SENTINEL-3 MISSION PERFORMANCE CENTRE: ENSURING A HIGH-QUALITY ALTIMETRIC DATASET

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ABSTRACT

Sentinel-3A is scheduled for launch in Oct. 2015, with Sentinel-3B to follow 18 months later. Together these missions are to take oceanographic remote-sensing into a new operational realm. To achieve this a large number of processing, calibration and validation tasks have to be applied to their data in order to assess for quality, absolute bias, short-term changes and long-term drifts. ESA has funded the Sentinel-3 Mission Performance Centre (S3MPC) to carry out this evaluation on behalf of ESA and EUMETSAT. The S3MPC is run by a consortium led by ACRI [1] and this paper describes the work on the calibration/validation (cal/val) of the Surface Topography Mission (STM), which is co-ordinated by CLS and PML.

1. INTRODUCTION

Radar altimetry is a mature discipline, with a tightly constrained error budget in terms of both the altimetric measurements and their corrections. With international concern about rising global mean sea level, there are also detailed requirements on monitoring any slow instrumental drift within the system. The cal/val for the Jason series of satellites has benefitted from already existing well-instrumented reference sites and the timing of the missions to overlap with their predecessors, providing rigorous inter-satellite calibration during these "tandem missions". However, Sentinel-3A and 3B will occupy different 27-day repeat orbits, neither of which has been used before for altimetry. Thus the cal/val effort for S-3A and S-3B needs to make use of existing reference sites, crossovers with existing missions and comparisons with models.

A particular challenge for the Surface Topography Mission (STM) is that the Sentinel-3 Ku/C Radar Altimeter (SRAL) uses the novel delay Doppler technology [2], which was first implemented on Cryosat-2. Considering the limited experience with this technology, it is necessary to carry out further evaluation of the instrument characteristics and the implementation of the SAR processing, plus ultimately deriving new models for wind speed and sea state bias consistent with the sensor and retracker behaviour. The instrument will operate in Low Rate Mode, like previous altimeters, for the first 27-day cycle and then adopt SAR mode for all subsequent cycles. The S3MPC will be responsible for assessing and validating both modes of operation.

The S3MPC project began in autumn 2014, a full 12 months before the projected launch of S-3A, in order to enable the partners to detail the planned procedures, and have the necessary hardware and software in place ready for the launch. This paper describes the intended efforts of the many Expert Support Laboratories (ESLs), who will assess SRAL's performance over a number of different surfaces. Many of the ESLs have had extensive cal/val experience during the Envisat and Cryosat-2 missions, with that work being used to illustrate the plans described here.

2. INSTRUMENT CALIBRATION AND MONITORING

To make accurate estimates of the sea surface topography requires accurate estimation of range, orbit altitude and geophysical corrections. In terms of hardware, the S3MPC's chief concerns are the performances of the SRAL altimeter, and the MWR radiometer.

2.1. SRAL

A first part of this is the examination of waveforms to find whether a clear leading-edge is being recorded and to continue the work of the Sentinel-3 Commissioning

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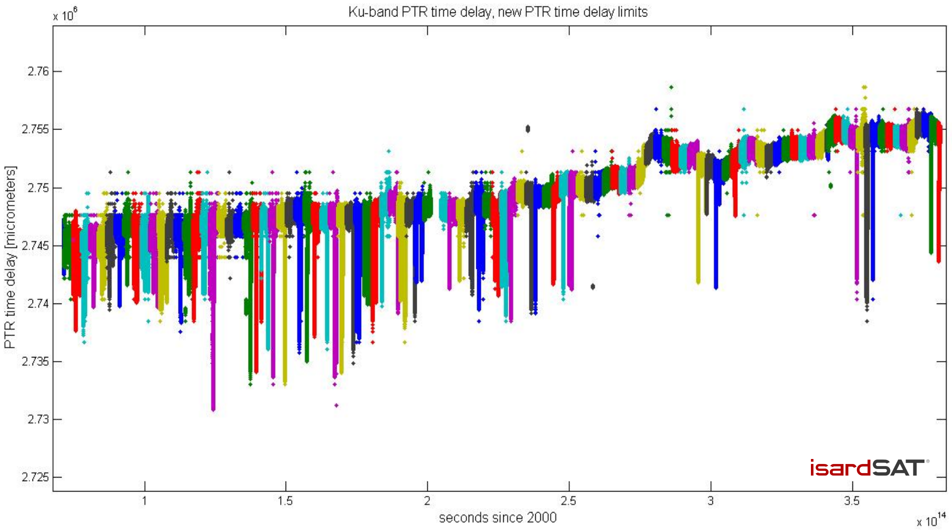

Figure 1. Time series of measurements of the Point Target Response (PTR) from Envisat, where the orbital fluctuations can also be observed (different colours for different cycles).

