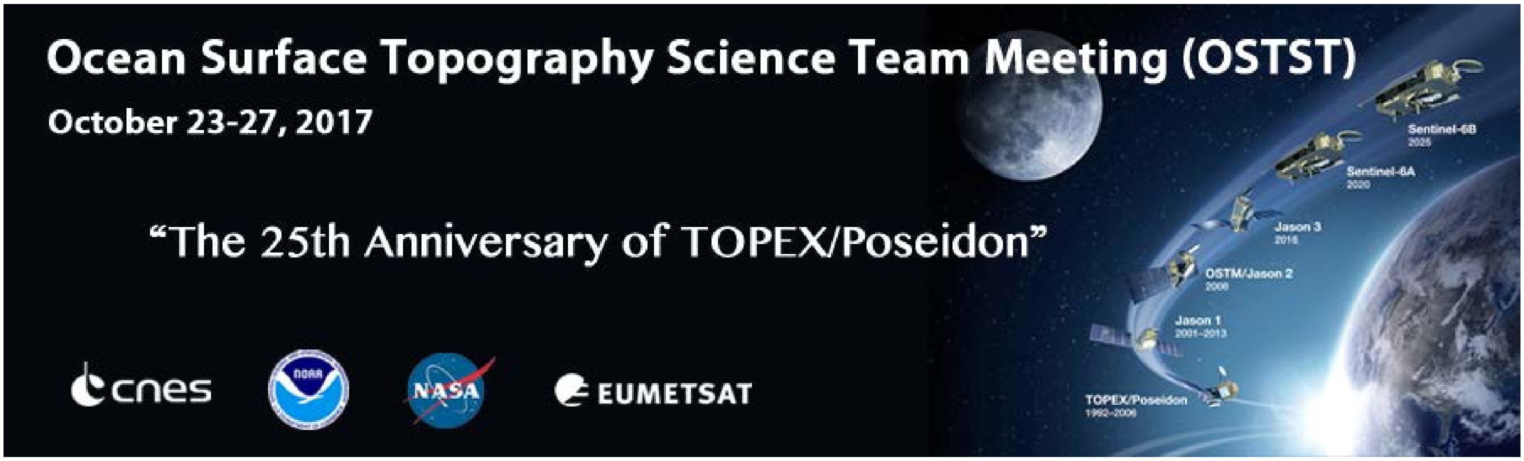

Report of the

Ocean Surface Topography Science Team Meeting

Hilton Miami Downtown

Miami, FL, USA

October 23-27, 2017

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Contents

1 Executive Summary

The 2017 Ocean Surface Topography Science Team (OSTST) Meeting was held in Miami, Florida, October 23-27. In celebration of the 25th anniversary of the launch of TOPEX/Poseidon, this ocean surface topography science team meeting included special splinter sessions on analysis of currently available Synthetic Aperture Radar (SAR) altimeter Mission data with a focus on benefits in coastal areas and other water surfaces. The primary objectives of the OSTST Meeting were to (1) provide updates on the status of Jason-2 and Jason-3; (2) conduct splinter meetings on system performance (orbit, measurements, corrections, and advances in SAR processing), altimetry data products, science outcomes, and outreach; (3) hold special splinter sessions on coastal altimetry as well as altimetry for the cryosphere and hydrology. The meeting lasted 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://meetings.aviso.altimetry.fr.

Jason-3 was launched from Vandenberg Air Force Base on January 17, 2016, and all of its systems and instruments are operating nominally. After flying in tandem approximately 80 seconds behind Jason-2 for a period of 5 months while data was evaluated, Jason-3 became the new reference altimetry mission on June 21, 2016. After that, Jason-2 was moved into an interleaved orbit in October 2016 on an adjacent ground track with a 5-day lag. This orbit was identical to the one flown by Jason-1, and was designed to provide improved spatial and temporal coverage of sea surface height observations.

Jason-2 (launched in June 2008) remains in operation and continues to provide data of excellent quality, but with reduced availability due to issues with the satellite's attitude control system. In March 2017, after about 5 months in its interleaved orbit, Jason-2 began to have issues with its attitude control system. In July 2017, Jason-2 was moved to a Long Repeat Orbit (LRO) approximately 27 km below the reference orbit as recommended by the OSTST in 2016.

Despite some prolonged data outages between March and July of 2017, the satellite has resumed operation and is expected to continue to operate nominally about 70 percent of the time. Occasional outages due to warming of the satellite during certain phases of its orbital precession are expected to occur every few months, lasting for a few weeks at a time. During the 2017 meeting, the OSTST carefully assessed the impact of these outages. In light of this assessment, the OSTST adopted two recommendations:

1. **As long as Jason-2 remains in the Long Repeat Orbit, it provides valuable data for operational users and for improvements in mean sea surface estimates despite gaps created by safe holds. The OSTST therefore encourages efforts to minimize future Jason-2 gyroscope failures.**

2. **The OSTST recognizes that valuable geodetic measurements can be made in the Jason-2 Long Repeat Orbit even if some performance is degraded, such as the loss of the radiometer. The OSTST recommends consulting the Extension-of-Life (EoL) group if rapid decisions need to be made.**

Since the 2017 OSTST Meeting the four partner agencies (CNES, NOAA, EUMETSAT, and NASA) have jointly agreed to extend the operations of the Jason-2 mission through the end of calendar year 2019, in recognition of the importance of Jason-2 data for both the scientific and operational communities.

During the opening plenary session, a special invited talk was presented by a local official on planning and policies for adaptation to sea level rise and flooding in Miami-Dade County, as well as an invited talk by Lisa Beal of the Rosenstiel School of Marine and Atmospheric Sciences (RSMAS) at the University of Miami (see section 2). After the opening plenary a science keynote session was held. Four invited, keynote talks were also given (see section 3).

The Copernicus Sentinel-6/Jason Continuity of Service (S6/JCS) mission, the successor to Jason-3, is now in full development with the partner Agencies (EUMETSAT, ESA, NASA and NOAA with CNES providing support). In addition, the recently formed Sentinel-6 Mission Advisory Group (MAG) was described and its relationship to the OSTST was explained. The MAG is a small group of experts, chaired by the OSTST Project Scientists, selected by the partner agencies to advise the S6/JCS Project on scientific and technical issues. The MAG will also continue to report to and report back from OSTST to ensure that OSTST and MAG activities are aligned and shared.

Finally, presentations on new and upcoming missions (e.g. SWOT, the new ESA Sea Surface Kinematics Monitoring Mission (SKIM), CFOSAT etc.) were presented for information on their status and development plans.

2 Opening Plenary

The 2017 Ocean Surface Topography Science Team (OSTST) Meeting was held in Miami, Florida, October 23-27. In celebration of the 25th anniversary of the launch of TOPEX/Poseidon, this ocean surface topography science team meeting included special splinter sessions on analysis of current SAR data with a focus on benefits in coastal areas and other water surfaces and lasted for the entire week. On behalf of the Project Scientists (Josh Willis, NASA; Pascal Bonnefond, CNES; Eric Leuliette, NOAA; Remko Scharroo, EUMETSAT; Craig Donlon, ESA), Pascal Bonnefond presented the agenda and explained logistics.

After opening the meeting, a special presentation on local sea level rise impacts in Miami-Dade County was given by Katherine Hagemann, Resilience Program Manager for Adaptation at the Office of Resilience for Miami-Dade County. Hagemann discussed the numerous efforts being planned and undertaken in Miami-Dade County to improve resiliency against flooding and other local impacts due to sea level rise.

In addition, an invited talk entitled "Broadening not Strengthening: A 24-year altimeter proxy for the Agulhas Current" was presented by oceanographer Lisa Beal of the Rosenstiel School of Marine and Atmospheric Sciences (RSMAS), at the University of Miami. With co-author, Shane Elipot (RSMAS), Beal used satellite altimeter observations to reconstruct both the strength and width of the Agulhas Current, a powerful western boundary current that rounds the southern tip of Africa before returning west. The current, which has broadened but not strengthened over the past 22 years, plays a key role in the transport of heat and the ocean overturning circulation.

2.1 Program and Mission Status

The program managers presented the status of altimetry and oceanographic programs at NASA (Nadya Vinogradova), CNES (Juliette Lambin), EUMETSAT (François Parisot), NOAA (Eric Leuliettte) and ESA (Jérôme Benveniste).

Nadya Vinogradova (NASA HQ) gave a summary of the NASA Ocean Program. The NASA/NOAA investigations of the OSTST were competed through NASA's ROSES program in 2016. 56 proposals were reviewed and 21 proposals have been selected for NASA funding from 2017 through 2020. Synergies between the OSTST and other programs under the NASA Physical Oceanography Program were also discussed. The new NASA Sea Level Change Science Team was also selected during 2017, including the selection of OSTST member Ben Hamlington (Old Dominion University) as team leader, as were the ECCO (Estimating the Circulation and Climate of the Ocean) assimilation modeling efforts led by OSTST member Ichiro Fukumori (Jet Propulsion Laboratory).

Thierry Guinle, on behalf of Juliette Lambin (CNES) reported on the CNES Ocean Program status by illustrating the current and future constellation in which CNES is involved (Figure 2.1-1 & Figure 2.1-2). Guinle showed photos of the CNES instrument SWIM (Surface Waves Investigation and Monitoring) in China, where integration into CFOSAT (Chinese-French Oceanography Satellite) were under way, as well as completed hardware for the Ka-band interferometer for the SWOT (Surface Water Ocean Topography) mission. He also announced that Amaury Larue de Tournemine will replace Philippe Escudier as CNES Ocean Program Manager starting January 1st , 2018.

Figure 2.1-1 Ocean missions in operation, in which CNES is involved.

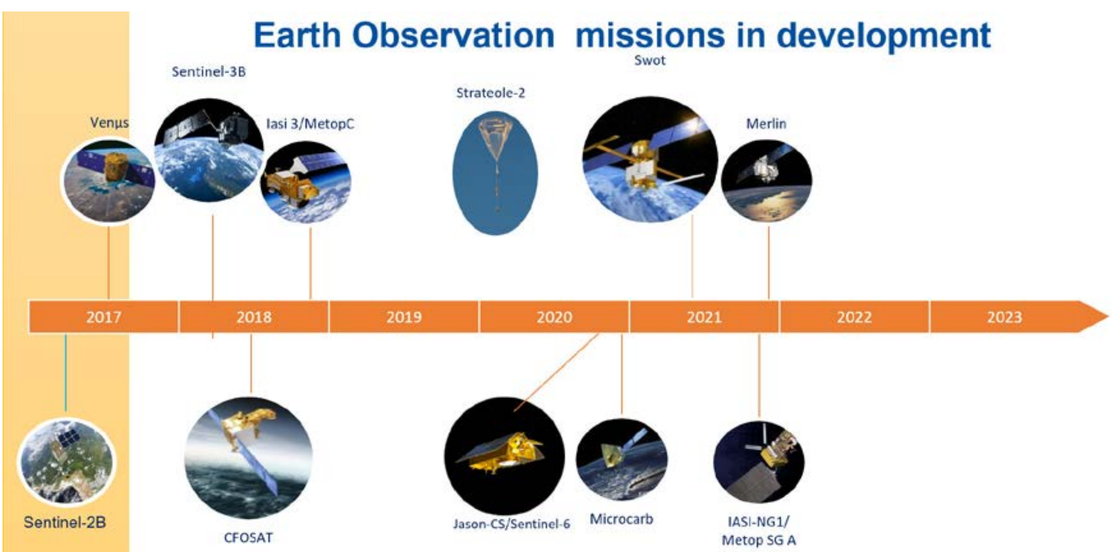


Figure 2.1-2 Planned ocean missions, in which CNES is involved.

François Parisot (EUMETSAT) reported on the status of EUMETSAT Oceanography Programme. EUMETSAT is committed under agreement to support Copernicus through the following activites: operations of Sentinel-3, Jason-3, Sentinel-6/Jason-CS, Sentinel-4, and Sentinel-5, as well as delivery of operational data and support services to the Copernicus Marine Service for these missions, as well as selected for some third party data from its partners (e.g., U.S., China, India, etc.). Subject to EU agreement, EUMETSAT will also support the Copernicus Climate Change monitoring service and user requirements for the Copernicus Marine, Atmosphere and Climate Services. Regarding Sentinel-3A, all altimeter and radiometer products are operational and release of Level 1, 2 and 3 products had occurred by the middle of 2017. Progress on finishing the Sentinel-3B spacecraft is ongoing and launch is expected in 2018. In addition to supporting Jason-2 in its Long Repeat Orbit and Jason-3 as the reference altimeter mission, EUMETSAT continues to support Sentinel-3A SRAL instrument, which is providing high-resolution SAR (Synthetic Aperture Radar) globally and L1A, L1B, L1BS and L2 products are fully operational. L1A products are new to altimetry and Parisot encouraged users to investigate their application. Finally, EUMETSAT continues to support development of Sentinel-6/Jason-CS, which will provide high resolution SAR altimetry along the reference track and is in discussions with ESA and the EC on missions beyond Sentinel-3 and Sentinel-6.

Eric Leuliette (NOAA) reported on NOAA Jason-mission Program Status. NOAA continues production and distribution of Jason-2 and Jason-3 data. The NOAA/NESDIS Science Program continues to support the National Weather Service as well as the OSTST, NOAA OceanWatch/CoastWatch and PolarWatch services, as well as the Sentinel-3A validation team and Operation IceBridge. In addition, it supports Jason calibration and validation, the NOAA Jason Measurement System Engineer (Alejandro Egido), and NOAA Jason data assimilation projects (NWS seasonal and ENSO predictions and HYCOM for hurricane intensity forecasting). NOAA participated in funding the OSTST, supporting 5 proposals in addition to the 21 selected for support by NASA. Finally, NOAA contributed to the Sentinel-3A validation efforts by coordinating an under-flight of Sentinel-3A by aircraft supporting NASA's Operation IceBridge mission in 2017.

Jérôme Benveniste (ESA) presented the ESA Programme Status. Envisat RA2&MWR V3.0 data is set for delivery in the last quarter of 2017. Updates should improve both climate and mesoscale data quality. Concerning CryoSat-2, the space and ground segments are in very good status and well fitted to continue mission exploitation until 2022, and the mission data is being widely used by the cryospheric, oceanographic and operational communities. The North-American CryoSat Science Meeting met 20-24 March 2017 in Banff, Alberta, Canada (www.cryosat2017.org). A CryoSat Special Issue on Advances Space Research is planned for early 2018 (many papers are accepted and some are still under review). Finally, a list of on-going activities in R&D, Training and Outreach was presented (SCOOP, SHAPE, SPICE, DEDOP, SARvatore, SARINvatore, S3SARvatore, BRAT, GUT …).

The Project Managers reviewed the status of the Jason missions. The status of both the Jason-2 and Jason-3 Projects was presented by Christophe Maréchal (CNES) on behalf of all the Project Managers. For Jason-2, all core science payloads are operating nominally and the satellite is in good condition except for the attitude and orbit control system. Jason-2 was moved to the interleaved orbit in October 2016 and operated nominally until March 2017, when a series of safe hold modes were triggered by issues with the satellite gyroscopes. The spacecraft has three gyros and two are required for to maintain the pointing accuracy needed to meet Level 1 science requirements. After several weeks of study, it was determined that two of the satellites gyros stopped functioning whenever their temperatures exceeded 25°C, triggering a satellite safe hold. Such temperatures are routinely reached once every two months or so, for a period of up to a few weeks. In light of this, it was decided to move the Jason-2 spacecraft to the Long Repeat Orbit recommended by the OSTST in 2016, where it can continue to operate without risk to the reference orbit. Studies are underway to reduce gyro temperatures by changing the orientation of the satellite, and increase internal dissipation of heat. However, outages due to this issue are expected to continue, and will likely limit data availability to around 70%, with 4-5 periods of unavailability per year unless further workarounds are developed and implemented. Now that the spacecraft has reached its final orbit, fuel depletion maneuvers are also being scheduled to reduce the amount of hydrazine on board to further reduce the risk of orbit pollution in the unlikely event of a collision. Apart from the issue with the gyros, performance of all systems continues to exceed requirements, including pointing, altimeter performance, DORIS, AMR and GPSP. In addition, OGDR, IGDR, and GDR production and latency all meet or exceed requirements, outside of the safe hold mode periods. Overall, Jason-2 still provides excellent measurement quality after 9.5 years in orbit, but availability is currently reduced to approximately 70%.

Jason-3, which took over as the reference mission on June 21, 2016, is fully operational with all redundant systems available. All of the core payload and passengers are operating nominally, as is the ground segment. A new onboard Digital Elevation Map (DEM) was uploaded successfully on August 31, 2017, and provides a major leap in the number of ground targets defined over land for river and lake monitoring. Jason-3 is now observing more than 4300 rivers and 350 lakes, and early validations suggests very good performance. Satellite pointing, altimeter performance, DORIS, AMR and GPSP are all stable and providing data of excellent quality. Cold sky calibration maneuvers to provide mm-level stability for the AMR data have been executed and the calibration schedule was recently updated by CNES to reduce GDR latency. OGDR, IGDR and GDR production are all meeting latency requirements and are of excellent quality. Global Jason-3 system availability has been 99.99%, easily exceeding requirements. Finally, it was noted that recommendations from the previous OSTST have been implemented including: immediate release of GDR products, cold sky calibrations more frequently than every 60 days and relaxation of GDR latency requirement to a maximum of 90 days.

Pierrik Vuilleumier (ESA) gave an update on the status of the upcoming Sentinel-6/Jason-CS mission. Sentinel-6/Jason-CS will continue the Jason series of research and operational oceanography missions. Two satellites will be commissioned, with the first launching in November 2020 and the second launching in 2025. Responsibility for the mission is shared between EUMETSAT, ESA, NASA and NOAA, with CNES providing expert support. Satellite CDR last June was successful and all hardware is in production. Poseidon-4, a new altimeter developed by ESA, will operate in SAR mode and use on-board processing to reduce data volumes over the majority of the earth surface. A limited amount of data that has not been processed can be sent to ground and discussions as to which areas will be selected are on-going. The NASA AMR-C radiometer will incorporate both an onboard calibration system for maintaining long-term stability as well as a high frequency channel to improve coverage near the coastline. The mission also includes a radio occultation payload for Numerical Weather Prediction services. Ground segment development is on track and launch data of the first satellite (Jason-CS-A) is currently planned for November 2020.

Nadège Quéruel (CNES) gave an update on the status of the SARAL/AltiKa Mission. The SARAL/AltiKa mission continues to perform nominally after more than 4 years on orbit, and to provide data with accuracy comparable to Jason-2. All altimeter systems are operating nominally and continue to provide high quality data and have good agreement with Jason-3, and OGDR, IGDR and GDR data product production continues to meet or exceed all requirements. Since July 2016, SARAL has operated in the SARAL Drifting Phase (SARAL-DP), in which the satellite's ground track and altitude have been allowed to drift. Based on the observed altitude decay, mesoscale sampling characteristics are expected to remain excellent for 10 more years. In this orbit, SARAL/AltiKa continues to provide additional observations for both mesoscale ocean forecasting and analysis as well as improvements in the marine geoid.

Craig Donlon (ESA/ESTEC) gave an update on the status of the Sentinel-3 Mission. The Sentinel-3 mission is composed of two identical satellites flown together in the same sun-synchronous orbital plane, separated by 140°. Both satellites embark a SAR Radar Altimeter (SRAL) instrument supported by a dual frequency microwave radiometer. The European Commission, ESA and EUMETSAT have responded to the altimetry community request to adjust the original phasing of the two satellites at 180° (which would result in sub-optimal mesoscale sampling) to a new baseline of 140°. Sentinel-3A is now in routine operations with all data available to any user under the Copernicus free and open license agreement. A decay in the total power of the Ku-band altimeter has been observed, but it is predicted to remain within specifications and the root cause is under investigation. However, both the satellite and ground segment operation is nominal and Level 1 and 2 products have been released to users. Sentinel-3 provides an innovative L1A product that contains all of the waveforms within each SAR burst to the users together with calibration information. This product is designed to allow all users free and open access to the low-level data in order to spearhead new innovative SAT processing methods. Sentinel-3B Flight Acceptance Review is in progress and launch is expected in early 2018. A tandem phase between Sentinel-3A and -3B lasting 4-5 months with a separation of time of 30 seconds has been approved (with Sentinel-3B flying ahead of -3A). After the tandem phase, Sentinel-3B will move to its position ±140° out of phase with Sentinel-3A. Follow on satellites (Sentinel-3C and Sentinel-3D) are now being built as operational replacements for the A and B units. Donlon also noted the ESA support to the operation and development of the Crete Transponder unit located at the crossover between S3A and S3B, and close to the Jason reference orbit as part of the FRM4ALT project (http://www.frm4alt.eu/). FRM4ALT has organized an International Review of Altimetry cal/val and applications in Chania, Crete, Greece, April 23-26, 2018 (see http://www.frm4alt.eu/component/content/article/8-news/71-frm4alt-int-workshop).

Cédric Tourain (CNES) provided an update on CFOSAT (China France Oceanography Satellite), a wind and wave scatterometer mission to measure spectral properties of these phenomena at global scales. To be launched in September, 2018, CFOSAT will carry a Ku-band wind scatterometer called SCAT and wave scatterometer called SWIM. It will provide global coverage within 3 days, in near real time, with geolocalistion better than 5 km. The Ku-band wind scatterometer (SCAT) will measure sigma0 and wind speeds for speeds from 4-24 m/s, and wind direction within 20°. SWIM, a Ku-band aperture radar will measure directional wave spectra using rotating off-nadir beams that are combined during ground processing.

Finally, Lee Fu provided an update on the SWOT mission (Surface Water and Ocean Topography mission). The mission will carry a SAR imaging 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. The Critical Design Review is scheduled for February 2018. The launch vehicle has been selected to be a SpaceX Falcon-9, and science data systems development is on schedule. Science priorities include validating models at fine scales and high-frequency, as well as assessment strategies to deal with incoherent tides and waves that cannot be easily removed from the observations. Calibration and validation efforts involving gliders to sample the top 500 m of ocean variability are underway and early results are promising. But demonstrating that SWOT has met its tight performance requirements at small wavelengths remains a challenge.

2.2 Other reports and issues

Before the splinter sessions Craig Donlon (ESA/ESTEC) gave a presentation on the first meeting of the Sentinel-6/Jason-CS Mission Advisory Group (MAG). The MAG is a small, formal panel of altimetry experts selected by the partner agencies to advise and support Sentinel-6/Jason-CS Project on scientific and technical issues that arise during implementation. The MAG is chaired by the same Project Scientists as the OSTST and shall maintain a close working relationship with the OSTST. The MAG will be dissolved once the two-satellite mission is fully commissioned into operations. The aim of the MAG is “to deliver competent, independent and unprejudiced advice to the Partners by addressing questions raised during implementation relating to any aspect of the Sentinel-6/Jason-CS Mission Performance.” The first MAG meeting took place close to ESA/ESTEC, Noordwijk, The Netherlands, June 12-13, 2017. Ongoing MAG discussions include a proposal to exercise both side-A and the redundant side-B altimeter electronics during the tandem phase with Jason-3, the feasibility of acquiring more raw SAR data from the altimeters (as opposed to compressed SAR data) over the open ocean, alternative processing approaches to SAR data and creation of the mask that will switch between raw and compressed SAR data over the ocean. The second meeting will take place in the U.S. in February 2018.

On behalf of the other Project Scientists, Eric Leuliette (NOAA) presented discussion topics for consideration by the splinter sessions. These included consideration of calibration and validation methods to verify stability of global and regional mean sea level requirements placed on Sentinel-6/Jason-CS, the possibility of switching on the side-B altimeter on Jason-CS during its tandem phase with Jason-3, assessment of whether alternative SAR processing is feasible on Sentinel-3 and Jason-CS, and the impact of descoping MLE3 fields in the baseline products for Jason-CS.

3 Keynote Science Session.

After the opening plenary session, a special Keynote Science Session was held, including four invited talks. These included Christopher Watson (Univ. of Tasmania), who discussed estimates of global mean sea level rise based on the satellite altimeter record. Recent work provides additional support for a small correction to the early part of the TOPEX/Poseidon record, and a small acceleration in the rate of rise during the 20+ year record. Shenfu Dong (CIMAS, Univ. of Miami and NOAA/AOML) discussed changes in the South Atlantic Meridional Overturning Circulation. Using altimeter data to reconstruction overturning rates and meridional heat transport in the ocean, Dong et al. found that ocean heat transports carried heat out of the subtropical South Atlantic in the 1990s, but heat began to converge in the region in recent decades. In addition, while air-sea heat fluxes dominated heat storage rates before 2005, ocean heat transports played a larger role after. Lynn Shay (RSMAS) presented satellite-derived estimates of ocean heat content. These estimates use both satellite based observations of sea surface temperature and sea surface height to estimate mixed layer depth, and heat content between the surface and the 26°C isotherm to better understand the interaction between tropical storm and upper ocean temperatures. Finally, Jean Tournade (IFREMER) presented estimates of iceberg populations around Greenland and Antarctica derived from CryoSat-II SARin data. Careful analysis of radar returns in these regions makes it possible to detect icebergs as well as estimate their area and height above the water (freeboard). Frequency distributions of iceberg size, freeboard, and regional distribution around both Greenland and Antarctica were presented.

4 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://meetings.aviso.altimetry.fr

The posters were grouped into the following categories:

- Application development for Operations [11 posters]
- Instrument Processing (Propagation, Wind Speed and Sea State Bias) [1 posters]
- Instrument Processing (Measurement and retracking) [4 posters]
- Outreach, Education & Altimetric Data Services [10 posters]
- Precise Orbit Determination [3 posters]
- Quantifying Errors and Uncertainties in Altimetry Data [4 posters]
- Regional and Global CAL/VAL for Assembling a Climate Data Record [19 posters]
- The Geoid, Mean Sea Surfaces and Mean Dynamic topography [6 poster]
- Tides, internal tides and high-frequency processes [8 posters]
- Advances in Coastal Altimetry: measurement techniques, science applications and synergy with in situ and models [15 posters]
- Science Results from Satellite Altimetry: Climate data records for understanding the causes of global and regional sea level variability and change [10 posters]
- Science Results from Satellite Altimetry: Large Scale Ocean Circulation Variability and Change [11 posters]

- Science Results from Satellite Altimetry: Mesoscale and sub-mesoscale oceanography [29 posters]
- Science Results from Satellite Altimetry: 25 years of satellite altimetry for Cryosphere and Hydrology: from experimental to emerging operational applications [15 posters]
- Others (poster only) [6 posters]

5 Splinter Sessions

The splinter sessions were organized as follows:

Monday, October 23:

  - Science I: Climate data records for understanding the causes of global and regional sea level variability and change [6 oral]

Tuesday, October 24:

  - Instrument Processing (Part I): Measurement and retracking [5 oral]
  - Precision Orbit Determination (Part I): Measurement and retracking [6 oral]
  - Instrument Processing (Part II): Measurement and retracking [5 oral]
  - Precision Orbit Determination (Part II): Measurement and retracking [5 oral]
  - Instrument Processing (Part III): Propagation, Wind Speed and Sea State Bias [5 oral]
  - Outreach, Education and Altimetric Data Services [6 oral]
  - Science (Part II): Large Scale Ocean Circulation Variability and Change [5 oral]

Wednesday, October 25:

  - Application development for Near Real-Time Operations [5 oral]
  - Regional and Global CAL/VAL for Assembling a Climate Data Record (Part I) [6 oral]
  - Advances in Coastal Altimetry: measurement techniques, science applications and synergy with in situ and models [3 oral]
  - Regional and Global CAL/VAL for Assembling a Climate Data Record (Part II) [4 oral]
  - Science (Part IV): 25 years of satellite altimetry for Cryosphere and Hydrology: from experimental to emerging operational applications [6 oral]
  - Quantifying Errors and Uncertainties in Altimetry Data [4 oral]
  - Science (Part III): Mesoscale and Submesoscale Oceanography [6 oral]

Thursday, October 26:

  - The Geoid, Mean Sea Surfaces and Mean Dynamic topography [5 oral]
  - Tides, internal tides and high-frequency processes [5 oral]
  - Round tables for each splinter

Links to the presentations are available on the meeting website:
http://meetings.aviso.altimetry.fr

5.1 Application development for Operations

Chairs: Gerald Dibarboure, Alejandro Egido, Gregg Jacobs, Carolina Nogueira Loddo

The Application Development for Operations splinter session for the 2017 OSTST took place on Wednesday October 25. There were 5 talks and 11 posters presented, and the oral session was very well attended (> 60 attendees).

