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CryoSat: ESA's ice mission – Eight years in space

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Abstract

CryoSat-2 is a satellite of the European Space Agency that was launched in April 2010. It is intended to monitor changes in the thickness of the marine ice, floating in the polar oceans, and to measure variations in the thickness of the vast ice sheets that overlie Greenland and Antarctica.

The CryoSat-2 satellite has replaced the original CryoSat, which became lost due to a launch failure in October 2005.

CryoSat-2 carries an innovative radar altimeter called SIRAL (Synthetic Aperture Interferometric Altimeter). It has two radar antennas, which met the measurement requirements for ice-sheet elevation and sea-ice freeboard with unprecedented accuracy. The satellite orbits the planet at an altitude of around 720 km with a retrograde drifting orbit inclination of 92° and a "quasi" repeat cycle of 369 days (30 days sub-cycle). CryoSat-2 is therefore able to reach latitudes up to 88° covering more than 4.6 million km^2 of unexplored areas over the poles when compared with previous polar missions carrying an altimetry.

The mission has achieved its prime objectives and is delivering high quality data, providing unique contributions to several Earth Science and applications domains, including ice, ocean, geodesy and hydrology, both at global and regional scales.

The purpose of this paper is to provide a general overview of the mission and of its main scientific achievements after eight years in space.

Keywords: CryoSat; Altimetry; SIRAL; Sea-ice; Land ice; Marine; Earth Explorers

1. Introduction

CryoSat was the second mission to be selected in 1999 as part of the European Space Agency's Earth Explorer Programme, set up to develop research missions and to address key Earth scientific challenges identified by the science community, while demonstrating new technology in observing techniques (CryoSat Science Report, 2003).

The satellite was launched in the afternoon of the 8th April 2010 by a Russian Dnepr rocket from Bajkonour Cosmodrome in Kazakhstan, four and half years after the original CryoSat satellite was destroyed in a launch failure of a Russian *Rockot* over the North Pole. The current satellite is therefore CryoSat-2; however, the mission is known as CryoSat.

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CryoSat-2 orbits the planet at an altitude of around 720 km with a retrograde orbit inclination of 92° and a "quasi" repeat cycle of 369 days (30 days sub-cycle). The orbit is not sun-synchronous and allows the orbit plane to drift naturally around the sun direction for about 0.75°/day. This orbit selection offers high-density coverage over the Polar Regions while allowing sufficient measurements down to the south of Greenland. The satellite is able to reach latitudes up to 88° covering more than 4.6 million km^2 of unexplored areas over the poles when compared with previous polar altimetry missions like ERS1/2, ENVISAT and current ones like Sentinel-3.

2. Scientific objectives

The CryoSat mission was designed to contribute to the resolution of many debatable environmental issues related to global warming and its effect on the cryosphere (Wingham et al., 2006). It has two important scientific goals:

(1) To determine the regional and basin-scale trends in Arctic sea-ice thickness and mass
(2) To determine the regional and total contributions to global sea level of the Antarctic and Greenland ice sheets.

CryoSat's secondary scientific objectives goals include measurements of the seasonal cycle and inter-annual variability of Arctic and Antarctic sea-ice mass and thickness, and the determination of variation in the thickness of the world's ice caps and glaciers.

As one of the flying satellites of ESA's Earth Explorers fleet, CryoSat is therefore the first European ice mission which has the objective to measure changes in the Earth's ice masses over different spatial scales (Table 1).

CryoSat was conceived to ensure that at the end of its operational lifetime (3.5 years), the residual uncertainty in ice trends was no more than 10% greater than the limit of its natural variability. This leads to the mission performance requirements in Table 1.

The performance of the mission was achieved during its initial programmatic lifetime (e.g. 3.5 years after launch) and continues after eight years in flight to deliver high quality data, providing unique contributions to several Earth Science and applications domains, including ice, ocean, geodesy and hydrology, both at global and regional scales.

3. Satellite and science instrument

CryoSat's main payload is a radar altimeter called SIRAL, which stands for **S**ynthetic Aperture Radar and **I**nterferometric **R**adar **AL**timeter. The altimeter is derived from the conventional pulse-limited altimeter called Poseidon-2 onboard the US-French Jason-1 mission. SIRAL is a single-frequency Ku-band radar (13.575 GHz). The design of SIRAL is nevertheless fundamentally different compared to previous conventional pulse limited altimeters as it is able to obtain high-resolution SAR and SARIN waveforms exploiting the phase coherence of the echoes. The SIRAL altimeter flying on CryoSat is thus the precursor of a new generation of high-resolution altimeter systems like those flying today on Sentinel-3 and Sentinel-6.

The altimeter can be operated in three main modes:

(a) In Low Resolution Mode (LRM). A conventional pulse-width-limited altimeter, which offers continuity with earlier altimeter missions such as ERS and ENVISAT. This mode is primarily used both over flat ice sheet regions of Greenland and Antarctic and over the oceans.
(b) In Synthetic Aperture Mode (SAR). It improves the along-track resolution, allowing the distinction of the narrow leads of open water between sea-ice floes. This mode is in fact primarily used over sea-ice (Fig. 1).
(c) In dual-channel synthetic aperture/interferometric (SARIn) mode. Used primarily at the edges of the major ice sheets this mode provides improved along-track resolution of SAR, which is further enhanced by the receiving channel of the second antenna. Both antennae are identical and mounted side-by-side, forming an interferometer in the across-track direction. The combination of the two receiving signals allows the derivation of the angle of arrival of radar echoes in the across-track direction and therefore, a precise identification of the location from which the echo is generated.

Since the start of the mission, the above operational modes have also been used over areas not originally foreseen. This has been considered necessary in order to fulfil a number of scientific requirements that are not directly linked to the cryosphere (Section 5.3). For example, SAR data over oceans has been helpful for the definition of

Table 1
The CryoSat science and measurement requirements (CryoSat Science Report, 2003).

	Sea Ice 10^5 km^2	Ice Sheets Regional scale 10^4 km^2	Ice Sheets 13.8 10^6 km^2
Minimum Latitude (deg)	50	72	63
Mission Requirement	3.5 cm/a	8.3 cm/a	1.0 cm/a (130 Gt/a)
Measured	<3.0 cm/a (Ricker et al., 2014)	<4.8 cm/a (McMillan et al., 2014a)	<0.2 cm/a (McMillan et al., 2014a)
SIRAL Mode	SAR	SARIn/LRM	SARIn/LRM

