REAPER
Reprocessing 12 Years of ERS-1 and ERS-2 Altimeters and Microwave Radiometer Data

Brockley, David J.; Baker, Steven; Femenias, Pierre; Martinez, Bernat; Massmann, Franz Heinrich; Otten, Michiel; Paul, Frederic; Picard, Bruno; Prandi, Pierre; Roca, Monica

DOI
10.1109/TGRS.2017.2709343

Publication date
2017

Document Version
Final published version

Published in
IEEE Transactions on Geoscience and Remote Sensing

REAPER: Reprocessing 12 Years of ERS-1 and ERS-2 Altimeters and Microwave Radiometer Data

David J. Brockley, Steven Baker, Pierre Féménias, Bernat Martínez, Franz-Heinrich Massmann, Michiel Otten, Frédéric Paul, Bruno Picard, Pierre Prandi, Mònica Roca, Sergei Rudenko, Remko Scharroo, and Pieter Visser

***Abstract*— Twelve years (1991–2003) of ERS-1 and ERS-2 altimetry data have been reprocessed within the European Space Agency (ESA) reprocessing altimeter products for ERS (REAPER) project using an updated, modern set of algorithms and auxiliary models. The reprocessed data set (identified as RP01) has been cross-calibrated against the reprocessed ENVISAT V2.1 data. The format of this reprocessed data set is network common data form (version 3). The new data set shows a clear improvement in data quality beyond that of previous releases. The product validation shows reduction of the mean standard deviation of the sea-surface height differences from 8.1 (previously available product) to 6.7 cm (RP01). This paper presents the details of how the reprocessing was conducted and shows selected results from the validation and quality-assurance processes. The major improvements of the REAPER RP01 data set with respect to the previous ESA ERS radar altimetry (RA) products are due to the use of four ENVISAT RA-2 retrackers, RA calibration improvements, new reprocessed precise orbit solutions, ECMWF ERA-interim model for meteorological corrections, new ionospheric corrections, and new sea state. The intent of this paper is to aid the reader in understanding the benefits of the new data set for their particular use-case.**

***Index Terms*— Altimetry, European remote sensing (ERS), microwave radiometer (MWR).**

Manuscript received October 12, 2016; revised March 18, 2017; accepted April 14, 2017. Date of publication June 15, 2017; date of current version September 25, 2017. This project was supported by the European Space Agency under Contract ESRIN 22163/09/I-OL "ERS Altimetry Data Set Reprocessing Chain." *(Corresponding author: David J. Brockley.)*

D. J. Brockley and S. Baker are with the Mullard Space Science Laboratory, University College London, RH5 6NT Dorking, U.K. (e-mail: d.brockley@ucl.ac.uk; steven.baker@ucl.ac.uk).

P. Féménias is with ESA ESRIN, 00044 Frascati, Italy (e-mail: Pierre.Femenias@esa.int).

B. Martínez and M. Roca are with isardSAT, 08042 Barcelona, Spain (e-mail: Bernat.Martinez@isardSAT.cat; Monica.Roca@isardSAT.cat).

F.-H. Massmann is with the Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, 14473 Potsdam, Germany (e-mail: fhm@gfz-potsdam.de).

M. Otten is with the European Space Operations Centre, 64293 Darmstadt, Germany (e-mail: Michiel.Otten@esa.int).

F. Paul is with IFREMER Technopole de Brest-Iroise, 29280 Plouzané, France (e-mail: Frederic.Paul@ifremer.fr).

B. Picard and P. Prandi are with Collecte Localisation Satellites, 31520 Ramonville-Saint-Agne, France (e-mail: bpicard@cls.fr; pprandi@cls.fr).

S. Rudenko was with the Helmholtz Centre Potsdam GFZ German Research Centre for Geosciences, 14473 Potsdam, Germany. He is now with Deutsches Geodätisches Forschungsinstitut der Technischen Universität München, 80333 Munich, Germany (e-mail: sergei.rudenko@tum.de).

R. Scharroo was with Altimetrics LLC, Cornish, NH 03745 USA. He is now with EUMETSAT, Darmstadt, Germany (e-mail: remko@altimetrics.com).

P. Visser is with the Faculty of Aerospace Engineering, Delft University of Technology, 2629 HS Delft, The Netherlands (e-mail: P.N.A.M.Visser@tudelft.nl).

Digital Object Identifier 10.1109/TGRS.2017.2709343

I. Introduction

The European Remote Sensing (ERS) missions began on July 17, 1991 with the launch of ERS-1 into a polar orbit, with an inclination of 98.52°, and continued with the launch of ERS-2 on April 21, 1995. The primary scientific objectives of the mission were oceanography and geodesy; however, the range of instruments carried widened the use of the mission significantly beyond these fields.

Both satellites carried the Ku-band radar altimeter (RA), also the along-track scanning radiometer (ATSR-1/MWR), C-band synthetic aperture radar, and wind scatterometer. The key purpose of the microwave radiometer (MWR) was to provide an accurate tropospheric correction to the range measurements retrieved by the altimeter. The ground processing of the telemetry from these instruments yielded the RA waveform product (WAP) [1] and ocean product (OPR) [2], which were distributed to users following the completion of the commissioning of the satellites. Over the course of subsequent years, many incrementally improved versions [3] of these products were released as processing defects were detected and corrected, and the operational behavior of the instruments and platform was better understood.

Scientists making use of altimetry data often need a long time-series of data to be able to accurately characterize trends and cycles in geophysical parameters. Data sets such as these can only be compiled by consolidating observations made by a number of missions. To achieve this, any biases between the missions must have either been corrected, or at least assessed and understood. Such biases often vary with time, due to causes such as changes in hardware performance (aging or damage), orbital effects on hardware (thermal flexure), or changes in data processing (bug-fixes/ upgrades).

ERS-1 was calibrated over the Venice tower, providing an estimated bias of −41.5 cm with a total uncertainty of ±2 cm [4]. The ERS-2 altimeter was cross-calibrated against ERS-1 and TOPEX/Poseidon altimeters [5]. The Environmental Satellite (ENVISAT) RA-2 was calibrated in absolute terms for both its range over the Mediterranean sea with a regional calibration [6], and for the first time in altimetry, its backscatter, using a European Space Agency (ESA) transponder [6].

Another hindrance in the compilation of long-term data sets is the fact that most altimetry missions to date have produced data in a file format that was specific to that mission.

Additionally, where there are parameters that seem at first to represent the same physical quantity in the differently formatted outputs of two missions, there are often subtle differences in the set of corrections that have been applied, or not applied, to that quantity. Standardized, self-describing file formats can avoid the need for data format conversion, and reduce the likelihood of using mismatched parameters. Network common data form (netCDF [7]) is an example of such a file format, and is becoming a defacto standard for the provision of altimetry data.