5.1.1 Round table summary

1. **Jason-2 operations: Recommend prolonging the data stream as long as possible, having more coverage is better than less. Prevent and recover quickly from safe-holds to provide data as quickly as possible.**
   a. Present operations result in safe-holds with prolonged data outages
   b. Operating the satellite differently is a balance between possible reduction in safe-holds versus possible degradation in water vapor radiometer
   c. A degradation is preferable to long outages
2. **Near Real Time Products: Recommend consistency of accuracy, processing, and access of sea surface height anomaly across levels 2-4 and consideration of user applications.**
   a. There is particular disparity in coastal data sets, though understandable since algorithm development has been under way. Coalescence processing and products.
   b. We recognize that there is not a central source of consistency across satellite programs.
   c. Input from end users is required. Recommend moving request for information to the GODAE RCOM. Reach out to users to compile requirements.
3. **Data coverage requirements: There is demonstrated requirement for 4 coordinated accurate nadir altimeters to meet ocean applications based on recent understanding of ocean eddy fronts and impact on meteorological response to frontal positioning.**
   a. Wave applications have demonstrated advancement from 2 to 4 nadir altimeters. Other data sources (Sentinel-3 SAR) also add predictive skill.
   b. Frontal positions are critical to hurricane path and intensification due to heat flux exchange.

c. Yann Drillet – experiments show advancement of 1 day in predictive skill as model resolution is increased and observation density increased from 2 to 4 satellites.

d. Accurate positioning enables targeted ocean observations during critical events.

e. Present constellation is not meeting the requirement for 4 coordinated accurate nadir altimeters. Future prospects with coordinated Sentinel-3A and Sentinel-3B along with Sentinel-6/Jason-CS are positive. Developing future observations is required.

4. **SWOT applications –** Recommend bringing this issue to the GODAE DA task team. Increase coordination of SWOT assimilation efforts to understand impact of ocean processes on applications.

    a. Several groups are involved in SWOT OSSEs, though there is not significant coordination.

    b. John Wilkin will introduce the topic to the GODAE DA task team secretary to invigorate efforts over the coming year.

    c. We must build experiments over the coming year in a coordinated manner to ensure applications for SWOT are addressed, which can aid in extending cal/val plans.

5. **Recommendation: Support other efforts that are providing data for cal/val in OSTST (Woods Hole STRATUS):** Contact GOOS and GCOSS physics and observations panel secretary.

5.1.2 Oral Presentation Summary

The first talk by Lofti Aouf on the "Combined assimilation of Sentinel-1 and Sentinel-3A wave data in operational wave model: investigation on bias for SAR mode altimetry" (Figure 5.1-1), explored the use of SAR directional wave spectra to improve the SWH estimation by assimilating SAR wave spectra provided by Sentinel-1A and 1B SAR imaging instruments (providing dedicated wave move and other wide swath imager products) together with the significant wave heights retrieved by Sentinel-3A. First waves climatology based on wave products from operational database is implemented for all ocean basins to identify the areas of swell dominant sea state. In particular the talk focused on the primary swells with wavelength ranged between 300 and 400 m (with hints that these can be seen in S3 SAR altimeter data). The combined assimilation was performed for the southern winter of 2017 (June to September) because of many events generating swell systems. The results presented shows that the combined assimilation improves significantly the mean wave parameters. The validation with independent altimeters wave heights reveals the reduction of the bias (30 to 40%) after the assimilation mostly in the high and intermediate latitudes.

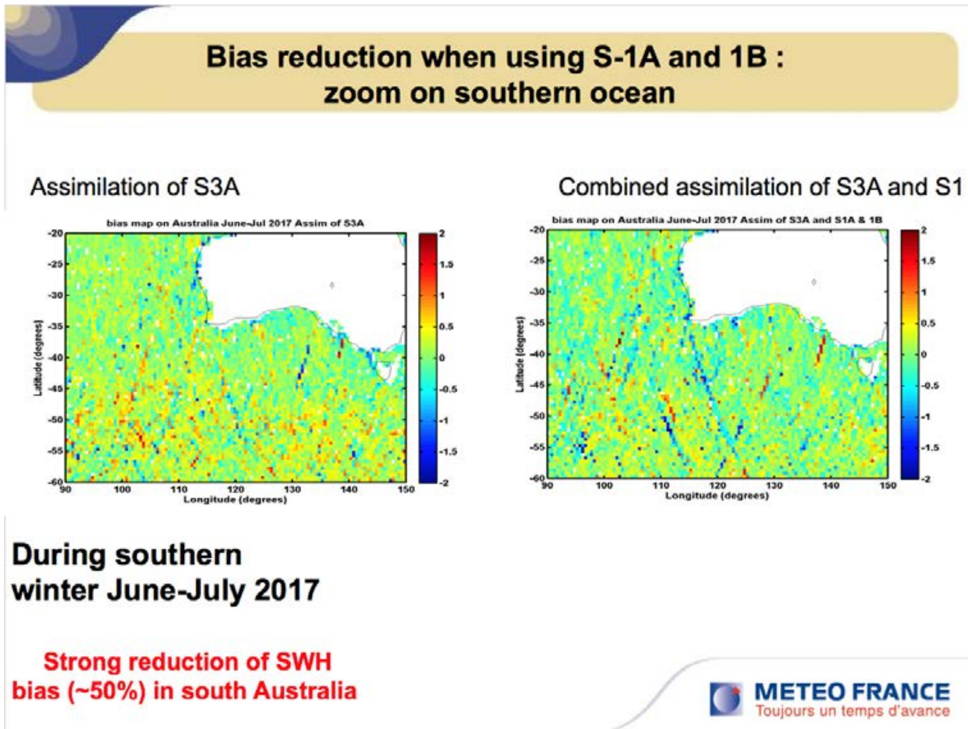


Figure 5.1-1 From the talk by Lofti Aouf

The second talk by Joseph D'Addezio titled "High-Resolution 3DVAR for Constraining Submesoscale Dynamics" (Figure 5.1-2), investigated the use of high resolution Surface Water Ocean Topography (SWOT) to analyze the capabilities of SWOT data for observing submesoscale phenomena. Developed in anticipation of real-time SWOT data, an Observation System Simulation Experiment (OSSE) evaluates potential forecast improvements enabled by future SWOT data. To generate a divergent simulation over the same time period, the initial condition was perturbed while using the same boundary conditions and surface forcing as was used in the simulated truth. As expected, mesoscale and submesoscale features between the two solutions diverge. The simulated truth was then sampled at real observation locations throughout 2016, and the observations were provided to the Navy Coupled Ocean Data Assimilation (NCODA) 3DVAR. The first simulation (the Control run) used only current observation systems to establish a baseline estimate of convergence by mainly constraining the mesoscale ocean features. Test SWOT data, created from the simulated truth using the Jet Propulsion Laboratory's (JPL) SWOT simulator, was used for two additional experiments (one containing all estimated errors and the other with none). The addition of simulated SWOT data both increases the rate and magnitude of convergence when compared with the Control run. The difference between the experiments using SWOT data with full errors and no errors provides a range of expected performance the satellite data will provide when operating, showing that assimilation of observations of the 'truth' using current observation systems proved effective at reducing errors and constrained spatial scales were quantified.

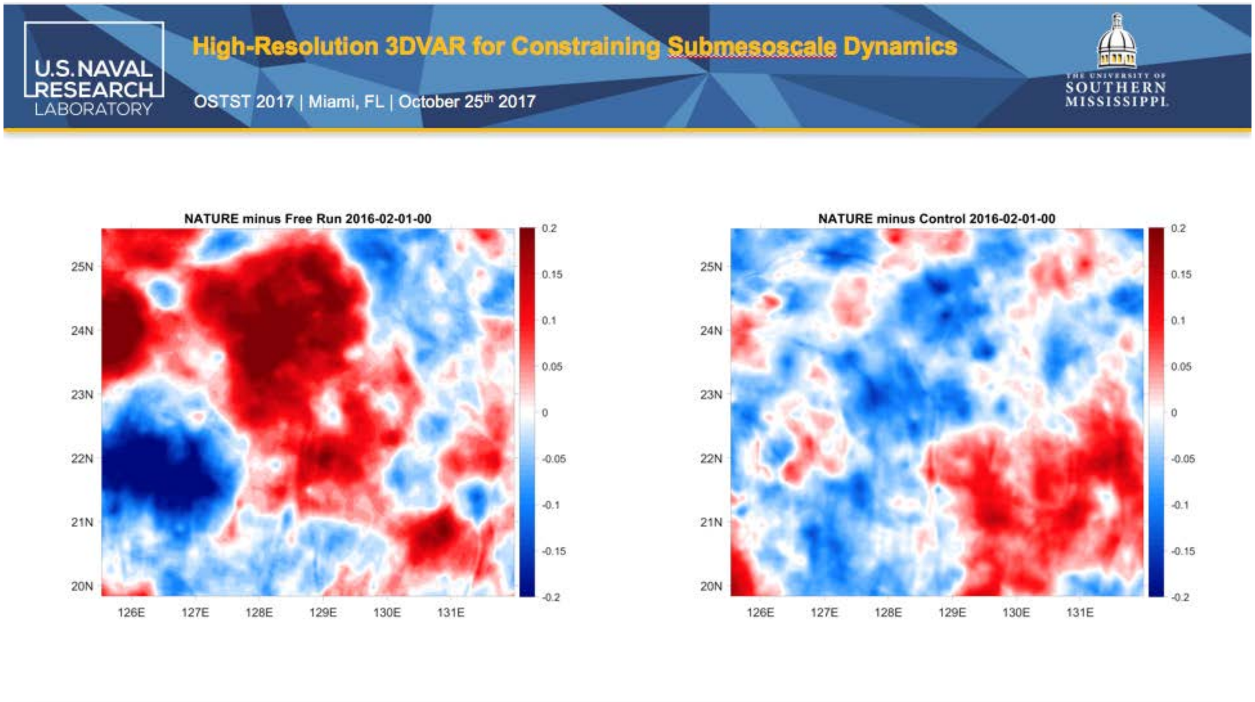


Figure 5.1-2 From the talk by Joseph D'Addezio.

The third talk given by Yann Drillet was on the role of “Altimetry to constrain ocean analysis and forecasts” (Figure 5.1-3). Altimetry data is one of the key observing network to constrain ocean analysis and forecasts from mesoscale to large scale. Since October 19, 2016, and in the framework of Copernicus Marine Environment Monitoring Service (CMEMS), Mercator Ocean delivers in real-time daily services (weekly analyses and daily 10-day forecasts) with a new global 1/12° high resolution system. The ocean modelling component is the NEMO platform driven at the surface by the IFS ECMWF atmospheric analyses and forecasts. Observations are assimilated by means of a reduced-order Kalman filter with a 3D multivariate modal decomposition of the forecast error. Along track altimeter data, satellite Sea Surface Temperature and in situ temperature and salinity vertical profiles are jointly assimilated to estimate the initial conditions for short term numerical ocean forecasting. A 3D-VAR scheme provides a correction for the slowly-evolving large-scale biases in temperature and salinity.

Future challenges include the assimilation of large swath altimeter data when available. Preliminary assimilation of simulated observations show a clear benefit of 2D swath data compared to 1D track. It does not only improve the Sea Surface Height analysis and forecast but also allow a better velocity field estimation which should represent a significant benefit for Mercator Ocean and Copernicus users. The sensitivity to the complex error of those data will be assessed in the near future but the first results that were presented were very promising.

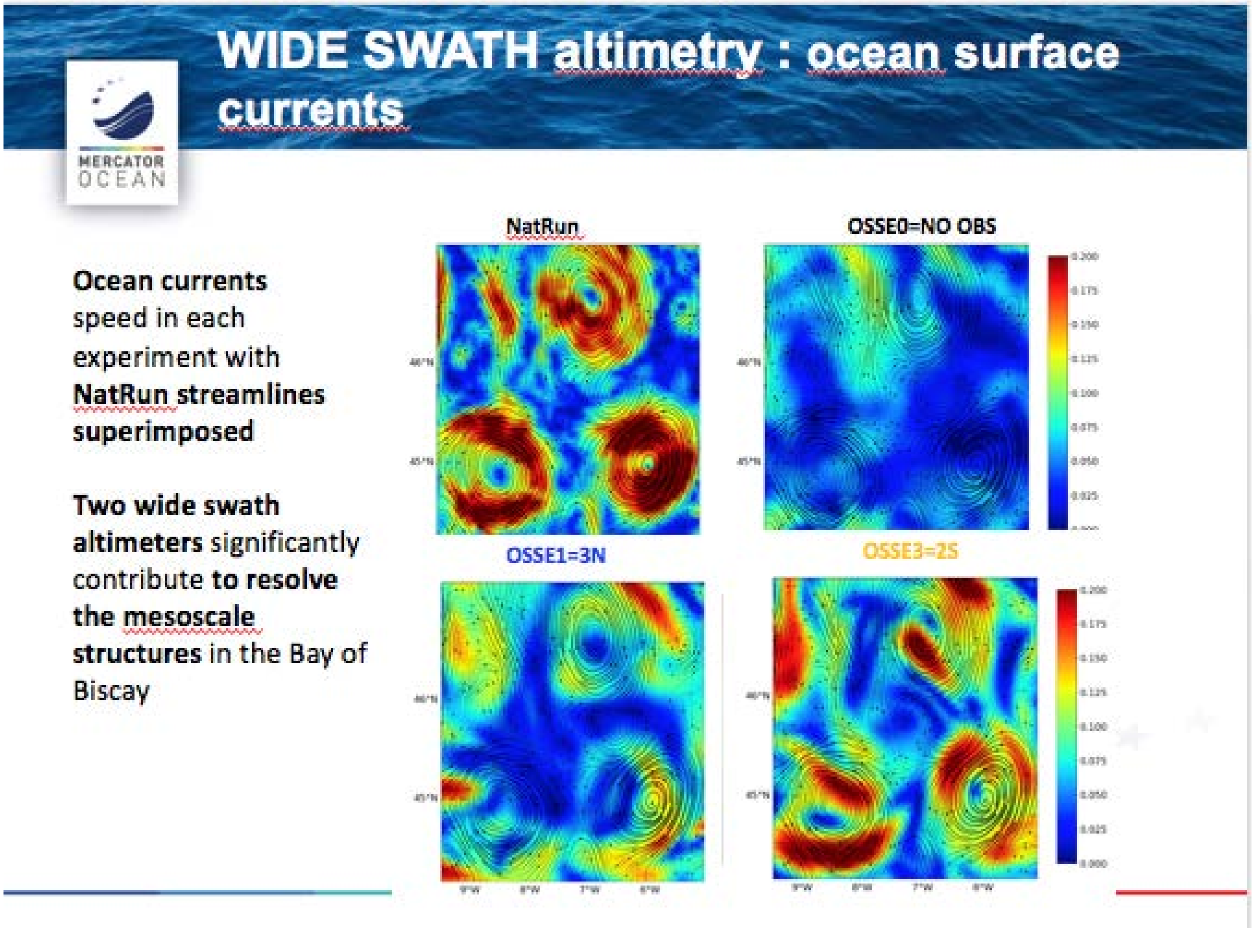


Figure 5.1-3 From the talk by Yann Drillet

The fourth talk by Zhijin Li, assessed the "Predictability of Submesoscale Flows Using Multiscale Data Assimilation of Satellite Altimetry" (Figure 5.1-4), on the representation of circulations down to submesoscales of the order of 1 km. Sub-km horizontal grid spacing is increasingly used in regional forecasting models to resolve submesoscale flows. To ensure a positive impact of satellite altimetry data in a model of sub-km grid spacing, we need to deal with a set of particular difficulties. Among those difficulties are the limited footprint size of altimetry measurement, dynamical imbalance, spatial localization and temporal intermittency, and others. Leveraging a real-time multiscale three-dimensional variational data assimilation (MS-3DVAR) and forecasting system, which supports the Salinity Processes in the Upper Ocean Regional Study (SPURS) field campaign in the North Atlantic Ocean in 2012-2013 (SPURS-1) and the eastern Tropical Pacific ocean in 2016-2017 (SPURS-2), and the SPURS multi-scale observing network, they illustrate those difficulties, and demonstrate positive impacts of multi-satellite altimetry on the prediction of submesoscale flows.

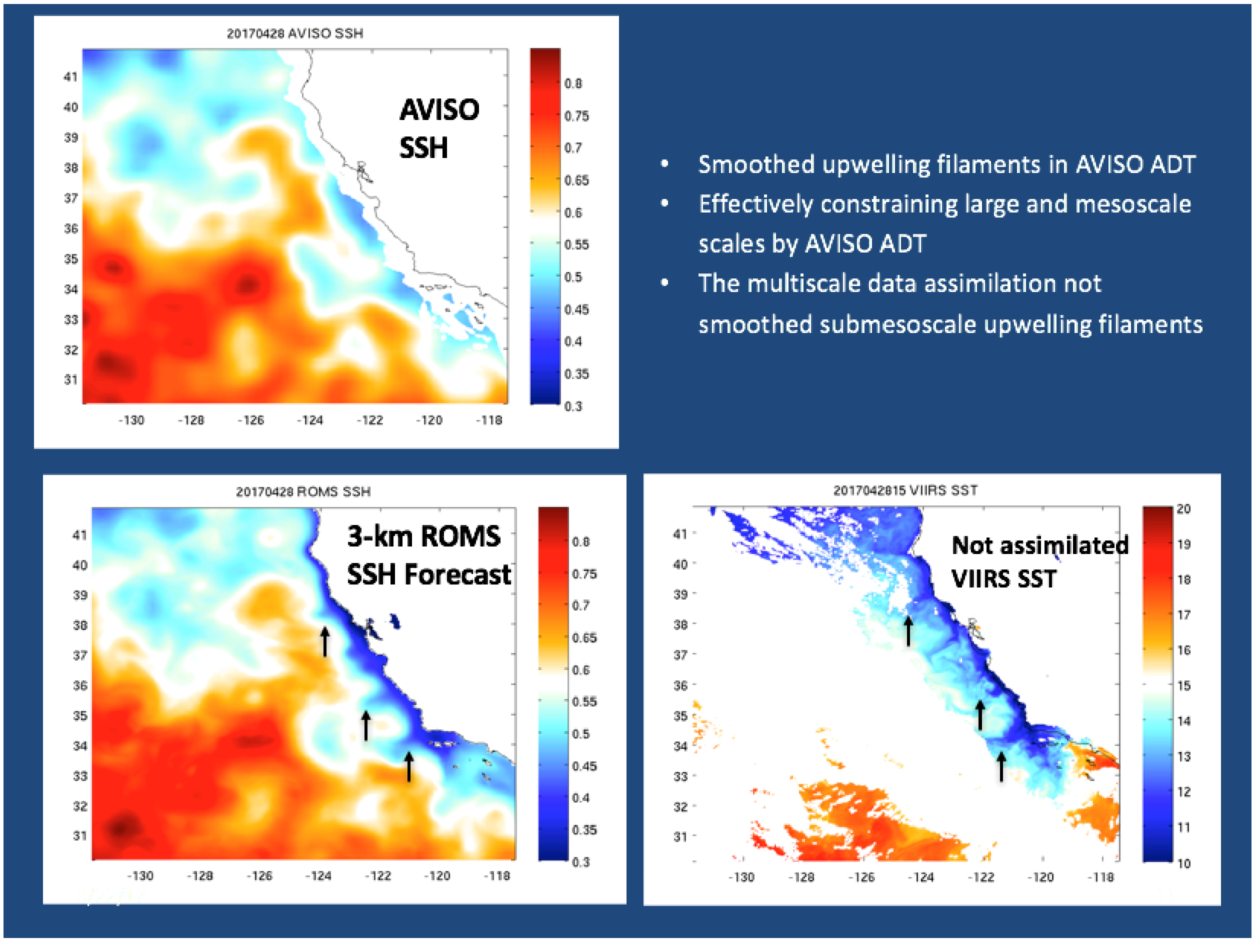


Figure 5.1-4 From the talk by Zhijin Li

The fifth and final talk, presented by Matthieu Le Hénaff, had as a title "Combining altimetry with in situ data: quantitative impact assessment of operational ocean observation strategy in hurricane applications using Observing System Experiments and OSSEs" (Figure 5.1-5). The authors presented the combination of altimeter data with data from other satellites and in situ platforms by operational monitoring and prediction centers, and, a quantitative assessment of the benefit of the current and future components of the observing network, by ocean Observing System Simulation Experiments (OSSE) system developed by the Joint Ocean Modelling and OSSE Center (OMOC) of NOAA/AOML, CIMAS, and RSMAS, University of Miami. Assimilation of observations corrected the upper-ocean heat content ahead of the storm, enabling the coupled model to more accurately predict the heat flux from ocean to atmosphere that fuels the storm. The OSE-OSSE results demonstrate that in situ ocean observations combined with altimetry play an important future role toward improving intensity forecasts of tropical cyclones.

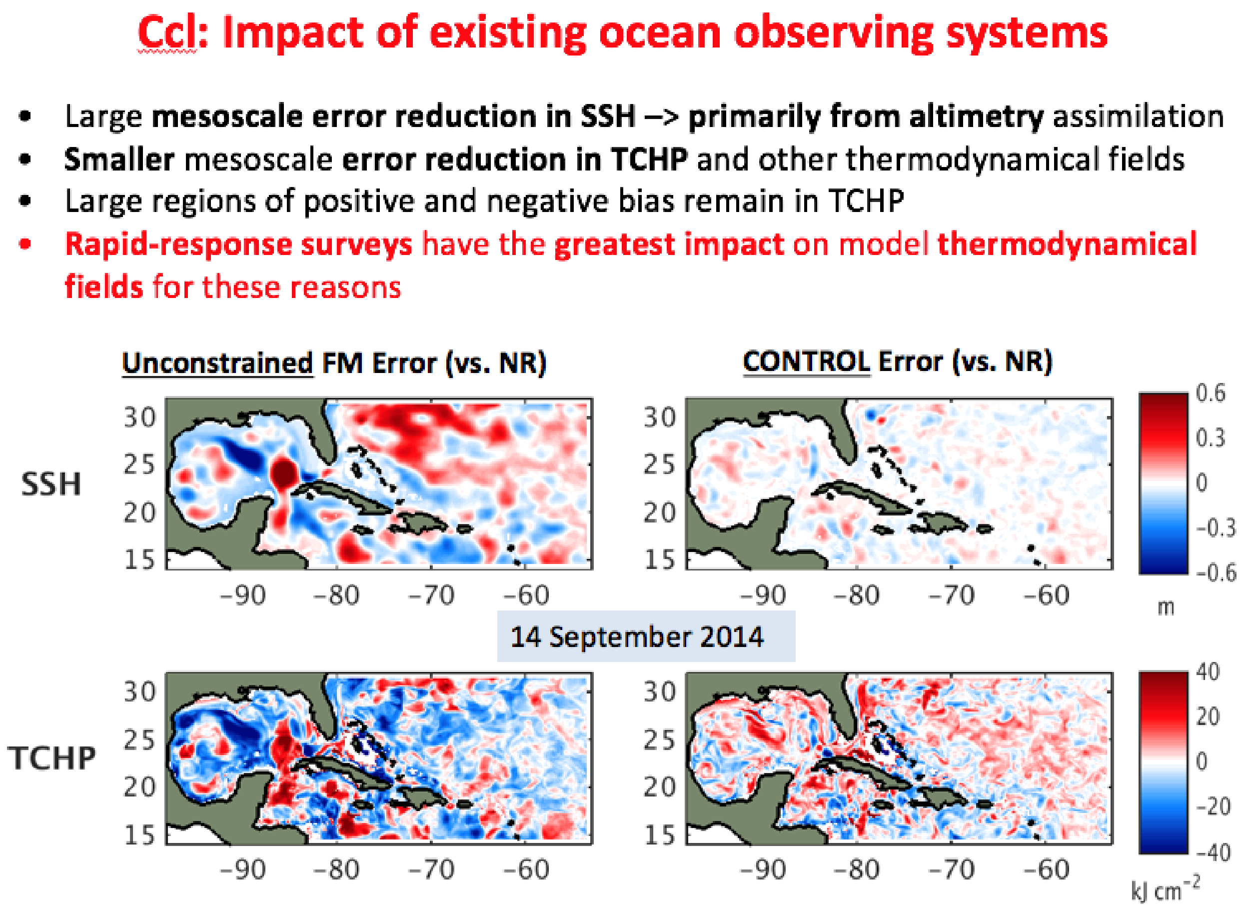


Figure 5.1-5 From the talk by Matthieu Le Hénaff

5.1.3 Poster summary

APOP_001: One case study on how satellite and in situ ocean observations help to improve hurricane forecasts (Gustavo Jorge Goni et al.)

This poster highlights the current efforts to implement and maintain a suite of observational efforts that utilize data from satellite and autonomous platforms to better understand air-sea processes during high wind events. The example presented corresponds to the joint use of underwater gliders and satellite altimetry, which have shown to improve the correct representation of ocean conditions and improved forecast for the Hurricane Gonzalo (2014).

APOP_002: Value added Sentinel-3A sea level products by the Marine Altimetry L2P-L3 Service operational since end of June 2017 (Sabine Philipps et al.)

This poster presents the Sentinel-3 Marine Altimetry L2P-L3 Service developed by CNES and its subcontractor CLS in the frame of the Copernicus Program funded by the European Union, under an EUMETSAT Contract. The Service was pre-operational since mid-December 2016 and is fully operational since the 27th of June 2017. Detailed information on the L2P and L3 products is presented as well as on the distribution of the products to the users.

APOP_003: Impacts of oil spill on satellite altimetry measurements (Cheng Yongcun et al.)

This poster presents a study that exploits the availability of Environmental Response Management Application (ERMA) oil cover, daily oil spill extent, and thickness data acquired during the Deepwater Horizon (DWH) oil spill accident, occurred on 2010, which provides a unique opportunity to evaluate the impact of surface film on altimeter data. In this study, the Jason-1/2 passes nearest to the DWH platform are analyzed to understand the waveform distortion caused by the spill as well as the variation of $\sigma 0$ as a function of oil thickness, wind speed, and radar band. The study shows that high-resolution altimeter data can certainly help better evaluate the thickness of oil spill, particularly at low wind speeds.

APOP_004: G-REALM: Investigating the Sentinel-3A data set for the next phase of Operational Lake and Wetland monitoring. (Charon Birkett et al.)

The poster presents the G-REALM, a NASA/USDA funded operational program offering water-level products for lakes and reservoirs that are currently derived from the NASA/CNES Topex/Jason series of radar altimeters. In the next phase of the G-REALM program, focus is on the creation of near real time Sentinel-3A water level products, which will ultimately be merged with those derived from SARAL and ENVISAT. Operational Sentinel-3A products will assist observation of short-term agricultural drought, while the archival SARAL/ENVISAT products will help assess the longer-term hydrological drought.

APOP_005: NOAA's Jason Products (David Donahue et al.)

The poster presents the interagency Jason-2 and Jason-3 missions measurements to help track global sea level rise, ocean currents, and upper ocean heat content (sea surface height, wind speed, and significant wave height) and also addresses the four partner agencies mission roles and responsibilities: the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA) Jet Propulsion Laboratory (JPL), the Centre National d'Etudes Spatiales (CNES), and the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT).

APOP_006: The quasi-operational 4D-Var ocean data assimilation/prediction system for the western North Pacific at JMA (Toshiyuki Sakurai et al.)

The poster describes the plan from Japan Meteorological Agency (JMA) to introduce a new coastal ocean assimilation/prediction system (MOVE/MRI.COM-JPN (referred here after as MOVE-JPN)) in 2020 after an update of super-computer systems of JMA. It focuses on MOVE-4DVAR that consists in both MOVE-JPN and MOVE-Seto. Some modifications made to suit operational requirements are presented. In the quasi-operational mode, 10-days assimilation and subsequent 11-days prediction are executed in a daily basis. This leads to usage of the latest observation data in the analysis. The near-real time observational data such as satellite sea level anomalies (SLA), in-situ temperature and salinity profiles, and analyzed SST data (prompt analysis of MGDSST (Merged satellite and in situ Global Daily Sea Surface Temperature)) are assimilated. In-situ observation of temperature and salinity are obtained via GTS, e-mail and facsimile. Validation results against in-situ measurements is also presented.

APOP_007: Jason-2 and Jason-3 Near-Real Time Products Latency over the Past Year (Donald Richardson et al.)

The latency of Jason-2 and Jason-3 near-real time Operational Geophysical Data Records (OGDR) over the past year is examined using timeliness statistics against the requirement that product distribution be less than 3 hours from data collection. Major gaps in the ODGR production will be addressed, as well as periods of large latencies.

APOP_008: CMEMS SEA LEVEL THEMATIC ASSEMBLY CENTER, ACHIEVEMENTS AND PERSPECTIVES (Yannice Faugere et al.)

The DUACS system produces high quality multimission altimetry Sea Level products for oceanographic applications, climate forecasting centers, geophysic and biology communities... These products consist in directly usable and easy to manipulate Level 3 (along-track cross-calibrated SLA) and Level 4 products (multiple sensors merged as maps or time series) and are available in global and regional version (Mediterranean Sea, Arctic, European Shelves …).

Since mid 2015, the operational production of the along track and Sea Level maps is now generated as part as the Copernicus Marine Environment and Monitoring Service (CMEMS). The system today merges data from 6 satellites (Jason-3, Sentinel-3, Jason-2, Altika, Cryosat-2 and HY2A). This poster presents the main achievements of the SLTAC during the 3 years of CMEMS, as well as the perspectives.