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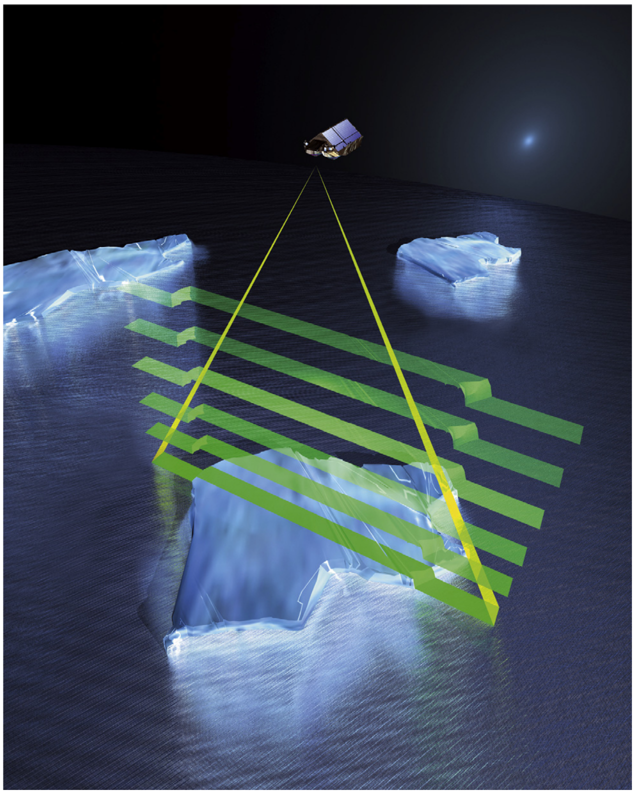

Fig. 1. SIRAL SAR mode over ice floes. Credits (ESA).

the Copernicus Sentinel-3 mission. Currently, a number of applications related to hydrology and oceanography are exploiting successfully the benefits of SAR and SARIN measurements when compared to conventional altimetry.

SIRAL measures the distance from the satellite to the surface with an uncertainty of just a few tens of centimetres. Thanks to the high-density sampling, many measurements are averaged. This brings the system's performance to the level needed to satisfy the mission objectives. The exact position of the satellite at the time of each measurement is needed to convert this simple measurement of range into something scientifically meaningful that is the height of the surface above some known reference. To achieve this, CryoSat-2 flies a DORIS Receiver, a special radio receiver that picks signals up from a network of more than 50 transmitting stations evenly spread around the Earth. By measuring the Doppler shifts of these signals, the *Range-Rate* can be determined. The DORIS receiver is added to a passive laser retro-reflector, which allows precise range measurements to be taken by ground-based laser-ranging stations.

The final item in this collection of high-precision payload equipment is a set of three identical Star Trackers, which are also the principal three-axis attitude measurement sensors of the satellite in normal operation mode. The Star Trackers are required to complement the SIRAL interferometer measurements and identify the baseline orientation with high accuracy, which is mandatory information for the interferometric processing. They are lightweight, low-power-consuming, fully autonomous devices. They are accommodated so that the Sun and Moon can each blind only one head at any time; this makes the whole sensor system single-failure tolerant. Recently, this has been upgraded to a new on-board software.

CryoSat-2 has virtually no moving parts with the only exceptions being a couple of valves in the propulsion system. The Attitude and Orbit Control System (AOCS) is in fact where the absence of moving parts is particularly evident, where gyroscopes and reaction wheels are usually commonplace.

As mentioned, the Star Trackers are the main systems that provide real-time measurements of the satellite's orientation with reference to the stars and together with DORIS time and orbit information allows the on-board software to calculate the satellite's orientation with respect to the Earth (Fig. 2).

Scientific measurements require the production of torques to turn the satellite and keep pointing to the Earth within the required tolerance. CryoSat's main means of generating such torques is to use electromagnets (magneto torques) interacting with the Earth's magnetic field. Finally, a small set of cold-gas thrusters of 10 MN guards against excessive pointing errors and provides the necessary yaw steering rotation.

The attitude-control system has other sensors that are used in case of emergencies. These include an ingenious Earth-Sun sensor, which measures the difference in temperature between a black and a mirrored surface on each face of the satellite. From these inputs, the on-board software calculates the direction with respect to the Sun and the Earth.

4. Mission operations

4.1. Space and ground segment

After eight years in orbit, the status of the satellite is very good. Funds for operating the mission have been approved until the end of December 2019 and a further extension will be proposed to extend it until end of 2021 within the current Earth Observation Envelope Programme (EOEP-5). With the exception of the power subsystem, which had to be switched to its backup system in October 2013, all other satellite subsystems are on the their initial primary hardware. The on-board consumables are sufficient to operate the satellite until at least 2025.

To maintain a reference orbit with an equidistant node crossings distribution and 1 km tolerance at equator, orbit housekeeping manoeuvres are required on average once a month but more often during periods of high solar activity. They are always performed to minimise impact on data return and sometimes in conjunction with Collision Avoidance Manoeuvres, required to avoid space debris in collision trajectory. The mission was originally not designed to manoeuvre away from space debris. However, the improvement of the space debris monitoring network and

