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Advance in Space Research - Editor

November 27th, 2017

Dear Editor,

Please find enclosed our revised manuscript entitled "CryoSat Ocean Product Quality Status and Future Evolution" (**ASR-D-17-00195R1**) for consideration for publication in the *CryoSat Mission Special Issue* of *Advance in Space Research*.

We have revised the manuscript, corrected remaining spelling/typos, updated the references and implemented all the suggested improvements.

We hope that you will find this 2nd revised version of the manuscript appropriate for publication.

Sincerely yours,

Jérôme Bouffard, PhD

CryoSat Ocean Product Quality Status and Future Evolution

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Abstract

The main objectives of this paper are to present the status of the CryoSat ocean products and to give an overview of all associated quality control and validation activities. Launched in 2010, the polar-orbiting European Space Agency's (ESA) CryoSat mission was primarily developed to measure changes in the thickness of polar sea ice and elevation of the ice sheets. Going beyond its ice-monitoring objective, CryoSat is also a valuable source of data for the oceanographic community. The satellite's radar altimeter can measure high-resolution geophysical parameters from the open ocean to the coast. To enable their full scientific and operational exploitation, the ocean products continuously evolve and need to be quality-controlled and thoroughly validated via science-oriented diagnostics based on multi-platform *in situ* data, models and other satellite missions. In support to ESA, the CryoSat ocean validation teams conduct this quality assessment for both the near real time and offline ocean products, both over short time scales (daily and monthly monitoring) and long-term stability (annual trends). Based on the outcomes from these quality analyses and feedback from scientific oceanographic community, ESA intends to upgrade the CryoSat Ocean processing chain for Autumn 2017.

Key words:

CryoSat, Satellite Altimetry, Ocean, Quality assessment, Long-term stability, Ocean product evolution, Climate

1 Introduction

CryoSat-2 (hereafter CryoSat) is a 7-year radar altimetry mission, launched on 8 April 2010 with the primary objectives to monitor variations in the thickness of the Earth's marine ice cover and continental ice sheets (Wingham et al, 2006). The primary payload on-board CryoSat is the Synthetic Aperture Interferometric Radar Altimeter (SIRAL), which has been monitoring the Earth's cryosphere with unprecedented accuracy and precision (Parrinello et al., 2017; introduction of this CryoSat Special Issue). However, beyond the primary mission objectives, CryoSat also represents a valuable source of data for the oceanographic community. The quasi-geodetic orbit of CryoSat and the design of its altimeter are fundamentally different from the majority of existing ocean altimeters with the ability to reach polar regions and obtain higher-resolution data. These two specialties have opened the door for innovative data processing developments and have also contributed to improving the characterisation of the surface topography dynamics over the polar, coastal and open ocean domains.

The choice of the CryoSat orbit was initially the result of a trade-off between the desired high density of crossover points over the Polar Regions and the need to sufficiently cover south Greenland (see Figure 1). For this, the CryoSat 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 non-sun-synchronous and the satellite drifts through all angles to the Sun in approximately 16 months. The repeat cycle for CryoSat orbit should be 369 days, corresponding to 5344 revolutions. However, the CryoSat orbit does not repeat exactly after each cycle, as is usually the case for ocean-oriented altimetry missions. CryoSat's ascending nodes are repeated from cycle to cycle within a few tens of 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, entailing fluctuations up to nearly 4 km from cycle to cycle. Despite this drifting geodetic orbit, which is not optimal for oceanographic applications, CryoSat has compensated for the loss of ENVISAT for operational oceanography and the characterisation of mesoscale dynamics (Labroue et al. 2012, Dibarbourre et al. 2011, Le Traon et al., 2015). CryoSat has also greatly contributed to enhancing the quality of the global mean sea surface (Andersen et al., 2015) and monitoring of the Arctic geostrophic circulation (Armitage et al., 2017), through the intensive sampling of polar and altimetric inter-track areas that are not covered by conventional ocean-oriented missions.

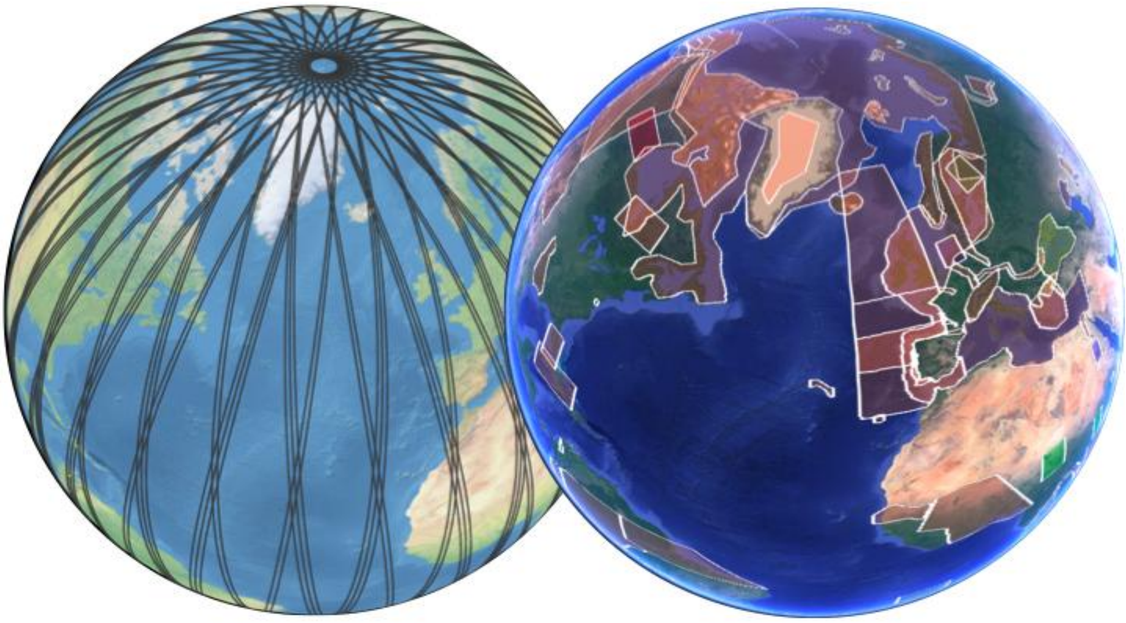

Figure 1: (left) CryoSat ground track coverage from 01/10/17 to 05/10/17 (black lines) and (right) Geographical mask of acquisition according to operational mode (version 3.9, in place since 30 January 2017) More details on: https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/cryosat/content/-/asset_publisher/VeF6/content/geographical-mode-mask-7107

SIRAL is the primary instrument on-board CryoSat and is considered the precursor for a new generation of altimeter systems, like those for the Sentinel-3 and Sentinel-6 ocean topography missions. The SIRAL instrument combines a conventional pulse-limited radar altimeter with synthetic aperture and interferometric signal processing (see Table 1). This single frequency Ku-band radar altimeter is capable of operating in three modes: Low Resolution Mode

(LRM), Synthetic Aperture Radar (SAR) and SAR Interferometric (SARIn or SIN) burst modes.

Table 1: SIRAL Instrument Characteristics

Radio frequency	13.575 GHz (single frequency Ku-band)
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
Burst mode PRF	N/A in LRM, 85.7 Hz in SAR, 21.4 Hz 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 / SIN, 0.4684 m for LRM
Data rate	60 kbit/s for LRM, 12 Mbit/s in SAR, 2x12 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

Each mode was initially designed for optimal measurements over different surfaces. The measurement modes are operated on-board according to a geographical mode mask (see Figure 1), which is updated regularly to allow for the changing extent of sea-ice and to track sea ice boundaries. Over the oceans and ice sheet interiors, CryoSat generally operates in LRM, similar to traditional pulse-limited radar altimeters. Over sea ice, SAR mode is used, whereby coherently transmitted echoes are combined via a delay-Doppler processing, reducing the illuminated surface area (Raney, 1998). SAR mode is mainly used to carry out high-resolution measurements of floating sea ice. CryoSat's most advanced mode is generally used around the margins of continental ice sheets and over mountain glaciers where topography is steep. Here, the altimeter performs SAR altimetry measurements and uses a second antenna as an interferometer to determine the across-track angle to the earliest radar returns. This SARIn mode provides the exact location of the surface being measured.

The CryoSat geographical mode mask is however not static and regular updates are made by the European Space Agency (ESA), considering requests from the coastal altimetry and oceanographic community. A number of changes have been made over the past seven years in order to stimulate research and development activities (e.g. SARIn boxes over Cuba and Greece islands, SAR box over North East Atlantic), and to support the quality assessment of Sentinel-3 ocean topography data during the commissioning phase (e.g. SAR box over the Pacific). Although the primary mission objective of CryoSat is to observe the cryosphere, its measurements over the ocean are indeed of great value to the oceanographic and climate research communities, as testified by many contributions to the Ocean Surface Topography Science Team (OSTST) meetings (http://www.aviso.altimetry.fr/en/user-corner/science-teams/ostst-swt-science-team.html) and Coastal Altimetry Workshops (www.coastalt.eu/community).

Consequently, thanks to fruitful collaborations with the Centre National d'Études Spatiales (CNES) and the National Oceanic and Atmospheric Administration (NOAA), ESA has developed and implemented its own CryoSat Ocean Processor (COP), to operationally generate CryoSat products specifically designed for oceanographers. The COP includes up-to-date and ocean-oriented algorithms and corrections in order to bridge the gap between previous and future ocean missions as well as to contribute to a better knowledge of polar circulation. Since 2014, CryoSat data are processed simultaneously by both Ice and Ocean processors, generating a range of operational ocean products, with specific latencies, alongside the original ice products (see Figure 2). The CryoSat Ice processors and the COP operate almost independently and follow two distinct processing baselines. The COP uses input Level 0 (L0) LRM and SAR data and generates Level 1B (L1B) and Level 2 (L2) products using Pseudo-Low Resolution Mode (PLRM) techniques over the SAR mode patches of the global mask, by processing the pulse-limited echoes incoherently, as in the conventional LRM concept (Scharroo, 2014). These products are generated at two latencies: Intermediate Ocean Products (IOP) generated typically two to three days after acquisition for medium-range ocean forecasting (using the CNES Medium Orbit Ephemeris (MOE)); and Geophysical Ocean Products (GOP) generated typically 30 days after acquisition with consolidated orbits (using the CNES Precise Orbit Ephemeris (POE)) and corrections for longer-term, retrospective and climate studies. They complement the Near-Real Time (NRT) Fast Delivery Marine (FDM) products currently generated by the Ice processor (using the Doris Navigator Orbit).

