REAPER: Reprocessing 12 years of ERS-1 and ERS-2 Altimeter and Microwave Radiometer Data

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***Abstract*— Twelve years (1991-2003) of ERS-1 and ERS-2 altimetry data have been reprocessed within the European Space Agency (ESA) REAPER (REprocessing Altimeter Products for ERS) project using an updated, modern set of algorithms and auxiliary models. The reprocessed dataset (identified as RP01) has been cross-calibrated against reprocessed Envisat V2.1 data. The format of this reprocessed dataset is netCDF (version 3). The new dataset 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 cm (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 dataset with respect to the previous ESA ERS radar altimetry products are due to use of four Envisat RA-2 retrackers, radar altimetry 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 dataset for their particular use-case.**

***Index Terms*—Altimetry, ERS, Microwave radiometer**

I. INTRODUCTION

The European Remote Sensing (ERS) missions began on 17th July 1991 with the launch of ERS-1 into a polar orbit, with an inclination of 98.52º, and continued with the launch of ERS-2 on 21st April 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 (SAR) and wind scatterometer. The key purpose of the microwave radiometer 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. Datasets 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 (ageing or damage), orbital effects on hardware (thermal flexure), or

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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 ±2.0 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 datasets 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 de-facto standard for the provision of altimetry data.

The ERS-1 mission ended on 10th March 2000 due to failure of the attitude control system, which prevented the satellite from orientating the solar panels towards the sun. The final working gyroscope on ERS-2 failed on 13th January 2001, limiting the ability of the satellite to maintain nominal pointing. This was followed by failure of the on-board tape storage system on 22nd June 2003, which limited 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 5th September 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 dataset for ERS that was cross-calibrated with Envisat. The approach taken to the reprocessing activity was to create a homogeneous ERS dataset, processed with a uniform set of algorithms and models. The dataset 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 datasets 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) datasets. The L2 dataset was delivered to ESA for dissemination and archiving. This first reprocessing output of the REAPER project is identified as the RP01 dataset. The dataset covers the time period 3rd August,1991 to 2nd June 1996 for ERS-1 and 15th May 1995 to 4th July 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 dataset 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 dataset, 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:

- Section 2 describes the methodology applied during the reprocessing; which algorithms and models were chosen or developed
- Section 3 elaborates on the contents of the dataset
- Section 4 presents the results obtained during the validation and quality-assurance processes performed upon the reprocessed dataset
- Finally, Section 5 concludes this paper with an overview of the current status of the REAPER dataset, 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 knowledge of altitude obviously translate directly into errors in 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 dataset.

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 was 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 (NAPEOS) [11], and `Earth Parameter and Orbit System - Orbit Computation (EPOS-OC) software' [12]. The altimetry databases used to collect and check the results were Radar Altimeter Data Base System at TU Delft (RADS) [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 is described in Tables 1-3 in [16].

The details on the computation and evaluation of these orbit solutions are given by [16]. Satellite radar altimeter 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 ~50 mm to ~21 mm when compared to the DGM-E04 reference orbit. The RMS of altimeter crossover residuals was reduced from 8.2 cm (DGM-E04 orbit) to 7.4 cm (REAPER combined orbit), i.e. by 8 mm, for ERS-1 and from 7.3 cm (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 $(3.5\ \text{cm})^2$. 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 for example 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/).

