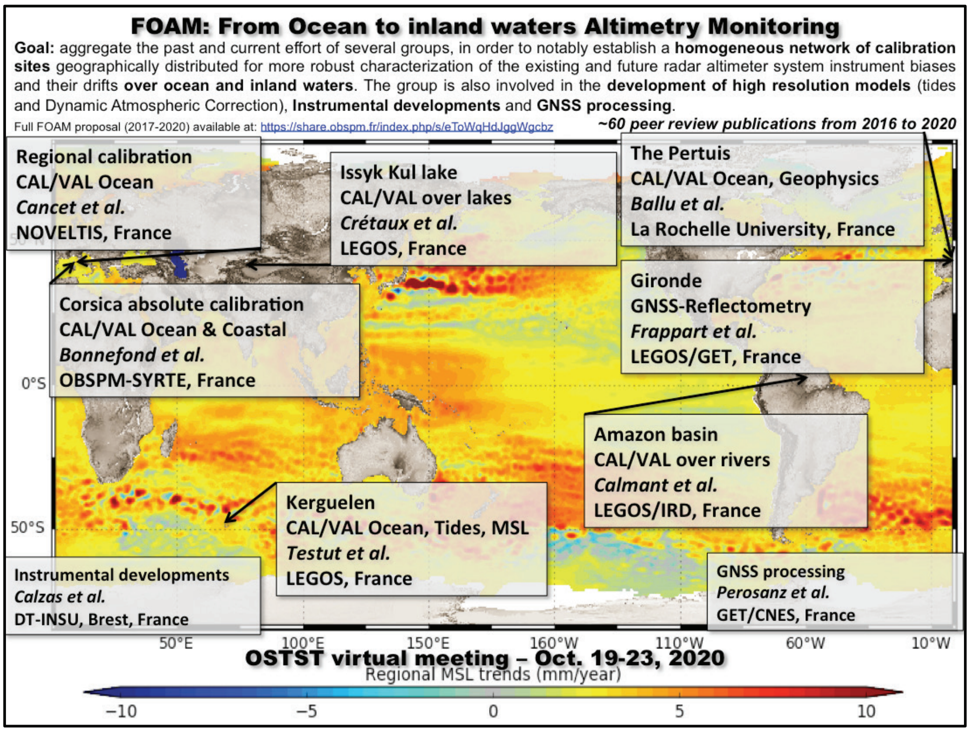


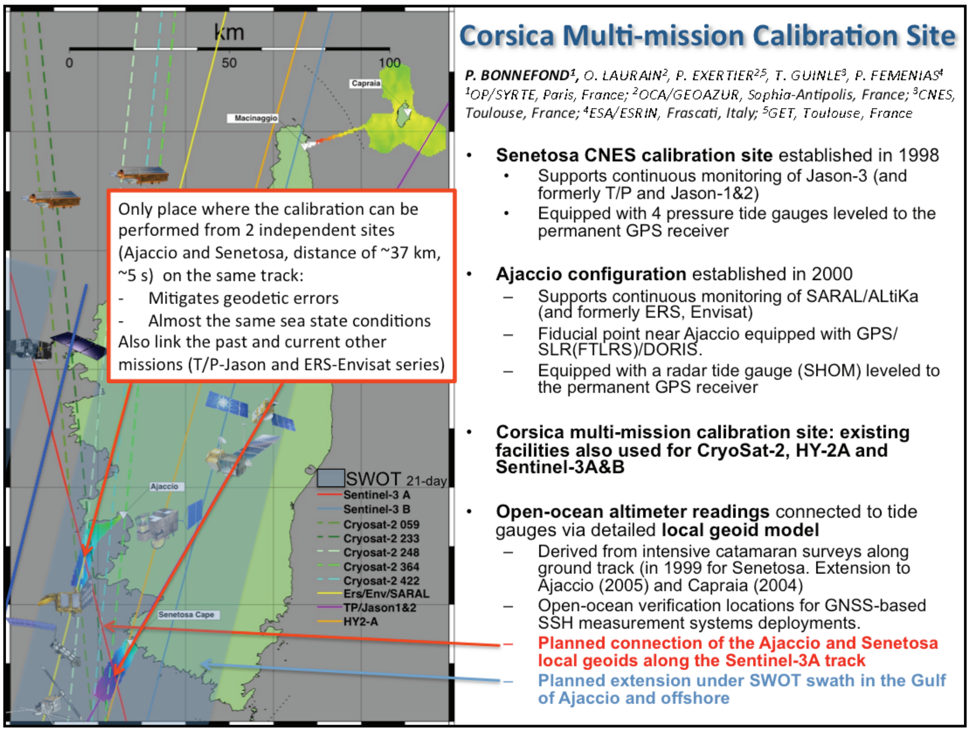
Current estimates of regional and global change in mean sea level are only possible through careful and continuous Calibration and Validation (Cal/Val) of the altimetry missions. Cross calibration of past, present and future altimetry missions will remain essential for the realization of a continuous and homogeneous series of sea level (Ablain et al., 2015; Fu and Haines, 2013). There is no doubt, however, that calibration of an altimeter requires a multiple approach, including using both in situ calibration sites and global studies based on the global tide gauge network. The relative calibration between different missions flying on the same period through crossover analysis or by along-track comparisons during tandem phase of the missions is also an important contribution for the Calibration/Validation activities (Cal/Val). All these techniques are considered complementary and fundamental in oceanography (Ablain et al., 2010; Bonnefond et al., 2010; Haines et al., 2010; Mertikas et al., 2018; Watson et al., 2011).

The traditional concept of in situ calibration of an altimeter involves direct satellite overflight of a site equipped with dedicated instruments. If it is essential that such a calibration site has means of in situ sea-level observation — using for example a classic tide gauge, a mooring or a floating system equipped with GNSS —, it is fundamental, however, to link the observed sea level to a terrestrial reference frame comparable to that used to analyze altimetry satellite measurements. In an ideal situation, the site of the experiment is located on a repetitive ground track (or better still on a crossover point between ascending and descending tracks), and far enough off the coast to avoid contamination of the altimeter or radiometer by reflections on land.

The potential for a number of geographically correlated errors within the altimetry system underscores the need for calibration experiment to be placed at different locations across the globe. The ability to sample the various systematic errors and characterize them in an absolute sense is one of the important advantages of a set of well-distributed calibration sites on Earth. This ensures a diverse sampling of ocean, inland waters and atmospheric conditions, and allows the use of different methodologies and processing software to help isolate systematic errors in all geodetic techniques involved. We present the salient results of the FOAM project (2017-2020), funded in the framework of the Ocean Surface Topography Science Team (thought as a multi-mission approach), at various sites (Corsica, Kerguelen, île d'Aix, Pertuis Charentais, Arcachon Bay, Gironde Estuary, lakes and rivers…) where the local conditions are different from each other and where permanent instruments and infrastructures already exist and will be reinforced.

The proposed CAL/VAL activities are thus focused not only on the important continuity between past, present and future missions but also on the reliability between offshore, coastal and inland altimetric measurement. In addition, we enter a new era of altimetry (Synthetic Aperture Radar and wide swath altimetry) and our group will take a particular focus on the new measurement systems and their reliability with the past ones (Low Resolution Mode). Our objective is to aggregate the past and present effort and expertise of several groups, in order to notably establish a homogeneous and optimized network of calibration sites geographically distributed for more robust characterization of the existing and future radar altimeter system instrument biases and their drift.

Full FOAM proposal (2017-2020) available at: https://share.obspm.fr/index.php/s/eToWqHdJggWgcbz



Corsica Multi-mission Calibration Site

The Corsica experiment which makes a collective reference to the instrumentation and facilities located in the western part of the Mediterranean at Ajaccio-Aspretto, Senetosa, and on the island of Capraia (Italy), is used to maximize the capability of performing the absolute calibration of a range of altimeters (see Figure left for the respective sites and the satellites ground tracks). On the other hand, it implies preserving the coherence of the overall Corsica experiment in terms of geodesy despite the diversity of instruments, approaches and geophysical conditions in addition to the range of distances between the sites.

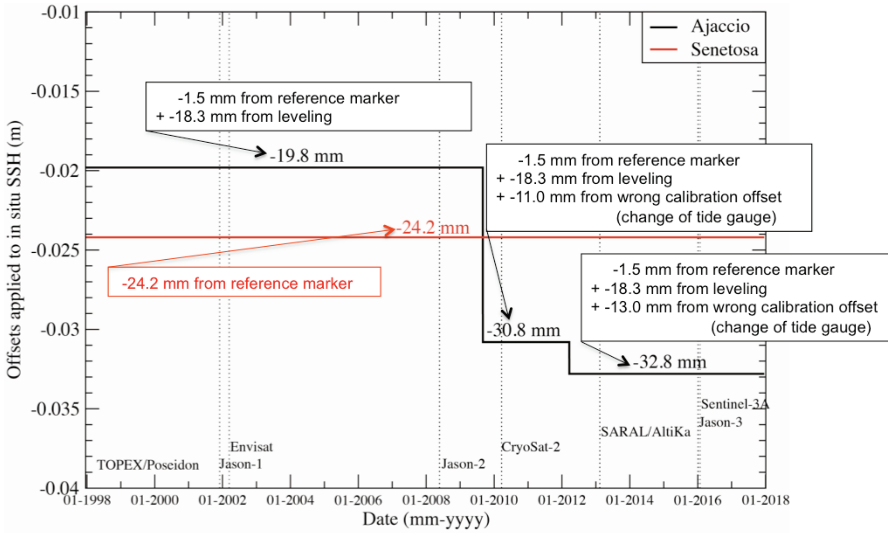
Since the development of the Ajaccio and Senetosa sites, absolute calibration were performed independently at each site depending of the overflying mission without any means of verifying the reliability of their respective geodetic datum (absolute sense). However, thanks to the configuration of Sentinel-3A repeat ground track and some CryoSat-2 passes, it has been possible to determine two distinct SSH biases at each site for each altimeter overflying both Senetosa and Ajaccio with a time delay of about five seconds (about 37 km). As a consequence, it allowed us to compare these biases and thus interconnect both datum. Moreover, because the SARAL/AltiKa mission was placed on a drifting orbit phase since July 2016, a similar interconnection between both Ajaccio and Senetosa datum has been achieved.