The ERS-1 mission ended on March 10, 2000 due to failure of the attitude control system, which prevented the satellite from orientating the solar panels toward the sun. The final working gyroscope on ERS-2 failed on January 13, 2001, limiting the ability of the satellite to maintain nominal pointing. This was followed by failure of the on-board tape storage system on June 22, 2003, which limited the data acquisition to regions where the satellite was visible from a ground station. The mission finally ended after the planned decommissioning of the platform on September 5, 2011, during which burns were made to place the satellite into a decaying orbit and empty the fuel tanks.

The end of the ERS missions and new improved background models became available in meanwhile provided an opportunity to assess all of these impacts, and to conduct a reprocessing activity designed to create a consolidated altimetry data set for ERS that was cross-calibrated with ENVISAT. The approach taken to the reprocessing activity was to create a homogeneous ERS data set, processed with a uniform set of algorithms and models. The data set was to be cross-calibrated with ENVISAT and, originally, to be provided to users in a similar format to ENVISAT. That was done during the reprocessing altimeter products for ERS (REAPER) project, during which it became apparent that future missions were standardizing on a netCDF representation for products, and that it was likely that future reprocessing activities on older data sets would also use that output format. Therefore, it was decided that the output of the REAPER project would become a netCDF product aligned with the format proposed for Sentinel-3, rather than a binary format similar to the old ENVISAT format as originally envisaged.

The reprocessing activity has now concluded, and a per-cycle quality assurance process has been performed on the output Level-1 (L1: observations corrected for factors due to the instrument and presented in engineering units) and Level-2 (L2: further corrected for geophysical effects and presented in scientific units) data sets. The L2 data set was delivered to ESA for dissemination and archiving. This first reprocessing output of the REAPER project is identified as the RP01 data set. The data set covers the time period from August 3, 1991 to June 2, 1996 for ERS-1 and from May 15, 1995 to July 4, 2003 for ERS-2. The L2 product is provided on a pass-by-pass basis, where each pass may contain both ascending and/or descending orbital track data, and starts and ends at the points determined by the downlink to the ground station, rather than being cut from pole-to-pole.

The REAPER RP01 L2 data set can be obtained via fast registration on the ESA website [8].

This paper presents the necessary background information to allow the user to fully understand the content of the reprocessed data set, and how that content was derived from the Level-0 (L0, raw telemetry) measurements. Selected observations from the commissioning and quality-assurance phases of the project are presented to allow the user to make an informed decision on the applicability of the data to a specific use.

The remainder of this paper is set out as follows.

1) Section II describes the methodology applied during the reprocessing, which algorithms and models were chosen or developed.
2) Section III elaborates on the contents of the data set.
3) Section IV presents the results obtained during the validation and quality-assurance processes performed upon the reprocessed data set.
4) Finally, Section V describes the conclusion with an overview of the current status of the REAPER data set, and lists future improvements that could be made in a subsequent reprocessing activity.

II. Reprocessing Methodology

A. Orbit

Errors in the knowledge of the position of the spacecraft around the orbit have a direct impact upon the altimetric measurements. Errors in the knowledge of the altitude obviously translate directly into errors in the surface height. Moreover, errors in the knowledge of the rate of change of altitude also translate into surface height errors via the Doppler correction to range. Errors in the along-track position appear as apparent errors in the measurement of the time tag. For these reasons, use of an accurate orbit solution is an essential first step in providing an accurate data set.

To produce a high-quality orbit solution for the REAPER project, three institutes independently computed new precise orbit solutions: TU Delft, ESOC, and GFZ. Different software were used for the production of each solution, but the software considered the same set of models and output to the same LPOD2005 [9] reference frame. The software systems used for precise orbit determination were NASA/GSFC GEODYN [10], NAvigation Package for Earth Observation Satellites [11], and "Earth Parameter and Orbit System-Orbit Computation software" [12]. The altimetry databases used to collect and check the results were RA Database System (RADS) at TU Delft [13], [14] and the Altimeter Database and Processing System (ADS) [15] developed at GFZ. A set of standards, models, and tracking data used for the ERS-1/2 precise orbit determination are described in [16, Tables 1–3].

The details on the computation and evaluation of these orbit solutions are given in [16]. Satellite RA crossover analysis was performed on the solutions using RADS and ADS to assess the improvement of each of the orbit solutions. The comparison used the DGM-E04 orbit [18] as a reference solution. In addition, a combined solution (created by averaging the three independent solutions) was included in the comparison. The combined solution gave the best performance. In this solution, radial errors were found to be reduced from

TABLE I

STATISTICS OF SSH STANDARD DEVIATION FOR ERS-1 CYCLES 43–53 AND ERS-2 CYCLES 1–11

	Mean (cm)	StdDev (cm)
E1 REAPER	6.796	0.3443
E2 REAPER	6.696	0.4602
E1 REF	6.958	0.146
E2 REF	6.983	0.2809
E1 OPR	8.162	0.1738
E2 OPR	8.212	0.2356

TABLE II

STATISTICS OF SSH STANDARD DEVIATION FOR ERS-2 CYCLES 76–85

	Mean (cm)	StdDev (cm)
E2 REAPER	7.228	0.2921
E2 REF	7.713	0.3843
E2 OPR	8.66	0.4905

~50 to ~21 mm when compared to the DGM-E04 reference orbit. The rms of altimeter crossover residuals was reduced from 8.2 (DGM-E04 orbit) to 7.4 cm (REAPER combined orbit), i.e., by 8 mm, for ERS-1 and from 7.3 (DGM-E04 orbit) to 6.4 cm (REAPER combined orbit), i.e., by 9 mm, for ERS-2 [16]. In terms of power, these reductions amount to about 3.5 cm^2. Fig. 1 shows clear improvements in the mean crossover height differences for all REAPER orbits, as compared to the DGM-E04 orbits. This can mostly be contributed to the improvement of the gravity field from DGM-E04 (an ERS-tailored model based on JGM-3) [17] to the GRACE-based EIGEN-GL04S [18]. Geographical patterns are dominated by remaining errors in the gravity field and by remaining systematic errors in the altimetric data records. (See the patterns in Fig. 1 that follow the geomagnetic equator which suggest errors in the ionospheric range correction.) Because of these remaining systematic errors, the geographical patterns differ rather little among the new orbits. The new ERS-1 and ERS-2 orbit solutions form part of the official REAPER products and are available as such. (They are also available at ftp://dgn6.esoc.esa.int/reaper/.)

B. Microwave Radiometer

The L0 data from the MWR were reprocessed by CLS as part of the REAPER project. The reprocessing used the same system as was used for the recent reprocessing of ENVISAT data [19], with the intent of achieving a consistent cross-calibration with ENVISAT.

The output L1b MWR brightness temperature (TB) data set was used as an input to the L2 processing of the altimeter data for the computation of the wet tropospheric correction (WTC).