APOP_009: Reconstruction of the surface ocean topography and associated dynamics using image data assimilation in the prospect of the SWOT mission (Pierre Brasseur)

In the prospect of the SWOT mission, a new approach is presented to reconstruct the dynamics of the upper ocean as accurately as possible, using image data assimilation to extract meso- and submesoscale information from the high-resolution scenes that will be captured by future altimetric constellations. It is based on a two-step analysis scheme that combines a reduced-order Gaussian observational update, and a non-Gaussian observational updates to adjust the fine-scale using Lyapunov exponents associated to the structure of the flow (Duran et al., 2016).

APOP_010: Ocean Surface Altimetry with CyGNSS (Mashburn Jake et al.)

CyGNSS is a constellation of 8 small satellites launched in December 2016 that carries the Surrey Satellite Technologies (SSTL) SGR-ReSI GNSS Reflections (GNSS-R) receiver. Developed as the primary science instrument for CyGNSS, the SGR-ReSI receiver performs real time onboard navigation and generates delay- Doppler correlation maps for Earth reflected GPS L1 C/A ranging signals. While these functions were designed primarily to facilitate the retrieval of ocean surface wind speeds, this research explores ocean surface altimetry retrievals using the CyGNSS data sets. The data sets analyzed here span March 18 – June 3, 2017 at +/- 38 deg latitude.

APOP_011: On the improvement of high resolution AROME winds for operational wave forecast under cyclonic conditions: validation with altimeters wave data (Lotfi Aouf et al.)

This poster presents an upgrade of the high resolution atmospheric system AROME-OM of Meteo-France, dedicated for regional domains (west-indies, La Reunion and French Polynesia). In this version from September 2017 the AROME-OM system is forced by 1-D ocean mixed layer with initial conditions of sea surface temperature (SST) provided by the Mercator operational ocean model. The goal of this study is to investigate the impact of two wind forcing provided by the upgraded AROME-OM atmospheric system on the wave forecast during cyclones and hurricane events. The first wind forcing is using only the sea surface temperature from operational Mercator ocean system, while the second wind forcing is issued from AROME-OM model forced by 1-d ocean mixed layer with SST from mercator system as initial conditions.

Two events have been investigated for this study: cyclone Fantala in the indian ocean (March 2016) and hurricane Matthew (October 2016) in the Carribean sea. A base line run of the wave model MFWAM with wind field from old version of AROME-OM system is also performed for these two events. The validation with altimeter wave heights is also presented.

5.2 Instrument Processing: Corrections

Chairs: Shannon Brown, Estelle Obligis

5.2.1 Recommendations:

There was one main question posed to the instrument processing corrections splinter:

Would increasing the frequency of the Jason-3 AMR cold sky calibrations to improve the long term stability?

The answer is mathematically yes, but given current constraints on when the maneuvers can be performed, the benefit would be minimal given current radiometer drift rate. The project implemented a new calibration schedule based on the 2016 OSTST recommendation to increase the calibration frequency. This new schedule is nearly optimal. The schedule, illustrated in Figure 5.2-1, extended the yaw period to 20 days and added a calibration maneuver to the start and end of that period. This means that the calibrations are done in intervals of 20 and 40 days, which is close to the optimal case of every 30 days. **The IPC does not recommend an additional increase in frequency at this time.** Should the radiometer drift rate change, this issue can be revisited.

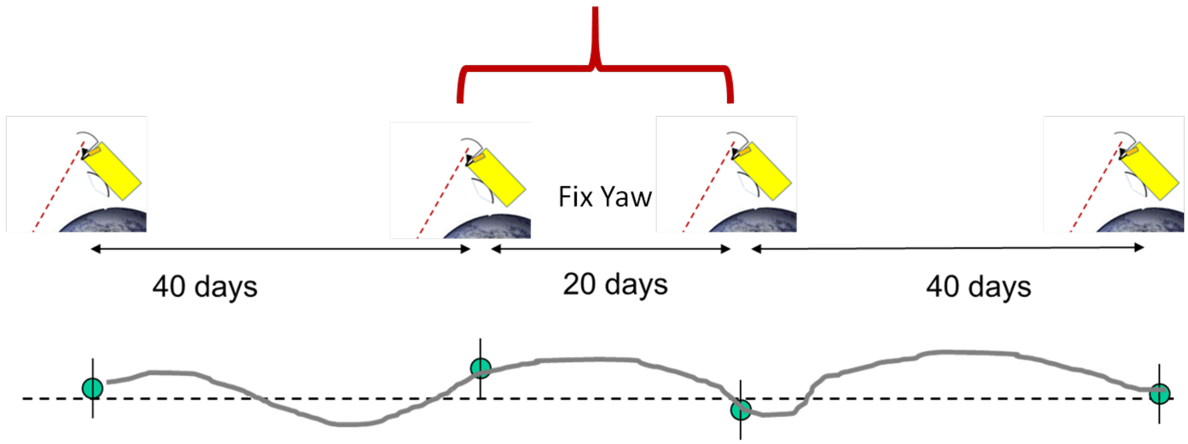
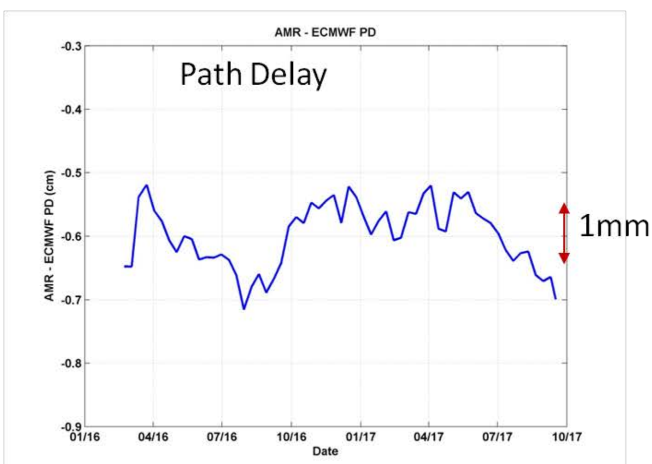


Figure 5.2-1 Illustration of the cold sky calibration schedule.

5.2.2 IPC Results Summary

The instrument-processing splinter on corrections featured several presentations on the wet tropospheric path delay correction. The presentations focused on the Jason-3 cold sky calibrations, the Sentinel-3 MWR performance and future radiometer designs.

The cold sky calibrations were shown to be critical to stabilizing Jason-3 AMR. The radiometer has been drifting since launch. Since the drift is limited to the noise diodes, a single ended calibration, using only the cold sky data, can be performed. The radiometer is demonstrated to be stabilized to + 0.1K level. This translates into the path delays being stabilized to better than ± 1mm over mission to date. The global mean difference between the Jason-3 AMR PD and that from ECMWF is shown in Figure 2.1-2. The regional trends are also shown in Figure 5.2-2. No significant residual calibration trend is observed.



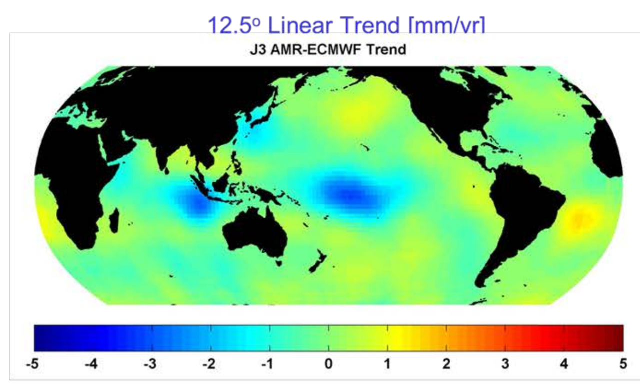


Figure 5.2-2 Global mean and regional trends of the Jason-3 AMR path delay relative to the ECMWF model.

An assessment of the Sentinel-3A showed that the instrument is performing well overall. The performance was shown to be similar to other water vapor radiometers. A comparison between Jason-3 and Sentinel 3A is shown in Figure 5.2-3. The RMS difference with respect to Jason-2 and Jason-3 is less than 1.3 cm. An analysis of the coastal performance shows the S3A product can be reliably used up to about 25km from land.

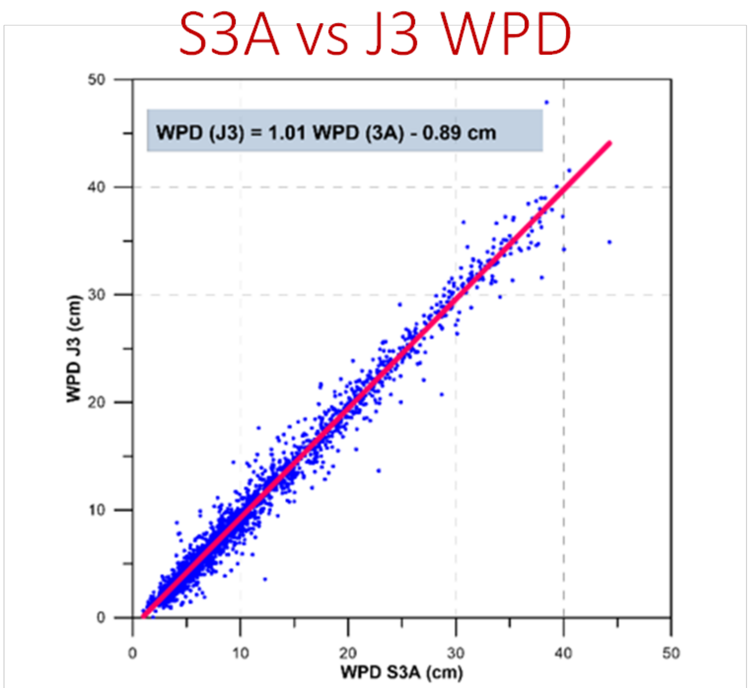


Figure 5.2-3 Scatter plot of Sentinel 3A and Jason-3 wet path delays at co-incident points.

There is an effort to develop improved products from the radiometer as well as new (non-path delay) products. Algorithms are being developed to improve the Sentinel-3A performance in the coastal zone. Empirical algorithm has been developed that improves retrieval of wet path delay near Corsica. This product is currently undergoing validation. In addition, a new interpolation scheme will be soon available to improve the retrieval of wet path delay close to the coast. For hydrology applications, an inland water wet path delay retrieval algorithm is being developed and validated over Lake Issyk-kul, as illustrated in Figure 5.2-4. Finally, the MWR data planned to be used in a new algorithm under development to estimate sea ice type.

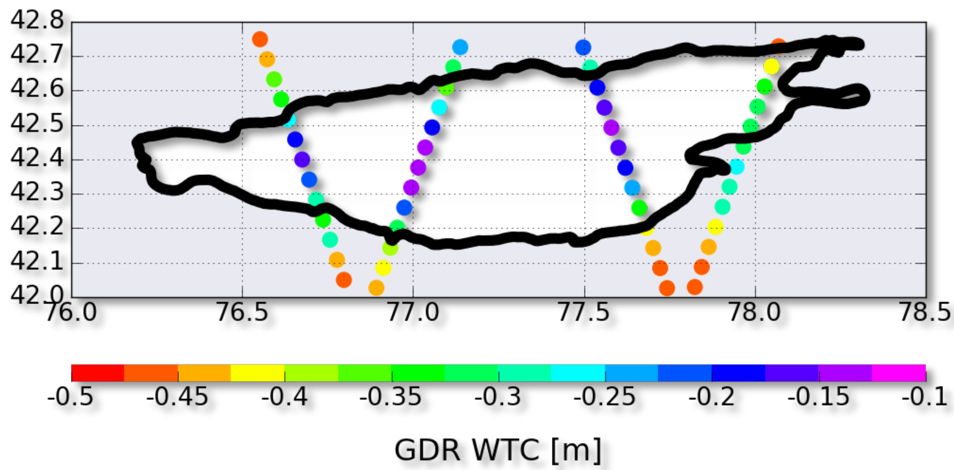


Figure 5.2-4 Example Sentinel 3A wet path delay over Lake Issyk-kul.

In addition to analyzing the performance of existing radiometers, we must also look ahead to the future. A detailed study of the optimal radiometer channel set was presented. A specific question that study evaluated was the need for an 18.7 GHz channel in radiometer wet path delay retrieval (e.g. 2 vs 3-freq radiometer). A correlation plot, shown in Figure 5.2-5, clearly illustrates the sensitivity between the various geophysical variables and measurements. The 18.7 GHz channels is sensitive to surface conditions (roughness + SST = emissivity) but also very sensitive to water vapor. It was found through simulation that the best retrieval performance comes from a three-frequency algorithm using the 18.7 GHz channel. The next best alternative is to use a 2-frequency algorithm with information from the Ka-band sigma0. The results using the Ku-band sigma0 showed the worst performance of the three cases considered. It should be noted that this conclusion is valid in a global statistical sense, but may not represent results near land or in areas of high-spatial variability at the surface – which could lead to regional biases. These conclusions will be revisited using real data from the GMI + Ka/Ku PR observations on GPM.

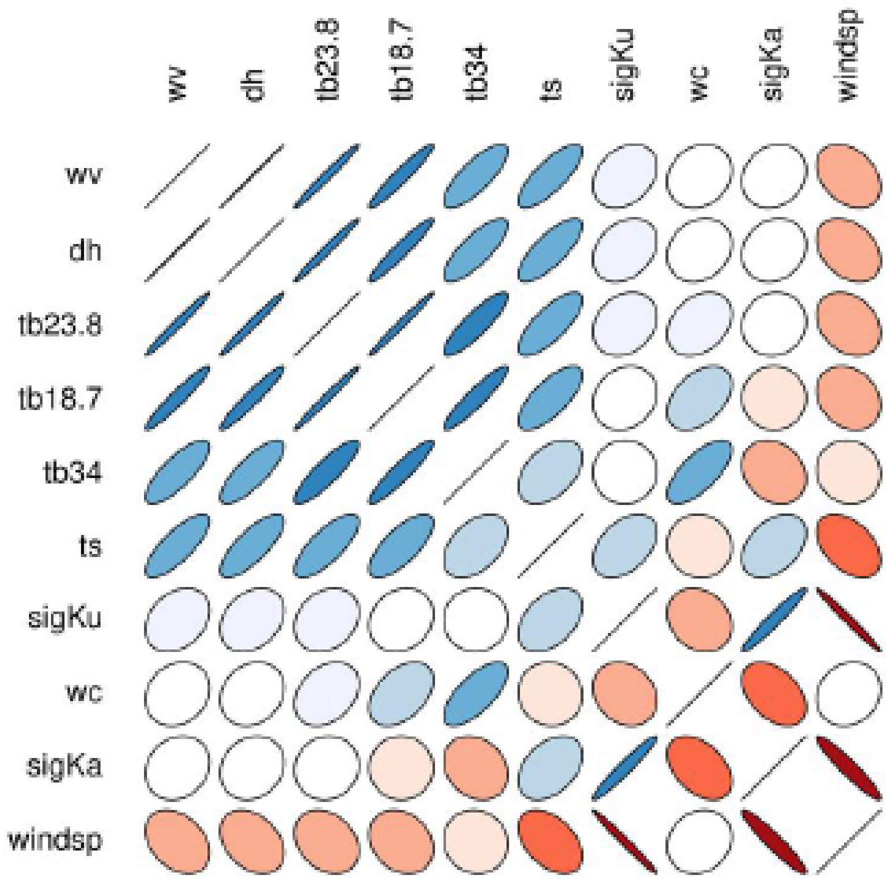


Figure 5.2-5 Correlation plot between several variables related to wet path delay retrieval.

5.3 Instrument Processing: Measurements and Retracking

Chairs: François Boy, Phil Callahan, Marco Fornari and Walter Smith

The Instrument Processing: Measurements and Retracking Splinter (IPM) had ten oral presentations and four posters as well as a lively round table discussion. P. Thibaut recalled that the most general way of thinking about retracking (in fact, any kind of instrument processing) is that it consists of a model of the measurement process containing the physical parameters of interest and a method for comparing measurements to the model to estimate the parameters. For altimetry, the measurement model is what is often called the Hayne model (Reference 2; based on Brown, Reference 1): the altimeter waveform is a convolution of the flat surface response (FSR) with the surface height probability distribution function (PDF) and the instrument point target response (PTR). All are functions of range or time of flight, and the FSR and PTR can also be functions of Doppler frequency (representing off-nadir returns) in SAR systems. The main parameter is the range to the surface, and the model may also include the significant wave height (SWH), noise level, backscatter coefficient, surface slope, and off-nadir angle. There is both intrinsic correlation of some of these parameters and correlation introduced by the solution method. Solution methods include least squares (weighted or unweighted), maximum likelihood (MLE, assuming that the noise covariance is known), and direct search with various methods. In the end, all methods require some linearization as the overall measurement model is quite complex.

Specialized cases of this general way of thinking were presented in several talks. P. Thibaut described an Adaptive Retracker that includes mean square slope in the surface model and uses Nelder-Mead optimization with likelihood criteria. The likelihood criteria include the correct statistics for each range gate. The retracker has been demonstrated for both SARM and LRM. It shows large benefits over open ocean including internal waves and "blooms" and especially for retrieving SWH. It also handles ice leads; and inland water. The adaptive retracker is compatible with other enhancements, particularly for the PTR. (See additional information in Reference 3.)

The ALES+ is an enhancement of the Adaptive Leading Edge Subwaveform (ALES) retracker that has been discussed for several years. It uses a reduced (sub) waveform near the leading edge. The enhancement lies in using an estimate of the waveform "peakiness" to select a width parameter for the waveform and an external estimate of the tail for peaky waveforms (see Figure 5.3-1). The width parameter is usually associated with SWH, but for very peaky waveforms it is more related to the fall off of the tail. The tail is usually related to the antenna beam width and off-nadir pointing but can be corrupted when the scattering scene is not uniform. In the open ocean, non-uniformity is often related to rain, slicks, or ice. Near coasts or ice or for ice leads the non-uniform scattering is from land or ice. ALES+ improves performance over current processing of ERS-2 and EnviSat in all the domains, although less in coastal areas than the original ALES. A sample DTU/TUM gridded Arctic and Antarctic SSH product is available from Sea Level CCI.

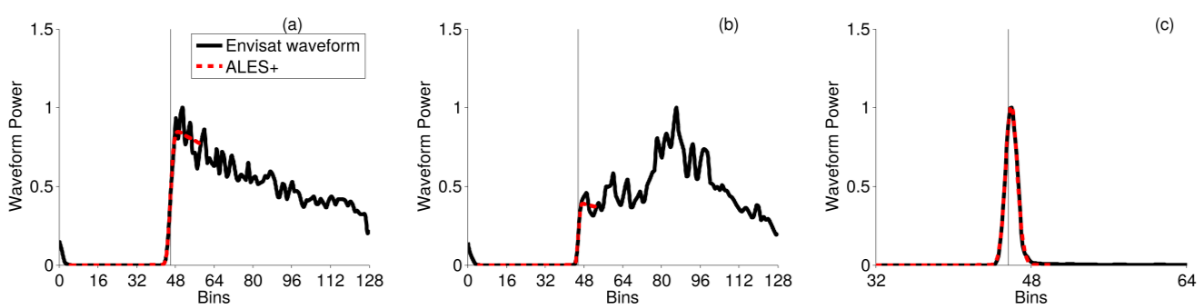


Figure 5.3-1 (Passaro, et al.). Examples of the reduced waveforms used by ALES+. (a) Open Ocean; (b) Coast; (c) Leads/Inland Water.

As mentioned above, parameters in retracking are always correlated. The net effect depends on both model (mainly, is off-nadir angle estimated) and estimation method. Correlation effects are most clearly seen in relatively low variability areas where the "spectral hump" in the SSH anomaly spectrum is most noticeable and at wavelengths <~100 km. Several of the retrackers in general use for LRM data (unweighted: ALES, MLE3, MLE4, PEACHI/Newton-Raphson; weighted: PEACHI/Nelder-Mead) for Jason-2, Jason-3, and AltiKa (only MLE4) in a region of the south Pacific where the spectral hump has previously been observed were analyzed and compared using auto- and cross-spectra of the output parameters. AltiKa results were usually similar to Jason but in some cases showed the effects of higher sampling rate (40 Hz) or the partially beam-limited nature of the signal. All methods behaved similarly for SSH for wavelengths > 100 km. As expected from the discussion above, ALES showed the least spectral hump but the highest noise floor as it uses less of the waveform but not the often-corrupted tail (it does not retrieve off-nadir angle). MLE3 showed the largest hump as it uses the waveform tail but, by not solving for off-nadir angle causes, effects there to distort the solution for range and SWH. SWH spectra showed similar results, although there was good agreement only to about 500 km. Sigma0 (waveform amplitude) spectra showed a strong hump for methods that solve for off-nadir angle. Cross spectra show that more than 50% of the variance in sigma0 is due to correlation with (variance of) off-nadir angle for wavelengths < 50 km. Cross spectra (admittance) of SSHA with SWH (effectively sea state bias, SSB; see Figure 5.3-2) showed that the effect is not only tracker dependent but also wavelength dependent and is above 5% for all methods for wavelengths < 100 km. The wavelength dependence is particularly strong for the Nelder-Mead method as it effectively uses weighted fitting. Overall it is clear that the spectral hump is mainly due to correlated errors and that more attention should be paid to these effects, especially for SSB.

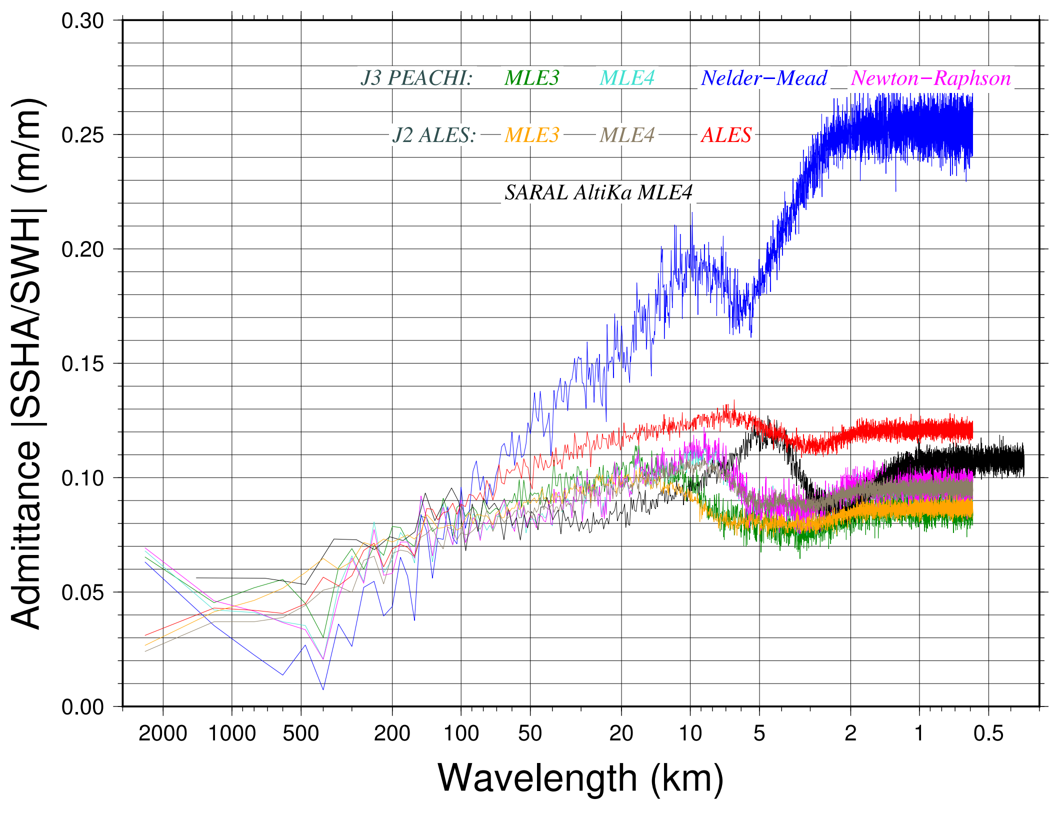


Figure 5.3-2 (Smith et al.). Sea Surface Height Anomaly (SSHA) – SWH Admittance: Sea State Bias. Color legend shows altimeters and methods.

A second type of correlation is that between pulses used to form the observed LRM waveform. It is most significant in the leading edge. Early results estimated that a pulse repetition frequency (PRF) of 2-4 kHz provides all the information that correlation of speckle from the surface would allow. Egido et al. used CryoSat-2 full bit rate data (18 kHz) to show that there are significant improvements in the estimation of geophysical parameters by increasing the PRF from 2 to 9 kHz based on PLRM data analysis (MLE4, Brown model). The effective number of looks shown in Figure 5.3-3 is limited near the leading edge as expected from the early analysis, but there are large gains in effective looks in the early noise area and waveform tail. The increased number of looks greatly reduces the noise in estimating the noise floor and off-nadir angle, thus improving the overall solution. SSH and SWH RMS are improved by 10-25% for 2 to 8 m SWH for 9 kHz vs 2 kHz PRF; sigma0 and off-nadir angle are improved by more than 30%. It should be noted that there is an SWH-dependent bias between 2 kHz and 9 kHz data for SSH (1-2 cm) and SWH (<~5 cm) retrievals.

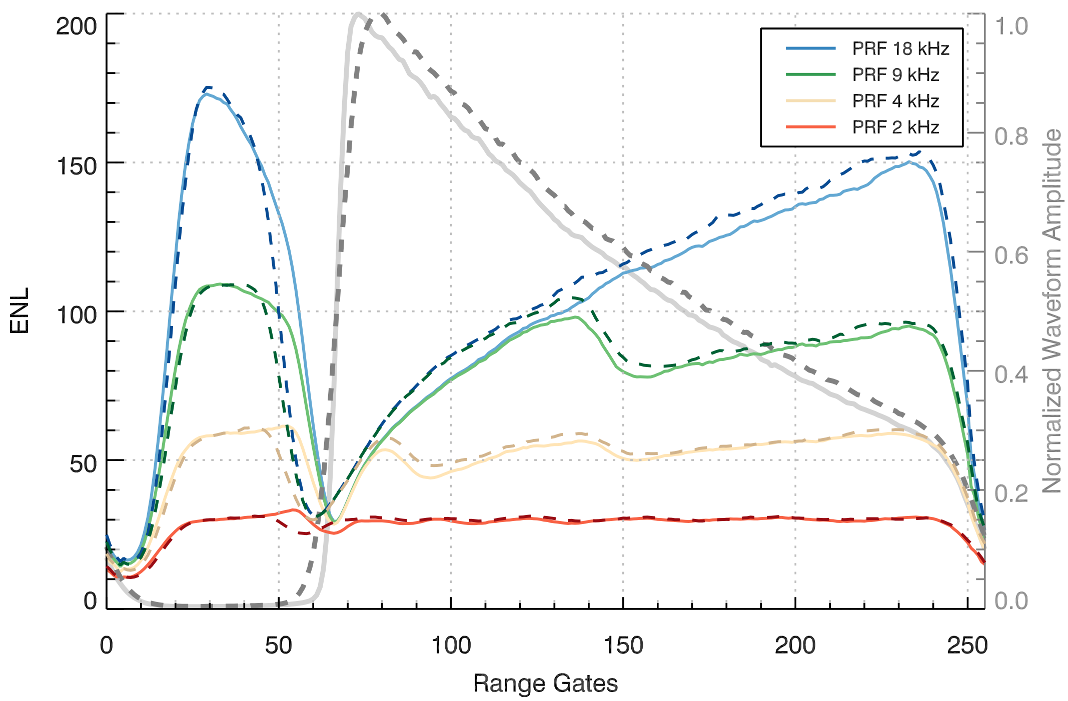


Figure 5.3-3 (Egido et al.). Effective number of looks within the waveform. Waveforms are synthesized from CryoSat-2 full bit rate data.

T. Moreau et al. investigated removing the bias between SAR and pseudo-LRM in wave height. They demonstrated that ignoring the range walk in the unfocused SAR approaches (pulses drift in the range window) as it is done currently in the operational processing chains leads to a distortion of the PTR, particularly in azimuth and for larger look angles as shown in Figure 5.3-4. This effect, not accounted for in the echo models available today, partially explains the SWH bias between SAR and PLRM. A correction is proposed and consists in compensating the range walk before applying the along track FFT. With this correction, the SWH bias is reduced by 7 cm. Further assessment will be achieved on a large dataset in 2018.

