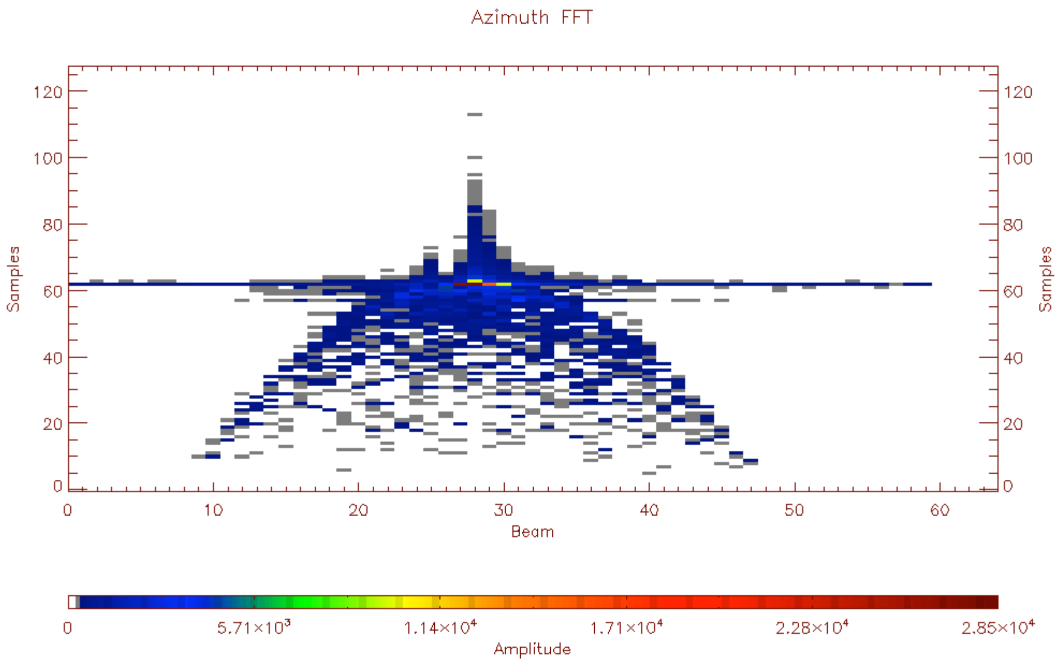


Figure 12: Azimuth FFT of a single burst: the nadir clutter is the 'line' in the middle

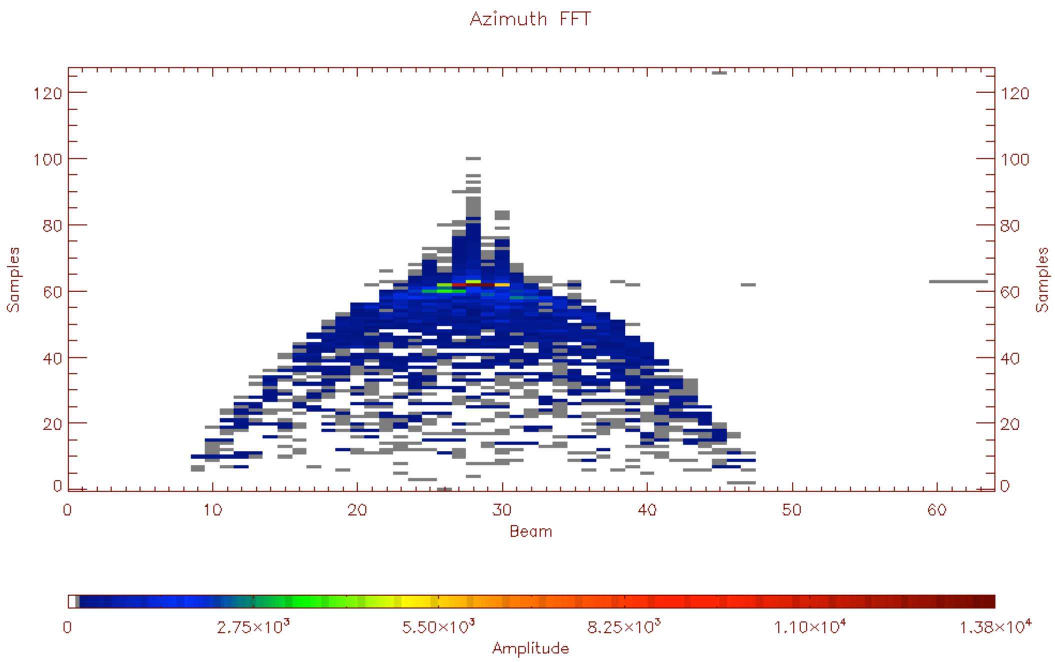


Figure 13: Azimuth FFT of a single burst with hamming: the nadir clutter is reduced