Unfortunately, the ENVISAT V2.1 TB data used as a reference for the intercalibration of ERS-1 and ERS-2 MWR TB proved to be affected by in-flight calibration problems (see [20, Sec. 5.4]) identified after the REAPER reprocessing.

Quality assessment (QA) activities have shown that WTC is currently too large by approximately 2 cm in both data sets [19].

An updated WTC for ENVISAT is available [21], so a future reprocessing of REAPER MWR data set will correct for this problem. Note that the model WTC is obviously unaffected.

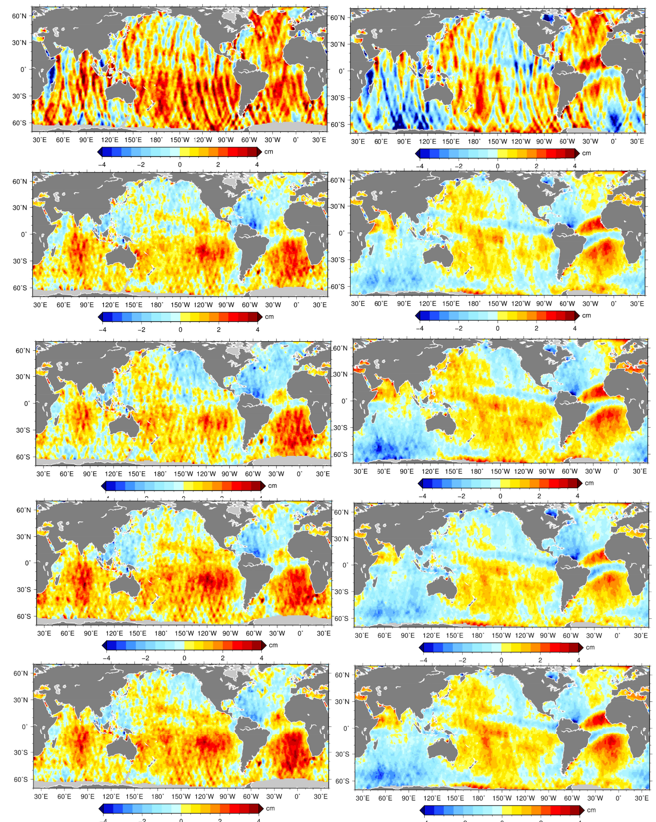

Fig. 1. Mean crossover height differences computed using different orbits: from top to bottom, DGM-E04 and four REAPER orbits (TU Delft, ESOC, GFZ, and combined one, for (Left) ERS-1 and (Right) ERS-2).

C. Level 1 and Calibration Reprocessing

The reprocessing activity to produce the L1 product focused on the provision of accurate calibration of the position and amplitude of the instrument point target response (PTR), the variability in response (transfer function) across the range window [intermediate frequency (IF) filter, or IF mask], and the provision of very accurate estimation of the on-board clock period (or frequency) (ultrastable oscillator (USO), USO-clock), which is expected to drift with age.

The altimeter internal delay is measured by means of the altimeter internal calibration mode. In this mode, the radar pulse is sent directly into the receive electronics of the altimeter, rather than through the antenna. This allows the time delay and change in power due to the electronics to be measured separately to the changes due to reflection from the surface of the earth. PTR records are analyzed on-ground to provide correction to both range (from the internal delay computation) and backscatter (from the internal attenuation computation), which are then applied during the L1 processing. A Gaussian fit to the PTR waveform provides the position and amplitude of each PTR retrieved on-board, being the PTR waveform corrected by the IF mask (see below) before fitting. After that, a smoothing is performed with all the PTR retrievals, both for delay and attenuation, to reduce the measurement noise, and then an interpolation is finally performed in order to output one pair of PTR corrections for every altimeter measurement. The application of these corrections to range and power at L1 results in improved estimates of height and backscatter at L2.

The IF mask is used in order to compensate the effect of the system transfer function in the altimetric and calibration waveforms. In order to collect the noise spectra, the altimeter is set to a specific mode that measures only the thermal noise of the instrument (no echoes from the ground). Once that the noise spectra are collected, they are processed on-ground in order to derive the IF mask correction. This processing assumes that variations in power across the window are only due to the response of the instrument. The IF mask is produced by averaging a number of individual IF measurements. This averaging is performed with a moving window that spans a month in time, in such a way that one averaged IF mask is produced every day. The averaged mask is then applied to each waveform data, using the closest averaged mask in time, as part of the L1 processing. During the original processing, ERS calibration data were not corrected by the IF mask measured in flight, but by a mask derived on the ground.

To allow direct comparison with older data sets, a decision was made within the REAPER project to provide datation and window delay (time delay from pulse transmission to the center of the echo window; used later in the L2 for the final range computation) at the same reference location as used in these older data set, rather than at the center of the tracking cycle (the set of pulses averaged on-board the satellite) as is typically done with more recent missions. The effect of this is that the averaged waveform presented with those time and range values is from an illuminated area of the surface that is offset by approximately 50-m along-track from the geo-located point (which is referenced to the center of the tracking cycle). This shift is because the range telemetered is measured ∼7 ms before the center of the tracking cycle. This is not the same as a 7-ms time-tag bias (where the time stamp does not correspond to the time of the range measurement): the range and time are correctly referenced to each other, and this affects only the delta-range from the retracking. A key factor in the decision was also that the instrument parameters to be used for the propagation of datation and window delay to the middle of the waveform were not provided in the L0 data and documentation in a way that enabled the computation.

The altimeter clock (USO) frequency was recalculated for the complete mission, and interpolated to retrieve a real USO frequency for every hour of the mission lifetime. During the L1 processing, the USO frequency (or period) is read from the USO auxiliary file, and used in the computation of the Level 1B parameters such as window delay or sigma-0 scaling factor (relates counts received to watts transmitted; later used in the L2 for the sigma-0 and wind-speed computation). We should note that there is therefore no need for any extra USO drift correction to be applied to the L2 data, since the real USO frequency (or period) value is used at all times in the processor.

D. Level 2 Reprocessing

In the L2 reprocessing chain, the same four retrackers used for processing ENVISAT data are executed for all records. The four retrackers used are as follows:

1) ICE1 (offset center of gravity technique) [22];
2) ICE2 [23];
3) sea-ice [24];
4) ocean [25].

A range measurement and a backscatter measurement are produced for each of these retrackers. (The ocean retracker also estimates a significant wave height.) The sea-ice and ICE1 range measurements are then further processed to produce a height measurement. In the case of the ICE1 retracker, that height measurement is corrected for slope effects, and the position of the echo on the surface is recalculated from nadir to the estimated point of closest approach on the surface via the use of a precomputed slope model.