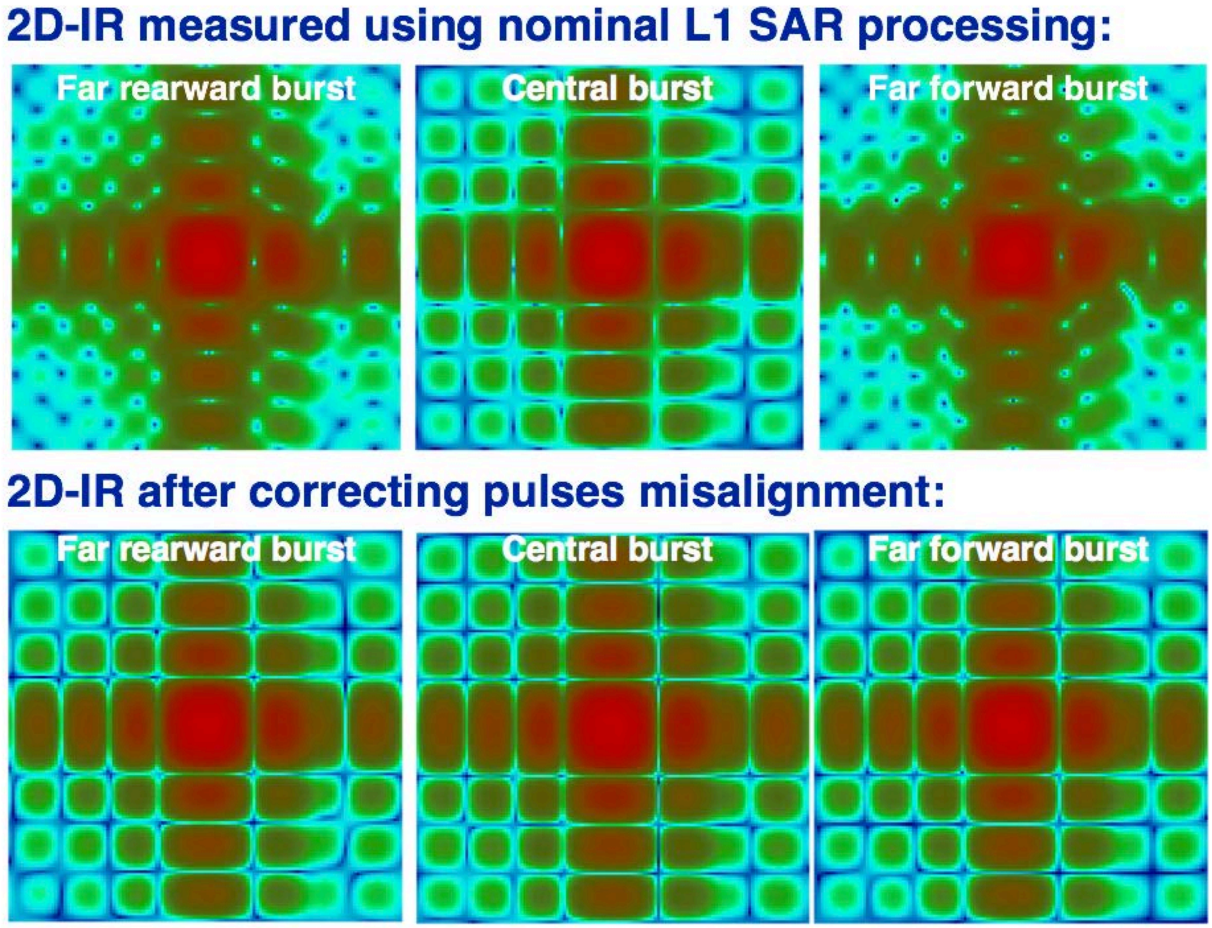


Figure 5.3-4 (T. Moreau et al.). The PTR is perturbed when range migration is not included, particularly in azimuth (upper images; azimuth in y direction). The perturbation of the PTR is largely corrected by range migration and should also be accounted for in parameter retrieval.

Then, *Boy et al.* addressed the swell effect on Sentinel-3 SRAL SAR measurements which induces an increase of the range/SWH noise. The underlying cause of the problem is that the along-track resolution of SAR mode data is similar to the wavelength of swell so that surface height and slope are no longer independent as is assumed in the nominal model. A new stacking approach is proposed (LR-RMC - Range Migration Correction) performing range migration on individual bursts in forming the waveform to be retracked. LR-RMC gives significantly improved performance with respect to standard SAR processing and fully removes the swell sensitivity.

Another presentation (Buchhaupt) investigated the effects of zero padding in SAR along-track (azimuth) processing. Zero padding effectively doubles the sampling rate from 20 to 40 Hz. In terms of spectra for short wavelengths, small improvement was found for SSH but a somewhat larger one for SWH.

SCOOP (Sentinel-3 SAR altimetry in the Coastal and Open Ocean Project) is an ESA project being done by a consortium of institutions aimed at assessing and improving the performance of

Sentinel-3 processing. The main outcome of SCOOP is to be a scientific road map for improving Sentinel-3 processing. ESA also runs the DeDop project (http://www.dedop.org) that is providing an open-source delay Doppler processer (code available at https://github.com/DeDop) allowing users to process data from L1A to L1B. The first test data set from processing CryoSat FBR data like Sentinel-3 is undergoing evaluation for ten varied areas of interest. Ten user-led case studies that demonstrate how L1A and SAR altimetry from Sentinel-3 are nearing completion. Another ESA activity led by isardSAT is comparing the precision of conventional Sentinel-3 and CryoSat-2 processing to delay Doppler processing with amplitude compensation and dilation compensation (ACDC) to improve the stacking of waveforms along track. Evaluation in two test areas show an improvement of up to 2 cm in SSH precision and up to 10 cm in SWH precision for SWH below 3 m (all methods perform similarly for SWH >~ 4 m).

The reprocessing of TOPEX data with retracking was reviewed and plans presented. A new version of TOPEX consistent with Jason version E with retracking, regenerated corrections, new orbits, and Jason-like format in NetCDF is in work. All the steps of retracking and calibration corrections will be revisited, particularly the WFF range calibration. The data will begin with the original Sensor Data Records (SDRs) in order to include 20 Hz values for range which were averaged to 10 Hz in previous versions of the GDR.

5.3.1 Instrument Processing Round Table

The most important conclusion from the round table was that a process is needed to get improved methods validated and put into use to get improved products users. Validation should include:

- Methods (statistics, etc.), metrics, criteria, test data sets (regions; including in situ if possible; global desirable)
- Independent assessment
- Documentation, specifications

In addition to a clear path to putting the methods into use for ongoing processing, a commitment for reprocessing of previous data is needed. The latter is somewhat challenging with the 25-year history of altimetry and the diverse agencies involved. Nonetheless, for a climate data record, the best consistent processing is needed.

The round table had responses to three of the questions posed by the project scientists.

Question 4. What would be the impact of descoping MLE3 fields in the baseline for JCS/S6 products (except for sigma0)?

- To avoid confusion, it may be best to put MLE3 fields only in the SGDR while keeping the GDR simple with only recommended values. Documentation must note whether the recommended values come from MLE3 or MLE4.

Question 6. What are the open issues that affect the continuity between LRM and SAR modes from SWH, roughness, swell and their impacts on SSH?

- As discussed in several presentations summarized above, the swell effect can largely be removed with improved stacking.

- Making full SAR SWH consistent with LRM is mainly solved.

Question 7. What areas should S6/JCS RAW SAR data (non-RMC) be collected (acquisition mask)?

S6/JCS Poseidon-4 will acquire all regions in interleaved mode providing access to both SAR and LRM data simultaneously. On-board Range Migration Correction processing (called RMC) is used to reduce the data rate sent to ground. However, it is possible to send some data to ground without on-board RMC processing applied (RAW-SAR). It was noted that there is a one year commissioning phase and that the mode mask can be uploaded.

Raw SAR data should be sent to ground in the more complex coastal regions. However, this leads to a potential conflict with a different data stream (on-board processed RMC) over the majority of the ocean surface and RAW-SAR data in the areas where calibration and validation are performed. A significant focus is required to ensure that results obtained in the coastal regions with RAW SAR data (i.e. no on-board processing applied) are using identical processing to the on-board RMC and the implication in the context of sea level is understood.

The main discussion focused on demonstrating that onboard RMC does not degrade the data quality (phase, signal accuracy). Key points:

- Analysis has already been performed by the project team but is not yet complete and further simulations will be available in 2018.

- Test data are available from the Sentinel-6/Jason-CS project since 2016 that could be used (please mail Craig.Donlon@esa.int or Robert.Cullen@esa.int for ftp access details).

- Additional tests can be done by performing RMC on "real" Sentinel-3 L1A data.

- Must insure that data can be transformed back to do full SAR processing without quality loss (the entire trailing edge cannot however be recovered).

- RMC technical description (high level) should be provided to users by the project.

5.3.2 References

1. Brown, G.S., *The Average Impulse Response of a Rough Surface and Its Application*, IEEE Transactions on Antenna and Propagation, Vol. AP. 25, N° 1, pp. 67-74, 1977.

2. Hayne, G. S., *Radar Altimeter Mean Return Waveforms from Near-Normal-Incidence Ocean surface scattering*, IEEE Transactions on Antennas and Propagation AP-28, No.5, 687-692, 1980.

3. A. Halimi, C. Mailhes, J. Tourneret, P. Thibaut, and F. Boy, *A Semi-Analytical Model for Delay/Doppler Altimetry and Its Estimation Algorithm*, IEEE Transactions on Geoscience and Remote Sensing, vol.52, issue.7, 2013. DOI : 10.1109/TGRS.2013.2280595

5.4 Outreach, Education & Altimetric Data Services

Chairs: Jessica Hausman, Vinca Rosmorduc and Margaret Srinivasan

5.4.1 Session presentations:

- The altimeter product suite for the Sentinel-6/Jason-CS mission; Remko Scharroo et al.
- New Data and Updates at PO.DAAC; Jessica Hausman
- The Antarctic Circumpolar Current as seen in Argonautica; Vinca Rosmorduc et al.
- Science communication through art, design, and hands-on activities; Laura Bracken
- OSTST-Related Outreach Activities; Edward Zaron
- Showcase of altimeter outreach & data services
    - Coastal Water Research Synergy Framework; Paolo Cippolini et al.
    - NOAA Coastwatch/Oceanwatch Altimetry Products; Jessica Burns et al.
    - What causes the large coral mortality observed in 2016 on Bunaken Island (Indonesia); F. Birol et al.
    - Copernicus Marine and Ocean Training Service; Vinca Rosmorduc et al.
    - Global Mesoscale Eddy Trajectory Atlas now on Aviso+; Vinca Rosmorduc et al.
    - New reference book on altimetry; Anny Cazenave et al.
    - RUS: Research and User Support for Sentinel Core Products; Isabelle Soleilhavoup et al.
    - Jason-3 Contest Results ; Danielle De Staerke et al.
    - A NASA Web Portal for Sea Level Change; Jessica Hausman et al.

5.4.2 Posters

- Broadview radar altimetry toolbox; Albert Garcia-Mondejar et al.
- Sar altimetry processing on demand service for cryosat-2 and sentinel-3 at ESA g-pod; Jérôme Benveniste et al.
- Aviso+ products & services: What's new?; Vinca Rosmorduc et al.
- Outreaching hydrology from space & SWOT; Vinca Rosmorduc et al.
- ArgoHydro, Hydrology in the classroom; Danielle De Staerke et al.
- SAR-RDSAR: A new Service on G-POD for SAR and RDSAR Products; Christopher Buchhaupt et al.

- NOAA Scientific Data Stewardship for Ocean Surface Topography Mission (OSTM)/Jason-2 and Jason-3 Products; Yongsheng Zhang et al.
- Access to Sentinel-3 Marine Center data; Bruno Lucas et al.
- NOAA Coastwatch/Oceanwatch Altimetry Products; Jessica Burns et al.
- X-TRACK regional altimeter products for coastal applications; Fabien Léger et al.

5.4.3 2016-2017 Highlights

Updates of data services were shared, as were new datasets distributed, or being considered for future missions. Some changes in data distribution were identified, as well.

The session is dominated by data services presentations, with fewer outreach and education activities. L. Bracken (U. Miami) shared some low-cost, local outreach activities in the area of Biscayne Bay and Miami in an invited talk. The activities described can be imitated in other regions.

The popular Outreach Showcase portion of the splinter allows OSTST members to present an outreach or data service activity they developed or participated in with one or two slides. This allows for a large number of activities to be shared.

A short discussion period after the formal presentations focused on teaching/training activities, support, and materials.

Data services

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

PO.DAAC showed evolutions in their services and data. Eumetsat presented the future Jason-CS/Sentinel-6 NetCDF data format. ESA had information on their G-POD service.

Outreach

Discussion of outreach and educational activities over the past year included anticipation of the SWOT and Jason-CS/Sentinel-6 missions, and planning to highlight the public engagement and applications opportunities.

Useful resources (figures, maps, movies, animations, schemes…) are currently available on the altimetry missions and other web sites, 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 graphic. If it does not exist, we can consider having it made for specific and future uses.

Education

Argonautica was focused on the Vendee Globe around the world sail race last year, with skippers launching buoys along the way, especially in the Antarctic Circumpolar Current.

A Jason-3 contest was launched by CNES, with the making of web sites around climate and the environment for students at different school levels (in French and in English).

5.4.4 Discussion

- For both outreach and data services:
  - What is missing?
  - What new method/ways/material would you like?
- Outreach
  - What would you consider as an incentive to outreach (more)
  - Do you find outreach has too much/too little space/visibility in OSTST?
- Data services
  - What features do you consider as a must-have for a data service (today)?
- At the cross-road: training
  - Which content, public, frequency, modality…? (face to face vs on line, theory vs practice, material to be re-used in teachers' lectures…)
  - What would you think useful in the specific case of altimetry / ocean topography / your own field of research?
  - What kind of material are you missing for your own lectures?

5.4.5 Recommendations

We would like the OSTST organizers to consider the possibility of proposing a "demonstration" format during next OSTST in addition to posters & orals, i.e. an area with tables / some tables scattered within the session poster, showed during poster sessions, ideally with a screen each on the wall or at least high enough, so that it is easy to show things to more than one person, and on something bigger than a laptop screen. This would give the opportunity of really showing interactive services (data services as well as some outreach material, or even applications)

Send us trainings & courses, and your ideas of figures/schemes/animations you'd like for them, so as to build up a library of such material you can use in your lectures

We will continue to invite people working at science centers/museums/aquariums/labs close to OSTST future meetings to participate in the outreach session. This will broaden the outreach activities introduced to the OSTST, and will serve to engage and educate the local community in the area of the meeting location. If OSTST members have ideas and/or contacts, please share them with the Outreach Leads.

The outreach & data services round table discussion time was used by the session leads for planning and discussion of priorities.

There was a question on whether "big data" talks should be within the "outreach & data service" session (thus shortening the time for those two topics), or within the session the processing aim at (thus diluting the visibility of the big data topic). This should be considered at least for the 2018 OSTST, "25 years of altimetry" meeting.

5.4.6 New Planned Efforts

The focus of the outreach team for the coming year will be on climate and hydrology education, public outreach, as well as on applications outreach for all of the current and especially the upcoming ocean altimetry missions—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/Sentinel-6 and Jason-3 education & public outreach and applications outreach
- Development of a SWOT GLOBE program (NASA, CNES, U. North Carolina, GLOBE Program collaboration)

Outreach events can be organized around the next meeting (25 years of altimetry/OSTST 2018). Some are already planned on the ESA side. There will be two possible outreach and data services sessions during those two meetings. We will have to think about the topics/thematics to be broached in each of them.

5.5 Precise Orbit Determination

Chairs: Sean Bruinsma, Alexandre Couhert and Frank Lemoine

5.5.1 Status of Jason-2 and Jason-3 GDR orbits

A review of the quality of the currently available Jason-2 and Jason-3 orbits was alternatively given by the Jet Propulsion Laboratory (JPL), Goddard Space Flight Center (GSFC) and Centre National d'Etudes Spatiales (CNES). For validation purposes, the independent products rely on different parameterization strategies and combinations of tracking instruments. JPL rlse16a/17a time series are GPS-only reduced-dynamic orbits, whereas GSFC dpod2014v04 and CNES GDR-E/F are SLR+DORIS dynamic and DORIS+GPS reduced-dynamic solutions, respectively. Figure 5.5-1 shows the level of agreement reached between the three POD analysis centers in term of radial RMS differences. All types of orbits compare at the sub-centimeter level (below 8 mm RMS for Jason-2 and 9 mm RMS for Jason-3).

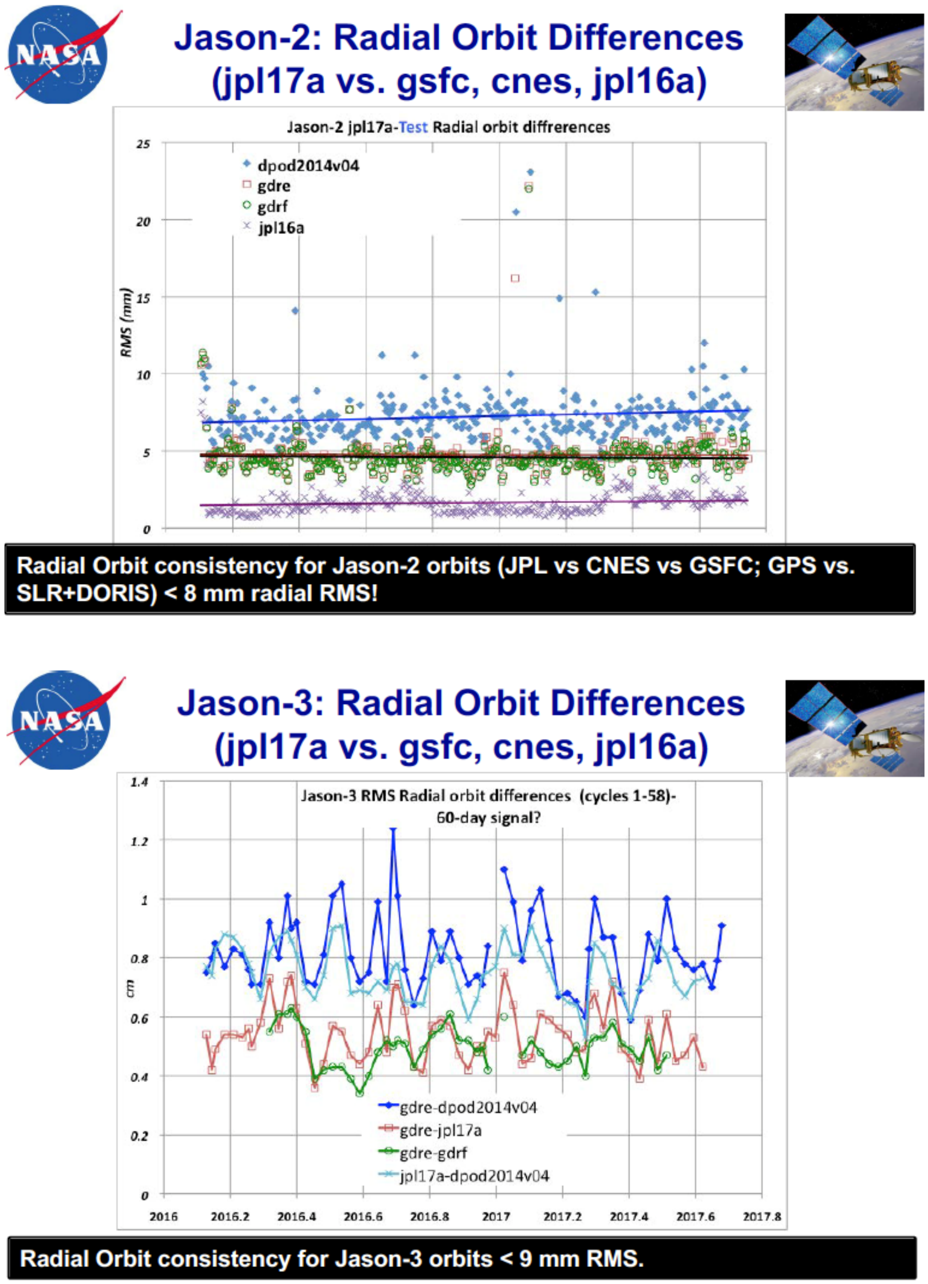


Figure 5.5-1 (Lemoine et al., 2017) RMS radial orbit differences for Jason-2 (top) and Jason-3 (bottom) between the CNES GDR-E/F DORIS+GPS reduced-dynamic orbits and alternative solutions: The JPL rlse16a/17a GPS-reduced-dynamic and GSFC dpod2014v04 SLR+DORIS dynamic orbits.

Proposed models for the next CNES GDR-F Standards were also introduced in the POD splinter session. The main evolutions concern updates on the models for the geopotential and the geocenter, the specification of the DORIS, GPS, and SLR tracking station coordinates (DPOD2014/IGS14/SLRF2014), the introduction of the long-term linear model for the pole, as well as changes to DORIS and GPS process and data screening. Independent SLR residuals over the reprocessed Jason-2 and Jason-3 orbits assess improvements between 2-6 mm RMS at all elevations and 1-2.5 mm RMS in the radial direction. Preliminary Jason-2 GDR-F solutions exhibit regional orbit difference drifts, with respect to JPL rlse17a time series, below ±0.5 mm/yr over the 9-year life span of the altimeter mission. As can also be seen from Figure 5.5-2, annual signals are at the 4-mm level (probably related to differences in the geocenter realization).

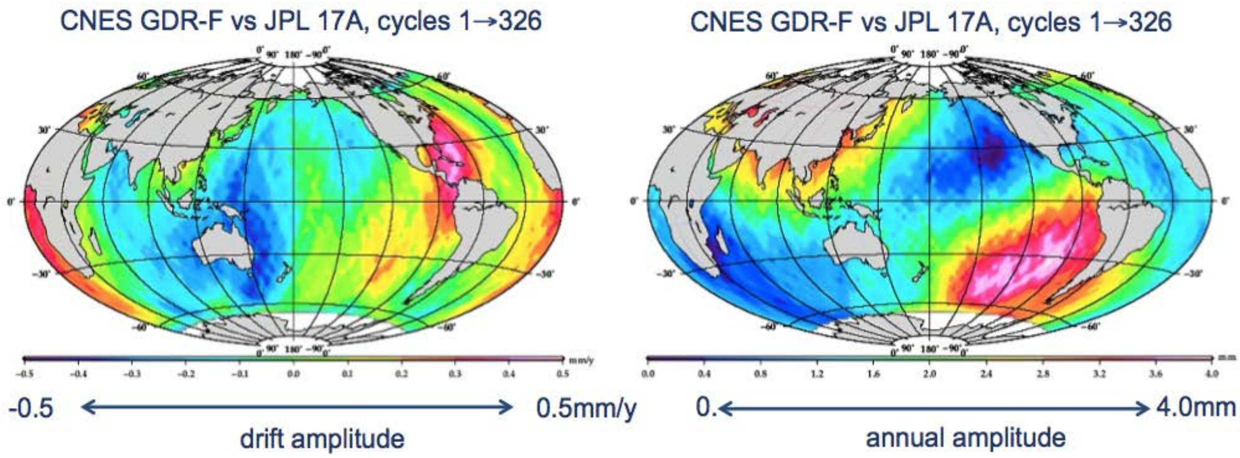


Figure 5.5-2 (Moyard et al., 2017) Jason-2 geographically correlated radial difference drifts (left) and 365-day signals (right) between the preliminary CNES GDR-F DORIS+GPS orbit series and JPL rlse17a GPS-reduced-dynamic solutions.

Almost two years since launch, we continue to confirm the improved performance of the Jason-3 GPS receiver compared with the Jason-2 GPS receivers (A or B side). Two more satellites, on average, are in view of the Jason-3 GPS receiver and fewer data gaps are evident. A dependency on the yaw-state regime now becomes apparent when looking at Figure 5.5-3 (bottom right) for the Jason-3 GPS receiver: fewer satellites are tracked when flying “forward” (due to the inclination of the GPS antenna). Because of the higher signal-to-noise ratio on Jason-2, this behavior cannot be observed.

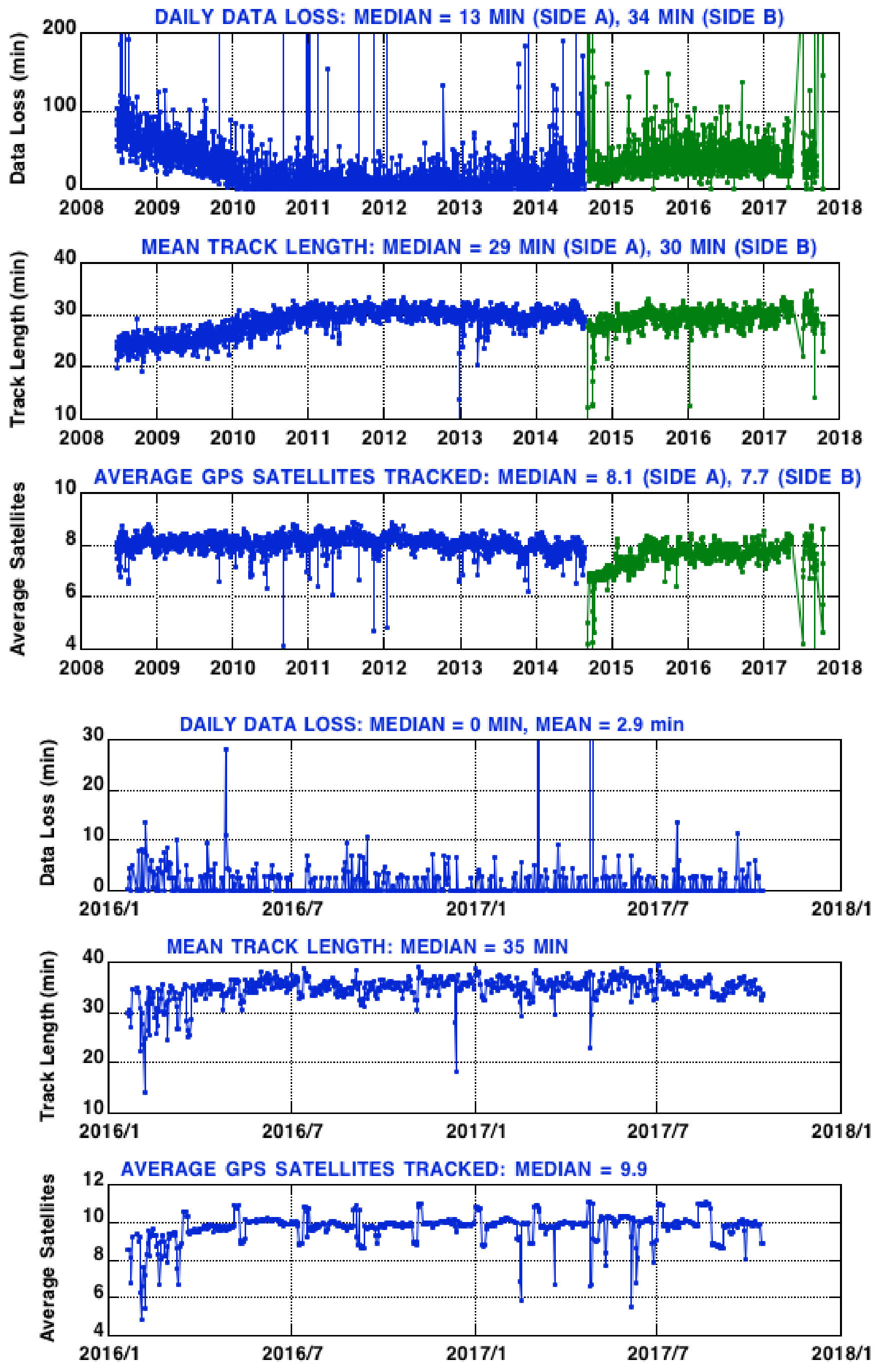


Figure 5.5-3 (Desai et al., 2017) Jason-2 (top) and Jason-3 (bottom) GPS receiver performance.

5.5.2 In-orbit calibration/validation of the Sentinel-3A mission

The current level or orbit accuracy reached by the different members (GMV, AIUB, CLS, DLR, ESOC, TU Delft, TUM, and CNES) of the POD Quality Working Group (QWG) requires accurate external validations to assess which parameterization choices and modeling options best suit Sentinel-3A's POD precision requirements. As a first step, a common set of core-network SLR stations was defined based on residual analysis using data from LAGEOS-2, Jason-2 and Sentinel-3A. The list of 9 selected stations (none of which require Post Seismic Deformation modeling) is given in Figure 5.5-4.

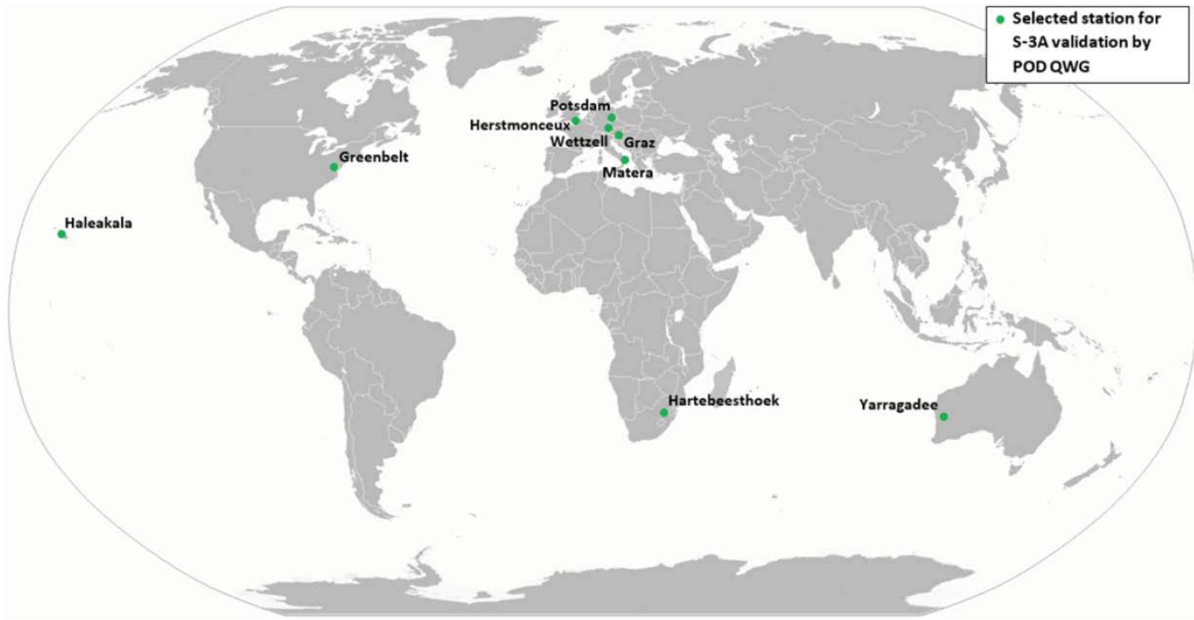


Figure 5.5-4 (Fernandez et al. 2017) SLR core-network stations selected by the POD QWG for Sentinel-3A validation.