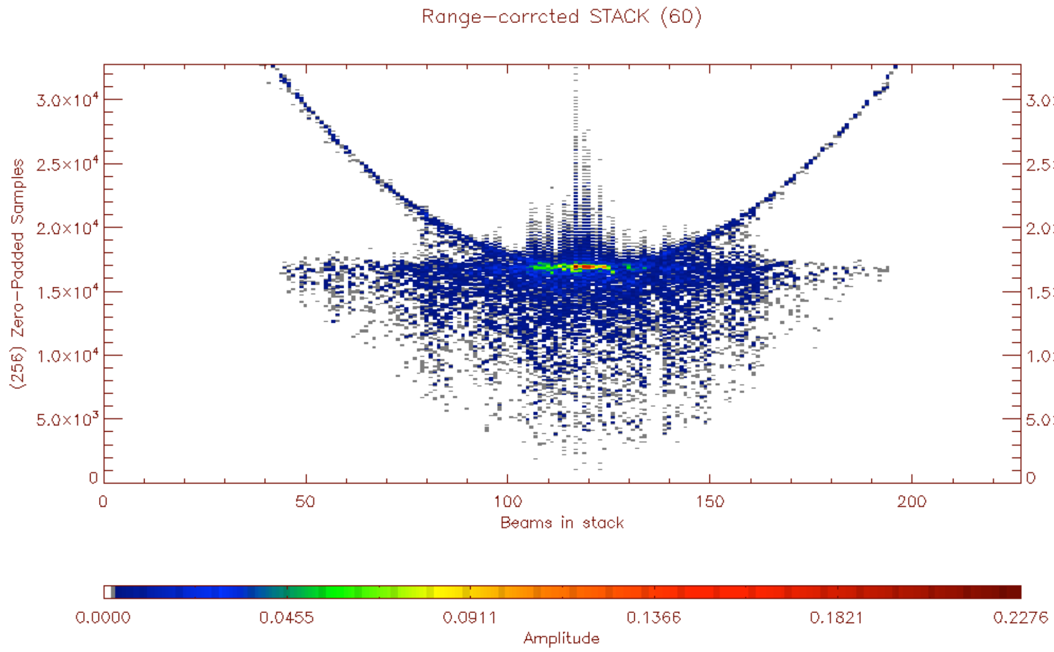


Figure 14: Stack 60 without hamming: here the parabola is the nadir clutter

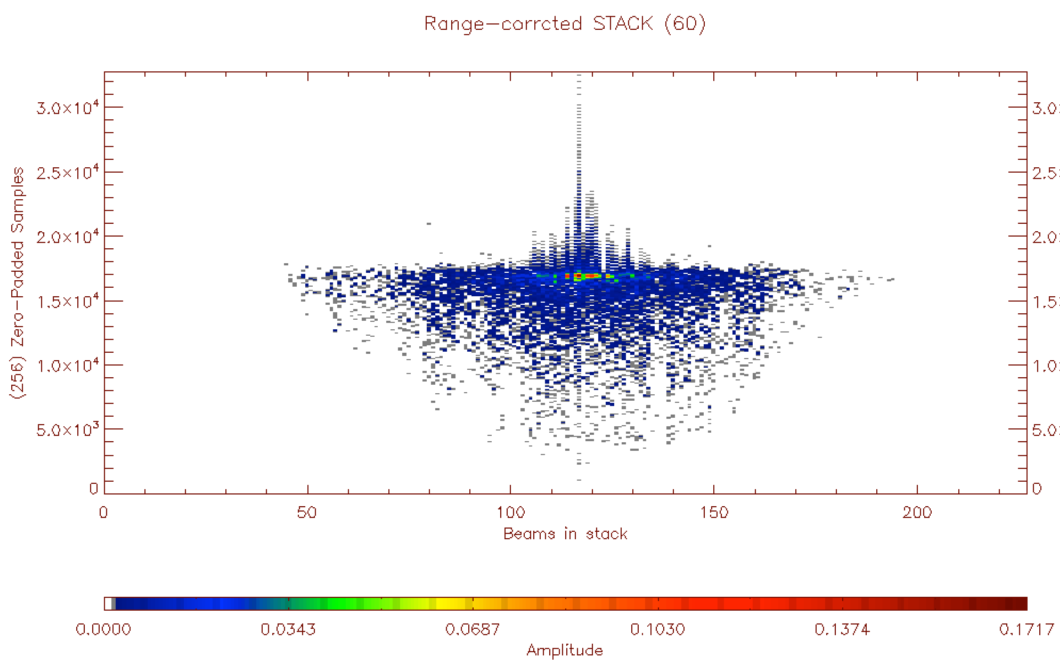


Figure 15: Stack 60 with hamming: the nadir clutter has disappeared

Note that the L1B waveform is obtained averaging all these beams in the stack.

2.3.5 Noise

Noise on the echo signal is also measured during in-flight calibration `noise_power_20_ku`. At level 1b, an estimate of the noise is given as the noise power measurement, but it is not subtracted from the waveforms. At level 2, noise is re-estimated as part of the retracking calculations. In SIN mode, this estimate is subtracted from the bins power before the retracking is done.

2.3.6 Echo Saturation

Echo saturation occurs when the power in the pulse varies more than the dynamic range of the receiver, causing distortions in the echo waveform. This mostly occurs in high-amplitude echoes from flat bright surfaces such as leads in sea ice or melt ponds on ice sheets. This condition is flagged in the MCD word `flag_mcd_20_ku` using bit `echo_saturated`

2.3.7 Doppler Correction

When there is a component of satellite orbital velocity vector directed along the line of sight from the satellite to the echoing point on the surface, the radar echo undergoes a corresponding Doppler shift. This is compensated by a range correction `dop_cor_20_ku`. All range corrections are defined such that they were added to the range measurement to give the true range.

2.4 Retracking and Parameters Derived From Echo Shape

2.4.1 Range Window and Window Delay

The distance between the satellite and the Earth surface varies around its orbit by several kilometres. However, in the vertical dimension the altimeter can only receive echoes within a 'range window' specified by the width of the frequency spectrum. In order to receive echoes all around the orbit, the time of the reception period must be continuously adjusted to try to keep a specific point on the leading edge of the echo waveform at a reference position within the window. The Cryosat-2 reference position is configurable, but it is for now centrally located, at bin 64 of the range window in LRM mode, bin 128 in SAR mode, and at bin 512 in SIN mode. Bins are counted from bin 0. The window delay `window_del_20_ku` refers to the 2-way time between the pulse emission and the reference point at the centre of the range window.

2.4.2 Reception Period

Information about the reception period time is represented in two ways. Either an initial height is given `h0_applied_20_ku`, followed by the rate of change in this height per tracking cycle `cor2_applied_20_ku`, or a coarse height `h0_lai_word_20_ku` and fine height adjustment `h0_fai_word_20_ku` are given, which must be added together. The tracking cycle is a fundamental interval common to all modes, of 47.2ms.

2.4.3 Range Window Sampling

In LRM, the range window explored is about 60m, covered by 128 data samples. In SAR mode it is about 60m, again covered by 256 data samples. In SIN mode, due to the slope variation in ice sheet margins, the range window is increased to about 240m, and is covered by 1024 samples. During processing the exact, calibrated, length of the data bins is retrieved from the instrument characterisation data file, the filename of which is found in the dataset description header within the data file, as described in section 6.5.

There are two types of waveforms provided in the LRM, SAR and SIN level-1b products.

1. Waveforms derived from classical LRM or those generated from SAR/SIN azimuth processing that are provided in the waveform group of the level-1b products (*L1B Product Spec Table 2.3.4-1 fields 71, 76 and 82*).

2. Pulse-width limited data extracted from all modes averaged over 1 second and provided in the average waveform group of the level-1b product (*L1B Product Spec Table 2.3.4-1 fields 56 and 66*).

It is a fact that radar altimeter power echo waveforms are aliased (see "Radar altimeter gate tracking: theory and extension", J.R. Jensen, IEEE Transactions on Geoscience and Remote Sensing, Vol 37, No 2, March 1999, section III B.)

During CryoSat-2 commissioning phase, it became clear that SAR processed data over specular surfaces was aliased and this was particularly evident when the satellite rate of change of altitude was large. The result rendered SAR (and SIN) level-1b data highly degraded over specular surfaces.

In general, the aliasing effect appears minor over diffuse surfaces such as ocean but is nevertheless present. In order to avoid aliasing, raw complex SAR and SIN echoes are now oversampled (since 01 February 2012, products version B) in the FBR to level-1b processor and as a result any user of the data needs to take this into account when using waveforms and determining range. However, although the sampling has changed, the resolution has not since it is fixed by the instrument impulse response.

LRM sampling remains the same as in earlier versions of the Cryosat-2 processors as sampling is fixed on-board and oversampling of the on-board complex data is not possible. However, the LRM data is affected by aliasing as in other altimeter missions.

What follows is a description of how to compute range to a given range bin for all cases.

For ALL LRM 20 Hz, ALL 1Hz, and for ALL Baseline-A data, and for any data gathered before 01-FEB-2012, use

Given the waveform array, $\Phi(n)$ (`pwr_waveform_avg_01_ku` or `pwr_waveform_20_ku` where n is the waveform sample number with a value $\forall n \in [0, N_s - 1]$ (any value between 0 and $N_s - 1$) and N_s is the mode dependent number of samples in any waveform:

$$N_s = \begin{cases} 128, & \text{LRM} \\ 128, & \text{SAR} \\ 512, & \text{SIN} \end{cases}$$

The range $R(n)$ to waveform sample n is given by $R(n) = \frac{T_w c}{2} - \frac{N_s c}{4B} + \frac{nc}{2B} = \frac{c}{2B}\left(T_w B - \frac{N_s}{2} + n\right)$ meters

where T_w is the window delay converted to seconds `window_del_avg_01_ku` or `window_del_20_ku` referenced to the central range bin $n = N_s/2$, the first range bin being $n = 0$,

c is the speed of light in vacuum, c=299792458 m/s, B is the measured chirp bandwidth, B=320000000Hz.

Hence, the range to the first waveform sample, $n = 0$, $R(0) = \frac{T_w c}{2} - \frac{N_s c}{4B}$ meters.

Each waveform sample covers a range of $\Delta r = \frac{c}{2B} = 46.84$ cm or a delay of $\Delta t = \frac{1}{B} = 3.125$ ns

For SAR & SIN 20Hz oversampled echoes in products version B, gathered after 01-FEB-2012

Given the oversampled power echo waveform array, $\Phi(n)$ `pwr_waveform_20_ku` where n is the waveform sample number with a value $\forall n \in [0, N_s - 1]$ (any value between 0 and $N_s - 1$) and N_s is the mode dependent number of samples in any waveform:

$$N_s = \begin{cases} 128, \text{ SAR} \\ 512, \text{SIN} \end{cases}$$

The range $R(n)$ to waveform sample n is given by $R(n) = \frac{T_w c}{2} - \frac{N_s c}{8B} + \frac{nc}{4B} = \frac{c}{8B}\left(4T_w B - N_s + 2n\right)$ [m]

where T_w is the window delay converted to seconds `window_del_20_ku` referenced to the central range bin $n = N_s/2$, the first range bin being $n = 0$,

c is the speed of light in vacuum, c=299792458 m/s, B is the measured chirp bandwidth, B=320000000Hz.