In addition to range and backscatter, a number of other geophysical parameters are derived from the ocean retracker. Wind-speed (via the Abdalla table for ENVISAT [26]) and significant wave height are estimated at 20 Hz. A 1-Hz regressed and filtered value is then produced for selected oceanographic parameters, such as range and significant wave height.

E. Auxiliary Models

A large number of geophysical and meteorological auxiliary models are used in the processing of altimetry data. Establishing a common baseline of models to be used in the processing of data sets from different missions is helpful when trying to consolidate data. The creation of more accurate models is continually the topic of on-going research, and the models that are now available are an improvement upon those used during the original processing of the WAP and OPR products.

The models used are as follows:

1) mean sea surface: CLS01 [27] and UCL04 [28] (improved at high latitude);
2) geoid: EGM2008 [29];
3) slope model: UCL/RP01 model [30];
4) using the ENVISAT models, corrected for the average ERS orbit;
5) sea-state bias: ALT/RP01 model;
6) created within the REAPER project using REAPER data and aligned to ENVISAT;
7) wind table: Abdalla wind table [26];
8) ocean depth/land elevation: MACESS;
9) a merge of ACE land elevation data [31] and the Smith and Sandwell ocean bathymetry [32];
10) surface type mask: terrainbase [33];
11) meteorological corrections: ERA-interim ECMWF [34];
12) ionospheric: GIM [35] (and NIC09 [36] when GIM is unavailable);
13) ocean tides: GOT 4.7 [37] and FES 2004 [38];
14) long-period tides: FES 2004 [38];
15) solid-earth tide: Cartwright and Tayler [39];
16) pole tide: Wahr [40].

A full set of meteorological and geophysical corrections are provided in the L2 product for the user to apply to the range values. For the height values, the appropriate set of corrections, chosen from the above list based on availability and surface type, has already been applied during the L2 processing. The appropriate set of corrections for land is the dry and wet tropospheric, ionospheric, solid-earth and pole tides, and the ocean-loading component (only) of the ocean tide. Over ocean, the inverse barometric correction and the remainder of the ocean tides are accounted for.

F. Reprocessing Environment

The French Research Institute for Exploitation of the Sea (IFREMER) was responsible for the final data-processing activities of the reprocessing campaign. The archive of ERS L0 data was physically present at the Centre for ERS Archiving and Processing at IFREMER (CERSAT), and the REAPER processing chains were installed upon the NEPHALAE [41] cloud computing system made available by IFREMER. This system allowed a significantly parallel approach to the reprocessing, and greatly reduced the time necessary to reprocess the data set. The final run of the reprocessing, which reprocessed the 15 years' worth of altimetry data across both ERS missions, was largely completed within a week of the start of processing. This capability to rapidly process data moves the limiting factors in data reprocessing to the algorithm design and implementation stage, and to analysis of the generated output.

III. REAPER Products and Their Format

The ERS-1/2 REAPER altimeter data set is composed of the following three product types.

1) RA**REAPER Geophysical Data Record—GDR (ERS_ALT_2_)** containing radar range, orbital altitude, wind speed, wave height, and water vapour from the ATSR/MWR as well as geophysical corrections. The details on this product can be found at https://earth.esa.int/web/guest/data-access/browse-data-products/-/asset_publisher/y8Qb/content/radar-altimeter-reaper-geophysical-data-record-gdr.
2) RA**REAPER Sensor Geophysical Data Record—SGDR (ERS_ALT_2S)** containing all of the parameters found in the REAPER GDR product (ERS_ALT_2_) with the addition of the echo waveform and selected parameters from the Level 1b data. The details on this product can be found at https://earth.esa.int/web/guest/data-access/browse-data-products/-/asset_publisher/y8Qb/content/radar-altimeter-reaper-sensor-geophysical-data-record-sgdr.
3) RA**REAPER Meteo Product—METEO (ERS_ALT_2M)** containing only the 1-Hz parameters for altimeter (surface range, satellite altitude, wind speed, and significant wave height at nadir) and ATSR/MWR data (TB at 23.8 and 36.5 GHz, water vapour content, and liquid water content) used to correct altimeter measurements. It also contains the full geophysical corrections. The details on this product can be found at https://earth.esa.int/web/guest/data-access/browse-data-products/-/asset_publisher/y8Qb/content/radar-altimeter-reaper-meteo-product-meteo.

It should be noted that GDR and SGDR products contain two data rates: a low rate of 1 Hz and a high rate of 20 Hz. Most 1-Hz data also represented at 20-Hz ones, whereas MWR (ATSR/MWR) data and the atmospheric and geophysical corrections are only given at 1 Hz. The REAPER METEO product contains only the low rate of 1-Hz data. All three REAPER products are global products including data over ocean, ice, and land.

The REAPER products are provided in the standardized netCDF format. Use of netCDF replaces the use of bespoke binary product formats, defined to meet the individual needs of each mission. The REAPER L2 products [42] have been designed with reference to the product format specified for Sentinel-3, and reuse the same name for fields that contain the same measurement or correction.

IV. Results and Discussion

A. Validation Overview

Validation of the REAPER products was performed using an initial processing of three years' worth of REAPER data products. A period of almost one year was processed from the ERS-1/-2 tandem phase, for each satellite, to allow a direct comparison between ERS-1 and ERS-2 (May 14, 1995–April 28, 1996). The final year of data was from ERS-2 during tandem operation with ENVISAT (July 22, 2002–June 2, 2003), to allow cross-calibration against that mission. Once the validation process was complete, the entire data set was reprocessed using the optimal configuration derived during validation to achieve intercalibration of the missions (ERS-2 to ENVISAT and then ERS-1 to ERS-2).

The results presented in the following sections are based on the analysis of this three-year data set. The data quality and performance of the REAPER processing was compared to original ERS-1 and ERS-2 OPR performance [43] and to the current version of the ERS-1 and ERS-2 data which is provided from the DUACS processing chains [44], with updated geophysical corrections and standards. (The details of this processing are given in [45].)

Once the entire data set was available, a per-cycle QA process was initiated to check the entire data set before delivery to the ESA distribution facility. This process covered more data than the validation, but in less detail. The results of this performance monitoring, conducted by UCL-MSSL, are publicly available online at the REAPER Performance Monitoring and Quality Assurance website [46].

B. Crossover Analysis

Analysis of sea-surface height (SSH) differences at crossover locations is an essential tool for satellite altimetry mission performance evaluation. Ideally, these differences should be zero, under the assumption that the true SSH does not vary over short periods. For the present analysis, we select only crossovers where the time difference between ascending and descending arcs is shorter than 10 days. When global averages are considered, they are computed following the removal of measurements from high latitudes (greater than 50°, due to high temporal variability), measurements from shallow water areas (depth shallower than 1000 m), and measurements from other areas of known high ocean variability.