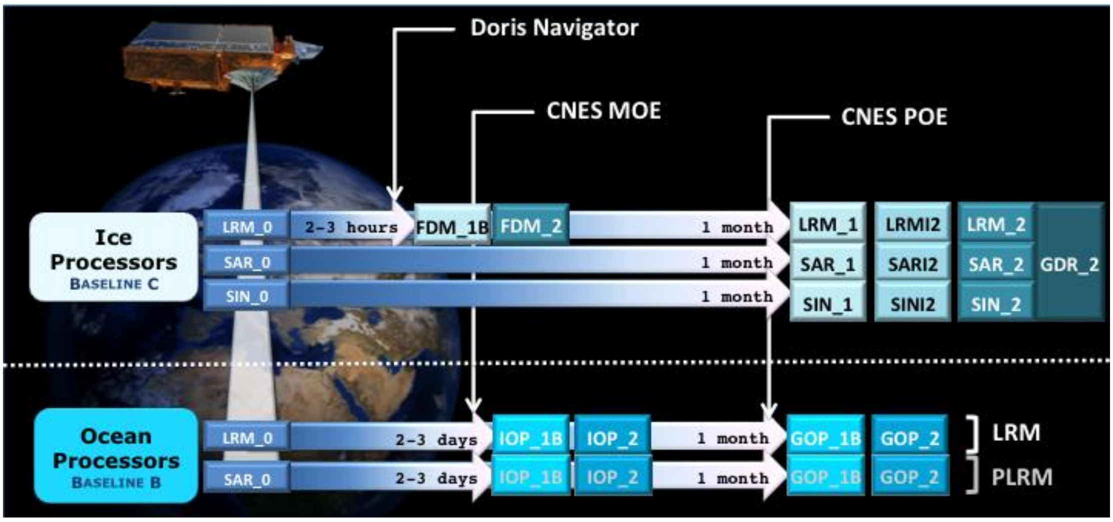

Figure 2: Two independent CryoSat processors for ice and ocean applications (FDM: Fast Delivery Mode, LRM: Low Resolution Mode, PLRM: Pseudo-LRM, IOP: Intermediate Ocean Product, GOP: Geophysical Ocean Product). The suffixes _1, _1B, _2 and I2 refer respectively to Level-1 (Level-1B + Full Bit Rate products), Level-1B, Level-2 and In-Depth Level-2 products. More details can be found at https://earth.esa.int/web/guest/-/products-overview-6975#_101_INSTANCE_VeF6_matmp

The CryoSat ocean products (FDM, IOP and GOP) are routinely monitored for Quality Control (QC) by the ESA/ESRIN Sensor Performance, Products and Algorithms (SPPA) office with the support of the Instrument Data quality Evaluation and Analysis Service (IDEAS+). These basic QC activities include checking data availability and processing completeness, the usage of the correct Auxiliary Data Files and calibration files in processing; and checking that no error flags are raised in the data.

Alongside these activities, the ocean products are analysed in more detail at the UK National Oceanography Centre (NOC), within the framework of the CryoSat Ocean product Quality Control and Validation (CryOcean-QCV) project. This activity includes two complementary aspects: i) global assessment and quality control of the data over the oceans; ii) validation against *in situ* observations, other altimetry datasets and numerical models. The global assessment is conducted both daily (for FDM and IOP) and monthly (for FDM, IOP, and GOP) for the sea surface height anomaly (SSHA), significant wave height (SWH), radar backscattering coefficient (sigma0), wind speed, and mispointing parameters. The validation is performed monthly for the GOP SSHA, geostrophic velocity, SWH and wind speed. Results of the assessment and validation are extensively described in daily and monthly reports available on the ESA website (see Section 3) and have been recently published in Calafat et al. (2017).

In parallel, a complementary quality assessment of the GOP Level 2 data is performed by the Delft University of Technology (TU Delft), as a continuation of previous calibration and validation activities performed by Naeije et al. (2011) and Schrama et al. (2014, 2016). The main goal is long-term monitoring; evaluating the stability of the measurement system and identifying potential biases and drifts. This is achieved through cross-calibration with concurrent ocean altimeter data from Jason-2 (launched 20th June 2008) which is considered as the reference mission from the completion of its commissioning phase and until it moves to an interleaved orbit (September 2016). Independently, this is also addressed by comparing the

GOP sea level anomaly with *in situ* data from a selected set of tide gauges. Since a good altimeter ocean product requires a very precise determination of the orbital height, the quality of CryoSat's precise orbit data from the Centre National d'Etudes Spatiales (CNES) is also assessed by independently generating precise orbits and cross-validating them (Schrama, 2017).

This paper provides an overview of the CryoSat ocean data quality status. After briefly presenting the COP baselines, the paper focuses on the activities and results associated with the ocean quality assessment, both from routine and long-term analysis. Finally, we discuss the forthcoming evolution of the processing chains and validation approaches to accommodate future releases of upgraded CryoSat ocean products. This paper is complementary to Bouffard et al. 2017 (this issue) focusing on the SIRAL performance, stability and quality control and validation activities over the sea-ice and land-ice domains.

2 CryoSat Ocean Product Characteristics

2.1 Content of the Level 2 Ocean Products

The CryoSat L2 ocean products mainly contain measurements of the sea surface height (SSH), the SWH and wind speed derived from the processing of the radar waveforms in both LRM and PLRM (over SAR patches). This is done by using the Ocean-3 or MLE-4 algorithm (Amarouche et al., 2004), where the measured waveform is fitted with a 4-parameter return power model, according to weighted Least Square Estimators derived from Maximum Likelihood Estimators (MLE). Fitting the raw waveforms with a waveform model (Brown, 1977) yields estimates of the location, amplitude and rising time of the waveform. The location or epoch is converted into the fundamental measure of range, which is then used to compute the SSH as detailed below. The amplitude of the waveform gives an estimate of the radar backscattering sigma0, which is then converted into wind following Abdalla (2007).

The waveform rise time (inversely proportional to the slope of the leading edge of the waveform) is directly linked to SWH in the Brown model.

The principal parameter generated by the COP is the SSH over a reference ellipsoid (WGS84 ellipsoid). SSH computation involves correcting the range for a series of propagation delays and geophysical effects and subtracting it from the orbit:

SSH = altitude – (range + ssha_corrections) *(Eq.1)*

where ssha_corrections is a sum of all range and geophysical corrections, which are identified by the addends in the sum below and are also available as individual fields in the CryoSat ocean products:

ssha_corrections = ionospheric correction + dry tropospheric correction + wet tropospheric correction + sea state bias + solid earth tide + ocean loading tide + ocean tide + long period ocean tide + geocentric pole tide + dynamic atmospheric correction + inverse barometric correction *(Eq.2)*

If a geoid model of sufficient accuracy is available, this can be subtracted from the corrected SSH to derive the dynamic topography of the ocean. However, more often the SSH is quality controlled, verified and used in the form of its anomaly (SSHA) with respect to a chosen Mean Sea Surface (MSS): *SSHA = SSH – MSS* *(Eq.3)*

For a description of the ocean products, we refer the reader to the CryoSat Product Handbook: https://earth.esa.int/documents/10174/125272/CryoSat_Product_Handbook. Further details on the specific geophysical parameters and corrections analysed in routine quality control and validation activities, as well as in the long-term analysis of the CryoSat ocean products can be also found in Sectionssections 3.1.1 and3.2.1 respectively.

2.2 Ocean Product Processing Baselines

The first CryoSat Ocean Processor (COP) became operational on 10/04/2014 and IOP and GOP for the period from 10/04/2014 to 22/02/2015 were generated with the COP Baseline-A. After this date, the COP was upgraded to Baseline-B with a new processing configuration and new Calibration 1 (Cal1) corrections. New Look-Up Table (LUT) corrections and CNES orbit model standard (GDR-E), required to align the ocean products with the operational Baseline-C ice products, were integrated on 01/04/2015. The Baseline-A ocean data were then definitively removed from the CryoSat dissemination server 6 months after the COP Baseline -B went in operation (see Figure 3).

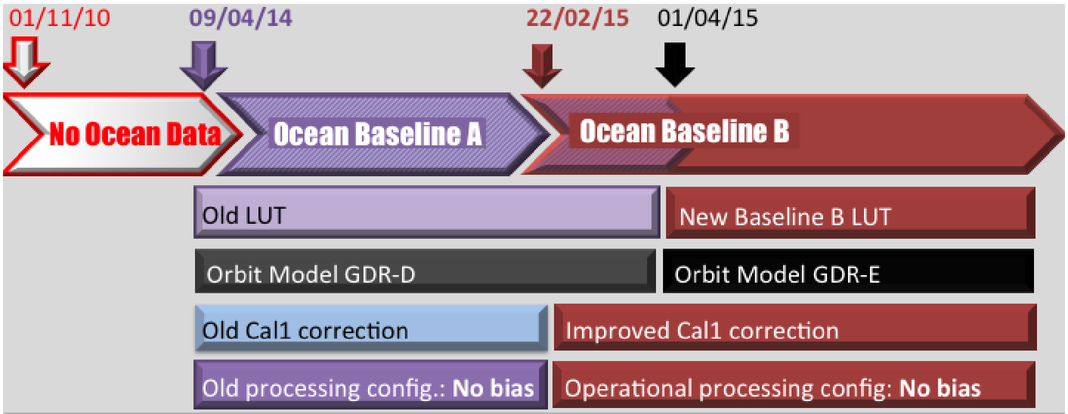

Figure 3: GOP availability and characteristics. Situation before November 2016.

Within the framework of the COP evolution activities, 12 months of GOP data (July 2013 – June 2014) were reprocessed with the updated Baseline-B GOP, for the purpose of internal testing and to define new algorithms in preparation for the future COP Baseline-C. IDEAS+ performed detailed validation of a 5-day Test Data Set (TDS) from each month of the campaign, including the verification of quality flags, parameter and correction values, as well as auxiliary and calibration file usage within the products. Following the good validation results obtained (see Section 3.2), ESA decided to extend the Baseline-B reprocessing campaign to the full CryoSat GOP L1B and L2 dataset from November 2010 to March 2015 and to disseminate the data to ocean users awaiting the COP Baseline-C and subsequent reprocessing campaign planned for 2018 (Figure 4). The full-reprocessed Baseline-B GOP dataset from November 2010 to March 2015 is accessible to registered users from the CryoSat dissemination server (ftp://science-pds.cryosat.esa.int).

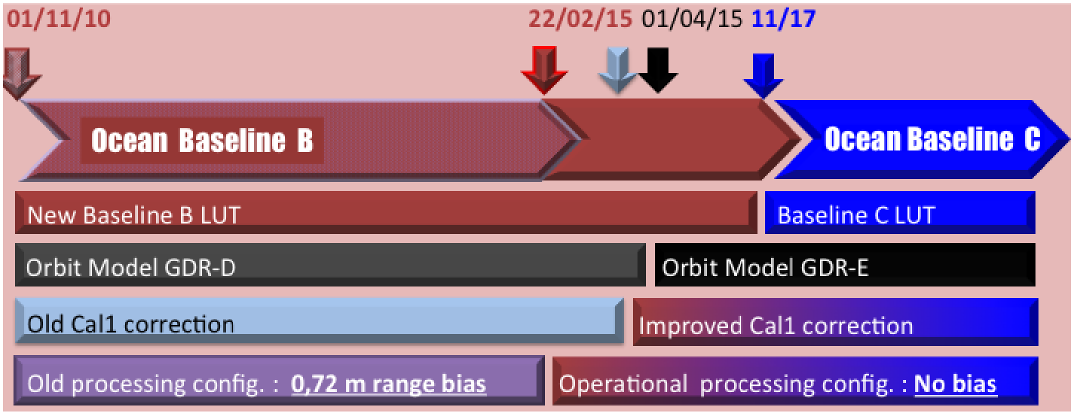

Figure 4: GOP availability and characteristics. Situation on November 2017 (before the COP Baseline-C processing campaign).