Hence, for example, the range to the first waveform sample, $n = 0$, $R(0) = \frac{T_w c}{2} - \frac{N_s c}{8B}$ meters.

Each waveform sample covers a range of $\Delta r_{os} = \frac{c}{4B} = 23.42$ cm or a delay of $\Delta t_{os} = \frac{1}{2B} = 1.5625$ ns

For SAR & SIN 20Hz oversampled echoes in products version C and later, gathered after 01-FEB-2012

As above, but for SAR mode $N_s = 256$, and for SARin mode $N_s = 1024$.

2.4.4 Echo Positioning and Scaling

In the data products the position of the echo within the range window varies with SIRAL mode. The instrument dynamically sets the range window and in LRM the window position is not changed by the data processing. In SAR and SIN modes echoes are averaged during data processing on the ground and the position of the window is then selected to best accommodate the resultant waveform.

In order to retain as much information as possible, the individual samples of each echo waveform are scaled to fit within the range 0 to 65535. They can be converted to power in watts using equation 4.2-1 with the parameters `echo_scale_pwr_20_ku` and `echo_scale_factor_20_ku` (or `echo_scale_pwr_avg_01_ku` and `echo_scale_factor_avg_01_ku`)

2.4.5 Retracking

At level 2, a procedure commonly referred to as retracking is performed. A specific point on the echo's leading edge, known as the retracking point, is used to mark the point of measurement of range to surface. The retracking point is defined relative to the shape of the whole echo and found using a model-fitting method. The offset of the retracking point from a reference point, which for Cryosat-2 is in the centre of the range window, is then calculated. This is the retracking correction.

The algorithms used for retracking vary with mode, see Table 2 below. For LRM and FDM (any surface type), the amplitude and epoch returned by the OCOG retrack performed upon the waveform, are used as the initial guesses for the fits performed by the CFI and land-ice retrackers. The primary results are returned in the variables `height_1_20_ku`, `height_1_20_ku`, and `height_1_20_ku`.

Table 2: L2 retrackers

Retracker ID	Mode LRM	Mode SAR	Mode SARin
1	Ocean CFI model fit	Diffuse echo – CPOM threshold of first peak	Wingham/Wallis model fit
		Specular echo – Giles model fit	
2	UCL land-ice	not used	not used
3	OCOG	not used	not used

Further details are given in reference 18, and background information in references 4 and 19, however (in brief) the CLS ocean retracker and UCL land-ice retrackers are model-fits to the LRM waveform. The ocean retracker fits a Hayne model waveform that is not adapted for CryoSat2 and the UCL retracker fits a Brown model adapted for CryoSat2. OCOG is well described in the literature.

For SAR mode, the Giles retracker is a model fit for specular lead waveforms, and a threshold retrack to the first peak of a smoothed waveform for diffuse echoes from sea-ice. In SARin mode, the Wingham/Wallis retracker fits a theoretical model to the portion of the power waveform that exhibits the maximum coherence. The phase difference is estimated at the retracking point to give the across-track angle. The SAR mode retracking is also performed on the SARin waveforms, with the results appearing in `height_sea_ice_floe_20_ku` (diffuse) and `height_sea_ice_lead_20_ku` (specular)

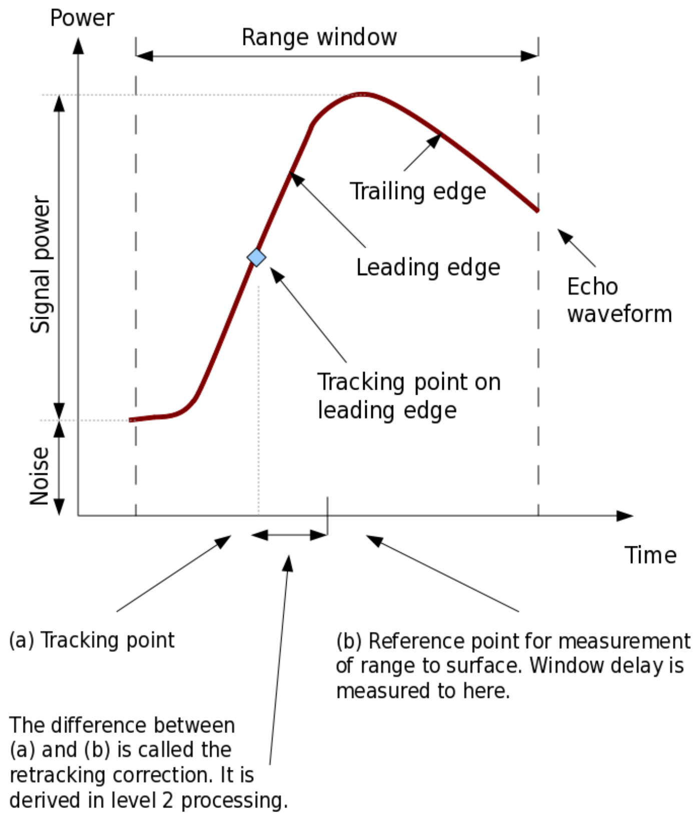


Figure 16: Idealised pulse-limited waveform in window

In the L2I, the variables `retracker_1_cor_20_ku`, `retracker_1_cor_20_ku`, and `retracker_1_cor_20_ku` hold the correction to range applied due to the retracking for each of the (up to) three retrackers.

It is not possible to locate the retracking point with the L2 products only. One would need to use L1B and L2 in tandem and in order to achieve this:

1) Convert L2 height to range using the altitude at 20 Hz from the L1B

2) Remove the geophysical corrections

3) Remove the L1B range (the window delay converted to range)

Over ocean, what is left following the steps above is the action of the retracker. This is slightly more complicated over ice due to the action of the slope.

The L2I also contain the range with only retracking and instrumental corrections applied (no geophysical corrections) in the variables `range_1_20_ku`, `range_1_20_ku`, and `range_1_20_ku`. This allows the user to apply their own geophysical corrections.

2.4.6 Backscattering

The radar backscattering coefficient (sigma-0) provides information about the observed surface. It is a function of the radar frequency, polarisation and incidence angle and the target surface roughness, geometric shape and dielectric properties. A discussion of all these factors is given online at http://earth.esa.int/applications/data_util/SARDOCS/spaceborne/Radar_Courses/Radar_Course_III/parameters_affecting.htm

At level 2, the backscatter coefficient is fully corrected, including instrument gain corrections and bias. A measurement is made for each retracker `sig0_1_20_ku`, `sig0_2_20_ku`, and `sig0_3_20_ku`.

2.4.7 Peakiness

Peakiness is a measure of how sharply peaked an echo is `peakiness_20_ku`. It is essentially the ratio of the highest bin value to the mean value of all bins above the retracking point. The higher the ratio, the more peaked the echo. High peakiness indicates a very specular reflection, such as that from leads in sea ice.

Further information is given in reference 18.

