GAVDOS/WEST CRETE CAL-VAL SITE: OVER A DECADE CALIBRATIONS FOR JASON SERIES, SARAL/ALTIKA, CRYOSAT-2, SENTINEL-3 AND HY-2 ALTIMETER SATELLITES

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ABSTRACT

This work presents and compares the latest altimeter calibration results for Jason series, the SARAL/AltiKa the Chinese HY-2 missions and the ESA missions of CryoSat-2 and Sentinel-3, conducted at the Gavdos/Crete calibration/validation facilities. At first, the Jason altimeter calibration values will be given for the ascending Pass No.109 and the descending Pass No.18, based on the GDR-E (Jason-1), GDR-D (Jason-2) and GDR-T (Jason-3) products. Secondly, these values will be cross-examined against the altimeter bias for the SARAL/AltiKa (GDR-T) satellite at Gavdos Cal/Val using its reference ascending orbit No. 571. The Chinese HY-2 satellite altimeter bias will be presented using the CRS1 permanent site in southwest Crete for the descending HY-2 Pass No. 280, at 20 Hz based on SGDR data products. Finally, values will be compared against the Sentinel-3 altimeter. Additionally, altimeter biases as determined by locally developed Mean Sea Surface models, will be presented and compared with the conventional sea-surface calibration methodology.

1. INTRODUCTION

The Global Climate Observing System has defined a list of 50 Essential Climate variables (ECVs). An ECV is a physical, chemical, or biological variable or a group of linked variables that critically contributes to the characterization of Earth's climate [1].

In 2010, the European Space Agency launched the Climate Change Initiative (CCI) to provide satellite-based climate data records for 13 Essential Climate Variables. Sea level is one of these ECVs and the aim is to realize the full potential of the long-term Earth observation archives that both ESA and third parties have established. The scientific challenge is to reduce the uncertainty of the global mean sea level (GMSL) trend below 0.3 mm/yr [2].

Direct estimation of the height for the global mean sea level, requires dense and uniform observations over the entire oceans. Tide gauges provide measurements of the local relative sea-level since the 18th century. Today, a large number of tide gauges are operational worldwide. For example, the Intergovernmental Oceanographic Commission Sea Level Station Monitoring Facility (IOC/SLMF) announced on 20-01-2016 that 829 active tide gauges stations were tracked [3]. However, a significant gap in monitoring open ocean exists as tide gauges are commonly installed in coastal regions. Moreover, these tide gauges are disproportionately located in the Northern Hemisphere whereas a vast number of them do not take into account land movements leading to misinterpretation of their data. Thus, an even smaller number of tide gauges are used for the analysis for a long-term change in the global mean sea level [3].

To fill this gap, precise measurements of the surface topography of the ocean, and of continental waters are made through satellite altimetry. An orbiting satellite emits electromagnetic waves to the surface of the Earth. It then records the reflected signals and their time of arrival. From these altimetric observations, the range from the satellite to the earth surface, as well ocean wave height and wind measurements can be determined precisely. In this manner, changes in the earth and the ocean system are monitored through satellite altimetry in an absolute sense and with respect to the center of mass of the earth.

Re-analysis of 20 years of satellite altimeter observations with improved algorithms and a joint validation procedure indicate that the uncertainties for the global mean sea level and regional trends are 0.2

Proc. 'Living Planet Symposium 2016', Prague, Czech Republic, 9–13 May 2016 (ESA SP-740, August 2016)

mm/yr and 1-2 mm/yr higher that the Global Climate Observing System requirements [4].