Figure 5.5-5 shows the offsets identified for all three POD instruments. As a consequence, the GPS receiver reference point needs to be translated by -1.8 cm in the radial direction (no phase map used). A ~2-cm cross-track error in the center of mass location of the satellite seems likely, as it is common to the DORIS, SLR and GPS tracking systems. Also, the Laser Retroreflector Array (LRA) reference point position will have to be corrected by 1.5 cm in the along-track direction. By the next Sentinel-3A reprocessing in the GDR-F Standards, the QWG members should continue to exchange information about this topic in order to confirm the robustness of these estimations. The feasibility of fixing integer ambiguities for the Sentinel-3A GPS receiver could also help to improve the estimation of the GPS offsets.

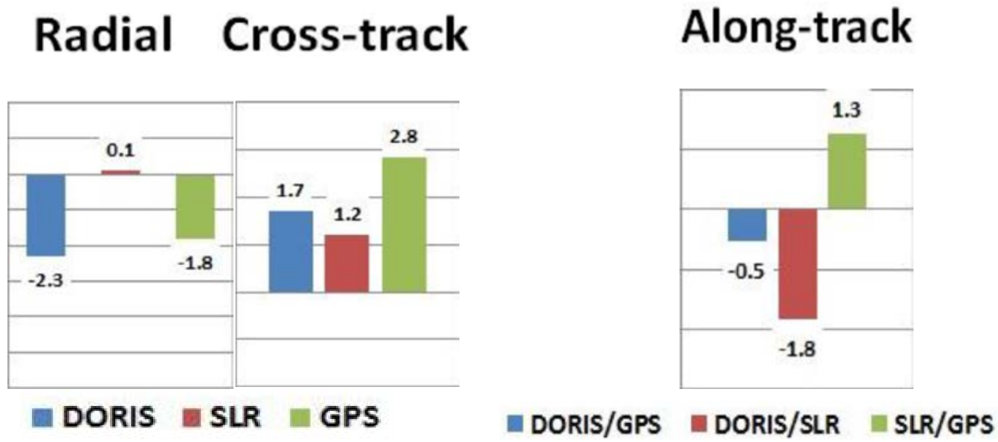


Figure 5.5-5 (Lakbir et al., 2017) POD instrument offsets (in cm) identified on Sentinel-3A.

5.5.3 Reducing tracking measurement errors

We demonstrate that improvements on Jason-3 orbits are possible using the integer ambiguity fixing. In contrast, half-cycle slips on the Jason-2 GPS receiver prevent ambiguities from being reliably fixed for that satellite. In Figure 5.5-6, Independent SLR data from different test orbits were used to evaluate the impact of fixing ambiguities. Only high-elevation (above 70°) SLR RMS residuals were considered, in order to better isolate the radial component of the orbit error. The SLR data show that the Jason-3 orbits with the fixed ambiguities have the lowest radial orbit performance.

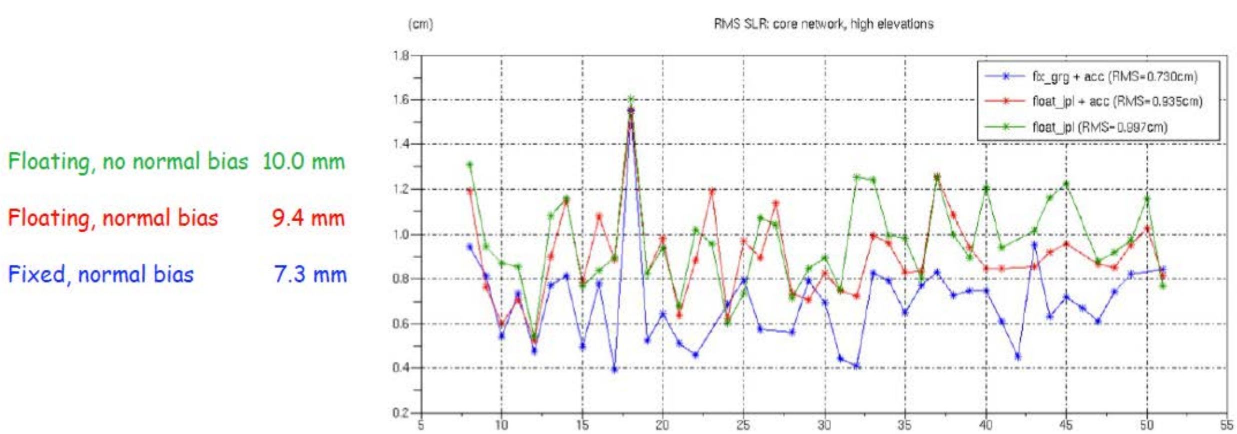


Figure 5.5-6 (Mercier et al., 2017) RMS of SLR residuals above 70° elevations for Jason-3 independent DORIS+GPS orbit solutions based on floating (red) and fixed (blue) GPS ambiguities.

Spurious along-track biases in floating solutions (originating from inconsistencies between pseudo-range and phase clocks) are corrected when ambiguities are fixed. This explains the 3-mm radial orbit improvement as seen by SLR residuals shown in Figure 5.5-6. The need for adjusting empirical normal acceleration biases is partly explained by an offset in the X satellite reference frame direction partly due to uncertainties in the CoM position or the GPS antenna phase center location.

The DORIS Ultra Stable Oscillators (USO) on-board the various altimeter satellites are affected in different ways when passing over the South Atlantic Anomaly (SAA). The DORIS USO's are quartz oscillators, and their sensitivity to radiation is determined by satellite altitude (or total incident dose), amount of shielding, and amount of pre-irradiation of the quartz crystals. In addition, quartz crystals from the same manufacturing lots and otherwise treated identically will also show stochastic differences in performance due to different impurities in each crystal. It is likely this latter factor which is the explanation for the higher sensitivity of the Jason-3 USO to the SAA, compared to Jason-2 at the start of its mission in 2008. The higher sensitivity of the Jason-3 DORIS oscillator to radiation (compared to Sentinel-3A or even Jason-2) is shown in Figure 5.5-7 **(bottom)**, where strong frequency variations of its USO are observed in the vicinity of the SAA region. The DORIS sites located in the SAA area at the altitude of the Jason satellites are also shown in Figure 5.5-7 **(top)**.

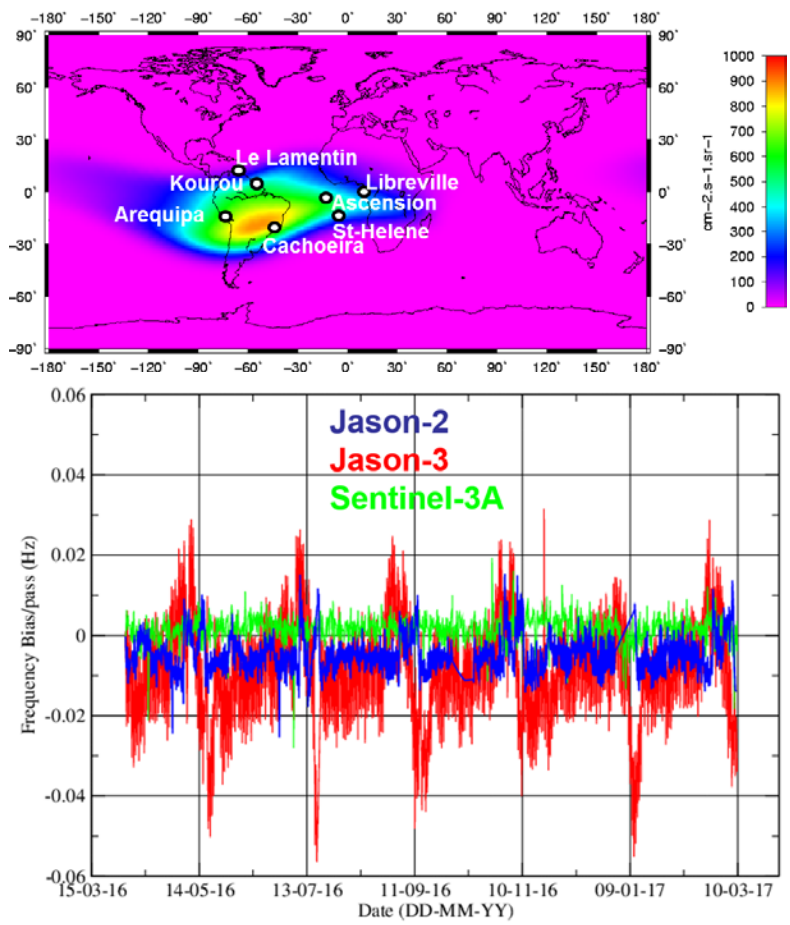


Figure 5.5-7 (Capdeville et al., 2017) SAA region as seen by Jason-3 (top) and different satellites on-board USO perturbations measured in its vicinity (bottom).

The T2L2 instrument, as a passenger of the Jason-2 satellite has helped to characterize the behavior of the DORIS USO. A model of its behavior can be derived based on the T2L2-derived observations of the USO, considering the SAA, long-term effects, changes in temperature, and observations of a beta-prime dependency in the variation of the USO frequency (see Figure 5.5-8). The experience with Jason-2 T2L2 can allow the derivation of a similar model for Jason-3 to mitigate or remove these signals. In addition to improving the DORIS modeling, the T2L2 instrument also has been used to characterize the timing offsets of the SLR stations. In an important metrological result, the T2L2 instrument revealed that some SLR stations over the Jason-2-time period have long-term persistent time biases of up to several microseconds. These biases are observed, notwithstanding the ILRS requirement to maintain timing synchronization with UTC to +/- 100 ns. We expect in the future to exploit this information to assess the impact on altimeter satellite POD.

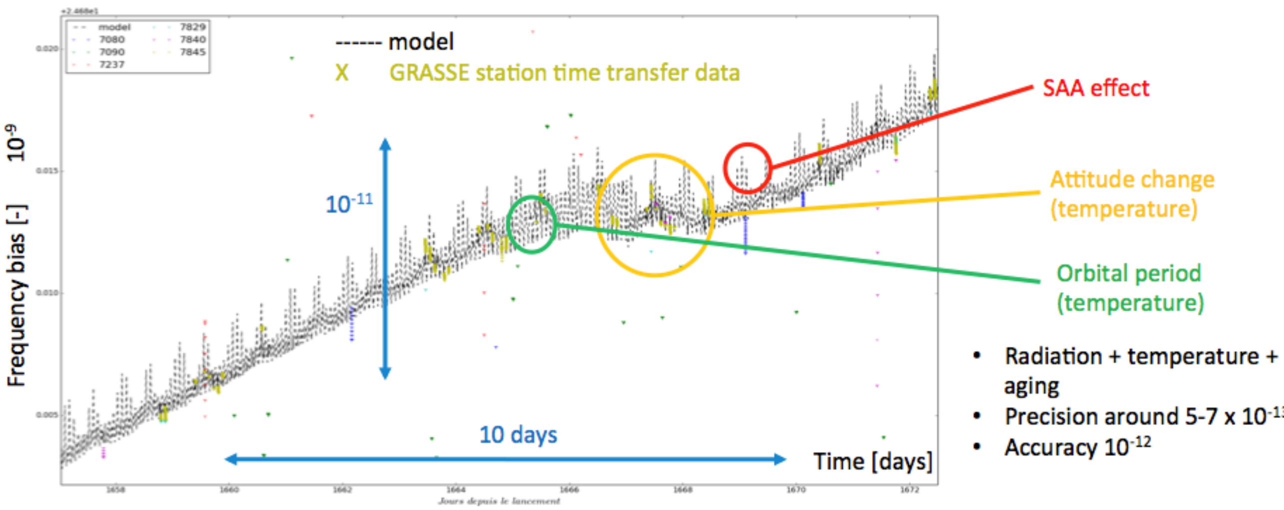
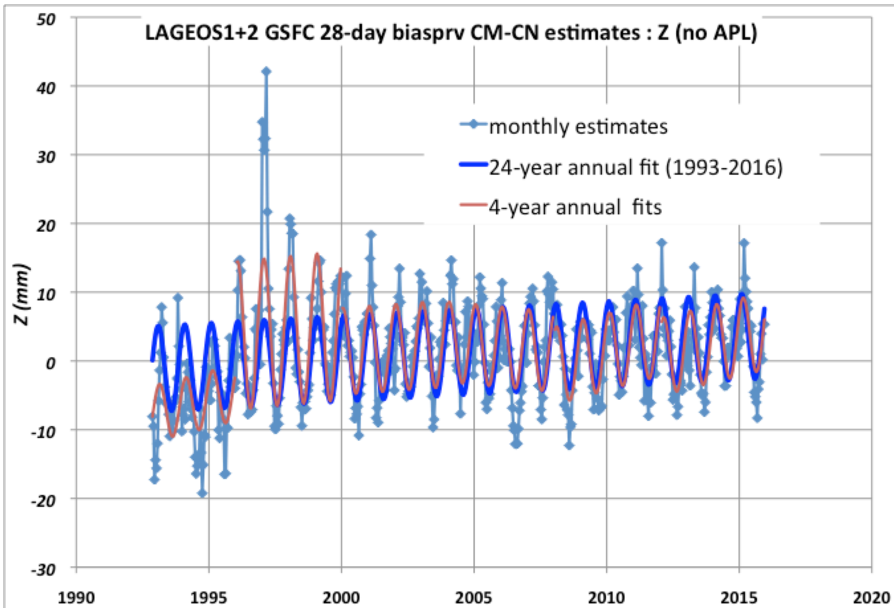


Figure 5.5-8 (Belli et al., 2017) DORIS USO model derived from T2L2.

5.5.4 Refining gravity field models of altimeter satellites' orbits

5.5.4.1 Geocenter motion estimation

Since our requirements for radial orbit accuracy are so stringent, we require accurate modeling of the geocenter motions for POD involving all tracking types. The current standards (GSFC std1504 and CNES GDR-E) used an annual model for the Earth geocenter variations. Unfortunately, this model is no longer satisfactory. Indeed, as can be seen from Figure 5.5-9, even the annual (seasonal) signal is dominant, a simple harmonic function is not adequate due to non-stationarity of the seasonal signal as well as due to the presence of interannual variations. The two Earth's geocenter motion estimates were obtained with SLR data from LAGEOS-1 and 2 at GSFC, and up to 11 geodetic satellites (including LAGEOS-1 and 2) at DGFI-TUM. The contribution of other geodetic techniques and the inclusion of additional SLR satellites, to the historical LAGEOS-1 and 2 solutions, would be of great benefit to unveil unexpected correlations when determining the Earth's center of mass. Indeed, current geocenter motion determinations probably suffer from correlations which are not handled correctly and may affect the geocenter estimates at the same level as the "true" geodetic signal. This is why using other missions than the LAGEOS satellites could be useful



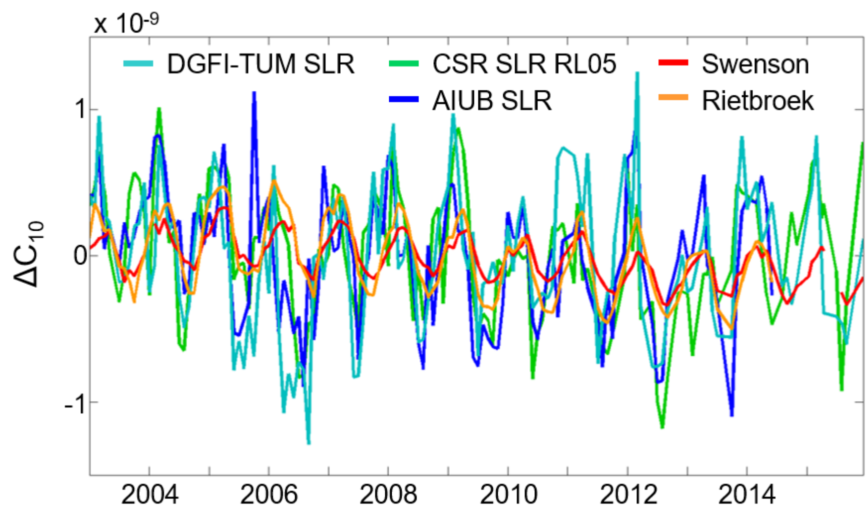


Figure 5.5-9 SLR-based Z geocenter motion monthly time series from LAGEOS-1 and 2 (top, Zelensky et al., 2017) and up to 11 geodetic satellites (bottom, Bloßfeld et al., 2017).

SLR stations transfer 100% of the geocenter motion to the orbit in Z. DORIS stations transfer about 75%. The GPS tracking system transfers about 30% with floating ambiguities, but this could reach more than 50% when fixing ambiguities (to be checked on Jason-3). These characteristics have probably more to do with the tracking techniques process than the dynamic parameterization of the orbit. As a consequence, without modeling geocenter motion, SLR+DORIS-based orbits are more closely tied to the crust than the GPS-based. Also, it has been previously observed that SLR+DORIS-based orbits become more consistent with GPS-based orbits when a geocenter model is applied. We expect an even better improvement in consistency if a geocenter model is also applied in the GPS processing. An approach was tested to enable the GPS products to be referenced with respect to the center of mass of the Earth (instead of the center of figure). A reduction of the ~4 mm annual signal to the 1-mm level, when comparing GPS-only and DORIS-only Jason-2 orbits in the North-South direction, was obtained with the introduction of a correction using the GPS satellite clock solutions (see Figure 5.5-10).

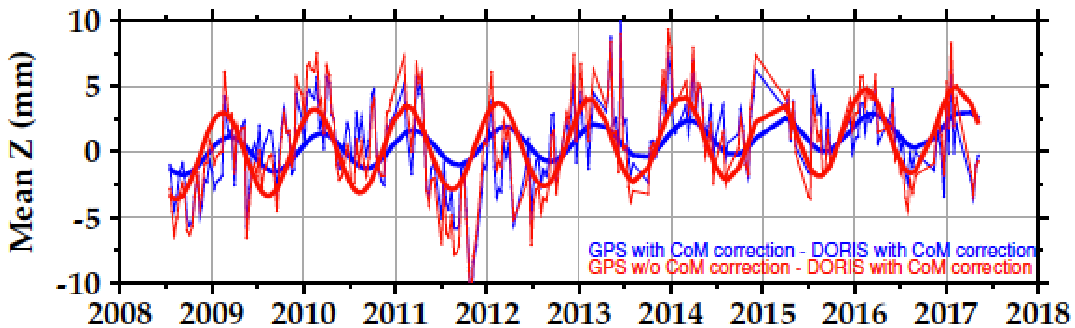


Figure 5.5-10 (Couhert et al., 2017) Jason-2 mean Z orbit differences between GPS-derived and DORIS-only dynamic orbits, before (red) and after (blue) correcting the GPS satellite clocks.

The new EIGEN mean Time Variable Gravity (TVG) field model (EIGEN-GRGS.RL03-v3.MEAN-FIELD), based on GRACE, GOCE and SLR data, was updated over 2 more years (mid-2014 to mid-2016). The impact of this extension is shown for the C_{20} spherical harmonic coefficient in Figure 5.5-11.

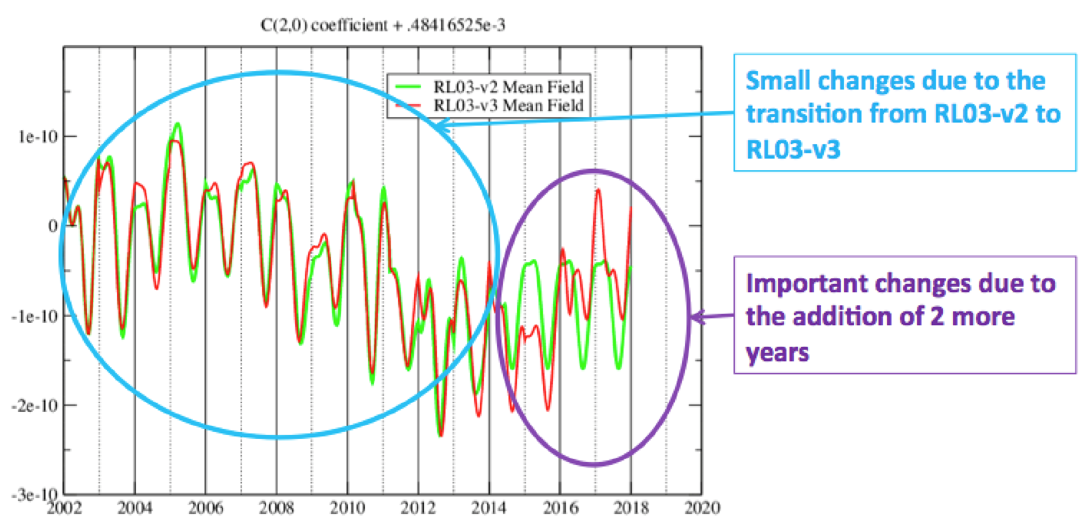


Figure 5.5-11 (Lemoine et al., 2017) Impact on the C20 spherical harmonic coefficient of the TVG model update.

A similar TVG model, based on the upcoming RL04 time series, will be used in the GDR-F Standards and the future Terrestrial Reference Frame (TRF) processing. We underscore the importance of such a mean TVG model, as the GRACE mission has faced periodic data gaps over the last several years due to aging of the spacecraft instrumentation.

5.5.5 ITRF2014/DTRF2014/JTRF2104 evaluations

Further evaluations of the different reference frame realizations were performed at DGFI-TUM, based on precise orbit solutions of 10 geodetic SLR satellites. The differences between ITRF2014, DTRF2014 and JTRF2014 are summarized in Table 5.5-1. Non-linear models were introduced for stations affected by Post Seismic Deformations (PSD) in ITRF2014, whereas non-tidal loading signals were modeled in DTRF2014. The JTRF2014 realization is unique in that a Kalman filter with specified process noise is used to provide weekly coordinate positions.

Solution	ITRF2014	DTRF2014	JTRF2014
Institute	IGN (Paris, France)	DGFI-TUM (Munich, Germany)	JPL (Pasadena, USA)
Software	CATREF	DOGS-CS	CATREF + KALMAN
Combination approach	Solution (parameter) level	Normal equation level	Solution (parameter) level
Station position	Position $\boldsymbol{X}_{\boldsymbol{ITRF}}(t_0)$ + velocity $\dot{\boldsymbol{X}}_{\boldsymbol{ITRF}}(t_0)$ + PSD model (for selected stations) + annual signals (on request)	Position $\boldsymbol{X}_{\boldsymbol{DTRF}}(t_0)$ + velocity $\dot{\boldsymbol{X}}_{\boldsymbol{DTRF}}(t_0)$ + non-tidal loading (NTL) models + SLR origin (Ori) + residual station motions (Res)	Weekly positions $\tilde{\boldsymbol{X}}_{\boldsymbol{JTRF}}(t_i)$

Table 5.5-1 (Rudenko et al., 2017) Main characteristics of the different realizations of the ITRS: ITRF2014, DTRF2014 and JTRF2014.

Despite the successive improvements in TRF realizations, the change from ITRF2008 to ITRF2014 still causes regional changes in Mean Sea Level (MSL) of up to ±0.3 mm/yr, as depicted in Figure 5.5-12 .

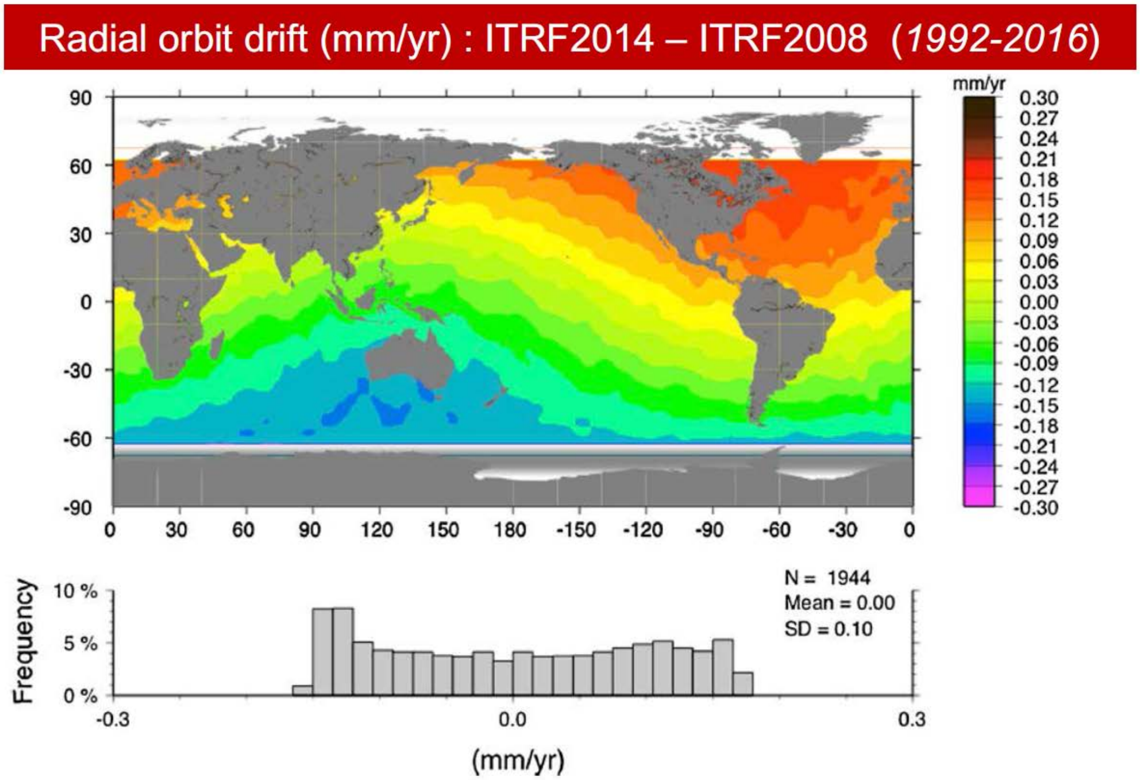


Figure 5.5-12 (Zelensky et al., 2017) Impact on regional MSL rate of switching from ITRF2008 to ITRF2014.

5.6 Quantifying Errors and Uncertainties in Altimetry Data

Chairman: Remko Scharroo and Michaël Ablain

5.6.1 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 8 abstracts were submitted to the splinter session, resulting in 4 oral presentations, and 4 posters. This year, a focus on **orbit errors** and **short wavelength errors** 4 talks complementary to these both subjects.

The main issues of the session have been listed hereafter.

Issue #1

Exhaustive description of error orbit has been performed by *F. Lemoine* (requirements, source of errors, uncertainty estimation): this kind of analysis is very useful to better understand sea-level errors.

Source of errors:

A. Reference Frame

B. Geophysical Models

- (1) Gravity Field (Static & Time-Variable Gravity).
- (2) Radiation Pressure Models (SRP, PRP).
- (3) Geocenter.

C. Data specific Modeling (examples)

- (1) SLR. Station accuracy; Biases; "Target" retroreflector correction
- (2) DORIS. USO effects (radiation, temperature).
- (3) GNSS. Draconitic effects on GPS satellites.

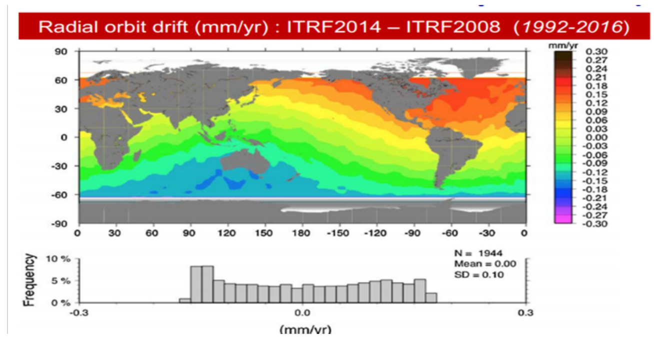


Figure 5.6-1 On left, the list of sources of errors impacting the orbit determination (Lemoine F. et al.), and right, the impact of using ITRF2008 instead of ITRF2014 solutions on regional MSL trends.

Issue #2

Cross-comparison between different several orbit solutions is useful to estimate derived sea-level estimations: application for TOPEX with 3 orbit solutions (GFZ, GSFC std1504, GRGS) has been performed by *S. Rudenko* and leads to a relevant error budget.