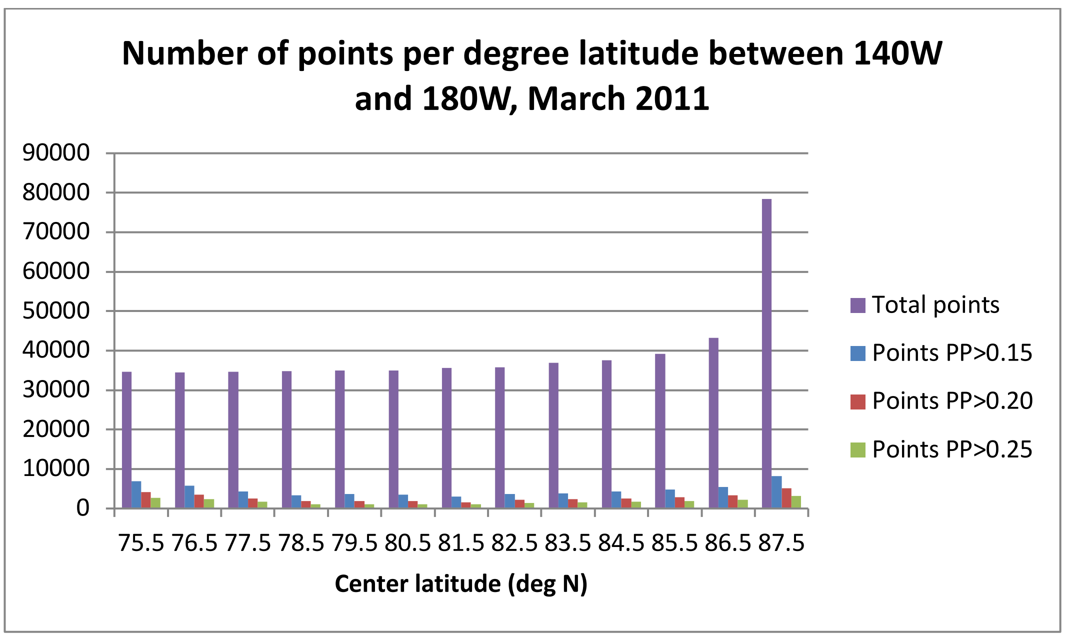


Figure 17: Peakiness by latitude

Above shows the total number of points available per degree latitude, between 140W and 180W for March 2011 along with the number of points with 'Pulse Peakiness' (PP) above certain thresholds. Higher PP indicates more 'specular' waveforms i.e. more like to originate from leads. The total number of Cryosat-2 measurements between 75N and 88N (between 140W and 180W) is 515000.

Below shows the number of points with PP greater than certain thresholds as a proportion of the total number of points recorded, per degree latitude, for March 2011. The number of points varies with latitude according to the proportion of sea ice cover, as well as, presumably, climatological conditions.

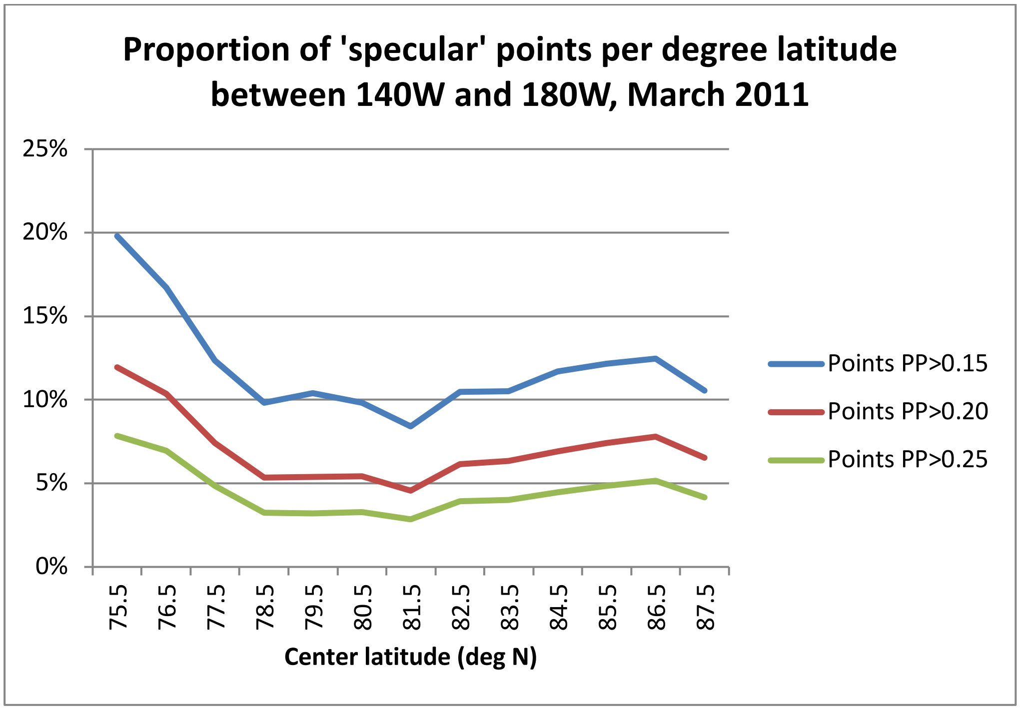


Figure 18: Proportion of specular points by latitude

2.4.8 Effects of Terrain

Since the type of surface affects the radar echo shape, a description of the surface at nadir, derived from the TerrainBase digital terrain model from the NOAA, is also given `surf_type_01`, and `surf_type_20_ku`. See also section 2.7.2 and reference 8.

2.4.1 Interferometric Mode

The purpose of the SIN mode is to allow the across-track angle offset of the echoing point to be determined directly (using interferometric phase information). In the L2 SIN data, the 20Hz latitude `lat_poca_20_ku` and longitude `lon_poca_20_ku` values provide the estimated position of the point of closest approach (as computed from the phase difference) and not the nadir. The nadir location is only present in the L2 data at 1Hz `lat_01` and `lon 01`. Each 20Hz sample produces only one location on the ground.

It is important to note that phase-wrapping can occur when the across track offset is great enough and this can have the effect of the echo appearing to come from the other side of the ground track. Normally, this is flagged `flag_sarin_ambiguity_warning_20_ku` by use of an ambiguity DEM `dem_height_20_ku` that shows where this effect is likely to have occurred, however these DEMs are only available for Greenland and Antarctica. If the user observes a sequence of records with increasing across-track offset and then an abrupt switch to the other side of the track, it is likely that phase-wrapping has occurred.

2.4.2 Significant Wave Height

Significant wave height (SWH) `swh_ocean_20_ku` is the average wave height, trough to crest, of the one-third largest waves in a particular geographic location. SWH can be derived from inspection of the echo waveform. The reflection from the wave crest is returned earlier than that from the trough, 'stretching' the leading edge of the waveform. The stretching increases with increasing wave height. Although not physical but only numerical, negative values of SWH are preserved.

2.4.3 Sea State Bias

Sea state bias `sea_state_bias_20_ku` is a combination of effects dependent on the wave height at the surface. The electromagnetic (EM) bias effect arises because wave troughs are better reflectors of energy than wave crests, due to their different distributions of specular-reflecting facets. This is the correction given under the title of sea state bias in the level-2 data. Sea state bias is derived from a model provided by CLS to ESA. For a general treatment of sea state bias see reference 14.

2.4.4 Wind Speed

The Abdalla2007 model is used to calculate wind speed `wind_speed_alt_20_ku` from the radar backscattering coefficient. See reference 8.

2.5 Range Corrections for Atmospheric Effects

An altimeter pulse is slowed slightly as it passes through the Earth's troposphere due to the refractive index of the atmosphere. The conversion of time delay to range using the speed of light in vacuum therefore has to be corrected for this small additional delay. The speed of light used in the processor is 299792458.0 metres per second.

2.5.1 Dry and Wet Tropospheric Corrections

The dry tropospheric correction `mod_dry_tropo_cor_01` compensates for the effect of non-polar gases such as oxygen and nitrogen. It has a typical range from 1.7 to 2.5m.

The wet tropospheric correction `mod_wet_tropo_cor_01` compensates for the effect of polar gases, mainly water vapour. It has a typical range from 0 to 50cm.

The dry and wet corrections rely on knowledge of the atmospheric pressure and temperature observations made on the Earth surface. These are supplied by Meteo France via the CNES SSALTO system, as described in section 2.8 and reference 8.