This Baseline-B reprocessed dataset is of good quality but, due to operational constraints, shows a bias and a slight inconsistency affecting LRM parameters (not PLRM). As detailed in Section 3.2, these expected biases could be easily corrected. Before 22/02/2015, the LRM range can be corrected by applying a spatial and temporal constant value of +0.7203 m. Before and after 27/03/2015, the LRM backscatter coefficients show an average difference of ~ 0.37 dB, linked to the use of different Cal1 corrections (estimation of internal delay of the SIRAL through measuring the impulse response). This could cause a mean difference of ~ +0.4 mm, ~2 mm and 1.1 m/s for the retrieved LRM sea state bias (SSB), SWH and wind speed respectively. These known issues are not critical for most oceanographic applications and will be fixed with the introduction of COP Baseline-C and associated reprocessing campaign (see Section 5).

In the meantime, the FDM (from the Baseline-C Ice processor) and the IOP and GOP (from the Baseline-B COP) continue to be distributed, regularly quality controlled and in-depth validated by ESA with the support of CryoSat mission partners from the TU Delft, the NOC and the IDEAS+ consortium.

3 Ocean Product Quality Assessment

3.1 Routine Quality Control and Scientific Validation

3.1.1 Data and Methods

IDEAS+ performs routine QC activities on all operational CryoSat products, which include checking L0 data availability; acquisition tracking and L0 echo errors; the product headers; the product formats and software versions; the Auxiliary Data File usage; the external correction error flags and the analysis of measurement parameters. IDEAS+ uses a number of different tools and software to perform their operational analyses. The CryoSat-2 Quality Control – Quality Analysis of Data from Atmospheric Sensors (C2QC-QUADAS) is an updated tool installed in April 2015 at the Payload Data Segment (PDS) and on local machines at Telespazio Vega UK. It is configured to monitor both operational and reprocessed ice and ocean data products, and to automatically generate daily and monthly QC reports, which form the basis of the IDEAS+ daily performance reports. The Quality Control for CryoSat (QCC) tool is installed at the PDS and is designed to perform a set of configurable checks on each product immediately after production. This information is checked and included in the IDEAS+ daily performance reports, which are uploaded daily to the ESA CryoSat webpage (https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/cryosat/daily-performance-reports).

Complementary to the IDEAS+ activities, more scientific Quality Control and Validation (CryOcean-QCV) activities are performed by the NOC using a fully automated system. This system first downloads the necessary CryoSat and validation datasets, then generates relevant statistics and figures using all available data, then compiles a report incorporating relevant text and figures, and finally uploads the report to the ESA file servers. The system is automated by a series of scripts, developed and implemented at the NOC. The data download is scheduled to run twice daily, whilst other scripts run daily or monthly, depending on the report type.

As part of the assessment, all CryoSat ocean data are screened according to scientific quality criteria (in addition to the quality control flags provided within the product files), including the use of minimum and maximum thresholds for the range and geophysical corrections and for the values of sigma0, SSHA, SWH and their corresponding 20 Hz standard deviations. The assessment is global in scope and includes coverage, completeness and data flow, global along-track analysis, crossover analysis, spectral statistics and derivation of error levels. Table 2 lists the models used to derive the various corrections, which in turn are used in the validation of the SSH and SSHA calculation in Baseline-B products, as described in *(Eq. 1)*, (*Eq.2)* and (*Eq.3*). Note that some models include more than one correction, for example the 2D Gravity Waves Model (MOG2D) is used to compute the Dynamic Atmosphere Correction (DAC), which includes the inverse barometric barometer correction. Another example is the ocean tide model, which includes also the loading tides and the long period tides. Such cases are highlighted in the table. The CNES-Collecte Localisation Satellites 11 (CNES-CLS 11) model is used as a reference MSS. It should be noted that the data products also contain alternative models for some of the variables, for example the Global Ocean Tide 4.8 (GOT4.8) tide model (Ray, 2013) is available as an alternative to Finite Element Solution 2014 (FES2014), and the Technical University of Denmark 10 (DTU10) MSS (Andersen and Knudsen, 2010) as an alternative to CNES-CLS11.

Table 2 - Models used by the NOC for the various corrections in the COP Baseline-B.

Corrections	Measurement or Model	Notes
Ionospheric (iono)	Global Ionospheric Map (GIM) (Near-Real-Time) (Mannucci et al., 1998)	Bent model (Bent et al., 1975) where GIM not available
Dry Tropospheric (dry_tropo)	European Centre for Medium-Range Weather Forecasts (ECMWF)	Operational model at its highest spatial resolution (1/8°), 6-hr interval
Wet Tropospheric (wet_tropo)	ECMWF	Operational model at its highest spatial resolution

		(1/8°), 6-hr interval
Sea State Bias (ssb)	LRM/PLRM: CLS model (Tran, 2012)	
Solid Earth Tide (solid_earth_tide)	Cartwright-Tayler-Edden model (Cartwright and Tayler, 1971; Cartwright and Edden, 1973)	
Ocean Tide (ocean_tide_sol1)	GOT4.8 (Ray, 2013)	
Ocean Tide (ocean_tide_sol2)	FES2004 (Lyard et al., 2006)	
Ocean Loading Tide (loading_tide_sol1)	GOT4.8 (Ray, 2013)	Already included in ocean_tide_sol1
Ocean Loading Tide (loading_tide_sol2)	FES2004	Already included in ocean_tide_sol2
Long Period Tide (long_period_tide)	FES2004	Already included in ocean_tide_sol1 and ocean_tide_sol2
Geocentric Pole Tide (pole_tide)	Desai (2002)	
Dynamic Atmospheric Correction (dynamic atmosphere)	MOG2D (Carrère and Lyard, 2003)	Includes low frequency
Inverse Barometric (inverse_barometric)	ECMWF	Operational model at its highest spatial resolution (1/8°), 6-hr interval. Already included in MOG2D DAC.

GOP SSHs are validated against tide gauge records from all around the world. The validation with tide gauge records includes both relative and absolute comparisons. The relative comparisons are between time series of sea level from tide gauges and GOP SSH anomalies; both referenced to an arbitrary zero level. The absolute validation is between absolute GOP SSHs and heights derived from tide gauge records, both ellipsoidal heights above the same reference ellipsoid, and is only possible at sites where there is a good levelling link between the tide gauge benchmark and a nearby Global Positioning System (GPS), i.e. the levelled height difference between the GPS station and the tide-gauge benchmark is known, and the distance between the GPS station and tide gauge is small. These sites include La Coruña, Spring Bay, Marseille, Ponta Delgada, Chichijima, Virginia Key, and Funafuti. The distance between the tide gauge and the GPS station is smaller than 2.6 km in all cases, and smaller than 5 m at four of the stations. Tide gauge records are obtained from the UK National Tide Gauge Network archives at the British Oceanographic Data Centre (BODC) (at 15-minute resolution) and the University of Hawaii Sea Level Center (UHSLC) (at 1-hour resolution). Ellipsoidal heights were computed using GPS station data obtained from Système d'Observation du Niveau des Eaux Littorales (SONEL) (http://www.sonel.org/). All GPS heights are defined with respect to ITRF2008, in consistency with the sea surface heights from CryoSat. GOP SSH anomalies are also compared with Argo-derived steric heights over the global oceans. The set of Argo profiles were obtained from the EN4.1.1 data set made available by the Met Office Hadley Centre (http://hadobs.metoffice.com/en4/).

The GOP SWH is validated against both *in situ* hourly buoy data obtained from the National Data Buoy Center (NDBC) and hourly modelled data from the WaveWatch III global wave model obtained from the Pacific Islands Ocean Observing System at the University of Hawaii. The Wavewatch III model provides hourly values of SWH over the global ocean at 1/2° spatial resolution. The Wavewatch III model is a third-generation wave model developed at NOAA/National Centres for Environmental Prediction (NCEP), which solves the random phase spectral action density balance equation for wave-number direction spectra (Tolman, 2009). The comparison between CryoSat SWH and buoy data are restricted to buoys located in the open ocean no closer than 20 km to the coast.

Finally, as part of the validation activities, geostrophic velocities are derived from the GOP SSHA and compared High Frequency (HF) radar surface velocities from four stations around the Australian coast (Bonney Coast, Rottnest Shelf, South Australia Gulfs, and Turquoise Coast) from the Australian Ocean Data Network (https://portal.aodn.org.au/), as well as against geostrophic velocities from the Ocean Surface Current Analyses Real time (OSCAR) (http://www.oscar.noaa.gov). The HF radar data are provided on a fine regular grid with a 1-

hour temporal resolution, whereas the OSCAR data are provided on a 1/3-degree grid with a 5-day temporal resolution.

3.1.2 Main Results

The full results of the CryOcean-QCV are disseminated in daily and monthly reports that are available on the ESA SPPA web server (https://earth.esa.int/web/sppa/mission-performance/esa-missions/cryosat/quality-control-reports/ocean-product-quality-reports). A comprehensive summary of the results has been recently published in Calafat et al. (2017). We provide here some examples to illustrate the level of analysis and validation.

The first example concerns the FDM data products, which are made available as soon as possible after acquisition, normally within 3 hours. This short latency from acquisition to dissemination is essential to enable NRT applications, and is assessed within the CryOcean-QCV reports. For example, Figure 5 illustrates the distribution of FDM data delivery latency for September 2016 and is typical of many of the monthly plots. The majority of data were delivered within 2–3 hours of the middle time of the measurements within the files.