Global mean radial orbit errors over the ocean:
-*RMS*: up to ~ 7 mm, *seasonal* negligible,
-*interannual* < 0.1mm/year, *decadal* < 0.05 mm/year

Regional upper bound radial orbit errors:
-*RMS* <11 mm, strong sub-seasonal signal;
-*Seasonal*: up to 6 mm, sources: Earth's time variable gravity field, stability of tracking station sub-networks, AOD gravity modelling, geocenter motion correction;
-*Interannual* (5 years): up to 1.2 mm/year, sources: z-component of the reference system, Earth's time variable gravity field
-*Decadal*: up to 1.0 mm/year (~interannual variability), sources: Earth's time variable gravity field model, reference systems only secondary

Figure 5.6-2 MSL TOPEX errors at different time and regional scales derived from cross-comparison between different several orbit solutions (Rudenko et al.)

Issue #3

a) Spectral analyses based on Fourier transform are often used to describe sea-level errors at small ocean scale, however they present some limitations (parameterization, sensitivity, large variance and could prevent the estimation of errors at short wavelengths.

b) The alternative approach proposed by C. Mailhes is based on Auto-Regressive Spectral Analysis with data pre-processing to warp the frequency.

c) It is recommended to test this method with realistic and large data sets to validate it.

Issue #4

a) The seasonal variations of number spectra and noise presented by *O. Vegara* are of main importance to characterize altimetry errors.

b) Improving these kinds of analyses at regional scales will allow to prepare the SWOT mission: SARAL/AltiKa and Sentinal-3A are good candidates for this purpose.

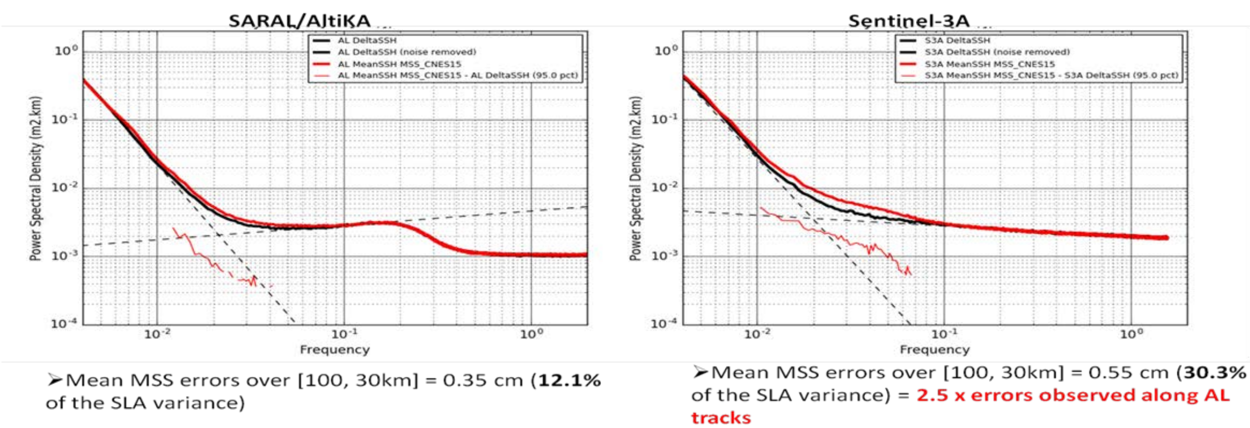


Figure 5.6-3 SLA power density spectrum for SARAL/AltiKa on left and Sentinel-3a on right.

5.6.2 Round table summary

Recommendation #1: How to correct the TOPEX-A GMSL Drift?

Recognizing the efforts currently performed on reprocessing the TOPEX data on JPL and CNES side, the best solution is to wait for the outcome of these efforts and include in the processing a newly produced internal path delay correction based on the analysis of the available Cal1 data (if possible). New validation phase must be performed, and this outcome is expected for next OSTST.

Recommendation #2: Error orbit solutions

To regularly update historical POD solutions based on gravity field variations, ITRF changes, and model improvements, as extrapolation of gravity fields variations and ITRF solutions into the future has proven to significantly affect the sea level time series.

Recommendation #3: Are our cal/val methods sufficient to verify the Jason-CS/Sentinel-6 global and regional mean sea level stability requirements?

- A 1 mm/yr cannot be verified over a 1-yr commissioning period with tide-gauge comparison, we need a longer time series to check the requirement with this method. The ESA FRM4ALT Review on International Altimeter Cal/Val Activities will be held in Chania, Crete 23-25th April 2018 and provides a useful venue to review the cal/val needs for Sentinel-6/JCS.

Recommendation #4: Considering the possibility of switching on the redundant altimeter on JCS/S6 during the cal/val phase with Jason-3. If feasible, what is the number of cycles that the redundant altimeter should operate?

We are not convinced that switching for redundant side for a short period provides sufficient information to warrant the exercise: we recommend not to activate the redundant JCS side during tandem.

5.6.3 Conclusions

From the last OSTST, several improvements have been performed on altimeter error characterization especially at short wavelengths with new insights in altimeter error better characterized and understood and with new methods to characterize errors or assimilate them in models.

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.

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

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

5.7.1 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;
3. Enable a seamless and accurate connection between the current (OSTM/Jason-2 and Jason-3) and legacy (TOPEX/Poseidon and Jason-1) time series, and

4. Enable the development of Level 3 and Level 4 products by an accurate analysis of any regional bias between the Reference mission and the other flying altimeters (currently SARAL, Sentinel-3A, CryoSat, HY-2).

To succeed in these objectives, the general approach is to pool the talents and resources of the project and science teams. Engaging the science team in the continuous CALVAL effort has been one of the hallmarks of success for the TOPEX/Poseidon and Jason altimeter programs. The CNES and NASA research announcements have consistently emphasized CALVAL, recognizing that the science investigators conducting research in some of the most demanding applications (e.g., mean sea level) are often positioned to offer the most innovative CALVAL solutions.

During the first 6 months of each new mission, an intensive verification effort is conducted by all members of the Verification Team in order to verify the integrity of the system—and to make adjustments where necessary—before starting the routine GDR production. However, the verification effort continues afterwards on a routine and permanent basis. These ongoing efforts are essential for ensuring the integrity of the long-term climate record at the 1-mm/yr level.

CALVAL 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. CALVAL activities also encompass issues related to data return, such as data editing and flagging. We also encourage CALVAL presentations on specialized topics, such as the characterization of SSH in Arctic Ocean sea ice leads, and the examination of the impacts of SWH, swell, and roughness on SSH data quality.

Because of the usual large number of contributions, the CALVAL splinter is separated into two parts:

1. Local CALVAL (focusing on in-situ bias estimates) and
2. Global CALVAL (focusing on the assessments of correction terms and error budget).

5.7.2 Results from in-situ calibration sites

The latest (2017) results from the dedicated in-situ calibration sites are provided in Table 5.7-1 and Figure 5.7-1. They show good consistency across legacy and current missions. While the SSH bias estimates have evolved, particularly for Jason-3 as additional overflights accumulate, there are no significant and unforeseen differences from the prior year's (2016) results. In particular, absolute SSH bias estimates for the reference (Jason-class) missions range from –2 to +3 cm. The specific sources of larger (decimeter-level) biases that have plagued historical versions of the data products have been gradually identified and removed, a decades-long process that has been informed by careful and continuous monitoring from the dedicated (absolute) calibration sites.

Mission	Bass Strait	Harvest	Corsica	Gavdos	Average
TOPEX-A	+8	+7	0		**+5**
TOPEX-B	+19	+10	0		**+10**
Poseidon-1		–11	–12		**–12**
Jason-1 GDR-E	+47	+23	+19	+39	**+33**
Jason-2 GDR-D	+19	+20	–8	–8	**+6**
Jason-3 GDR	–2	–1	–31	–24	**–15**
SARAL/AltiKa		–37	–74	-47	**–53**
Sentinel-3A	+36		+22	+6	**+21**

Table 5.7-1. Absolute SSH bias values (in mm) for different missions and from the different calibration sites (using in situ SSH measurements)

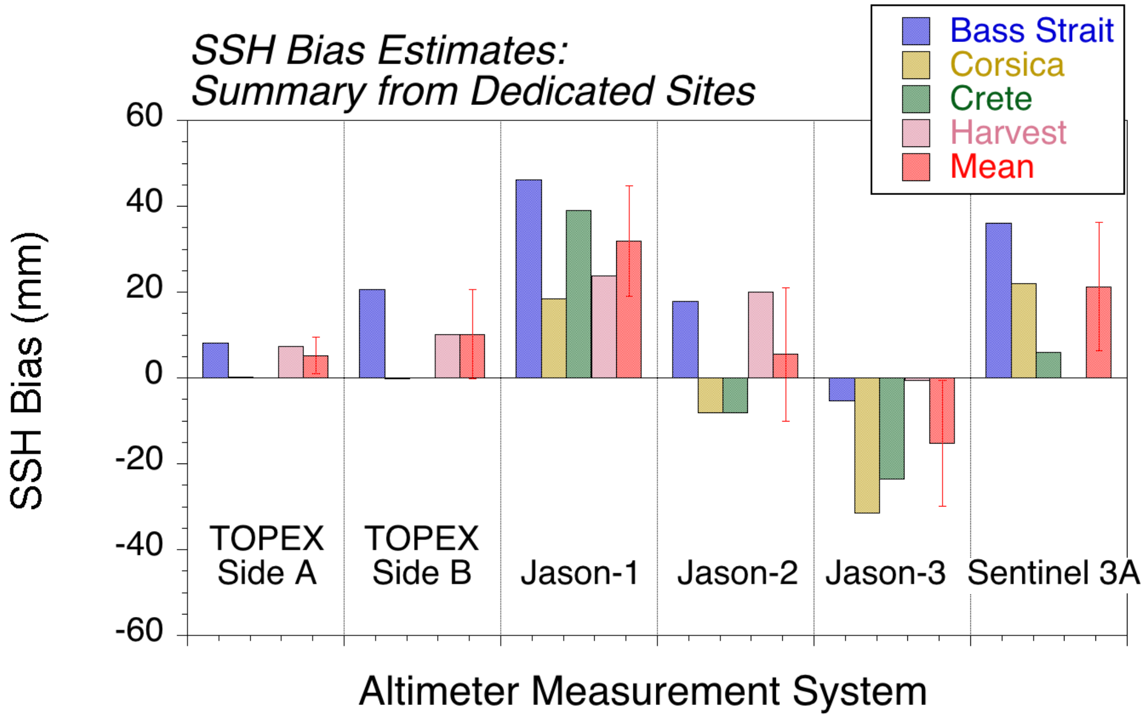


Figure 5.7-1 Absolute SSH bias values (in mm) for different missions and from the different calibration sites (using in situ SSH measurements).

The TOPEX/POSEIDON (T/P) and Jason-1 systems are no longer in operation, but are subject to ongoing evaluation as procedures and data products are enhanced. Calibration records continue to support that the sea-surface height (SSH) biases of the T/P measurement systems are indistinguishable from zero. However, the T/P CALVAL results will need to be updated when the next version of the TOPEX Retracked GDR (RGDR) is released.

SSH from the current (E) version of the Jason-1 GDR products remains biased slightly high (by ~3 cm), with differences at the 1–2 cm level (1σ) among the different calibration sites. SSH from the current (D) version of the Jason-2 GDR products is unbiased, or slightly biased with questionable significance (~1 cm on average for all the calibration sites). However, important differences (1–2 cm, 1σ) also exist among the different calibration sites. Understanding the source of these site-to-site differences (e.g., geographically correlated altimeter measurement system errors or in-situ errors?) is an important challenge, and provides one motivation for an upcoming (April 2018) workshop in Chania, Greece ("International Review Workshop on Satellite Altimetry Cal/Val Activities and Applications" sponsored by the European Space Agency, EUMETSAT and the IAG/IUGG Commission 2).

Concerning Jason-3, new (2017) analysis continues to support that all data products (OGDR, IGDR and GDR-D) are of very good quality with very small differences compared to Jason-2 during the verification phase. However, the Jason-3 SSH is slightly lower (by 2 cm on average) than comparable values from Jason-2. Detailed analysis shows that this relative SSH bias is due mainly to the Ku-band range, but probably also to the C-band range. Together, they lead to smaller (by < 1 cm) ionosphere delays for Jason-3.

The in-situ sites also provide results for the SARAL/AltiKa system, showing that its SSH measurements are biased low by ~5 cm. New results for Sentinel-3A (S3A) suggest that SSH observations from the current product are unbiased, or slightly positively biased (~2 cm) with questionable significance. Systematic differences of ~1 cm between observations from the traditional (low-resolution) and SAR mode range measurements were noted at both Bass Strait and Corsica.

The transponder installed in Crete at a crossover point (CND1) of the Jason-3 and Sentinel-3A ground tracks continues to provide absolute calibration results focused on the altimeter range component of the measurement systems. Mertikas et al. reported range biases of +3 ± 3 cm and +0 ± 1 cm, respectively for Jason-3 and Sentinel 3A (also Garcia-Mondejar et al. poster). In view of the sign difference (for SSH bias and range bias), these results are quite coherent with the in-situ determination of SSH bias from the same location. In particular, both techniques suggest that the Sentinel 3A altimeter is measuring shorter than its Jason-3 counterpart (also consistent with the overall results provided in Table 1). The transponder technique is showing increasing promise in contributing to the understanding of the overall measurement system, and offers a unique perspective on the fundamental behavior of the altimeter in isolation from sea-state effects.

Also reflected in the session was the increasing role of precise GPS buoys in supporting the altimeter calibration initiatives. Watson et al. showed new results from repeated buoy deployments in the Bass Strait (also Legresy et al. poster). These results provide the foundation for improving the Bass Strait datum underlying the SSH bias determinations. The Australian team also showed short-baseline GPS buoys results (connecting the S3A and Jason-3 deployment sites over a 9-km distance). The high (~1 cm) precision achieved for this baseline has obvious implications for the future SWOT mission. Haines et al. showed Jason-2 and -3 altimeter calibration results from two long-term GPS buoys campaigns: 1) Daisy Bank (off the Oregon coast) in the summer of 2016, and 2) Monterey Bay in the summer of 2017. The results showed that retrievals of SSH, SWH, wet path delay and ionosphere are competitive with Harvest for all altimeter calibration metrics. Likewise for Corsica, Bonnefond et al. showed good agreement between traditional (tide gauge) and pelagic GPS (zodiac) techniques for determining the SSH bias of the SARAL measurement system. GPS is used on a ship for campaigns at the Lake Issykul (Kyrgyzstan) calibration site (Cretaux et al). Jason-3 and Sentinel 3A results from this location are consistent with the overall results depicted in Table 1. The absence of sea-state biases, and dynamical ocean effects implies a unique value for this site. Observations from the lake were also used to illustrate the persistent accuracy of the S3A measurements as the shore is approached (within 1 km).

Meanwhile, regional calibration methods from Cancet et al. have been employed at all three historical calibration sites (Corsica, Harvest, and Bass Strait) and continue to mature. This technique shows great promise for reducing errors by increasing the number of available overflights, thus improving the link between in-situ and global calibration and validation results.

Finally, Leuliette et al. presented comparisons of TOPEX/Jason and Sentinel-3A with tide gauges. They showed that the range of drifts in TOPEX/Jason-gauge results using different strategies to remove vertical land motion (VLM) from the gauges is consistent with an uncertainty of ±0.4 mm/year. They presented results of the variances and the effective degrees of freedom from residual differences between the gauges and each altimeter. The results from Jason-2 and Jason-3 with suggest that annual bias changes in Jason-CS/Sentinel-6 global mean sea level can be monitored to < 1 mm. However, the impact of systematic errors, like gauge availability and vertical land motion, need further study. The drift in 15-months of Sentinel-3A (0.9 mm/year) with respect to the gauges is not significant (95%), but the Jason-3 drift over 20 months, 2.3 ± 1.1 mm/year (95%), may be.

5.7.3 Global validation studies

More than 20 months of in-flight Jason-3 data were available at the time of the 2017 OSTST meeting. The in-flight data are demonstrating >99.9% data availability (after accounting for calibration maneuvers and uploads to the altimeter). In-flight performance is excellent, with various metrics proving that Jason-3 has similar data quality to Jason-2 (Figure 5.7-2).

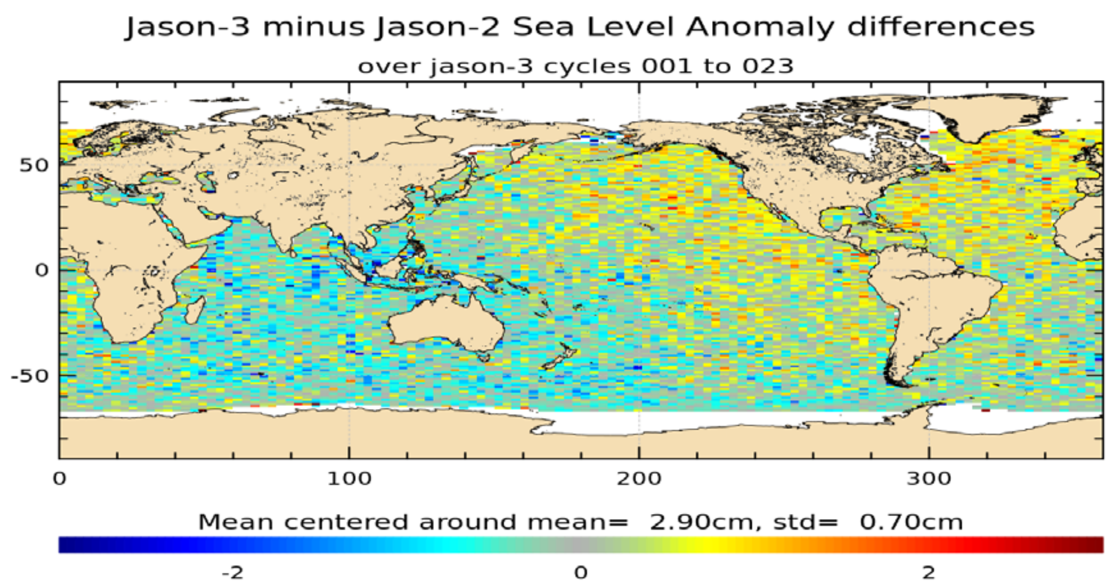


Figure 5.7-2 Average of sea level anomaly differences between observations from Jason-2 and Jason-3 during the tandem phase reveals a relatively small hemispherical pattern that is likely related to orbit errors (Roinard et al.).

Nevertheless, a 120-day spurious signal with an amplitude of ~1 cm is observed in the Jason-3 sea surface height anomalies derived from the Geophysical Data Records (GDR) (Figure 5.7-3). This signal appears to be sensitive to the ocean tide model as well as orbit solution. For example, the 120-day signal is not observed in the Jason-3 sea surface height anomaly data when using the FES2014b ocean tide model and GPS-based orbit solutions from the Jet Propulsion Laboratory (JPL) (Figure 5.7-4).

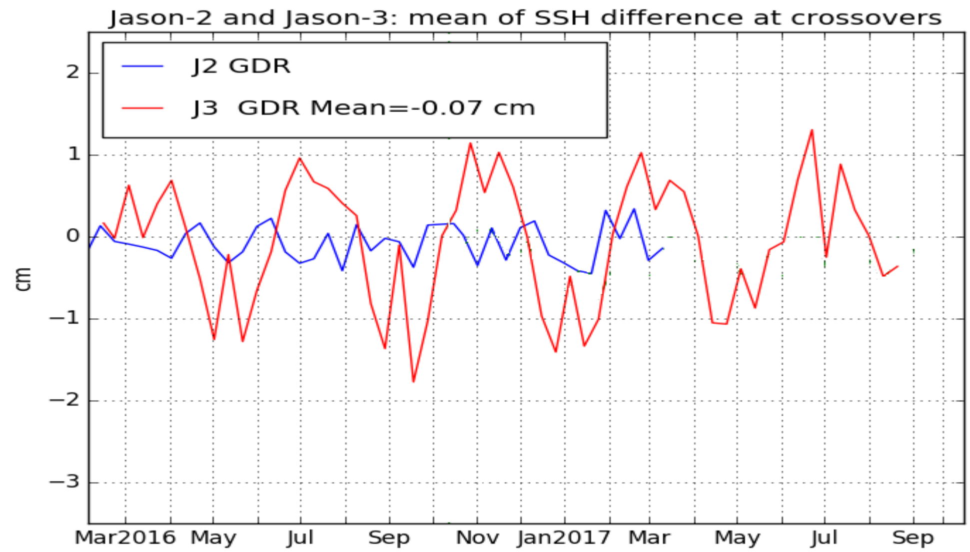


Figure 5.7-3 A 120-day signal with an amplitude of 1 cm is observed in averages of sea surface height anomaly crossover differences from Jason-3 GDR data. This signal is not observed in the coincident Jason-2 GDR data (Roinard et al.).

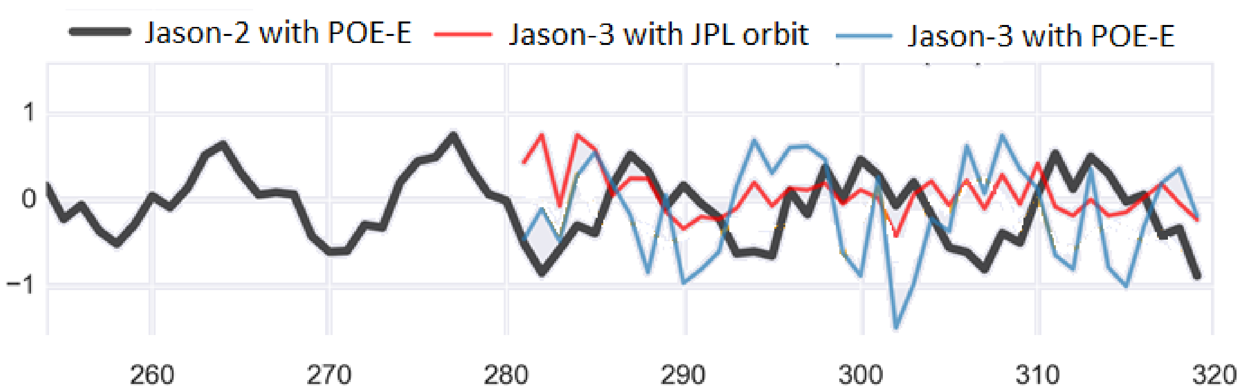


Figure 5.7-4 The 120-day signal is not observed in the Jason-3 data when using JPL's GPS-based orbit solutions and the FES2014b ocean tide model. (Roinard et al.)

The Jason-3 Advanced Microwave Radiometer (AMR) continues to exhibit significant drifts. The routine calibrations that are applied to GDR processing are proving to be particularly valuable for removing these drifts and ensuring the long-term stability of the Jason-3 data record (Figure 5.7-5). The cold-sky calibrations that are routinely performed on Jason-3 are particularly useful for computation of the AMR calibration coefficients.

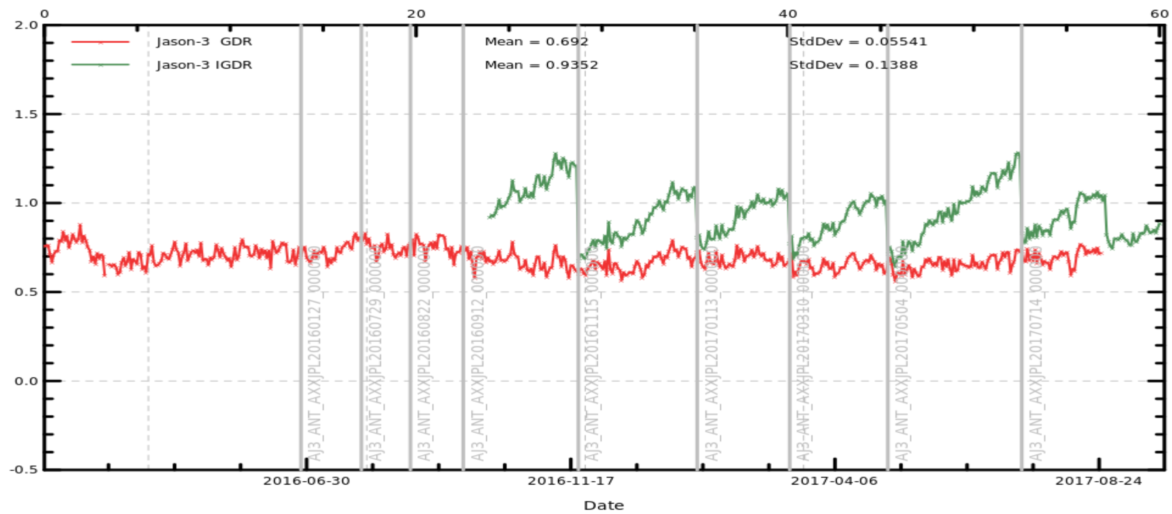


Figure 5.7-5 The Jason-3 GDR data benefit from routine calibrations of the AMR data, as the AMR continues to exhibit significant drifts. The figure shows averages of differences between AMR and ECMWF wet troposphere corrections. AMR calibrations are always applied in GDR data, while IGDR data use the best available calibrations from as long as 90 days earlier (Roinard et al.).

A recent reprocessing of cycles 5-16 of Sentinel-3A data has been performed. Cycles 1-4 could not be calibrated due to an issue with the Payload Data Ground Segment. These four cycles will be reprocessed in early 2018, including a new version of the retracking algorithm (SAMOSA v2.5). The sea surface height, significant wave height, and wind speed measurements are all meeting requirements. Crossovers between the Sentinel-3A (both SAR and PLRM) and Jason-3 data reveal a bias of 7.5 cm with Jason-3. The Sentinel-3A SAR and PLRM data have a small bias of 1 mm. The Sentinel-3A SAR data has a significantly lower noise floor of 1.0 cm (at 2 m SWH) than the PLRM data (1.7 cm at 2 m SWH) (Figure 5.7-6) but the spectrum content is red colored which tends to be correlated with swell. The Sentinel-3A PLRM data have a drift of < 1 mm/year when compared to Jason-3. However, over this one year period, the SAR data have a significant trend of 4 mm/year when compared to the PLRM data.

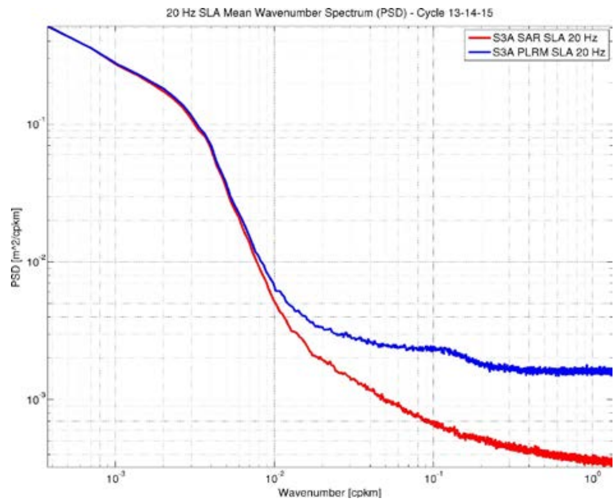


Figure 5.7-6 The Sentinel-3A SAR data prove to have a significantly lower noise floor than the PLRM data (Martin-Puig et al.)

Several presentations were also addressing the validation of the other flying missions, all using a geodetic and/or Long Repetitive Orbit: CryoSat, Jason-2, HY-2 and SARAL. For all 4 missions the data quality remains excellent and will support future generation of MSS models.

5.7.4 Round table summary

Key points raised by the Project Scientists:

1. **Jason-CS/Sentinel-6 Stability Requirement.** The group recommends:
   a) Consolidation of methods and results from tide gauge comparisons to address whether the gauges can validate the requirements.
   b) The requirement documents language be clarified and circulated to the OSTST to ensure fruitful discussions of this topic.
   c) Continued studies of systematic errors, particularly vertical land motion.
2. **Jason-CS/Sentinel-6 Side B.** The group recommends:
   a) A consistent altimeter configuration during tandem phase.
   b) Long duration Jason-3/Jason-CS/Sentinel-6 cal/val period given the new satellite platform and altimeter configuration.
3. **Dedicated cal/val sites:** The group recommends:
   a) Exchange of data between different cal/val groups to investigate application of differing approaches on observed bias differences at various sites.
   b) Continuation of diversity of techniques. Local conditions and instruments are unique.
   c) Providing guidelines and standards (e.g., experience from ESA Fiducial Measurements) could be applied.
   d) Investigation of science-driven cal/val in addition to requirements-driven cal/val.
4. **Absolute cal/val of sigma0:** The group finds that the tandem cal/val phases are important for relative calibration of sigma0.
5. **Retracking Techniques:** The group recommends:

a) Creation of independent analysis methods to investigate advantages and drawbacks of potential algorithms, with the process agree-upon by the contributing investigators.

5.8 The Geoid, Mean Sea Surfaces and Mean Dynamic topography

Chairs: Ole B. Andersen and Yannice Faugere

This splinter had a total of 5 oral presentations and 6 posters which is a significant increase compared with previous years.