All recent results and history of the Corsica calibration site are available in this paper:

Bonnefond, P., Exertier, P., Laurain, O., Guinle, T., Féménias, P. (2019) Corsica: A 20-Yr Multi-Mission Absolute Altimeter Calibration Site, Advances in Space Research, Special Issue « 25 Years of Progress in Radar Altimetry », doi : https://doi.org/10.1016/j.asr.2019.09.049

Update of the geodetic datum

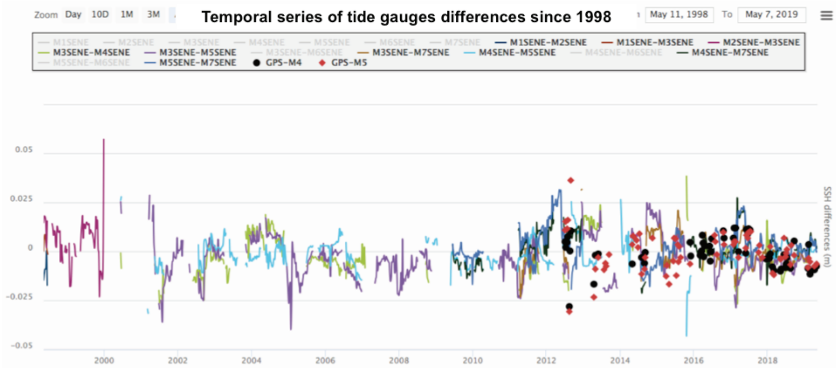
It sometimes takes time to clean out our closet…



The SSH biases for all the missions have been recomputed based on these geodetic datum changes.
(see Bonnefond et al. 2019 (https://doi.org/10.1016/j.asr.2019.09.049) in 25YPRA ASR Special issue)

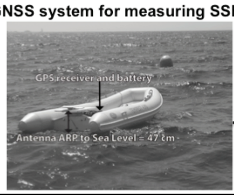
Since the start of the Calibration/Validation activities in Corsica, 1998, the geodetic datum and instruments as well as the methodologies have been continuously upgraded in view of determining (in absolute sense) and monitoring the SSH bias of many altimetric space missions on the long term. Bonnefond et al. (2019) describes the different aspects (events, campaigns and regular controls) of the work that have been carried out in both the Senetosa and Ajaccio sites, and it presents the most recent results that have been achieved in terms of geodesy: leveling, GNSS positioning, in situ calibrations, and above all absolute SSH biases. A long process of "data archeology" has permitted to improve the consistency of the data series that enter in the overall monitoring and, more particularly, to understand the origin of the offsets that were identified before either at Ajaccio or Senetosa (see Figure above). We showed that the long-term stability of any ground motion can be achieved at a precision better than few tenths of millimeters per year and that the regular leveling of in situ instruments (tide gauges) ensure a repeatability of the geodetic links to the reference markers of no more that 1 mm over several years. In addition, we highlighted the need for the careful long-term monitoring of in situ measurements measuring sea level; (i) performing pressure calibration for bottom pressure tide gauges or by using a contact probe for the radar ones, (ii) using multiple tide gauges to monitor their relative behavior and (iii) using independent measurement systems (e.g. GNSS-based) to compare SSH measurements. As a result, we show that from these processes it is possible to reach consistent measurements (in absolute sense)

Stability of in situ measurement system
Comparisons with independent measurements



Average differences at the few millimeters level with ~1 cm standard deviation
Stability of the differences better than ~0.1 mm/yr

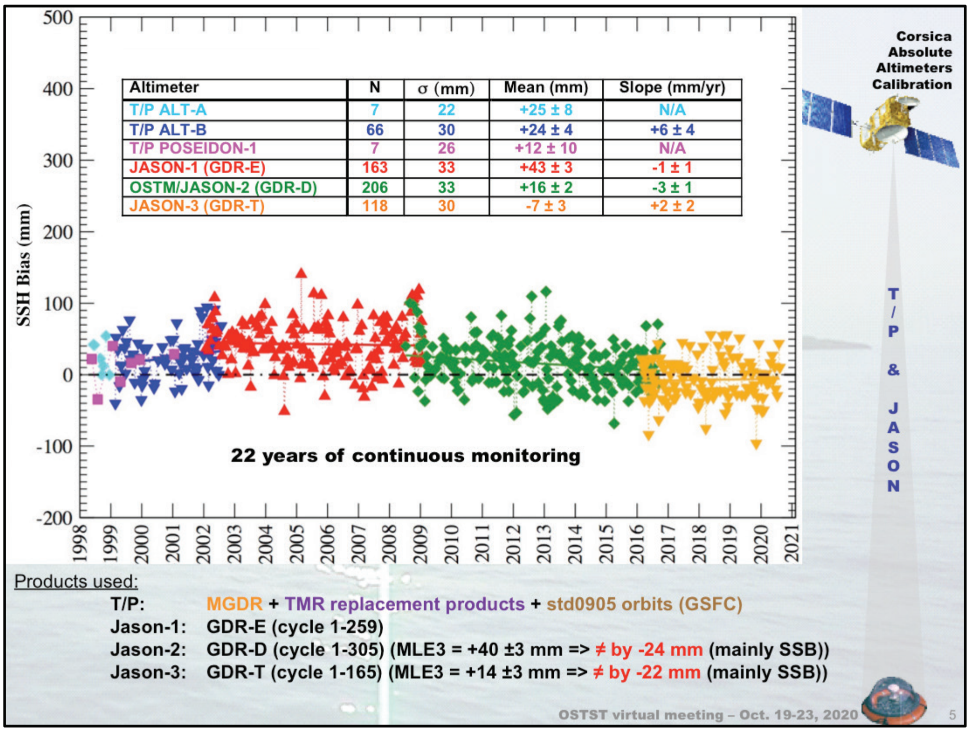
GNSS system for measuring SSH



Type of comparaison	Mean (mm)	σ (mm)	Drift (mm/yr)	Number
between tide gauges since (1998)				
M3SENE-M4SENE	-2.3	10.9	-0.07 ± 0.02	10184
M3SENE-M5SENE	-3.6	12.0	+0.07 ± 0.02	16357
M4SENE-M5SENE	-0.9	7.1	+0.05 ± 0.01	13026
between GNSS et tide gauges (since 2012)				
GPS-M4SENE	-0.6	7.7	-0.28 ± 0.47	64
GPS-M5SENE	-0.5	9.4	-0.28 ± 0.52	83

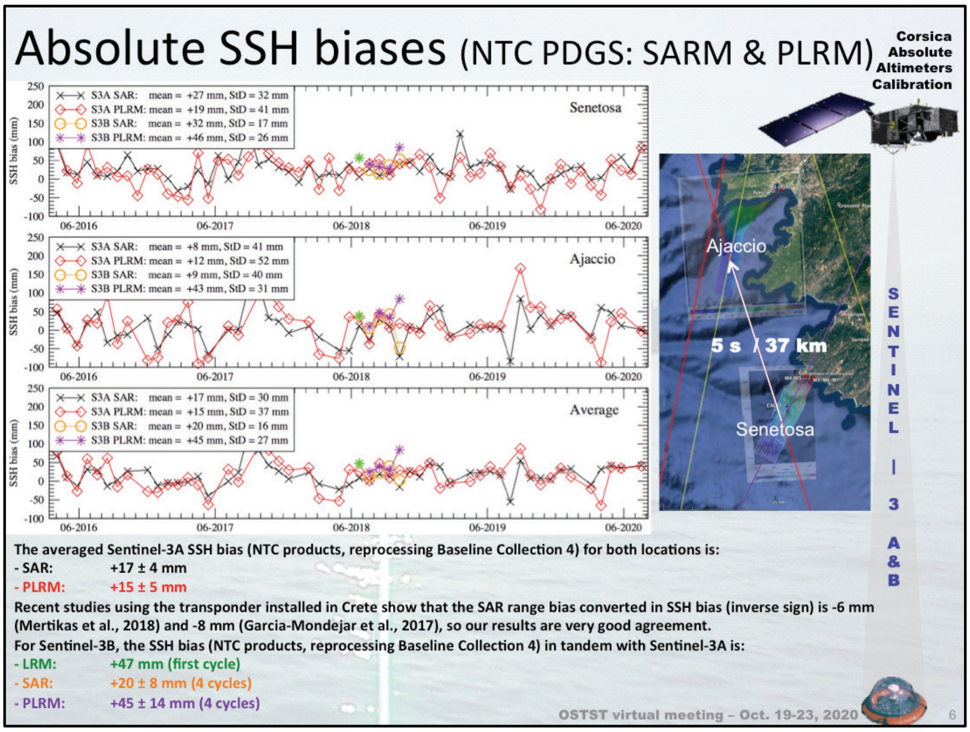
Over a period of more than 20-yr, we have analyzed the SSH differences by pair between the tide gauges deployed at Senetosa since 2001 (Figure). As a result, the averaged differences are at the few millimeters level with ~10 mm standard deviation (Table). Moreover, the stability of the differences is globally better than ~0.1 mm/yr (over now more than 17 years for some time series). Finally, when two tide gauges are very close together (M4 and M5 or M3 and M7), the standard deviation is clearly lower than 1 cm (7.1 mm and 8.2 mm, respectively). On the other hand, when the distance is longer, the standard deviation is increasing to more than 10 mm (see for example M3-M4 and M3-M5 in Table). Thus, it reveals that, even at relatively short distance (~1.7 km), local conditions can make the sea level different at the few millimeters level in term of standard deviation.

