

Report of the

Ocean Surface Topography Science Team Meeting

Reston Hyatt

Reston, VA

October 19-23, 2015

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Organized by NASA, CNES, NOAA and EUMETSAT

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1 Executive Summary

The 2015 Ocean Surface Topography Science Team (OSTST) Meeting was held in Reston, VA, October 19-23. The meeting was held alongside the 9th Coastal Altimetry Workshop (CAW) in the same location on Oct 17-18. The primary objectives of the OSTST Meeting were to (1) provide updates on the status of OSTM/Jason-2 (hereafter, Jason-2), (2) conduct splinter meetings on the various corrections and altimetry data products, and (3) discuss the science requirements for future altimetry missions. The meeting lasted 3.5 days, to accommodate time for discussions during dedicated round tables for each splinter. This report, along with all of the presentations from the plenary, splinter and poster sessions are available on the AVISO website: <http://www.aviso.altimetry.fr/en/user-corner/science-teams/ostst-swt-science-team/ostst-2015-reston.html>.

Since the meeting in October, Jason-3 was successfully launched from Vandenberg Air Force Base on January 17, 2016 aboard a Falcon 9 launch vehicle built by SpaceX. All of Jason-3's systems and instruments are operating nominally and as of February 12, it was maneuvered into position approximately 80 seconds behind Jason-2 where it will spend six months while the data is evaluated relative to Jason-2. After that, Jason-2 will be moved into an interleaved orbit on an adjacent ground track with a 5-day lag, identical to the one flown by Jason-1.

Jason-2 was launched in June 2008 on the former ground track of Jason-1 and TOPEX/Poseidon. All systems are in good condition and the satellite is operating nominally after 7.5 years in orbit. The mission has been approved to be extended up to 2017 at both CNES/EUMETSAT and NASA/NOAA. No major events occurred this year on the platform side. After a switch to GPSP-B on September 8, 2014, several software patches have been applied and the side-B performance is now as good as the side-A instrument. From a global point of view, Jason-2 continues to collect data that meets all mission and level-1 science requirements. After consideration by the splinters and a dedicated "Extension of Life" working group (referred to as the "EoL subgroup", the OSTST adopted the following recommendations: ***The OSTST recommends that Jason-2 be moved to a geodetic orbit, preferably at +35 km altitude (12+247/401), to support geodetic studies if and when it becomes feasible.*** Although this orbit was identified as desirable, the OSTST also acknowledged that further study and consideration of future launches and the overall health of the altimeter constellation, by both the Projects and the OSTST Jason-2 EoL subgroup, are needed in order to determine the optimal timing of any move to a geodetic orbit.

In order to improve long-term stability of global mean sea level estimates based on altimeter data, the Jason-3 project will implement a calibration maneuver, designed to point the Advanced Microwave Radiometer (AMR) toward deep space, approximately once per month. In recognition of the importance of maintaining long-term stability in both Jason satellites, the OSTST also adopted the following recommendation: ***The Jason-2 Project should consider implementation of the radiometer calibration maneuver that will be implemented on Jason-3 in order to provide a cold-sky calibration look for the AMR on Jason-2 after it has been successfully demonstrated on Jason-3.*** Improvement of radiometer performance on future missions was also discussed in the Instrument Processing splinter. Airborne instruments have demonstrated the capabilities of high-frequency radiometers to provide improved wet path delay correction near land. ***Therefore, the OSTST again recommends that future altimetry missions should consider adding additional higher-frequency radiometer channels in order to improve coastal and inland water wet path delay corrections.***

Continuity and maintenance of the long-term sea level record being of the utmost importance, the OSTST also made two recommendations regarding past missions and future missions. Although the

mission has long since ended, data from TOPEX/Poseidon remains widely used in scientific studies and is a key part of the sea level climate data record. ***The OSTST recommends that the Jason projects continue to support efforts to bring TOPEX/Poseidon data in line with modern altimetry standards. In addition, we recommend that all altimeter missions develop a plan to provide open, freely available and up-to-date documentation of all processing techniques and project events for official releases of altimeter data and to archive all relevant information at the end of each mission.***

Three keynote talks were given during plenary sessions of the OSTST (see section 4).

Finally, during the meeting several members of the OSTST expressed a desire to issue some type of statement highlighting the importance of satellite altimetry for monitoring and understanding climate change in advance of the 2015 Conference of Parties (COP21), which is the annual review meeting for the United Nations Framework on Climate Change. Although no language was formally adopted by the team during the meeting, meeting co-chairs Pascal Bonnefond and Josh Willis penned an open letter to the organizers of COP21, which was signed by more than 280 supporters and many on the OSTST. The letter was delivered in person by Pascal Bonnefond to several key participants in COP21. The letter can be read in full on Change.org: <https://www.change.org/p/cop21-deciders-ask-the-cop21-to-recognize-sea-level-rise-as-the-top-indicator-of-climate-change>

2 Introduction

The 2015 Ocean Surface Topography Science Team (OSTST) Meeting was held in Reston, VA, October 19-23. The meeting was held alongside the 9th Coastal Altimetry Workshop (CAW) in the same location on Oct 17-18. On behalf of the Project Scientists (Lee-Lueng Fu and Josh Willis, NASA; Rosemary Morrow and Pascal Bonnefond, CNES; John Lillibridge, NOAA; Remko Scharroo, EUMETSAT), the meeting was opened by Josh Willis who presented the agenda and discussed logistics.

3 Program and Mission Status

The program managers presented the status of altimetry and oceanographic programs at NASA (Eric Lindstrom), CNES (Philippe Escudier), EUMETSAT (François Parisot), NOAA (Laurie Miller) and ESA (Jérôme Benveniste).

Philippe Escudier (CNES) first reported on the CNES Ocean Program status by illustrating the current and future constellation in which CNES is involved at various level of contributions (Figure 1). The main priorities were identified in terms of support for altimetry. The first is support for high-quality nadir altimetry for medium resolution oceanography through multiple partnerships, as is the case for Jason-2, Jason-3, Sentinel-3, HY-2, SARAL/AltiKa, and Sentinel 6/Jason-CS. The second is to support high-resolution oceanography through programs such as SWOT. CNES received 36 proposals to the SWOT solicitation, including 17 focused on oceans, 14 on inland waters, and 5 focused on a combination of the two. Selections were to be announced in mid-November. A new announcement of opportunity for the nadir altimeter team (the OSTST) will be come out in 2016.

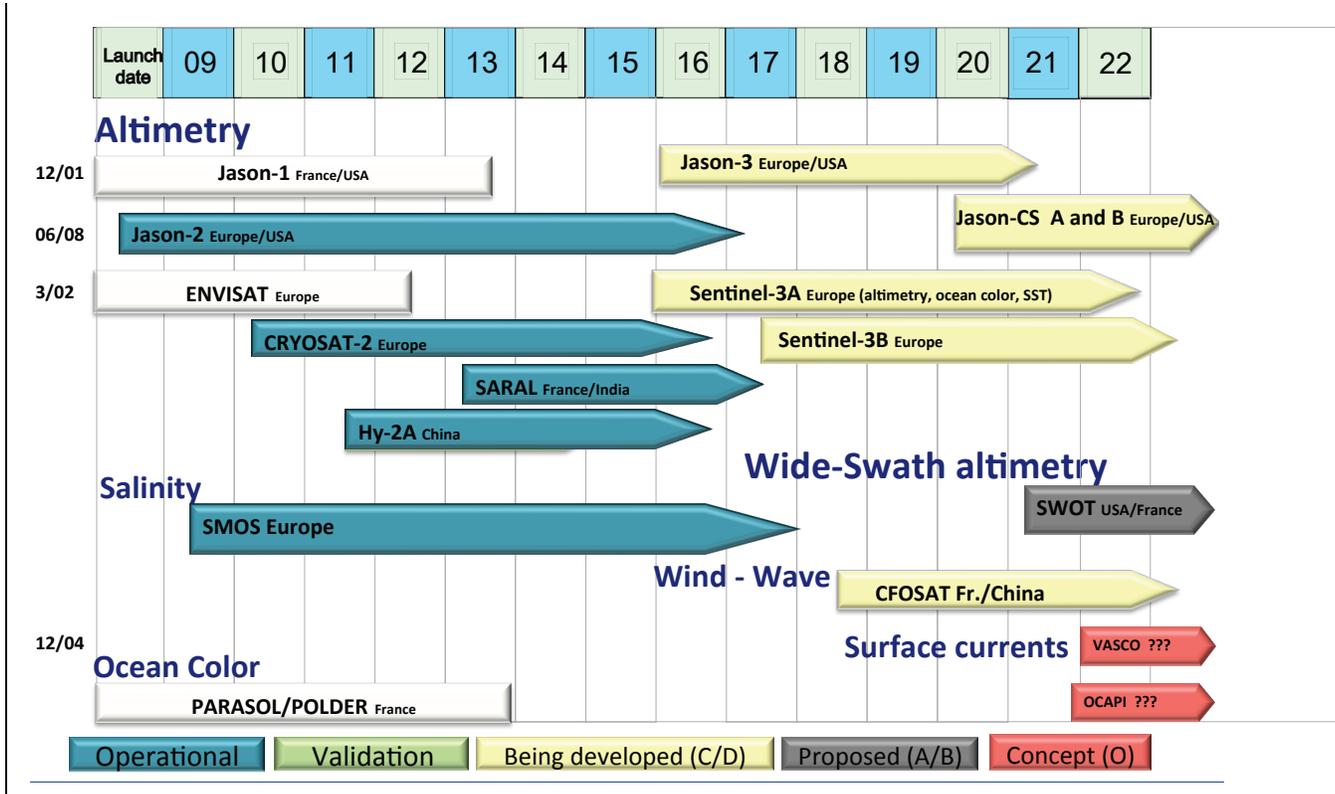


Figure 1. Ocean missions in which CNES is involved at various levels of contributions

Eric Lindstrom (NASA HQ) gave a summary of the NASA Ocean Program. The SWOT Mission Science Team was completed through NASA's ROSES program in 2015. 67 proposals were reviewed on the US side and results were to be announced in September. The first SWOT science team meeting will be in the U.S. during Spring of 2016. Several upcoming announcements of opportunity were noted including, the NASA Salinity Science Team, the Sea Level Change Team, the Interdisciplinary Science Team and the OSTST, all of which will have announcements in the 2016 ROSES call. The OSTST proposals will be due at the end of May 2016, and may include explicit connections to the Sea Level Change Team.

François Parisot (EUMETSAT) reported on the status of EUMETSAT Marine Programmes. Agreements have now been signed to allow EUMETSAT to support, Jason-3, Sentinel-3 and Sentinel-6/Jason-CS. Jason-CS will continue to carry out the reference mission beyond Jason-3 with some significant technical differences. These include a new platform, a nominal 5.5-year lifetime with additional 2 years possible, and simultaneous operation of both high-resolution (SAR altimetry) and low-resolution (conventional altimetry) data collection along the ground track. In addition, operations of Jason-CS will be carried out by EUMETSAT as opposed to NOAA for Jason-3.

Laury Miller (NOAA) reported on NOAA Jason-mission Program Status. NOAA successfully transitioned control of Jason-2 operations to the new merged Jason-2/Jason-3 ground system on September 30, 2015. After the launch of Jason-3 NOAA will control and downlink telemetry for both Jason-2 and Jason-3. Pending approval by Congress, NASA will assume overall responsibility for the US contribution to Jason-CS. NOAA is working with NASA to determine NOAA's role in support of the Jason-CS mission.

Jérôme Benveniste (ESA) presented the ESA Programmes by first recalling the status of the ERS-1&2 and Envisat reprocessing. The ERS reprocessed data sets, called "REAPER" cover the period from July 1991

to June 2003 and are available at <https://earth.esa.int/>. The CryoSat-II mission continues to operate nominally and continues to be exploited by researchers and near real time users for study and applications involving sea ice, land ice and ocean topography. The launch of Sentinel-3A is scheduled for February 16, 2016.

The Project Managers reviewed the status of the Jason missions. Jason-2 Project status was given by Thierry Guinle. All systems are in good condition and the satellite is operating nominally after 7 years in orbit, and the passengers perform satisfactorily. Both CNES/EUMETSAT and NASA/NOAA approved the extension of the mission up to 2017. No major events occurred this year on the platform side and after the switch to the GPSP-B side receiver, the GPS payload has been performing nominally. After several software updates to GPSP-B, it's performance is now comparable to that of the original side-A instrument. Overall Jason-2 continues to collect data that meets all mission and level-1 science requirements: the global Jason-2 system availability is 100%, exceeding the 95% requirement. Moreover, the near real-time product (OGDR) latencies also largely exceed the requirements (75% within 3 hours and 95% within 5 hours) as measured by EUMETCast (90% and 99% respectively) and NOAA ESPC (96% and 99% respectively). The accuracy for real-time orbit from DIODE (DORIS) over the period is ~ 2.8 cm (radial rms). Concerning the AMR, with ARCS processing, the residual drift of GDR-D wet path delay (PD) is estimated to be < 1 mm/year over mission life. Although Jason-2 is performing well the project requested the OSTST to endorse a specific Extension of Life Orbit.

Status of the Jason-3 Project was discussed by Gerard Zaouche. At the time of the meeting, Jason-3 was in storage with a plan to launch in late 2015 or early 2016. Since that time, Jason-3 was successfully launched on January 17, 2016 aboard a SpaceX Falcon 9 launch vehicle. The launch and orbit injection was successful, and as of February 12, 2016, Jason-3 was maneuvered into an orbit approximately 80 seconds behind Jason-2, where it will remain for approximately 6 months while it's data is evaluated in relation to Jason-2. All instruments and ground segments appear to be operating nominally.

Several other missions were summarized by key individuals. Thierry Guinle gave an update on the status of the SARAL/AltiKa Mission. The SARAL/AltiKa mission continues to perform nominally after 2.5 years on orbit, and provides data with accuracy comparable to Jason-2. After a Safe Hold on October 6-9, 2014 caused by failure of a reaction wheel, the satellite recovered successfully, but some concerns about reaction wheels remain. Station keeping for SARAL was not maintained within the 1 km ground track between March 31, 2015 and May 8, 2015, but subsequently returned to normal operations. However, long-term ground track maintenance after three years on orbit (Feb 2016) remain uncertain. A request was made for input from the OSTST on whether a relaxed ground track, or drifting orbit would be more desirable for AltiKa users in the long run.

Pierrick Vuilleumier (ESA) also gave a brief update on the status of the upcoming Jason-CS mission. Jason-CS will continue the Jason series of research and operational oceanography missions. Two satellites will be commissioned, with the first launching in mid-2020 and the second launching in 2025. The project will be governed through a Joint Steering Group and will involve contributions from ESA, EUMETSAT and NASA.

Finally, Lee Fu provided an update on the SWOT (Surface Water and Ocean Topography Mission). Launch of the SWOT mission is scheduled for October, 2020. The mission will carry an interferometer as well as a traditional nadir-altimeter and operate at a 21 day repeat. Mission science objectives include observation of mesoscale and submesoscale ocean process. Science and engineering teams will develop

new calibration/validation technique and geophysical corrections in order to develop high-resolution altimeter products.

Status reports on both US and European Sea Level initiatives were provided by Steve Nerem (US) and Benoit Meyssignac (France). PI-led research from several key members of the NASA Sea Level Change Team were reviewed by Steve Nerem. In addition to maintaining a sea-level research related website, the Sea Level Change Portal, the NASA team is also dedicated to advancing the status of regional sea level projections. Benoit Meyssignac described the ESA Climate Change Initiative (CCI) sea level product is a fully reprocessed, climate-quality altimeter data set that includes 7 missions and covers 1993-2013. The new product employs the latest geophysical corrections and has reduced uncertainty over more traditional products gridded products.

Before the splinter sessions began, Gerald Dibarboure gave an overview of the study of possible EoL orbits for Jason-2. After an exhaustive study and communications among the EoL subgroup, an EoL orbit that is 35 km above the reference orbit was recommended. This orbit provided a good compromise between sampling mesoscale ocean signals in conjunction with Jason-3 and improving estimates of the marine geoid. On behalf of the other Project Scientists, Remko Scharroo (EUMETSAT) presented discussion topics for consideration by the splinter session. These included evaluation of the EoL orbit suggested by G. Dibarboure as well as maintenance of the orbit for SARAL/AltiKa.

4 Keynote Talks

During the opening plenary session, three keynote talks were also given. These included Benjamin Hamlington, who discussed the record of global sea level rise throughout the 20th Century. Such estimates range from 1 to 2 mm/year, depending on differences in methodology, selection of tide gauges and estimates of vertical land motion. Ananda Pascual discussed the ALBOREX experiment. The experiment used a wide array of observations, including remote and in situ observations and numerical models to study small-scale variability and frontogenesis in the Alboran Sea. Finally, Angelique Melet discussed coupled climate simulations and the large spread in their simulation of thermal expansion of the oceans in a warming climate.

5 Poster Sessions

A poster session was conducted on Thursday and the posters were on view during the coffee breaks throughout the entire meeting. Links to the posters are available on the meeting website:

<http://www.avis.altimetry.fr/en/user-corner/science-teams/ostst-swt-science-team/ostst-2015-reston.html>.

The posters were grouped into the following categories:

- Application development for Operations (previously Near Real Time splinter)
- Instrument Processing: Corrections (Troposphere and Ionosphere, Wind Speed and Sea State Bias)
- Instrument Processing: Measurement and retracking (SAR and LRM)
- Outreach, Education & Altimetric Data Services
- Precise Orbit Determination
- Quantifying Errors and Uncertainties in Altimetry Data
- Regional and Global CAL/VAL for Assembling a Climate Data Record

- Science Results from Satellite Altimetry: Mean sea level monitoring: how to reconcile altimetry, tide gauges, land motion and other in situ observations?
- Science Results from Satellite Altimetry: Mesoscale and sub-mesoscale ocean processes: current understanding and preparation for SWOT
- Science Results from Satellite Altimetry: Large scale and global change ocean processes: the ocean's role in climate
- The Geoid, Mean Sea Surfaces and Mean Dynamic topography
- Tides, internal tides and high-frequency processes
- Others (poster only)

6 Splinter Sessions

The splinter sessions were organized as follows:

Tuesday, October 28:

- Instrument Processing (Part I): Corrections
- Instrument Processing (Part II): Measurement and retracking (SAR and LRM)
- Outreach, Education and Altimetric Data Services
- Science (Part I): Mean sea level monitoring: how to reconcile altimetry, tide gauges, land motion and other in situ observations?

Wednesday, October 29:

- Precision Orbit Determination
- Application development for Operations (previously Near Real Time splinter)
- Tides, internal tides and high-frequency processes
- Regional and Global CAL/VAL for Assembling a Climate Data Record
- Science (Part II): Mesoscale and sub-mesoscale ocean processes: current understanding and preparation for SWOT
- The Geoid, Mean Sea Surfaces and Mean Dynamic topography

Thursday, October 30:

- Quantifying Errors and Uncertainties in Altimetry Data
- Science (Part III): Large scale and global change ocean processes: the ocean's role in climate
- Round tables for each splinter

Links to the presentations are available on the meeting website: <http://www.avis.altimetry.fr/en/user-corner/science-teams/ostst-swt-science-team/ostst-2015-reston.html>.

6.1 Instrument Processing

6.1.1 Corrections

Chairs: Shannon Brown, Estelle Obligis

The Instrument Processing Splinter focused on two topics – sea state bias (SSB) correction and the wet tropospheric corrections. Detailed summaries are given below. The main recommendations/keypoints from the session are:

- **Ka-band altimeter missions should account for the SST dependence of backscatter to avoid regional biases in products (e.g. wind speed)**
- **On-going and future altimeter projects should consider additional airborne measurements to study small-scale water vapor variability and test the performance of enhanced high-frequency radiometers under diverse weather conditions**
- **If wet path delay stability is critical for the remainder of the Jason-2 mission, then routine cold sky maneuvers should be considered**

Bellingham et al discussed SAR mode altimetry and sea state bias. There is currently no SSB models developed for SAR altimetry, but these will be important for future missions, including Sentinel-3, Jason-CS and SWOT. For along-track SAR mode, the SAR altimetry footprint is strongly asymmetric. For example, it can be 2-10km in the cross track direction, but 300 m in the along track direction, as illustrated in Figure 6.1.1.1. This introduces uncertainty from possible effects of ocean swell and swell direction on the SAR mode waveforms leading to swell induced biases in the SSH. An 8 month study on understanding SAR mode SSB corrections and impacts of the asymmetric sampling is underway. Currently, there is limited data available from Cryosat. Sentinel-3 when launched will provide additional data for validation.

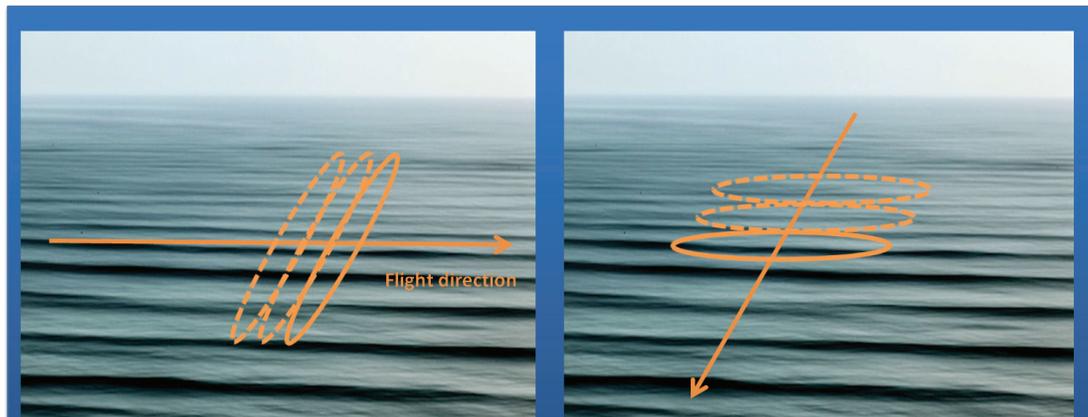


Figure 6.1.1.1. Illustration of the SAR mode footprints relative to swell direction.