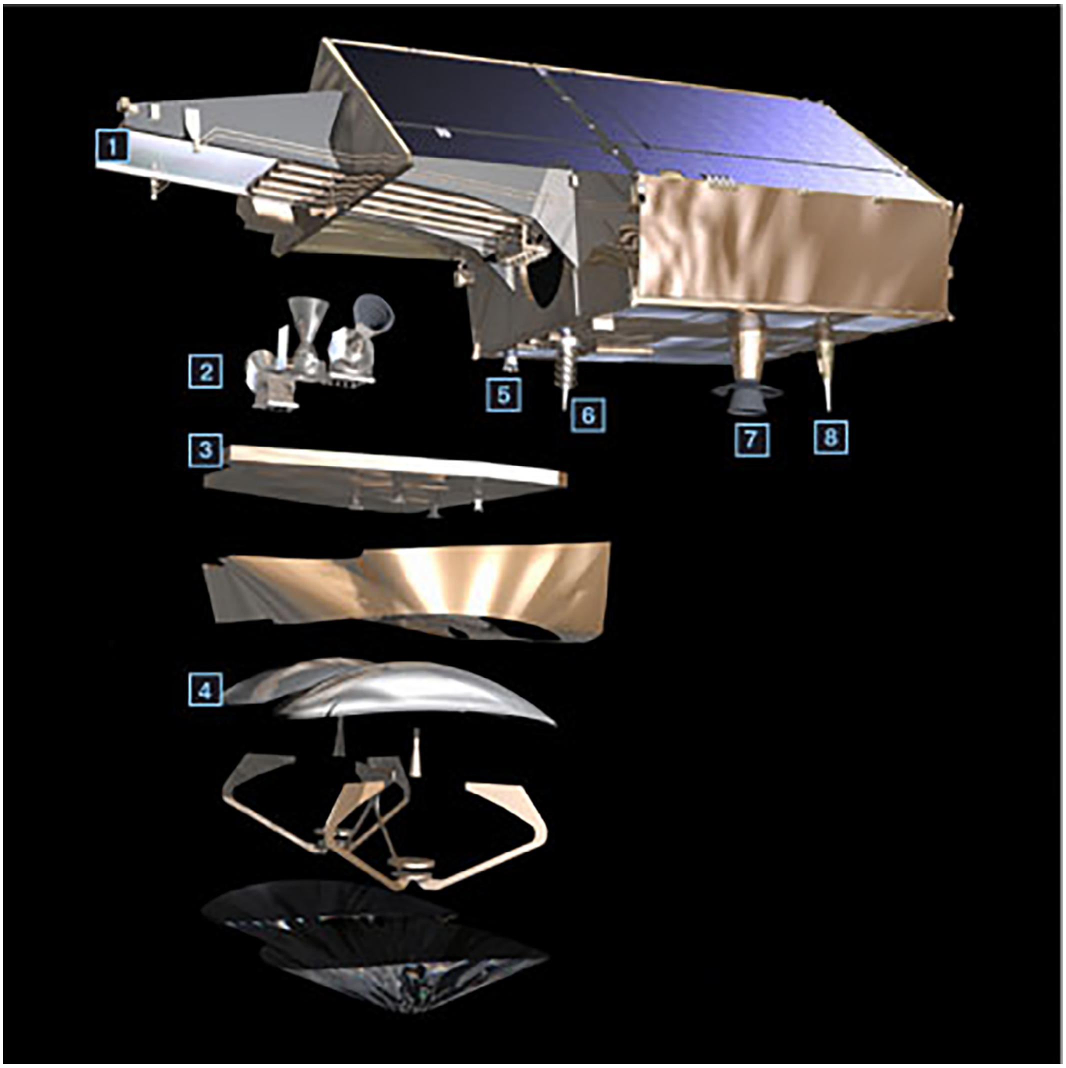

Fig. 2. **(1) Radiator:** a heat-radiating panel at the top of the nose structure which houses the SIRAL electronics under the solar array; (**2) Star tracker:** three mounted directly on the antenna bench, (**3) Antenna bench:** stable and rigid support structure isostatically mounted to the satellite nose; (**4) SIRAL antennae:** rigid mounted to the antenna bench immediately beneath the SIRAL electronics; (**5) Laser retro-reflector:** reflects incoming laser tracking pulses directly back to the ground-based laser station; (**6) DORIS antenna:** receives signals from a global network of radio beacons for orbit determination; (**7) X-band antenna:** transmits the huge volume of SIRAL measurement data to the ground when the satellite is above the horizon at Kiruna, Sweden; (**8) S-band helix antenna:** receives telecommand from the ground and transmits status and monitoring information. Credits (ESA).

the ability to predict the threat well in advance, has allowed reconsideration of such operations and now they are part of the normal flight procedures. Since the launch, the satellite has performed thirteen *Collision Avoidance Manoeuvres* and one of them was to avoid one piece of debris, which was at a radial distance less than 5 m from the satellite.

The system architecture of the ground segment has been kept simple (Fig. 3). The main parts of the ground segment are the planning facility at ESRIN (I), the Mission Control Centre at ESOC (D), the single ground station at Kiruna (S) and the Long Term Archive at CNES (F), which has been recently replaced by the Earth Observation Data Archiving Service (EODAS). As well as providing the link to the satellite, the SSC's Kiruna ESRANGE station also hosts the data processing and disseminating system. From here the scientific data is distributed directly to users via a centralised system.

CryoSat measurements are driven by a geographical mode mask that is updated monthly to consider the changes of the sea-ice extent. The initial geographical zones were specified by the original proposal and by the first two Announcements of Opportunity in 2004 and in 2009. Since then, the zones have significantly evolved to support new research streams, often beyond the original mission objectives. Other zones have been added to support the calibration of the on-board altimeter. The resulting patchwork of geographical zones forms the heart of the mission planning system, which is shown in Fig. 4. The switching sequences between different SIRAL modes are planned and sent to the satellite three weeks in advance but if necessary, last minute changes are feasible.

All the data generated by SIRAL is recorded on-board since the satellite is only in contact with Kiruna station for brief periods. Typically there are 12 passes of 5–10

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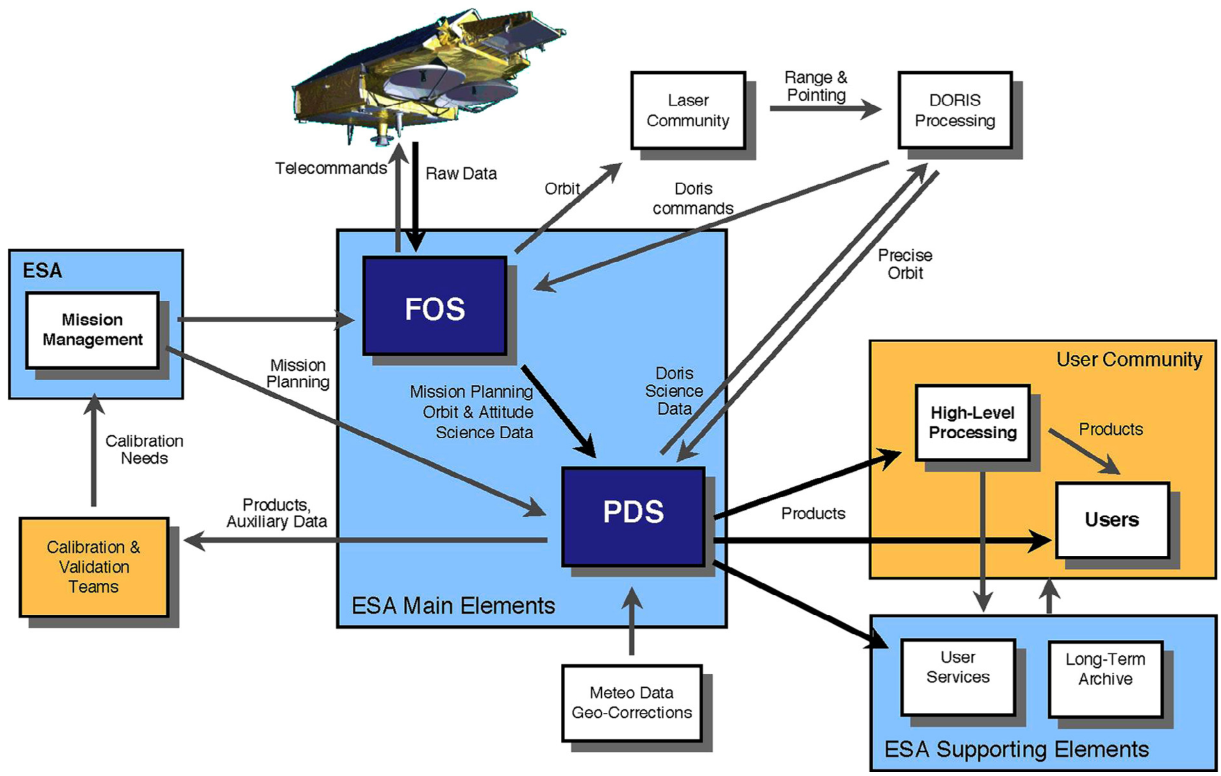

Fig. 3. CryoSat Mission Ground Segment. FOS is the Flight Operation System; PDS is the Payload Data System. Credits (ESA).