We also use our GNSS-based sea level measurement system regularly to achieve some comparisons with the tide gauges. This is done at the time of each deployment and retrieval of the tide gauges at Senetosa (about every 3-4 months) but also for some Jason overflights. The results presented in Table show also a very good consistency at the millimeter level. The drift between both determinations is relatively large but not significant because of the short time series (6 years) and, more importantly, because the GNSS-based sea level measurements are not continuous (few determinations by year not evenly distributed).



Reference missions (TOPEX/Poseidon, Jason-1, Jason-2, Jason-3)

The Senetosa calibration facilities have been initially developed to monitor the performance of TOPEX/Poseidon and to follow the Jason legacy satellite altimeters. This site provides more than 20 years of SSH observations for these missions. As discussed in Bonnefond et al. (2019), a particular care has been taken to insure the stability of the geodetic datum and the instruments' measurements. Because the time series are composed of only one determination every ten days, it is however difficult to derive any drift of the altimeters' SSH biases, even over several years. The linear trend values the Figure are thus given only for information and are not statistically significant. On the other hand, the mean values of the SSH biases are determined with a high level of confidence with a standard error of few millimeters (2 mm for the longer time series of Jason-2). The mean SSH biases range from -11 (Jason–3) to +43 mm (Jason-1) with a standard deviation of 18 mm: this shows that inter-mission biases still exist at the level of several centimeters and this reinforces the need of tandem verification phase between consecutive missions to insure the consistency of the climate record of these reference missions.

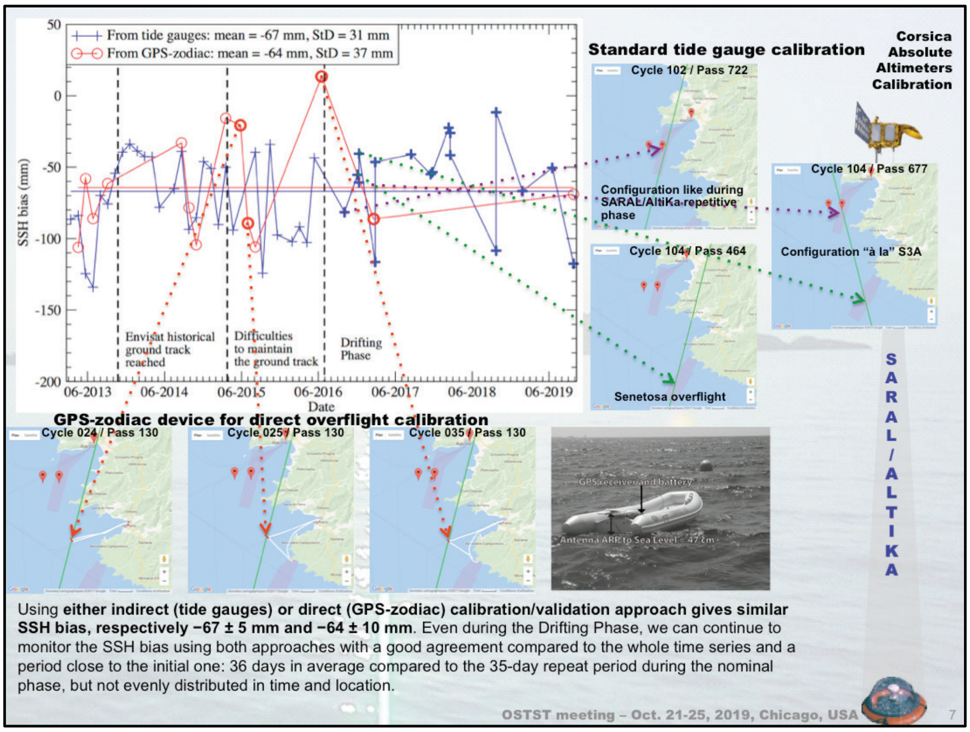


Sentinel-3A and Sentinel-3B

The Sentinel-3A ascending pass #741 overflies the Senetosa site and the Ajaccio one ~5 s later. This allows us to compare the SSH biases, which can be independently determined at both locations, and then to assess geodetic references together with in-situ measurements. The Figure shows the time series of Sentinel-3A and Sentinel-3B for Senetosa (top), Ajaccio (middle) and the average of both sites (bottom). The times series are given for the two modes that are used to derive the sea surface height from the radar measurements: (i) the SAR (Synthetic Aperture Radar) mode and (ii) the PLRM (pseudo LRM) mode that mimics the classic LRM.

In summary, for Sentinel-3A, the averaged SSH bias for both locations is +17 ± 4 mm in SAR mode and +15 ± 5 mm for PLRM mode. For Sentinel-3B, the averaged SSH bias (based only on 4 cycles) for both locations is +20 ± 8 mm in SAR mode and +45 ± 14 mm for PLRM mode. On cycle 9, Sentinel-3B was in LRM mode so this SSH bias of +47 mm (green star on the Figure) has been excluded from the statistics. However, this value is within the error bar of the PLRM time series, and so is not statistically different considering the small number of cycles.

Recent studies using the transponder installed in Crete show that the SAR range bias (inverse sign for SSH bias) for Sentinel-3A is +6 mm (standard deviation of 12 mm) (Mertikas et al., 2018) and +8 mm (standard deviation of 12 mm) (Garcia-Mondejar et al., 2017). For Sentinel-3B, preliminary result shows a range bias of -3 mm (standard deviation of 18 mm) (Garcia-Mondejar, personal communication). So our results are in very good agreement with transponder ones (differences within 15-17 mm) considering that difference between these two determinations can be due to the geophysical corrections (notably the SSB) as already mentioned for CryoSat-2 (section 4.4).

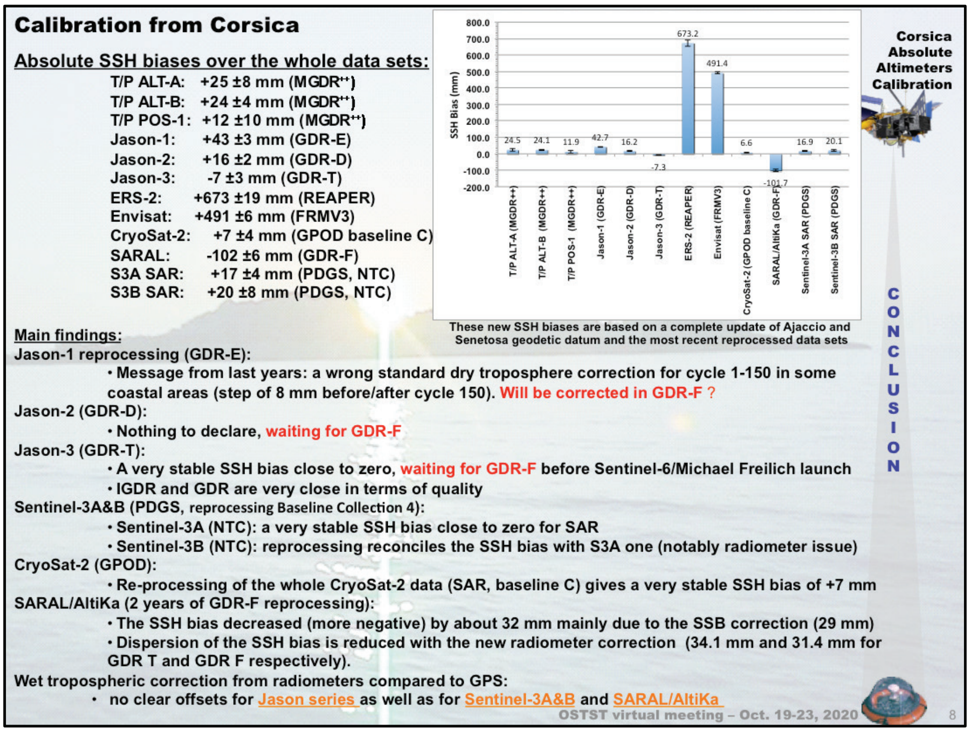


SARAL/AltiKa

SARAL/AltiKa, launched in February 2013, was intended to be a gap filler mission between Envisat and Sentinel-3 and, consequently, it flies on the same orbit as Envisat. However, this new satellite not only provides a continuation of the ERS-Envisat time series but also provides a new technology: the AltiKa instrument is a Ka-band altimeter and has an embedded dual-frequency radiometer. The enhanced band-width (35.75 GHz, 500 MHz) provided by the single frequency Ka-band altimeter leads to a better vertical resolution as well as improving the spatial resolution thanks to the Ka-band's smaller footprint. Then, the Ajaccio calibration site has allowed us to monitor SARAL/AltiKa by still using the same approach. The first results published in Bonnefond et al. (2015) have demonstrated that the mission improves the coastal measurements as close as 3–6 km. It has been seen through a higher number of data available and a much lower land contamination in comparison to Envisat (same ground track). A particular effort has been made for monitoring SARAL/AltiKa with the deployment of our GNSS-based sea level measurement system (GPS-zodiac, see Figure at bottom right) as often as possible when the sea conditions have permitted to do it in safe conditions. The objective was to cross compare the direct and indirect approaches described in the beginning of Bonnefond et a. (2019). The direct approach has permitted us to make measurements even during the period when the difficulties with the satellite reaction wheels did not permit the ground track to be accurately maintained (from March 2015 until the Drifting Phase in July 2016). This is illustrated in the Figure (bottom maps) for three cycles (24, 25 and 35) when the satellite was too far from the nominal ground track and did not overflight the geoid map. As a result of the direct approach, the SSH biases (bold red circles in the Figure) are consistent with the rest of the time series. Since the beginning of the Drifting Phase, SARAL/AltiKa has overflown both Corsica calibration sites (Ajaccio and Senetosa) in different configurations (see the right part of the Figure). The SSH biases have then been computed using Senetosa or Ajaccio tide gauges or even both when the satellite have overflown both areas (shaded in purple on the Figure maps). The derived SSH biases (bold blue crosses in the Figure) are also consistent with the rest of the time series.