In order to achieve this level of accuracy, sensors onboard satellite altimetry are calibrated prior to their launch. Unfortunately, no matter how sophisticated the instruments are, once in space they degrade with time, e.g., due to thermal, mechanical or electrical effects or exposure to UV radiation, etc. [5]. Thus, in order to monitor the satellite sensor performance once in orbit, post launch calibration processes with ground truth processes must take place. The objective is to define the sensor responses to known signal inputs that are traceable to established reference standards. For satellite altimetry missions, several post-launch calibration methodologies have been proposed and implemented:

- *Tide-gauge network*. This technique was proposed in [6] and involves the processing of the measurements obtained from high-quality tide gauges to determine regional and global long-term (seasonal) trends in sea level variation.
- *Cross-over calibrations*. The multi-mission cross-over analysis aims at estimating errors for all altimeter systems operating simultaneously at the same sea surface location and almost simultaneously, but has mainly been used to determine altimetric range biases [7].
- *Sea-surface calibration* at permanent calibration sites. This technique is performed by dedicated calibration/validation sites located under the satellite's ground track. These sites are equipped with diverse scientific sensors (i.e., tide gauges, GNSS receivers, buoys, meteorological sensors, etc.) to provide accurate estimates of the absolute altimeter measurement bias and altimeter's stability. In addition, monitoring of the satellite's microwave radiometer is also performed mainly via dedicated GNSS-derived troposphere dealys. Currently, there exist only four such sites in the world [8, 9, 10, 11] that operate continuously for more than a decade.
- *Transponder calibration*. The idea for incorporating land-based transponders was initially introduced in [12]. This technique has been used for the calibration of Envisat [13], Jason-2 [14], CryoSat-2 [15] and HY-2A [16] altimetric missions.

The first two techniques provide relative altimeter calibration, whereas the remaining two give absolute estimates for the altimeter bias. It is not the purpose of this paper to provide details on the pros and cons of each method. This work presents the absolute and relative satellite altimeter bias results as determined by these Cal/Val techniques as applied at the Permanent Altimetry Calibration Facility (PACF) in Gavdos/Crete, Greece.

The present paper is structured as follows: Section 2 describes the PACF's infrastructure and instrumentation. Section 3 presents the multi-mission sea-surface calibration results after 13 years of PACF's operation. In Section 4, preliminary results on transponder calibrations are given, followed by Section 5, where the outcome of direct comparison of the sea-surface heights are determined at selected crossover points at sea. In Section 6, the final conclusions are presented along with a discussion on the future evolution of the PACF.

2. THE PACF SETTING

Certain criteria must be fulfilled to provide absolute calibration of satellite altimeters when the *sea-surface calibration* technique has been employed. These are summarized as:

- The distance between the calibration facility and the satellite's nominal ground track should be as small as possible, and preferably less than 2-3 km;
- The facility's tectonic motion must be monitored dynamically to determine the absolute height of the reference surface above ellipsoid;
- Appropriate modelling of the parameters that influence the calibration procedure must be applied. The atmospheric delays (wet and dry troposphere, ionosphere) must be accurately known. In addition, the geoid undulation, the mean sea surface, the mean dynamic topography, the significant wave height, etc., have to be modelled for incorporation in the sea-surface calibration technique.
- Any land contamination on both the altimeter and radiometer signals has to be taken into account to obtain valid satellite measurements.

Fig. 1 presents the ground tracks of the currently operating altimetry missions and the location of the main Cal/Val sites of the permanent altimeter calibration facility: Gavdos, RDK1, and CRS1.