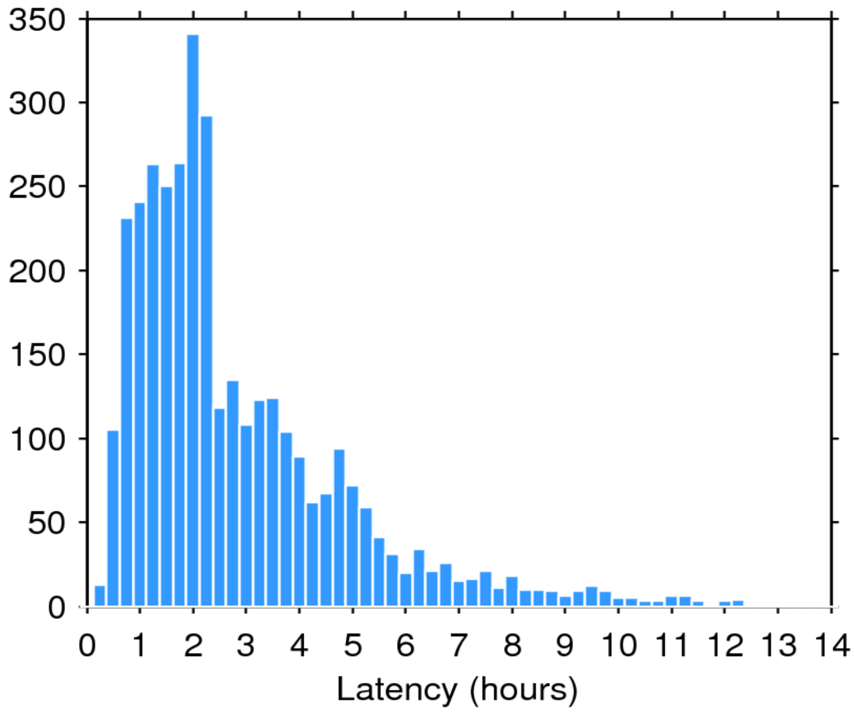

Figure 5: Histogram of the FDM data delivery latency for September 2016. The y-axis shows the number of files that are made available with a delay of x-hours with respect to the mean time of the records stored in the file.

Our second example concerns the SWH, which is an important measurement from satellite altimetry for wave climate studies, the study of extreme events and the validation of wave models. As shown in Calafat et al. (2017), there is a good agreement between SWH from CryoSat and that obtained from the WWIII data. A typical example of the agreement between WWIII and GOP can be seen in the similar distributions of SWH in Figure 6.

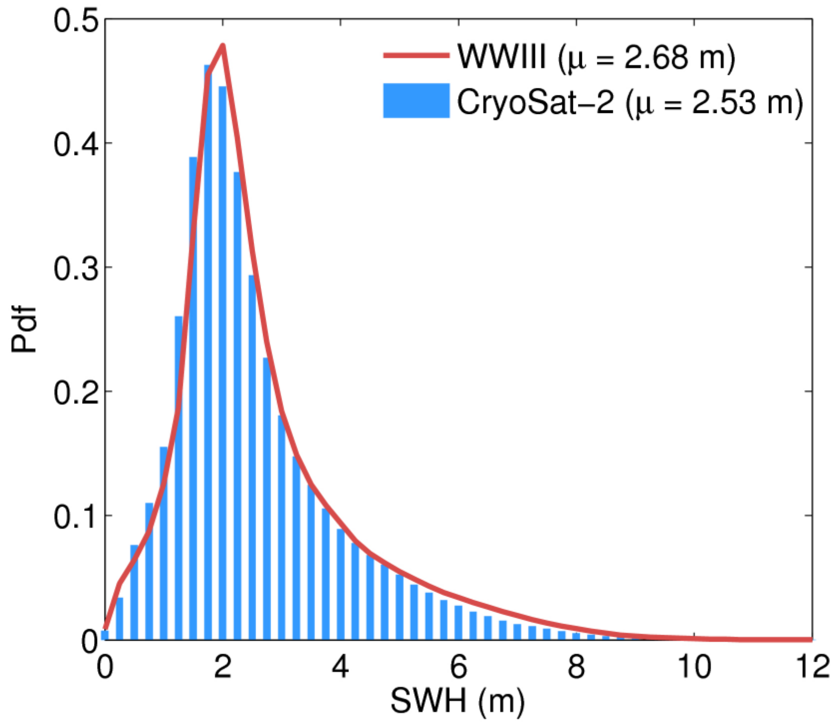

Figure 6: Histograms (normalised to have a total area of 1) of the GOP SWH (blue bars) and the SWH from the Wavewatch III model (red line) for September 2016.

Two examples are used to illustrate the quality of the SSH measurements from CryoSat and the derived geostrophic velocities. Geostrophic currents are calculated as a function of latitude from GOP data within two study regions, one region in the Atlantic Ocean (20˚N – 40˚N, 315˚E – 325˚E) and another in the Pacific Ocean (20˚N – 40˚N, 220˚E – 230˚E). The velocities are calculated using the optimal difference operator by Powell and Leben (2004) and are compared with the equivalent data from OSCAR in Figure 7 for September 2016. With a few obvious exceptions in the Atlantic at lower latitudes and at 33˚N (Figure 7, top), the OSCAR and GOP derived velocities agree in terms of magnitude and direction.

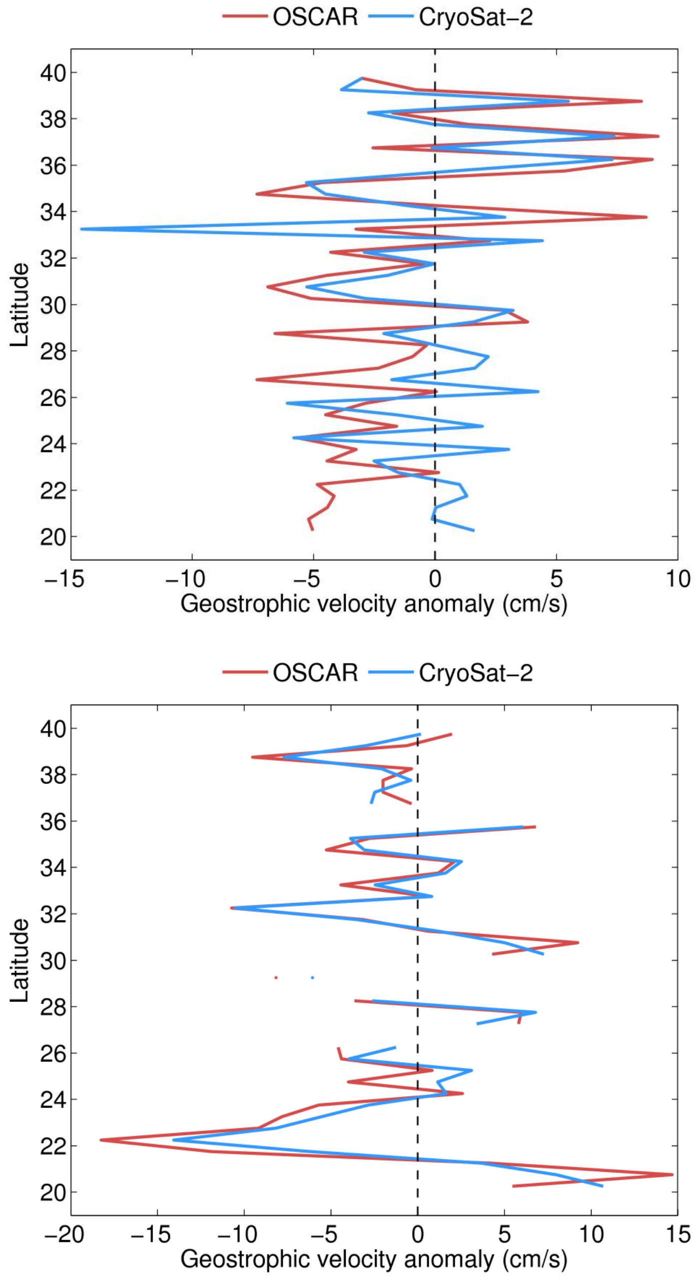

Figure 7: Comparison of the GOP geostrophic velocity anomalies with geostrophic velocity anomalies from the Ocean Surface Current Analyses – Real time (OSCAR) for September 2016 in the Atlantic (top, 20˚N – 40˚N, 315˚E – 325˚E) and Pacific (bottom, 20˚N – 40˚N, 220˚E – 230˚E) boxes as a function of latitude (i.e., for each latitude the geostrophic velocities have been averaged over the longitudes within the box). GOP geostrophic velocities have been computed using the optimal difference operator by Powell and Leben (2004).

The monthly reports produced for CryOcean-QCV include a selection of randomly selected Argo floats for which the steric height anomalies are calculated over the top 1000 m. These anomalies are then compared with the SSHA from GOP data. A sample plot is shown in Figure 8 (top), and the movement of the given float, in this case ID 5904174, is given in Figure 8 (bottom). The GOP SSHAs are calculated by interpolating the ground track data from a 1° by 1° grid, every 10 days in order to match the 10-day cycle of an Argo float.

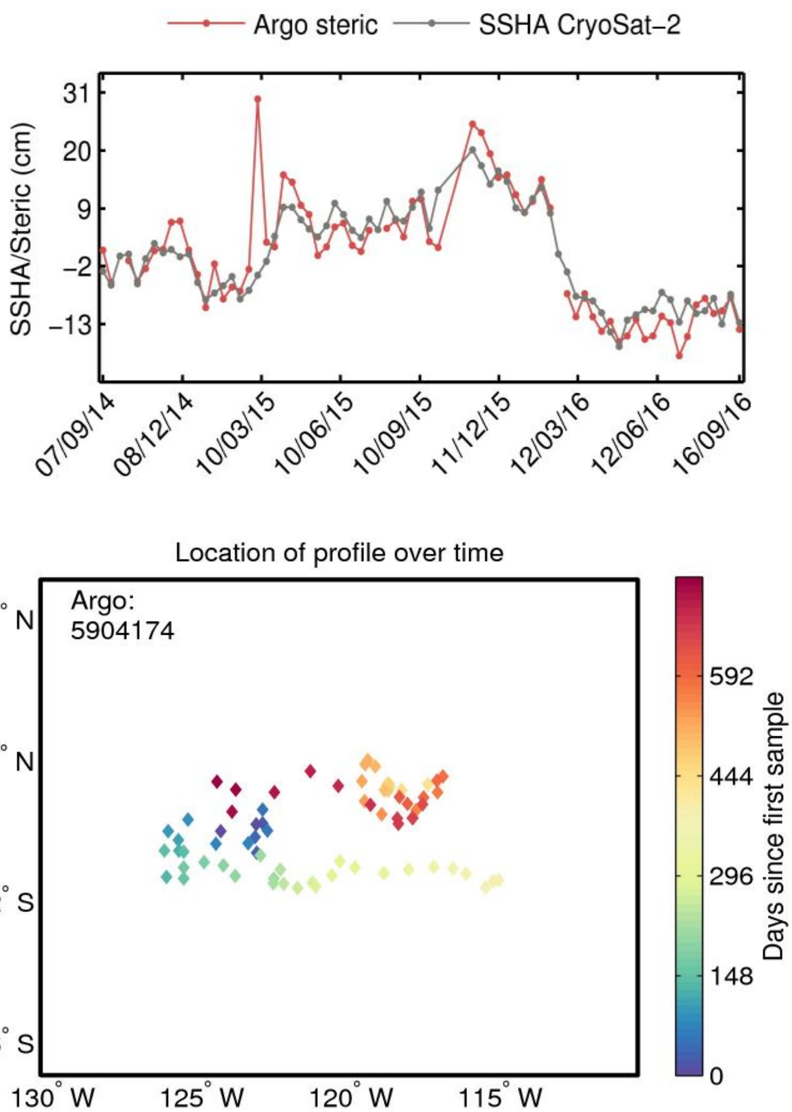

Figure 8 Comparison of the GOP SSHA and the steric height anomaly (referred to 1000 m) for one particular Argo float (top). The location of the Argo float over time (bottom).