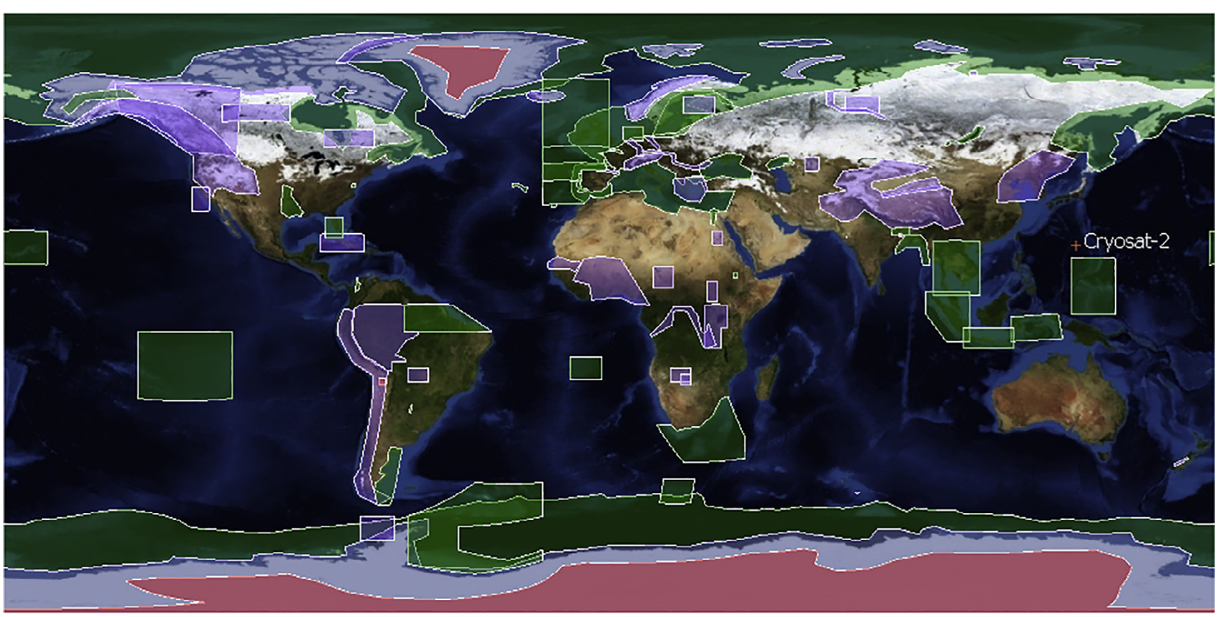

Fig. 4. Geographical mode mask 3.9. CryoSat is designed to acquire continuously while revolving around our planet, switching automatically to its three measurement modes according to a geographic mode mask. SAR (green) is operated over sea-ice areas and over some ocean basins and coastal zones. SARIn) (purple) mode is used over steeply sloping ice-sheet margins, over some geostrophic ocean currents and over small ice caps and areas of mountain glaciers. It is also used over some major hydrological river basins. LRM is operated over areas of the continental ice sheets (red), over oceans and over land not covered by other modes. Credits (ESA). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

min duration each day, occurring on consecutive orbits where the data is downlinked at 100 Mbps. These contacts are usually followed by a gap of two or three blind orbits where there is no contact with the ground. In that case, the data is collected on-board the solid-state recorder and downlinked to ground when visibility is established.

There are other data flows in the system since CryoSat, like any altimeter mission, needs auxiliary data from a variety of sources. For example, precise orbits are computed by an expert group at CNES in Toulouse (F). They receive the data from the DORIS instrument as soon as it is available. It takes around 30 days to compute and check the orbits to the highest accuracy. This data is then sent back to Kiruna and incorporated into the CryoSat data products.

4.2. In-flight calibration

The CryoSat in-flight calibration plan includes all calibrations required to improve the end-to-end acquisition chain.

The plan foresees periodic SIRAL instrument calibration to characterise the radar performance, which can vary in time, for example, due to aging. Calibrations are carried out to correct biases and temporal degradation of the altimeter transfer function, amplitude, gain, and path delay and to check degradation of the phase difference between the two receiving antennas.

To maintain the quality of the products at the highest level, the plan foresees two main activities:

– Transponder calibration with the scope of characterising the altimeter absolute range, absolute datation and the interferometric baseline orientation (Fornari et al., 2014).
– Interferometer calibration with the objective of characterising the degradation of the interferometer baseline. It is carried out every 16 months by rolling the satellite by $\pm$ 0.4 deg and using the ocean as a known external target characterised by a uniform rough surface with known slope (Scagliola et al., 2017).

4.3. Data products

Scientists have free and open access to all CryoSat data that can be downloaded from a dedicated FTP server (ftp://science-pds.cryosat.esa.int). Access to data is granted after submitting an on-line registration form and acceptance of the *Terms & Conditions*. Online registration is available at https://earth.esa.int/web/guest/pi-community/apply-for-data.

The mission generates about 30 GB per day of science raw data (L0) that is processed on the ground as soon as all the input (auxiliary) files become available. Typically, the so-called *offline products* are available around 30 days after acquisition.

The ground segment has significantly evolved since launch. The two major changes are the production of *Near Real Time* (NRT) data for the meteo-ocean community and operational sea-ice application and the development of the CryoSat ocean product chain, which is independent from the original ice product chain.

NRT data for the meteo-ocean community requires a subset of altimeter data (i.e. wind speed and wave height) available, 2–3 h from sensing which is relaxed to two days for the sea-ice Arctic and Antarctic operational use. Clearly, the timing of three hours cannot always be met due to the blind orbits, but this is statically accomplished 76% of the time.

The CryoSat ocean chain has been developed in response to a number of requirements coming from the ocean and coastal zone community. The full list of available products is listed in Table 2. More details on CryoSat products characteristics and quality can be found in Bouffard et al. (2017a, 2017b).

4.4. Validation campaigns

Validation campaigns are an important element of the CryoSat mission and are fundamental to support the mission's science goals. The purpose of these campaigns is mainly to address the crucial error budgets of the geophysical retrievals such as sea-ice freeboard. The validation campaigns use different acquisition techniques such as laser, radar, sonar or electrometric induction. It has extensive *in-situ* and airborne components while also making use of other satellites and airborne datasets acquired over the same regions. The CryoVEx (CRYOsat Validation Experiment) campaigns have been carried out since 2002 on a regular basis in the Arctic region and are frequently composed of several teams from different European institutions in what is considered an excellent representation of a successful large team effort to measure the polar regions. International collaborations with other space agencies are equally fostered, such as the collaboration between CryoVEx and NASA's Operation IceBridge, on-going since 2010 in the form of joint flights, and the more recent collaboration with JAXA (ALOS-2 data) and CNES (AltiKa data). Such collaborations have brought unique synergies and complementarities to the observations by making use of the different mission capabilities and resources. CryoVex Campaign datasets can be freely downloaded from https://earth.esa.int/web/guest/campaigns.

5. Overview of scientific achievements

5.1. Floating ice

The first estimates of Arctic sea ice thickness and volume (Fig. 5), derived from CryoSat measurements, were restricted to the central region (Laxon et al., 2013). Subsequent work (Kwok and Cunningham, 2015; Ricker et al., 2015; Tilling et al., 2015) extended these measurements in space and time. Altogether, these studies show a marked decline in autumn sea ice volume across the Arctic relative to estimates derived from ICESat over the period 2003–2008, in keeping with the long-term decline in sea ice extent. Tilling et al. (2015) report a 33% increase in ice volume in autumn 2013 and 2014, attributed to the retention

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Table 2
CryoSat products available to all registered users free and open.