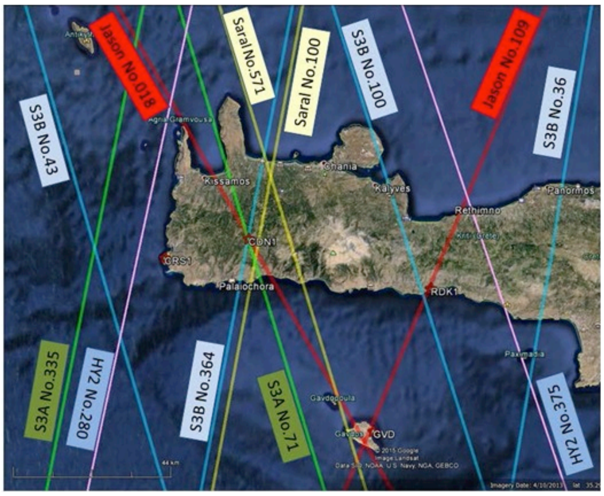
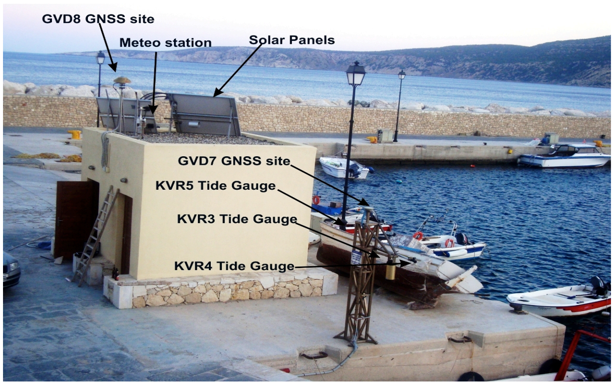
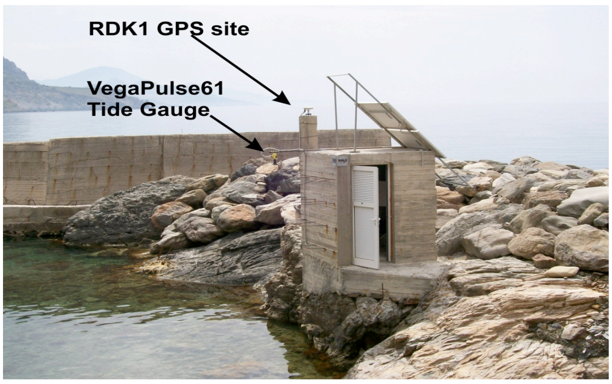


Figure 1. The permanent calibration infrastructure for satellite altimetry in Gavdos and West Crete, Greece.

It is obvious, from the ground tracks shown, that the PACF can be used for calibrating both ascending and descending orbits of several missions (i.e., Jason-1, Jason-2, Jason-3, Sentinel-3A). The various instrumentation, operating at the PACF sea-surface Cal/Val sites, is presented in Fig. 2.





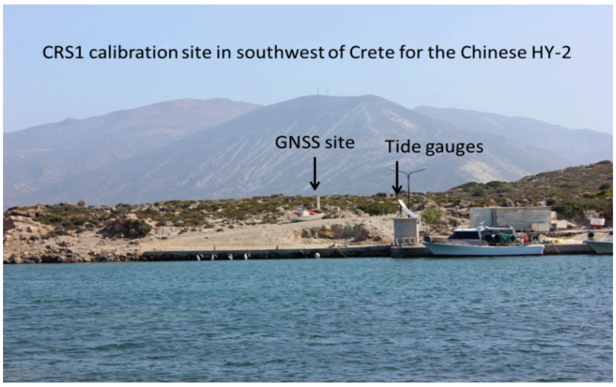


Figure 2. The Gavdos (up), RDK1 (middle) and CRS1 (down) Cal/Val sites constitute the PACF components for sea-surface altimeter calibration.

Currently, a network of 17 GNSS receivers, 8 tide gauges, 6 automated meteorological stations and several auxiliary scientific sensors, is active, continuously operating that supports sea-surface calibration at the PACF in Gavdos and West Crete.

The CDN1 *transponder altimeter calibration* site has been presented in detail in [17]. It is a location on the west Crete mountains at an elevation of about 1100 m where four satellites (Sentinel-3A, Sentinel-3B, Jason-2, Jason-3 and SARAL) are flying over. As shown in Fig. 3, the transponder at CDN1 site is to calibrate, on a regular basis, the Sentinel-3 and Jason satellites, where in addition, other calibrations of CryoSat-2 are carried out, whenever this satellite flies over that site.