In addition to the CryOcean-QCV analysis, which mainly focuses on short-term variability (daily, monthly) and seasonal time scales, complementary analyses are conducted to assess the long-term performance and stability of the GOP and to identify potential drift and bias.

3.2 Long- Term Analysis and Data Quality Stability

3.2.1 Data and Methods

To assess the long-term quality of the CryoSat GOP in comparison with other reference ocean altimetry missions, geophysical parameters such as SSHA, SWH, backscatter (sigma0), and wind speed referenced to 10 m height (U10) are monitored and cross-calibrated. This is done using the Radar Altimeter Database System (RADS) http://rads.tudelft.nl/rads/rads.shtml (Scharroo et al., 2016). RADS is a coordinated effort between EUMETSAT, NOAA, and Delft University of Technology (TU Delft), and constitutes an internationally appreciated validated, calibrated and consistent altimeter data set, comprising over 20 years of sea level products, to help both expert and entry-level users in science and education to apply altimeter information in their own investigations. Since multiple users are involved in examining the data and the regular updates to the database, RADS is one of the most accurate and complete databases of satellite altimeter data to date, and therefore is most suited for referencing and cross-calibrating the CryoSat GOP data. The 1 Hz L2 CryoSat data that are available in RADS, have been constructed from re-tracking L1B LRM data and wherever the instrument is in SAR mode, using the Full Bit Rate (FBR) data to reduce SAR to PLRM (Scharroo et al., 2013; Scharroo, 2014).

The operational Baseline-B GOP L2 data that are analysed here, are distilled from the ESA's ftp server and cover the period from April 2015 to July 2016 and the reprocessed data from February 2012 to April 2015. First, they are stored in subcycles, according to the RADS cycle definition for CryoSat, with the following sequence: 4 times (29+29+27 days) plus 29 days makes 369 days, which is the theoretical repeat cycle for CryoSat. The data are also archived in RADS format, choosing the appropriate data fields to facilitate the cross-calibration with

Jason-2, for example by decomposing the total tide into ocean tide and load tide. The DAC is considered as the total inverse barometric correction (the static low frequency part and the high frequency part of the tidal and atmospheric signal). The square root of the off-nadir pointing is taken, and the orbital altitude, geoid, and mean sea surface are referenced to the TOPEX reference ellipsoid (a=6378136.3 m, 1/f=298.257). The remaining GOP data fields are untreated and copied directly to the corresponding RADS fields. SSHA are calculated and Jason-2 data are chosen for comparison and crossover analyses for the same period (Jason-2 cycles 132 to 294). Table 3 summarises which data fields from the GOP are entered into RADS and describes the treatment of the data. The data are not altered in order to ensure that they remain as close as possible to the original GOP product.

Table 3: The RADS format and the treatment of the L2 GOP data when entered into the RADS. The GOP field numbers are taken from the IOP and GOP Product Format Specification (ACS/ CLS, 2013).

RADS item	Item no.	RADS comment	GOP field	GOP to RADS treatment
Time	101	UTC since 1985-01-01 00:00:00 [s]	1	d*86400+s+μs/1d6+sec00[a]
Lat	201	Latitude [degrees north]	7	*untreated*
Lon	301	Longitude [degrees east]	9	*untreated*
Alt	425	Orbital altitude [m]	11	WGS84 to TOPEX ref.[b]
Alt rate	501	Orbital altitude rate [m/s]	13	*untreated*
Range	601	Instrument corrected altimeter range [m]	21	*untreated*
Dry tropo	701	Dry tropospheric correction [m]	36	*untreated*
Wet tropo	802	Wet tropospheric correction [m]	37	*untreated*
Iono	906	GIM ionospheric correction [m]	40	*untreated*
Inv bar	1002	High-frequency inverse barometric correction [m]	39–38	*untreated*[c]

Inv bar	1004	Total inverse barometric correction [m]	39	*untreated*
Tide solid	1101	Solid earth tide [m]	84	*untreated*
Tide ocean	1213	FES2004 ocean tide [m]	79–83	total ocean tide − load tide
Tide ocean	1219	GOT4.8 ocean tide [m]	78–82	total ocean tide − load tide
Tide load	1313	FES2004 load tide [m]	83	*untreated*
Tide load	1319	GOT4.8 load tide [m]	82	*untreated*
Tide pole	1401	Pole tide [m]	85	*untreated*
SSB	1502	CLS sea state bias [m]	41	*untreated*
Geoid	1610	EGM2008 height [m]	74	WGS84 to TOPEX ref.
MSS	1614	DTU10 mean sea surface [m]	73	WGS84 to TOPEX ref.
MSS	1615	CNESCLS11 mean sea surface [m]	72	WGS84 to TOPEX ref.
SWH	1701	Significant wave height [m]	44	*untreated*
Sig0	1801	Backscatter coefficient [dB]	51	*untreated*
Wind speed	1901	Altimeter wind speed [m/s]	87	*untreated*
Range rms	2002	Std dev of range (20 Hz) [m]	23	*untreated*
Range num	2101	Number averaged 20 Hz ranges [count]	24	*untreated*
Topo	2206	MACESS ocean depth/elevation [m]	75	*untreated*
Peakiness	2401	Peakiness [-]	16	*untreated*
Flags	2601	Engineering flags [-]	90&14	RADS flags (bits 2,4,5,11)
SWH rms	2802	Std dev of SWH (20 Hz) [m]	47	*untreated*
Sig0 rms	2902	Std dev of sig0 (20 Hz) [dB]	53	*untreated*
Off nadir	3001	Waveform off-nadir pointing [degrees]	62	take square root
Ref frame	3801	Reference frame offset [m]	-	- [d]

[a]sec00=473299200 sec. offset to get time relative to 1 January 1985 instead of 1 January 2000

[b]RADS employs the TOPEX ellipsoid definition: a = 6378136.3m, $1/f$ = 298.257

[c]correction used for tide gauges analyses

[d]unknown a priori and therefore not applied initially

SSHA are subsequently created by taking the difference between orbit and range and subtracting all corrections and lastly subtracting a MSS model, as described in *(Eq. 1)*, (*Eq.2)* and (*Eq.3*). For the corrections and models that have multiple options, it is necessary to choose the same correction as is used in the altimeter data you want to compare (Jason-2 in this case).

To validate the ocean sea level data with tide gauge observations the revised local reference data are extracted from the Permanent Service for Mean Sea Level (PSMSL) database at NOC/ Natural Environment Research Council (NERC) (Holgate et al., 2013; PSMSL, 2016). An effort is made to ensure that before comparison both altimetry and tide gauge data have matching physical content by using monthly averaged tide gauge data, thereby filtering out most of the residual high frequency tidal and atmospheric signals. The total ocean tide correction and the high frequency part of the atmospheric signal are applied to the altimeter data, therefore keeping the low frequency static inverse barometer in the altimeter data. Next, monthly altimeter grid solutions are constructed, combining data per month (~1 subcycle), and spatially Gaussian distance weighting gridding with a σ =0.5°, a horizon of 3σ and grid-spacing of 0.25°, and used to produce SSHA time series at the tide gauge station locations. All the available, matching tide gauge and altimeter data were used, and an integer number of consecutive years were analysed to enable the estimation of drift over the years 2013, 2014, and 2015. The tide gauge data available for the chosen time span were selected, reducing the dataset from 1468 gauges to 491. For the next step in aligning the altimetry based SSHA to the tide gauge measurements; only stations with a correlation higher than 0.7 and a standard deviation of $\sigma < 0.1$m were considered. A common bias in the tide gauges, which are referenced to local mean sea level and not to the TOPEX reference ellipsoid, was also removed. The 72-cm offset present in the GOP data prior to February 2015 (see Section 2.2) was also removed, and stations with data gaps were excluded. This reduced the dataset further to 213 gauges, which were used for the following statistical analyses.

3.2.2 Main Results

Within the framework of long-term GOP analysis, orbit crossover analysis was performed on the L2 GOP altimeter data, spanning February 2012 to July 2016. Crossovers were analysed between CryoSat and Jason-2 passes (dual satellite crossovers) and between ascending and descending passes from CryoSat and Jason-2 separately (single satellite crossovers), with a maximum crossover time difference of 15 days; a narrower time interval would leave very few CryoSat crossovers spread non-uniformly over the globe.

The mean crossover differences between CryoSat and Jason-2 passes provide the biases between CryoSat and the calibrated Jason-2. As a reference for both satellites the CNES/CLS11 mean sea surface and the GOT4.8 ocean tide and ocean load corrections are applied. Comparing CryoSat with Jason-2 (CryoSat minus Jason-2) basically gives a range bias with respect to Jason-2. However, for Jason-2, a calibrated range bias with respect to the TOPEX reference ellipsoid is already applied and therefore the mean crossover difference between CryoSat and Jason-2 gives a calibrated range bias for CryoSat. From the statistics, an overall range bias change is observed in February 2015, where the SSHA cycle averages change from minus 72cm (prior to February 2015) to approximately zero (after February 2015) due to configuration changes in the Baseline-B COP baseline (see Section 2). As a result of this change, it was decided to investigate a 1-year period before this date (period 1: 15 June 2013 to 15 June 2014) and a 1-year period after (period 2: 5 June 2015 to 15 June 2016). Table 4 provides the matching overall dual-crossover statistics. Crossovers have been edited to discard SSHA crossover values greater than two times the standard deviation, in order to incorporate only crossovers that are not strongly affected by ocean mesoscale variability. As stated before, the standard criterion t < 2 days would eliminate too many crossovers.

SWH, sigma0 and wind speed have also been included in the crossover analyses. Since the two points evaluated in a crossover analysis can be relatively far apart in time for the time scales at which these parameters can change, it can still be seen that taking the mean of the crossover differences would average out those difference (mean values are close to zero). They do constitute a means of quality checking the parameters. Therefore, it can be concluded that the CryoSat GOP is of the same quality as the CryoSat RADS product and also very close to the calibrated Jason-2. The only striking difference is in the range and the sigma0 biases. This difference should be studied in more detail because the SSB also has a dependency on sigma0.

Table 4: Dual crossover mean and standard deviation from CryoSat and Jason-2 orbit crossovers for SSHA, SWH, σ^0, and wind speed.