SIRAL Product	Type	Main Characteristic	SIRAL Mode	Distribution
ICE – Baseline C (EE Format)	Full Bit Rate	• Time-ordered, raw data from the SAR and SARIn modes, prior to the application of the synthetic aperture, interferometric or accumulation processing • In LRM, echoes are incoherently multi-looked on board the satellite prior to download	SAR SARIn	30 days
	L1b	• Multi-looked echoes • Waveform power data are averaged • SARIn data contains multi-looked phase	SAR SARIn	NRT (3 h) Polar Region
		• Full engineering and geophysical corrections are applied	LRM SAR SARIn	30 days
	L2 & L2i	• Time-ordered geophysical measurements • Full engineering and geophysical corrections are applied • L2i provides more fields L2	LRM SAR SARIn	30 days
	GDR	• Consolidated L2 type products on orbit basis (ANX to ANX) containing LRM, SAR and SARIn	LRM + SAR+ SARIN	30 days
OCEAN – Baseline C (NETCDF Format)	L1b & L2	• **NOP** – Near Real Time Ocean Products for NRT marine applications • Uses Doris Navigator Orbit • L1b has similar characteristics to the ice L1b • L2 contain time-ordered geophysical corrections and measurements of the sea surface height, the significant wave height and wind speed derived processed with ocean-oriented algorithms	LRM SAR SARIn	NRT (3 h)
	L1b & L2	• **IOP** – Intermediary Ocean Product for medium-range ocean forecasting • Uses Medium Orbit Ephemeris (MOE) • L1b and L2 have similar characteristics to the NOP, except the orbit and the inclusion of the MOG2D correction (Carrère and Lyard, 2003)	LRM SAR SARIn	3 days
	GDR	• **GOP** – Geophysical Ocean Product with consolidated orbits • Uses Precise Orbit Ephemeris and corrections for longer-term, retrospective and climate studies • Uses GPD+Wet Tropospheric Correction (Fernandes and Làzaro, 2016) • Pole-to-Pole (P2P): Generated per orbit, combining successive L2 GOP spanning between the North and South poles into multi-mode concatenated products. • Consolidated L2 type products on orbit basis (Pole to Pole) containing LRM, SAR and SARIn	LRM SAR SARIn	30 days
FDM (EE Format)	L2	Fast Delivery Ocean for oceanographic and meteorologist use. Will be discontinued and replaced by the NOP in 2018.	LRM	NRT (3 h)

of thick sea ice northwest of Greenland during 2013 after a relatively cool summer (Kwok and Cunningham, 2015) and also to large-scale wind-driven ice convergence west of the Canadian Arctic Archipelago.

It has also been shown that sea ice thickness measurements derived in near real time from fast-delivery CryoSat data relying on preliminary orbits are of comparable accuracy to those produced using the final release data product (Tilling et al., 2016). Although deriving comprehensive sea ice thickness measurements in the southern hemisphere remains a challenge, there has been some progress towards this goal. In particular, the consistency of ENVISAT and CryoSat radar freeboards retrieved over Antarctic sea ice has been assessed (Schwegmann et al., 2016) and during the growth season, mean and modal freeboards agree typically to within 3–10 cm, respectively, offering promise for long-term data records.

Interactions between the radar transmitted signal and the sea ice floes remain a significant source of uncertainty; for example, a positive correlation has been found (Ricker et al., 2015) between buoy measurements of snow freeboard and CryoSat radar freeboard estimates during heavy accumulation events, and it has been suggested that early snowfall may have introduced a bias into CryoSat measurements collected in autumn 2013. A more detailed comparison (Armitage and Ridout, 2015) of radar freeboards and aircraft measurements over Arctic sea ice showed that CryoSat transmitted signal penetrates up to $82 \pm 3\%$ into the snow layer over first-year and multi-year ice, whereas AltiKa echoes are scattered from roughly the midpoint ($46 \pm 5\%$) of the snow layer over both types. In other work (Guerreiro et al., 2016), CryoSat and Altika measurements have been combined to estimate snow depth on Arctic sea ice, revealing thinner cover on both multi-year (32–57%)

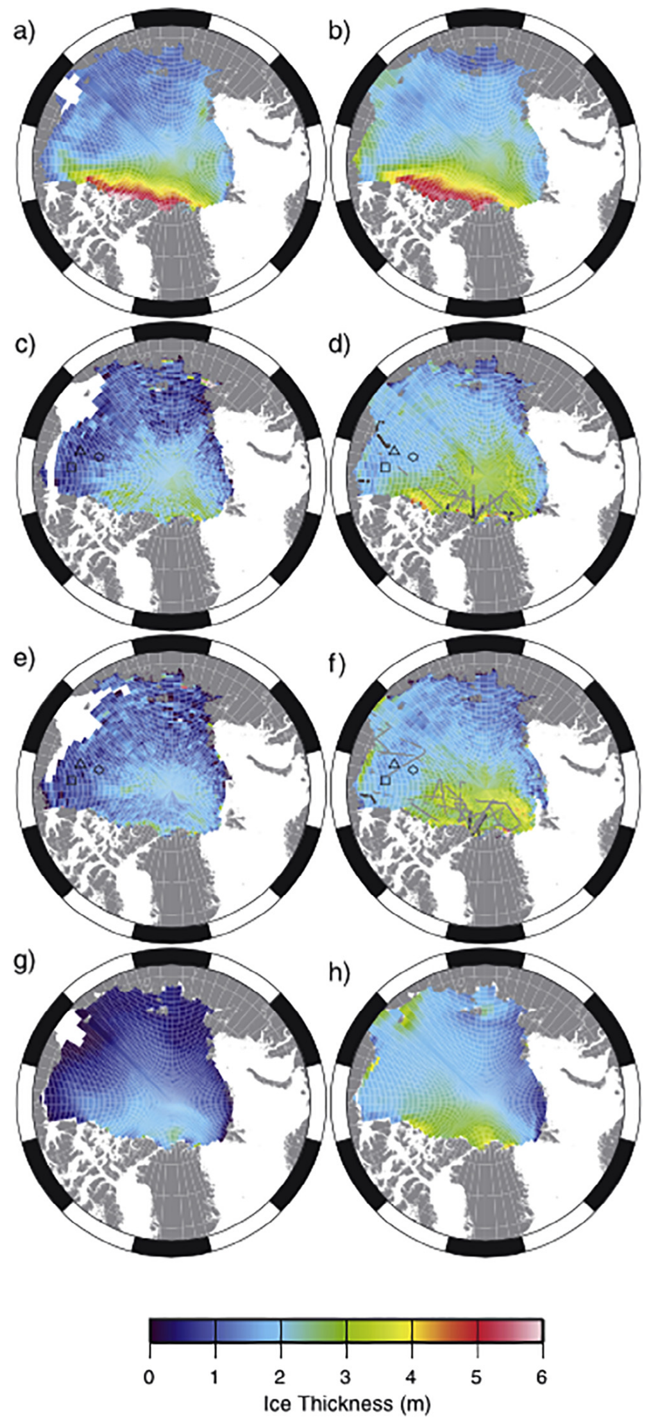

Fig. 5. CryoSat sea ice thickness compared with PIOMAS and ICESat ice thickness measurements. The data are restricted to the "ICESat" domain covering the central Arctic Ocean. (a) 2003–7 average ICESat ice thickness for October/November and (b) 2004–8 average for February/March. (c and d) CryoSat thickness for October/November 2010 and February/March 2011 and locations of the airborne EM data (black lines) and OIB data (grey lines) used for validation, ULS moorings (triangle, circle, square). (e and f) CryoSat thickness for October/November 2011 and February/March 2012 and locations of the airborne EM data (black lines) and OIB data (grey lines) used for validation. (g) PIOMAS for October/November 2011 and (h) February/March 2012 (Laxon et al., 2013 – Courtesy of GRL – Permission under review).

and first-year ice (63–75%) relative to the 1954–91 Warren climatology. An alternative approach to this problem is to modify the sea ice freeboard retrieval algorithm; for example, Kurtz et al. (2014) have shown that a waveform-fitting technique is capable of better reconciling the sea ice thickness data recorded from laser and radar altimetry data sets than traditional threshold-based re-tracking approaches.