Team on the assessment of the acquisition and tracking modes. The full characterisation of the SRAL instrument requires the monitoring of the internal instrument parameters for a proper compensation of the geophysical retrievals by the instrument effects. Such instrumental effects are: (1) the path within the instrument (internal path delay or attenuation, measured through the Point Target Response, PTR, during the CAL1 instrument mode, see Fig. 1), (2) fluctuations or drift of the clock the drives the instrument timing (Ultra Stable Oscillator, USO), or (3) instrument transfer function, mostly affected by the Intermediate Filter (measured through the CAL2 instrument mode).

Figure 2. Protective dome housing the radar transponder based on Svalbard.

Finally, an external calibration of the whole altimeter system is provided by radar transponders. One has been deployed for many years in Svalbard (Fig. 2), where it has been used for the calibration of CryoSat-2, providing very accurate results of range, datation and interferometric baseline biases; and a new one will be employed on Crete.

The transponders return a precisely amplified version of the signal back to the satellite, enabling quantification of any range bias (through the observed delay), datation bias (by contrasting time of quickest return to overflight time), and permitting a measure of the total gain of the radar system and thus an absolute calibration of the backscatter strength, σ^0. Such a system will return very precise values, but only for 1 or 2 overpasses within a 27-day repeat cycle.

2.2. MWR Brightness Temperatures

A two-channels microwave radiometer (S3-MWR, 23.8 and 36.5 GHz) is flown with the altimeter in order to correct the altimeter range for the excess path delay resulting from the presence of water vapour in the troposphere. Additional Level-2 radiometer geophysical parameters are the atmospheric attenuation of the altimeter backscattering coefficient, the cloud liquid water content and the integrated water vapour. The radiometer will perform measurements of brightness temperature (BT) in both bands interpolated to the location of the altimeter footprints.

These BT measurements will be assessed in three different manners using the same approach applied with success for the assessment of Envisat and AltiKa radiometers [3-4]. Combining these metrics, the brightness temperatures will be fully validated providing very good confidence in the quality of Level 2 radiometer geophysical parameters.

Firstly a radiative transfer model (from the Université Catholique de Louvain [5-6]) will be applied to the ECMWF reanalysis of the atmospheric conditions to infer what radiances should be observed; this is then contrasted with the satellite records (Fig. 3).

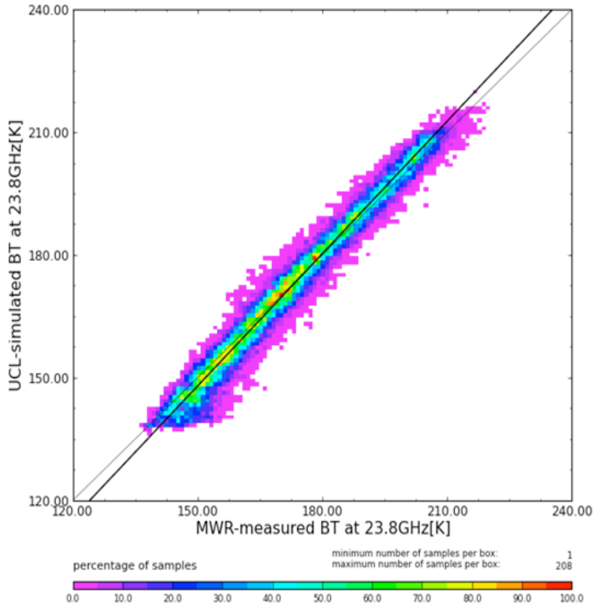

Figure 3. Scatter plot of 23.8 GHz BT from Envisat against output from the Radiative Transfer Model.

Secondly there will be a comparison with coincident measurements from other radiometers. This was previously done for Envisat, revealing problems with the calibration of the 36.5 GHz channel. With radiometers on other altimetric missions such as Jason-2, Jason-3 and AltiKa, plus swath measurements from scanning systems such as AMSU-A, there will be plenty of comparisons; however care is required as not all operate at exactly the same frequencies as Sentinel-3. The analysis will make use of the 'Double Difference' method whereby both radiometers are compared to the predictions of an atmospheric model, and their departures from the modelled behaviour are contrasted.