	June 2013 until June 2014				June 2015 until June 2016			
	SSHA [m]	SWH [m]	sigma0 [dB]	Wind speed [m/s]	SSHA [m]	SWH [m]	sigma0 [dB]	Wind speed [m/s]
Mean	-0.787	-0.011	-0.780	1.890	-0.067	-0.009	1.155	-3.129
RMS	0.043	1.202	1.806	4.233	0.047	1.253	1.796	4.380

Finally, Table 5 provides for the same data products and data fields the satellite single crossovers (for period 2: 5 June 2015 to 15 June 2016). When edited exactly in the same manner, the SSHA crossover RMS is slightly higher for CryoSat GOP than for CryoSat RADS and Jason-2. We conclude that the GOP product is of similar quality as both CryoSat RADS and Jason-2 RADS. The latter has lower crossover RMS because of its geographically limited coverage up to 66°N and 66°S.

Table 5: Single crossover statistics for CryoSat GOP data, for CryoSat RADS data and Jason-2 RADS data (period 2: June 2015 until June 2016)

	SSHA[m]		SWH [m/s]		sigma0 [dB]		Wind speed [m/s]	
	mean	RMS	mean	RMS	mean	RMS	mean	RMS
CryoSat GOP	0.001	0.063	-0.003	1.259	0.023	2.256	-0.063	4.898
CryoSat RADS	0.005	0.056	-0.035	1.286	0.049	1.995	-0.139	3.996
Jason-2 RADS	0.000	0.040	-0.005	1.235	-0.003	1.650	0.009	3.953

There are two ways to estimate the timing bias, either from crossover minimisation or from the dependency of along-track residuals with the satellite range rate; both give similar results. The envelope of timing biases from crossovers (with a maximum crossover standard deviation multiplied by two and a maximum time gap of 15 days) has been computed for the CryoSat GOP covering the period from February 2012 to July 2016. The overall average timing bias is 0.1 ms, Figure 9 shows the daily estimated values (green), along with the mean crossover difference (red) and RMS (blue). The regression lines suggest a very steady timing bias, and also a stable crossover RMS at around 5 cm. If we exclude the main occurrence of the 72-cm offset in February 2015 and perform a fit to the SSHA crossover mean RMS prior to and after that date, the drift in both cases is smaller than 0.5 mm/ year, indicating a very good stability comparable with the general uncertainty in sea level trend estimates. This conclusion of course assumes that the calibrated reference mission Jason-2 is not drifting. Any similar drifts in one or more of the corrections used would not be revealed by this cross calibration.

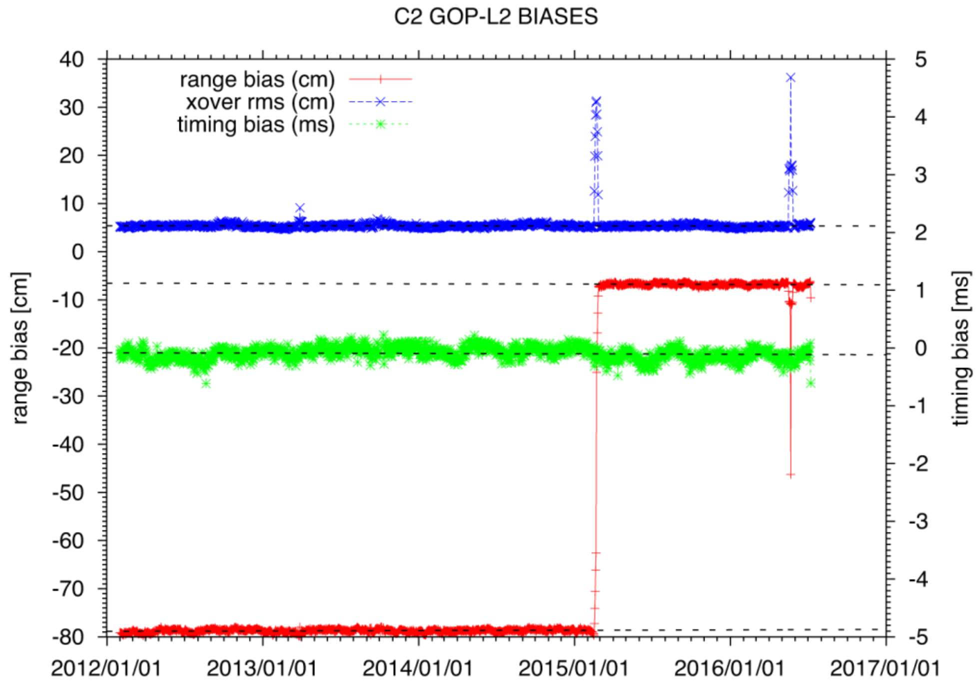

Figure 9: Range bias (red) and timing bias (green) for CryoSat GOP cycles 24 - 81 (February 2012 until July 2016) along with the crossover standard deviation (blue).

After applying the 72-cm bias change (subtracting a 72 cm bias) the comparison is conducted with the 213 selected tide gauges. The result is a mean correlation of R=0.85, a mean standard deviation of σ=5.6 cm, and a mean tilt of the difference of −0.5 mm/year (SSHA – tide gauge), which is comparable with the number found previously for the stability of the range. It is known that certain tide gauges may have problems if they are located on sediment and not bedrock or if they suffer from unknown vertical tectonic motions. However, the screening method adopted should remove most tide gauges affected by these problems. Figure 10 plots the locations of the 213 tide gauge stations used in this study (grey crosses). The blue crosses represent the ten best comparisons when sorted by correlation and the red crosses represent the worst two comparisons when sorted by standard deviation.

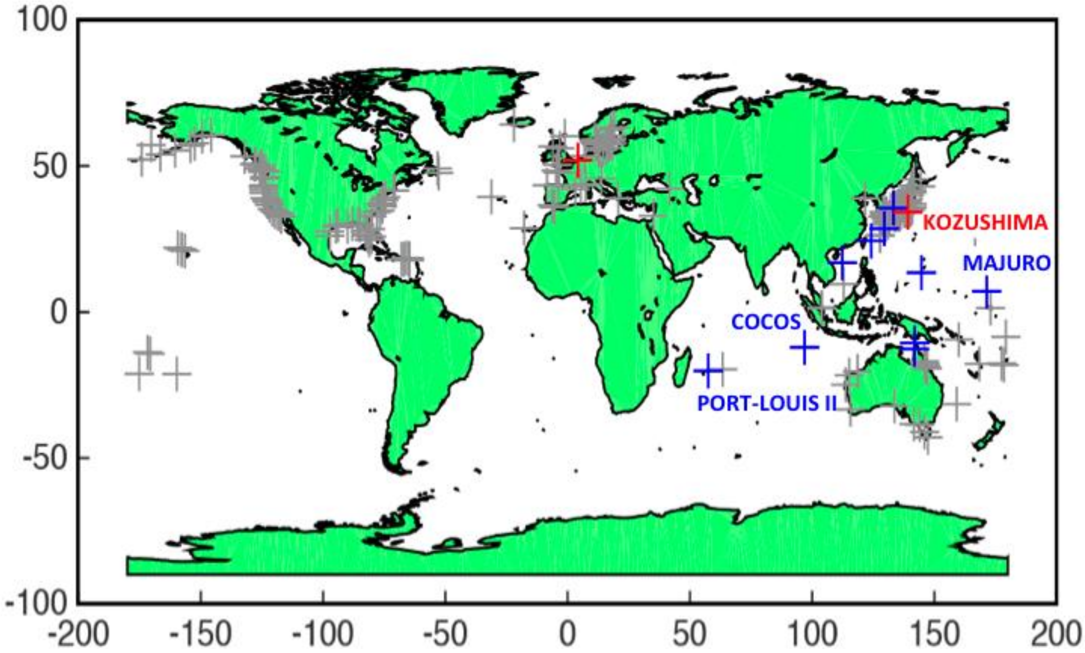

Figure 10: Locations of the 213 PSMSL tide gauge station used in this study (grey). The 10 best solutions sorted by correlation (blue), and the 2 worst solutions sorted by standard deviation (red).

Figure 11 shows the three best solutions in terms of correlation and the worst solution in terms of standard deviation, where the correlation (Co), the standard deviation (St), the bias (Bi), and the trend difference (Sl) are given (refer to Figure 10 for the position of corresponding tide gauges).

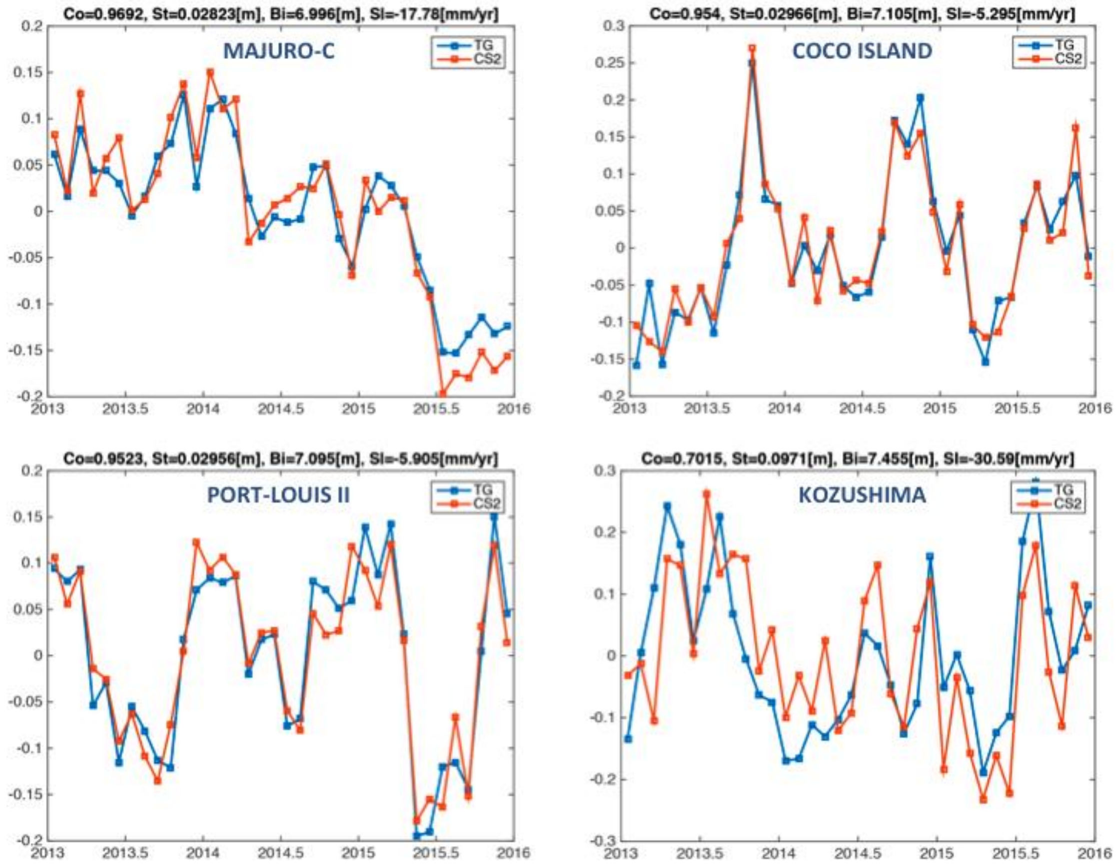

Figure 11: Sea level data comparisons between PSMSL tide gauges (in blue) and CryoSat GOP (red). Locations of the tide gauge stations are reported on Figure10. The top two graphs and the bottom left graph show the three best results in terms of correlation (>0.95) and the bottom right graph shows the worst result in terms of standard deviation (≤ 10 cm). The graphs are each annotated with the correlation (Co), the standard deviation (St), the bias (Bi), and the trend difference (Sl).