In summary, using either the indirect (tide gauges) or direct (GPS-zodiac) calibration approaches gives similar SSH bias, respectively −67 ± 5 mm and −68 ± 11 mm. Even during the Drifting Phase, we can continue to monitor the SSH bias every 36 days in average (not evenly distributed in time and location) compared to the 35-day repeat period during the nominal phase.

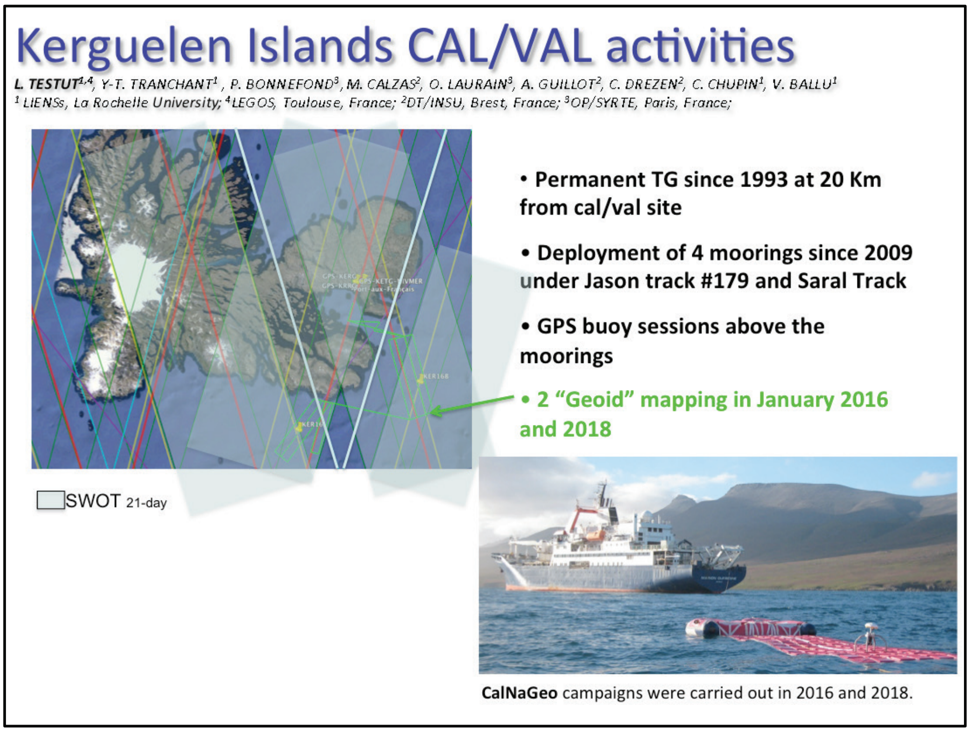
The SARAL/AltiKa GDR-F products has been also analyzed and compared to the GDR-T using the Ajaccio calibration site for the subset of reprocessed data (year 2013 and 2014). The SSH bias was calculated using the wet tropospheric correction from the model. The model/radiometer difference is: +10.8 mm and -6.6 mm for the GDR T and GDR F respectively. The SSH bias decreased (more negative) by about 32 mm mainly due to the SSB correction (29 mm). We have not used the new 3D SSB field for the moment. The bias, which was already quite important and still unexplained, is therefore worsening and reaches ~ 10 cm (see Corsica conclusion slide).



Conclusion

Since the start of the Calibration/Validation activities in Corsica, 1998, the geodetic datum and instruments as well as the methodologies have been continuously upgraded in view of determining (in absolute sense) and monitoring the SSH bias of many altimetric space missions on the long term. Bonnefond et al. (2019) describes the different aspects (events, campaigns and regular controls) of the work that have been carried out in both the Senetosa and Ajaccio sites, and it presents the most recent results that have been achieved in terms of geodesy: leveling, GNSS positioning, in situ calibrations, and above all absolute SSH biases. A long process of "data archeology" has permitted to improve the consistency of the data series that enter in the overall monitoring and, more particularly, to understand the origin of the offsets that were identified before either at Ajaccio or Senetosa. We showed that the long-term stability of any ground motion can be achieved at a precision better than few tenths of millimeters per year and that the regular leveling of in situ instruments (tide gauges) ensure a repeatability of the geodetic links to the reference markers of no more that 1 mm over several years.

Based on several updates of the geodetic datum established on both Corsica sites and using the 20-yr series of sea level measurements, we have computed a new series of absolute SSH biases for a number of altimetric missions, using the most recent reprocessing of their data. The results are synthetized in the Table and show that the absolute SSH biases are at the level of few millimeters to few centimeters for most of the missions except for ERS-2 and Envisat suggesting that a constant error (e.g. internal path delay) still remains, despite the recent reprocessing. For the longest time series the standard error is at the level of few millimetres giving a high level of confidence in our results. Moreover, independent approach based on transponders can help to discriminate sea side effects from range bias; in that case, the comparisons made for either CryoSat-2 or Sentinel-3A&B show consistent results with the SSH biases determined in this study.

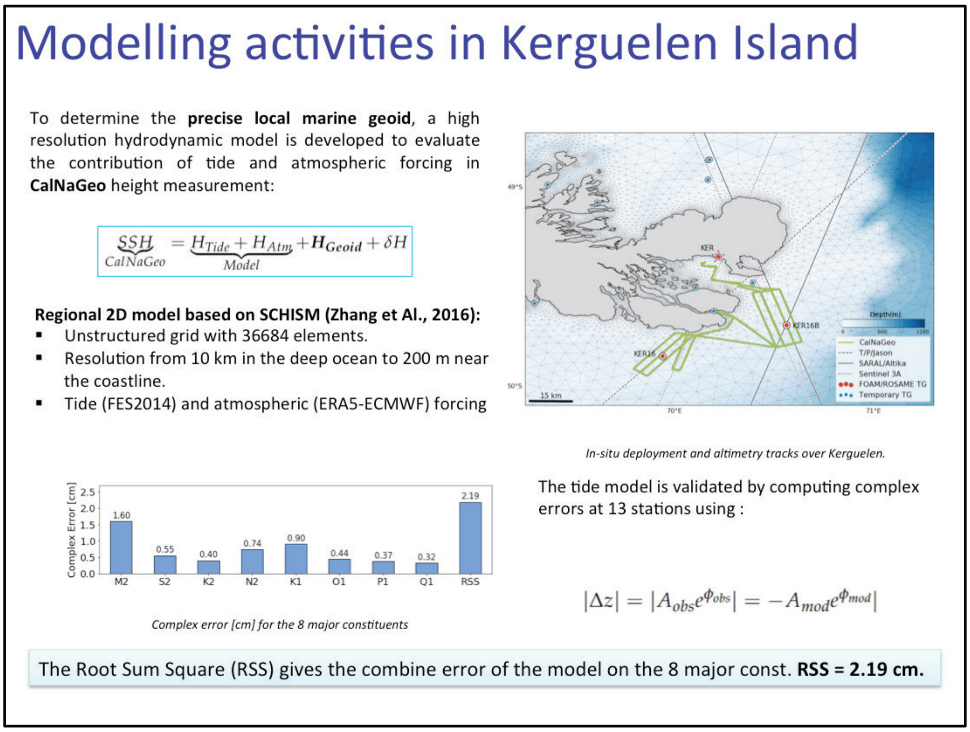


Map : Main satellite tracks around Kerguelen Island. Satellite tracks are :

1. red and blue respectively for Sentinel-3A and Sentinel-3B
2. purple for T/P and Jason
3. Yellow for ERS–1&2, Envisat and SARAL/AltiKa.

The pins indicate the location of the tides gauges as well as the position of the moorings deployed under the Jason and SARAL/AltiKa).

The reference tide gauges part of the observatory including a permanent GPS station and a weather station.



In the context of FOAMproject (CNES), a new CAL/VAL site is proposed on the Island of Kerguelen, to complement other sites by providing CAL/VAL of altimeter height measurements in different sea-state conditions.

CalNaGeo, a GNSS towed sheet has been designed to map the Sea SurfaceHeight (SSH). Two CalNaGeo campaigns were carried in 2016 and 2018.