The third aspect of the MWR monitoring is the use of natural targets as references. The hottest BT values over the Amazon rain forest will be monitored, since this is known to be a stable reference with an emissivity close to that of a blackbody [7]. The ocean itself provides the cold reference; the coldest BTs are monitored, applying a statistical selection that removes the main part of the geophysical variation [8].

3. OCEAN VALIDATION

The S3MPC will concentrate on 3 aspects of the validation over the ocean — a global comparison, validation at coastal sites, and a comparison of wind and wave measurements with those from models and buoys.

3.1. Global Ocean Analysis

It is essential that the sea surface height values returned by Sentinel-3 are both self-consistent and also agree with those from other altimeters. A primary approach is through analysis of crossovers between ascending and descending altimeter tracks: if the region is oceanographically quiet, or the time separation of the tracks is small then the same sea level should be returned. Such an approach cannot deal with a bias in the observing system, but has been instrumental in highlighting errors in the orbits or geophysical corrections.

An extension of this is to contrast records between two observing systems. Ollivier et al. [9] calculated differences in contemporaneous sea level between Jason-1 and Envisat: initially large differences, with broad geographical patterns, were significantly reduced once the Envisat data had undergone the v2.1 reprocessing with updates.. Geographical patterns in the bias between two altimeters hint at erroneous corrections, for example if errors are greater in the regions of large waves, then sea state bias may be part of the cause.

The consortium will also be constructing a marine match-up database that will include data from all freely-available tide gauges coincident with Sentinel-3 overflights. This database will be used for both local comparisons and for contrasting global mean sea level records from altimetry and tide gauges. The contents of this database will be made available to all within the S3VT.

The determination of an appropriate sea state bias model for Sentinel-3A cannot be attempted early in the commissioning phase, as it relies on there being sufficient data for a robust calculation of the terms, and thus such work will begin later in the project.

3.2. Coastal Validation

The smaller footprint size achieved by delay Doppler altimetry should avoid many of the waveform contamination problems found for conventional altimetry near the coast, enabling geostrophic currents to be derived close to land. The project will make use of regional absolute height bias measurements obtained from already-established validation sites at Harvest, Corsica and Bass Strait [10], but will also assess the usefulness of high-spatial resolution high-precision measurements for investigating currents in the coastal zone.

There will be dedicated coastal validation for two sites around the southwest of the UK (Fig. 4). The first is the Western Channel Observatory, a well-instrumented site to the south of Plymouth, where an ADCP instrument has been deployed just underneath a buoy recording a full suite of meteorological parameters. This location is subject to frequent visits for biological sampling and so the instrumentation will be well maintained. The matched records of wind speed and direction will enable the Ekman component to be estimated and subtracted from the total current recorded by the ADCP.

The second site is in the Celtic Sea to the northwest of Cornwall, which is covered by a high-frequency radar system based at Pendeen and Perranporth. The radar system gives coverage out to 100 km from the coast at a resolution of order 2 km, returning values for both current and wave height. The coverage spans 2 passes of Sentinel-3A and 2 of Sentinel-3B. The Celtic Sea is subject to swell coming in from the North Atlantic and so will show a range of wave conditions. It has a number of offshore currents, and their position in altimeter and HF records may be compared to frontal features seen in other Snetinel-3 sensors.

Figure 4. Location of coastal validation sites off southwest UK, with the Western Channel Observatory being located just offshore of Plymouth.

3.3. Evaluation of Metocean Data

Range is not the only important information coming from the altimetric data stream. The waveforms recorded by conventional low rate mode (LRM) instruments have been used to infer significant wave height (SWH) and normalized radar cross section, σ^0. After adjustment for inter-satellite biases, these σ^0 values have been used to infer wind speed (WS) via a universal wind speed algorithm [11].

Two other meteorological parameters in the data stream are the Total Column Water Vapour (TCWV) and the liquid water content (LWC), which are derived from the radiometer BT values and used to produce corrections to the altimeter range, which are important at the centimetre-level.