The oral presentations were the following:

- The Jason-2 Mission Geodetic Phase (Egido et al)
- Improvements and limitations of recent mean sea surface models: importance for Sentinel-3 and SWOT (Pujol et al)
- GEOMED2: Geoid estimation of the Mediterranean Sea (Bruinsma et al)
- A combined mean dynamic topography model – DTU17cMDT (Knudsen et al)
- Comparison and synthesis of geodetic and oceanographic data to improve mean dynamic topography products – (Maximenko et al)

The posters were the following

- GEO_001 - Results from GOCE++ Dynamical Coastal Topography and tide gauge
- GEO_002 - Geomed2: gravimetric versus combined geoid model
- GEO_003 - A new OGMOC mean dynamic topography model – DTU17MDT.
- GEO_004 - GOCE User Toolbox and Tutorial.
- GEO_005 - State-of-the-Art Mean Sea Surface and Geoid Model assessment in the Arctic and implications for Sea Ice Freeboard Retrieval
- GEO_006 - Global and regional evaluation of recent Mean Sea Surfaces using the first year of Sentinel-3 and impact for updating the DTU15MSS

As the previous years the session covered the three topics of the session, Geoid, Mean Sea Surfaces and Mean Dynamic Topography. First, the good performance of Jason-2 LRO data was highlighted (Figure 5.8-1). A soon as 1 geodetic cycle is available, these data, will enter in the computation of new Mean Sea Surface Model, improving small scales along these uncharted tracks. This analysis also highlights the need for a consistent, 20-year reference period to compare, or merge different dataset. The impact of other geodetic mission, Jason-1G and

Cryosat-2 was demonstrated in the second presentation by Pujol et al. Figure 5.8-2 shows the improved performance of the "SIO" MSS (Sandwell) built using the robust large scale of the CNES CLS 15, combined with the High Rate geodetic missions. Locally 2cm^2 of error reduction is observed for scales between 10 and 100 km. Then, the accuracy of the altimetry derived Marine gravity and Mean Dynamic topography was also discussed. Figure 5.8-3 illustrates a deep analysis of the Geoid in the Mediterranean sea, showing that altimetric Geoid performs better in average though local improvements are obtained using Gravimetric Geoid. Figure 5.8-4 and Figure 5.8-5 illustrates the latest achievement and perspective of Mean Dynamic Topography developments.

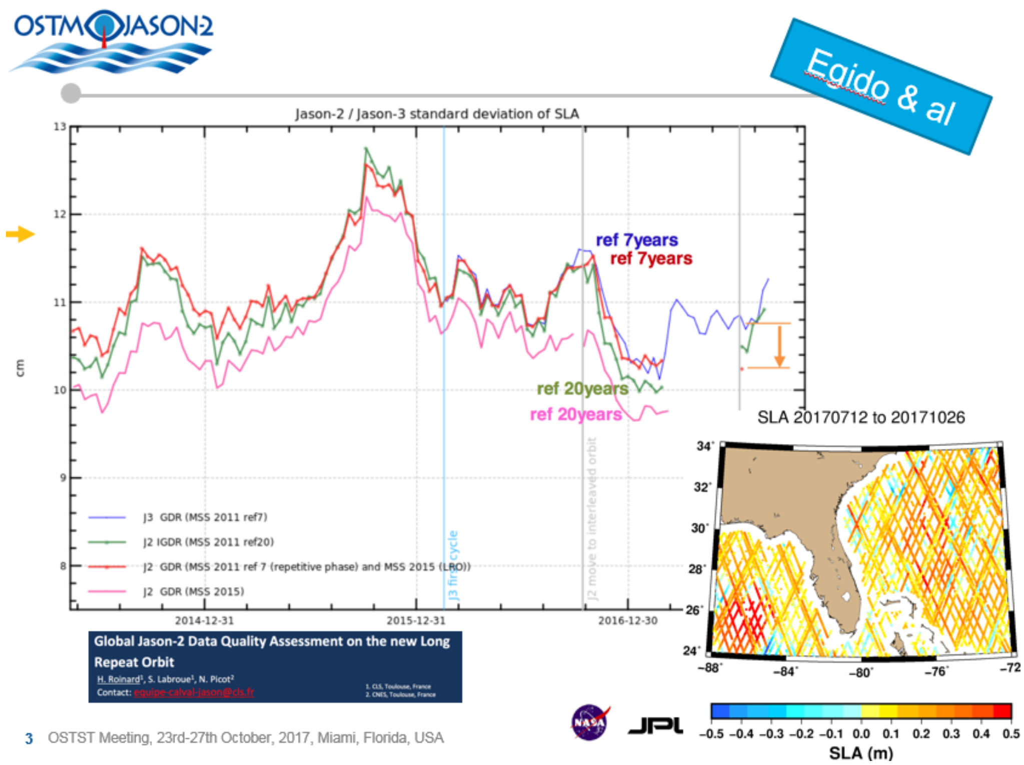


Figure 5.8-1: Illustration from (Egido et al) on the good performances of Jason-2 data even after the orbit change. Also highlights the importance of using the same reference period for the whole time series.

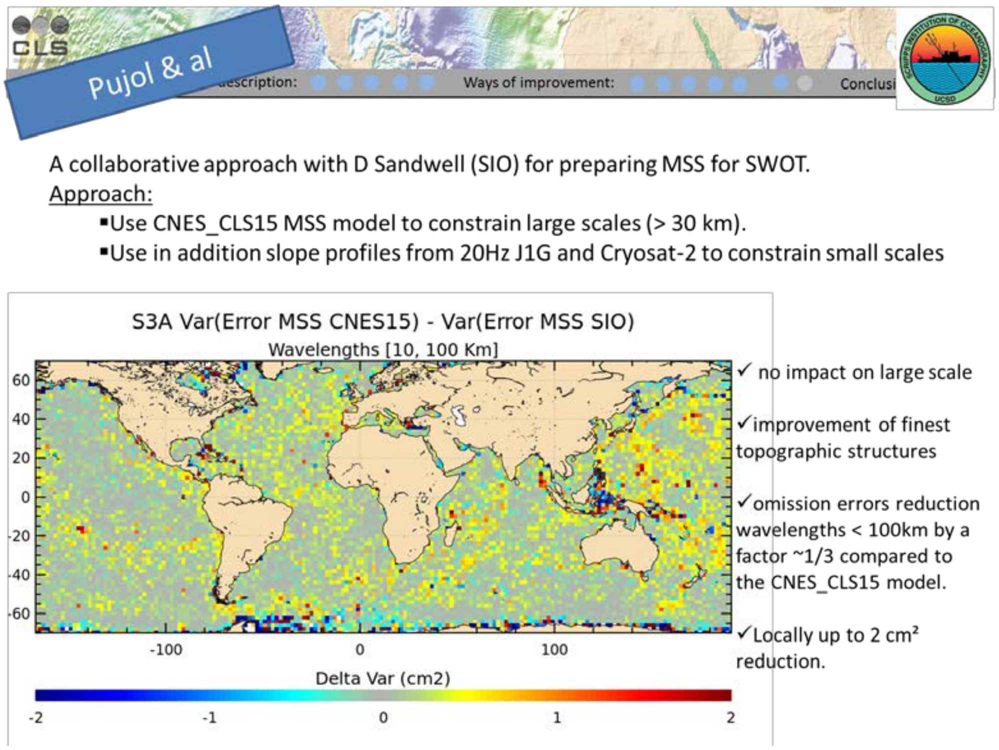


Figure 5.8-2: Illustration from Pujol et al on the positive impact at small scales of adding 20Hz information from geodetic missions on the CNES CLS 15 MSS

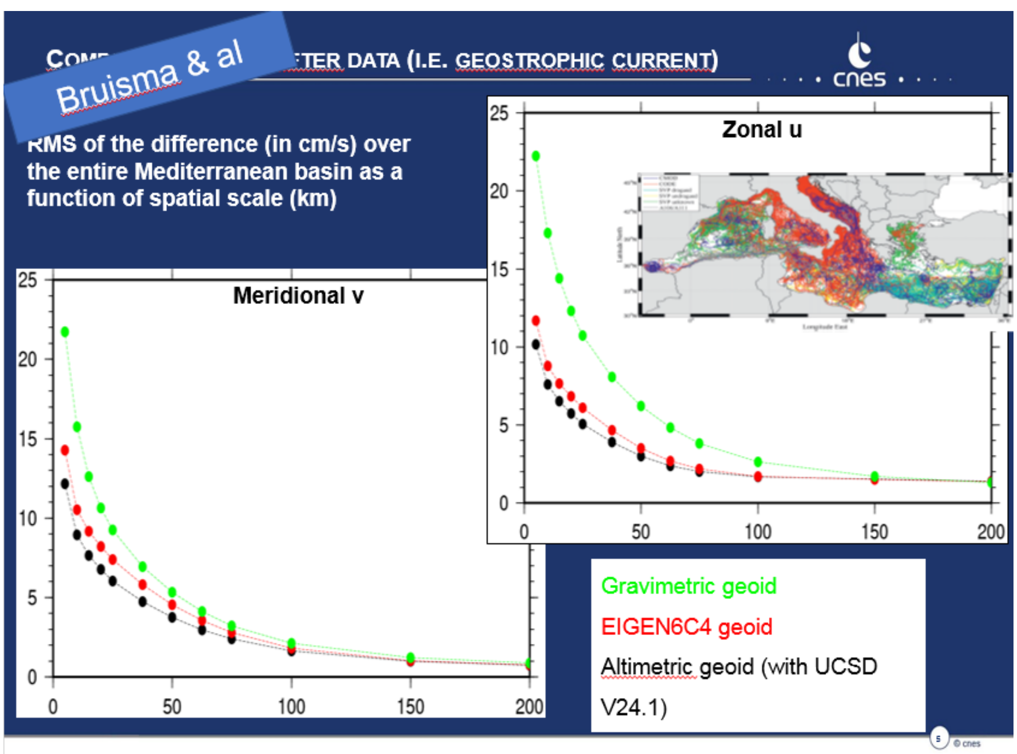


Figure 5.8-3: Illustration from (Bruisma et al) Assessment of performances of various Geoid. Altimetric Geoid performs better in average though local improvements are obtained using Gravimetric Geoid.

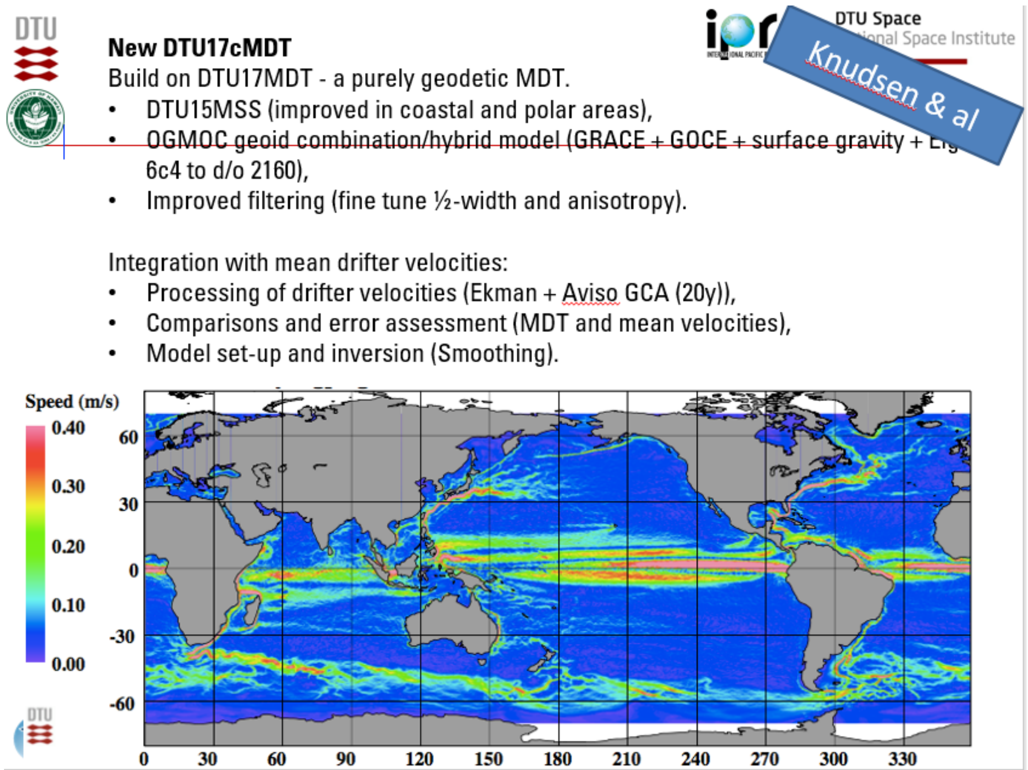


Figure 5.8-4: Illustration from (Kundsen et al) on the new DTU16 MDT

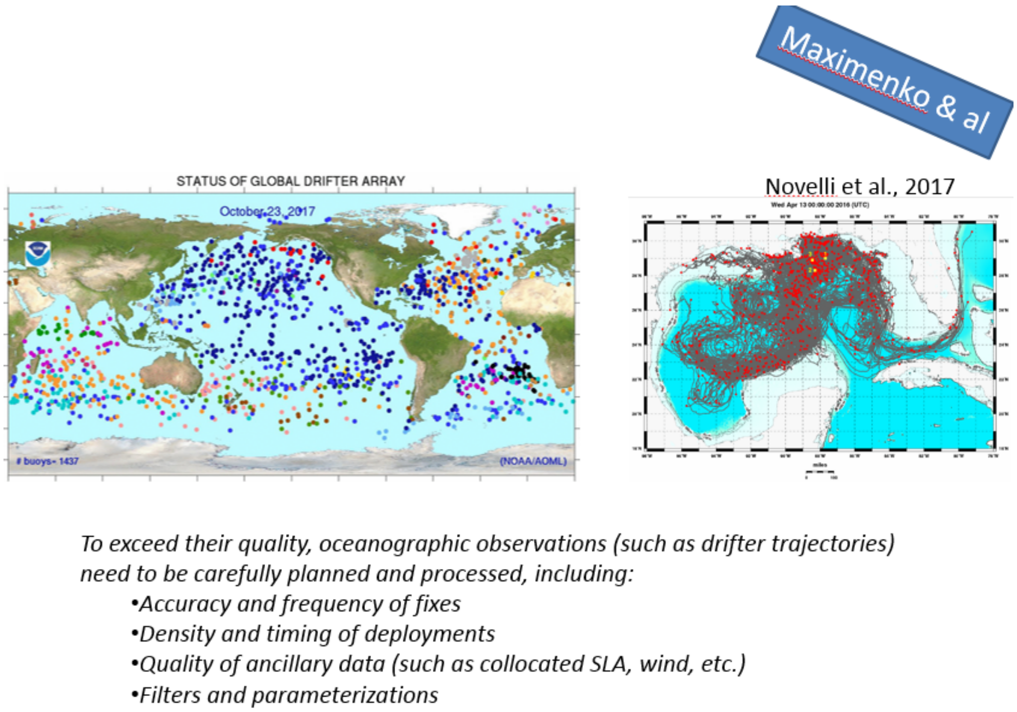


Figure 5.8-5: Illustration from Maximenko illustrating the high potential of new data-set to improve the accuracy of the MDT fields.

5.8.1 Conclusions

One of the main outcomes of the session roundtable discussion was the need of improvement of the MSS resolution, which will improve also directly MDT/Geoid. Indeed, MSS errors are greater than the signal below 30km wavelength. The improvement of instrumental processing demonstrated during this meeting (eg SAR LR-LRM) makes the MSS errors more predominant in the Sea level Error budget at those scales. Strong efforts must be made on the ingestion of optimally processed High Resolution (20Hz) geodetic measurements.

5.8.2 Recommendations:

Coastal MSS errors

Coastal MSS errors have been reduced (by more than 20%) in the last versions, but they remain too high for many applications (outcome of the coastal session).

The group recommends further studies on the quality of the MSS in the coastal zone and stresses:

- the need of a **consistent multimission dataset at high resolution in input of the MSS computation** (retracking T/P+JA1+JA2+JA3, corrections, …) and
- the need of **improving the methodology of extrapolation of MSS** at the coasts.

Jason-2 EoL scenarios

The following recommendation were made with respect to the Jason-2 EoL scenarios by the splinter group

- Considering the **importance of Jason-2 EoL for geodetic applications** and for
  - Improving the MSS for further improving the quality of oceanographic/operational use of satellite altimetry.
  - Improving the MSS in preparation for future high resolution missions (i.e., SWOT)

<u>The Splinter recommends the following:</u>

1. The Splinter encourages efforts to **maximize the operating time** of Jason-2 and the importance of completing at least 2 sub-cycles of 369 days (preferably more).
2. The Splinter stresses the importance to **maximize coverage** even in the case of degradation of the accuracy.
3. The Splinter urge the space agencies to **restart the mission as soon as possible in case of safehold** episodes to minimize data gaps
4. If Jason-2 lives through its first geodetic cycle the splinter **recommends to avoid data gaps in the second sub-cycle close to the data gaps during the first sub-cycle.**
5. Stressing the importance for **further simulation** studies to anticipate and mitigate possible safe-holds
6. Stressing the importance of maintaining a Jason-2 “scientific group” for off-line discussion of detailed and ad-hoc recomm

5.9 Tides, internal tides and high-frequency processes

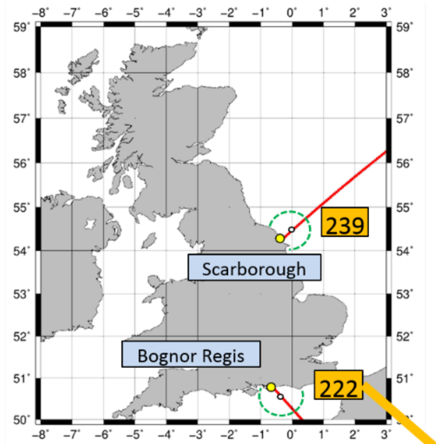
Chairs: Loren Carrere, Florent Lyard and Richard Ray

This year the Tides/HF splinter counted 5 oral presentations and 8 posters dedicated to barotropic tides, internal waves and high-frequency corrections.

5.9.1 Presentations

One talk focused on the improvement of barotropic tide models in coastal areas, and the 4 others focused on internal tides and internal waves.

Piccioni et al. presented some results about the benefit of ALES retracker to improve tidal models in coastal regions. The analysis is aimed at improving EOT11a tide model (empirical model). A very weak improvement is shown on the 2 regions tested (North Sea and Medsea). ALES gives more along-track observations below 20 km distance from Tidal Gauges, but no direct influence on results is found: different quality and distribution of data can affect the final results.



RSS – 8 waves [cm]	track 239	track 222
ALES	1.65	2.35
SGDR	1.70	2.43

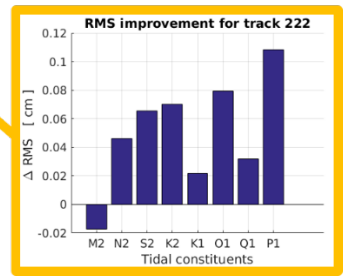


Figure 5.9-1 comparison of the impact of 2 retrackers on the modelling of tidal components

Zhao et al. presented the perspective for the next-generation internal tide models and some results about so-called internal tide oceanic tomography data. Current-generation internal tide models use constant amplitude and phase in time. The next-generation internal tide model will include time-variable amplitude and phase, and will account for incoherent internal tide caused by the seasonal and interannual variations, but eddies effect will not be addressed yet. A concept of using variability of internal tides to monitor ocean warming on a global scale was also presented, with some examples on the eastern tropical Pacific (correlated with the El Niño index) and in the North Atlantic (interannual variations consistent with Argo floats measurements).

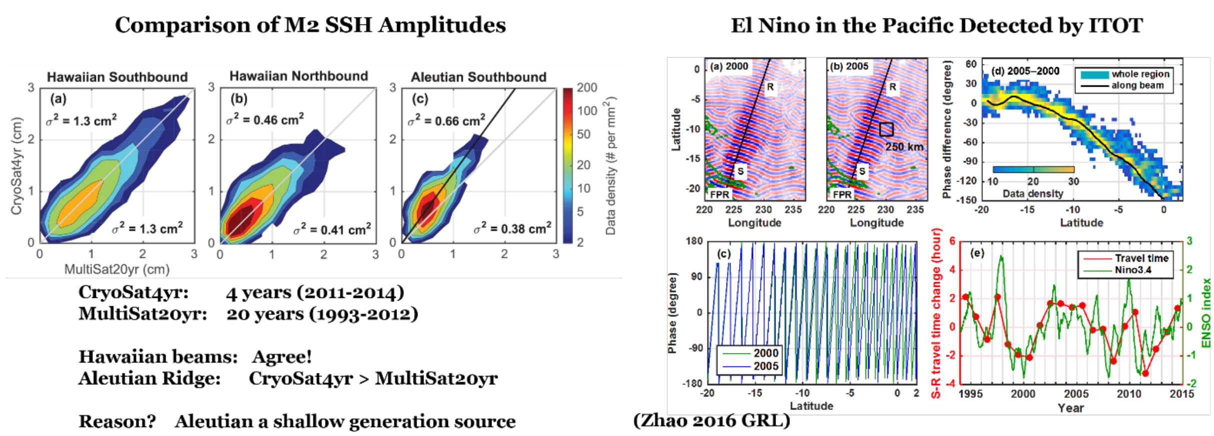


Figure 5.9-2 Comparison of M2 SSH amplitudes obtained using either 20 years of multi-sat altimetry or 4 years of Cryosat-2 mission, on 3 different north Pacific areas (left); and an example of ITOT solution to detect El Nino in the Pacific Ocean (right).

C. Ubelmann presented an attempt to map mesoscales and internal tides in a single massive inversion. The variational mapping approach allows to better handle a wide range of scales in time and space – plane-wave basis for mode-1 and mode-2. The IT field seems rather consistent with existing IT models, with a notable higher level of energy (by ~30%). A global run might be doable with appropriate effort (computationally expensive: 1010 parameters, accurate specification of global MS/IT components, …).

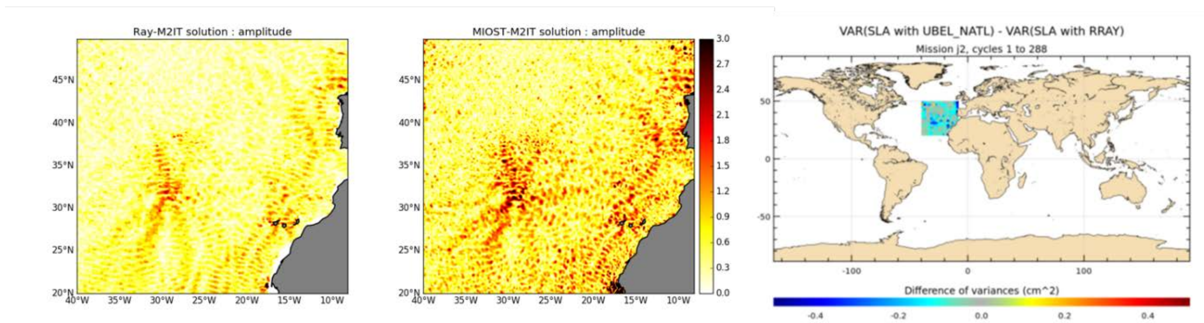


Figure 5.9-3 amplitude of the M2 IT solution on the Azores region, from Ray and Ubelmann (left and middle panels respectively); on right panel, Jason-2 crossovers variance difference when using the Ubelmann model or the Ray model (cm²).

L. Carrere presented the results of the comparison study of 7 internal tides (noted IT) models focusing on coherent internal tides. Compared to analysis presented in 2016, new releases from E. Zaron, G. Egbert and L. Erofeeva, and Z. Zhao, and also 2 news models from Arbic and Ubelmann have been considered, and R. Ray model is used as the reference IT correction. The analysis is based on altimetry variance reduction diagnostics for three missions Jason-2, AltiKa and Cryosat-2, on a 2D spectral analysis of Jason-2 SLA, and on in situ thermistors comparisons. Results point out that Zaron and Ray M2 models are close but Zaron model removes even more variability than Ray on many IT regions. Ubelmann model shows promising results but the IT solution may also remove some large scale/barotropic signal. HYCOM solution is not as good as empirical models proposed, showing that pure IT hydrodynamic modelling is not yet enough accurate. Some complementary investigations are needed for O1 and S2 frequencies, and some more in situ data comparison would be valuable.

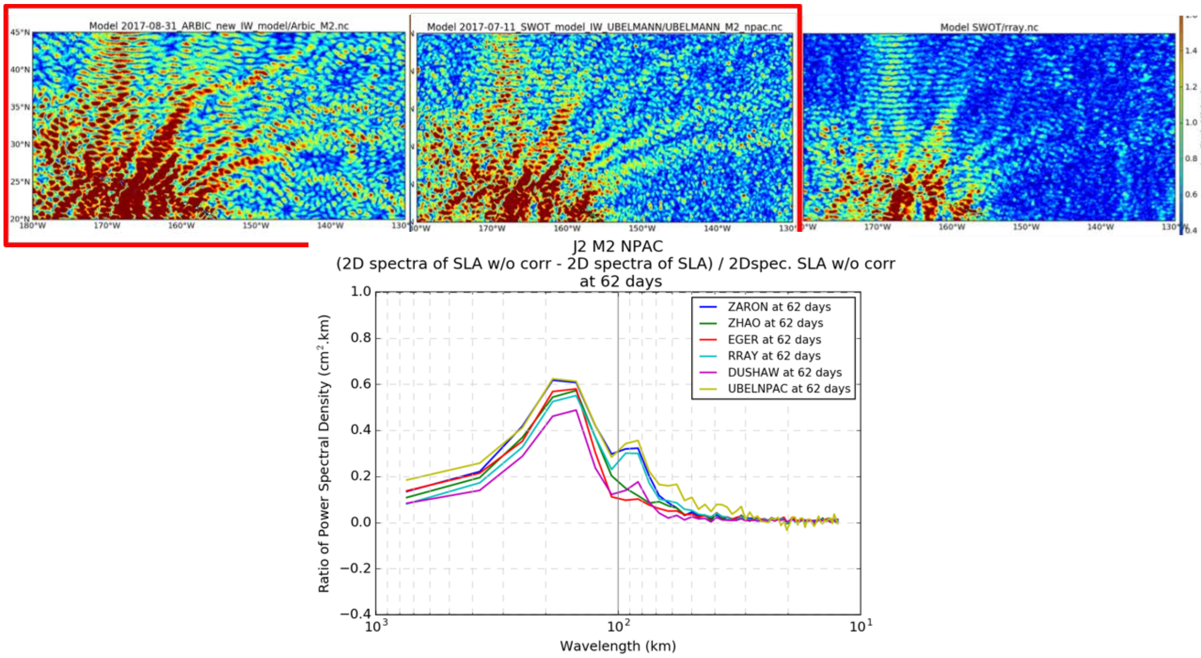


Figure 5.9-4 Above : Amplitude maps of M2 IT from new models HYCOM (left panel) and Ubelmann (middle panel), compared to Ray model (right panel). Below: percentage of energy removed at M2 frequency, thanks to each IT correction for J2 SLA.

B. Arbic et al. presented some comparison of internal gravity wave spectra in high resolution global simulations with observations. Some results of high-resolution simulations of HYCOM and MIT-gcm models with simultaneous atmospheric and tidal forcing have been presented, showing that both models carry coherent internal tides, incoherent internal tides, and a partial IGW continuum. Some comparison of simulations to observations and to theoretical predictions have been presented and the work is ongoing. The IGW continuum simulation demands high spatial resolution models. HYCOM is used to make global maps of the SSH signatures of incoherent internal tides, to estimate the Near-equatorial Pacific semidiurnal energy fluxes and the IGW continuum.

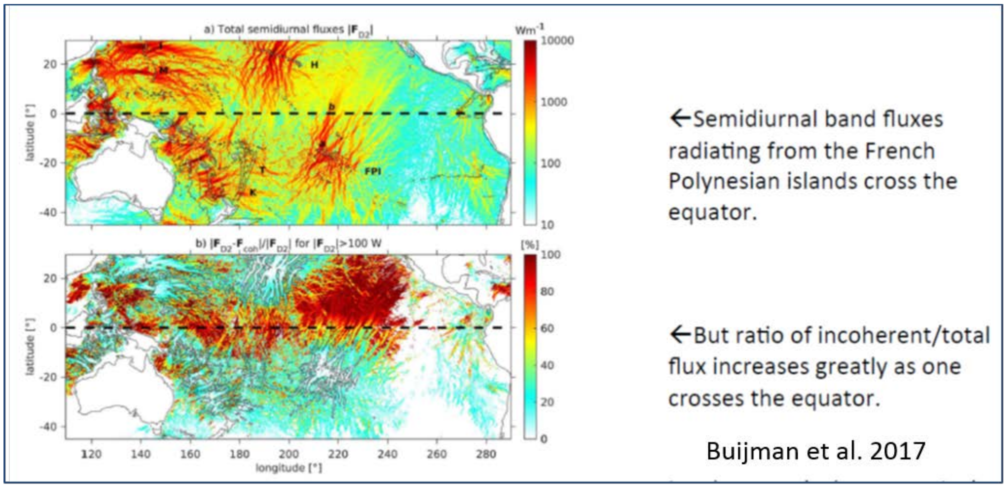


Figure 5.9-5 Near-equatorial Pacific semidiurnal energy fluxes in HYCOM, Buijman et al. 2017.