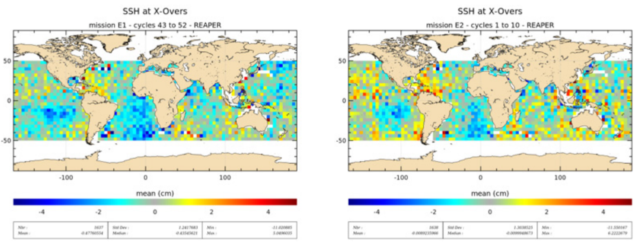

Fig. 2. Map of the mean of SSH differences at crossovers for (left) ERS-1 and (right) ERS-2 estimated from the final REAPER commissioning data set (COM6) over the first 10 cycles of ERS-2.

A first evaluation of the spatial distribution of the mean SSH differences at crossovers from REAPER data shows north/south pattern (not shown here) with a few centimeters amplitude, which suggests a residual time-tag bias. After empirical correction for a small, 0.6-ms pseudo time-tag bias (i.e., correcting as if it were a time-tag bias but without confirming that as the source), this pattern is removed and the resulting maps of mean SSH differences at crossovers are shown in Fig. 2. These are computed at mid-latitudes only as these regions have more stable SSH statistics, making them a more reliable validation target. Over the validation phase between ERS-1 and ERS-2, both missions show common geographically correlated patters with amplitudes up to a few centimeters: negative patches in the southern Atlantic Ocean and the eastern tropical Pacific Ocean, positive patch in the western part of the North Atlantic Ocean.

The standard deviation of SSH differences at crossovers provides a measurement of the mission performance and its stability over time. Fig. 3 displays the evolution of per-cycle measurements of the standard deviation of SSH differences at crossovers for the historical ERS OPR product, the OPR with updated standards and geophysical corrections, and REAPER data. Clearly, REAPER provides a large improvement over the historical OPR performance. Over the verification period between ERS-1 and ERS-2, the mean standard deviation of SSH differences at crossovers is only about 6.7 cm for REAPER data, compared to about 8.1 cm for historical OPR. Except for two of the 30 cycles considered here, REAPER data also show a better performance than the updated OPR data.

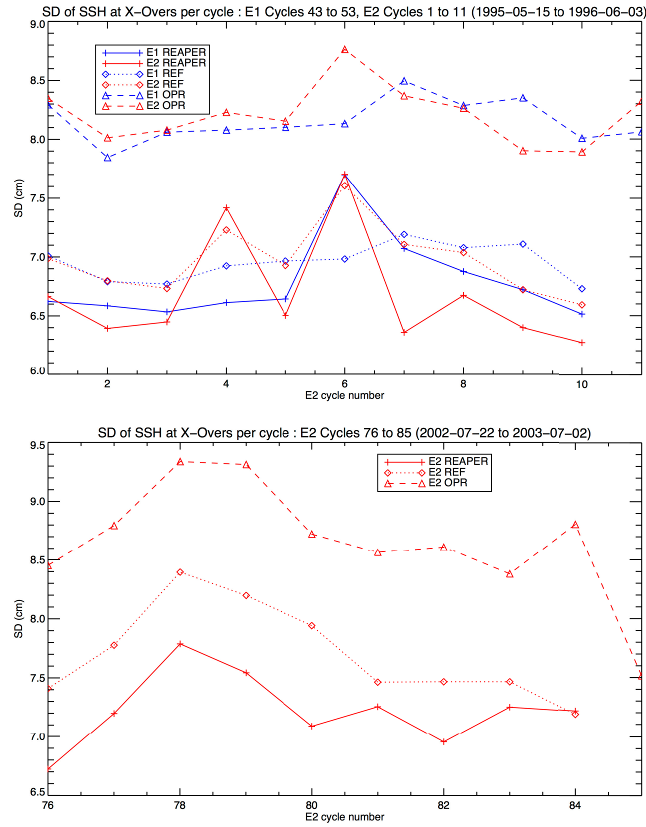

Fig. 3. Temporal evolution of the standard deviation of SSH differences at crossovers for latitudes below 50°, bathymetry greater than 1000 m, and low oceanic variability areas. The statistic is derived for historical OPR, updated OPR (REF), and REAPER data, and is tabulated in Tables I and II.

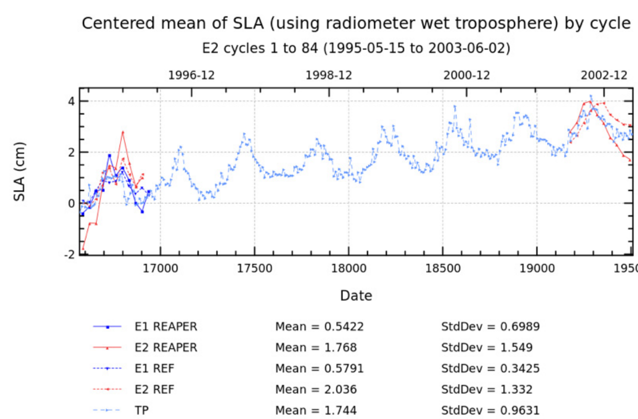

Fig. 4. Temporal evolution of the global mean SLA for all latitudes below 66° from REAPER and updated OPR ERS-1 and ERS-2 data, TOPEX/Poseidon data are overlaid to provide a reference.

C. Sea Level Anomaly Analysis

SSH biases are estimated between ERS-1 and ERS-2, and between ERS-2 and ENVISAT, each time using the validation period between missions (see Section IV-A). The results show a small -0.5 ± 0.15 cm bias between ERS-1 and ERS-2 (ERS-1 lower than ERS-2) and a 28.3 ± 0.16 cm between ERS-2 and ENVISAT.

Fig. 4 shows the temporal evolution of the cycle mean sea level anomalies (SLA) from ERS-1, ERS-2, and TOPEX/Poseidon data. For ERS missions, both the REAPER and updated OPR data (REF) are shown. A good agreement is observed in general between REAPER and TOPEX/Poseidon data. However, the REAPER ERS-2 data show a drift at the beginning of the period, which is not observed by other missions. Future work will determine if this drift is from the MWR processing anomaly detailed in Section II-B, or from another source. In general, the REAPER data show a slightly lower standard deviation of SLA than the updated OPR data, which indicates an improved performance. For example, in the ERS-2 overlap period with ENVISAT, OPR has a standard deviation of 0.41 cm, RP01 of 0.35 cm, and ENVISAT of 0.30 cm.

The conclusion is that the current state of the REAPER data set (RP01) is an improvement over the previous ERS-1/-2 altimetry data sets that have been made available to users.

V. Conclusion

The REAPER RP01 data set presents 12 years of ERS altimetry data, cross-calibrated both within the mission and with ENVISAT V2.1. The data format is netCDF 3 to allow ease of access from a range of standard tools across the main computing platforms. The data set is fully described in the accompanying product handbook [41], and the self-documenting capabilities of netCDF have been used to present useful documentation within the data set itself. The REAPER data set will therefore be both useful and accessible to researchers wishing to make use of the ERS altimetry data.