Pires et al. discussed a new proposal for SSB modeling with three parameters exclusively derived from altimetric data. Previous SSB corrections have used either 2 parameters, significant wave height and wind speed, or 3 parameters, including additionally mean wave period. For the 3rd parameter, this has come from the wave watch III model. This study used a third indicator that was a function of sigma-0 and SWH, which was a proxy for wave period. In this way, only altimeter data were used. The work is on-going, but the results are promising. A plot of the cross-over variance reduction from the Tran model is shown in Figure 6.1.1.2.

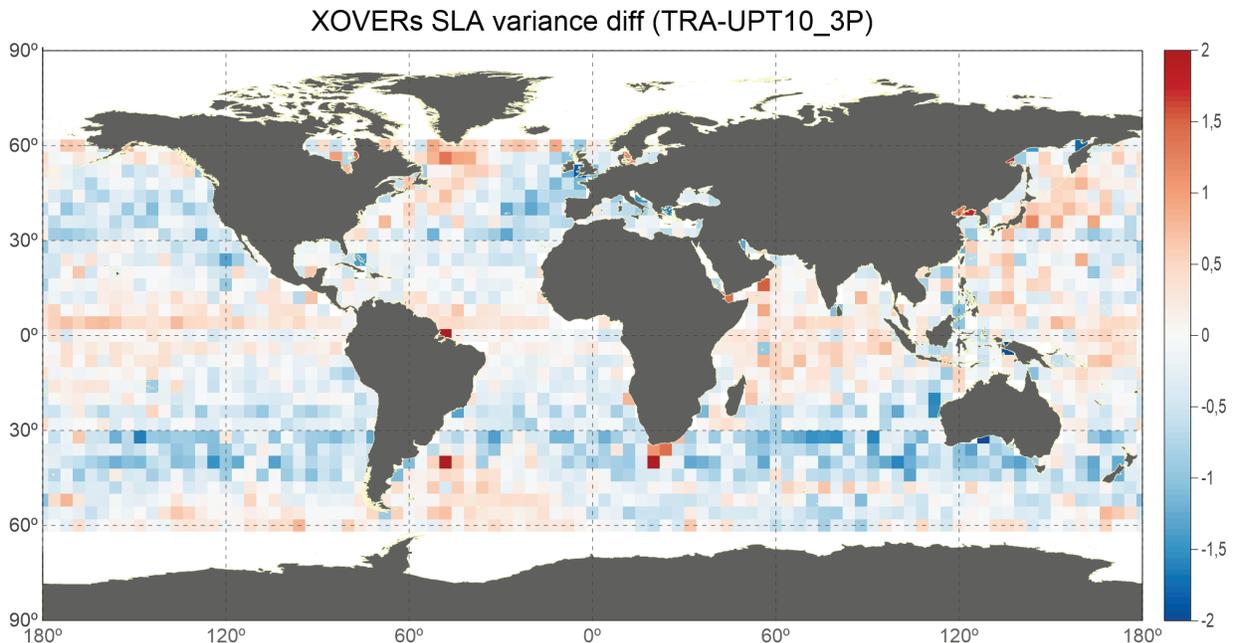


Figure 6.1.1.2. Cross-over variance reduction using the UPT10 3-parameter model compared to the Tran et al. model.

Fernandes et al. discussed the GPD+ product, which included inter-calibrated wet path delays for eight altimetric missions. GPD+ combines coastal GPS-based processing with open ocean objective analysis processing to provide global data for any altimeter mission. All available microwave derived PD data were inter-calibrated using SSMI sensors and applied to eight altimetry missions. This product is useful for missions without a radiometer and also for data gaps. An example of the inter-calibration adjustments applied to Topex/Jason series are shown in Figure 6.1.1.3.

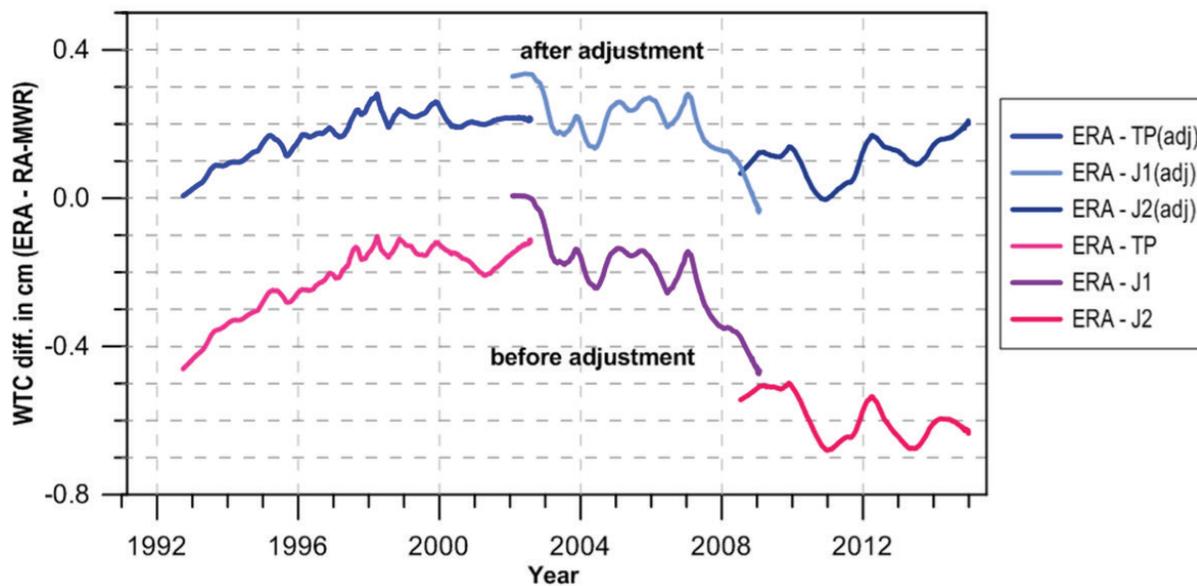


Figure 6.1.1.3. Jason and Topex radiometer PD before and after inter-calibration adjustment using SSMI.

Picard et al. discussed the spatial and seasonal variability of the spectral variation of the wet tropospheric correction. This is important for swath altimetry, but also a consideration for nadir altimetry. The SWOT error budget assumes a global PD spectrum, but it is known that this varies regionally and seasonally. This study generated maps of the spectral slope to understand the geographic patterns and how they change over the year. The largest values for the spectral slope were found to be in more humid regions and in the northern hemisphere summer. An illustration of the slope and the geographic distribution is shown in Figure 6.1.1.4.

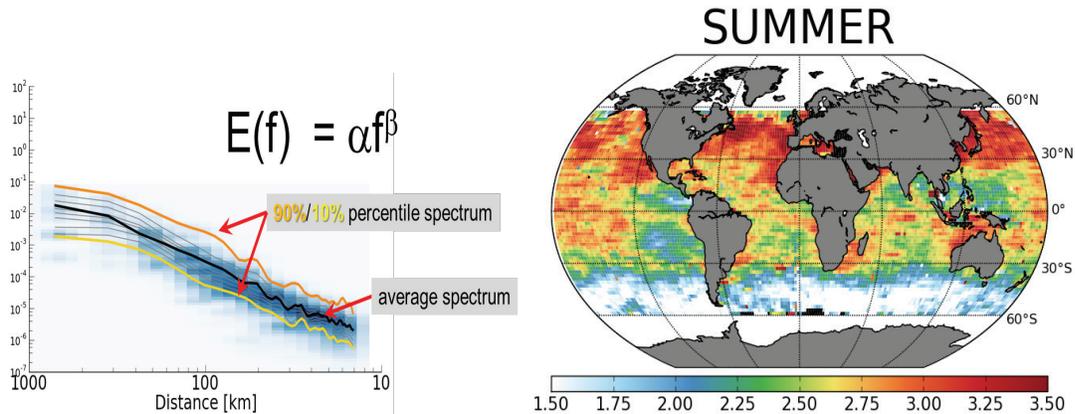


Figure 6.1.1.4. Spectral variation of wet path delay and the geographic distribution of the slope.

Brown et al. provided an evaluation of high-resolution path delay data from the airborne HAMMR instrument. This instrument includes a copy of the AMR on Jason-2/3 but also high frequency channels at 90,118,130 and 166-183 GHz. It is different from the AMR in that the antenna scans, providing a swath of data below the flight path. The high resolution (500m) PD data derived from the HAMMR 18-34 GHz channels were used to evaluate the high frequency spatial spectrum that cannot be resolved by satellite data. The study shows that in the cases analyzed, the spectral slope at high frequencies was consistent with that derived from satellite data at lower spatial frequencies. This is illustrated in Figure 6.1.1.5. A second part of the study used the high-frequency radiometer channels to demonstrate what improvement could be realized on future altimetry missions that include these channels. It shows that open ocean performance could be achieved within a few km from the coast.

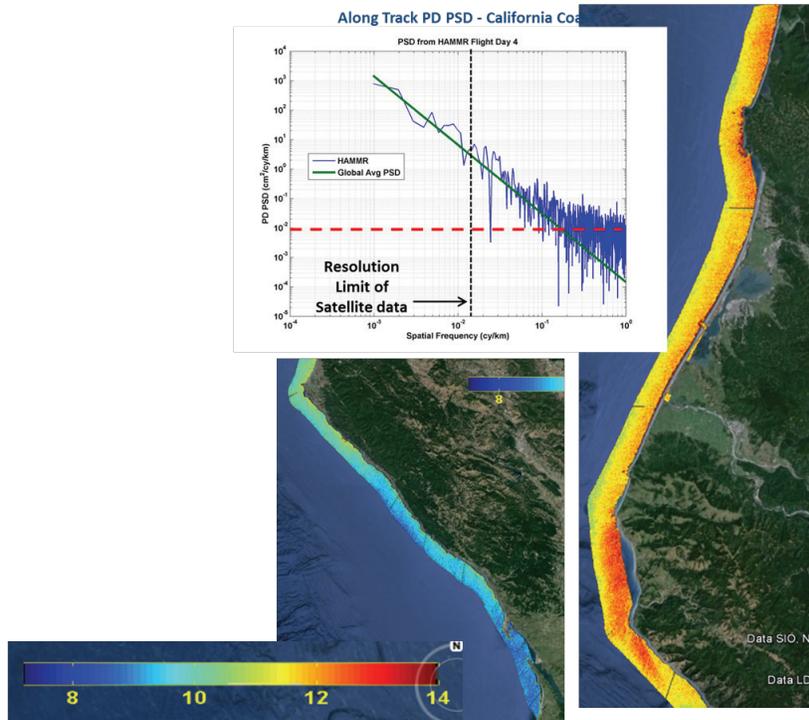


Figure 6.1.1.5. Illustration of high resolution PD data from HAMMR and the derived PD spectral slope.

Vandemark et al. discussed issues involved in global wave model application to routine SSB range corrections. It showed that 1-2 cm² of gain still possible in sea state geophysical corrections (SSB). Work is on-going to include wave information in SSB corrections. A second part of this study showed the impact of not accounting for the variation of Ka-band ocean surface reflectivity with SST. This impacts AltiKa, SWOT and other future Ka-band altimetry missions. The result is a regional bias in the wind speed estimate, up to 1 m/s. This is illustrated in Figure 6.1.1.6. Future processing algorithms should take this into account.

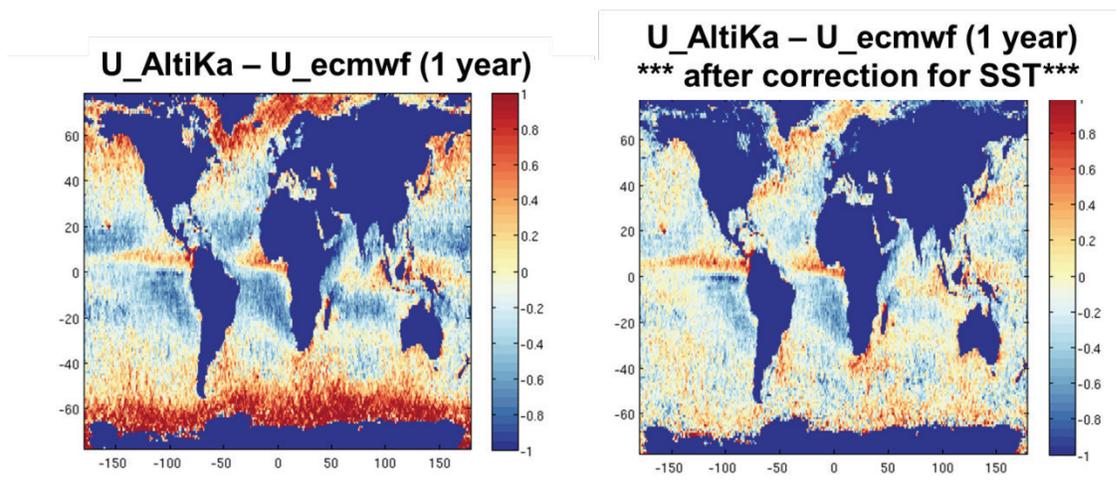


Figure 6.1.1.6. AltiKa wind speed bias relative to ECMWF before and after SST correction.

6.1.2 Measurement and retracking (SAR and LRM)

Chairs: Phil Callahan, Robert Cullen, Jean-Damien Desjonquères & Walter Smith

In the IP Measurement and re-tracking splinter the following oral presentations were made:

1. *Retracked TOPEX Climate Data Record*, P. Callahan, J. McMichael, B. A. Williams, D. Vandemark and H. Feng.
2. *On the signature of swell for the Cryosat-2 SAR-mode wave data*, L. Aouf and L. Phalippou.
3. *Separation of Coherent and Incoherent Scattering Components from Delay/Doppler Altimeter Waveforms*, A. Egido and W. H. F. Smith.
4. *Impact of the antenna diagram approximation in conventional altimetry WF processing - Application to SARAL/AltiKa data*, S. Le Gac, F. Boy, A. Guillot, J.D. Desjonquères, N. Picot, J.C. Poisson, F. Piras, G. Bracher, P. Thibaut & G. Valladeau.
5. *Level-2 Assessment of Along-Track Antenna Pattern Compensation for SAR Altimetry*, S. Dinardo, M. Scagliola, M. Fornari and J. Benveniste.
6. *Improved SAR-mode ocean retrievals from new Cryosat-2 processing schemes*, T. Moreau, L. Amarouche, J. Aublanc, A. Vernier, P. Thibaut, F. Boy and N. Picot.
7. *Sea Level Continuity between open ocean and sea-ice regions in the Arctic: LRM Processing Solutions*, J-C. Poisson, P. Thibaut, D. Hoang, A. Guillot, N. Picot, G. Quartly, A. Kurekin & J. Benveniste

In addition, the following posters were presented:

1. *Simultaneous multi-waveform retracking in coastal regions : application to the NW Mediterranean Sea*, Niño et al.
2. *SENTINEL-3 STM Products & Processing Algorithms Definition*, Loddo, et al.
3. *“PEACHI Jason-3”: a processing laboratory for innovative altimetry products*, Le Gac et al.
4. *Using SARAL/AltiKa to improve Ka-band altimeter measurements for coastal zones, hydrology and ice: status of the PEACHI project*, Valladeau et al.
5. *A new method to determine the antenna pointing directly from Altimeter SAR mode data*, Ray et al.
6. *ERS-2 mission reprocessing for long-term continental surfaces studies*, Legrésy et al.
7. *A Fast Convolution based Model for SAR Altimetry Waveforms and their Retracking*, Buchhaupt et al.
8. *SAR Altimetry at 80 Hz*, Dinardo et al.
9. *Performance analysis between autonomous tracker median and new version of OLTC mode*, Auge et al.
10. *Open-Sea CryoSat-2 data in SAR and PLRM mode in South East Pacific and North East Atlantic*, Fenoglio-Marc et al.
11. *A global coastal altimetry dataset for coastal dynamics and sea level research*, Passaro et al.

The splinter chairs considered two issues relevant to instrument processing that were discussed in the round table session. There were:

1. Jason-2: Extension of Life (EoL).

Here the panel made no recommendation apart from noting that Geodetic Mission EoL data are needed to improve the marine geoid at sub-mesoscale (30 – 150 km) and at shorter scales (see point 2 below).

Specifically, with respect to instrument processing the chairs note that at these scales, LRM re-tracking issues are important and care is needed.

2. Given the estimated measurement noise for SARAL and SAR, can we start to detect smaller mesoscale structures from 30-150 km along track?

Here the splinter panel noted, as shown in previous OSTST meetings over the past few years, that the process of measuring and re-tracking waveforms in the sub-mesoscale (30 to 150 km region) Sea Surface Height (SSH) can introduce correlated errors with pulse-width limited (low resolution waveforms) data and to a lesser extent with higher frequency systems (Ka band AltiKa). This is observed by the characteristic 'spectral bump' for low-resolution altimeter measurement systems. The problem can be resolved by SAR processing of high rate waveforms or minimized by specialized retracking and editing of low resolution data.

It was further noted that the geoid in this band is highly correlated with bathymetry, and thus improving geoid/bathymetry coherence will provide a quasi-validation. Finally, it was observed that improving the geoid at these scales requires new geodetic phase altimeter data.

6.1.2.1 Sea State Bias and Long Swell

In a paper presented by *Aouf, et al.*, it was shown that global wave model forecast skill does improve when assimilating Cryosat SAR data which is a reassuring result but there is a warning that when very long-wavelength swell propagates along-track there is a bias in SWH when compared with the Météo-France Waveform model (MFWAM). The impacts of along-track swell on retrievals is not new but clearly there is some work needed to improve the understanding of this effect and how to mitigate it. This will be best served with Sentinel-3 that will operate in its SAR mode over all surfaces and may be compared with observations from other missions, for example, imaging SAR.

Other studies of SAR-mode SWH resolution and Sea State Bias are on-going and will benefit from Sentinel-3.

6.1.2.2 Retracking

There has been a continued move to improve re-tracking methods. *Callahan et al.* explained the TOPEX re-tracking exercise based on an upgrade completed during 2015. The internal range calibration has been identified as an issue. Some issues still require resolution between JPL and CNES.

An active area of research continues to be undertaken in coastal regions for which improvements are being made. The ALES re-tracked multi-mission global products have been made available on the PO-DAAC servers. Jason-2 products are available and those for Jason-1 and the EnviSat RA-2 are being planned for release in the near future.

Poisson et al. explained the results of a study using a new adaptive re-tracker model, termed *IceNew*, applied to EnviSat RA-2 and AltiKa and allowing for transitions between ocean and sea-ice echoes. The model will be adapted and applied to CryoSat data in due course.

Niño et al. showed the complexities of re-tracking in coastal regions and have developed a means of simulating pulse-width limited returns in coastal regions in order to compare real with simulated cases. The group achieves this by means of describing topography in a DEM and adding parametric corrections

as a profile. They now intend to observe the differences between various re-tracking methods and increase the complexity of ocean structures within the simulations.

6.1.2.3 Continued improvements in LRM processing

In the presentation by *Le Gac et al.* they made the observation that the Brown model antenna approximation differs from the actual sensor antenna pattern by as much as 0.6dB for the case of AltiKa which has a narrow antenna beamwidth. It was observed that antenna pattern corrections are particularly important for Ka band. AltiKa is beam limited as well as pulse limited leading to as much as 4cm error in range and 12cm error in SWH for an 8m SWH; both due to the difference between real vs Gaussian approximation. Plots of retrieved mis-pointing angle show a clear wave height dependence as a function of retrieved mis-pointing angle (Figure 6.1.2.2). Figure 6.1.2.3 shows the impact of performing corrections demonstrating minimization of the retrieved mis-pointing angle versus retrieved SWH. With this study concentrating on AltiKa, it is observed that other missions might benefit from a similar analysis.