All four of these parameters (SWH, WS, LWC & TCWV) will be compared to analysis data from the Integrated Forecasting System at ECMWF. Fig. 5 shows a similar analysis for WS from Envisat. There will also be a special investigation of locations where metocean buoys are sited, using triple collocation analysis, which provides an estimate of the errors, by assuming that the errors in the three inputs (altimeter, buoy and model) are independent. The comparisons to model output can be done on a daily basis, but those involving the *in situ* sensors will be aggregated on a weekly or monthly basis, due to their scarcity.

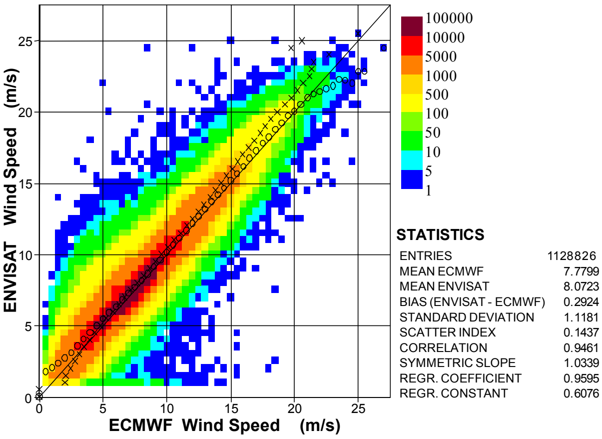

Figure 5. Example of scatter-plot validation of Envisat wind speed records against ECMWF analysis.

Examination of the simultaneous observations at Ku- and C-band also provides a means of monitoring any changes in σ^0 calibration [12-13].

4. ICE VALIDATION

The scientific applications of altimeter data have long extended to surfaces other than ocean. To ensure that SRAL data can be used with confidence over the cryosphere it is essential that the S3MPC activities cover this realm.

4.1. Sea Ice

Altimetric returns in a region of sea-ice are complicated, with the ice floes providing a diffuse reflector, generating waveforms similar to those over open ocean, whereas the ocean surface glimpsed in leads acts as a specular reflector, giving spiky waveforms. Thus a pivotal part of interpreting waveform data in this region is characterizing the nature of the reflecting surface, before applying the appropriate retracker. This ability to correctly classify the return echoes will be assessed by comparison to high-resolution SAR imagery of the sea-ice region using Sentinel-1 data. Prior investigations using Cryosat-2 data have demonstrated the applicability of the approach (see Fig. 6), but some modification may be needed for the different characteristics of the SRAL altimeter.

Subsequently both lead- and floe-waveforms need to be retracked to give a surface height. Any bias between these retrackers will be estimated by contrasting.

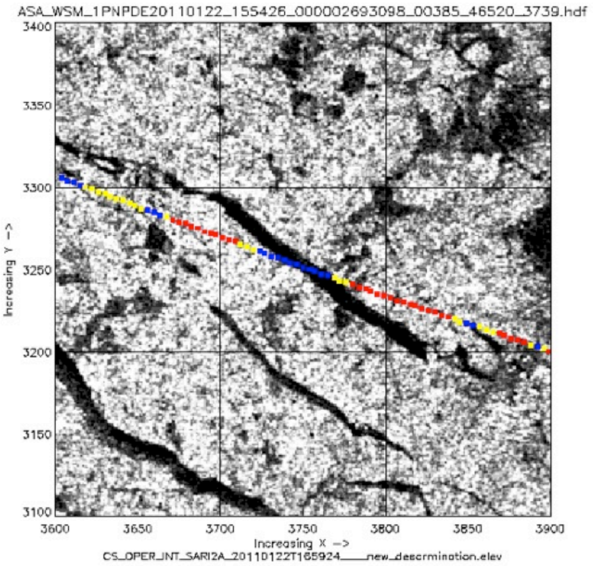

Figure 6. Altimetric waveform classification compared with coincident SAR data from a different platform. This illustration shows ASAR data as the grey-scale background with the leads appearing as thin black lines, whilst the coloured dots represent the independent classification of the Cryosat-2 waveform data (blue-leads; red-floes; yellow-uncertain).

records in a region of thin broken ice, such as the Eurasian Basin of the Arctic Ocean. Then the difference between floe and lead retrackers will be used to infer the ice freeboard, and thence thickness (Fig. 7). These estimates may then be compared with records from other altimetry missions or *in situ* data.