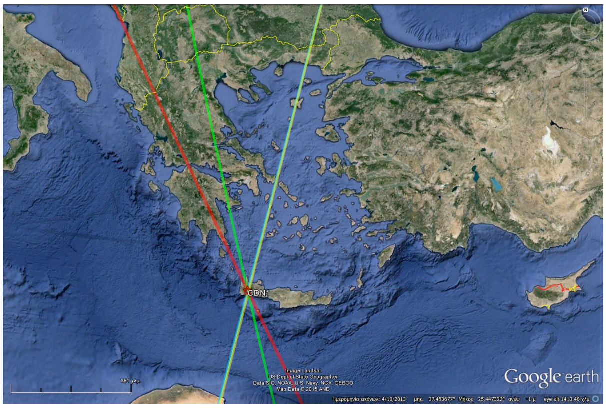


Figure 3. The CDN1 transponder calibration site can be routinely used for the calibration of Jason-2/Jason-3/ mission (red ground track, Sentinel-3A (green ground track) and Sentinel-3B (blue ground track). The SARAL/AltiKa mission (yellow) may be also calibrated if this site is upgraded to a Ka-band transponder.

The main scientific instrument installed at the CDN1 site is the microwave transponder. Nonetheless, a series of other ground instruments (i.e., GNSS receiver, meteorological sensors, etc.) also support transponder calibrations in this mountainous site.

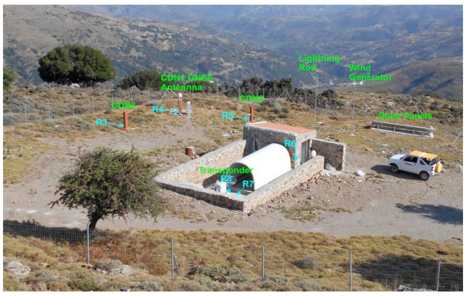


Figure 4. The CDN1 transponder calibration site.

An examination of Fig. 1 and 3 reveals that *relative altimeter calibration* techniques can also be carried out at this PACF. For example, multi-mission crossover points exist in the open sea (Jason/AltiKa, Sentinel-3A/AltiKa, Sentinel-3A/Sentinel-3B, Sentinel-3B/HY-2A) but also on land (Jason/Sentinel-3, Sentinel-3/CryoSat-2, Jason/CryoSat-2). In addition, sea-surface calibration over ascending and descending orbits of the same mission (Jason ascending Pass No.018/descending Pass No.109, Sentinel-3A ascending Pass No.071/descending Pass No.007) may reveal directional errors for the altimeters (Fig. 5).

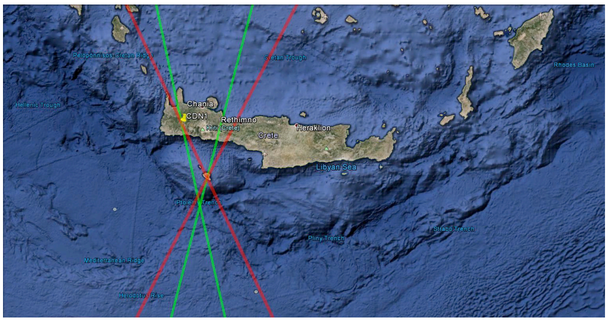


Figure 5. Various crossovers of ascending and descending passes for Jason (red) and Sentinel-3A (green) missions.

Another unique characteristic of the PACF facilities is that, for the first time, is possible to calibrate the same satellite using both transponder and sea-surface techniques on the same orbit. This is currently feasible for Jason Pass No.018 and Sentinel-3A Pass No. 071 but may be further extended to Sentinel-3B Pass No. 364 (Fig. 1), as well.