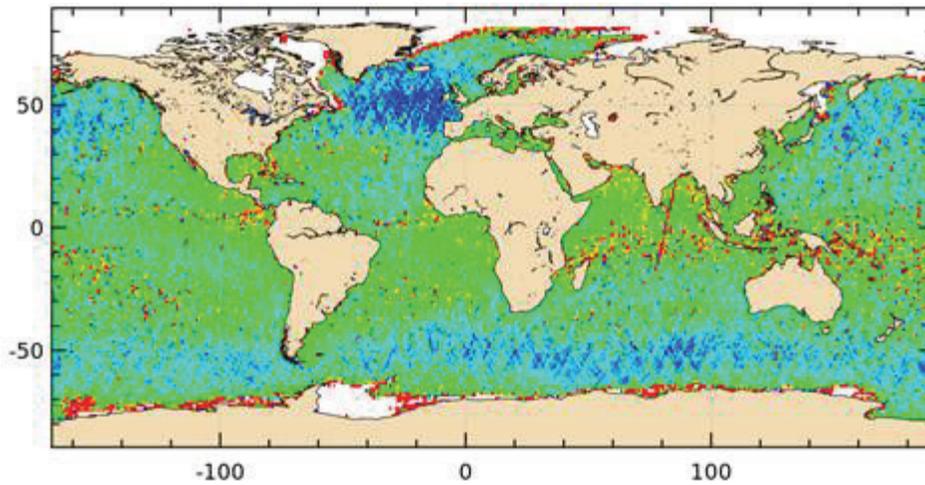


Figure 6.1.2.2 Altika data without antenna compensation, Le Gac showed a high dependency in function of the waveheight is observed on the mis-pointing angle estimation

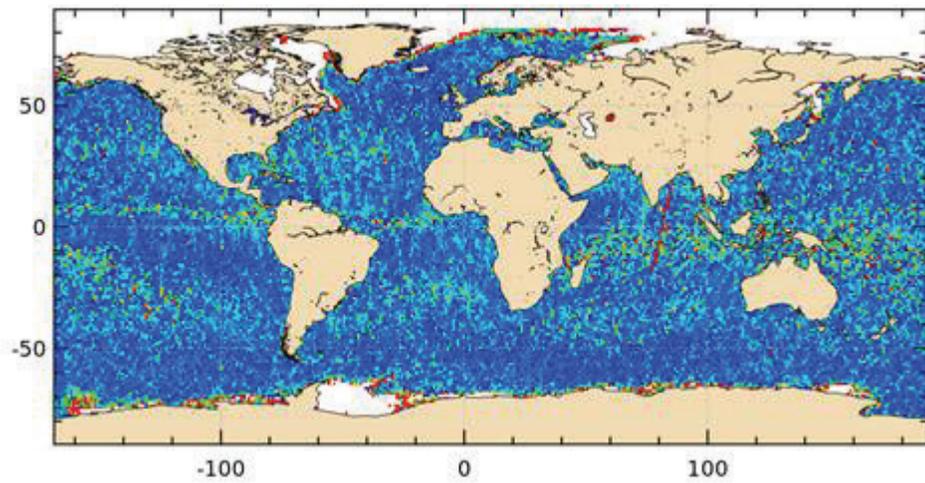


Figure 6.1.2.3 Altika data with antenna pattern compensation, Le Gac

Finally, the splinter recognized a great deal will be learned with the new data sets from Sentinel-3 that will generated in SAR mode globally allowing for work to commence on developing global ocean SAR SSB models.

6.1.2.4 New ways of processing SAR data

Dinardo et al. showed that for SAR processing by compensating the stack by the real antenna pattern (termed antenna pattern compensation – APC) the effective number of looks (ENL) can be improved by up to 6%. Interestingly, minimal difference can be observed in the retrieved SSH anomaly spectrum whereas the wave height spectrum was slightly worse with APC applied and slightly better for the σ^0 spectrum.

In a separate poster presentation, by *Dinardo et al.*, modifying the processing algorithm to increase along-track sampling (“84 Hz”, 80 m along-track), shows benefit in the coastal zone. This posed the question of whether operational processors should be optimized for coastal ocean in this respect.

Fenogolio et al. showed the improvements of SAR processing vs LRM processing by selecting different open ocean regions and noting anomaly spectra for these regions. Concluding, they presented that SAR and PLRM methods measure the same monthly sea cycle but SAR measures it with higher precision.

6.1.2.5 SAR sensitivity to platform mis-pointing

The poster presented by *Ray et al.*, demonstrated the impact of uncertainty in pointing knowledge on SWH and range retrieval and that it can be made very small (less than mm in range, for example) by using an analytical model of Doppler Delay Map (DDM) applied to selected CryoSat-2 in-orbit SAR data without the use of attitude information normally processed from star tracker quaternion information. The test case presented yielded 0.17 mm error in range and 1.3 mm in SWH. The demonstration has potential benefits for SAR processing but it is clear further independent studies are needed to confirm this approach or investigate other approaches.

6.1.2.6 Moving towards a fully focused processing of SAR

The session highlighted an interesting use of the CryoSat SAR data being exploited over coastal regions with the potential for extension over sea ice and inland water. The paper presented by *Egido and Smith* was a study to identify if incoherent and coherent scattering components can be separated using the Full Bit Rate (FBR) products available from the CryoSat-2 mission. The basic premise is that static land may provide a coherent signal whilst the ocean provides an incoherent signal. Although that aspect of the study was not achieved, the team investigated development of a fully-focused SAR capability, despite this not being a functional design of the radar. In order to do this, they speculated that if the full phase history of echoes derived from the closed burst SAR data can be re-constructed then, theoretically, the along-track resolution can be improved from ~300m to just ~0.5m, Figure 6.1.2.4.

The preliminary work has shown an improvement can be made, though some problems re-construction of the full phase history assumed to be due to the closed burst nature of the radar timing. At this time the full 0.5m resolution is not achievable and an averaging is required that drops the resolution to about ~30 m depending on configuration (see example in Figure 6.1.2.5).

In addition, a factor ~2 improvement on SNR can be achieved due to the increase in the effective number of looks. This opens an interesting concept for use with the Sentinel-3 mission. The difference in instrument timing chronogram may well shed some light on the capacity to achieve focused processing. It is further assumed the near continuous pulse transmission of the Sentinel-6/Jason-CS radar, Poseidon-4 may result in a fully realizable phase history re-construction. It is observed that future high-resolution altimeter missions might benefit from specific burst to burst phase coherence requirements.

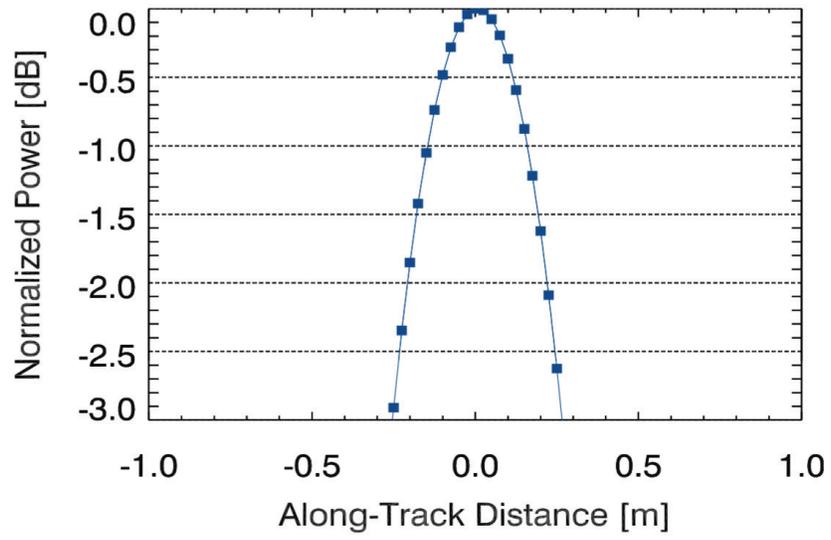


Figure 6.1.2.4 Theoretical CryoSat along-track resolution of ~ 0.5 metres can be achieved with a fully focused SAR processing.

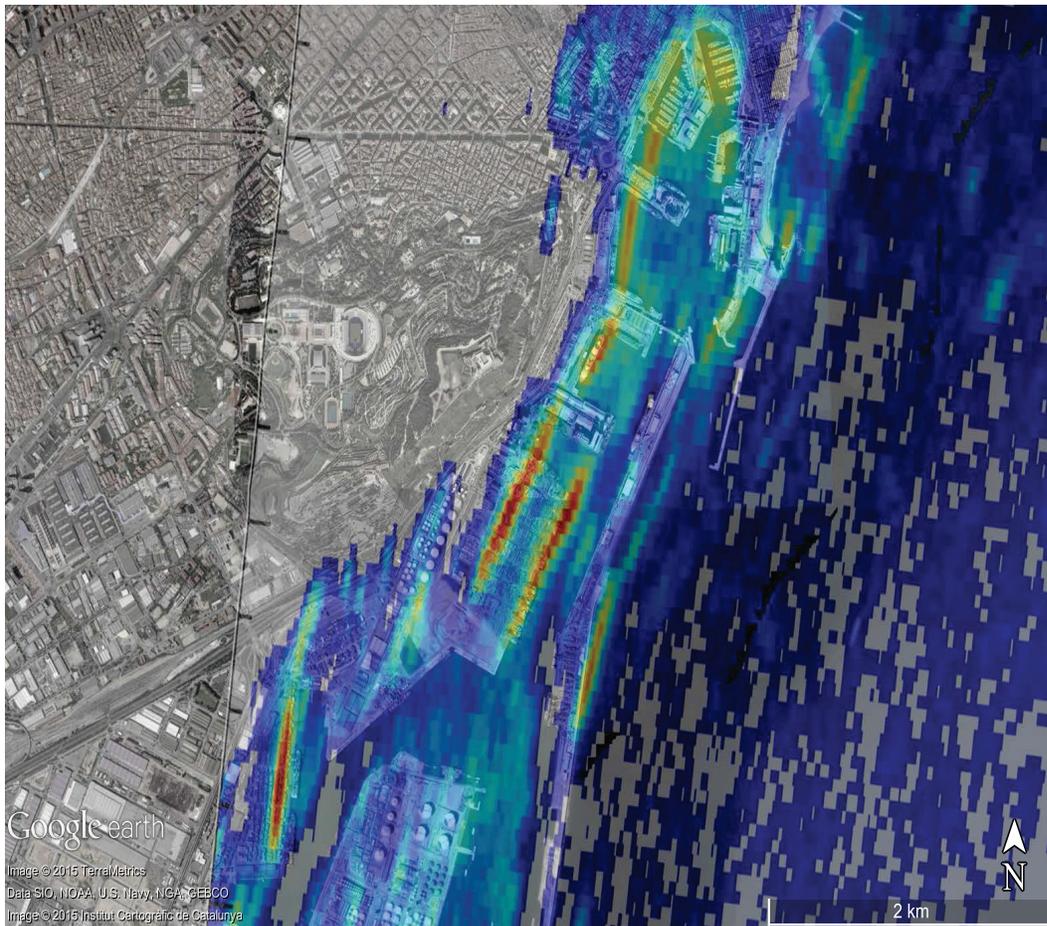


Figure 6.1.2.5 Fully focused SAR processing of data collected in the Barcelona region with a de-sampling to ~30 metres resolution

6.1.2.7 Data sets availability

In addition to the re-tracked TOPEX climate data record presented by *Callahan et al.* that will be available (it may now be available) on PO-DAAC servers, some other dedicated data sets are available. These are:

PEACHI products (<http://odes.altimetry.cnes.fr/>) as presented in the poster, *G. Valladeau et al.*

ALES products for Jason-2 are available on the PO-DAAC server with other mission data being made available in due course: (ftp://podaac.jpl.nasa.gov/allData/coastal_alt/L2/ALES) as presented in the poster *M. Passaro et al.*)

The panel awaits products for both the soon to be launched Jason-3 and Sentinel-3 (see, *Loddo, et al*). It should be noted that the European Copernicus Marine Environment Monitoring Service (CMEMS <http://marine.copernicus.eu>, previously known as MyOcean) is in charge of the processing and distribution of some altimetry products formerly distributed by Aviso+. Registering can be registered at <http://marine.copernicus.eu/web/56-user-registration-form.php>.

6.1.2.8 Recommendations

- The splinter chairs noted that, ideally, both science and calibration algorithms used within the operational and science missions need to be made available to all and fully documented in order to facilitate climate studies.
- Minimization of geographically correlated errors: It was noted that a specific mission level requirement was made for TOPEX for no geographically correlated errors. Other missions have not always made this an explicit requirement although there is a specific requirement for the Sentinel-6/Jason-CS missions. Hence, it was noted that other future missions should have this requirement.
- Sentinel-3 commissioning phase: it is recommended that the commissioning consortia make a specific effort to collect and analyze data to calibrate biases in pitch and roll. Due care must be taken not to rush this process. Ideally, it was considered that data be acquired both at beginning and end of commissioning phase, both in LRM and SAR modes.
- CryoSat attitude: it is recommended that biases need to be re-analyzed with the Baseline-C (the latest operational processor that commenced generating products in the summer 2015) and discordant results need to be understood.
- The dependence of σ_0 on Sea Surface Temperature: This is due to the reflection coefficient that needs to be included for Ka band and considered for other cases.
- The perennial question of whether SSB should use σ_0 or wind speed was raised again. With this in mind can the Crete transponder (to be used for Jason and Sentinel-3 missions) be used to make an absolute calibration of σ_0 ? If so, then this calibration should be made during commissioning and regularly throughout operations of relevant missions.

6.2 Outreach, Education & Altimetric Data Services

Chairs: Jessica Hausman, Vinca Rosmorduc and Margaret Srinivasan

6.2.1 Session presentations:

- Updated Altimetric Datasets and Services at PO.DAAC (Hausman)
- SAR altimetry processing on demand service for Cryosat-2 and Sentinel-3 at ESA G-POD (Dinardo et al.)
- Radar Altimetry Toolbox (Garcia-Mondejar et al.)
- Multivariate Reconstruction of Sea Level from 1900 to Present (Hamlington et al.)
- Outreaching a space technique through its climate applications: Jason-3 (Rosmorduc et al.)
- Observations of El Niño impacts using in situ GLOBE protocols and satellite data (De Staerke et al.)
- SHOWCASE of altimeter outreach
 - Coastal Product from SARAL/AltiKa for the Gujarat (India) coast (Chaudhary et al.)
 - Aviso+ mobile/light version (Rosmorduc et al.)
 - "Database for Hydrological Time Series of Inland Waters" (DAHITI) (Schwatke et al.)
 - Argonautica new data access (De Staerke et al.)
 - OSTST/satellite altimetry outreach activities (Zaron et al.)
 - A global map of the M_2 internal tide (Zhao et al.)

6.2.2 Posters

- Regional X-TRACK altimeter products for coastal applications: updates and evolutions (Fuller et al.)
- Swot on Aviso+: promoting the mission, explaining the technique (Rosmorduc et al.)
- Aviso+ products & services: what's new? (Rosmorduc et al.)
- New datasets for ODES (Online Data Extraction Service) (Rosmorduc et al.)
- Database for Hydrological Time Series of Inland Water (DAHITI) (Schwatke et al.)
- Sentinel-6/Jason-CS Altimeter Products and Performance Budget (Remko Scharroo et al.)
- CTOH altimetry products (L1 to L4) for ocean and continental surfaces applications (Florence Birol et al.)
- NOAA archive and access services for Jason-2/3 products (Baker-Yeboah Sheekela et al.)
- Sea Level Experiments for Climate Science Outreach (Andrei Iskra et al.)
- The Colorado Center for Astrodynamics Research Ocean Data System (Robert Leben et al.)

6.2.3 2014-2015 Highlights

Updates of data services and tools were shown this year.

The outreach activities presented were varied, mostly focused on climate change and/or El Niño.

The short (1 to 2 slides) format of the “outreach showcases” is still rather successful. It allows OSTST members to share an outreach activity they participated in but which was not the subject of a full-fledged presentation.

6.2.4 Data services

Data Services provide a way of exchanging information and linking projects and users together so users can benefit from the wide variety of altimetry-derived data available.

The PO.DAAC presented new datasets (NRT SARAL/AltiKa GPS orbit corrections, OSCAR 1/4°, Integrated Multi-Mission Ocean Altimeter V3, Jason-1 GDR-E), new pages on their web site, with a forum and links with NOAA and other data services. Web services, and a focus on Data management best practices, with also the use of DOI are being put in place.

ESA modified its service dedicated to SAR altimetry-specific processing, with the capability to process remotely and on demand CryoSat-2 SAR data (available on ESA G-POD web portal at https://gpod.eo.esa.int/services/CRYOSAT_SAR/).

Old Dominion University has new climate-related indicators. CTOH, Aviso and DGFI showed their updated data and services in posters. ISRO, U. Washington and DGFI in Outreach Showcases.

IsardSat showed their first updated release of BRAT (now “broadview” instead of “basic” radar altimetry toolbox) for Sentinel-3 data.

The round table discussed the ways of guiding users towards the dataset most appropriate to their needs.

6.2.5 Outreach

Outreach and educational activities of the past year include continued promotion of the societal benefits of ocean altimetry data, highlights of the Jason-2 mission, and anticipation of the Jason-3 and SWOT missions. The team has generated several products (handout materials and web-based informational products) to promote the science and applications of the data. In addition, our emphasis on climate literacy has been used to engage our target audiences (public and educational) with outreach and education products and events.

Useful resources (figures, maps, movies, animations, schemes...) are now available on the web or on the computers and in databases of the outreach team. We remind OSTST participants that they should not hesitate to ask for general presentation material or a specific theme or figure. If it does not exist, we can consider having it made for future uses.

Some outreach activities in France around either or both COP21 and Jason-3 launch were shown. A mobile version of the Aviso+ web site is currently being reviewed, for release end of 2015.

The round table discussed the impact and outreach possibilities of having both the Climate conference in 2015 and the Jason-3 (and Sentinel-3) launch the same year. There were also some discussions about the web sites accessibility which must be taken into account as much as possible. If possible we recommend that you consult with an accessibility expert

6.2.6 Education

E. Zaron (Portland State University) shared several hands-on experiments he has developed and demonstrated to local public audiences, including an internal tide simulator.

Ideas for SWOT education activities through the GLOBE Program focused on the El Niño phenomenon were presented by JPL and CNES. A new interface has been released to access Argonautica educational project data. The aim was to provide easier access to the archived data.

6.2.7 Recommendations

Jason-3 and Sentinel-3 launches with the COP21 Climate conference in Dec. 2015 is an opportunity to promote altimetry and its uses in climate study and monitoring. OSTST members should thus prepare for those launches as well as the climate conference. We recommend that OSTST attendees support applications user communities and applications science, and advise us about their activities related to the applied and operational uses of individual and multimission data sets.

Storm surges are another topic with potential public impact, and thus interest.

OSTST members are also involved in and shared a number of training courses.

Collectively, we would like to:

- 1) advertise activities of the OSTST more widely (i.e. on the Aviso, JPL, etc. web sites), and
- 2) share material and methods. One example is “kitchen experiment” descriptions, which are often informative and useful experiments that share scientific concepts with the general public using familiar materials from home (or at least easily bought). If you have “hands-on” activities, try to write a rough description to share it, and send it to the outreach team.

OSTST members can make a significant difference in their local communities by participating in school activities, supporting local events involving climate science and science educations, and volunteering (or agreeing to support) training sessions or class visits at local schools and general public venues. The work done by other team members can make this task more accessible to both the scientists and their audiences. If we are aware of your activities, we can support you by facilitating these interactions. The development of international collaborations between students is another area that can be more developed via shared resources and communication. Translating educational materials into other languages could be a 'low hanging fruit' on resource-sharing trees.

6.2.8 New Planned Efforts

The focus of the outreach team for the coming year will be on climate and global change education and public outreach, as well as applications outreach for all of the current and especially the upcoming ocean altimetry missions— OSTM/Jason-2, Saral/AltiKa, Jason-3, Sentinel-3, Jason-CS (Sentinel-6), and SWOT. The anticipated elements of this focus (not withstanding new opportunities) will include:

- Jason-2/OSTM, SWOT, Saral/AltiKa, Jason-CS and Jason-3 education & public outreach and applications outreach
- Jason-3 launch activities, including movies
- Altimetry and multisensor applications promotion
- Coverage of science team research and other applications on the web
- Development of a SWOT GLOBE program (NASA, CNES, U. North Carolina, GLOBE Program collaboration)
- Presentations about altimetry and applications made available to the community
- Specific climate-related material

6.3 Precise Orbit Determination

Chairs: Sean Bruinsma, Alexandre Coubert and Frank Lemoine

6.3.1 Status of Jason-2 GDR orbits

Both CNES, JPL, and NASA GSFC have produced new versions of orbits for Jason-2. The new orbits from the CNES are designated version 'E' (**GDR-E**). For the "**GDR-E**" the salient differences with the GDR-D are: (I) the orbits are GPS+DORIS-only reduced-dynamic using Satellite Laser Ranging (SLR) data for validation; (II) A new parameterized static+time-variable gravity from the GRGS is applied; (III) a calibrated solar radiation pressure model is used for Jason-2. The new JPL orbits are "**rlse15a**". As with the "**rlse14a**" orbits, these GPS-only orbits are reduced-dynamic and use bias-fixing. The new NASA GSFC orbits are designated '**std1504a**'. The salient improvements include: (I) use of quaternions to model the solar array orientation attitude changes, rather than using a nominal attitude law; (II) a parameterized fit to an SLR-DORIS-data determined gravity model to model the time-variations in the low degree gravity field. Both the CNES and the NASA GSFC teams now forward model the Earth geocenter variations using the annual terms derived by Ries (2013).

The different versions of the Jason-2 orbits agree radially to between 4 - 8 mm radial RMS over a 10-day repeat cycle, as shown by the differences of these orbits with the JPL reduced-dynamic orbits "**rlse15a**". (See Figure 6.3.1). The sets of reduced-dynamic-based orbits (**GDR-E**) vs. "**rlse-15a**" show a particularly close agreement, between 4-5 mm radial RMS, due to the communality in the use GPS data and a

reduced-dynamic analysis strategy. Table 6.3.1 shows that the external validation by means of SLR, is also at the 8 mm level. For the **GDR-E** and the JPL “**rlse15a**” orbits, the SLR data are independent.