To determine the precise local marine geoid, a high resolution hydrodynamic model is developed to evaluate the contribution of tide and atmospheric forcing in CalNaGeo height measurement.

INFRASTRUCTURE

The site of Kerguelen is overflown by many altimetry missions including TP/J, SARAL/AltiKa and Sentinel-3A.

In addition to CalNaGeo campaigns of 2016 and 2018, the area benefits from substantial instrumentation, including:

• Permanent tide gauge at Port-au-Français (KER) since 1993, part of the ROSAME tide gauges network. (RED STAR)

• KER16 and KER16B deployed during FOAM campaign of 2016, providing 4years of measurements under Jason and SARAL tracks. (RED DOTS)

• Tidal Constituents computed from 10 temporary tide gauges. (BLUE DOTS)

MODEL

The model used in this study is SCHISM in the 2D barotropic mode (Zhang et Al., 2016), with an unstructured grid of 36684 elements. The resolution of meshes depends on the bathymetry and slopes, varying from 10 km in the deeper ocean to 200 m near the coastline. Tide elevations and potential are derived from the FES2014 atlas in its assimilated version (Noveltis, Legos and CLS). Pressure and wind fields are recovered from the ERA5 reanalysis data set of ECMWF.

Tide Validation:

The tide model is validated by computing complex errors at 13 stations (temporary dataset and FOAM/KER tide gauges). After performing harmonic analysis on observed and modeled water levels, the Root Sum Square (RSS) gives the combine error of the model. **RSS = 2.19 cm**

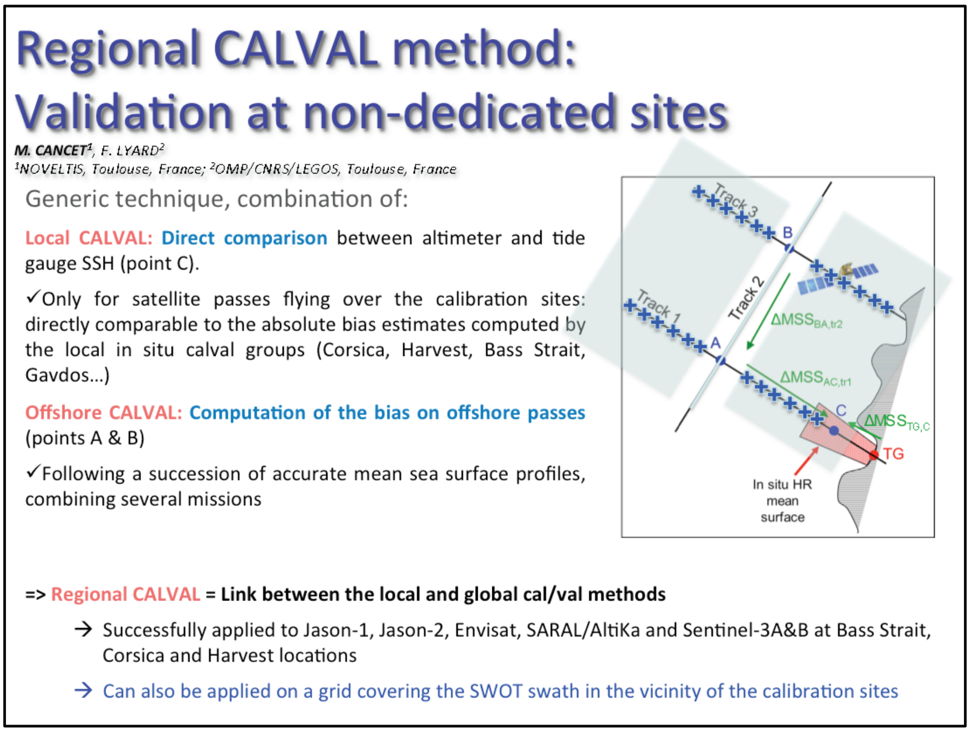
Crossovers and comparison to FES2014:

An indicator of the model ability to remove the non-stationary part of sea-level in CalNaGeo measurement is to investigate the differences at crossover points before and after corrections.

The RMSE of these errors is computed for 2 areas, corresponding to **TP/Jason** and **SARAL/Altika areas.**

For each calibration area, the RMSE is computed for SCHISM model and FES2014.

On the **TP/Jason area**, RMSE=3.3 cm for SCHISM against 4.8 cm for FES2014. It represents a gain in accuracy of almost 1.5 cm. However, our results are worse than expected in the **SARAL/Altika area** with a RMSE of 4 cm for SCHISM model against 2.7 cm for FES2014.



The classical local absolute in situ calibration techniques can be applied only to the satellite tracks flying directly over or very close to the dedicated sites, provided that a high resolution local geoid is available.

NOVELTIS has developed a regional Cal/Val technique, which aims at increasing the number and the repeatability of the altimeter bias assessments by determining the altimeter bias both on overflying passes and on satellite passes located up to a few hundred kilometers away from the calibration site. In principle this extends the single site approach to a wider regional scale, thus reinforcing the link between the local and the global Cal/Val analyses. The method is totally generic and can be used with any altimetry mission, at any calibration site. It provides homogeneous altimeter bias estimates computed with exactly the same protocol at the various calibration sites, thus avoiding inconsistencies linked to the different methods when comparing the results from one site to the other. The method also provides a means to maintain a calibration time series for satellite altimetry missions without specific dedicated calibration sites (Envisat, SARAL/AltiKa, CryoSat-2, Sentinel-3A&B…). This method will also be of particular interest for the SWOT mission.

The technique was initially implemented at the Senetosa calibration site, which has been operated by the OCA for the CNES since 1998 and is dedicated to the calibration and validation of the missions on the Topex-Jason nominal orbit (Jan et al. 2004, Cancet et al. 2013) and, more recently, to the Sentinel-3A mission (Bonnefond et al., 2018b). The regional calibration method was then implemented at the Ajaccio site, which has been used since 2008 for the verification of ERS-2, Envisat, SARAL/AltiKa and Sentinel-3A more recently, and at the Harvest (California) and Bass Strait (Tasmania) calibration sites dedicated to the missions on the Topex-Jason nominal orbit. As the method is totally generic, it was implemented at these three sites for Jason-1, Jason-2, Envisat, SARAL/AltiKa and Sentinel-3A&B.

The results obtained with the regional calibration method have been systematically compared to the bias estimates computed with the local in situ calibration methods used at the various sites, in close collaboration with the local teams (OCA (Bonnefond et al.), JPL (Haines et al.) and the University of Tasmania (Watson et al.)), as well as with the global calibration and validation results.

In addition, each calibration site is characterized by specific geophysical conditions. The Corsica site is located in the North-Western Mediterranean Sea where the oceanic tide amplitudes are rather low. On the other hand, the Harvest and Bass Strait calibration sites are subject to more energetic and complex oceanic conditions. The comparison of the regional altimeter bias estimates at these various calibration sites is consequently a valuable exercise as it provides information both on the stability of the altimeter range estimate but also on the quality of the tide and DAC corrections in these regions.

Finally, the Harvest site is dominated by swell conditions, while the Senetosa and Bass Strait sites generally undergo wind waves conditions, which may have an impact on the quality of the Sea State Bias correction provided in the altimetry products. Some recent works have also shown the interest of this Cal/Val technique to assess the Sea State Bias correction (SCOOP project for ESA and analysis of the Jason-1 absolute bias for CNES).

Regional CALVAL method: Validation at non-dedicated sites

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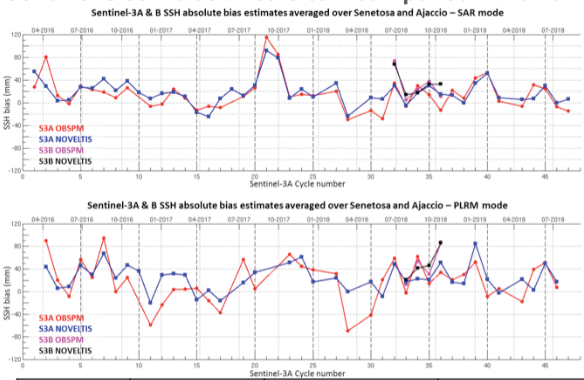
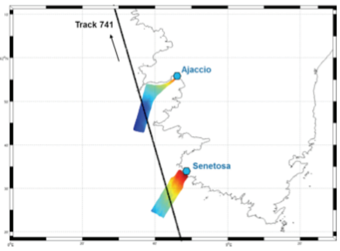
[1]*NOVELTIS, Toulouse, France;* [2]*OMP/CNRS/LEGOS, Toulouse, France*

Sentinel-3 SSH bias in Corsica – comparison with OBSPM results





Satellite	Processing center	SAR		PLRM	
		SSH bias (mm)	# cycles	SSH bias (mm)	# cycles
Mean (Senetosa/Ajaccio)					
S3A	OBSPM	+16 ± 4	42	+18 ± 6	38
S3A	NOVELTIS	+19 ± 3	44	+24 ± 4	39
S3B	OBSPM	+19 ± 7	4	+46 ± 16	4
S3B	NOVELTIS	+24 ± 5	4	+49 ± 14	4

General comments:

- ➔ Very good agreement between both processing centres (OBSPM and Noveltis)
- ➔ S3-A bias estimates for SAR mode are consistent for both sites in Corsica (more noise in PLRM)
- ➔ S3-B bias estimates are locally slightly higher than S3-A bias due to the model wet tropo correction choice for the SSH computation.