In addition to monitoring sea ice thickness, CryoSat measurements have been used to study other aspects of ice-covered oceans including leads and ice shelves. Sea ice leads are of interest for ice deformation and regional climate modelling and for navigation, and information on their distribution can be derived as a by-product of sea ice thickness measurements. CryoSat observations have been used to qualitatively evaluate leads detected in AMSR-E passive microwave imagery (Röhrs and Kaleschke, 2012) and to estimate lead area fraction as part of a supervised classification of MODIS imagery (Wernecke and Kaleschke, 2015). Following a major fracturing event in the Beaufort Sea in 2013, the resulting Arctic-wide lead width follows a power law statistical distribution with an exponent of 2.47 ± 0.04 for the winter seasons from 2011 to 2014. Floating ice shelves are an important interface between the ice sheets and the polar oceans and knowledge of their thickness is of value for a wide range of scientific applications including mass budget calculations and modelling of ocean melting within sub-shelf cavities. Chuter and Bamber (2015) have derived a new map of Antarctic ice shelf thickness from four years of CryoSat measurements which agrees to within 3.3% of airborne radar measurements at the Amery Ice Shelf on average, and to within 4.7% at the grounding line.

5.2. Land ice

A major objective of CryoSat measurements is tracking changes in the elevation and mass of the polar ice sheets. This has been done in Antarctica (Helm et al., 2014; McMillan et al., 2014a) and in Greenland (Helm et al., 2014; McMillan et al., 2016) (Fig. 6), with consistent results from independent studies. The two ice sheets are together estimated to have lost 503 ± 107 km3/yr of ice in the period January 2011–2014, with Greenland responsible for three quarters of the change (Helm et al., 2014). Using similar data (McMillan et al., 2014a, 2016), the volume changes translate into rates of mass loss of 159 ± 48 Gt/yr and 269 ± 51 Gt/yr in Antarctica and Greenland, respectively. The high-resolution of CryoSat ensures that the ice sheets are adequately surveyed even in coastal regions, and allows changes at individual outlet glaciers to be monitored in detail. An extreme melt event in the interior part of Greenland during July 2012 was detected (Nilsson et al., 2015) in CryoSat measurements due to the impact on the radar scattering horizon. The effect was to introduce an apparent elevation increase of 56 ± 26 cm. Though large, the effect can be accounted for by making an empirical adjustment to elevation time series in the affected region (McMillan et al., 2016).

In other work, CryoSat measurements have been combined with TanDEM-X interferometry to generate a high-resolution digital elevation model of the surface topography of the marginal region of Thwaites Glacier in the Amundsen Sector of West Antarctica (Kim and Kim, 2017).

The large number and wide geographical distribution of Earth's glaciers and ice caps and the fine spatial resolution of CryoSat allows changes in their elevation to be monitored in detail – often for the first time. The Austfonna ice cap in Svalbard – the largest in the Eurasian Arctic – is a notable example; although only modest changes had been recorded in the past. McMillan et al. (2014b) used CryoSat observations to document rapid ice loss from a formerly slow-flowing, marine-based sector due to ice thinning at rates in excess of 25 m/yr. Contemporaneous observations of ice flow confirmed that the loss is associated with a 45-fold increase in ice discharge, and the imbalance has been associated with rising regional temperatures. Although conventional CryoSat measurements have been used to monitor changes at some mountain glaciers of British Columbia (Gower, 2017), full interferometric swath-mode processing of the mission data (Hawley et al., 2009) is a more effective tool for studying glaciers and ice caps with complex terrain. The technique has been applied to track surface elevation changes at the Devon Ice Cap (Gray et al., 2015) and at six major ice caps in Iceland (Foresta et al., 2016) on monthly and annual timescales. When compared to airborne laser data, CryoSat swath-altimetry height measurements typically agree to within 1 m. It is estimated that Icelandic ice caps have lost 5.8 ± 0.7 Gt/yr in the last decade, ~40% less than the preceding 15 years (Gray et al., 2015).

A third and significant application of CryoSat measurements in glaciology has been the study of sub-glacial hydrology – in particular the episodic drainage and filling of lakes situated beneath ice sheets. McMillan et al. (2013) first used CryoSat SARIn measurements to map both the perimeter and depth of a 260 km^2 surface depression above a sub-glacial lake in East Antarctica and in combination with earlier ICESat laser altimeter observations, estimated that between 4.9 and 6.4 km^3 of water had drained from the lake between 2007 and 2008. Similar work at the Mercer and Whillans ice streams in West Antarctica (Siegfried et al., 2014) showed that two sub-glacial lake drainage events occurred in the same hydrological catchment within a nine-month period. The advantage of CryoSat interferometric measurements over conventional satellite altimetry is their tendency to track the rim of depressions above lake sites as the point of closest approach, which provides an accurate assessment of lake area from which volume changes can be deduced. By applying swath altimetry, it is possible to resolve sub-glacial lake activity with even finer detail, for example at the Thwaites Glacier in West Antarctica where a system of lakes has been discovered (Smith et al., 2017). In their synthesis, Fricker et al. (2016) review a decade of progress in observing and modelling Antarctic sub-glacial water systems, including key results derived from CryoSat measurements in addition to other approaches.