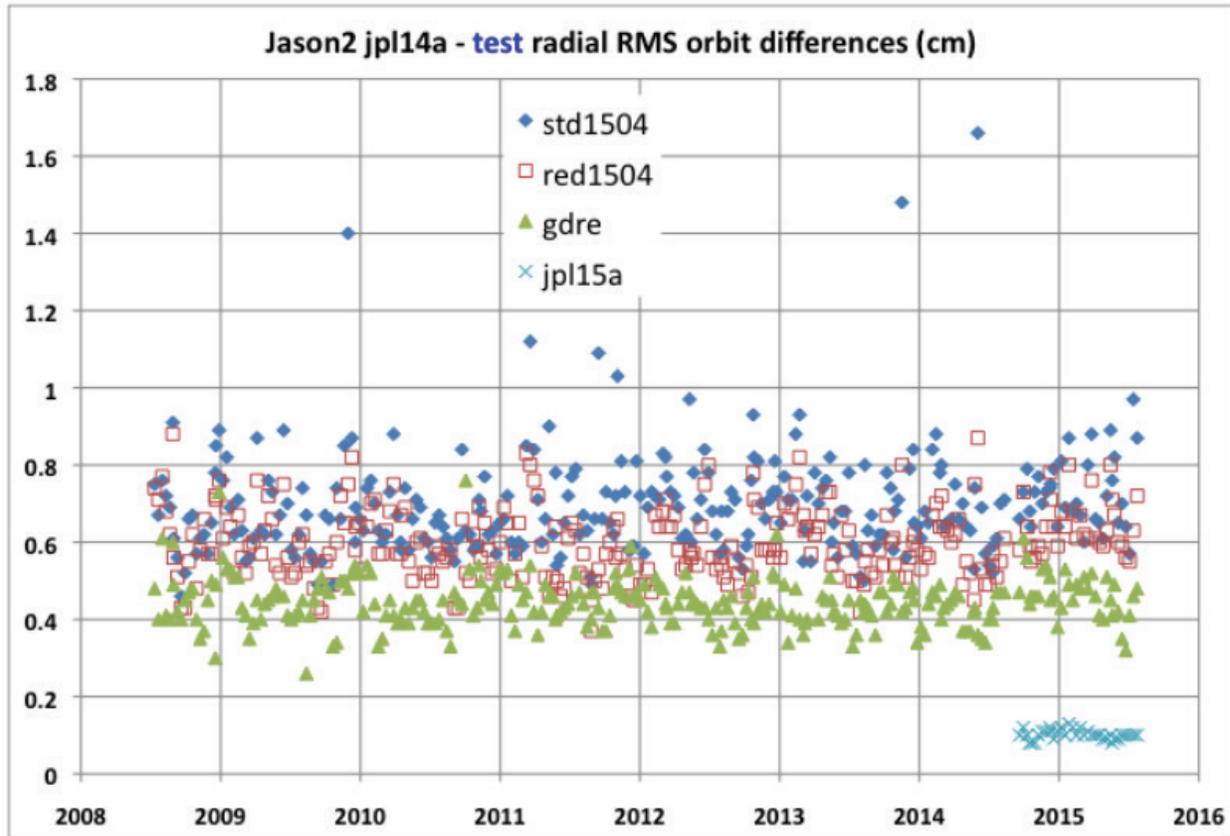


Figure 6.3.1 (Lemoine et al., 2015): RMS of radial orbit differences between Jason-2 CNES GDR-E GPS+DORIS reduced dynamic orbits (green) and GSFC STD1504 DORIS+SLR dynamic orbits (blue), GSFC RED1504 DORIS+SLR reduced-dynamic orbits (red), and JPL RLSE15A GPS-only reduced-dynamic orbits.

	CNES GDR-E	GSFC STD1504	JPL RLSE15A
All elevations	0.95	1.19	0.87
High elevation only	0.76	0.77	0.66

Table 6.3.1. Jason 2 SLR residuals, in cm.

Spectral analysis of the radial orbit differences with JPL rlse14a sampled at fixed geographic locations shows the large reduction of the error at 118 days for the CNES **GDR-E** and NASA GSFC **std1504a** orbits, compared to the previous sets of orbits from those institutions (GDR-D, std1204). The large improvement is due to the improved non-conservative force modeling in the new orbits. The difference at the annual period is now by far the largest (1.5 – 2.0 mm) (see Figure 6.3.2).

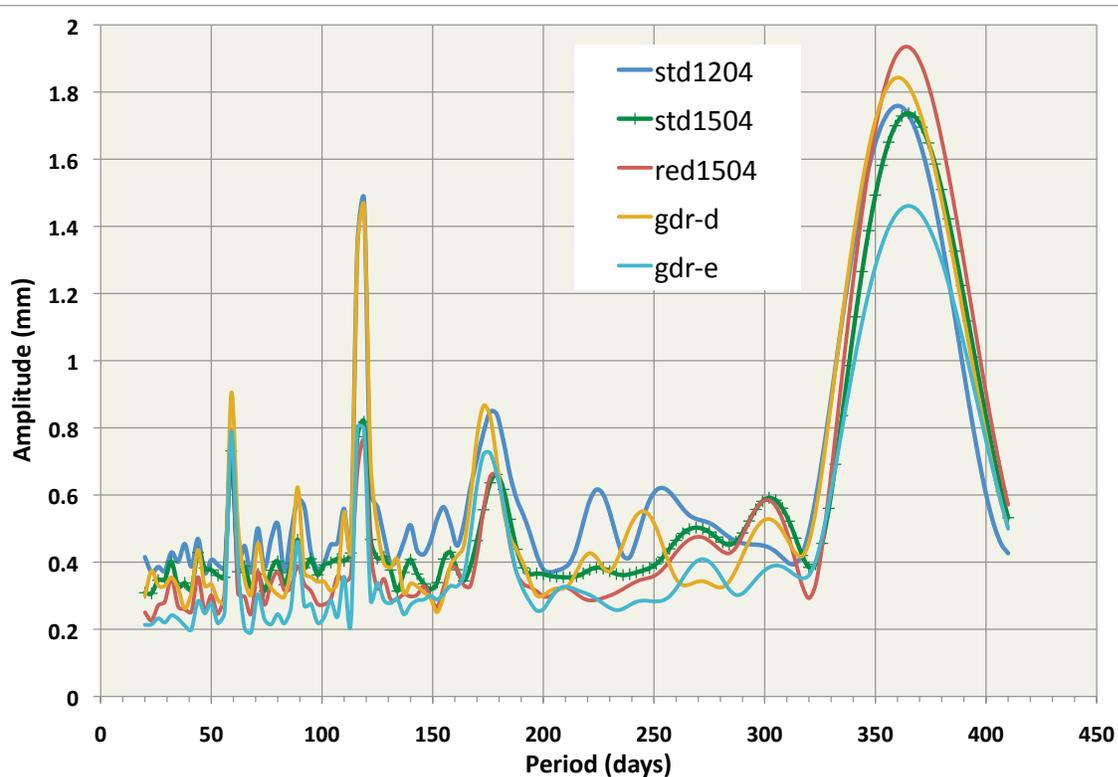


Figure 6.3.2 (Lemoine et al., 2015): 2D projection spectral analysis *jpl14a-“test”* radial orbit differences sampled at fixed geographic locations for the NASA GSFC orbits (*std1204*, *std1504*, *red1504*), and the CNES orbits (*GDR-D* and *GDR-E*). Note the large reduction in radial orbit differences for the new orbits at the 118-day period (from an amplitude of 1.5 mm to ~0.8 mm).

6.3.2 Tracking system status (GPS, SLR, DORIS)

6.3.2.1 GPS

After an anomaly on GPS receiver A, the GPS Receiver B (GPSP-B) was activated on Aug. 26, 2014. It only started returning data on Sept. 10, 2014. Initially the GPSP-B tracked fewer satellites and had a shorter mean tracking path length. After the implementation of a series of software updates, the number of satellites tracked and mean tracking length is on par with the performance of GPSP-A. However, in terms of daily data loss, GPSP-B exhibits a median data loss of 30 min compared to 12 min for GPSP-A (cf. see Bertiger et al., 2015).

6.3.2.2 SLR

The acquisition of SLR tracking data for Jason-2 is still without any issues, but the quality may inadvertently deteriorate even for stations in the core network. In July 2015, the standard deviation of the Greenbelt SLR data increased by a factor of 3-4 because of an unannounced instrument change (test of a new photon counter). In November, another incident involving Greenbelt made the tracking data unusable for POD validation. The Jason-2 POD team informed the ILRS that these kinds of surprise interventions are extremely disruptive for operational users.

In view of the concerns discussed at the 2014 OSTST meeting about station biases in particular, a first analysis comparing biases determined on the geodetic satellites LAGEOS-1/2 and Starlette and Stella was completed. In general, Bruinsma et al. (2015) found that biases determined with the geodetic satellites can be applied to the altimeter missions, but for several stations biases are observed to be a function of altitude. The analysis will be continued in 2016 in collaboration between CNES and GSFC.

6.3.2.3 DORIS

The tracking performance of the DORIS measurement system remains stable over time. At the 2015 OSTST meeting, Lemoine et al. (2015) reported an increase in DORIS RMS of fit from 2012 onwards from 0.37 mm/s to ~0.41 mm/s. However subsequent analysis following the OSTST revealed that the increase in RMS of fit was an artifact of omitting the newest DORIS stations. When the new DORIS stations were included using the DPOD2008v15 station coordinate set (Willis et al., 2015), the RMS of fit to the DORIS format2.2 Doppler data was found to be stable, and varied between 0.37 to 0.39 mm/s after 2012.

6.3.3 Non-tidal Time-Variable Gravity (TVG) modeling strategies for altimeter satellites

6.3.3.1 GRACE-derived mean gravity field models

GSFC (6x20 annual terms), JPL (JPLRL05M) and CNES (EIGEN-GRGS.RL03-v2.MEAN-FIELD) all use a background GRACE-derived mean gravity field model. The new model for GDR-E represents TVG to degree and order 80, with bias, drift, annual and semiannual variations estimated on an annual basis. The difference of this mean field with the monthly GRACE solutions becomes small, as shown in Figure 6.3.3. The model is available on the GRGS website (http://grgs.obs-mip.fr/grace/variable-models-grace-lageos/mean_fields). The std1504 orbits from NASA GSFC used a parameterized fit to a time series of low-degree (5x5) SLR-DORIS data-derived solutions over three time periods. The background geopotential model was GOCO2S, based on GRACE and GOCE data. The annual variations for GRACE were modeled using a fit to the NASA GSFC GRACE spherical harmonic solutions to degree 20.

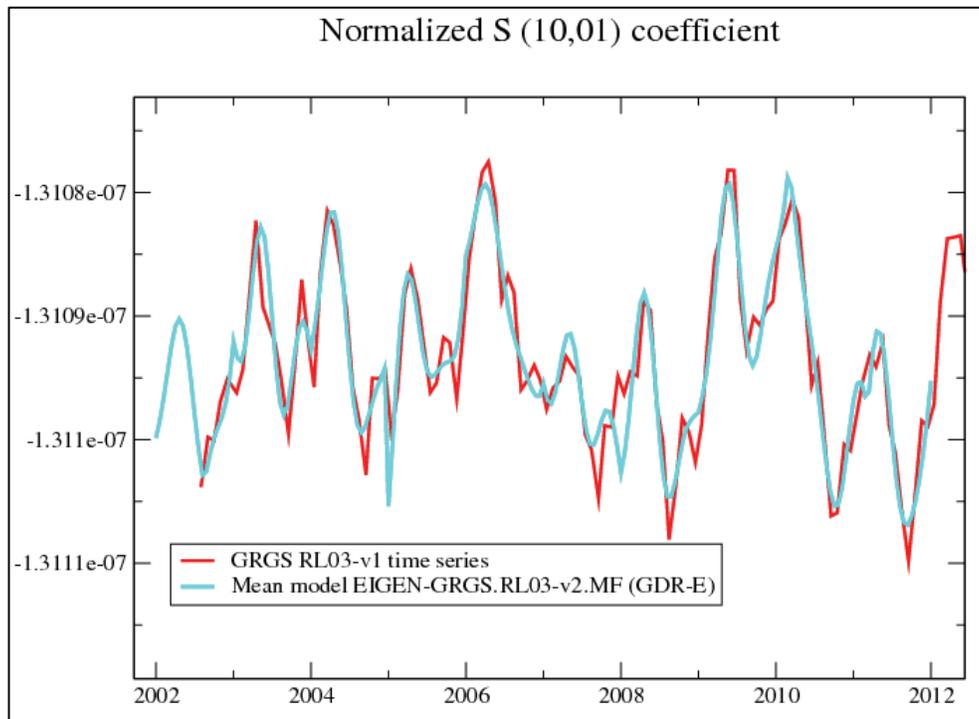


Figure 6.3.3 (J.M. Lemoine et al., 2015): The spherical harmonic coefficient $S(10,1)$ of the mean model for GDR-E (blue) compared with the monthly GRACE solutions.

6.3.4 Current work and future improvements

6.3.4.1 ITRF2014

A new realization of the International Terrestrial Reference Frame (ITRF) will be released by the end of 2015. The preliminary version of the IGN solution (ITRF2014p) was released a few weeks before the OSTST. Solutions are expected from the DGFI and from JPL, although the latter will likely be a time series of solution based on propagation of solutions with a Kalman filter. The new feature of the ITRF2014p solution is the explicit modeling of post-seismic displacement using different functions to accommodate the relaxation following earthquakes. This will allow improve modeling of station motion for many sites, compared to using linear velocity models for station displacement. Testing of the different reference frame realizations will be a leading activity in 2015-2016. Some preliminary evaluations were completed by Bruinsma et al. (2015) using a few years of SLR data on LAGEOS, and a 20-30% decrease in RMS of fit was observed. Tests by NASA GSFC following the OSTST show a significant improvement in the Jason-2 RMS of fit for DORIS-only orbits using ITRF2014p. Over cycles 1-260 (July 2008 – August 2015), the DORIS RMS of fit for DORIS-only orbit improves from 0.3759 mm/s to 0.3635 mm/s for ITRF2014p compared to DPOD2008v15.

An important POD concern with the new ITRF will be the availability of coordinate solutions for all stations used in altimeter satellite POD. For ITRF2014p, the DORIS complement is missing 27 stations compared to the DPOD2008v15 station coordinate complement, based on ITRF2008. This is usually because of short occupations for some sites in the ITRF2014p solution. Similar issues will need to be addressed for the SLR and GPS stations before the new ITRF2014 can be used in operational POD for altimeter satellites. We expect to participate in evaluations of these extended models with the respective geodetic services (e.g. IIRS, IDS) however we are reliant on their efforts to produce these

extended POD models as that is beyond the scope of our normal work at the CNES and NASA GSFC POD centers.

6.3.4.2 Relative orbit centering

At the 2014 OSTST meeting at Lake Constance, Germany, an annual geocenter model (“Climatological model” SLR-only; from J. Ries, 2013) was thoroughly tested by the different POD analysis centers. Even though the model tends to improve consistency between independent DORIS-only and GPS-based orbits, discrepancies remain to be elucidated, in the North/South direction. In order to overcome this issue, attempts were made to estimate independently the geocenter motion using either the GPS network and constellation, or the DORIS stations simultaneously with Jason-2 orbit. The first outcomes did not appear conclusive in Z.

A way to bypass geocenter-related difficulties is to compute a terrestrial reference frame explicitly around the instantaneous CM of the whole Earth. Doing so, Bertiger et al. (2015) showed that adjusting geocenter with frame (de-weighting GPS for the Z component) significantly impacts their Jason-2 GPS-based reduced-dynamic orbits and potentially improves quality metrics (**Figure 6.3.4**).

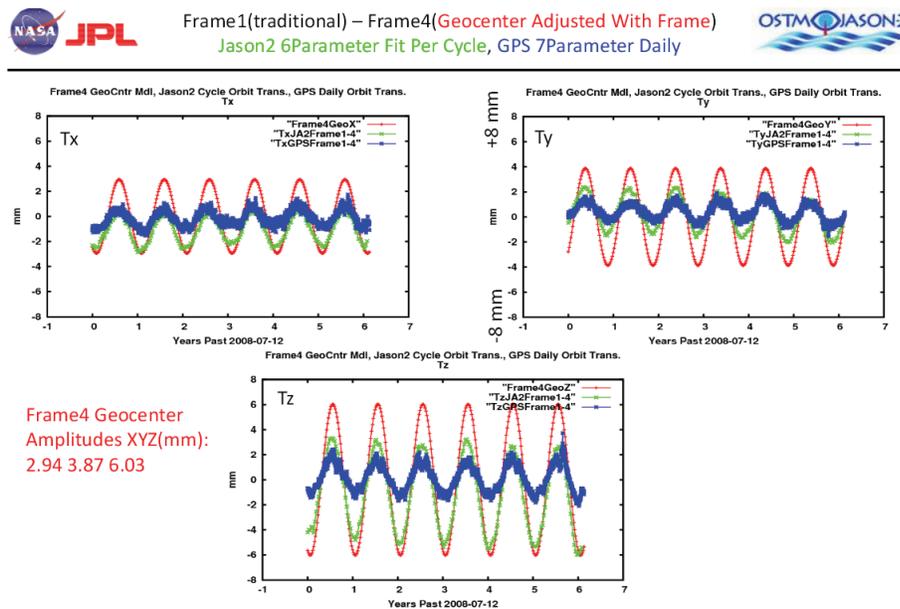


Figure 6.3.4 (Bertiger et al., 2015): Frame and orbit translation parameters (for Jason-2 and GPS) between Frame1 (comparable to previous ITRF realizations) and Frame4 (geocenter accounted for in the frame).

Further efforts were also pursued to look at the geocenter motion in an integrated approach using Jason-2 DORIS data. Couhert and Mercier (2015) pointed out that a significant error source in DORIS Z-component geocenter determination originates from tropospheric correction modeling deficiencies (affecting vertical station positioning). The solution tested to avoid this major source of error was to estimate the vertical displacement of each DORIS station, while adjusting geocenter with Jason-2 DORIS-only orbit. As can be seen in **Table 6.3.2**, additionally solving for vertical displacements improves the SLR residuals with respect to only solving for the global translation network motion. Besides, a small crossover variance reduction (positive values mean improvement w.r.t. using SLR-only CoM model, cf. “COM”) is found when computing Jason-2 DORIS-only orbits with the geocenter motion as seen by

DORIS (“3 trans.”, 1.5 mm²) and even slightly better with the vertical displacements additionally estimated (“3 trans. + vert.”, 1.8 mm²).

	SLR (cm)		Crossover	
	high el.	All	mm	mm ²
No CoM	1.09	1.99	5.1	-0.2
COM	1.07	1.95	5.2	0.
3 trans.	1.11	2.06	5.8	1.5
3 trans. + vert.	1.09	1.91	5.6	1.8

Table 6.3.2: (Couhert and Mercier, 2015). Independent SLR and altimeter crossover residuals statistics for different orbit solutions.

6.3.5 Conclusions and recommendations

It is important to understand that the process of orbit determination for Jason-2 is operationally dependent on the derivation of models of time-variable gravity over the altimeter dataset period. The availability of GRACE-like solutions (GRACE-FO and beyond) must therefore be defended for future altimeter missions.

The trend of increasing residuals as well as station biases for some of the core network SLR stations – those that provide substantial amounts of data (e.g. Yarragadee, Greenbelt) - must be elucidated. The POD team (CNES and GSFC specifically) will continue their investigations, specifically by comparing results obtained on geodetic targets with SLR residuals of altimeter missions; the input of the International Laser Ranging Service (ILRS) will be solicited to elucidate this issue. The new reference frame ITRF2014 may already solve a large part of the problem.

6.4 Application development for Operations (previously NRT)

Chairs: Emilie Bronner, Gregg Jacobs, Remko Scharroo, and John Lillibridge

There were 6 talks and 6 posters presented, and the session was well attended (> 100 attendees).

6.4.1 Oral presentation summary

The first talk by **Lotfi Aouf**, ‘Are the SAR wave spectra of S1-A ready for use in the operational wave model MFWAM?’ discussed the improvements to the swell forecast (especially directional information) when Sentinel-1 SAR wave-spectra data are assimilated into the MFWAM model. The normalized scatter index of SWH was improved for the analysis and forecasts for up to 3 days. Further improvement was achieved, particularly for the analysis and 1-day forecast, when a combination of Sentinel-1 data and altimetric SWH data was assimilated.