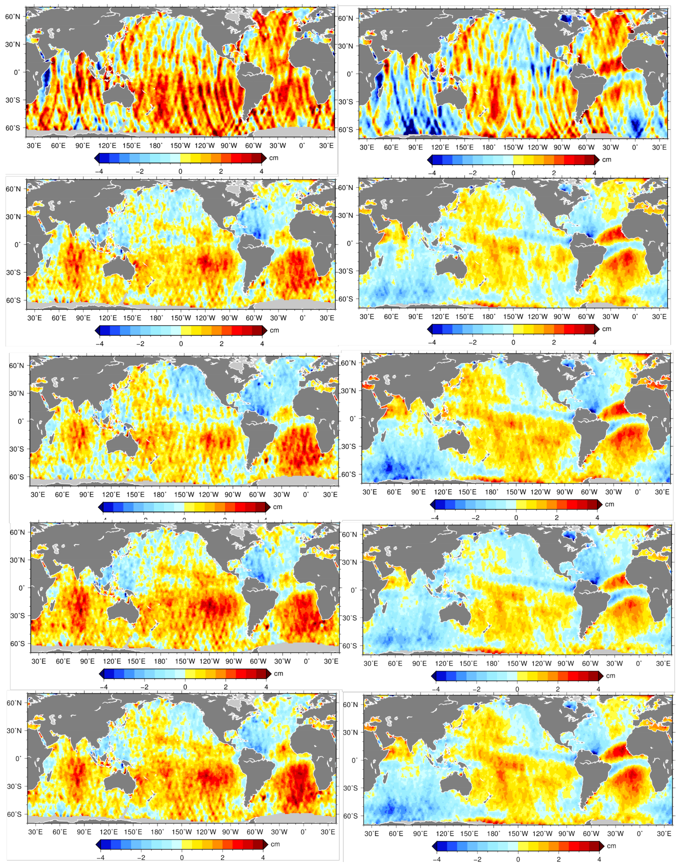

Fig. 1. Mean crossover height differences computed using different orbits: from top to bottom, DGM-E04 and four REAPER orbits (TU Delft, ESOC, GFZ, and combined one, for ERS-1 (left) and ERS-2 (right))

B. *Microwave Radiometer*

The L0 data from the microwave radiometer 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 microwave radiometer (MWR) brightness temperature (TB) dataset 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 inter-calibration of ERS-1 and ERS-2 MWR TB proved to be affected by in-flight calibration problems (see section 5.4 in [20]) identified after the REAPER reprocessing.

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

An updated WTC for Envisat is available [21] so a future reprocessing of REAPER MWR dataset will correct for this problem. Note that the model wet tropospheric correction is obviously unaffected.

C. *Level 1 and Calibration Reprocessing*

The reprocessing activity to produce the L1 product focussed 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 filter, or IF-mask), and the provision of very accurate estimation of the on-board clock period (or frequency) (Ultra Stable Oscillator, 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 result in improved estimates of height and backscatter at L2.

The Intermediate Frequency *(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 due only 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 datasets, a decision was made within the REAPER project to provide datation and window delay (time delay from pulse transmission to the centre of the echo window; used later in the L2 for the final range computation) at the same reference location as used in these older dataset, rather than at the centre 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 centre of the tracking cycle). This shift is because the range telemetered is measured ~7 ms before the centre of the tracking cycle. This is not the same as a 7-millisecond time-tag bias (where the timestamp does not correspond to the time of the range measurement): the range and time are correctly referenced to each other, 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:

- ICE1 (Offset Centre Of Gravity technique) [22]
- ICE2 [23]
- Sea-ice [24]
- Ocean [25]

A range measurement and a backscatter measurement are produced for each of these retrackers (the ocean retracker also estimates 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 pre-computed 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 datasets 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:

- Mean Sea Surface: CLS01 [27] and UCL04 [28] (improved at high-latitude)
- Geoid: EGM2008 [29]
- Slope model: UCL/RP01 model [30]
    - Using the Envisat models, corrected for the average ERS orbit
- Sea-state Bias: ALT/RP01 model
    - Created within the REAPER project using REAPER data and aligned to Envisat.
- Wind Table: Abdalla wind table [26]
- Ocean Depth/Land Elevation (ODLE) : MACESS
    - A merge of ACE land elevation data [31] and Smith and Sandwell ocean bathymetry [32]
- Surface type mask: Terrainbase [33]
- Meteorological Corrections: ERA-Interim ECMWF [34]
- Ionospheric: GIM [35] (and NIC09 [36] when GIM is unavailable)
- Ocean Tides: GOT 4.7 [37] and FES 2004 [38]
- Long Period Tides: FES 2004 [38]
- Solid Earth Tide: Cartwright [39]
- Pole Tide: Wahr [40]

A full set of meteorological and geophysical corrections is 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 are 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 dataset. The final run of the reprocessing, which reprocessed 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 dataset is composed of the following three product types:

1) **Radar Altimeter 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) **Radar Altimeter 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) **Radar Altimeter 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 (brightness temperature at 23.8 GHz and 36.5 GHz, water vapour content, 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 microwave radiometer (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 re-use 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 direct comparison between ERS-1 and ERS-2 (14 May 1995 to 28 April 1996). The final year of data was from ERS-2 during tandem operation with Envisat (22 July 2002 to 2 June 2003), to allow cross-calibration against that mission. Once the validation process was complete, the entire dataset was reprocessed using the optimal configuration derived during validation to achieve inter-calibration 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 dataset. 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 dataset was available, a per-cycle QA process was initiated to check the entire dataset 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 sea surface height 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.

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 eastern tropical Pacific Ocean, positive patch in the western part of the North Atlantic Ocean.

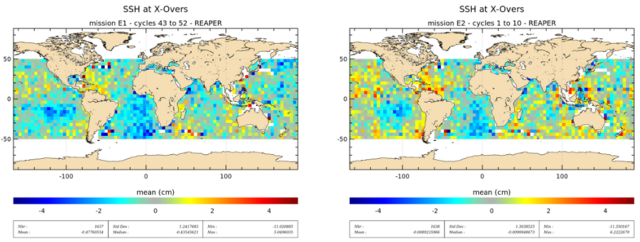

Fig. 2. Map of the mean of SSH differences at crossovers for ERS-1 (left) and ERS-2 (right) estimated from the final REAPER commissioning dataset (COM6) over the first 10 cycles of ERS-2

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.