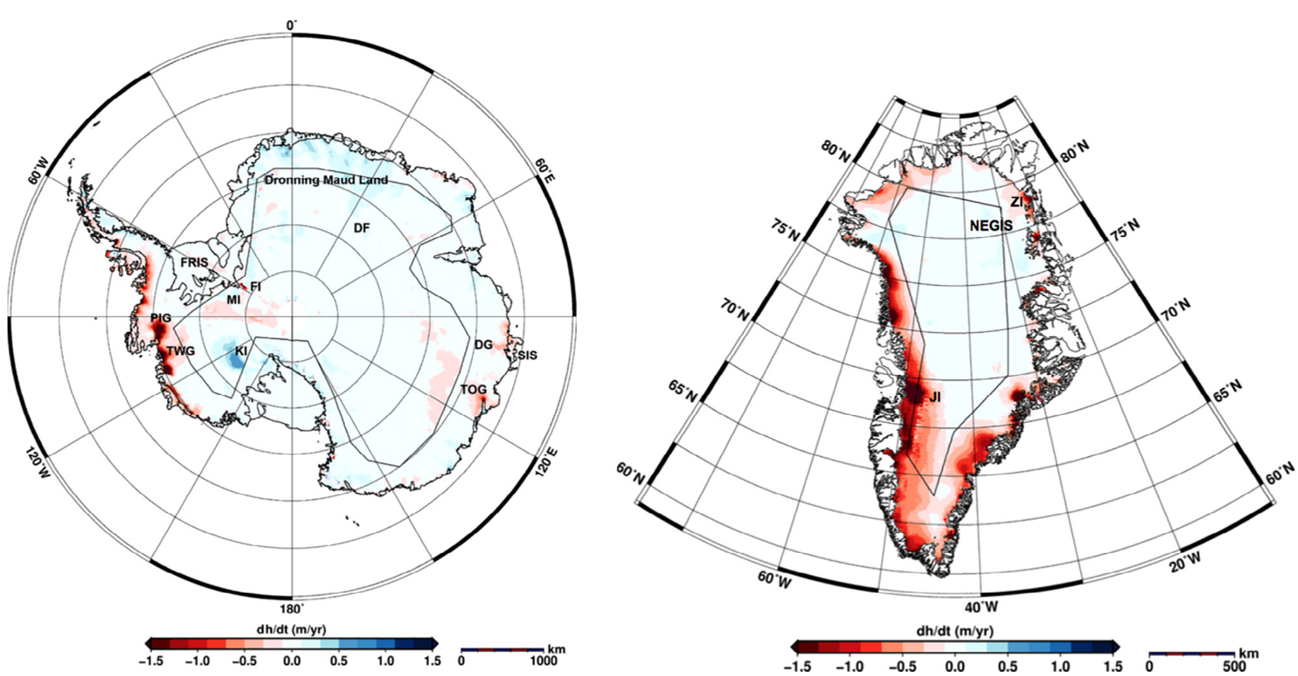

Fig. 6. Map of elevation change of Antarctica between January 2011 and January 2014 derived from along-track processing of three full CryoSat-2 cycles. Credits: Helm et al. (2014). Courtesy of the authors.

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5.3. Beyond ice

Despite a non-optimised orbit for "water", data from CryoSat has improved the monitoring of hydrological surfaces (Fig. 7) including reservoirs and lakes (Göttl, et al., 2016; Jiang et al., 2017; Nielsen et al., 2015, 2017) and river basins (Boergens et al., 2017; Villadsen et al., 2015). Thanks to initiatives such as the ESA CRUCIAL (CryoSat-2 Success over Inland Water and Land) project, the development of new SAR/SARIN – based on processing algorithms approaches targeted for hydrology, are becoming mature (Moore et al., 2014) and will be further enhanced by the new generation of sensors (Sentinel-6/Jason-CS, IceSat2, SWOT). The community is now investigating how to improve modelling and forecasting capabilities through integration of these high-resolution observations within hydrological models (Schneider et al., 2016, 2017).

Over the ocean, CryoSat SAR and LRM measurements already address numerous issues of worldwide relevance from global to regional scales and from the open-ocean to the coastal areas. Several oceanographic studies show that CryoSat is, at least, as useful as repeat orbit ocean missions regarding the characterisation of low-frequency signals such as sea level rise (Calafat et al., 2017) and El Niño/La Niña events and Mesoscale dynamics (Dibarboure et al., 2012; Smith and Scharroo, 2009) and associated with a cascade of Eddy kinetic Energy (Dufau et al., 2016), as well as internal tides (Zhao, 2016), coastal dynamics (Cipollini et al., 2017) and their roles on the transport of biogeochemical and biological organisms. Moreover, recent studies show that the SARIN mode – uniquely on CryoSat – is particularly important over complex coastlines (e.g. Archipelagos, Estuaries and Fjords), for catching across-track sea level signatures on the shelves and near shore (Abulaitijiang et al., 2015) and could potentially improve the resolution of multi-satellite mesoscale fields (Dibarboure et al., 2013).

Due to its "drifting" orbit and high-resolution measurements, CryoSat has improved the quality of global mean dynamic topography, mean sea surface (Andersen et al., 2015) and gravity models (Sandwell et al., 2014), by filling the large gaps of observations in-between the tracks of missions with repetitive orbit. The high inclination orbit of the satellite has also extended our monitoring capability over the Polar Oceans, tracking the low frequency sea level trend in the presence of sea ice (Andersen, and Piccioni 2016) and characterising the regional variations of the

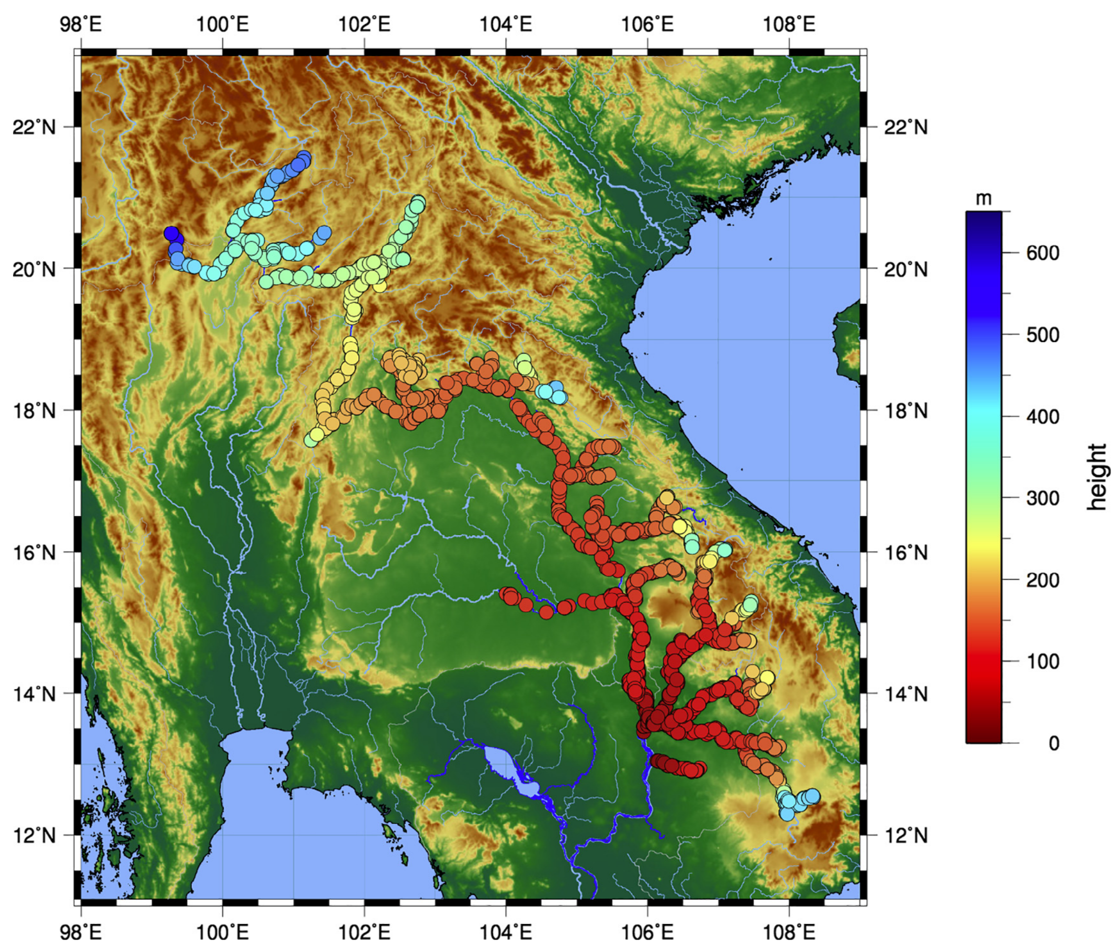

Fig. 7. Water level over the Mekong Basin derived from CryoSat SAR Measurement (Extract from Boergens et al., 2017) Courtesy of authors.