In summary, the long-term analysis of CryoSat GOP shows a steady timing error of 0.1 ms, and a stable range bias of 6.7 cm with no marked drift with respect to calibrated Jason-2 (TOPEX reference ellipsoid and reference mission). These results obtained over the ocean are perfectly consistent with the results deduced from external calibrations performed on the ground at the Svalbard transponder, which also show very stable values (see Bouffard et al., 2017; this issue). When validated against 213 selected PSMSL tide gauges, covering the period 2013-2015, the altimeter data have a correlation R=0.85, a mean standard deviation σ =5.61 cm, and a drift of −0.54 mm/year, again showing very stable measurements and no marked drift in the reference frame. Considering that TU Delft's orbit solutions and laser residuals RMS are 0.4 mm/s and 1.27 cm, respectively and that they match the CNES POE (used in GOP) to within 1.5 cm radially, without showing any drift (Schrama et al., 2016; Schrama, 2017), the final conclusion is that the CryoSat GOP Baseline-B are comparable with the reference missions. Complementary analyses on reprocessed and upgraded GOP datasets (Baseline-C, see Section 4) are planned for 2018, in order to extend our results over a larger period and therefore confirm that the CryoSat ocean products would represent a valuable addition to long-term climate studies

4 Brief Overview of CryoSat Ocean Processing Evolutions

ESA are continually working to improve the quality and scientific value of the CryoSat ocean products, by implementing improvements to the processing chains. Work is currently underway to test and implement the latest version processors, the COP Baseline-C. The Baseline-C upgrade concerns both the L1B and L2 processing chains and is expected to bring significant improvements to the quality of L1B and L2 products relative to the previous Baseline-B products. The new processors will generate ocean products for all data acquisition modes (LRM, SAR and SARIn), therefore providing complete data coverage for ocean users. The upgrade will add innovative algorithms to the ocean chains and refine some of the already implemented ones, and will add a number of new parameters and corrections to the products. Some of the expected evolutions are briefly described below. Routine distribution of the COP Baseline-C is starting in November 2017 (see Figure 4).

4.1 New NetCDF and Pole-2-Pole Ocean Product Format

In order to ensure the homogeneity with other altimetry missions and to maximise the uptake and use of CryoSat data by scientific users, ESA are currently upgrading the existing processing chains in order to distribute all CryoSat products in NetCDF format compliant with the Climate and Forecast Convention (http://cfconventions.org). NetCDF is considered to be more user-friendly than the Baseline-B COP Earth Explorer format, with data stored in a way to allow efficient subsetting. Interfaces to NetCDF are based on the C library and are available in numerous languages (e.g. Matlab, IDL, Python, Octave), therefore enabling a wide range of software applications to read NetCDF files. Moreover, the Baseline-C COP will generate new L2 Pole-to-Pole (P2P) products for IOP and GOP. Two P2P products will be generated per orbit, combining successive products spanning between the North and South poles into multi-mode concatenated products.

4.2 New Near Real Time Ocean Products

The COP architecture was initially designed so that it could be easily adapted to generate L1B and L2 products in NRT with an approximate latency of 3 hours from data acquisition. In particular, the COP is already able to use the Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) Navigator Orbit (Jayles et al., 2015). Nevertheless, the current Baseline-B COP configuration requires some adaptations to generate NRT Ocean Products (NOP). Numerous evolutions will be implemented to significantly improve the quality of the NOP with respect to the current FDM products generated by the Ice processor, such as the integration of full SAR delay-Doppler processing (see Section 4.2) and the addition of new ad-hoc corrections. As a result, the NOP is intended to replace the FDM products in mid- 2018.

4.3 Full Ocean Delay-Doppler Processing

ESA's SAR Altimetry MOde Studies and Applications (SAMOSA) retracker algorithm (Cotton et al, 2016) is being implemented and tested within the Baseline-C COP L2 processor. For this, the SAMOSA retracked SAR and SARIn waveforms are generated using new processors, which build on the Ice processor heritage but are correctly reconfigured for ocean applications. The SAMOSA retracker computes the 20 Hz epoch, amplitude, SWH and wind speed for SAR and SARIn (without using phase information). The 20 Hz altimeter range is then derived from the computed epoch and from the retracker range. The backscatter coefficient is derived from the computed amplitude and a scaling factor derived from the orbits and Automatic Gain Control (AGC) values. 1 Hz altimeter range, SWH and backscatter coefficients are also computed, simply by averaging the 20 Hz parameters. The SAMOSA derived 1 Hz and 20 Hz parameters are generated together with the PLRM parameters using the MLE-4 ocean retracker not only for SAR (as in COP Baseline-B) but also for SARIn patches. Therefore, the format of the L2 NOP, IOP and GOP products will be updated to include all these new fields.

4.4 New Range and Geophysical Corrections

The Baseline-C COP products will include several new range and geophysical corrections, such as improved ocean and loading tidal corrections from the recent FES2014 and GOT4.10 (Zawadzki et al 2016; Carèrre et al. 2016; https://datastore.cls.fr/catalogues/fes2014-tide-model/) as well as the updated MSS from CNES (MSS_CNES_CLS15) and DTU (DTU MSS15). Since CryoSat does not carry an on-board microwave radiometer, one of the major COP upgrades concerns the inclusion of an improved wet tropospheric correction. The algorithm developed by the University of Porto, in the scope of the ESA CryoSat Plus for Ocean (CP4O) project, combines external wet path delay data from multiple sources by space-time objective analysis. More details on the approach can be found in Fernandes and Lazàro (2016).

5 Conclusions and Perspectives

The quality control and validation activities performed by ESA with the support of the NOC, TU Delft and IDEAS+ demonstrate that the CryoSat ocean products compare very well with *in situ* measurements and model outputs and, in spite of the short analysed periods, do not show any significant drift over time. The results confirm that the ocean products are comparable with reference ocean-oriented altimetry missions (e.g. Jason-2) and are perfectly suited for oceanographic applications.

The crossover analyses of GOP already revealed a very stable monitoring system capable of contributing to the Global Climate Observing System (GCOS) Essential Climate Variables (ECVs). ESA will continue to track possible biases, drifts and jumps in the data, and try to identify the potential causes and implement improved corrections. Another exercise will be to investigate the transitions from SAR to LRM and vice versa. Suggestions for improving sigma0 and wind speed could lead to reduced crossover RMS together with a tailored SSB correction. Concerning the tide gauge comparisons; the analyses will be extended to include inter-comparisons with Jason-3 data and updated CryoSat RADS data.

The quality control and validation tools are currently being upgraded to accommodate the upcoming processor upgrades to COP Baseline-C, as described in Bouffard (2016) and Bouffard et al. 2017 (this issue). The tools will be adapted to ingest the new L1B and L2 products in NetCDF format, including the new NOP and GOP and IOP P2P products from the ocean processor. In terms of product content the main changes concern the addition of native SAR/SARIN data over the relevant regions in the geographical mode mask, and a number of new parameters including updated geophysical corrections. These changes are expected to further improve the quality of the CryoSat ocean products and further promote their application to a broad range of oceanographic and climate studies.

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*Detailed Response to Reviewers
Click here to download Detailed Response to Reviewers: ASR-BOUFFARD-Reply-2-reviewers-R#2-FINAL.pdf

Point-by-point responses to the Editor & Reviewers' comments

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Manuscript: ASR-D-17-00195R1

CryoSat Ocean Product Quality Status and Future Evolution

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We would like to thank both reviewers and editor for their constructive reviews of our manuscript, which have provided us with an opportunity to strengthen the paper. In the following, we provide response to the additional minor comments raised. For clarity, in the material below any text from the reviews has been italicized in black whereas our responses are in blue. We have revised the manuscript, corrected remaining spelling/typos, updated references and implemented all the suggested improvements.

Comments from Reviewer#2

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Manuscript. ASR-D-17-00195R1
Title: CryoSat Ocean product Quality Status nd Future Evolution
Authors; Bouffard, J., et al.

Summary:
The revision of this manuscript has resulted in a very well-written and clear paper. The new paper will be extremely valuable for users of cryosat ocean products. I congratulate the authors especially on the exceptional clarity of the introduction (section 1).

The authors very extremely thorough in responding to the comments of the reviewers from the first version of the paper. As far as I'm concerned I have no further technical comments on the manuscript, and I recommend "Accept pending minor reviosion", as there are a few syntactical issues, clarifications of acronyms, and possible updating of one image that are probably still necessary.
We thank the reviewer#2 for her/his very positive assessment of the contribution of our article.

Minor Comments.

1. figure 1. I suggest to try and improve the quality of Figure 1. It is a bit hard to see the ground tracks.
Figure 1 has been redrawn, improved and splinted into 2 sub-plots: one shows the CryoSat ground tracks (in large black lines instead of thin white lines) whereas the other shows the geographical mask version 3.9. Moreover the resolution of the Figure has been enhanced.

2. "delay-Doppler". Please be consistent throughout the manuscript to use the hypen for this term.
OK done. The term "Delay-Doppler" with the hyphen has been used throughout the manuscript.

3. pp. 6 line 18. "taking on board requests" --> "considering requests"
OK. Modification done as suggested.

4. Figure 2. Not all terms referenced in the Figure have been defined.
e.g. LRM_1, LRM2, LRM_2, etc.

The caption has been updated by defining all terms referenced on Figure 2.

5. pp. 8 line 37. "quality assessment of the GOP Level 2 data are " --> "quality assessment of the GOP Level 2 data is"
OK done, sentence rephrased accordingly.

6. pp. 8 Lines 37-46. The first sentence of that paragraph is a run-on sentence. The usual solution for a run-on sentence is rework the material into shorter, crisper sentences.
As suggested, this section has been rephrased and splinted into shorter sentences

7. pp. 9. Line 35. "so-called" --> Please Delete this adjective. It has a rather connotation.
This adjective has been deleted

8. pp. 9. MLE4 processing. If possible, can a reference be supplied for this waveform processing standard?
Reference to Amarouche et al. (2004) has been added

9. Table 2., pp14 Re ECMWF. Which ECMWF version was used? Operational or Re-analysis? 3hr or 6hr?
Information added in Table 2: "Operational model at its highest spatial resolution (1/8º), 6-h interval"

10. Table 2. pp. 15. Carrere -> Carrère
OK. Typo corrected

11. pp. 22 line 18. "what treatment of the data has been" -> "what was the treatment of the of the data" Possibly Last part of sentence modify to the following for clarity " ... The data are not altered in order to ensure they remains as close as possible to the original GOP product."
OK. Part of the sentence modified accordingly

12. Re Figure 11. I suggest to cite the names of the tide gauges and GLOSS tide number in the caption for the four sites that are shown.