The Sentinel-3A configuration in Corsica is of particular interest, as the same track (741) flies close to both calibration sites, in Ajaccio and Senetosa, which gives the opportunity to estimate the absolute bias of the altimeter range at the two sites within a few seconds. During the tandem phase, the Sentinel-3B flew on the same orbit as Sentinel-3A, with a 30-second shift between the two satellites. This gave the opportunity to compare the SSH measurements of both satellites at the two calibration sites in Corsica within a very short timeframe. In situ data, geodetic datum and all necessary information are shared by the Paris Observatory/SYRTE and the French Riviera Observatory/GEOAZUR with NOVELTIS for the extension of the absolute calibration through a regional method. The Sentinel-3A&B bias estimates were computed by NOVELTIS both for the SAR data and the PLRM data, on track 741 (nominal orbit for Sentinel-3A, tandem phase for Sentinel-3B). In this configuration, no tide nor DAC corrections were applied to the altimetry and tide gauge sea surface heights.

The Sentinel-3A bias estimates are very consistent for both sites and both modes, within 1 cm. In general, the largest bias values are linked with large SWH, as the SSB correction available in the products is not optimal, neither for SAR or PLRM data. The fact that the Sentinel-3B bias estimates are 1 cm and 2 cm higher than the Sentinel-3A bias estimates for the SAR and PLRM data respectively, whatever the Corsican site, had raised question as other calval groups (including transponder analyses) found lower biases estimates for Sentinel-3B. However, this is explained by the choice of the wet tropospheric correction. Indeed, OBSPM has identified a 2-cm difference between the two wet tropospheric corrections (radiometer and model) available at the Corsica calibration site during the Sentinel-3B tandem phase. In the results presented here, the wet tropospheric correction from the model is used to compute the altimeter SSH, which explains that the Sentinel-3B SSH bias is higher than the Sentinel-3A SSH bias. When using the radiometer wet tropospheric correction, the results are consistent with the ones of the other calval groups.

The time series and statistics on the bias estimates computed by NOVELTIS and the OBSPM for both missions and both modes, and averaged over the two sites, also are compared. Whatever the computation method, the Sentinel-3A and Sentinel-3B SSH bias estimates are very close, with differences within a few millimetres which are mainly due to the selection of the data, which is specific to each processing technique.

Regional CALVAL method: Validation at non-dedicated sites

M. CANCET[1], F. LYARD[2]
[1]NOVELTIS, Toulouse, France; [2]OMP/CNRS/LEGOS, Toulouse, France

Sentinel-3A bias in Corsica – Regional estimates in Senetosa

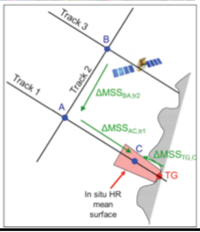
Configuration:

- Sentinel-3A offshore crossover points (tracks 741 and 044) with Jason-2 and Envisat tracks (green dots)
- MSS profiles along Jason-2 and Envisat tracks to link the offshore Sentinel-3A SSH and the Senetosa tide gauge SSH.
- Ocean dynamics:
  - high-resolution regional ocean tide model from NOVELTIS,
  - TUGO-m global simulation from LEGOS to remove the atmospheric effects (inverse barometer and high-frequency signals – avail. only until Dec. 2017).

General comment:

➔ Very stable results from one crossover to the other, generally within less than 1 cm.

Senetosa	SAR			PLRM		
PB 2.33 (MPC S3) cycles 1 – 26	Mean (mm)	Standard deviation (mm)	Number of cycles	Mean (mm)	Standard deviation (mm)	Number of cycles
Track 741 (local) *no ocean dyn. corr.*	23 ± 5	24	24	24 ± 6	28	23
Track 741 (local)	22 ± 5	26	24	22 ± 6	30	23
Track 741 X J2 085	10 ± 6	31	24	11 ± 8	36	23
Track 044 X Env 887	20 ± 7	33	25	21 ± 10	47	23
Track 044 X J2 222	16 ± 5	27	25	22 ± 8	40	23
Regional mean	**17 ± 6**	**29**	**25**	**19 ± 8**	**38**	**23**



In order to increase the number of the Sentinel-3A SSH bias estimates in Corsica, offshore SSH bias estimates have been computed using the regional technique.

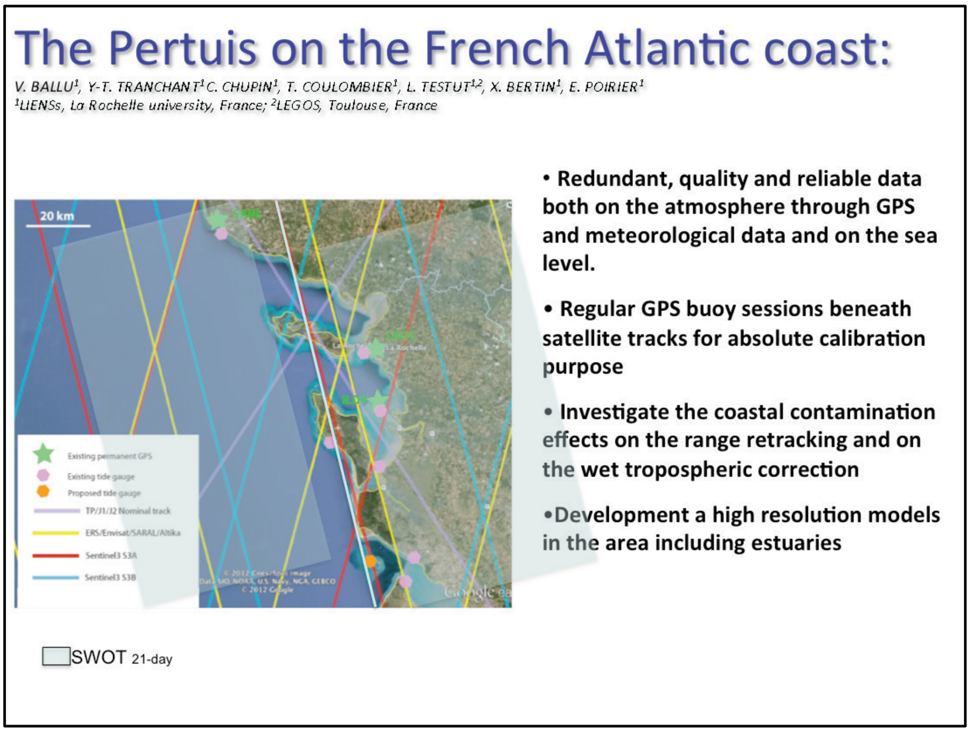
Here we present the regional SSH bias estimates computed in Senetosa. The map shows the configuration in Corsica and the selected offshore crossover points (green dots) between the Sentinel-3A mission and the Jason-2 and Envisat missions. Along-track mean sea surface profiles computed along the Jason-2 and Envisat nominal tracks were used to make the link between the offshore Sentinel-3A SSH and the Senetosa tide gauge observations. A high-resolution mean sea surface was used to link the altimetry and the tide gauge observations at the comparison point (point C in the generic diagram of the regional technique).

In order to take into account the differences in the ocean dynamics between the offshore altimeter crossover points and the tide gauge stations at the coast, the ocean tide and the atmospheric corrections were applied to the altimetry and tide gauge SSH using the same models for both types of observations. The ocean tide signal was removed using a high-resolution regional ocean tide model developed by NOVELTIS. A global simulation from the TUGO-m model (ex-MOG2D model) provided by LEGOS was used to remove the effects of the wind and atmospheric pressure on the sea surface heights at all time scales (inverse barometer and high-frequency signals). Because this atmospheric correction solution is available only until December 2017, the Sentinel-3A offshore SSH bias estimates were computed until cycle 25 for track 741 and cycle 26 for track 044.

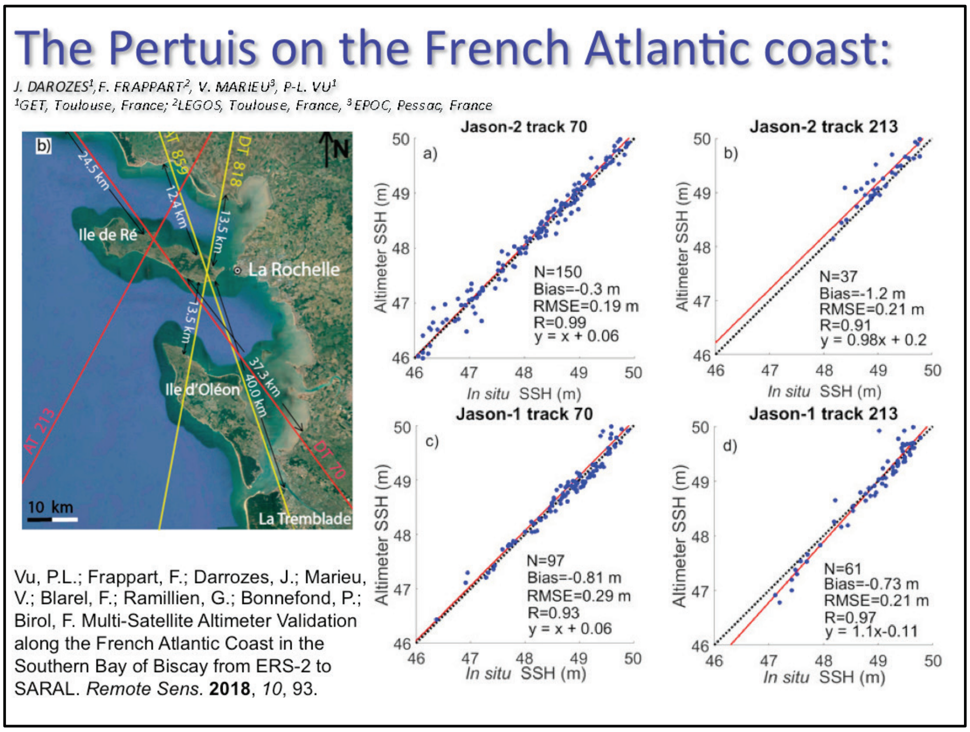
The table gives the Sentinel-3A regional SSH bias estimates in Senetosa, both for the SAR and the PLRM products, at the three selected crossover points.