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dynamic topography over regions not covered by conventional ocean missions (Armitage et al., 2017), improving our knowledge on the complex interaction between ocean and ice (Fig. 8).

Over shorter time scales, wind speed, significant wave height and sea level parameters derived from CryoSat Near-Real-Time marine products, are widely used for operational purposes being merged with complementary data or assimilated into operational forecasting systems such as the ones from DMI, CMEMS, ECMWF and NOAA. Therefore, CryoSat measurements are contributing to improving the predictions of extreme events (e.g. storm surge), sea state and weather, which can then be exploited by policy makers to optimise decisional processes related to marine safety, security and risk as well as to the sustainable management of human activities that have an impact on the marine ecosystems (aquaculture, fisheries, tourism, offshore industry).

Monitoring and forecasting the space-time variability of hydrodynamic features is, however, a challenging task requiring not only high-resolution along-track measurements from a single mission, but also homogeneous data products computed from a dense multi-mission constellation. The coordinated efforts made for the standardisation of CryoSat with respect to other ocean surface topography missions have thus represented a key component to ensure that the scientific and operational returns of the mission are maximised over the ocean.

For example, the integration of CryoSat into the Radar Altimeter Database System (RADS, Scharroo et al., 2016) by EUMETSAT, NOAA, and Delft University of Technology (TU Delft) has been particularly suitable for referencing, cross-calibrating and homogenising CryoSat ocean data product with respect to processing algorithms and geophysical corrections used in other ocean missions. CryoSat based mono and gridded multi-mission products are also produced by SSALTO/DUACS in the framework of the CNES CPP (CryoSat Processing Prototype) project with the objective to enable the oceanographic community to exploit Cryosat like any other altimetry mission. Besides this, the ESA "CryoSat Plus for Oceans" (CP4O, Cotton et al., 2010) project has also participated in building a sound scientific basis for new scientific and operational applications of CryoSat over the open ocean, polar ocean, coastal seas, inland water and for sea-floor mapping.

All these multi-agency initiatives have allowed the generation and the evaluation of new methods and products that enable the full exploitation of the capabilities of the SIRAL altimeter and extend their application beyond the initial mission objectives.

Based on this heritage and fruitful on going collaborations with partner agencies, ESA has developed and implemented its own CryoSat Ocean Processor (COP) to generate CryoSat products specifically designed for oceanographers (Calafat et al., 2017). The COP products include up-to-date and ocean-oriented algorithms and corrections that could bridge the gap between previous and future ocean missions as well as contributing to a better knowledge of polar circulation. Future processing evolutions are planned to improve the quality of the CryoSat products and promote them to a broad range of applications over multiple domains.

6. Conclusion

CryoSat-2 was launched in April 2010, four and half years after the original CryoSat satellite was destroyed in a launch failure of a Russian *Rockot* over the North Pole. CryoSat was the second mission to be selected in 1999 as part of the European Space Agency's Earth Explorer Pro-

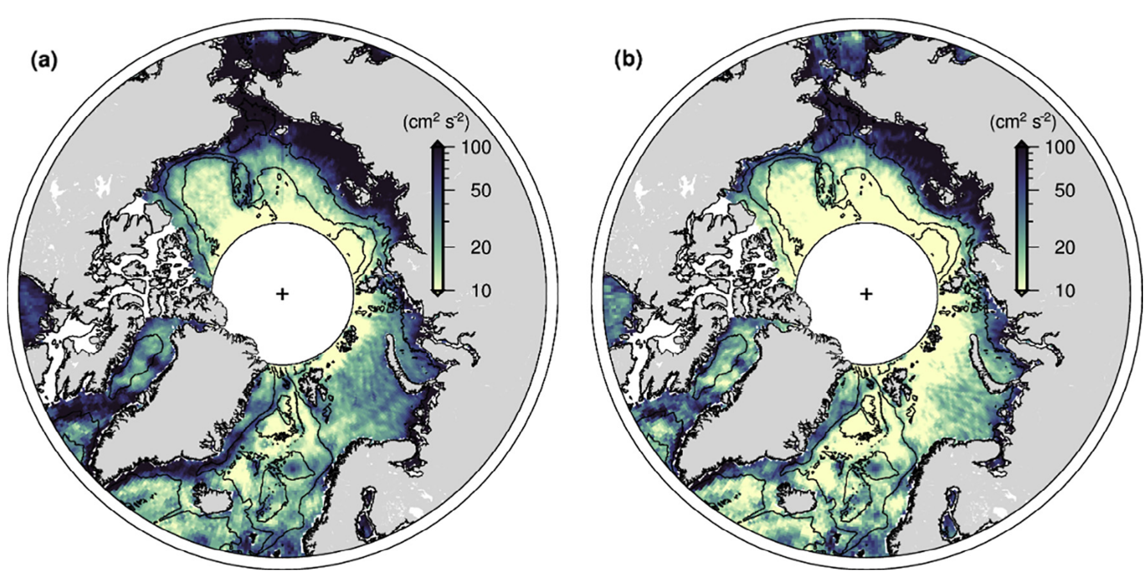

Fig. 8. The November–June (a) and July–October (b) eddy kinetic energy. Depth contours are drawn at 50 m, 1 km and 3 km, taken from the ETOPO1 global bathymetry model (Armitage et al., 2017). Courtesy of the authors.

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gramme that was set up to develop research missions to address key scientific challenges identified by the science community, while demonstrating revolutionary technology in observing techniques.

After eight years in orbit, both the space and ground segment are in excellent state and fit to continue the exploitation phase until the middle of the next decade. The mission performance has surpassed the design specifications, delivering high quality data and providing unique contributions to several novel research and applications in Earth Science, both at global and regional scales.

The mission has already generated data that has proven to be fundamental to the data records of sea-ice volume and ice sheet elevation changes. However, the large variety of challenges and scientific outcome emerging from the CryoSat mission, identify this Earth Explorer as a classic example of a mission, scientifically intended for one domain that has successfully enlarged its portfolio of applications during its current lifetime including potential transit into an operational framework.

Clearly, there is still much to be done. The mission will continue to determine decadal trends in ice sheets, ice caps, glaciers and sea ice mass to separate seasonal and inter-annual variability from long-term trends, and to robustly determine the impact of climate change on these trends. But new challenges are arising at the horizon such as the validation of the role of snow loading in the Arctic sea-ice, whose nature is now changing towards a system that is more similar to the Antarctic one. The mission is fit to continue observations within the framework it was designed for almost two decades ago and at the same time, it is committed to taking-up new challenges counting on synergies with existing and future missions like AltiKa, ICESat-2 and Sentinels.

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