A secondary benefit of the creation of the data set is the establishment of a reusable reprocessing framework that can be used for future reprocessing activities on the ERS altimetry data. This may be an incremental improvement of the data set due to improvements in models or algorithms, or an increase in the temporal scope of the data set by adding data through to the end of the ERS-2 mission in 2011. Adding to the scope in that way is hampered by the fact that the on-board tape recorder on ERS-2 failed, limiting data availability to the periods when the satellite was in line-of-sight of a ground station. For this reason, any additional data will be partially complete at best.

The major improvements of the REAPER RP01 data set with respect to the previous ESA RA products are due to use of four ENVISAT RA-2 retrackers, RA calibration improvement, new reprocessed precise orbit solutions, ECMWF ERA-interim model, NIC09 ionospheric correction until 1998, GIM ionospheric correction up to 2003, new sea-state bias, etc. The assessment of the REAPER data quality versus the ERS OPR and WAP data shows a clear improvement in terms of accuracy over the tandem periods between ERS-1, ERS-2, and ENVISAT missions (currently assessed periods).

The validation and quality-assurance process identified some problems present within the reprocessed data that can be targeted for improvements in future reprocessing activities. Full details are given in the REAPER product handbook [42], but those with the most impact upon the product are reproduced in the following.

1) Errors in the reprocessing of the MWR data have resulted in a WTC that is too large by around 2 cm.
2) There are jumps, both forward and backward, in the time stamp due to on-board single-bit errors in the clock.
3) The calibration of backscatter, wind-speed, and significant wave height can be further improved.

The speed with which the NEPHALAE system was able to process the data in the first reprocessing indicates that future reprocessing campaigns (for all missions) will be able to devote more time to analysis and development of the processing chains than to the actual processing activity. This indicates that a more iterative workflow to the reprocessing is feasible, with results from initial processing runs feeding corrections back to be used in the final run. For the REAPER project specifically, it has resulted in the creation of a processing infrastructure that can easily and quickly handle future algorithmic and data improvements.

Work on another reprocessing of the ERS altimetry data is planned but not yet scheduled. The intention is to again bring the REAPER data set into alignment with the newly reprocessed ENVISAT data set that is expected to be released by then, and to address all known problems. Additional algorithmic and data format improvements are also under development. Further improvement of the ERS orbit quality is expected, when using new reference frame realizations, e.g., ITRF2014, new time-variable gravity field models, and other background models used for precise orbit determination.

The work performed in the construction and operation of the reprocessing chains has both delivered an improved product, and laid the groundwork for future reprocessing activities. The REAPER RP01 data set is a significant advance on the previously available ERS-1/-2 altimetry data sets, and the REAPER project looks forward to feedback and results from the wider scientific community.

References

[1] *Altimeter Waveform Product ALT.WAP Compact User Guide, Issue 4.1*, Infoterra Lmt., Leicester, U.K., 2001.

[2] *Altimeter & Microwave Radiometer ERS Products User Manual, Version 1.2*, CERSAT, FR, Plouzané, France, 2001.

[3] R. Scharroo, "A decade of ERS satellite orbits and altimetry," Ph.D. dissertation, Dept. Aerosp. Eng., Delft Univ. Technol., Delft, The Netherlands, 2002.

[4] *The Calibration of the ERS-1 Radar Altimeter, The Venice Calibration Campaign, Issue: 2.0*, document ER-RP-ESA-RA-0257, Mar. 1993.

[5] J. Benveniste, "ERS-2 altimetry calibration," in *Proc. 3rd ERS Symp.*, Florence, Italy, 1997, pp. 17–21.

[6] M. Roca *et al.*, "RA-2/MWR in-flight performance—Preliminary results," in *Proc. IEEE Int. Geosci. Remote Sens. Symp.*, vol. 1. Jun. 2002, pp. 611–613, doi: 10.1109/IGARSS.2002.1025121.

[7] R. K. Rew, G. P. Davis, S. Emmerson, and H. Davies, "NetCDF user's guide for C, an interface for data access," Unidata Program Center, Boulder, CO, USA, Tech. Rep. Version 3, Apr. 1997.

[8] *ESA Earth Online Fast Registration*, accessed on Jun. 8, 2017. [Online]. Available: https://earth.esa.int/web/guest/pi-community/apply-for-data/fast-registration

[9] J. Ries, "LPOD2005: A practical realization of ITRF2005 for SLR-based POD," presented at the Ocean Surf. Topogr. Sci. Team Meeting, Nice, France, Nov. 2008. [Online]. Available: http://www.aviso.altimetry.fr/fileadmin/documents/OSTST/2008/oral/ries.pdf

[10] D. E. Pavlis, S. Poulouse, and J. J. McCarthy, "GEODYN operation's manual," SGT Inc., Greenbelt, MD, USA, Tech. Rep., 2006.

[11] *The Navigation Package for Earth Observation Satellites*, accessed on Jun. 8, 2017. [Online]. Available: http://www.positim.com/napeos.html

[12] S. Zhu, C. Reigber, and R. König, "Integrated adjustment of CHAMP, GRACE, and GPS data," *J. Geodesy*, vol. 78, nos. 1–2, pp. 103–108, 2004.

[13] M. Naeije, R. Scharroo, E. Doornbos, and E. Schrama, "Global altimetry sea-level service: GLASS," Delft Inst. Earth-Orientated Space Res., Delft Univ. Technol., Delft, The Netherlands, Final Rep. NUSP-2 Rep. GO 52320, 2008, p. 107.

[14] *RADS Radar Altimetry Database System at TU Delft*, accessed on Jun. 8, 2017. [Online]. Available: http://rads.tudelft.nl

[15] T. Schöne, S. Esselborn, S. Rudenko, and J.-C. Raimondo, "Radar altimetry derived sea level anomalies—The benefit of new orbits and harmonization," in *System Earth via Geodetic-Geophysical Space Techniques*, F. M. Flechtner *et al.*, Eds. Berlin, Germany: Springer, 2010, pp. 317–324.

[16] S. Rudenko, M. Otten, P. Visser, R. Scharroo, T. Schöne, and S. Esselborn, "New improved orbit solutions for the ERS-1 and ERS-2 satellites," *Adv. Space Res.*, vol. 49, no. 8, pp. 1229–1244, Apr. 2012.

[17] B. D. Tapley *et al.*, "The JGM-3 gravity model," *J. Geophys. Res.*, vol. 101, no. B12, pp. 28029–28049, Dec. 1996.

[18] J.-M. Lemoine *et al.*, "Temporal gravity field models inferred from GRACE data," *Adv. Space Res.*, vol. 39, no. 10, pp. 1620–1629, 2007.