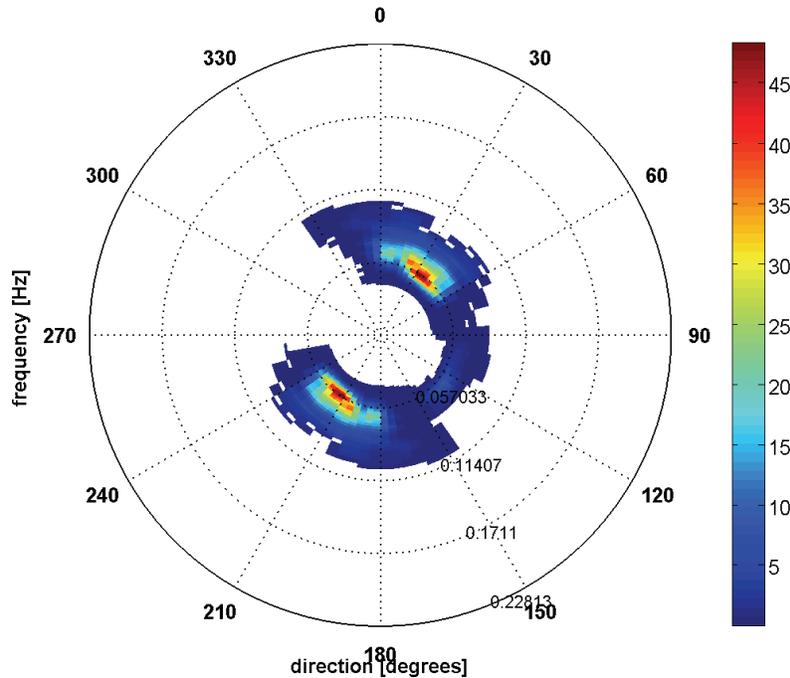


Figure 6.4.6 Example of wave spectrum from Sentinel-1A WaveMode-1

The next talk by **Zhijin Li** 'Improved Representation of Eddies in Fine Resolution Forecasting Systems Using Multi-Scale Data Assimilation of Satellite Altimetry' looked at improving the model resolution of submesoscale features during the Salinity Processes in the Upper Ocean Regional Study (SPURS) field campaign. The assimilation of altimetry data improved the spatial resolution of the model, realistically reproducing submesoscale features observed in high resolution SST SPURS measurements. An eddy flux divergence analysis from the reanalysis showed that both mesoscale and submesoscale flux divergences account for a significant part of the salinity budget in the maximum salinity SPURS region.

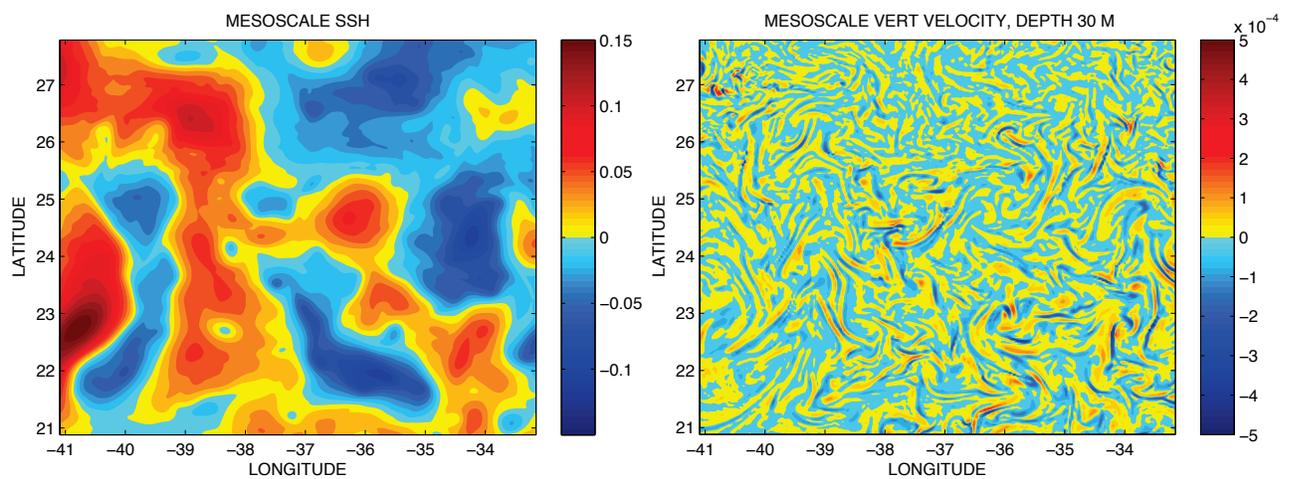


Figure 6.4.7 Mesoscale Sea Surface Height (left) and Vertical Velocity @ 30m (right) from 3-km resolution ROMS model

The third talk by **Eileen Maturi, et al.**, ‘NOAA Operational Satellite Derived Oceanic Heat Content’ described the Ocean Heat Content (OHC) products currently being produced by NOAA’s Office of Satellite & Product Operations. Of the 7 ocean basins where tropical cyclones regularly occur, OHC products are being generated in 4 of them: the N. Atlantic, NE Pacific, NW Pacific, and SW Pacific/Australia. The OHC products are based on a 2-layer reduced gravity model constrained by altimetric SSH and a blended 5-km SST analysis (GOES+POES). An example of the response of OHC to super-typhoon Haiyan (Nov. 3-11, 2015) illustrated the utility of the data for studying hurricane intensification.

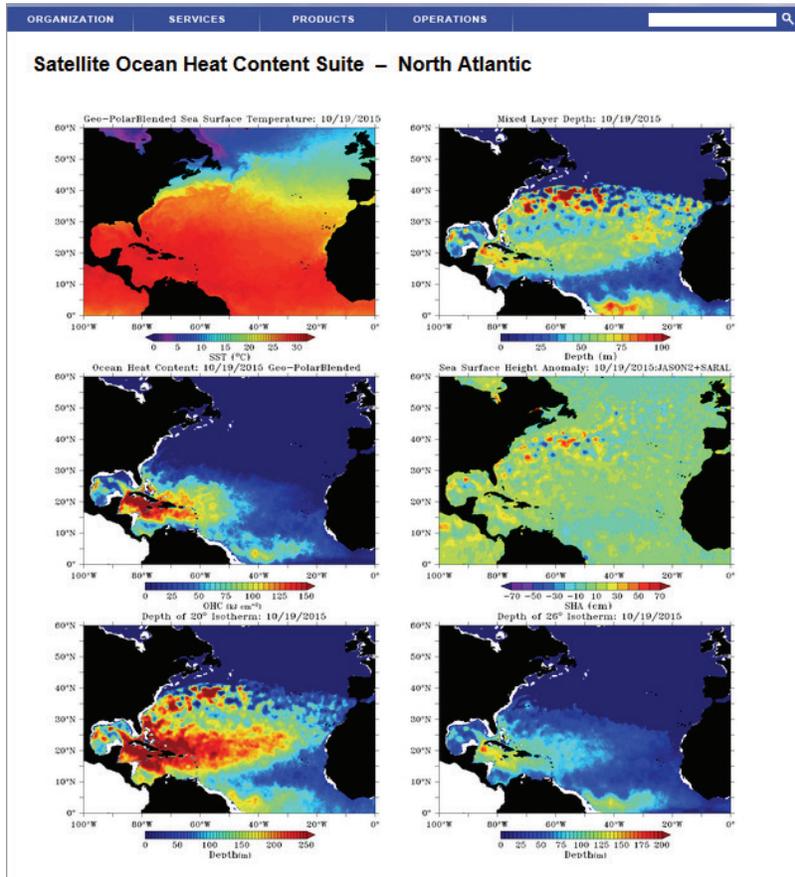


Figure 6.4.8 NOAA Ocean Heat Content analysis for 2015-10-19 in the N. Atlantic

The fourth talk by **Liyan Liu** ‘On the use of recent altimeter products in NCEP ocean forecast system for the Atlantic (RTOFS Atlantic)’ discussed the benefits of assimilating altimetry data into the HYCOM-based Atlantic RTOFS model, being run operationally at NOAA’s National Weather Service. Sea surface heights from Jason-2, Cryosat-2 and SARAL/Altika, from the Naval Oceanographic Office’s value-added data sets, are assimilated along with SST and in situ temperature/salinity profiles. Recently the mean dynamic topography grids from SSALTO/DUACS have been incorporated so that SSH as well as SSHA and absolute currents are available from the RTOFS model.

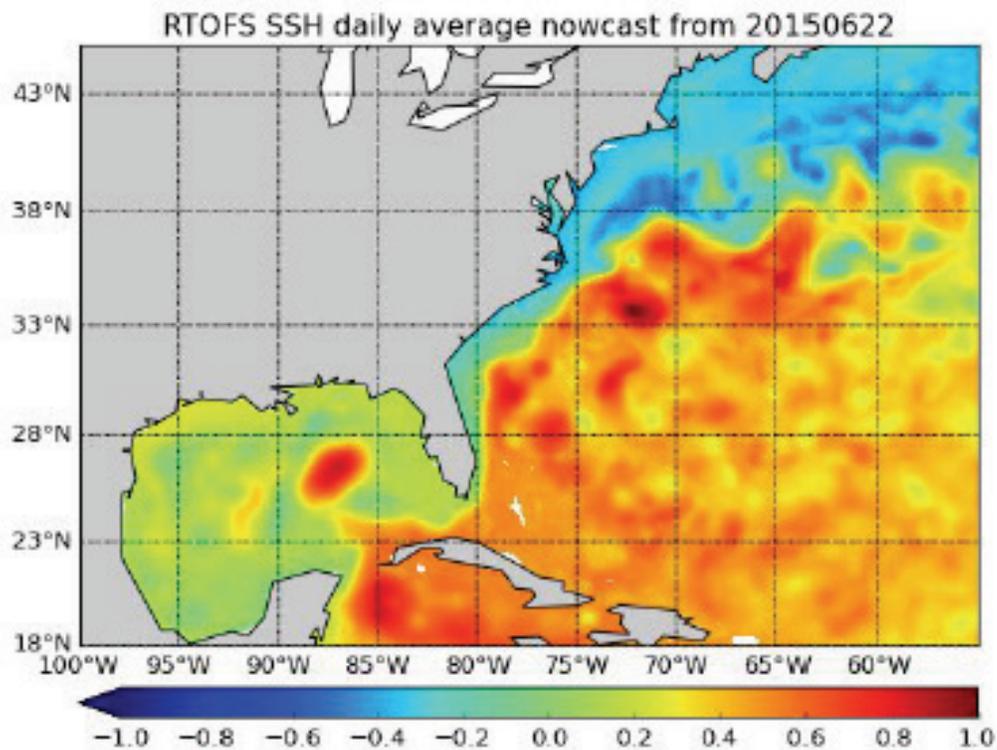


Figure 6.4.9 RTOFS Sea Surface Height Nowcast for 2015-06-22

The fifth talk by **David Griffin** 'Operational Oceanography in support of the search for MH370' provided an update on the tragic loss of Malaysian Air Flight MH370, and the recent finding of the airplane's flaperon on Isle de La Reunion. Based on analyses of undrogued surface drifters and the wave + ocean models, the combination of Ekman drift and wave-induced Stokes drift could explain the debris found on La Reunion coming from the primary search area SW of Australia. In other words, modeling and drifters do **not** cast doubt on the "7th arc" 39-32S search area. An interesting aside was the notion that the Stokes-Coriolis effect is not accounted for in the momentum equation of ocean models. Could this be responsible for some of the model-data misfit we observe?

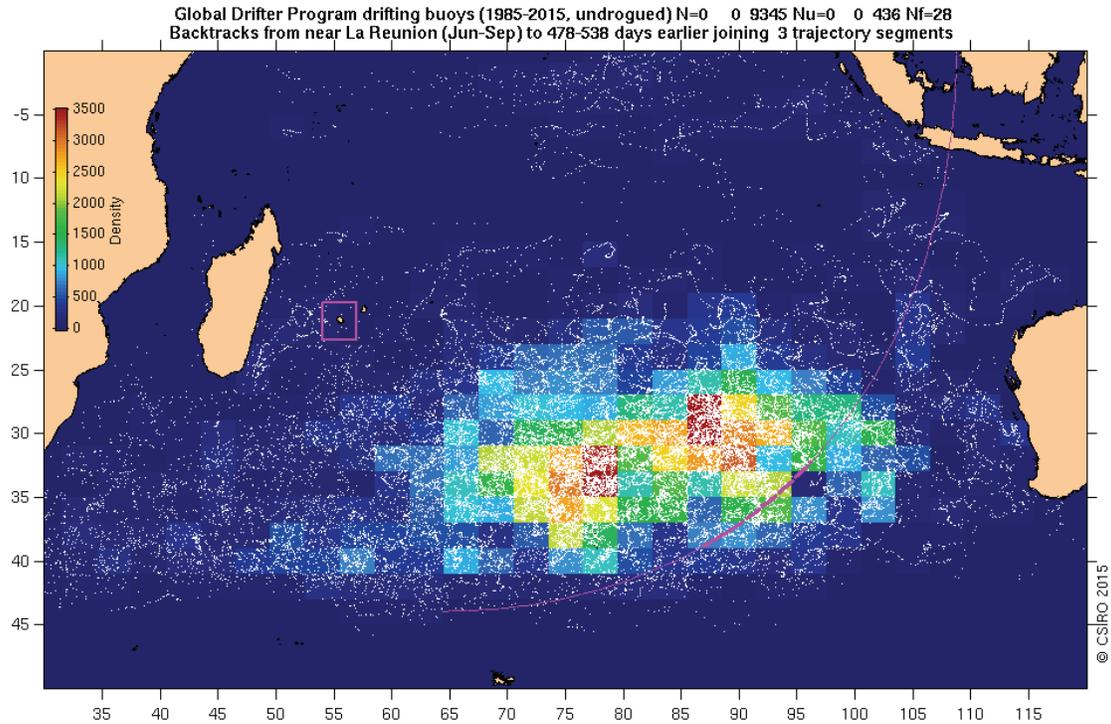


Figure 6.4.10 Likelihood function from global drifters that encounter La Reunion (rectangle) vs. MH370 search arc (purple curve)

The final talk by **Nikolai Maximenko, et al.** 'Predictability of marine debris motion, simulated with numerical models and diagnosed using oceanographic satellite data' continued the analysis of the spreading debris field from the 2011 Tōhoku earthquake and tsunami. After more than 5 years, the debris has now reached the W. Coast of the U.S. as well as Hawaii, and has been well modeled by the Univ. of Hawaii Surface CUrrents from Diagnostic (SCUD) model. This debris presents an ecological hazard due to the transport of non-native Asian species, which could become invasive. The model predicts that debris with different windages not only move at different speeds, they also have different destinations. Based on the results from three different debris models (SCUD, NOAA's GNOME, & Japan's SEA-GEARN/MOVE-K7) approximately 700 boats are still floating in the Pacific "garbage patch" and will continue washing ashore in the next several years.

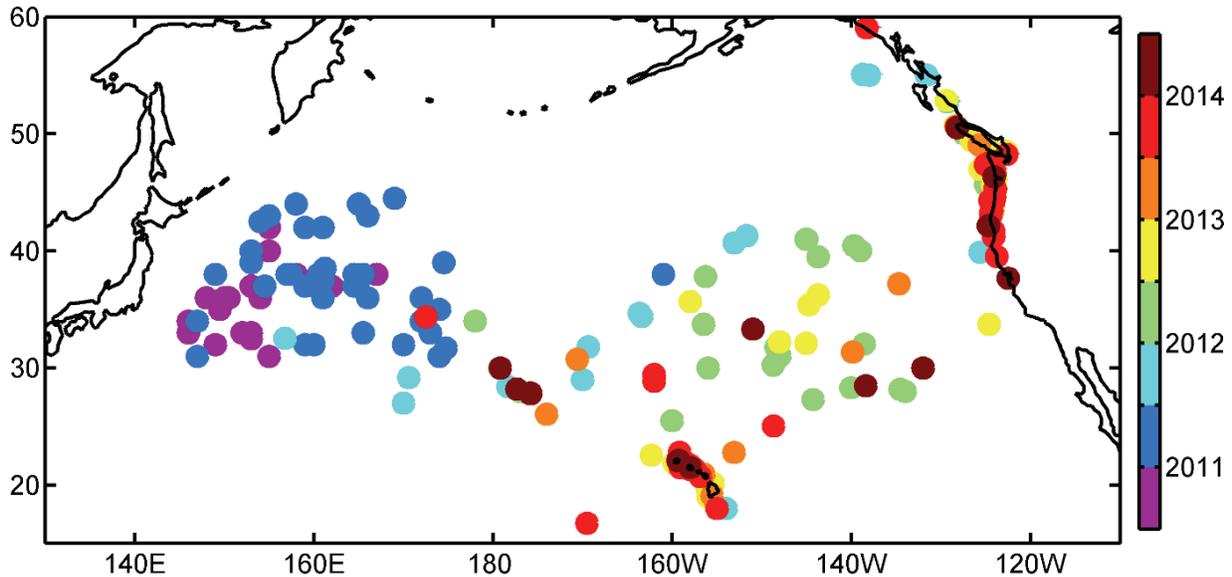


Figure 6.4.11 Reported locations of boats, and times of the reports (colored by year)

6.4.2 Round table summary

With respect to the subjects proposed by the OSTST project scientists for discussion, the following points were noted and presented in the final closing plenary:

1. Jason-2 Extension of Life

For operations the best scenario is to stay on the interleaved track as long as possible.

Geodetic data may benefit SWOT through improved MSS.

By how much do we expect Jason-2 Extension-of-Life to contribute to reducing MSS errors?

In terms of orbit selection, we endorse G. Dibarboure's recommendation.

When we have 6 operational satellites, the incremental benefit of Jason-2 will be less

However, this will **still** not be oversampling the ocean...

2. SARAL/AltiKa Drifting Orbit

SARAL/AltiKa has a bigger influence on ocean forecasts than Jason-2 (perhaps even J2+J3).

A drifting orbit will be sub-optimal, but would be desirable if it ensures a significantly longer mission.

When it's time to move, try to optimize the drifting orbit to benefit the MSS.

Is there any possibility that onboard fuel will be consumed prematurely, due to station keeping?

If possible, maintain the +/-1km orbit until Jason-3 is launched.

3. Other Issues

Jason-3 Launch Delay

- The sooner we get Jason-2 into the interleaved orbit the better.
- It isn't a matter of bridging a gap: we will lose operational capability altogether.
- We are living in fear of losing ocean forecasting: Jason-2 is beyond its design life; SARAL has health issues; Cryosat-2 sampling isn't sufficient for ocean predictions.
- However, please do NOT launch Jason-3 until it is absolutely safe to do so!

COP21 Recommendation

- We support the altimetry for climate recommendation, but also suggest stressing regional as well as global sea level rise, as well as mentioning extreme events.
- We should also put forward recommendations to operational satellite groups such as WMO & IOC

We need to reduce data latency from current 2+ hours to ~ 1 hour for wind/wave applications.

- This can only be achieved with a S. Hemisphere ground station - action to investigate possible options.

6.4.3 Poster summary

Saleh Abdalla, et al. 'Cryosat-2 Wind & Wave Products: Preparation for Sentinel-3' describes a validation exercise comparing SAR-mode wind/wave data from Cryosat-2 with the operational models at ECMWF. SWH SAR-mode data tends to overestimate the wave field compared to the WAM model as well as in situ buoy measurements (more so in the Atlantic than Pacific Cryosat-2 SAR boxes): 5% higher than the model; 3.5% higher than buoys. Altimetric wind speed estimates agree better with the ECMWF model with negligible biases in both regions.

Carolyn Cooper, et al. 'Satellite Altimetry Sea Surface Height Anomaly Processing at the Naval Oceanographic Office Altimetry Data Fusion Center' provides an overview of the data processing system at NAVO's Altimetry Data Fusion Center (ADFC). Their value-added data sets for Jason-2, Cryosat-2, and SARAL/AltiKa are utilized both within the Navy (operational ocean models) but also by NOAA/NESDIS and NWS. The poster presents examples of routine monitoring statistics, as well as the technical details on data treatment.

Yannice Faugère, et al. 'DUACS Sea Level Products, a Step Beyond with Jason-3 and Sentinel-3' explains how the SSALTO/DUACS system will utilize the upcoming Jason-3 and Sentinel-3A altimetry missions to further enhance its multi-mission capability. DUACS provides level-3 (along-track cross-calibrated sea level anomaly) as well as gridded level-4 data sets, currently based on Jason-2, Cryosat-2, SARAL/AltiKa, and most recently HY-2A. The addition of two new missions, and the challenges of seamlessly integrating the SAR-mode data of Sentinel-3A present both challenges and new opportunities.

Isabelle Pujol, et al. 'New Release of DUACS Products: 20 Years of High Resolution Sea Level Time Series Reprocessed' in the first of her two posters describes the two-decade reprocessing effort at DUACS. Enhancements in this latest reprocessed data set include improved mesoscale resolution, greater data recovery in coastal regions, more realistic geostrophic currents, and a more precise time series of global sea level rise. Users need to be aware that the reference time period has been changed, when making comparisons with earlier DUACS data sets.

Isabelle Pujol, et al. '21 Years of Reprocessed Lyapunov Exponents from Altimetry Available on AVISO+' in this second poster describes a novel new altimetry data product 'Lyapunov Exponents'. These exponents are computed from geostrophic current estimates using the level-4 (gridded) DUACS multi-mission products. They serve as a proxy for mesoscale "fronts" associated with converging currents. These are an inherently Lagrangian, particle-oriented, calculation which is more complex than standard Eulerian parameters. These products are an excellent example of the push by altimetry into the submesoscale domain.

Toshiyuki Sakurai, et al. 'Operational ocean data assimilation/prediction system for the western North Pacific at JMA' provides an overview of the near real-time operational systems being run by Japan's meteorological agencies. Their system assimilates altimetric sea level anomaly data from DUACS along with SST and in situ temperature and salinity measurements. The model assimilates data with a 3DVAR system known as MOVE (Multivariate Ocean Variational Estimation system) and provides both nowcast/analysis and forecasts of the ocean state. An important regional product is monthly forecasts of SST and surface currents in the seas surrounding Japan. The system currently utilizes only Jason-2 data, but a multi-mission altimetry assimilation scheme is envisioned for the near future.

6.5 Tides, internal tides and high-frequency processes

Chairs: Loren Carrere, Florent Lyard and Richard Ray

This year the Tides/HF splinter counted 7 oral presentations and 4 posters dedicated to tides, and 1 poster dedicated to HF signals.