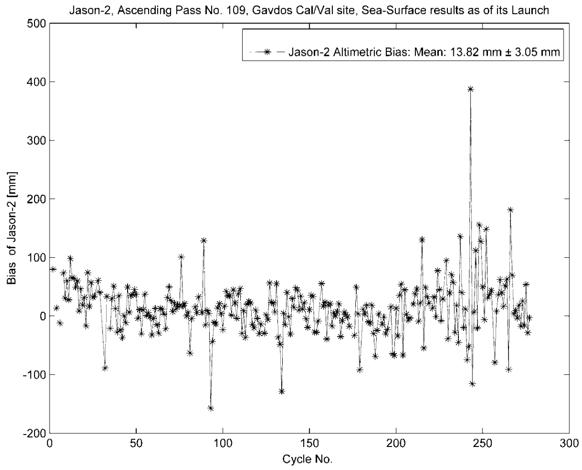
In the following Sections recent calibration results for all operational satellite altimetry missions are presented.

3. SEA-SURFACE CALIBRATION

The PACF facilities have been provided absolute altimeter range bias employing the sea-surface calibration for more than a decade. The methodology for determining the Jason range biases has been initially presented in [11]. For example, Fig. 6 illustrates the range bias estimation for the Jason-2 Pass No.018 and Pass No.109 as from its satellite launch in 2008 till now. Results for Jason-1 are not presented hereafter, as at the moment of writing this paper no complete products of GDR-E had been released.

In order to connect the recently (2016) launched Jason-3 mission with the Jason-2 reference mission, absolute bias of Jason-3 are provided in Fig. 7 for its initial cycles of operation.

In [18] the sea-surface calibration technique for the SARAL/AltiKa mission has been described. This satellite's latest calibration results are presented in Fig. 8. Similarly, [19] provides details on the calibration of the Chinese HY-2A satellite altimeter, employing the CRS1 \Cal/Val site of the PACF facilities in south west Crete.



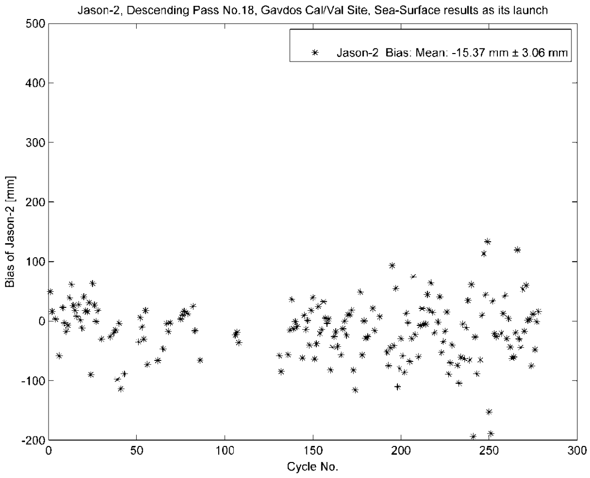


Figure 6. Long-term calibration of Jason-2 for the ascending Pass No. 109 and the descending Pass No. 018, based on GDR-D products.