5.9.2 Posters:

- 2 on global models DTU16 and DAC
- 4 on regional/coastal tides models (Weddel sea, northern Bay of Bengal, Arctic + regional bathymetry)
- 2 on in situ measurements (CalNaGeo GNSS + Gliders and ADCP)

E. Zaron showed results of experiments with tidal analysis and assimilation of CryoSat-2 altimetry in the Weddell Sea and on adjoining ice shelves. Although the orbit of CryoSat-2 was not designed to observe tides, useful accurate estimates of the M2, S2, K1, and O1 tides have been obtained. CryoSat-2 tides agree with in situ measurements better than existing data-assimilative models for M2 and S2, and, except for K2, their accuracy is similar to the data-assimilative models for the smaller tides. Issues related to the mean surface and treatment of off-nadir returns from SARin mode data are also presented.

Y. Cheng et al. presented results about a further improvement of DTU global ocean tide model in shallow waters and Polar Seas. An updated model DTU16 representing all major diurnal and semidiurnal tidal constituents was developed based on FES2012 model and validation results have been presented showing good improvement compared to other existing model in the arctic.

O. Andersen et al. presented first results from the CP4O initiative about the improvement of the Arctic Ocean Bathymetry and Regional Tide Atlas. A first evaluation of existing bathymetry in the Arctic (R-TOPO2, IBCAO etc) has been performed and the methodology to derive bathymetry from high resolution gravity is also described. Improved gravity being the fundament for improved bathymetry, the first gravity results from DTU17 in the Arctic ocean and some evaluation against existing marine data sources are presented.

L. Carrere et al. presented some results of improvement of the performances of the DAC for the three delivery modes corresponding to Near Real Time (NRT-OGDR) products, Short Time Critical (STC-IGDR) and Non Time Critical (NTC-GDR). First improvement consisted in extending the meteorological forecast window until 10 days in the future (D+10). Impact analysis of using the new FES2014 parameters (mesh and bathymetry) have also been performed and some ways of improvements for the S1S2 processing are also proposed.

M. Cancet et al. presented a new CNES project aimed at improving the bathymetry on a number of continental shelves. The work is divided in several steps: 1/ an inventory of existing datasets and methods to derive the bathymetry on the shelves ; 2/ the integration of the collected datasets into a reference global bathymetry dataset ; 3/ the evaluation of this new bathymetry dataset through hydrodynamic modelling and the production of regional tidal models. The poster highlighted the methodology followed in the project and the first investigations about the inventory of existing datasets.

M. Ishaque et al. presented results about estimating tidal constants in the near-shore domain from Jason1-2-3 archive at 20Hz sampling rate, with a case study for the northern Bay of Bengal. The analyses allow extending shoreward the coverage of standard altimetric tidal constants by about 10km (depending on the track considered, within the Bay of Bengal), compared to the standard altimetric products. The observational coverage of this new altimetric tidal constants estimates, extended towards the shore, opens promising prospects for the tidal modeling community, as it corresponds to the coastal strip where the various tidal model solutions diverge most from one another.

F. Durand et al. presented results of a pilot experiment in the near-shore region of the northern Bay of Bengal during the 2014 post-monsoon season, along SARAL track #810. The observational strategy is based on an original ship-borne towed GNSS device: CalNaGeo. This device allows an accurate, multi-scale monitoring of the SSH variability within a few centimeters accuracy. The study opens up bright prospects for both thematic and cal/val activities of the future high-resolution nadir and swath altimetric missions (Sentinel-3 and SWOT), in a key-region of the tropical fresh water cycle.

G. Serazin et al. presented an analysis of the high-frequency and small-scale dynamics of sea surface height around New-Caledonia from in situ available observations. Structure functions are applied on ADCP shiptracks for the first time and give interesting insights to characterize the small-scale distribution of Kinetic Energy. In the Vauban channel, two dynamical regimes between the surface layers are highlighted, likely SQG dynamics, and the interior, likely internal waves. We confirm that gliders are valuable tools to capture the M2 internal wave as well as HF vertical velocities. The consistency between altimetry and glider measurements for the M2 internal wave is encouraging for the use of SWOT for describing internal waves.

5.9.3 Important Topics

- Alternative processing approaches such as fully-focused SAR processing are emerging. Will the current Sentinel-3 and Jason-CS/Sentinel-6 systems allow for novel processing approaches to be fully exploited?
    - Such alternative approaches are interesting for coastal altimetry/coastal models
    - New processing/retracking takes time to evaluate. A benchmark for validation of these new processing has been proposed and it needs to be continued.
- Coastal tides
    - Continuity of corrections between offshore and onshore is mandatory.
    - Regional modeling is needed for tides and corrections (DAC …)
    - Extrapolation of tide models over coasts is needed if we don't want to lose altimeter measurements. But the extrapolation process needs to be further evaluated (cf Zaron method).
- S1S2 in DAC/tides
    - This is an important issue at global and local scale.
    - Actual climatologies are old and shall evolve.
    - Test of higher resolution atmospheric forcing may help but one must be careful to atmospheric data discontinuities for long-term studies.
- SWOT
    - Calval site in California use gliders in situ measurements
- Gliders are impacted by internal tide (IT) effects
- Regional OSSEs with assimilation are needed to model/correct this signal as accurately as possible.
    - Concerning the deadline to provide IT correction for SWOT mission:
- About 1 year before launch is OK
- But IT correction should be used in standard altimetry as soon as possible.
    - More in situ validation data would be valuable for IT validation (drifters, gliders …) => in situ measurement campaigns are needed.
    - Local high-resolution tide models on estuaries and rivers are needed, and in situ measurement campaigns are also needed for calibration.
- Incoherent tides
    - Many initiative have been started to try to model the monthly/annual modulations of IT: these initiative need to be continued.
    - We need to anticipate the assimilation and mapping of SWOT data for IT => this is a challenge.
    - MIT-GCM simulations are now available => these solutions could be tested for IT correction (solution with assimilation)

5.10 Advances in coastal altimetry: measurement techniques, science applications and synergy with in situ and models

Chairs: Marcello Passaro, Ted Strub and Florence Birol

In this splinter we had three invited talks and a number of posters covering the following issues of coastal altimetry:

- The technical aspects of processing altimetry data in the coastal zone, including waveform analysis and retracking and the geophysical corrections;
- The synergy with other satellite/in-situ observations;
- The synergy with regional and coastal ocean models.

In summary, the development of new altimeter waveform retracking techniques has led to significant progress as well as many of discussions concerning the geophysical altimeter corrections and auxiliary information. As shown in Figure 5.10-1 below, significant errors still exist in tidal model solutions on the shelf and near the coast, mainly due to uncertainty in the high-resolution bathymetry in those areas. The need of improvements in the coastal wet tropospheric corrections, sea state bias and DAC were also pointed out.

In the last years, several independent coastal-dedicated altimetry datasets have been published. While this shows the increasing progress of the discipline, it has also increased the complexity for users with minimal experience in the use of altimetry data. The altimeter data would be more widely used if there were a unified and synthesized data set composed of all altimeters.

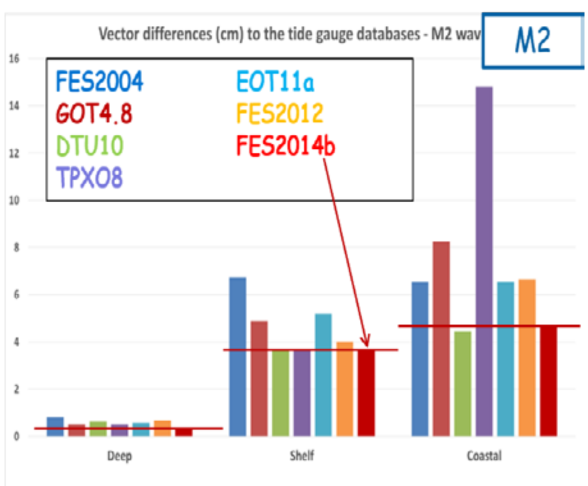


Figure 5.10-1 Differences between model and tide gauge solutions for M2 constituent and for different tidal model as a function of the ocean area considered. From Sharroo and Fernandes talk.

Today, we have six altimeters in orbit, which is a very favorable situation to capture the variability of the coastal ocean, where the scales of both time and space are smaller than in the deep ocean. The collocated sea level, SST and ocean color measurements provided by Sentinel-3 also provide a unique opportunity to better understand the fine scales of variability and our capability to observe them with altimetry. The comparison and combination of altimeter SLA with in-situ observations, such as tide gauge data, drifters and coastal radars, and subsurface data from gliders, undulating vehicles and ADCP surveys, largely extend the field of application of altimetry observations

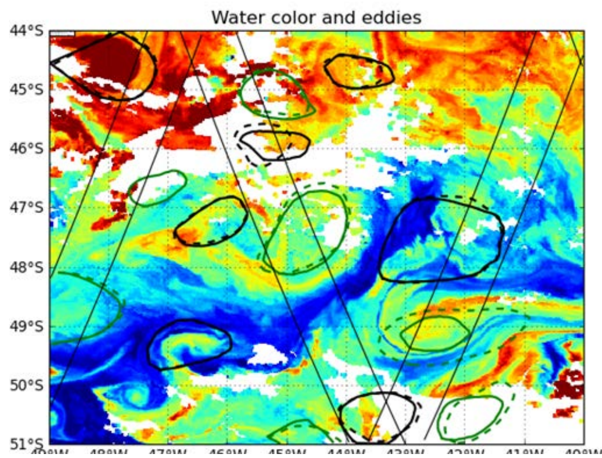


Figure 5.10-2 Ocean color and eddy contours superimposed for a particular date. From J. Bouffard talk.

The use of coastal altimetry data in the ocean modeling community was also discussed. Assimilation of coastal altimeter data into high resolution coastal or regional ocean models allows us to resolve the finer coastal ocean scales with higher resolution than possible with altimeter observations alone.

The recommendations that emerged from the talks and the discussion are:

- A standard and user-friendly coastal-dedicated altimetry data set is needed in order to facilitate the efforts of coastal oceanographers and sea level scientists.
- The geophysical corrections should be provided at rates higher than 1 Hz in order to better exploit the added value of high-rate altimeter measurements (range, swh and wind).
- The Mean Sea Surface and Mean Dynamic Topography products are very important for coastal applications and need to be recomputed with coastal altimetry products.
- The advances that have been made in coastal altimetry are still poorly exploited. Efforts are needed in terms of documentation, multi-mission reprocessing, combination of the different retracking and correction solutions and user-friendly products.

- More interactions are needed between the SWOT team and the coastal altimetry community to better understand the observational capability of SWOT for the finer ocean scales.

The coastal modeling and altimetry communities need more interactions in order to understand the needs and what is feasible in modeling and observations.

5.11 Science (Part I): Climate data records for understanding the causes of global and regional sea level variability and change

Chairs: Benjamin Hamlington and Benoit Meyssignac

5.11.1 Summary

There were three main scientific themes in this session: 1) improvement estimates of trends and acceleration in global mean sea level, 2) coastal vs. open ocean sea level; and 3) Impact of internal variability on global and regional sea level.

Based on talks by Chris Watson and Steve Nerem, there is evidence emerging of an acceleration in the satellite altimeter global mean sea level record. The importance of accounting for the drift in TOPEX A associated with the Cal-1 mode was highlighted in both of the presentations and a number of posters. This correction was found to have a significant impact on the estimates of rate and acceleration during the 24-year satellite record. It was shown that with careful consideration of variability contributing to the global mean sea level time series, a significant acceleration could be extracted that was partially validated with estimates from other observation systems (Figure 5.11-1).

There were several talks and posters that discussed the relationship between internal variability (seasonal and decadal) and regional sea level change on a range of timescales. The impact was found to be on the order of several centimeters on a regional level and on the millimeter level on global scales (specifically from ENSO and PDO-like decadal variability). It was demonstrated for the eastern coast of the United States that this variability can serve to significant exacerbate the long-term sea level rise at the coast.

There were multiple talks and posters focused on coastal sea level and the connection between open ocean and the coast. This was discussed and refer to as a topic of high importance, and one needing further investigation going forward. The impact of re-tracking and correction choices was demonstrated in a talk by Paolo Cipollini. With appropriate choices, coastal rates of sea level rise from the satellite altimetry were found to be comparable to those measured at nearby tide gauges. In a separate talk by Yingli Zhu, trends computed from tide gauges and nearby altimetry data were compared, showing good agreement in some locations and poor agreement in others. The degree of agreement was tentatively related to coastal ocean dynamics. It should be noted that these two studies differed in the focus on re-tracking and correction. Lastly on the topic of coastal sea level, Justin Stopa gave a presented a study that used satellite altimeter and SAR data to examine trends and interannual variability in the wave climate, with the importance in the context to coastal sea level/sea state was discussed.

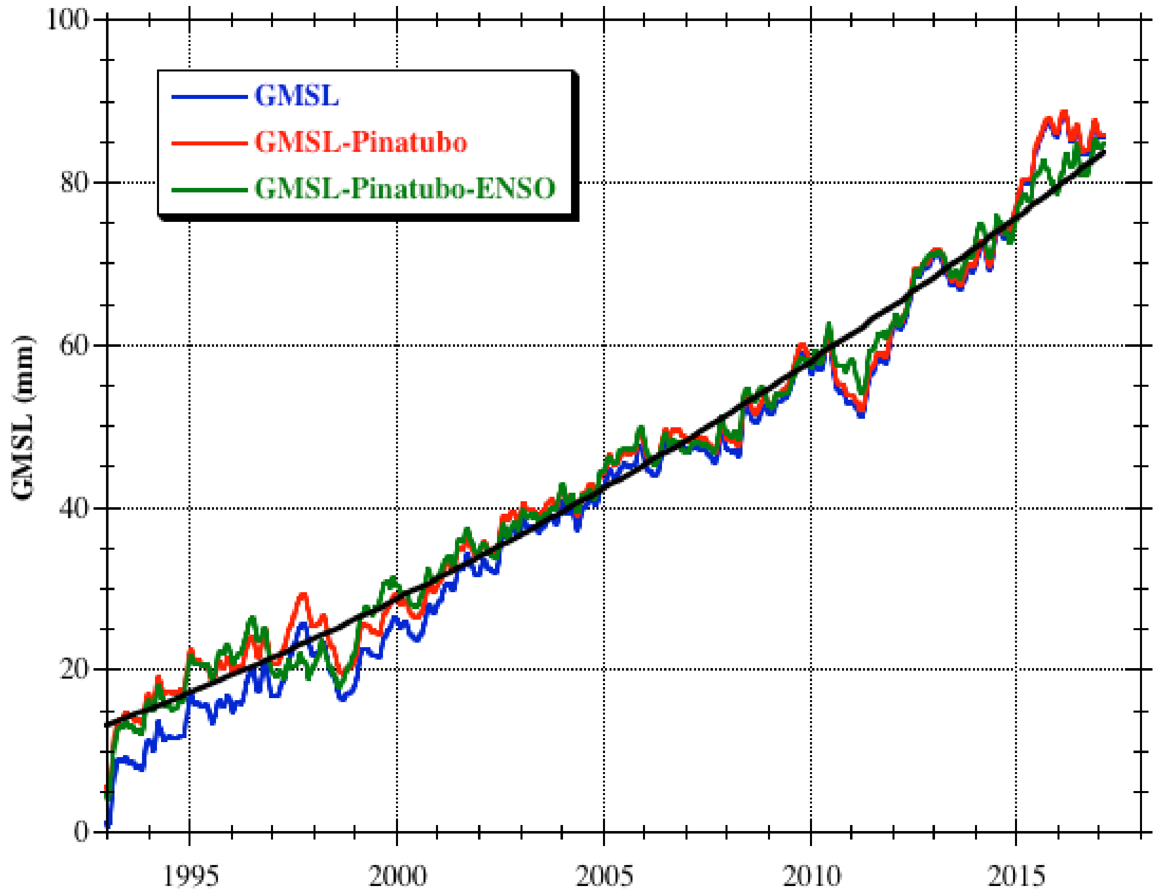


Figure 5.11-1 Corrected global mean sea level time series from 1993 to present. Red: Corrected for the impact of Mt. Pinatubo at the beginning of the record. Green: Corrected for impact of Mt. Pinatubo and interannual to decadal variability associated with ENSO.

5.11.2 Conclusions

- The importance of accounting for the drift in TOPEX A associated with the Cal-1 mode was highlighted and found to have a significant impact on the estimates of rate and acceleration during the 24-year satellite record.
- Internal variability (interannual to decadal) continues to have large impact on the satellite record both on regional and global scales.
- Further work is needed on the connection between sea level at the coast and sea level in the open ocean.
- With careful consideration of correction and re-tracking, there is agreement between trends measured at tide gauges near the coast and satellite altimeter measurements, although this agreement appears to be somewhat dependent on ocean dynamics.

5.11.3 Presentations

- Chris Watson: Further understanding the global mean sea level record over the satellite era
- Steve Nerem: Understanding the Acceleration of Sea Level Rise During the Altimeter Era
- Se-Hyeon Cheon: Impact of Pacific Ocean Variability on Global Mean Sea Level
- Paolo Cipollini: Sea level monitoring in the coastal zone: Impact of retracking and correction choices
- Ricardo Domingues: Evidence of coastal sea level changes along the east coast of the United States associated with the Florida Current transport and heat content using satellite altimetry and hydrographic observations
- Justin Stopa: Wave climate observed from satellites: trends and interannual variability
- Yingli Zhu: Comparison of coastal and open ocean sea level

5.12 Science (Part II): Large Scale Ocean Circulation Variability and Change

Chairs: LuAnne Thompson and Thierry Penduff

This session had 16 submissions, with 5 oral and 11 poster presentations. The research covered the globe with regional studies in the North Pacific, Tropical Indian Ocean, North and South Atlantic and the Southern Ocean, and global studies. Altimetry is being used throughout the globe to gain insight into large scale ocean processes, boundary current variability and air-sea interaction. The presentations covered three main themes:

1. Altimetry has become crucial for extending in situ and moored time series to investigate boundary current variability beyond what is available from in situ data (presentations from Artana, Beal, Saraceno, Ferrari, Hosmay, Goes, Dong). Altimetry is now regularly being used to constrain ocean reanalysis products, and these new proxies can help to evaluate reanalysis performance in these boundary currents.
2. Global altimetric sea surface height measurements along with model simulations have allowed the community to better differentiate atmospherically forced and intrinsic ocean variability up to multi-decadal scales. This raises new issues for the detection/attribution of observed signals, and to understand the role that changes in ocean circulation may play in climate (Penduff, Leroux, Bulusu, Melice, Anderson, Qiu, Haykal)
3. Altimetric sea surface height is increasingly being used to study air-sea interaction, both as a proxy for thermocline depth in the tropics (Han) and as a proxy for upper ocean heat content in the mid-latitudes (Thompson). These studies show the potential for using sea surface height in investigations of the role of the ocean below the surface mixed layer in coupled ocean-atmosphere variability.

These communications led to a wide-ranging discussion about the role of altimetry in understanding the ocean's role in climate variability, focused on potential future avenues of research in ocean climate variability:

1. Bringing together the communities that are using altimetry to investigate largescale, mesoscale, and submesoscale variability would allow deeper understanding of the interaction of the different scales of motions and their role in large scale ocean variability.
2. Interaction between coastal altimetry and open ocean altimetry in western boundary currents could improve the use of altimetry in western boundary current studies.
3. Altimetry is increasingly being used to extend back in time features that are measured by in situ measurements such as western boundary currents transport, vertical structure of temperature etc. This suggests that best practices for performing such studies should be made available to the scientific community at large.
4. Altimetric sea level has become increasingly important in the study of variability of large scale ocean circulation. On climate time scales, the sea surface height record is relatively short. An increased focus on using the existing record along with high resolution ocean-only models as well as coupled climate models such as is available via the Climate Modeling Intercomparison Project may be warranted.

5.12.1 Oral Presentations:

- Artana: Malvinas Current volume transport at 41°S: a 24-year long time series consistent with mooring data from 3 decades and satellite altimetry
- Bulusu: Southern Ocean Circulation and Climate Variability
- Han: Observed Decadal Sea-Level Variations Over the Tropical Indo-Pacific Basin: Association with and Indicators for Varying Walker Cells and Climate Modes
- Qiu: Dynamical Links between the Decadal Variability of the Oyashio and Kuroshio Extensions
- Thompson: Using Sea Surface Height to examine Air-Sea Interaction in the North Atlantic Ocean in Winter

5.12.2 Poster Presentations:

- Penduff: Quantifying uncertainties on regional sea level change induced by multidecadal intrinsic oceanic variability
- Haykal: A Western Tropical Atlantic Circulation Analysis Using Statistics and Satellites
- Melice: Investigation of the intra-annual variability of the North Equatorial Counter Current/ North Brazil Current eddies and of the instability waves of the North tropical Atlantic Ocean using satellite altimetry and Empirical Mode Decomposition
- Goes: The Brazil Current Variability from XBT data and satellite altimetry
- Artana: Performance of MERCATOR operational model at the Brazil Malvinas confluence
- Sraceno: Malvinas current dynamics from in situ and satellite altimetry data
- Ferrari: Satellite altimetry and current-meter velocities in the Malvinas Current at 41°S: comparisons and modes of variations

- Lopez: A reconstructed South Atlantic Meridional Overturning Circulation time series since 1870
- Baltazar: Arctic Freshwater fluxes with EO data and first results
- Leroux: Learning from large-ensemble ocean simulations to better interpret satellite and in-situ ocean data. - The Occiput large-ensemble dataset and some applications

5.13 Science (Part III): Mesoscale and sub-mesoscale oceanography

Chairs: Lee-Lueng Fu and Rosemary Morrow

This session had 7 oral presentations and 29 posters. Renewed interest in this subject is largely due to the preparation for the future SAR-interferometry SWOT mission providing 2D images of SSH capable of resolving the smaller mesoscales. The most recent alongtrack missions have reduced noise levels (reprocessed Jason-3, SARAL, Sentinel-3-SAR) which also allow us to observe finer scale structures in 1D along the tracks.

Most mesoscale studies are based on the gridded MSLA maps, but a number of studies addressed improvements to the mapping. T. Farrar noted that the most recent AVISO maps with latitudinally-varying temporal decorrelation scales damp out the barotropic Rossby wave signal in the Pacific. A recommendation was to set the temporal decorrelation scales to the minimum value everywhere (eg 17.5 days). A. Amores noted that only 25% of eddies in the western Mediterranean Sea can be detected in AVISO maps compared to eddy-resolving models. Various posters explored using different mapping techniques (statistical, dynamical) to better maintain the small-scale features observed alongtrack.

A number of studies are using the alongtrack data directly for mesoscale studies, including wavenumber spectra based on SARAL and S3, in different regions, with varying spectral slopes (O. Vergara), and using alongtrack SSH gradients to better position Southern Ocean fronts (D. Chambers).

One major question to resolve over the upcoming years is the observation and separation of balanced dynamics and internal waves / internal tides. Different statistical techniques are being explored to estimate these signals from models, in-situ and altimetric data, including Helmholtz decompositions (B. Qiu; C. Rocha; S. Gille), structure functions (G. Serazin), different covariance structure in OI mapping (C. Ubelmann), etc.

The session also included studies describing new mesoscale SSH and surface current products and model evaluation, the link between altimetric mesoscale structures and biogeochemical applications, and studies addressed the future SWOT SSH mission and the future SKIM surface current, ice-drift and wave mission (pre-selected for ESA's EE9).

5.14 Science (Part IV): 25 years of satellite altimetry for Cryosphere and Hydrology: from experimental to emerging operational applications

Chairs: Charon Birkett, Jérôme Bouffard Jean-Francois Crétaux

For the first time, elements of hydrosphere and cryosphere were combined in a 2017 OSTST splinter session. The majority of abstracts (23 in total) looked more to technical investigations rather than basic science research, but included topics pertaining to icebergs, sea ice, and ice sheets, and river dynamics, lake storage, climate change, and natural hazards. Data from altimetric instruments onboard ENVISAT, CryoSat-2, Sentinel-3A, SARAL and Jason-2,-3 (radar) and ICESat-1 (laser) were utilized with increasing exploration of SAR mode data for improved spatial resolution. An overview of the merits of the ICESat-2 (laser, launch 2018) mission was also presented. Improved data processing methods, especially waveform retracking and associated new data processors, were also topical, aiming for improved Range estimations across varying terrains.

With regards to the Hydrosphere projects, the SWT found that **Jason-3** was performing well despite some initial data losses (cf Jason-2) in both open and closed loop modes, and that the enhanced DEM (cycle 58/pass160 onwards) was now minimizing data losses. **Sentinel-3A** was also performing well, especially SAR mode which was allowing surface acquisitions to be made much nearer to river banks and lake coastlines. It was noted that SAR mode implementation within the future **Sentinel-6/Jason-CS** mission will enhance operational services, and that the Sentinel-3A, -3B, -6 constellation will open up new science and applied science programs. The SWT also recognized that with the launch of **ICESat-2** (2018) there will be a new dataset with a greatly enhanced along track resolution and spatial coverage. In addition, there will be opportunities for inter-mission cross-calibration and field campaigns.

With regards to the various Cryospheric projects, an increasing number or groups are looking to SARIn mode data from **CryoSat-2**. This mode is particularly relevant to iceberg detection and freeboard estimation, and as such offers a new operational application. SARIn mode can also be exploited to process the high-resolution swath elevations over ice sheets and glaciers. In general, there are consistent results over the Antarctica ice sheet (Vostok Lake) between the data offered by **CryoSat-2, Sentinel-3A** and **SARAL**. SAR mode is more promising than LRM but further processing requirements are required.

- There is scope for further Jason-3 DEM improvements, but it would assist operational programs if DEM uploads could be more frequent.
- Data for Sentinel-3A cycles 001-004 is urgently required for time series mergers with SARAL products.
- The SWT community is requesting clarification on the use of Sentinel-6/Jason-CS SAR mode over the continents. Are hydrological requests being accepted? Use of a global mask?

- The Hydrosphere SWT recognizes the various enhanced signal-processing techniques (e.g. FF-SAR, retracking) being explored, and supports the need for additional research efforts and associated cal/val projects.
- CryoSat-2 SAR data is more promising than LRM, but processing refinements are required.
- CryoSat-2 SARIn data processing is mature with respect to land ice applications, and could be tested/refined for sea ice and ocean surface applications.
- Any future Polar Topography mission should have Ka-Ku band capabilities to retrieve snow-depth over sea ice, and to better assess the impact of radar penetration into the snow pack.

6 Closing Plenary

The closing plenary took place on Friday morning. Each splinter session provided a summary and comments on the discussion items posed at the beginning of the meeting. In addition, Paolo Cipollini (NOC) provided a summary of the 10th Coastal Altimetry Workshop, in Florence, Italy 21-24 Feb 2017. Nicolas Picot discussed the current GDR status for altimetry missions. Currently Jason-2 and Jason-3 reprocessing is not a high priority given the good current state of the GDRs. TOPEX/Poseidon and SARAL/AltiKa will be reprocessed during 2018, and preparation for applying GDR-E standards to Jason-2, Jason-3 and SWOT altimeters will begin soon. Future Jason GDR standards still need to be carefully assessed and consolidated.

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 (other specific recommendations can be found in the splinters summaries):

Recommendations:

- **As long as Jason-2 remains in the Long Repeat Orbit, it provides valuable data for operational users and for improvements in mean sea surface estimates despite gaps created by safe holds. The OSTST therefore encourages efforts to minimize future Jason-2 gyroscope failures.**
- **The OSTST recognizes that valuable geodetic measurements can be made in the Jason-2 Long Repeat Orbit even if some performance is degraded, such as the loss of the radiometer. The OSTST recommends consulting the Extension-of-Life (EoL) group if rapid decisions need to be made.**
- **OSTST supports the FRM4ALT initiative of ESA. The first meeting of FRM4ALT Review on International Altimeter Cal/Val Activities will be held in Chania, Crete 23-25th April 2018.**
- **The OSTST recognizes the importance of regular reprocessing of the historical missions with common standards at the level of current missions.**

OSTST Appreciations:

The OSTST would like to express its appreciation to the agencies and operational teams for the following:

- The rapid and successful move of Jason-2 to the Long-Repeat Orbit
- Recovery of Jason-2 from multiple Safe Hold Modes and the gyroscope investigation
- The effort made by the Project to increase the number of cold sky calibrations for Jason-2, Jason-3
- The past and on-going reprocessing effort of all the altimetric missions (TOPEX, Jason, ERS, Envisat, CryoSat-2, Sentinel-3A, …)
- Preparations for Sentinel-3B, IceSat-2, and GRACE-Follow-on
- The agencies' efforts to launch Sentinel-6A/Jason-CS-A in late 2020, which should allow for a tandem phase with Jason-3 and extend the 25-year altimetry climate data record.

Finally, the 2018 OSTST meeting will be held in conjunction with the "25 years of progress in radar altimetry" symposium, 24-29 September 2018 in Ponta Delgada, Azores.