6.5.1 Presentations

Two talks focused on the new barotropic tides models on global ocean (FES2014) and in Arctic region. One presentation focused on the notorious 59-days problem in TP and Jason mean sea levels. Three other talks focused on internal tides and one on internal waves, motivated especially to prepare for SWOT.

L. Carrere presented the final results of new global FES2014 tidal model, which is an improvement of FES2012 model; model has been developed in collaboration with CNES/CLS/LEGOS/NOVELTIS. Results are significantly improved in many places, in deep ocean, in shallow waters, and at high latitudes including in the Arctic ocean. The validation is still on-going. The tidal elevation and the tidal currents will be available on a $1/16^\circ$ grid in 2016. A scientific paper is in preparation.

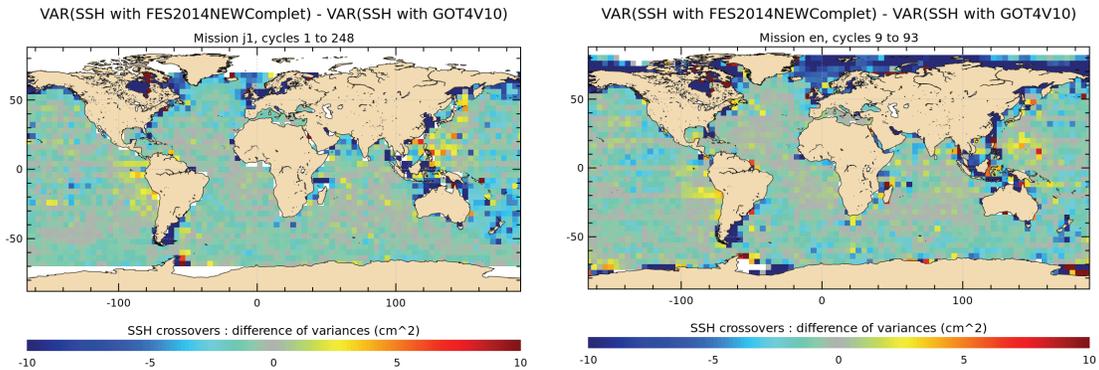


Figure 6.5.12 : Variance reduction for Jason-1 and ENVISAT crossovers when using FES2014 tidal model instead of GOT4V10 (cm²)

L. Zawadzki talked about the 59-days problem in T/P and Jason mean sea levels, due to inconsistencies of satellites at β' period (S2 alias). GOT4.10 and FES2014 are two valid solutions to ensure a low 58.77-day error on Jason-1 and Jason-2 MSL (<1mm). FES2014 is a good compromise to ensure a consistent error between T/P and Jason-1/2 MSL. Most of the 58.77-day error is due to the assimilation of T/P SSH (mostly visible in Indian Ocean). But part of this error is also likely due to the assimilation of Jason-1 and Jason-2 SSH (visible in Atlantic Ocean). A scientific paper is in preparation.

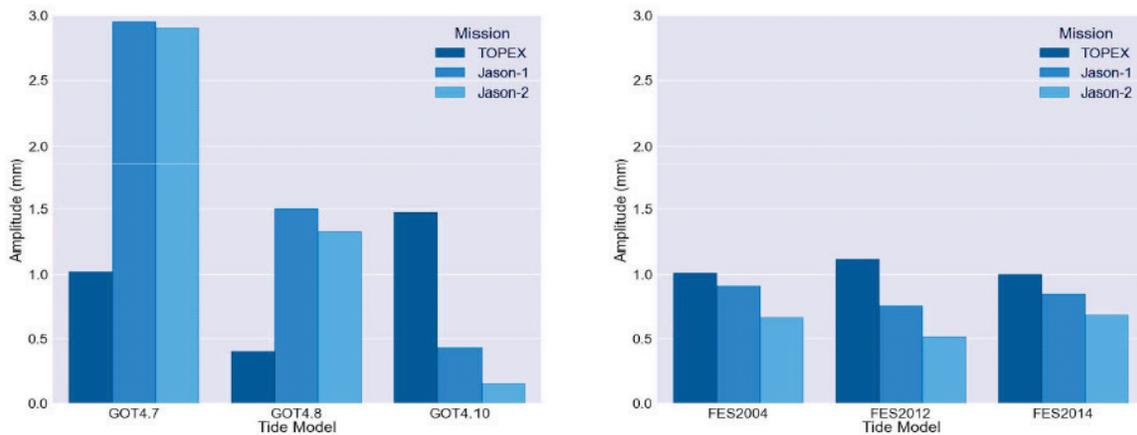


Figure 6.5.13 : Amplitude of 58.77 day signal in TOPEX, Jason-1 and Jason-2 GMSL series, changing ocean tide correction. Selection on latitudes (<50°), bathymetry (> 1000m) and oceanic variability (< 20cm).

M. Cancet presented a new regional tidal model for Arctic Ocean developed in collaboration with ESA/NOVELTIS/DTU. The mesh has been refined to 4 km on coasts. Preliminary results show that the regional purely hydrodynamic model shows equivalent performances to global assimilated models for semi-diurnal waves. More work is needed on diurnal waves. Next steps are to study the influence of the sea ice extent and to perform the assimilation.

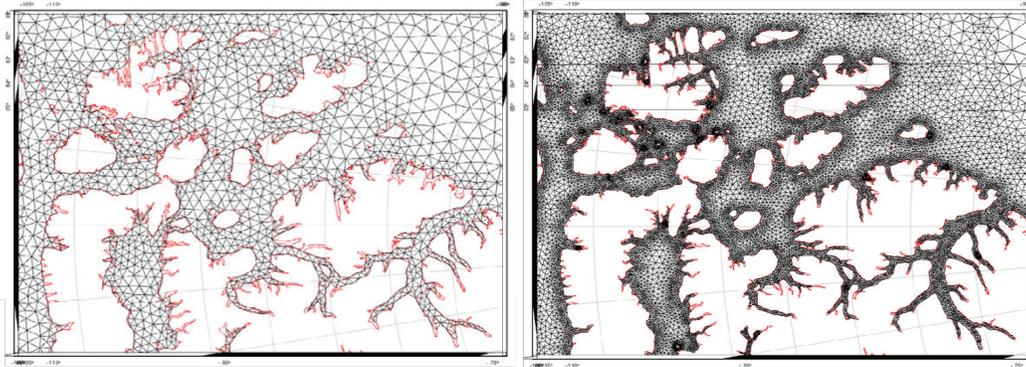


Figure 6.5.14 : initial global mesh (left) and refined regional mesh (right) in Arctic region. Resolution of the refined mesh is 4 km on coast and 8 km offshore.

R. Ray presented a strictly empirical tidal analysis of satellite altimetry to produce a M2 internal tides atlas. The advantage of this approach is that no dynamical assumption is made about ocean waves, which allows testing dynamic theories. But the present altimeter constellation is barely adequate to map very short scales signals. The results show strong interest of this internal tide empirical atlas to correct altimetry. A last focus is made on M2 internal tide leakage in last version DUACS 2014 of AVISO grids, and thus the previous DUACS 2010 grids have been used as “mesoscale correction” prior to tidal analysis in this study. Results are to be published in JPO paper 2016 “Coherent M2 internal tides”.

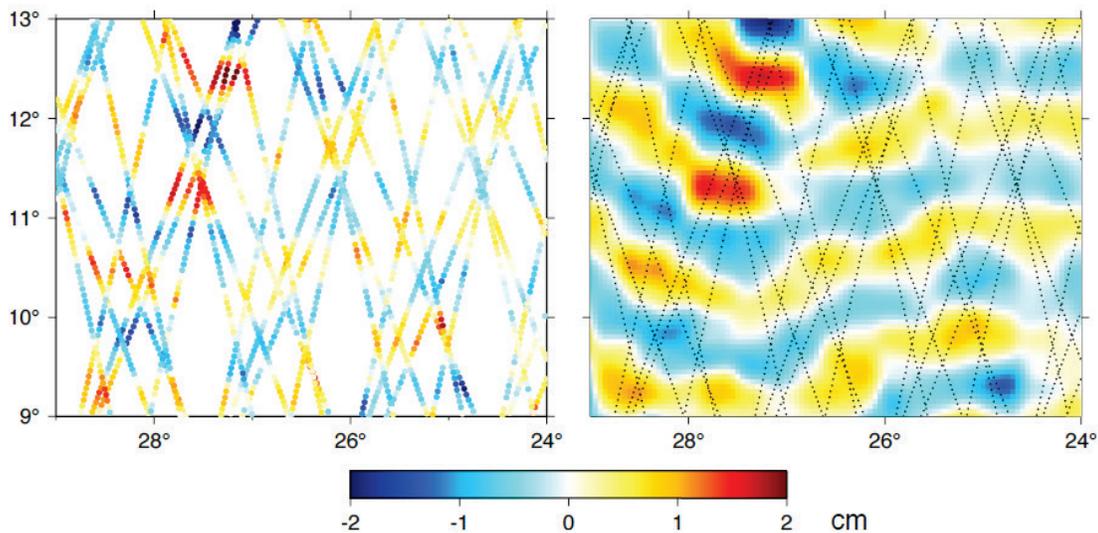


Figure 6.5.15 : zoom view of gridding.

Z. Zhao presented a v0.0 global internal tide model computed from multi-satellites altimetry for main waves M2, S2, O1, K1. Method is based on a plane wave fit of SSH(x,y,t) data in a fitting window defined by the internal tides wavenumbers given by World Ocean Atlas 2013. The method is also applied to Cryosat-2 data showing very interesting results. The model is still in development phase and other main waves should also be computed.

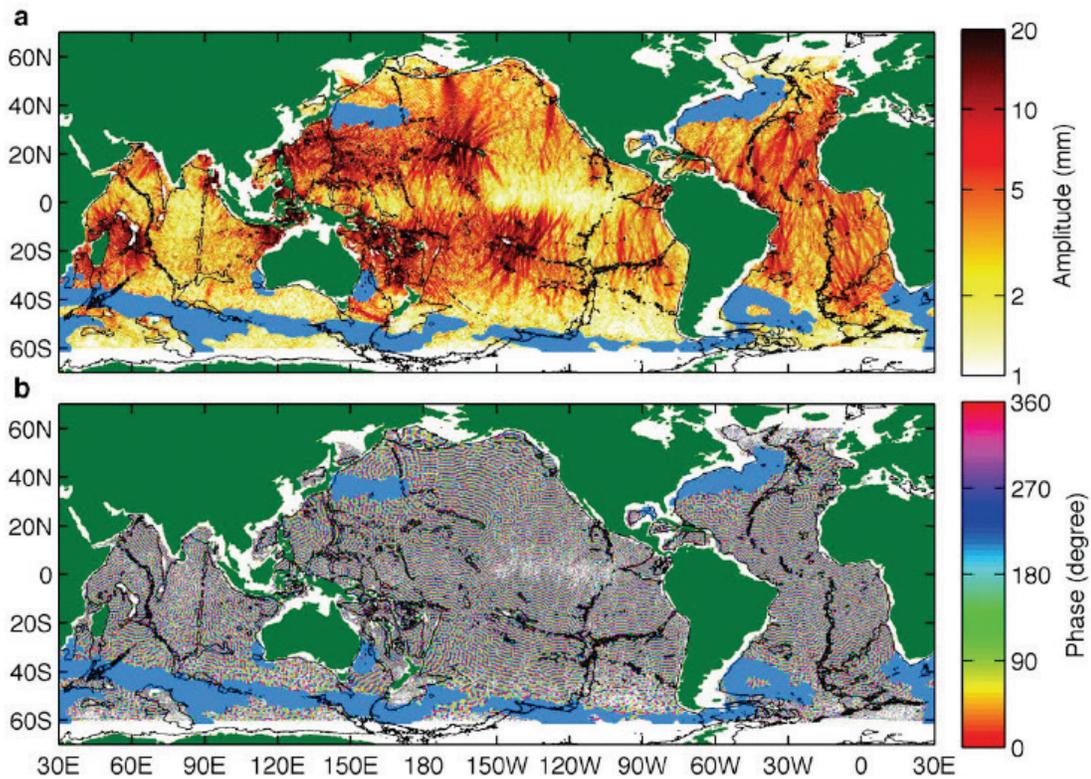


Figure 6.5.16 : Global mode-1 M2 internal tides.

F. Lyard presented a few slides about an internal wave modeling exercise using T-UGOm 3D model, performed at LEGOS. HYCOM (time-stepping) and T-UGOm (frequency domain) get similar solutions. But 3D frequency-domain modeling is extremely cheap, compared to time-stepping, and accurate. LEGOS will base future internal tides corrections on T-UGOm model (frequency-domain) coupled with data assimilation (frequency-domain).

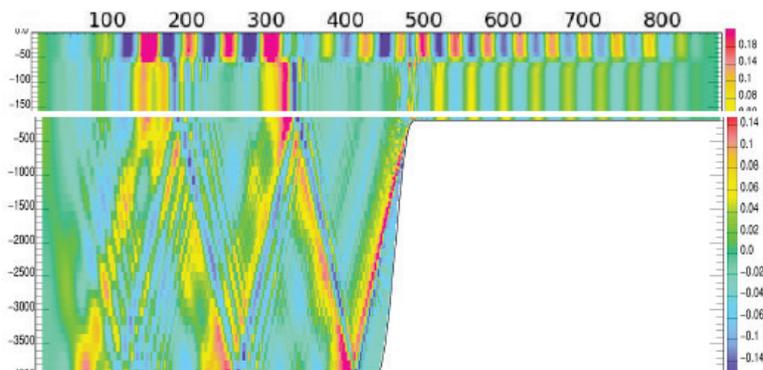


Figure 6.6.17 :T-UGOm simulation using a surface mixing layer and a uniform N, $K_z t_{ugo} = 0$

M. Alford presented results about internal wave spectrum inferred from profiling moorings. The goal of the study was to determine a global map of where internal wave SSH will dominate observed SWOT signals. Full-depth profiling moorings and tows confirm Farrar's hypothesis that IW's will be observable by SWOT at some locations. Modal content is key for the calculation of SSH and for wavenumber content but it is poorly constrained (need full depth dataset).

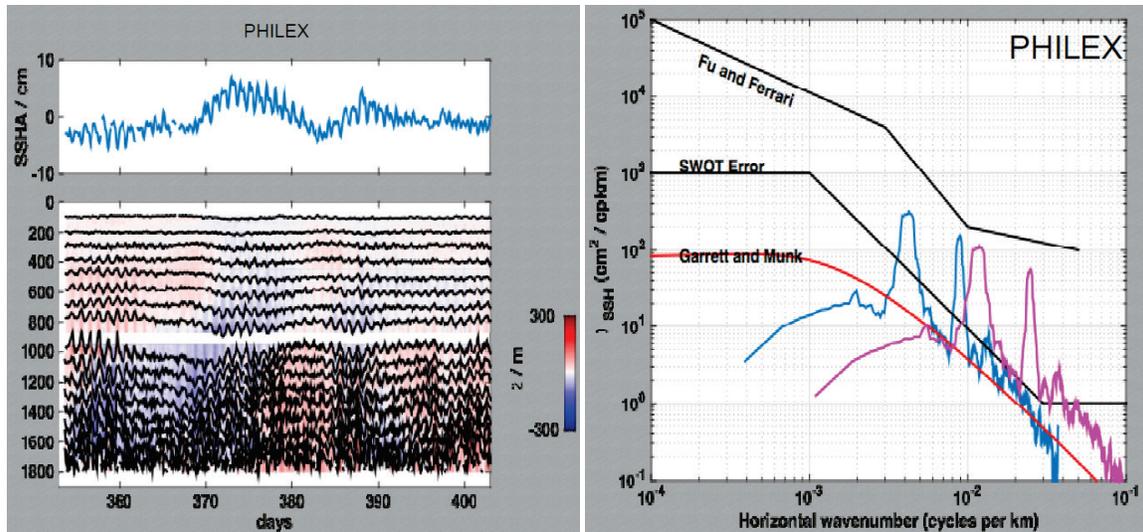


Figure 6.5.18 : time series (left) and horizontal wavenumber spectra (right) of mooring PHILEX showing that IW can dominate observed SWOT signal.

6.5.2 Posters

Cheng et al. presented a barotropic tidal estimation in China Seas based on satellite altimetry. Zaron et al. proposed a new analysis of surface internal tides using dual-satellite altimetry from Jason-2 and Cryosat-2 to quantify stationary and non-stationary tides. A new global internal tides model solution based on a data-assimilative reduced gravity model was presented by Egbert et al. A new revised pole-tide correction for satellite altimetry was also presented (Desai et al.) to replace the old Wahr correction (1985) used since T/P. Carrere et al. presented results about improvements to dynamic atmospheric loading model (DAC) using atmospheric forecasts and also a variable sea ice cover.

6.5.3 Splinter and round table topics:

- Jason-2 EOL orbit:
 - No strong preference, but we should check aliasing of the proposed orbit.
- SARAL orbit:
 - Some in favor of letting it drifting
 - Some in favor of staying around repetitive track ± 5 km
- Internal tides are a big issue for new HR/SWOT missions.
 - Several teams work on the subject and different initiatives should be continued: estimating and mapping the IW surface signatures using altimetry and/or models (coherent part), quantifying and understanding the incoherent part of the internal tide signal, identification of processes which lead to loss of coherency of IW.
 - A CNES SWOT study (L. Carrere) aims at testing some new internal tide models early next year, and some points have been raised :
 - Is it too soon? Current models are fledglings, but the idea is to provide a first evaluation of available models to anticipate the impact for SWOT/HR missions.
 - How to do it?
 - Using independent altimetry, if there is any, is a good approach.

- Using PIES, but they are often deployed in boundary currents, where IW models are likely not accurate, so location of the data need to be check before use.
 - Many subtleties would need to be taken into account or at least firstly identified (e.g., coupling with surface tide ...)
 - Need to iterate to get an agreement on the inter-comparison procedure
- Coastal tides are still an issue as the error of barotropic models in shallow waters/coastal regions remain stronger than in deep ocean. We need better bathymetry fields, higher resolution mesh, and also regional models. Arctic model is promising.
 - Final results of FES2014 global tidal model are very good on global ocean, in deep and shallow waters and in the Arctic region. This model is recommended to be used for altimetry products.

6.6 Regional and Global CAL/VAL for Assembling a Climate Data Record

Chairs: Pascal Bonnefond, Shailen Desai, Bruce Haines, Eric Leuliette, and Nicolas Picot

6.6.1 Introduction

Determining the random and systematic errors in the fundamental instrument observations and in the Level-2 geophysical data products is a continuing process that involves participation of both the project teams and the OSTST investigators. The principal objectives of joint verification are to:

1. Assess the performance of the measurement system, including the altimeter and orbit-determination subsystems;
2. Improve ground and on-board processing; and
3. Enable a seamless and accurate connection between the current (OSTM/Jason-2) and legacy (TOPEX/Poseidon and Jason-1) time series.

CAL/VAL efforts are essential to ensure the integrity of the long-term climate record at the level of 1-mm/yr. These activities are conducted based on dedicated in-situ observations, statistics, cross comparisons between models, different algorithms and external satellite data. The studies go well beyond validation of the overarching error budget underlying the mission requirements. They focus in particular on the temporal and geographically correlated characteristics of the errors. Reduction of this class of errors is critical, since they are conspicuously damaging to estimates of ocean circulation and sea level. Because of the usual large number of contributions it has been decided to separate the CALVAL splinter into two parts:

1. Local calibration/validation (focusing on bias); and
2. Global calibration/validation (focusing on corrections quality assessment and error budget assessment)

6.6.2 Results from in-situ calibration sites

Ensemble results from the dedicated in-situ calibration sites and regional campaigns show the following consistent results (e.g., Figure 6.6.1). Sea surface height (SSH) from the current version D Jason-2 GDR products is unbiased, or slightly biased with questionable significance. SSH from the current version C Jason-1 GDR products is biased high by 9 cm. Preliminary analysis of a test version of the Jason-1 GDR-E products confirms significant reduction in the SSH bias, due mainly to the correction for the Poseidon-2

internal path delay. A residual bias of ~3 cm is observed, and is larger than predicted at the 2014 OSTST meeting, due primarily to the level of the sea state bias (SSB) model, which represents an evolution over the current Jason-2 GDR-D model. The legacy TOPEX/POSEIDON systems continue to be unbiased. However, a new version of the Retracked GDR (RGDR) diverges significantly with the MGDR and tide gauges prior to mid-1995 and warrants investigation (see Beckley et al., Roinard et al. and Shah et al.). The in-situ sites also provide results for the SARAL/AltiKa system, showing that its SSH measurements are biased low by 4 cm.

The Harvest and Bass Strait sites now yield Jason-2 drift estimates of less than or 1 mm/yr and are statistically insignificant. However, systematic patterns in the calibration series from all sites remain, with an observed drift of -4 mm/yr at the Corsica site. These results raise questions about the regional stability (or sensitivity to sea states) of the altimetric measurements, and on the stability of the in-situ observations themselves (e.g., water level and vertical land motion). A spurious drift in the C-band range from Jason-2 at the Harvest site also warrants investigation.