Do the authors mean the tide gauge at the Japanese city of "Kozushima"? If so the heading of that sub-figure might need to be updated.
The positions of the 4 selected tide gauge stations are reported on Figure 10, the Japanese city name has been corrected as suggested and the caption of Figure 11 has been updated.

13. pp. 32., top paragraph.
Re the DORIS Navigator Orbit a possible citation for the near-real time orbits would be the following (unless Jayles et al. wrote a Cryosat-2 specific paper) "DORIS/DIODE: Real-Time Orbit Determination Performance on Board SARAL/AltiKa" Jayles, C., J-P. Chaveau, A. Auriol, Marine Geodesy, 38(S1), 233-248, 2015, doi: 10.1080/01490419.2015.1015695.

There is also a Jayles et al. (2010, Adv. Space Res) reference that might be pertinent although those results in this paper predate the work on Cryosat-2.
Suggested reference (Jayles et al., 2015) added.

14. pp. 32, top paragraph. "preliminary meteorological files" I'm not sure what is meant by this. from DORIS or another source? Maybe it is best to excise this phrase if the explanation would be too involved.
We agree. Reference to "preliminary meteorological files" removed in the updated manuscript.

Comment from Reviewer#3

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Reviewer #3: Second review of the paper
Manuscript Number: ASR-D-17-00195
Title: CryoSat Ocean Product Quality Status and Future Evolution

General assessment

The paper aims at reporting the status of the ESA CryoSat altimeter satellite ocean products, give an overview of associated quality control and validation activities and present the ongoing and future developments. As stated in my first review, this type of paper is very useful to gather information that often is spread in many technical reports and a relevant complement to more scientifically oriented papers that present more detailed validation studies.

The topic is scientifically relevant, as the COP includes up-to-date and ocean-oriented algorithms and corrections, bridging the gap between previous and future ocean missions as well as contributing to a better knowledge of ocean and in particular polar circulation.

The revised version accounts for most of the suggested corrections in my previews review and also for some pertinent comments from another reviewer, which altogether improved the quality and clarity of the paper. Therefore, I suggest its approval for publication in ASR, subject to the minor points listed below.

The authors would like to thank the reviewer#3 for this positive assessment. We accepted most of the suggestions made and changed the manuscript accordingly. Our point-by-point responses are presented below.

Detailed minor corrections

Page 10, line 35-This done -> This is done
OK done

Page 14, line 5 - IDEAS+ performs routine QC activities on all operational CryoSat products, which includes - > IDEAS+ performs routine QC activities on all operational CryoSat products, which include
OK. Modification done.

Page 15, line 5 - minimum and maximum thresholds for the range corrections - > minimum and maximum thresholds for the range and geophysical corrections
OK. Modification done.

Page 15, line 25 - Also refer the SSB model used.
OK done: LRM/PLRM: CLS model (Tran, 2012)

Page 17, line 30 - NOAA/National Centres for Environmental Protection (NCEP) -> NOAA/National Centres for Environmental Prediction (NCEP)
OK. Modified accordingly.

Page 22, line 53 - First they stored - First they are stored
OK. Sentence modified accordingly

Page 22, line 29 - Since the Cryosat orbit does not have an exact repeat cycle, as discussed in the introduction, in the sentence "exact repeat cycle for CryoSat" either write "exact" or

remove this word.
OK. The word "exact" has been removed and replaced by "theoretical" in the revised version.

Page 26, line 46 - Remove the word "minus" or the signal "-"in minus -72cm. If you wish to emphasize that is negative please use for example "the negative value - 72 cm"
OK "-" removed.

Page 29, lines 40, 41 - please clarify the sentence: "Please note that the difference (of what?) is analysed, so any 'natural' sea level rise would be measured by both tide gauge and altimeter and cancel out."
This sentence has been removed to avoid potential confusions.

Caption of Figure 10 - remove repeated word "locations": station locations -> stations
OK the word "locations" has been removed

Page 31, line 44 - The analysed periods of one year do not allow proper conclusions about the long term stability of the instrument. A note on this should be added, emphasising that this should be performed using data since the beginning of mission.
The sentence has been reformulated in order to address the reviewer comment:" *the CryoSat GOP Baseline B are comparable with the reference missions. Complementary analyses on reprocessed and upgraded GOP datasets (Baseline C, see section 4) are planned for 2018, in order to extend our results over a larger period and therefore confirm that the CryoSat ocean products would represent a valuable addition to long-term climate studies."*

Page 32, line 12 - please update this sentence according to the most recent developments.
The sentence has been updated as suggested: "Routine distribution of the COP Baseline-C is starting in November 2017". Moreover Figure 4 has been also updated by including the COP Baseline C on the scheme.

Page 33, lines 57, 58 and page 35, line 11 - to be consistent with the rest of the paper use "range and geophysical corrections", as the wet tropospheric correction is a range and not a geophysical correction. Range corrections are range errors due to the interaction of the radar signal with the atmosphere and the sea surface. dry, wet, iono and SSB; tides and DAC are geophysical corrections, since these do not model errors in the measured range but rather refer to specific geophysical phenomena.
We fully agree with this comment. Modification done

Page 34, line 39 - "and do not show any significant drift over time" -> suggest to add "and, in spite of the short analysed periods, do not show any significant drift over time"
OK. Modified accordingly.

Comments from the editor
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Both reviewers were impressed with this revision; thank you for taking such care with this version.
This has been achieved thanks to the involvement and joint efforts of all co-authors. We are indeed convinced that this paper could be a key reference for the CryoSat Ocean users.

I still have some problems with a few references, particularly those apparent presentations that may (or may not) have been published. Here is a list of what I noted.
The reference list has been carefully revised, completed and updated as necessary.

Andersen, O. B., and Knudsen, P. (2010). The DTU10 mean sea surface and mean dynamic topography - Improvements in the Arctic and coastal zone. In: Ocean Surface Topography Science Team Meeting, October 2010, Lisbon, Portugal.

If this is just a presentation, please say "presentation at ..."
OK "Presentation at" added when appropriated

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Andersen, O. B., Knudsen , P., Stenseng, L. (2015). The DTU13 MSS (mean sea surface) and MDT (mean dynamic topography) from 20 years of satellite altimetry. In: Jin, S. and Barzaghi R. (eds) IGFS 2014. International Association of Geodesy Symposia, Volume 144, Springer , 111-121, doi: 10.1007/1345_2015_182

The publisher's city should be included.
OK. The publisher's city ("Berlin") has been added

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Bouffard, J., F??m??nias, P., Parrinello T. and Bojkov B. (2016). CryoSat Mission: Data Quality Status and Next Product Evolutions, 4th CryoSat User Workshop, 9-13 May 2016, Prague, Czech Republic: ESA.

Again, is this just a presentation? If so, please cite it as a presentation.
OK "Presentation at" added

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Carr??re L., F. Lyard, M. Cancet, A. Guillot, and N. Picot, (2016). FES 2014, a new tidal mode - Validation results and perspectives for improvements. In: Proceeding of the ESA Living Planet Conference, 9-13 May 2016, Prague, Czech Republic: ESA.

This implies a publication. Please cite page numbers or paper number. If only on a CDROM please list this also. If only on the internet (and not printed), please give the www address.
This paper is an oral presentation of the Living Planet Symposium. The associated content is however not accessible in the proceeding (CD ROM, http://www.spacebooks-online.com/product_info.php?cPath=104&products_id=17659).

The FES2014 details and access to model outputs are accessible on https://datastore.cls.fr/catalogues/fes2014-tide-model/
This Web address has been added in section 4.5 of the manuscript and the reference has been changed into "Carrère L., F. Lyard, M. Cancet, A. Guillot, and N. Picot, (2016). FES 2014, a new tidal mode - Validation results and perspectives for improvements.

Presentation at the ESA Living Planet Conference, 9-13 May 2016, Prague, Czech Republic."

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Cotton, P. D., Andersen O., Berry, P., Cipollini, P., Gommenginger, G., Martin-Puig, C., Stenseng, L., Benveniste, J., and Dinardo, S., (2010). The SAMOSA Project: Assessing the Potential Improvements offered by SAR Altimetry Over the Open Ocean, Coastal Waters, Rivers and Lakes. In Proceeding of the ESA Living Planet Symposium, 28 June - 2 July 2010, Bergen, Norway: ESA.

Same as the previous reference.
This publication has been replaced by a more recent one, including the www address to access to the manuscript (published in *Proceeding of the ESA Living Planet Symposium*, CD ROM, no page number):
Cotton, P. D., O. B. Andersen, L. Stenseng, F. Boy, M. Cancet, P. Cipollini, C. Gommenginger, S. Dinardo, A. Egido, M.J. Fernandes, P. Nilo-Garcia, T. Moreau, M. Naeije, R. Scharroo, B. Lucas, and Benveniste J. (2016). Improved Oceanographic Measurements with CryoSat SAR Altimetry: Results and Roadmap from ESA CryoSat Plus for Oceans Project. In *Proceeding of the ESA Living Planet Symposium*, 9-13 May 2016, Prague, Czech Republic, ESA Special Publication SP-740 (CD-ROM), 2016. http://www.satoc.eu/projects/CP4O/docs/0519cotton%20_CP4Oroadmap.pdf

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Naeije, M., Schrama, E., and Scharroo, R. (2011). Calibration and validation of CryoSat-2 low resolution mode data. In: Proceedings of the CryoSat Validation Workshop, 1-3, ESA Special Publications: ESA/ESRIN, SP-693.

Do you have page numbers or paper number?
Paper published in *Proceeding of the CryoSat Validation Workshop* (CD ROM, no page number). The reference has been updated as follow:

Naeije, M., Schrama, E., and Scharroo, R. (2011). Calibration and validation of CryoSat-2 low resolution mode data. In *Proceedings of the CryoSat Validation Workshop*, 1-3 February 2011, ESA Special Publication SP-693 (CD ROM).

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Scharroo, R., E. Leuliette, M. Naeije, C. Martin-Puig, and N. Pires (2016). RADS Version 4: An Efficient Way to Analyse the Multi-Mission Altimeter Database. In: Proceedings of the ESA Living Planet Symposium, 9-13 May 2016, Prague, Czech Republic: ESA, ESA-SP 740, .428.

I assume 428 is a paper number but is there something missing between the comma and period (740, .428)?
Same as previously (CD ROM). The reference has been updated as follow:
Scharroo, R., E. Leuliette, M. Naeije, C. Martin-Puig, and N. Pires (2016). RADS Version 4: An Efficient Way to Analyse the Multi-Mission Altimeter Database. In *Proceedings of the ESA Living Planet Symposium,* 9-13 May 2016, Prague, Czech Republic, ESA Special Publication SP-740 (CD-ROM).

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