[19] A. Ollivier and M. Guibbaud, "Envisat RA2/MWR reprocessing impact on ocean data," CLS, Ramonville St-Agne, France, Tech. Rep. SALP-RP-MA-EA-22083-CLS, Mar. 2012. [Online]. Available: http://www.aviso.altimetry.fr/fileadmin/documents/calval/validation_report/EN/EnvisatReprocessingReport.pdf

[20] R. Scharroo and P. Visser, "Precise orbit determination and gravity field improvement for the ERS satellites," *J. Geophys. Res.-Oceans*, vol. 103, no. C4, pp. 8113–8127, 1998.
[21] (Jun. 27, 2014). *Envisat RA2: Updated MWR Wet Tropospheric Correction for Altimetry V2.1 Dataset*. [Online]. Available: https://earth.esa.int/web/guest/missions/esa-operational-eo-missions/envisat/news/-/article/envisat-ra2-updated-mwr-wet-tropospheric-correction-for-altimetry-v2-1-dataset
[22] J. L. Bamber, "Ice sheet altimeter processing scheme," *Int. J. Remote Sens.*, vol. 15, no. 4, pp. 925–938, 1994.
[23] B. Legrésy and F. Rémy, "Altimetric observations of surface characteristics of the Antarctic ice sheet," *J. Glaciol.*, vol. 43, no. 144, pp. 265–275, 1997.
[24] S. Laxon, "Sea ice altimeter processing scheme at the EODC," *Int. J. Remote Sens.*, vol. 15, no. 4, pp. 915–924, 1994.
[25] E. Rodríguez, "Altimetry for non-Gaussian oceans: Height biases and estimation of parameters," *J. Geophys. Res.*, vol. 93, no. C11, pp. 14107–14120, 1988.
[26] S. Abdalla, "Ku-band radar altimeter surface wind speed algorithm," in *Proc. Envisat Symp.*, Montreux, Switzerland, Apr. 2007. [Online]. Available: https://earth.esa.int/workshops/envisatsymposium/proceedings/sessions/3E4/463250sa.pdf
[27] F. Hernandez and P. Schaeffer, "The CLS01 mean sea surface: A validation with the GSFC00.1 surface," CLS, Ramonville St-Agne, France, Tech. Rep., 2001
[28] A. Ridout, "New mean sea surface for the CryoSat-2 L2 SAR chain," UCL, London, U.K., Tech. Rep. C2-TN-UCL-BC-0003, Jun. 2014.
[29] N. K. Pavlis, S. A. Holmes, S. C. Kenyon, and J. K. Factor, "The development and evaluation of the Earth Gravitational Model 2008 (EGM2008)," *J. Geophys. Res.*, vol. 117, no. B4, p. 4406, 2012, doi: 10.1029/2011JB008916.
[30] *Envisat RA2/MWR Product Handbook, Issue 2.2*, ESA, Frascati, Italy, Feb. 2007.
[31] P. A. M. Berry, R. A. Pinnock, R. D. Hilton, and C. P. D. Johnson, "ACE: A new global digital elevation model incorporating satellite altimeter derived heights," ESA, Noordwijk, The Netherlands, Tech. Rep. ESA Pub. SP-461, 2000, p. 9.
[32] W. H. F. Smith and D. T. Sandwell, "Global sea floor topography from satellite altimetry and ship depth soundings," *Science*, vol. 277, pp. 1956–1962, Sep. 1997.
[33] L. W. Row, D. A. Hastings, and P. K. Dunbar, "Terrainbase worldwide digital terrain data documentation manual, release 1.0," Nat. Geophys. Data Center CD-ROM, Boulder, CO, USA, Tech. Rep., 1995.
[34] D. P. Dee *et al.*, "The ERA-Interim reanalysis: Configuration and performance of the data assimilation system," *Quart. J. Roy. Meteorol. Soc.*, vol. 137, pp. 553–597, Apr. 2001.
[35] A. Komjathy and G. H. Born, "GPS-based ionospheric corrections for single frequency radar altimetry," *J. Atmos. Solar-Terrestrial Phys.*, vol. 61, no. 16, pp. 1197–1203, 1999.
[36] R. Scharroo and W. H. F. Smith, "A global positioning system–based climatology for the total electron content in the ionosphere," *J. Geophys. Res.*, vol. 115, p. 318, Oct. 2010, doi: 10.1029/2009JA014719.
[37] R. D. Ray, "A global ocean tide model from TOPEX/POSEIDON altimetry: GOT99.2," GSFC, Greenbelt, MD, USA, NASA Tech. Memo 209478, 1999.
[38] F. Lyard, F. Lefevre, T. Letellier, and O. Francis, "Modelling the global ocean tides: Modern insights from FES2004," *Ocean Dyn.*, vol. 56, pp. 394–415, Dec. 2006.
[39] D. E. Cartwright and R. J. Tayler, "New computations of the tide-generating potential," *Geophys. J. Int.*, vol. 23, no. 1, pp. 45–73, 1971.
[40] J. M. Wahr, "Deformation induced by polar motion," *J. Geophys. Res.*, vol. 90, no. B11, pp. 9363–9368, 1985.
[41] D. Battré, S. Ewen, F. Hueske, O. Kao, V. Markl, and D. Warneke, "Nephele/PACTs: A programming model and execution framework for Web-scale analytical processing," in *Proc. 1st ACM Symp. Cloud Comput. (SoCC)*, New York, NY, USA, 2010, pp. 119–130. [Online]. Available: http://doi.acm.org/10.1145/1807128.1807148
[42] D. J. Brockley, "REAPER—Product handbook for ERS Altimetry reprocessed products," UCL, London, U.K., Tech. Rep. REA-UG-PHB-7003 3.2, Apr. 2014.
[43] F. Mertz, F. Mercier, S. Labroue, N. Tran, and J. Dorandeu, "ERS-2 OPR data quality assessment long-term monitoring—Particular investigation," CLS, Ramonville St-Agne, France, document CLS.DOS/NT/06.001, 2006. [Online]. Available: http://www.aviso.altimetry.fr/fileadmin/documents/calval/validation_report/E2/annual_report_e2_2005.pdf
[44] P. Gaspar *et al.*, "The DUACS project: Towards operational use of altimeter data in coupled ocean-atmosphere models for climate studies and forecasts, [short communication]," *Elsevier Oceanogr. Ser.*, vol. 66, pp. 393–394, 2002. [Online]. Available: http://dx.doi.org/10.1016/S0422-9894(02)80045-9
[45] *SSALTO/DUACS User Handbook*, accessed on Jun. 8, 2017. [Online]. Available: http://www.aviso.oceanobs.com/fileadmin/documents/data/tools/hdbk_duacs.pdf
[46] *REAPER Performance Monitoring and Quality Assurance Website*, accessed on Jun. 8, 2017. [Online]. Available: http://reaper.mssl.ucl.ac.uk/qa/index.html

David J. Brockley received the M.Sc. degree in software engineering from the University of Birmingham, Birmingham, U.K., in 1995.