4.2. Land Ice

Altimetric returns from the snowpack on land ice are very different, with a mix of surface and volume scattering, plus the undulating topography producing significant returns from points not at nadir. Within the Sentinel-3 processing chain a number of different retrackers are applied in parallel e.g. Brown ocean model, Ice1, and Ice2. The project will look at the wide variety of estimates coming from each of these retrackers and examine their consistency within the mission and also how they compare to records from previous altimeters. This is a non-trivial exercise because all the altimeters have had slightly different operating characteristics (altitude, antenna beamwidth, polarization) which affect the precise values returned. . Maps of the various parameters will be compared with those from previous missions (Fig. 8) and especially with Cryosat-2, which should overlap with Sentinel-3. There will also be comparisons with *in situ* data, such as local GPS surveys and transits within Operation Ice Bridge

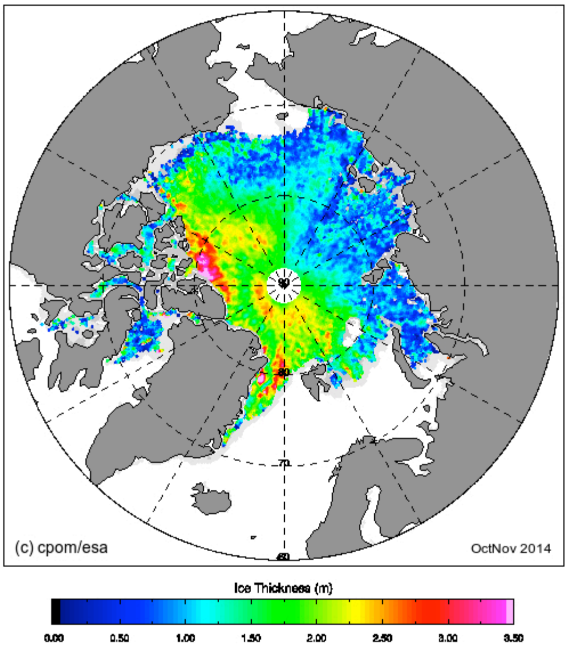

Figure 7. Arctic sea-ice thickness in October 2014, determined by differencing Cryosat-2 measurements of ice floes and leads. Such maps can be routinely updated (http://www.cpom.ucl.ac.uk/csopr/seaice.html)

5. INLAND WATERS AND RIVERS

The last few decades have seen increasing use of altimetry over inland waters and rivers, due to the existence of better digital elevation models and more agile retrackers enabling a greater return of data over such surfaces. This has not only increased the science performed using altimetry, but enabled these surfaces to contribute to the cal/val. This is work that is scheduled to commence in the Routine Operations Phase, when data from more than a year will be available.

5.1. Lake Issyk-kul

Calm lakes offer a particularly exciting opportunity for altimeter calibration. On the positive side many of the altimeter corrections can be negligible e.g. tides, inverse barometer effect and sea state bias. However, the challenges for an inland location are accurate estimates of the wet tropospheric correction (the radiometer-derived correction will not be valid) and that the altimeter signal is not corrupted by nearby land returns. Lake Issyk-kul in Kyrgyzstan has proven to be an excellent location for the evaluation of previous altimeters, because it offers a long transit, with good repeatability of GPS surveys (Fig. 9).