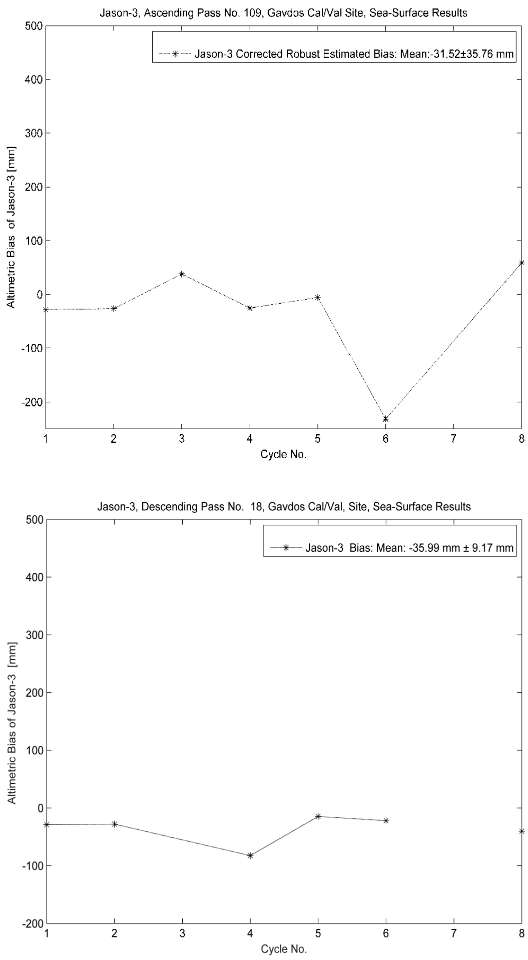


Figure 7. Jason-3 absolute calibration at the PACF facilities for its ascending Pass No. 109 and descending Pass No. 018, using IGDR-T products.

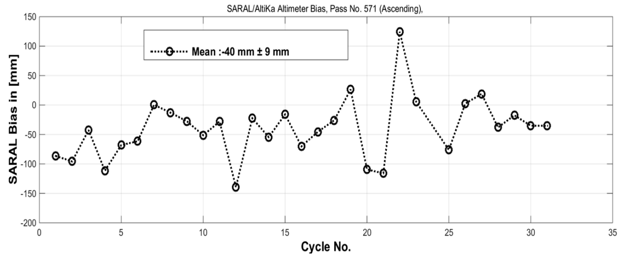
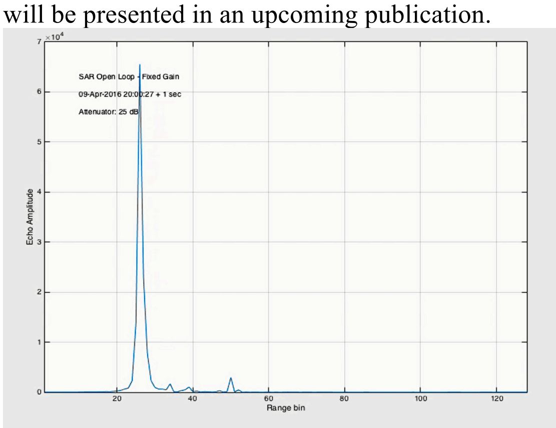


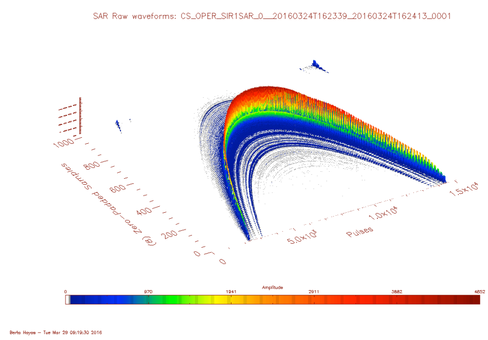
Figure 8. SARAL/AltiKa absolute calibration at the PACF facilities for its ascending Pass No. 571 using GDR-T products.

4. TRANSPONDER CALIBRATION

In the period between 2-Oct-2015 to 8-May-2016 the CDN1 site has been operational for transponder calibrations of Jason-2 (16 cycles), CryoSat-2 (5 passes), Jason-3 (6 cycles), and Sentinel-3A (3 cycles). Samples of responses for each satellite are presented in Fig. 9. Processing of these transponder responses to derive the altimetric range bias is currently ongoing and will be presented in an upcoming publication.



(a)