The Wet Tropospheric Correction is retrieved directly from ECMWF analysed grids. These correction files are then simply formatted to the Cryosat-2 PDS file standard before being directly used in the processor. The Dry Tropospheric Correction does not come from an auxiliary file but is computed by the processor using ECMWF surface pressure files. Over water (open water, semi-enclosed seas or enclosed seas and lakes), the surface pressure is equal to the mean pressure minus the climatology (computed with the pressure grids). Phases and amplitudes of S1 and S2 tide waves provided as Static Auxiliary Data files are also taken into account. Over land, the considered surface pressure is the mean pressure so the Dry Tropospheric Correction over land is computed with this sole mean pressure.

2.5.2 Inverse Barometric Correction

The inverse barometric correction `inv_bar_cor_01` compensates for variations in sea surface height due to atmospheric pressure variations, which is known as atmospheric loading. It has a typical range from -15 to +15cm and is calculated from data provided by Meteo France via the CNES SSALTO system, as described in section 2.8 and reference 8. This correction is only used in SAR mode and where the surface type is "open ocean".

2.5.3 Dynamic Atmospheric Correction

The dynamic atmospheric correction `hf_fluct_total_cor_01` compensates for variations in sea surface height due to atmospheric pressure and winds. It has a typical range from -15 to +15cm and is taken from the MOG2D model data provided by Meteo France via the CNES SSALTO system, as described in section 2.8 and reference 8. This correction is used by SIN, SID, LRM and FDM when the surface type is "open ocean".

2.5.4 Ionospheric Correction

The ionospheric correction, also called the ionospheric bias correction, compensates for the free electrons in the Earth's ionosphere slowing the radar pulse. Solar control of the ionosphere leads to geographic and temporal variations in the free electron content, which can be modelled, or measured, for example using the GPS satellite network. The correction has a typical range from 0.06 to 0.12 m. The level-1b data product contains values derived from the Global Ionospheric Map (GIM) `iono_cor_gim_01`, which uses GPS measurements, and from the Bent model `iono_cor_01`. The GIM is the nominal choice with the Bent model available as a alternative solution if GIM data is not available. The GIM is described online at:

http://iono.jpl.nasa.gov/gim.html

The Bent model is based on knowledge of a solar activity index, such as sunspot numbers, and is described online at:

http://modelweb.gsfc.nasa.gov/ionos/bent.html

The solar activity index used (the R12 index) is issued monthly and is defined in reference 5.

2.5.5 Derivation of Corrections

Most of the above corrections are provided on a meteo grid, a group of 6 dynamic files containing grids of surface pressure, ocean mean-sea-level pressure, wet and dry tropospheric corrections and U (east-west) and V (south-north) wind components. In addition a static file for the grid definition is required. This is the Gaussian Altimetric Correction Grid. A meteo grid covers a time span of 6 hours, and two meteo grids, one before and one after the requested date for the correction, are needed. The grids are interpolated in time and space to derive a correction value for each measurement.

These files are further defined in reference 8.

2.5.6 Application of Corrections to Range

The above corrections are added to the range measurement to give the true range.

Further background information is given in references 9 and 10.

2.6 Range Corrections for Tidal Effects

All tidal corrections adjust the range to appear as if it came from the mean land ice surface, or tide-free sea surface. The field Total Geocentric Ocean Tide (field #55) in the FDM products is not the same as the Ocean Tide field in the nominal L1B and L2 products. With the FDM products, the same convention as many other altimetry products, such as for EnviSat, Sentinel-3 and Jason-2, is used, where the total geocentric ocean tide provided in the products includes the loading tide and the long period tide. However in the nominal L1B products, the "ocean tide" field does not include the loading tide or the long period tide. For the L2 product, the users do not need to apply any tides as they are applied during the computation of height. However, if they are working with the L1B product and deriving their own surface height then they should apply the set of tides and meteorological corrections in the L1B that is suitable for their specific usage.

2.6.1 Ocean Tide

The ocean tide correction `ocean_tide_01` removes the effects of local tides i.e. those caused by the Moon, and the long-period equilibrium ocean tide correction `ocean_tide_eq_01` removes tidal effects due to the Sun. Typically this correction ranges from -50 to +50 cm. The FES2004 ocean tide model is used for this correction. This is further described in section 2.8 and reference 8.

2.6.2 Ocean Loading Tide

The ocean loading tide correction `load_tide_01` removes the deformation of the Earth's crust due to the weight of the overlying ocean tides. Typically this correction ranges from -2 to +2 cm. The FES2004 loading tide model is used for this correction. This is further described in section 2.8 and reference 8.

2.6.3 Solid Earth Tide

The solid Earth tide correction `solid_earth_tide_01` removes the deformation of the Earth due to tidal forces from the Sun and Moon acting on the Earth's body. Typically, this correction ranges from -30 to +30 cm. The Cartwright model is used for this correction. It is further described in section 2.8 and reference 8.

2.6.4 Geocentric Polar Tide

The geocentric polar tide correction `pole_tide_01` removes a long-period distortion of the Earth's crust caused by variations in centrifugal force as the Earth's rotational axis moves its geographic location. Typically, this correction ranges from -2 to +2 cm. It is derived from the pole location files. It is further described in section 2.8 and reference 8.

2.6.5 Application of Corrections to Range

The above corrections are added to the range measurement to give the true range.

For further information see references 9 and 11.

2.7 Deriving Range

The window delay is measured from the signal emission time to the centre of the range window. At level 1b the engineering calibrations are already applied to the window delay, as the Doppler correction and the COM offset. Thus, the range measurement has its origin at CryoSat-2 COM (as does the altitude measurement), and ends at the centre of the range window, point (b) in fig 2.5.5-1. The geophysical (atmospheric and tidal corrections) are not applied at level 1b. Range can be calculated using the parameters in the data product, taking into account the surface type.

The following equation is applicable:

range = (0.5 * c * window delay) + retracking cor. + surface-dependent geophysical cor.
(Eqn 2.7-1)

where c is the speed of light in vacuum.

At L2, 20 measurements have been corrected using the 1Hz corrections. No further interpolation is done and the same 1Hz correction is used for all 20 measurements as the corrections are slowly varying. The 20Hz and 1Hz measurements can be associated via the index variables `ind_first_meas_20hz_01` and `ind_meas_1hz_20_ku`.

2.7.1 Geophysical Corrections by Surface

Surface height w.r.t. reference ellipsoid = altitude - (retracked range + corrections), where the geophysical corrections necessary over each surface are as follows:

- Sea Ice:
  - Tides:
    - Ocean tide
    - Long period equilibrium ocean tide
    - Ocean loading tide
    - Solid Earth tide
    - Geocentric polar tide
  - Atmosphere:
    - Dry tropospheric correction
    - Wet tropospheric correction
    - Ionospheric correction

        - Inverse barometric correction

- Land Ice:
    - Tides:
        - Ocean loading tide
        - Solid Earth tide
        - Geocentric polar tide
    - Atmosphere:
        - Dry tropospheric correction
        - Wet tropospheric correction
        - Ionospheric correction

- Ocean:
    - Tides:
        - Ocean tide
        - Long period equilibrium ocean tide
        - Ocean loading tide
        - Solid Earth tide
        - Geocentric polar tide
    - Atmosphere:
        - Dry tropospheric correction
        - Wet tropospheric correction
        - Ionospheric correction
        - Dynamic atmospheric correction
    - Other:
        - Sea state bias

2.7.2 Surface Type

Note that although a flag for surface type exists at both L1b `surf_type_01` and L2 `surf_type_20_ku`, at L1b it is only provided at 1Hz resolution, which is lower than the 20Hz measurement resolution. Users must be careful in interpreting this flag in boundaries when selecting the range corrections needed. The DTM2000 static grid provides four states of the flag: 0 = open oceans or semi-enclosed seas; 1 = enclosed seas or lakes; 2 = continental ice; 3 = land.

2.7.3 Level-2 Application

At level 2, altitude and height are given, as well as uncorrected range. All corrections are already incorporated in the height measurement. They are listed in the dataset so that they can be removed or replaced if required.