For comparison purpose with the following lines, the first line in the table gives the results obtained for the direct comparison between the S3A SSH and the Senetosa tide gauge SSH on track 741, when no ocean dynamics correction is applied, over the period of availability of the atmospheric correction (cycles 1 to 26). The second line shows the results of the direct comparison on track 741 when using the ocean dynamics corrections. For all the other lines (individual crossover points), the ocean dynamics corrections were also applied. The regional mean is the average of all these estimates (local and offshore).

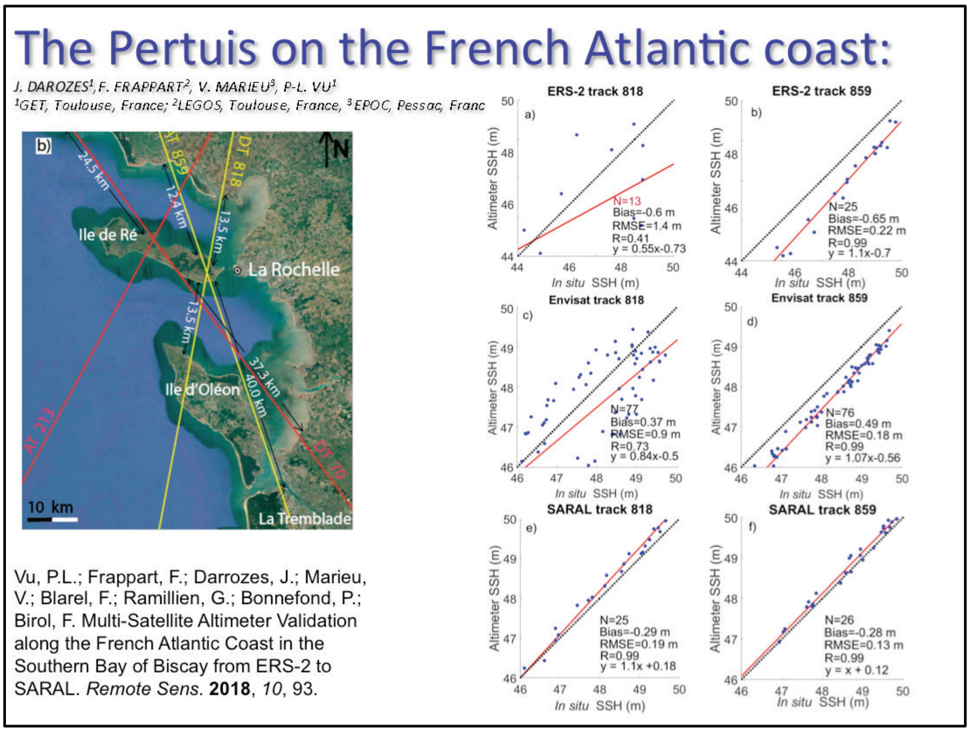
The results are stable from one crossover point to the other, generally within less than 1 cm. The variability of the SSH bias estimates is larger at the crossover point with the Envisat track 887. In the SAR product, this is mainly explained by rather strong SSH bias values for a few cycles. In the PLRM product, this is intensified by the strong SSH bias value on cycle 13. The Sentinel-3A regional SSH bias in Senetosa is quite consistent with the local estimates, both in terms of mean and variability.



Map : Satellite tracks in the area of the Pertuis, with existing tide gauges and GPS stations. The **proposed offshore tide gauge** is also shown in orange on the map (Cordouan lighthouse). In addition to the **three tide gauges collocated with on-land GPS** which are part of the SONEL program (La Rochelle, Ile d'Aix and Les Sables d'Olonne), four other tide gauges, belonging to the RONIM network are also available in the area and could benefit CAL/VAL activities in the area.



In this study, radar altimetry data from successive satellite missions, European Remote Sensing-2 (ERS-2), Jason-1, Envisat, Jason-2, and Satellite with ARgos and ALtiKa (SARAL), were used to measure sea surface heights (SSH). Altimetry-derived SSH was validated for the southern Bay of Biscay, using records from seven tide gauges located along the French Atlantic coast. More detailed comparisons were performed at La Rochelle, as this was the only tide gauge whose records covered the entire observation period for the different radar altimetry missions. The results of the comparison between the altimetry-based and in-situ SSH, recorded from zero to five kilometers away from the coast, had root mean square errors (RMSE) ranging from 0.08 m to 0.21 m, 0.17 m to 0.34 m, 0.1 m to 0.29 m, 0.18 m to 0.9 m, and 0.22 m to 0.89 m for SARAL, Jason-2, Jason-1, ENVISAT, and ERS-2, respectively. Comparing the missions on the same orbit, ENVISAT had better results than ERS-2, which can be accounted for by the improvements in the sensor mode of operation, whereas the better results obtained using SARAL are related to the first-time use of the Ka-band for an altimetry sensor. For Jason-1 and Jason-2, improvements were found in the ocean retracking algorithm (MLE-4 against MLE-3), and also in the bi-frequency ionosphere and radiometer wet troposphere corrections. Close to the shore, the use of model-based ionosphere (GIM) and wet troposphere (ECMWF) corrections, as applied to land surfaces, reduced the error on the SSH estimates.



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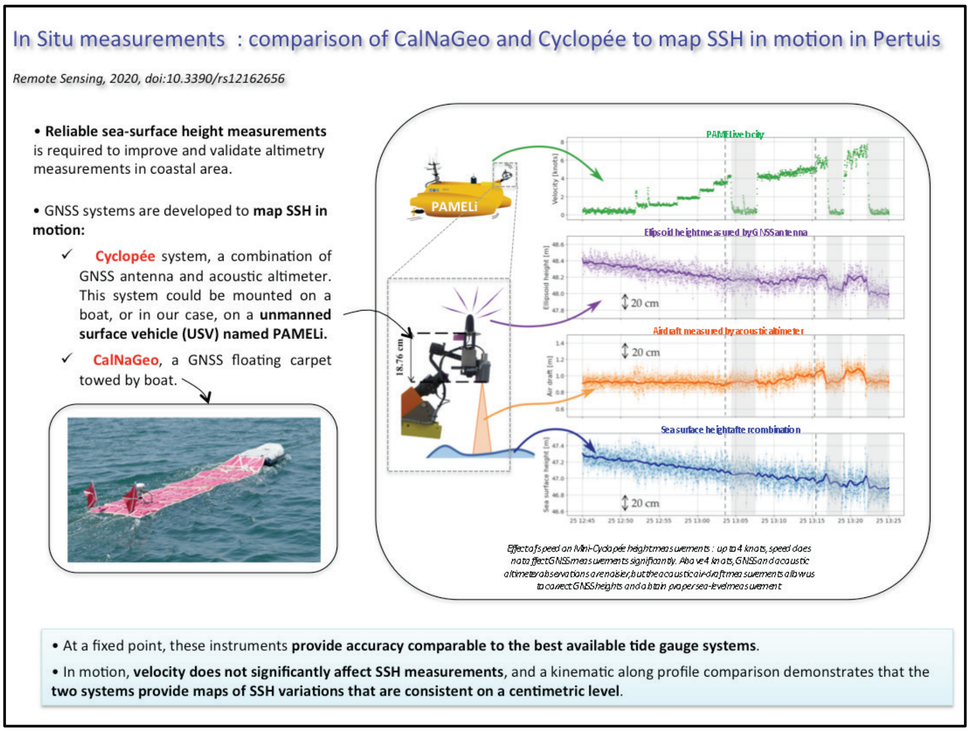


In coastal area, reliable in-situ sea-surface height measurements are required to improve and validate altimetry measurements. This paper aims to present the CalNaGeo towed carpet and the Cyclopée system mounted on PAMELi USV (Unmanned Surface Vehicle). These two systems are based on Global Navigation Satellite Systems (GNSS) to map sea surface height in motion. Through experiments carried out in the Pertuis Charentais area and in Noumea Lagoon, we demonstrate their capacity to measure sea level height at the centimetric level.