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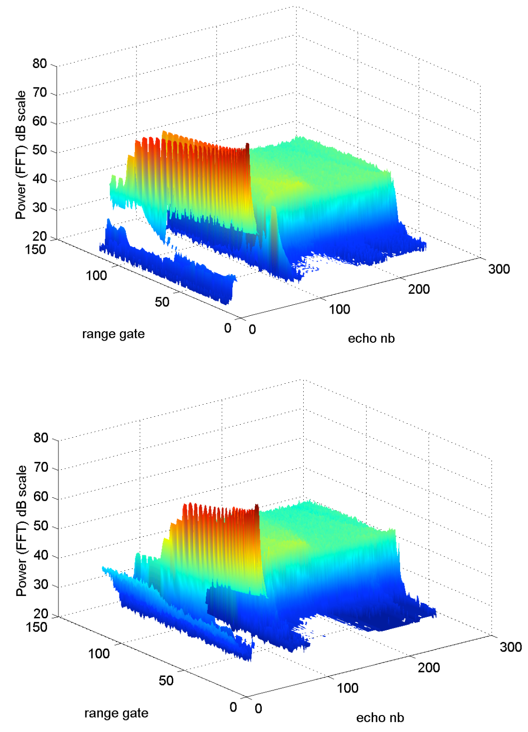

(c)

(d)

Figure 9. Illustration of the satellite signal responses to the transponder operation located at the CDN1 Cal/Val site. (a) Sentinel-3A, 9-Apr-2016 (credits: ESA), (b) CryoSat-2, 24-Mar-2016 (credits: ESA), (c) Jason-2, 27-Apr-2016 (credits: CNES), (d) Jason-3, 27-Apr-2016 (credits: CNES)

5. RELATIVE CALIBRATION

Multi-mission cross-calibration of Jason-2 Pass No.109 and SARAL/AltiKa orbit No. 571 at their cross over location south of the Gavdos island (Fig. 1) has also been performed. The processing methodology has been presented in [17] while the latest results are given below in Fig. 10. It can be seen that SARAL/AltiKa measures less than the Jason-2 altimeter.

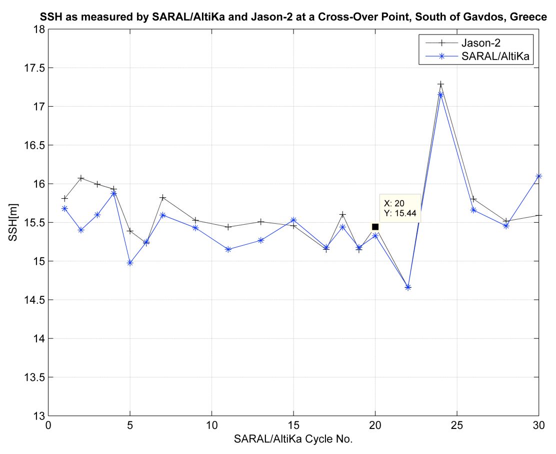

Figure 10. A crossover comparison of sea surface heights between SARAL/AltiKa against Jason-2 for a time window less than 3 days.

A similar investigation to obtain relative calibration of Sentinel-3 and Jason-2/Jason-3 missions is under investigation by this team and the results are expected to be announced soon.

6. CONCLUSIONS & FUTURE WORK

Post-launch calibration and validation of measurements obtained by scientific instruments on-board earth observing satellites is a challenging task that requires long-term commitment, high-level instrumentation, advanced modelling and processing methodologies, and traceability of all contributing errors.

In this work, the Permanent Altimeter Calibration Facility established in Gavdos and West Crete in Greece has been briefly presented.

The latest calibration results for Jason-2 and Jason-3 as well as for the SARAL/AltiKa altimeter have been given. It has been shown that directional errors of the Jason satellites have been revealed after calibrating at the same facility both ascending and descending passes.

Inter-calibration of the Jason-2 and Jason-3 tandem mission demonstrates that Jason-3 will continue to provide indispensable reference measurements for the global mean sea level monitoring.

Preliminary findings of the Jason-2 and Jason-3 transponder calibrations are encouraging, although more cycles have to be processed to arrive at a clear picture for the transponder uncertainty budget.

In the near future, modernization of the PACF facility's instrumentation will be performed through the Fiducial Reference Measurements for Altimetry project funded by ESA.

Finally, this team is currently developing new processing tools for inter-calibration of satellite altimeters and preparing the ground for the two-dimensional calibration of future altimetric missions such as the Surface Water and Ocean Topography (SWOT) mission to be launched in 2020.

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