2.8 Models Used

2.8.1 Static Auxiliary Data Files

This table lists the static auxiliary data files used in processing the data. These contain the models used, as listed in reference 8 for data provided via the Earth Explorer Geo Corrections CFI.

The slope model data (AUX_SLPMSL) is created from the following DEMs:

- Helm, Veit; Humbert, Angelika; Miller, Heinz (2014): Elevation Model of Antarctica derived from CryoSat-2 in the period 2011 to 2013, links to DEM and uncertainty map as GeoTIFF. https://doi.org/10.1594/PANGAEA.831392

- Helm, Veit; Humbert, Angelika; Miller, Heinz (2014): Elevation Model of Greenland derived from CryoSat-2 in the period 2011 to 2013, links to DEM and uncertainty map as GeoTIFF. https://doi.org/10.1594/PANGAEA.831393

The ambiguity DEMs (AUX_DEMMSL) are created from:

- Bamber, Jonathan L., Jose Luis Gomez-Dans, and Jennifer A. Griggs. 2009. Antarctic 1 km Digital Elevation Model (DEM) from Combined ERS-1 Radar and ICESat Laser Satellite Altimetry. Boulder, Colorado USA: National Snow and Ice Data Center
- Howat I.M., A. Negrete and B.E. Smith, 2014, The Greenland Ice Mapping Project (GIMP) land classification and surface elevation datasets, The Cryosphere, 8, 1509-1518

Files of 'grid' type have data distributed on a geographical grid. Files of 'data' type are non-geographical.

Table 3: Static auxiliary files

Type String (in Filename)	**Description**	**Type**	**Parameters (grid only)** All longitude coverage is [0,360] degrees
AUX_GEOID_	EGM96 geoid values	grid	Lat coverage [-88,88] degrees Step in latitude: 0.25 degrees Step in longitude: 0.25 degrees
AUX_MICOEF	Bent ionospheric coefficients file	data	
AUX_DIPMAP	Bent Modified Dip Map file	grid	Lat. coverage: [-88,88] degrees Step in latitude: 2 degrees Step in longitude: 2 degrees

AUX_MSSURF	UCL13 Mean Sea Surface values	grid	Lat. coverage: [-80,88] degrees Step in latitude: 0.0625 degrees Step in longitude: 0.0625 degrees
AUX_SDC_nn	UCL04 Snow Depth Climatology model (nn= month number)	grid	Lat. coverage: [0,90] degrees Step in latitude: 0.0625 degrees Step in longitude: 0.0625 degrees
AUX_SICCnn	UCL04 Sea Ice Concentration Climatology (nn= month number)	grid	Lat. coverage: [-90,90] degrees Step in latitude: 0.0625 degrees Step in longitude: 0.0625 degrees
AUX_SLPMSL	MSSL High resolution Slope models of Greenland and Antarctica	grid	Cartesian grids covering Antarctica, grid step = 1km, and Greenland, grid step = 800m
AUX_DEMMSL	MSSL high-resolution DEMs of Greenland and Antarctica	grid	Cartesian grids covering Antarctica, grid step = 1km, and Greenland, grid step = 800m
AUX_OCTIDE	FES2004 ocean tide model values	grid	Lat. coverage: [-90,90] degrees Step in latitude: 0.125 degrees Step in longitude: 0.125 degrees
AUX_TDLOAD	FES2004 loading tide model values	grid	Lat. coverage: [-90,90] degrees Step in latitude: 0.25 degrees Step in longitude: 0.25 degrees
AUX_ODLE__	MACESS Ocean Depth/Land Elevation values	grid	Lat. coverage: [-90,90] Step in Latitude: 1/30 degrees Step in longitude: 1/30 degrees
AUX_CARTWR	Cartwright and Edden tables	data	
AUX_LS_MAP	Four states surface identification grid created by CLS/CNES from GMT, GlobCover, Modis Mosaic of	grid	Lat. coverage: [-90,90] Step in Latitude: 1/30 degrees Step in longitude: 1/30 degrees

	Antarctica, and Water body outlines from LEGOS.		
AUX_PRSS00 AUX_PRSS06 AUX_PRSS12 AUX_PRSS18	Climatology pressure grids, four per day, for 0h, 6h 12h and 18h. Each grid point contains 12 values of climatological pressure, one for each month of the year	grid	Lat coverage:[-90,90] degrees Step in latitude: 0.5 degrees Step in latitude: 0.5 degrees
AUX_S1AMPL AUX_S2AMPL	The S1 and S2 tide grids of monthly means of global amplitude. Each grid point contains 12 values of amplitude, one for each month of the year	grid	Lat coverage:[-90,90] degrees Step in latitude: 1.125 degrees Step in latitude: 1.125 degrees
AUX_S1PHAS AUX_S2PHAS	The S1 and S2 tide grids of monthly means of global phase. Each grid point contains 12 values of phase, one for each month of the year.	grid	Lat coverage:[-90,90] degrees Step in latitude: 1.125 degrees Step in latitude: 1.125 degrees
AUX_WNDCHE	Abdalla2007 wind speed table	data	Sigma0 coverage: [5,19.6] Step in Sigma0: 0.2

2.8.2 Dynamic Auxiliary Data Files

The dynamic auxiliary data files used are mainly supplied by SSALTO, Système au Sol d'ALTimétrie et d'Orbitographie. They have a web presence at:

http://www.aviso.oceanobs.com/es/data/product-information/ssalto/index.html

They supply:

- the DORIS USO drift correction
- the meteorological files, sourced from Meteo-France via SSALTO, based on data from ECMWF
- the historical pole location files, used to derive the geocentric polar tide
- the solar activity R12 index files, used in the Bent model ionospheric corrections
- the daily GIM files (GIM is the Global Ionospheric Map)
- the daily MOG2D files (MOG2D is a barotropic model used for dynamic atmospheric correction)

The dynamic sea-ice concentration files are provided by University College London, and are online at http://cryosat.mssl.ucl.ac.uk/dsic These concentrations are derived from the NRT DMSP SSMI data of NSIDC.

DORIS USO Drift	CS_OPER_AUX_DORUSO
GPS Ionospheric Map	CS_OPER_AUX_IONGIM (daily file)
Instantaneous Polar Location	CS_OPER_AUX_POLLOC (daily increment)
Dynamic Sea Ice Concentration	CS_OPER_AUX_SEA_IC (each file has a validity of 3days)
Solar Activity Index	CS_OPER_AUX_SUNACT (monthly increment)
Surface Pressure	CS_OPER_AUX_SURFPS (daily meteo files for 00,06,12,18h)
Ocean Mean Pressure	CS_OPER_AUX_SEAMPS (daily meteo files for 00,06,12,18h)
WE Wind Component	CS_OPER_AUX_U_WIND (daily meteo files for 00,06,12,18h)
SN Wind Component	CS_OPER_AUX_V_WIND (daily meteo files for 00,06,12,18h)
Wet Troposphere Correction	CS_OPER_AUX_WETTRP (daily meteo files for 00,06,12,18h)
Dynamic Meteo Correction from Gravity Wave Model	CS_OPER_AUX_MOG_2D (daily meteo files for 00,06,12,18h)
Gaussian Altimetric Grid	CS_OPER_AUX_ALTGRD (updated only when the horizontal spatial resolution of the ECMWF model changes)

3 Cryosat-2 Data Supply

3.1 Cryosat-2 Ground System

The operational ground system (Payload Data System) is located at the Kiruna receiving station in Sweden. Cryosat-2 data products are distributed by FTP from this site.