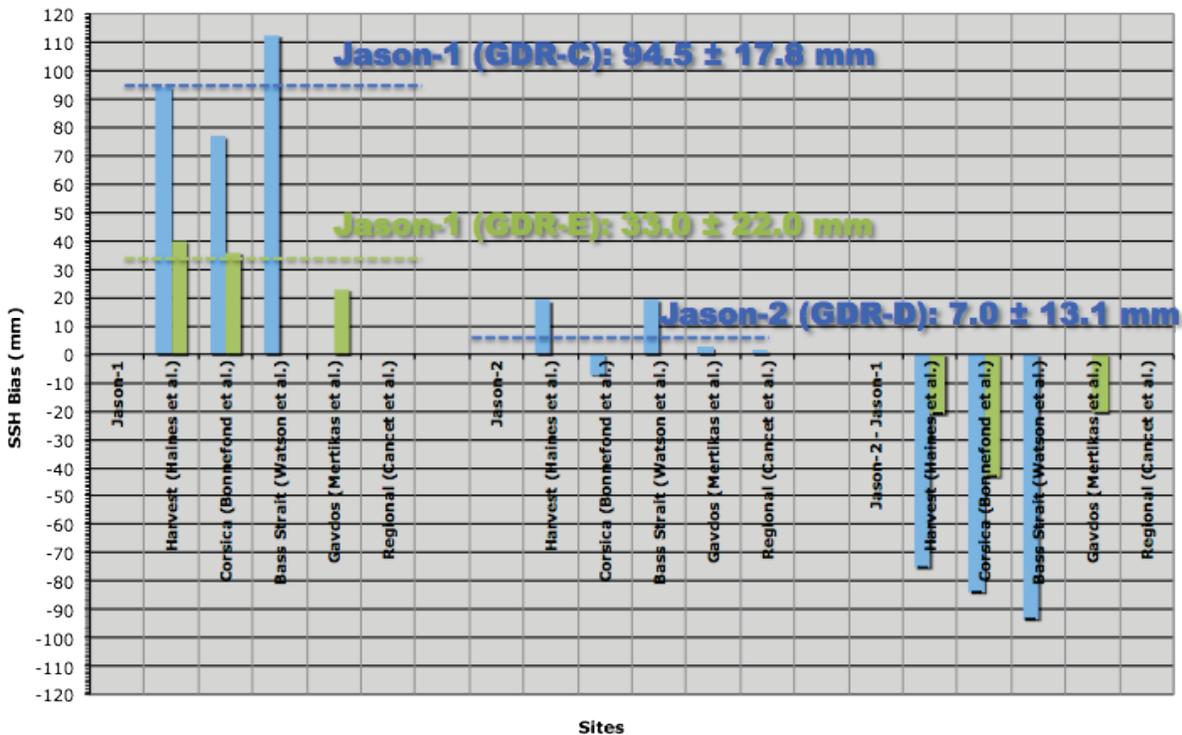


Figure 6.6.1. Absolute bias values for Jason-1 and Jason-2 from the different calibration sites using the latest versions of the official products (Jason-1 GDR-C and GDR-E and Jason-2 GDR-D).

Meanwhile, regional calibration methods from Cancet et al. have been employed at all three historical calibration sites (Corsica, Harvest, and Bass Strait) for the first time. This technique shows great promise for reducing errors by increasing the number of available overflights, and improving the link between in-situ and global calibration and validation results. Continuing evolution of tide gauge versus altimeter comparisons has led to new insights. For example, they have led to lower estimates of GMSL in one study (Watson et al.), due principally to TOPEX Side A data. Concerns about the Jason-2 drift have been largely resolved, with close agreement among multiple teams. Nevertheless, the tide gauge results highlight the importance of accurate land motion estimates, the development of rigorous error budgets from competing solutions, and the benefit of using different approaches to expose errors. Comparisons

between Argo and GRACE data are showing good closure for 2004-2014. However there are remaining open questions on the impact of deep layer thermal content, and the sensitivity to the GRACE solution used. The future Argo network is expected to improve the sampling of the content of the deep layer.

6.6.3 Global validation studies

6.6.3.1 Jason-2 Mission

More than 7 years of Jason-2 measurements are now publicly available as version D (O/I) GDR products. Validations activities on these products are performed as a joint effort between the CNES and JPL Cal/Val teams prior to their release. Data availability continues to be excellent, with 99.9% of over-ocean data available when excluding calibration and platform incidents. Sea surface height error, as determined from crossover analysis, is 3.5 and 3.6 cm for the Jason-2 GDR (version D) and Jason-1 (version C) data products (Philipps et al.). Observations of GMSL trend from multiple missions over the Jason-2 period show good agreement (Figure 2). We note that Prandi et al. reported a drift in differences between the Jason-2 radiometer (from IGDR-D data) and the ECMWF model (starting June 2015) that is not observed in similar differences from the SARAL radiometer. However, a calibration adjustment to the 18.7 and 23.8 GHz channels of the Jason-2 radiometer from the ARCS system has since mitigated this effect, and it does not exist in the Jason-2 GDR-D data products.



Figure 6.6.2. Good agreement in GMSL trend observations from multiple independent platforms over the Jason-2 period. (Philipps et al.)

The Jason-2 data products transitioned to using version E precise orbit determination (POD) standards starting with cycle 254, and the Jason-1 version E GDR products use this same standard for all cycles. The new POD standards have demonstrated an improved reduction in errors in regional sea level rise. In particular, the version E POD solutions are showing improved consistency between estimates of GMSL from the Eastern and Western Hemispheres when using either Jason-1 or Jason-2 data (e.g. Philipps et al. and Dettmering et al.).

Preliminary results on global calibration and validation on a test version of Jason-1 GDR-E data products showed improvements in SSH crossover variance (Figure 6.6.3), and improved consistency with Jason-2

data. Two anomalies in the test version of the Jason-1 GDR-E products were identified, namely in the value of applied range biases to account for internal path delay, and in the applied version of the GOT ocean tide model. A final reprocessing of the Jason-1 GDR-E products is expected to start in December 2015 and will correct these anomalies.

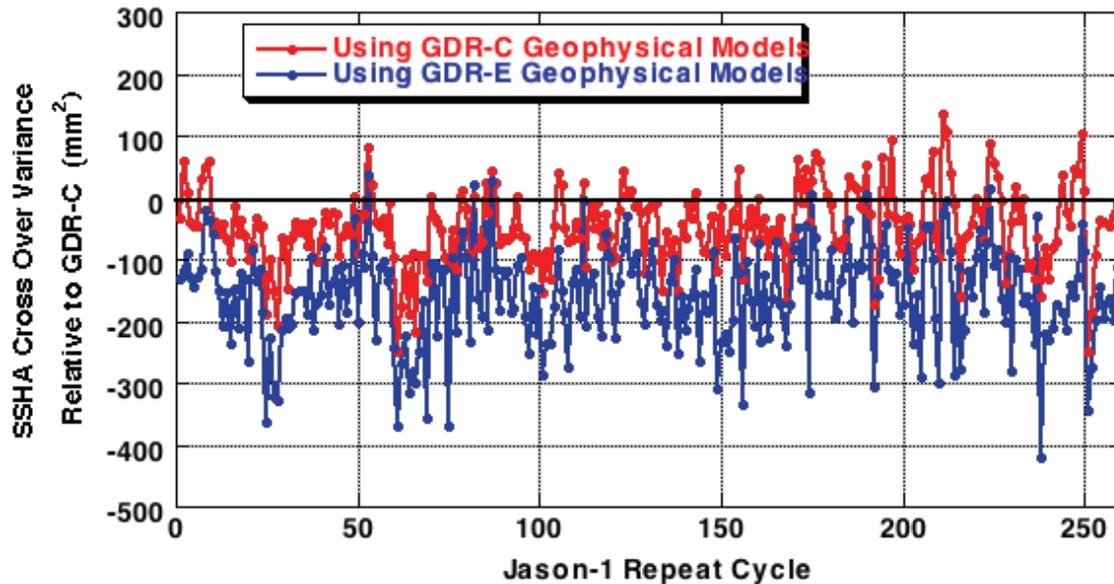


Figure 6.6.3. A preliminary version of version E GDRs for Jason-1 shows an average variance reduction in SSH crossovers of 157 mm². Approximately 70% of this variance reduction arises from the use of modern ocean tide models, while the remainder is the result of correcting the time tags of the measurements, and improved orbit and environmental corrections (Desai et al.).

Global calibration and validation results from the SARAL/AltiKa mission show continued excellent performance. Data coverage and quality are as good as, or better than, Jason-2. Missing measurements due to rain are significantly lower than expected. SSH crossover performance is similar to that from Jason-2 (e.g., Figure 6.6.4), and there is no significant drift relative to Jason-2. A range bias of ~ 5 cm remains unexplained. A new product standard that incorporates a variety of improvements is anticipated in 2016. Excellent data quality from CryoSat-2 is observed in both the Low-rate Mode (LRM) and SAR mode from all data centers. While HY-2A data are routinely processed by CNES, the data are not considered to have adequate long-term stability for demanding applications.



Figure 6.6.4. SARAL/AltiKa has slightly lower internal sea surface height crossover variance than Jason-2 (Prandi et al.). Lighter lines are when using model wet troposphere, and darker lines are when using radiometer wet troposphere.

6.6.4 Round table summary

Key points raised by the Project Scientists:

1. Comparisons between tide gauges and altimetry:

A separate science splinter ("Mean sea level monitoring: how to reconcile altimetry, tide gauges, land motion and other in situ observations?") included several presentations on the comparison of tide gauges and altimeters. It was recommended that the groups involved with tide gauges/altimetry comparisons work collectively to further understand and document the strengths and limitations of the techniques, with the goal of reporting back to the community at the 2016 OSTST meeting. The groups involved will agree on a set of milestones to achieve this undertaking. The group will work to define a set of sensitivity tests including investigation of site weighting strategies, network effects, and approaches for dealing with vertical land motion. This group was encouraged to work alongside the IAG Joint Working Group 3.2 (Vertical motion of the Earth's crust and sea level change) to provide a prioritized list of gauges that are most critical to the altimetry comparisons. The group supported the efforts to investigate tide gauge/GNSS deployments and their optimization for current and future missions. The group supports the work of the reference frame community to reduce reference frame errors and improve long-term stability, and is particularly anticipating the release of the new ITRF2014.

2. SWOT Preparation: From 1D to 2D Cal/Val:

The group is already considering the issue of developing capabilities to validate along-track SSH at scales from 30-150 km. They reviewed existing possibilities for using in-situ measurements (e.g., tide gauges, ADCP, drifters, airborne data, GPS buoys, etc). However a detailed description of each technique is needed to identify their advantages and disadvantages, error budgets, and the methods for linking altimeter and in-situ measurements. From the perspective of global Cal/Val, three techniques were specifically identified: multi-mission crossovers (e.g., Jason-3, Jason-CS, Sentinel-3A and -3B); increased spatial resolution from SAR measurements; and promising LRM processing techniques (e.g., Dcore, Two pass, Filtering, etc). The group considered the possibility of recommending a dedicated session to this topic at the 2016 OSTST meeting.

Recommendations:

1. Investigate and resolve discrepancies in the Jason-1 GDR-E.
2. Generate a living document that includes all of the altimetry history (products, events, etc) to defend the importance of continuity.
3. Release in-situ data and documentation to allow different groups to perform their own studies.

6.7 The Geoid, Mean Sea Surfaces and Mean Dynamic topography

Chairs: Ole B. Andersen and Yannice Faugere

This splinter had a total of 6 oral presentations and 2 posters

The oral presentations were the following:

- *(Sean Bruinsma)* The POD gravity field model for GDR-E: EIGEN-GRGS.RL03-v2.MEAN-FIELD
- *(Walter Smith)* Stacking repeat cycles of 40-Hz AltiKa data resolves the geoid anomalies of very small seamounts
- *(Ole Baltazar Andersen)* The DTU15 MSS (Mean Sea Surface) and associated MDT (Mean Dynamic Topography) focusing on Arctic issues and development
- *(Marie Isabelle Pujol)* The recent drift of SARAL: an unexpected MSS experiment
- *(Rory Bingham)* Assessing the contribution of GOCE and altimetry to improvements in geodetic MDT determination
- *(Cheng)* Variation of observed correlations between satellite altimetry and tide gauge data along US East Coast

The posters were the following

- *(Müller)* Pointwise comparison of geostrophic currents of altimetry-derived instantaneous Ocean Dynamic Topography with in-situ measurements
- *(Knudsen)* The updated geodetic mean dynamic topography model – DTU15MDT.

As the previous years the session covered the three topics of the session, Geoid, Mean Sea Surfaces and Mean Dynamic Topography. Concerning the Geoid, although no new Geoid solution has been presented, the errors of the last release of the ESA/GOCE geoid EGM-DIR-5 (based on GOCE, GRACE, Lageos) and TIM-5 (based on GOCE) were deeply investigated. Figure 6.7.19 and Figure 6.7.20 both illustrate the reduction of errors of the 1-5 releases. The last release of DIR and TIM Geoid have very close performance **about 3cm for wavelength around 200km**. These improvements will directly benefits to the orbit solution accuracy, and thus altimeter mission, through the use of IGEN-GRGS.RL03-v2.MEAN-FIELD based on DIR-5 in their calculation

The Mean Sea surface topic was also discussed in 2 of the presentations. At first, Pujol et al. focused on the error of the MSS and their limitation at small scales outside of the repeat ground track notably taking advantage of the recent drift of SARAL. Figure 6.7.3 shows the increase of the AltiKa SLA errors according to the distance to the nominal ground track: **a linear 0.4cm/km increase** is observed using CNES-CLS-11 MSS (Figure 6.7.21). The error budget of MSS is strongly reduced by the use of more recent MSS such as CNES-CLS-15 or DTU 15 (Figure 6.7.22). The use of Cryosat-2 and Jason-1 Geodetic in these solution strongly improved the spatial sampling Geodetic missions used in these recent solutions **largely contributes to improve the MSS precision** outside of the repetitive ground-track. However, these missions also introduce locally commission errors due to the residual ocean variability they may contain.

This issue directly links to the reference period on which are based MSS and MDT. For last MSS, CNES-CLS-15, DTU-13 and DTU 15, a 20-year reference period 1993-2012 has been used, as there is a strong interest to use a long time period as a reference in order to compute more meaningful anomalies. A recommendation of this session is thus to consider **this 20 year as a common reference** for the future MSS and associated SLA products.

Beside the across-track improvement, the along track resolution can be improved using the full rate of the altimetry products. Using 40Hz on AltiKa allows us to better resolves the geoid anomalies of very small seamounts (Figure 6.7.23).

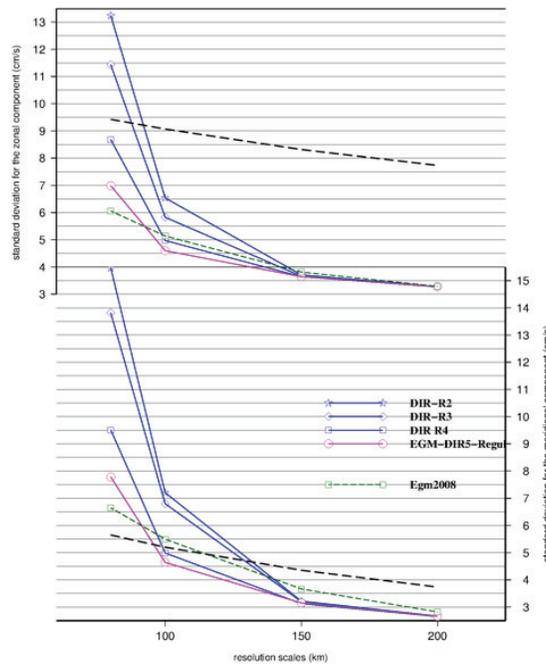


Figure 6.7.19: Illustration from Bruinsma et al. on DIR-5 performances assessment using drifter data

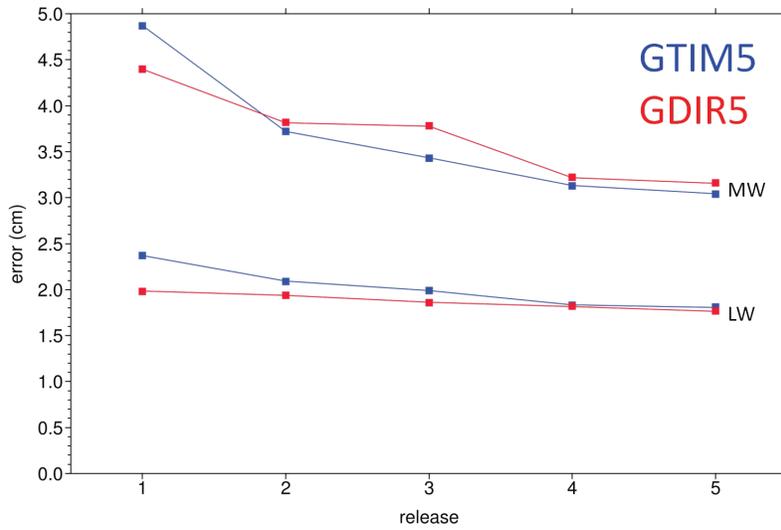


Figure 6.7.20: Illustration from (Bingham et al) on DIR-5 and TIM-5 informal MDT errors in wavelength bands(Reference MDT CNES-CLS09)

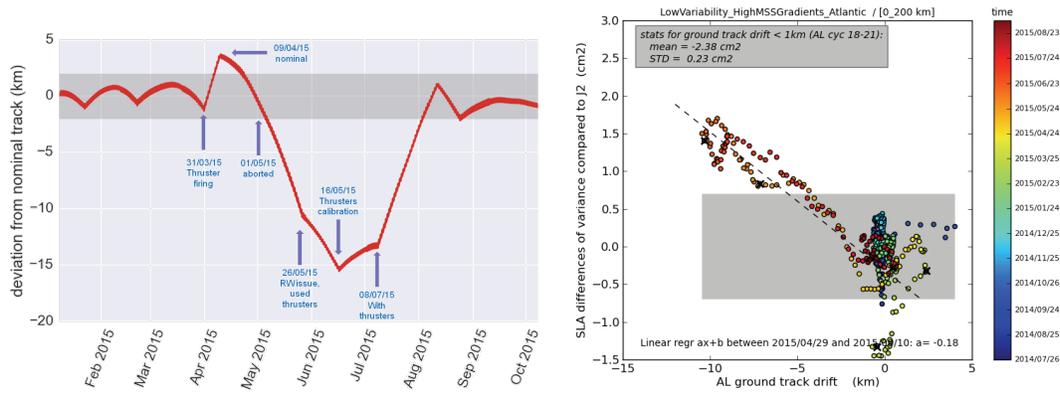


Figure 6.7.21: Illustration from (Pujol et al) on the omission error highlighted on MSS_CNES_CLS11 by the recent drift of SARAL

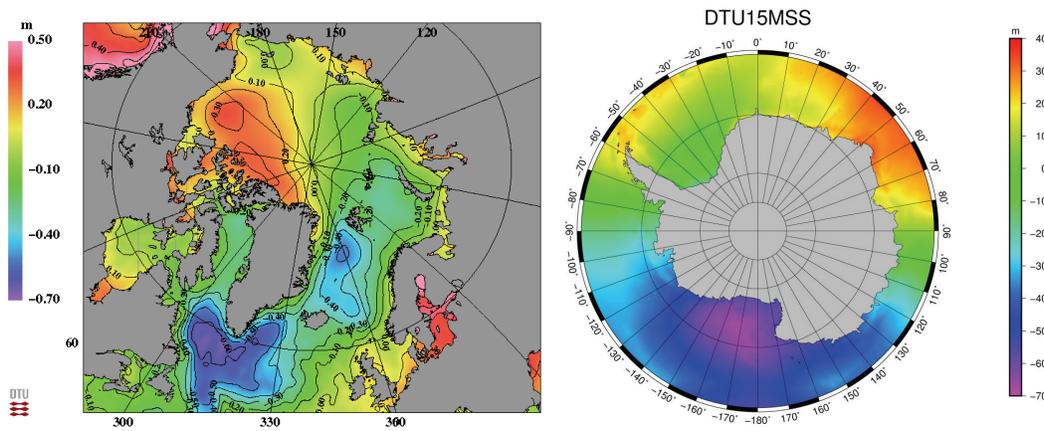


Figure 6.7.22: Illustration from (Andersen et al) on the new DTU15 MSS

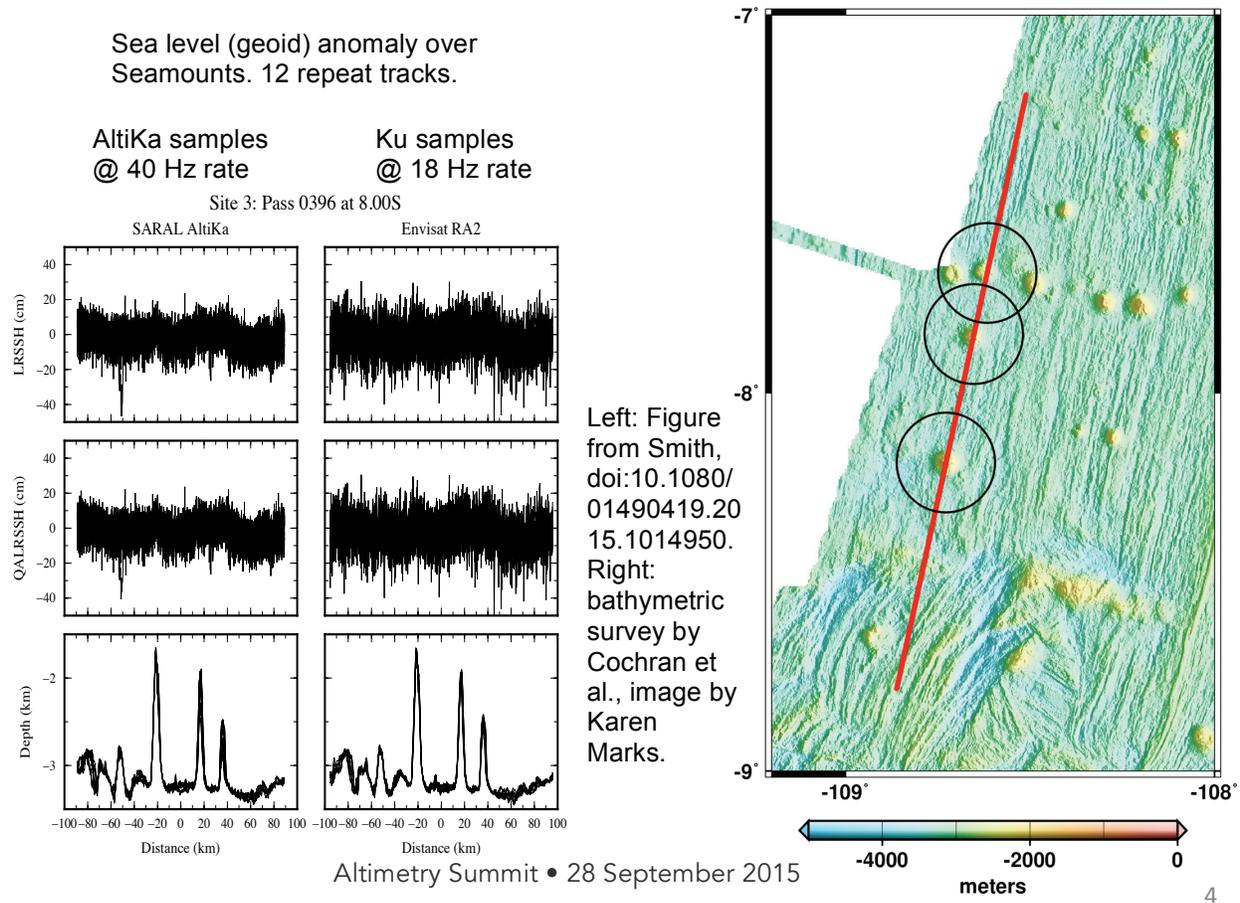


Figure 6.7.23: Illustration from Smith et al. on the fine geodetic information retrieve by the 40-Hz AltiKa data

Additionally to the presentation, a round table was organized with a focus on the End of life of Jason-2 and AltiKa.