Since 2002, he has been a Senior Software Engineer with the Mullard Space Science Laboratory, University College London, Dorking, U.K., where he is responsible for the maintenance and development of the Level 2 processing chains for the CryoSat2 ground segment.

Steven Baker was the REAPER Project Manager. He has provided support to the European Space Agency altimeter missions on ERS-1 and ERS-2, ENVISAT, CryoSat, and Sentinel-3 as part of the Expert Support Laboratories and through many other projects. He has been a Satellite Altimetry Expert with the Mullard Space Science Laboratory, University College London, Dorking, U.K., since 1991. His research interests include the remote sensing of the cryosphere and software engineering.

Pierre Féménias received the master's degree in engineering science from Pierre and Marie Curie University, Paris, France, in 1990.

From 1990 to 1994, he was with the LEGOS Research Laboratory, Toulouse, France, where he was involved in different altimetry related projects. In 1994, he joined the European Space Agency (ESA), Frascati, Italy, where he is currently the ESA Altimeter Data Quality Manager for the ESA earth observation missions (Sentinel-3, CryoSat, Envisat, ERS-2, and ERS-1). He is in charge of the respective ESA altimetry missions of the end-to-end sensor and product performance assessment and maintenance, through routine quality control, instrument calibration, product verification, calibration and validation, sensor performance monitoring and assessment, and corrective and perfective maintenance of the processing chains.

Bernat Martínez has been a Senior Engineer with isardSAT, Barcelona, Spain, since 2008. He is involved in several projects and missions (ENVISAT, Sentinel-3, CryoSAT-2, and HY-2A) related to processing raw products into L1 products. In the REAPER project, he was responsible for coordinating all algorithms, processors and products related to the calibration, time stamping, geolocation, and the computation of height and sigma0 parameters.

Franz-Heinrich Massmann received the (Dipl-Ing) Degrees in surveying from the University of Karlsruhe, Karlsruhe, Germany, and the University of Hannover, Hannover, Germany.

Since 1992, he has been a Senior Scientist with the GFZ German Research Centre for Geosciences, Potsdam, Germany—topics: satellite orbit determination, gravity field modeling, and satellite mission operations (CHAMP, GRACE, and GRACE-FO).

Michiel Otten, photograph and biography not available at the time of publication.

Frédéric Paul has been a Computer Engineer with the Laboratory of Oceanography from Space, French Institute for Sea Exploitation and Research, Plouzané, France, since 2006. His research interests include data platforms to manage and facilitating the use of remote sensing data for oceanography to support scientists' research activities, mainly in the frame of several projects for space agencies.

Bruno Picard received the Ph.D. degree in physical methods in remote sensing from the University de Versailles, Versailles, France, in 2004.

He joined Collecte Localisation Satellites, Ramonville Saint-Agne, France, in 2005, where he is currently the Head of the Microwave Radiometry Department. His research interests include calibration/validation, retrieval algorithms, and the long-term survey of microwave radiometers as SARAL/AltiKa, Sentinel-3, and SAPHIR on Meghatropiques mission.

Pierre Prandi received the Ph.D. degree in space oceanography from the University of Toulouse, Toulouse, France, in 2012.

He joined Collecte Localisation Satellites, Ramonville Saint-Agne, France, in 2012, where he is currently a Research Engineer. His research interests include the calibration/validation of satellite altimetry missions, such as SARAL/AltiKa, and ocean mapping methods.

Mònica Roca received the master's degree in electronics and telecommunications engineering from the Escola Tècnica Superior d'Enginyeria de Telecomunicació de Barcelona, Universitat Politècnica de Catalunya, Barcelona, Spain, in 1995.

She has more than 20 years of experience in altimetry. From 1994 to 2003, she was a System Engineer of the ENVISAT radar altimeter with the European Space Agency, ESTEC, Noordwijk, The Netherlands. She is currently the Founder and the Director of isardSAT group, with sites in Barcelona, Guildford, U.K., and Gdynia, Poland, a research company in the earth observation field, with a large expertise in all processing aspects of altimetry.

Sergei Rudenko received the Diploma degree in astronomy from Leningrad State University, Leningrad, Russia, in 1988, and the Ph.D. degree in physics and mathematics from Main Astronomical Observatory, National Academy of Sciences of Ukraine (MAO NASU), Kiev, Ukraine, in 2000.

He was a Research Scientist with the MAO NASU, from 1988 to 2001, and with the GFZ German Research Centre for Geosciences, Potsdam, Germany, from 2001 to 2016. Since 2016, he has been a Research Associate with the German Geodetic Research Institute, Technical University of Munich, Munich, Germany. His research interests include space geodesy, the precise orbit determination of the earth's artificial satellites, studies on sea level change, earth gravity field investigations, and studies on the earth rotation and reference frames.

Remko Scharroo received the M.Sc. *(cum laude)* and Ph.D. degrees in aerospace engineering from the Delft University of Technology, Delft, The Netherlands.

He was an Assistant Professor with the Delft University of Technology, where he taught subjects related to celestial mechanics, satellite instrumentation, and satellite orbit determination. He was a Post-Doctoral Fellow with the Laboratory for Satellite Altimetry, National Oceanic and Atmospheric Administration, College Park, MD, USA, from 2002 to 2004, after which he continued with the Laboratory as a Contractor, running his own company, Altimetrics LLC, for the next ten years. In 1990, he started the development of the Radar Altimeter Database System, which is used throughout the world by users of satellite altimetry. Since 1990, he has been involved in calibration and validation teams and science advisory groups for nearly every satellite altimeter. He is currently a Remote Sensing Scientist with the European Organisation for the Exploitation of Meteorological Satellites, Darmstadt, Germany.

Dr. Scharroo was a recipient of the American Geophysical Union Outstanding Student Paper Award in 1996 and the Fellowship from the International Association of Geodesy in 2003.

Pieter Visser received the Ph.D. degree Delft University of Technology, The Netherlands, in 1992.

He spent one year as an Exchange Visitor at the Center for Space Research, University of Texas at Austin, Austin, TX, USA. Over the years, he has been involved in several earth observation missions aiming at observing sea level change, melting ice caps, gravity, and magnetic fields. He has held many mission and science advisory positions for the European Space Agency (ESA), and several positions for the International Association of Geodesy (IAG). He chaired the COSPAR Panel on satellite dynamics from 2004 to 2012. He is currently a Chair Holder and the Head of the Section Astrodynamics and Space missions with the Faculty of Aerospace Engineering, Delft University of Technology, Delft, The Netherlands. His research interests include precise orbit determination of satellites and space geodesy.

Dr. Visser is a fellow of the IAG, a Full Member of the International Academy of Astronautics, and a member of the ESA Earth Science Advisory Committee.