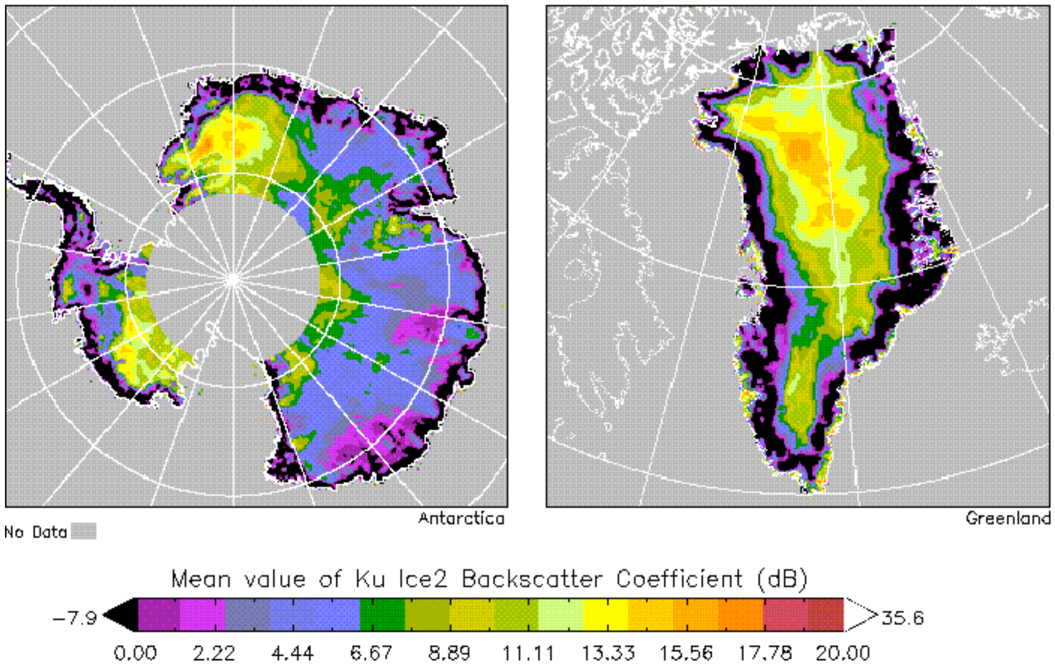

Figure 8. Maps of backscatter coefficient from the Ice2 retracker applied to Envisat data.

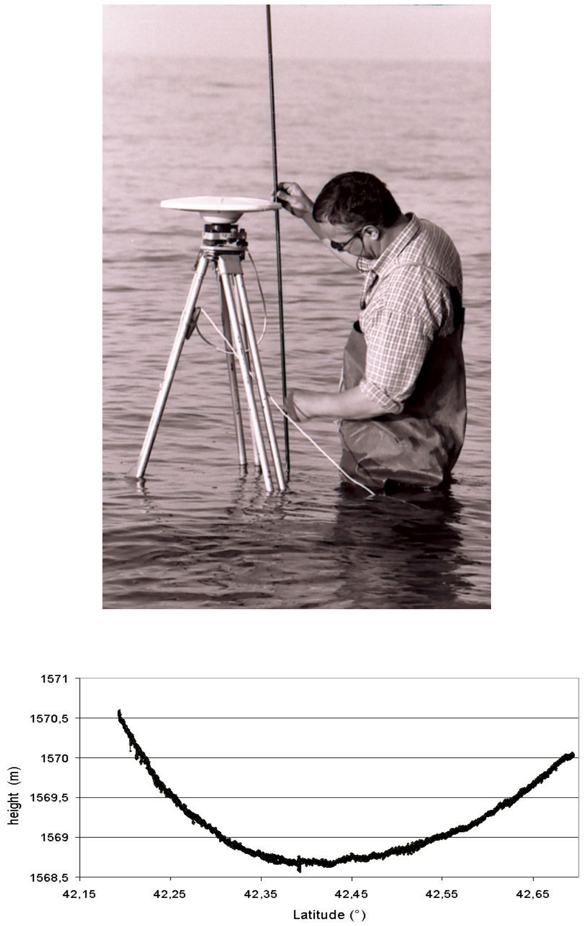

Figure 9. (upper) Field work to determine absolute lake level with a GPS system. (lower) Repeatability of profiles along Envisat track.

5.2. Other Lakes

There are many other lakes, for which regular reliable lake levels are recorded, with a network of ~100 big lakes in the Global Terrestrial Network for Lakes (GTN-L). Databases such as this were used by Ričko et al. [14] in their assessment of lake water levels recorded by several altimetrically-derived datasets. Through collaboration with the Russian State Hydrological Institute in St. Petersburg, the consortium will have access to daily data from a further 10 lakes, with another ~20 returning records on a monthly basis. These will be used to quantify errors in Sentinel-3 data, with comparisons also made to data from other missions to establish the long-term continuity and consistency of such lacustrine levels.

6. SUMMARY

The Sentinel-3 Mission Performance Centre has brought together a large number of European experts in altimetry. To fulfil their mission of ensuring the data from the surface topography mission are of the highest quality, these Expert Support Laboratories are adopting a number of validation techniques that they have previously utilised for Envisat and Cryosat-2, but are also developing new capabilities, especially to deal with the delay Doppler mode of operation, its smaller ground footprint, and thus the potential to record useful information nearer to the coast, and over much smaller lakes and rivers than before. The S3MPC is developing a series of analytical tools that will monitor the quality of Sentinel-3A and Sentinel-3B products, and will detect short-term changes in performance as well as long-term drifts in the system.

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