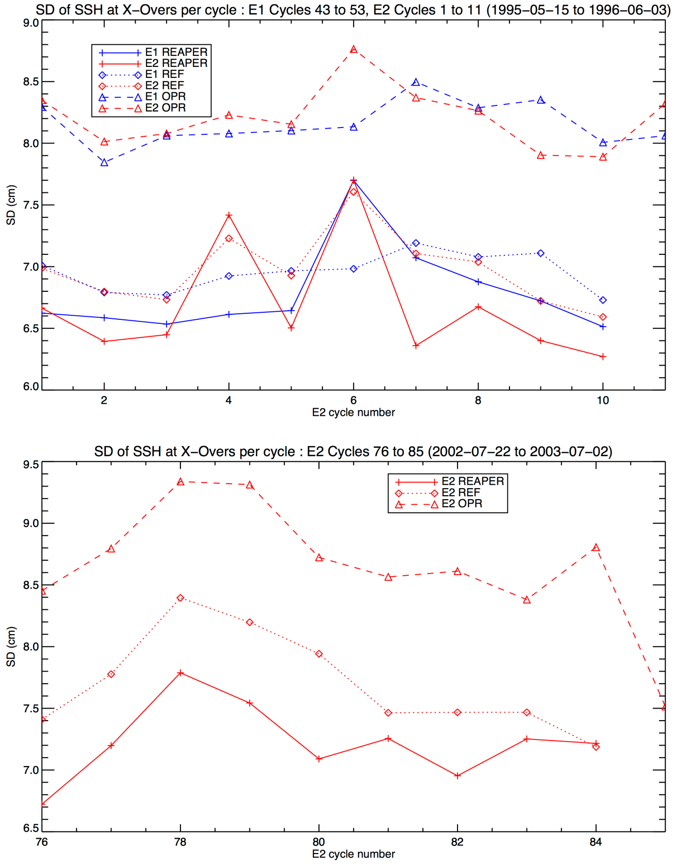

Fig. 3. Temporal evolution of the standard deviation of SSH differences at crossovers for latitudes below 50°, bathymetry greater than 1000 m and low oceanic variability areas. The statistic is derived for historical OPR, updated OPR (REF), and REAPER data, and is tabulated in Table I and Table II.

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

C. Sea level anomaly analysis

Sea surface height 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.

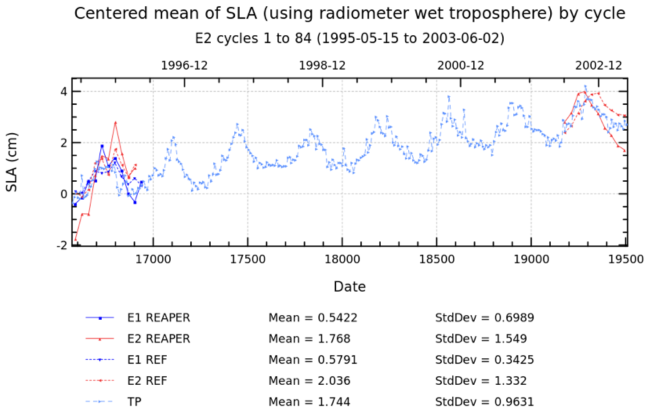

Fig. 4. Temporal evolution of the global mean SLA for all latitudes below 66° from REAPER and updated OPR ERS-1 & 2 data, TOPEX/Poseidon data are overlaid to provide a reference.

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

V. Conclusions and Potential Future Improvements

The REAPER RP01 dataset 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 dataset 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 dataset itself. The REAPER dataset will therefore be both useful and accessible to researchers wishing to make use of ERS altimetry data.

A secondary benefit of the creation of the dataset is the establishment of a reusable reprocessing framework that can be used for future reprocessing activities on ERS altimetry data. This may be an incremental improvement of the dataset due to improvements in models or algorithms, or an increase in the temporal scope of the dataset 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 dataset 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 below:

- Errors in the reprocessing of the microwave radiometer data have resulted in a wet tropospheric correction that is too large by around 2 cm
- There are jumps, both forwards and backwards, in the timestamp due to onboard single-bit errors in the clock
- 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 dataset into alignment with the newly reprocessed Envisat dataset 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, like 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 dataset is a significant advance on the previously available ERS-1/-2 altimetry datasets, and the REAPER project looks forward to feedback and results from the wider scientific community.

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