6.7.1 Jason-2 End of life Recommendations:

- RECOGNISE that it's a great achievement that J-2 is IN VERY GOOD SHAPE(full redundancy), and RECOMMEND early investigation of possible/various EoL scenarios
- RECOMMENDATION linked to the expected altimeter constellation in upcoming years.
 - Assuming we have two operational repeat satellite (J-3 & S-3A) +
 - Two additional satellites (AltiKa and/or C2 and/or HY2A and/or S-3B) flying.
- RECOMMEND to move J-2 to a GM mission as soon as possible in preparation for SWOT
- RECOMMEND to plan for TWO interlaced GM cycles to reduce cross track sampling to 4 km in order to improve resolution and generate next GENERATION MSS/Gravity/Bathymetry.
- RECOMMEND THAT TIMING IS CONSIDERED: Two interlaced GM cycles will take 800 days or 3 years. If SWOT will be launch in Dec 2020 a J-2 EoL GM should be initiated no later than Dec 2017
- RECOMMEND two Interlaced GM because we can not use interleaved orbit with J-1 GM
- RECOMMEND study if first GM can be phased to maximize info with J-1GM in case of J-2 failure (near interleaved but at other altitude)

- RECOMMEND to investigate the orbits (higher RECOMMEND THAT orbit with higher altitude than nominal orbit - codename 12+247/401 (1) and 12+239/407(2) is further investigated as it seems optimal with respect to optimal sea state and oceanographic use.
- RECOMMEND a study of orbit wrt sampling of oceanographic signals.
- RECOMMEND choice of with intermediate sub-Cycle in case of failure of the satellite

6.7.2 AltiKa End of life Recommendations:

Due to technical problems, two future orbit choices were outlined (35 or drift) we:

- RECOMMEND the not-maintained (drifting) orbit for MSS/Grav/Bath.
- RECOMMEND this phase to start as soon as possible (awaiting 3 years project meeting in early 2016)
- RECOMMEND to start investigating possible scenarios of drifting orbit (decrease) and investigate consequence for oceanographic signal (tides, mesoscale)
- RECOMMEND TO perform (i.e. 1 year) orbit simulation for 2 scenarios (low and high solar activity) for AltiKa drifting orbit
- RECOMMEND to consider timing and investigate consequence of several simultaneous geodetic missions

6.7.3 Other topics:

We finally also discussed the interest of having a dedicated MSS meeting in 2016, in order to have more time to discuss in details of the accuracy/future needs/ processing/ assessment/impact of various future Geodetic missions). These meeting could be possibly outside or adjacent to OSTST or SWOT meeting.

6.8 Quantifying Errors and Uncertainties in Altimetry Data

Chairman: Michael Ablain, Joel Dorandeu and Remko Scharroo

6.8.1 Overview

Objectives of this session are to strengthen the link between altimetry experts and applications regarding errors in the altimetry system. This covers information exchange in both directions: the exports informing the end-users about new insights about errors in altimetry, and the end-users providing their needs and requirements in terms of errors but also in terms of error formulation.

The splinter was fruitful given the number and diversity of talks and posters, each of them tackling the error topic with a different approach. A total of 10 abstracts were submitted to the splinter session, resulting in 6 oral presentations, and 4 posters. They can be classified in 3 parts relative to mean sea level errors, short wavelength errors and instrumental errors.

6.8.2 Mean Sea Level errors

L. Zawadzki et al. presented a study on the accuracy of the mean sea level continuous record with future altimetric missions: Jason-3 versus Sentinel-3a. The objective is to answer the question: what would be the impact on the GMSL of using S3-A instead of Jason-3 as reference mission? The main conclusion is linking Sentinel-3 MSL time series to Jason-2 has a strong impact on the global (and regional) MSL uncertainty, mainly due to the absence of a calibration phase. Therefore changing the historical TOPEX/Jason orbit for Sentinel-3a orbit would therefore exceed user requirements over 10 years even though it is only one component of MSL error budget.

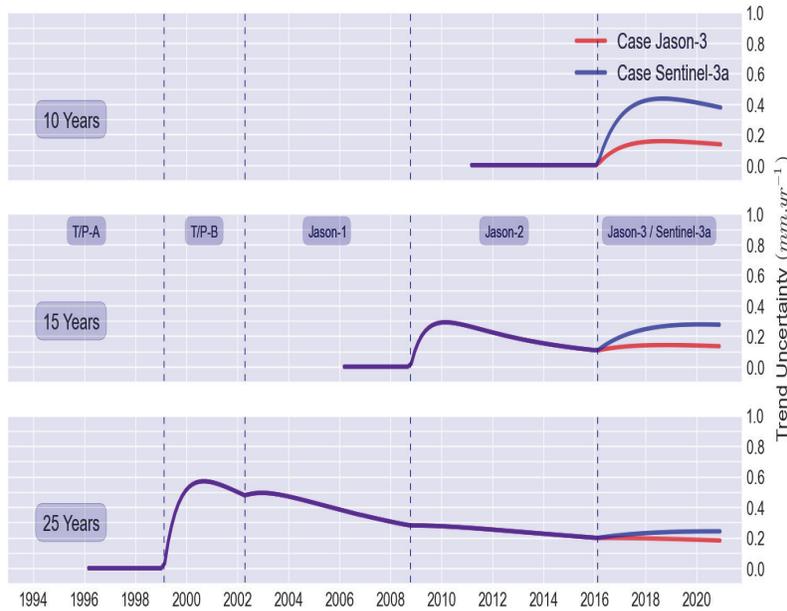


Figure 6.8.24: Impact of global Mean Sea Level inter-mission linking bias uncertainties on the estimation of the MSL trend over 10 years (Upper panel), 15 years (middle panel), 25 years (lower panel), in the cases of Jason-3 and Sentinel-3a.

Martin Scharffenberg et al. gave a talk about the uncertainty estimates of altimetric Global Mean Sea Level timeseries. The STORM/NCEP model [von Storch et al. 2012] has been used as synthetic truth to test the effects of applying different averaging methods. This work is an update of O. Henry et al., 2013. Depending on the method used, the uncertainties of the GMSL estimates needs to be considered larger by up to +6 mm.

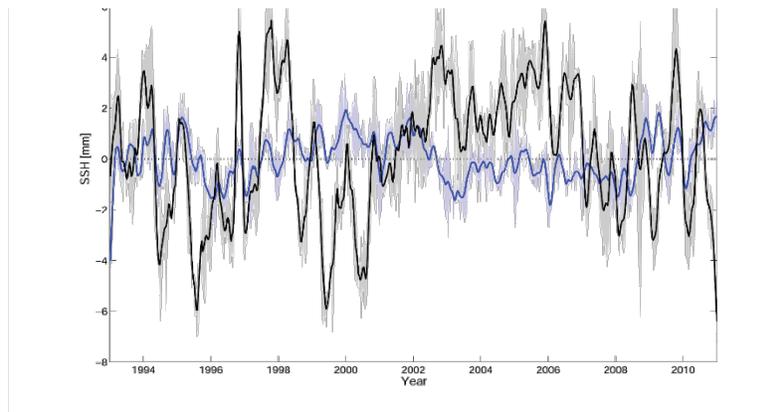


Figure 6.8.25: GMSL evolution (after removing the global trend) from altetry (black) and STORM/NCEP model (blue): due to the smaller variability in STORM as compared to satellite data the uncertainties for GMSL estimates serve as a lower bound

P. Prandi et al. gave a talk about the estimation of regional sea level trends accuracy. The objective is to provide a map of uncertainties of regional MSL trends (see figure below). Systematic uncertainties ranging between 1 to 3 mm/yr have been displayed. Results depend on the a priori description of errors:

if the error model is wrong, the results are. It is worth noting that accurate error covariance description is crucial.

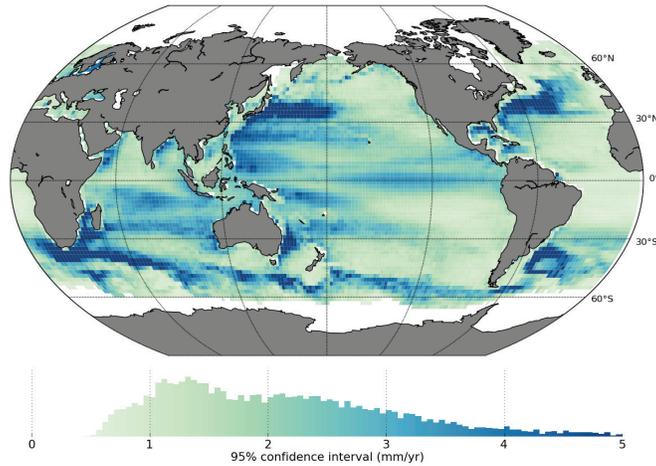


Figure 6.8.26: Map of MSL trend uncertainties

6.8.3 Short wavelength errors

P. Thibaut et al. presented the characterization of the altimeter mission performances over ocean. Most of past/present altimeter missions have been looked at and compared with the same processing applied: performances have been derived using different metrics. 20Hz std and PSD noise level are strictly equivalent at low SWH and coherent with simulations. PSD noise level for high SWH doesn't represent the instrumental noise. The following question is raised: does SWH/Swell introduce correlated errors in the estimates? Very good SLA performances of CS-2 SAR are highlighted but also of SARAL (Ka band / 40 Hz), even better SWH performances with Saral.

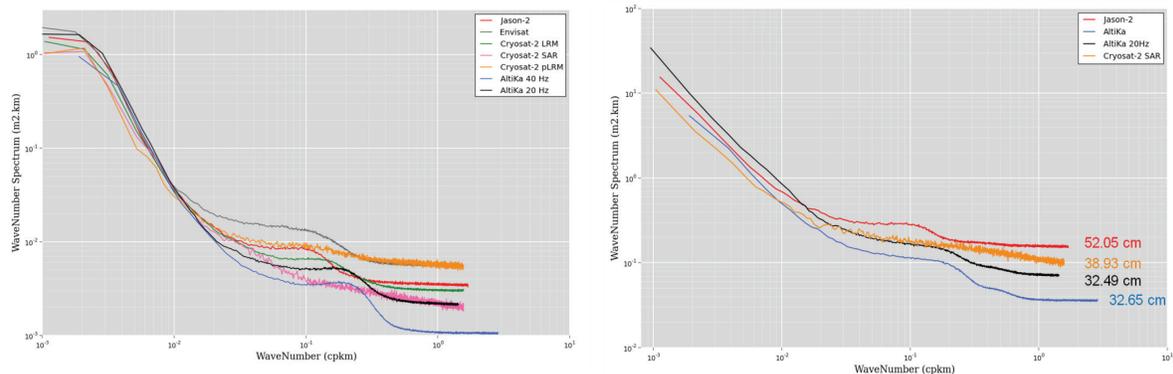


Figure 6.8.27: SLA and SWH spectra for several altimeter missions

E.D. Zaron et al. gave a talk about the identification and reduction of retracker-related noise in altimeter-derived sea-surface height measurements. An empirical approach to reducing the retracker-related SSH error was implemented, based on analysis of J1-J2 during the J2 cal/val orbit phase. Thanks to this approach, the high-wavenumber SSH noise floor is reduced by about 2cm^2 , depending on SWH. It is worth noting that the correction uses conventional 1 Hz data; although, it was inspired by 2-pass retrackers and the correction is not independent of the sea-state bias correction. This kind of method would be useful to better estimate the short wavelengths of ocean scales.

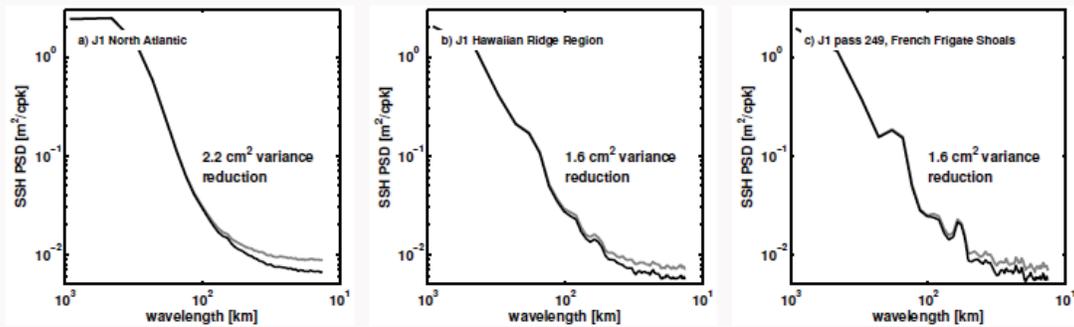


Figure 6.8.28: SLA spectra applying the Zaron et al.'s correction

6.8.4 Instrumental errors

D. Salvatore et al. presented the seasonal Effects on the Pitch Measurements for Cryosat-2. Thanks to pitch mispointing computed from Stack, a sinusoidal pattern in the Star Tracker estimation of the pitch mispointing has been detected (potentially correlated to sun illumination conditions). After removal of the sinusoidal pattern, the estimation of the pitch from Star Tracker and Stack are pretty consistent (around 3 millideg). It is essential to calibrate also the roll mispointing (that can be affected in the same way by solar illumination). We recommend to perform the same exercise routinely for Sentinel-3, as long as for the roll.

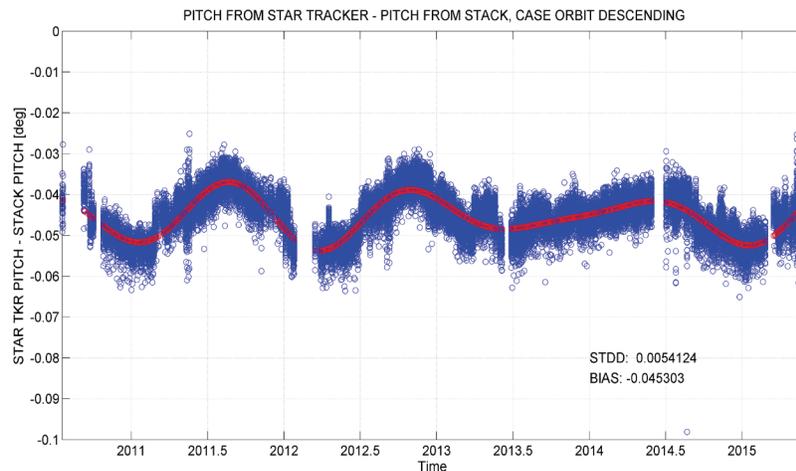


Figure 6.8.29: Evolution of the pitch mispointing on Cryosat-2

6.8.5 Conclusion

From the last OSTST, several improvements have been performed on altimeter error characterization: new insights in altimeter error at short wavelength and at climate scales have been characterized and understood, and a new method to characterize the error for climate scales has been developed.

In terms of recommendations, the splinter encourages feedbacks from end-users to better characterize the error for their studies. Moreover, the propagation of measurements errors into the final products should be further studied.

7 Closing Plenary

The closing plenary took place on Friday morning. In addition to the splinter summaries Paolo Cipollini reported on the 8th Coastal Altimetry workshop and Jerome Benveniste gave a summary of the Third Space for Hydrology Workshop, which took place in Frascati (Rome), Italy on September 15-17, 2015.

The meetings ended with the status of reprocessing. Phil Callahan discussed the TOPEX Reprocessing and update to GDR-C standards. Initial evaluation of retracked data has been completed and will be made available on the PODAAC server soon. Geophysical corrections still require updating and applicability of some corrections remains uncertain. Work on reprocessing will continue into 2016, with stronger help and collaboration with CNES. Nicolas Picot discussed the current GDR status for Jason-1 and Jason-2. Three years of Jason-1 data are now available processed to GDR-E standards. Plans to reprocess remaining Jason-1 and Jason-2 data to a new GDR-E standard are underway and Jason-1. For the CalVal phase, Jason-3 will be based on GDR-D standard with orbit in GDR-E, fully inline with the Jason-2 standard. The next product version will be defined after the CalVal phase.

The closing plenary session also had a discussion time slot, notably about the key points that were addressed to the splinters during the opening session. After discussion, the following Recommendations and Appreciations were adopted:

Recommendations:

- **Although the mission has long since ended, data from TOPEX/Poseidon remains widely used in scientific studies and is a key part of the sea level climate data record. The OSTST recommends that the Jason projects continue to support efforts to bring TOPEX/Poseidon data in line with modern altimetry standards.**
- **In light of the need for improved mean sea surface estimates for SWOT in 2020 (2-3 years needed), the OSTST recommends that Jason-2 be moved to a geodetic orbit, preferably at +35 km altitude (12+247/401), to support geodetic studies if and when it becomes feasible. Further study and consideration of future launches and the overall health of the altimeter constellation, by both the Projects and the OSTST Jason-2 EoL subgroup, is recommended to find precise criteria for the timing of the move to a geodetic orbit.**
- **The Jason-2 Project should consider implementation of the radiometer calibration maneuver that will be implemented on Jason-3 in order to provide a cold-sky calibration look for the AMR on Jason-2 after it has been successfully demonstrated on Jason-3.**
- **Airborne instruments have demonstrated the capabilities of high-frequency radiometers to provide improved corrections near land. Therefore, the OSTST again recommends that future altimetry missions should consider adding additional higher-frequency radiometer channels in order to improve coastal and inland water wet path delay corrections.**
- **We recommend that all altimeter missions develop a plan to provide open, freely available and up-to-date documentation of all processing techniques and project events for official releases of altimeter data and to archive all relevant information at the end of each mission.**

OSTST Appreciations:

- OSTST appreciates that CNES & NASA have nearly completed the Jason-1 reprocessing begun in 2013 as well as the funding and support provided by CNES & NASA for this activity
- OSTST recognizes the high value of the new Jason-1 data set for climate studies
- OSTST appreciates the Jason-3 project's efforts to launch in a safe yet timely manner
- OSTST appreciates the work of CNES & ISRO to continue to providing high quality data products for the SARAL/AltiKa mission. These data have been demonstrated to be of great value for climate and operational oceanography activities. A special issue of Marine Geodesy highlighting this high quality is now published: Volume 38, Supplement 1, 2015 (<http://www.tandfonline.com/toc/umgd20/38/sup1#.VimFdsuqjsl>)

During the closing plenary session, a lengthy discussion was held about the possibility of adopting an open statement from the OSTST to the 2015 Conference of Parties (COP21), which is the annual review meeting for the United Nations Framework on Climate Change. Although no language was formally adopted by the team during the meeting, co-chairs Pascal Bonnefond and Josh Willis penned an open letter to the organizers of COP21, which was signed by more than 280 supporters and many on the OSTST. The letter was delivered in person by Pascal Bonnefond to several key participants in COP21. The letter can be read in full on Change.org: <https://www.change.org/p/cop21-deciders-ask-the-cop21-to-recognize-sea-level-rise-as-the-top-indicator-of-climate-change>

Finally, the location and time of the 2016 OSTST Meeting was announced. The 2016 meeting will be held in La Rochelle, France, October 31 – November 4. It will be held in conjunction with an IDS workshop (Oct 31-Nov 1), and a SAR altimetry workshop (Oct 31).