3.2 Cryosat-2 User Products

3.2.1 Level-2 Geophysical Data Record

The main user product is the level-2 GDR (Geophysical Data Record), which fulfils the needs of most scientific researchers. The GDR contains the time of measurement, the geolocation and the height of the surface above the reference ellipsoid. The height is fully corrected for instrument effects, propagation delays, measurement geometry, and other geophysical effects such as atmospheric and tidal effects. Additionally the GDR contains some mode and quality flagging information and includes the geophysical corrections that were used to compute the height measurement. For measurements made in SAR mode a freeboard height, i.e. the height by which an ice floe extends above the water surface, is computed over sea ice. For measurements made in SIN mode the location includes any across-track offset due to topography. The orbit location is also included. Measurements are computed along track at intervals of approximately every 300 metres.

The GDR is supplied in full-orbit segments starting and ending at the equator. This means that all the measurements made in each mode, and processed by different chains, are consolidated, in correct time order, and share the same record format.

The frequency of consolidated L2 data records is approximately one per second, but each record contains a block of 20 higher-rate measurements. Consolidated L2 data files are partitioned into whole-orbit segments cut at the ascending equator crossing node (ANX) and therefore each consolidated L2 product is approximately 4948 seconds long.

L2 data are also available by mode. This has exactly the same file and record format as the GDR but the data files are segmented by measurement mode and their length is variable.

3.2.2 Freeboard Processing

Previous to baseline C products, two flavours of GDR existed, identified by the string SIR_GDR_2A or SIR_GDR_2B in the filename. In the '2A' version the final stage of processing over sea ice had not been run and the freeboard field is filled with -9999. The '2B' version was used to validate the processing.

Now the freeboard measurements are validated, the identification string will switch to SIR_GDR_2_, which will be the only flavour of GDR distributed for baseline C and later

3.2.3 Slope Correction

In general, over land ice the level-2 SIN and LRM data are slope-corrected. The SIN slope correction is calculated from the interferometric phase and the LRM from a digital elevation model (DEM). Details are given in reference 3.

For SIN mode, the echoing longitude and latitude differ from nadir according to the across-track offset computed from the phase difference. In LRM mode, they differ from nadir according to the result of the slope-correction algorithm and the slope model is used in the processor to determine where the first return came from. The method used for this is similar to ENVISAT. Please note, in SIN mode, the DEM is not used to determine where the echo came from. Instead, it is used to provide a flag that states whether the echo may be ambiguous due to phase wrapping.

The DEM used for LRM slope model creation is not the same as the DEM used for SIN ambiguity detection.

For the slope model in the LRM processing, the following DEMs are used to create the slope models:

- Helm, Veit; Humbert, Angelika; Miller, Heinz (2014): Elevation Model of Antarctica derived from CryoSat-2 in the period 2011 to 2013, links to DEM and uncertainty map as GeoTIFF. https://doi.org/10.1594/PANGAEA.831392
- Helm, Veit; Humbert, Angelika; Miller, Heinz (2014): Elevation Model of Greenland derived from CryoSat-2 in the period 2011 to 2013, links to DEM and uncertainty map as GeoTIFF. https://doi.org/10.1594/PANGAEA.831393

For the ambiguity detection in the SARin mode processing, the following DEMs are used:

- Antarctica: Bamber, Jonathan L., Jose Luis Gomez-Dans, and Jennifer A. Griggs. 2009. Antarctic 1 km Digital Elevation Model (DEM) from Combined ERS-1 Radar and ICESat Laser Satellite Altimetry. Boulder, Colorado USA: National Snow and Ice Data Center. Digital media.
- Greenland: Howat, I.M., A. Negrete, B.E. Smith, 2014, The Greenland Ice Mapping Project (GIMP) land classification and surface elevation datasets The Cryosphere, 8, 1509-1518, doi:10.5194/tc-8-1509-2014

3.2.4 Level-1b Data

Level-1b data are received by some users interested in the SIRAL instrument performance, and by some interested in algorithm development. It contains time and geolocation information and the SIRAL measurements in engineering units. Calibration corrections are included and have been applied to the window delay computations. Signal propagation delays and other geophysical corrections are included in the product but have not been applied to the range or time delay.

L1B data is segmented according to measurement mode and each mode has a slightly different record format to accommodate the difference in the echoes.

In pulse-limited (or LRM) mode averaged power echoes are included as for previous altimeter missions. Echoes are 128 samples (or 'bins') long.

In SAR mode the echoes which result from Doppler beam formation are included and consist of 256 samples. There are additional parameters which characterise the distribution of energy across the set of Doppler beams which are directed at a common surface location.

In SIN mode the echoes resulting from the Doppler beam formation process consist of 1024 samples. From the interferometric processing there is also an array of 1024 phase differences, and an array of 1024 coherence terms, computed by comparing the echoes received by both antennas.

3.2.5 Near Real Time Data

Near-real-time data is derived from the science data stream. It can be used for operational oceanography and meteorology, and to allow monitoring of satellite health and safety beyond the limits of the normal housekeeping telemetry. It is sometimes tailored to specific requirements during calibration and validation campaigns, and details must be obtained on a campaign by campaign basis. See reference 3.

Near Rea Time products deriving from Star Tracker Refined products are available after 24 hours from the data acquisition, because of the dependency from the Star Tracker Refining.

To allow availability of "real" Near Real Time SAR and SARIN products, a different chain has been dedicated to the specific operational mode to allow the generation of SAR/SARIN NRT products in short time (2/3 hours): the Star Tracker Refined product is replaced by the Star Tracker Level 0 products, available at the time of the downlink.

Background information is given in references 4 and 12.

3.2.6 Fast Delivery Marine Mode Data

Fast Delivery Marine Mode (FDM) data products are produced from LRM data only, processed as soon as possible after acquisition.

3.3 File Structure

Cryosat-2 products are comprised of two files, an XML header file, always named with a `.HDR` extension, and a product file, always named with a `.DBL` extension.

For a generic user, the DBL file should be enough to perform scientific use of the data, without the need of the corresponding HDR file. The HDR file is an auxiliary ASCII file which is designed to allow the user to quickly identify the product without looking inside the DBL, however it is not mandatory for scientific use of the data.

Each Cryosat-2 product is composed of two files:

- XML Header File (.HDR); this consists of a Fixed Header and a Variable Header

- Product File (.DBL); this is in netCDF format.

All of the information provided in the Fixed Header of the HDR file is listed below and most of this is actually also available in the DBL files as global attributes:

<File_Name> ; <File_Description> ; <Notes>; <Mission> ; <File_Class> ; <File_Type> ; <Validity_Start> ; <Validity_Stop> ; <File_Version> ; <System> ; <Creator> ; <Creator_Version> ; <Creation_Date>

It should be noted that the fields in the Fixed Header of the HDR are named and ordered slightly differently in the DBL but the core content of each field is the same.

The Variable Header of the HDR consists of an XML MPH and an XML SPH which have actually been derived from the corresponding attributes from the DBL file, consequently all the information provided in this Variable Header of both HDR and DBL is the same.

The XML header file has a fixed portion and a variable portion. The fixed portion has the same format in all Cryosat-2 files. The variable portion contains much of the same information as the global attributes in the product file but in XML format.

3.4 File Naming Convention

File names are constructed according to standard guidelines for Earth Explorer missions. All follow the conventional form

MM_CCCC_TTTTTTTTTT_yyyymmddThhmmss_YYYYMMDDTHHMMSS_vvvv.ttt

where:

MM = the mission identifier, which is CS for Cryosat-2

CCCC = file class which can be: OFFL (Off-Line Systematic Processing), NRT_ (Near Real Time), RPRO (ReProcessing), TEST (Testing), LTA_ (Long Term Archive)

TTTTTTTTTT= file type as defined in Table 4 below

yyyymmddThhmmss = start time window as extracted from Job Order

YYYYMMDDTHHMMSS = stop time window as extracted from Job Order

Avvv or Bvvv = the version number of the file. This can be incremented in the case of reprocessing. “A” corresponds to IPF1 version J and IPF2 version I or previous versions. “B” corresponds to IPF1 version K and IPF2 version J.

ttt = the extension: tgz for a gzipped tar file, HDR for an extracted header and DBL for extracted binary data.

Table 4: Relevant File Types

File type	Description
SIR_LRM_1B	SIRAL LRM level 1b
SIR_SAR_1B	SIRAL SAR mode level 1b
SIR_SARN1B	SIRAL SAR NRT mode level 1b
SIR_SIN_1B	SIRAL SIN mode level 1b
SIR_SINN1B	SIRAL SIN NRT mode level 1b
SIR_LRM_2_	SIRAL LRM level 2
SIR_SAR_2_	SIRAL SAR mode level 2 with ice freeboard measurements
SIR_SARN2_	SIRAL SAR NRT mode level 2 with ice freeboard measurements
SIR_SIN_2_	SIRAL SIN mode level 2
SIR_SINN2_	SIRAL SIN NRT mode level 2
SIR_SID_2_	SIRAL degraded SIN mode level 2
SIR_GDR_2_	SIRAL geophysical data record with ice freeboard measurements

This table shows only the file types relevant to the scientific data. Calibration modes and intermediate files (FBR and L2I) are excluded.

The geophysical data records (GDR) meet most scientific needs. A GDR covers a full orbit, starting and ending at the ascending node at the equator, and contains time-ordered records of data from all SIRAL systematic modes (hence no FDM).

3.5 Other Conventions

Background information on all sections below can be found in reference 12.

3.5.1 Latitude and Longitude Limits

Longitude is expressed from -180 to +180 degrees. Positive east does not contain 180.0, negative west does contain -180.0. This is the same definition as used by EnviSat.

3.5.2 Range Correction Sign Convention

The sign convention for all range corrections is that they are added to range.

Since **satellite altitude – range measurement = surface height** (Eqn 3.5.2-1)

it follows that

satellite altitude – (range measurement + ionospheric correction) = surface height corrected for the ionosphere effect (Eqn 3.5.2-2)

3.5.3 Timestamp Format

The timestamps in the measurement dataset records are TAI times in seconds past 00:00:00 on 1-JAN-2000.

Note that:

i) The time in the main and specific product headers is in UTC and not in TAI

ii) Time correlations between UTC and TAI are provided via the orbit files - these must account for the correct offsets due to leap seconds

iii) 1 Jan 2000 at 00:00 UTC = 1 Jan 2000 at 00:32 TAI

See the Hong Kong Time Service website for a detailed discussion of time measurement. http://www.hko.gov.hk/wservice/tsheet/timeserv.htm

3.5.4 Time in L2 GDR Records

In L2 products a record contains a group of 20 measurements together with a single set of other parameters. This gives a data rate of approximately one record per second, or 1 Hz, with measurements at approximately 20Hz. Timestamps for both are provided as above.

It is **important to note** that the 1Hz time corresponds to the first of the 20 measurements and not the middle. This is different from previous altimetry missions, such as ERS and EnviSat, but for good reasons.

Unlike previous missions the instrument telemetry does not create the block of 20 high-rate measurements with the 1 Hz parameters. In the case of Cryosat-2 this is purely a choice within the ground processing system to reduce the L2 data volume. The timestamp for records in the SAR and SIN modes is a function of the Doppler beam processing and not associated with a particular telemetry packet. If a group of 20 measurements spans a measurement mode change (or even 2) then the interval between each of the 20 blocks will not be regular. This would make a consistent definition of a 'middle' time rather difficult. Furthermore, a measurement stream may end at any point within the block of 20. In which case the unused blocks are zero-filled and only serve to pad out the data record. One can only be sure that there is at least one measurement in a record of 20.

For these reasons the 1Hz time is provided corresponding to the first measurement of the 20.

4 References and Acronyms

4.1 Reference Documents

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[3] Cryosat-2 Mission and Data Description CS-RP-ESA-SY-0059

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[5] PDS-SSALTO Interface Control Definitions, CS-ID-ACS-GS-0123

[6] Specification D'Interfaces Internes SSALTO: Orbitographie Mission SMM-IF-M6-EA-20174-CN

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[11] D.E. Cartwright and A.C. Edden, Corrected tables of tidal harmonics. Geophysical Journal of the Royal Astronomical Society, Volume 33, 1973, pages 253-264

[12] **CryoSat Ice netCDF L1B Product Format Specification C2-RS-ACS-ESL-5364**

[13] **CryoSat Ice netCDF L2 Product Format SpecificationC2-RS-ACS-ESL-5265**

[14] Sea State Bias in Radar Altimetry Revisited, Hausman and Zlotnicki, Marine Geodesy 33(S1):336-347, 2010

[15] SIRAL, a High Spatial Resolution Radar Altimeter for the Cryosat-2 Mission, Rey et al, Geoscience and Remote Sensing Symposium, 2001. IGARSS 2001. IEEE 2001 International, vol 7, pages 3080-3082

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[17] Earth Explorer File Format Standards PE-TN-ESA-GS-0001

[18] Cryosat-2 L2 Processor Design Summary Document CS-DD-MSL-GS-2002

[19] The Mean Echo and Echo Cross Product From a Beamforming Interferometric Altimeter and Their Application to Elevation Measurement, Wingham et al, IEEE Transactions On Geoscience And Remote Sensing, Volume 42, No 10, October 2004, pages 2305-2323

[20] Cryosat-2 IPF1 Design Summary Document CS-DD-MSL-GS-0008

[21] Brown Model Derivatives Walter, Smith 09 June 2009; revised 19 May 2011.

[22] Cryosat-2 IPF2 Sigma-zero Technical Note, CS-TN-MSL-GS-6005

4.2 Acronyms and Abbreviations

AGC	Automatic Gain Control
ANX	Ascending equator crossing Node
API	Application Programming Interface
ASCII	American Standard Code for Information Interchange
CAL 1-4	Calibration modes
CFI	Customer Furnished Item
CoG	Centre of Gravity
CoM	Centre of Mass
DAC	Dynamic Atmospheric Correction
DAD	Dynamic Auxiliary Data
DEM	Digital Elevation Model
DFCB	Data format control book
DORIS	Doppler Orbit and Radiopositioning Integration by Satellite
DS	Data Set
DSD	Data Set Descriptor
DSR	Data Set Record
DTM	Digital Terrain Model
EM	Electromagnetic
ESA	European Space Agency

ESL	Expert Support Laboratory
FOS	Flight Operations System
GDR	Geophysical Data Record
GIM	Global Ionospheric Map
GPS	Global Positioning System
IBC	Inverse Barometric Correction
IERS	International Earth Rotation Service
IPFDB	Instrument Processing Facility database
ITRF	International Terrestrial Reference Frame
L1B	Level 1b
L2	Level 2
LRM	Low Rate Mode (synonymous with Pulse Limited Mode)
LTA	Long Term Archive
MDS	Measurement Data Set
MDSR	Measurement dataset Record
MJD	Modified Julian Date
MOG2D	Modèle 2D d'Ondes de Gravité
MPH	Main Product Header
MSS	Mean Sea Surface
MSSL	Mullard Space Science Laboratory (UCL)
NOAA	National Oceanic and Atmospheric Administration
NRT	Near Real Time
ODLE	Ocean Depth / Land Elevation
PDS	Payload Data System

POE	DORIS Precise Orbit Ephemeris
RMS	Root Mean Squared
Rx	Receiver
SAD	Static Auxiliary Data
SAR	Synthetic Aperture Radar
SIN	SAR Interferometry
SBT	Satellite Binary Time
SID	SIN degraded mode
SIRAL	SAR Interferometric Radar Altimeter
SP	Source Packet
SPH	Specific Product Header
SS	Space Segment
SSALTO	Systeme au Sol d'ALTimétrie et d'Orbitographie
SSHA	Sea Surface Height Anomaly
SWH	Significant Wave Height
TAI	International Atomic Time (from the French, Temps Atomique International)
TEC	Total Electron Content
UCL	University College London
USO	Ultra-Stable Oscillator
UTC	Coordinated Universal Time
XML	Extensible Markup Language