<u>The study sites :</u>

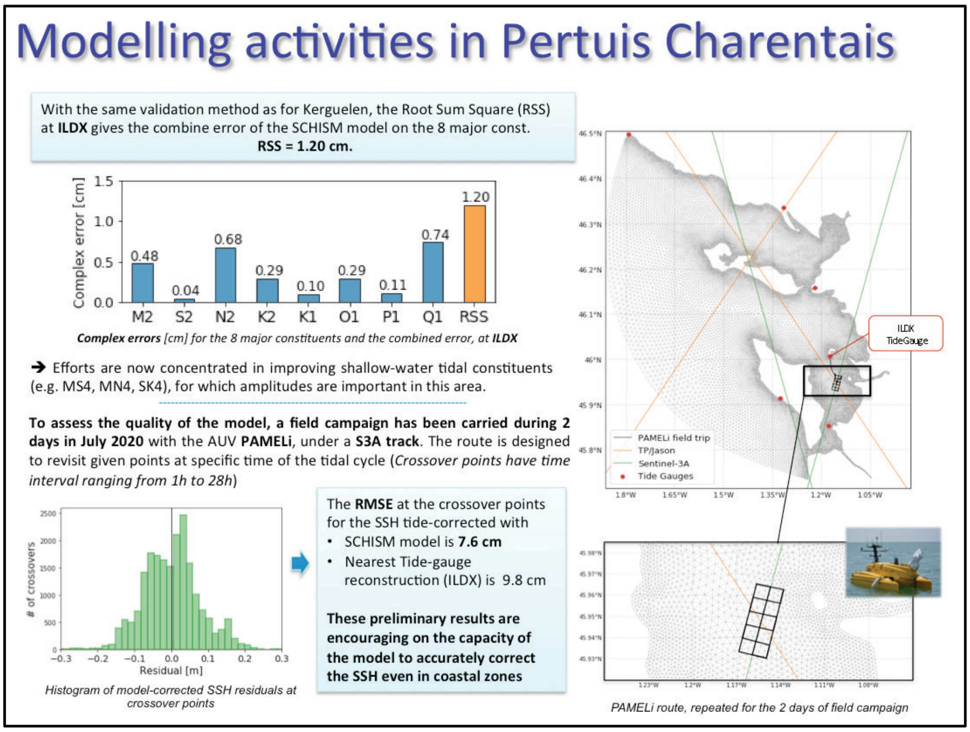
The Pertuis Charentais area and the Noumea Lagoon have different configuration and dynamics, and they allow to tackle different scientific questions. They are both highly covered by nadir altimetry missions and also future mission SWOT, and their GNSS and tide gauge networks and nearby research infrastructures make them relevant for cal/val activities.

<u>Main results :</u>

- ✓ We first compare the two systems to well-qualified tide gauge during “static sessions” (i.e. not moving horizontally). These sessions indicate that, despite an absolute bias of 1-2cm, the systems are stable and precise even over short measurement periods, with a standard deviation on the filtered time series residuals of around 4 mm. Although the systematic errors still need to be further investigated, our systems are comparable in terms of precision with the best available tide gauge.
- ✓ We designed tests to evaluate the effect of the vessel speed on water height measurements. We demonstrate that the towing speed of CalNaGeo does not affect its height measurements. For Cyclopée system mounted on PAMELi USV, we observe that, up to 4 knots, the vessel is stable, and speed does not affect GNSS measurements significantly. Above 4 knots, GNSS and acoustic altimeter observations are noisier, but the acoustic air-draft measurements allow us to correct GNSS heights and obtain suitable sea-level measurement up to a speed of 7 knots or if the drone stops.
- ✓ We finally compare both systems along the same profile and under the same weather conditions. On two consecutive days, the two systems mapped sea surface height (SSH) under trace 70 of Jason 3 altimetric mission (track length : 15km, average speed : 3.5knots). The mean difference between Mini-Cyclopée and CalNaGeo SSH measurement are 1.9 +/− 1.5 cm and 2.2 +/− 1.0 for the first and second sessions. This shows that, beyond systematics errors induced by GNSS processing or geodesic measurements, the two kinematic GNSS methods are consistent to measure SSH in motion at a centimetric level.

Link to the paper : https://doi.org/10.3390/rs12162656

More information about PAMELi USV : https://pameli.recherche.univ-lr.fr/?lang=en



The Pertuis area is overflown by many altimetry missions including TP/J, Sentinel-3 (A and B), and the future **SWOT** mission. **In order to support CAL/VAL activities in** Pertuis area, a **high resolution hydrodynamical** model based on **SCHISM** platform (Zhang et. Al., 2016) is being developed.

MODEL CONFIGURATION

- Unstructured grid with 49404 elements.
- Resolution from 2 km in the deep ocean to 50 m near the coastline.
  - ➔ Continuity from open ocean to coastal/estuarine zones, in adequation with today and future altimetry missions.
- Tide forcing: MAREST-2018 NEA atlas, developed in the framework of MAREST project (SHOM/LEGOS/Noveltis/CNES).

FIRST RESULTS

Tide Validation:

The tide model is validated by computing complex errors at ILDX TG. After performing harmonic analysis on observed and modeled water levels, the Root Sum Square (RSS) gives the combine error of the model. **RSS = 1.20 cm** for the 8 major constituents.

- However, the model accuracy have to be improved for **shallow water tidal waves** (e.g. MS4, MN4, SK4) resulting from the tide/ continental shelf interaction. For these waves, the main error source is the tide forcing itself. An investigation of the precise error budget is currently in progress, based on the comparison between offshore altimetry tracks and the tidal atlas.
- A substantial effort in the parametrization of bottom friction, which can have a strong impact on tidal amplitudes, remains to be done. Spatially variable bottom roughness, based on the local nature of sea-bed, are currently under investigations.

Crossover validation:

A field campaign has been carried during 2 days in July 2020 with the AUV **PAMELi**, under a **S3A track**. The route is designed to revisit given points twice during the day, and the second day is an overlapping of the outward journey.

Main objectives of the campaign:

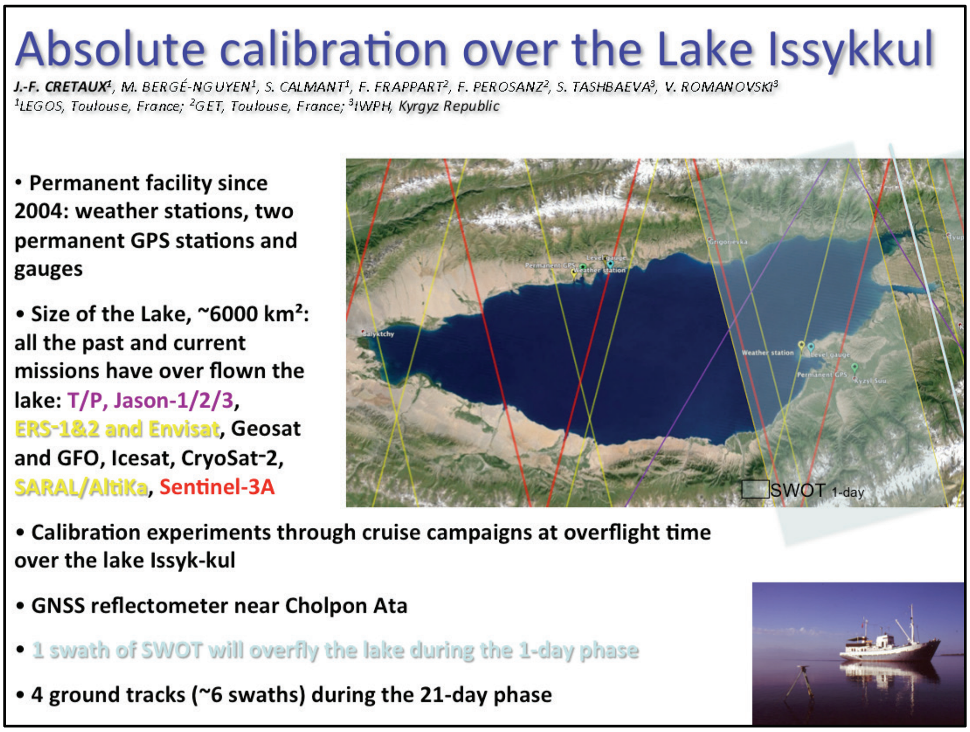
- Model validation under S3A track though exploitation of crossover points, which consists of pairs of measurements at different time.

  ➔ Methodology based on a careful study of crossovers time intervals, in order to avoid tide aliasing phenomena

- *Direct comparison with S3A sea height measurements, to give an assessment of the S3A coastal data quality [work in progress]*

Based on a **maximal distance** between two measurements of **50m** and **a minimal time interval of 1 hour**, **20880 crossover points** have been determined. The residual is computed at each crossover point, as the difference between the 2 measurements. The histogram of these residuals shows a distribution centered at 0.1 cm, and the **RMSE** of residuals is **7.6 cm**.

These preliminary results are encouraging, and already make this SCHISM configuration a better solution for correcting sea height measurements in the Pertuis area, in comparison of the nearest Tide-Gauge reconstruction.



Lake Issykul has a length of 180 km and a width of about 60/70 km. West part of the lake's shoreline is very shallow, while east, north and south part is covered with high mountains.

It is the region of the world the most far from any ocean well located in the center of the Eurasia

The seiches are not frequent, not too high (generally smaller than 10 cm) and they could be monitored as they are preferentially oriented in the East/West direction: an in situ gauge with data time sampling of 5 minutes is already installed in the East side of the lake where the effect is the highest.

The access is quite easy thanks to 16 years of collaboration between Legos and Kyrgyz institute of hydrology.

Vessel for navigation over the entire lake is possible all the year at a reasonable price for such boat.

Based on more than 16 years of GPS data combined to multi-satellite altimetry data, a Mean lake surface at high spatial resolution has been calculated (Berge-Nguyen et al., 2020).

The Lake Issykkul has also been selected for the C/V of the future SWOT mission.

History of collaboration beetwen Legos and IWPH

-2003 for 2 years

Collaborative Linkage Grant approaved by NATO: cal/val for radar altimetry

-2007 for 4 years

-CNES program for research (TOSCA) funded a full cal/val project for Jason-2 (FOAM) where Issykkul was the continental component

-2011 for 4 years

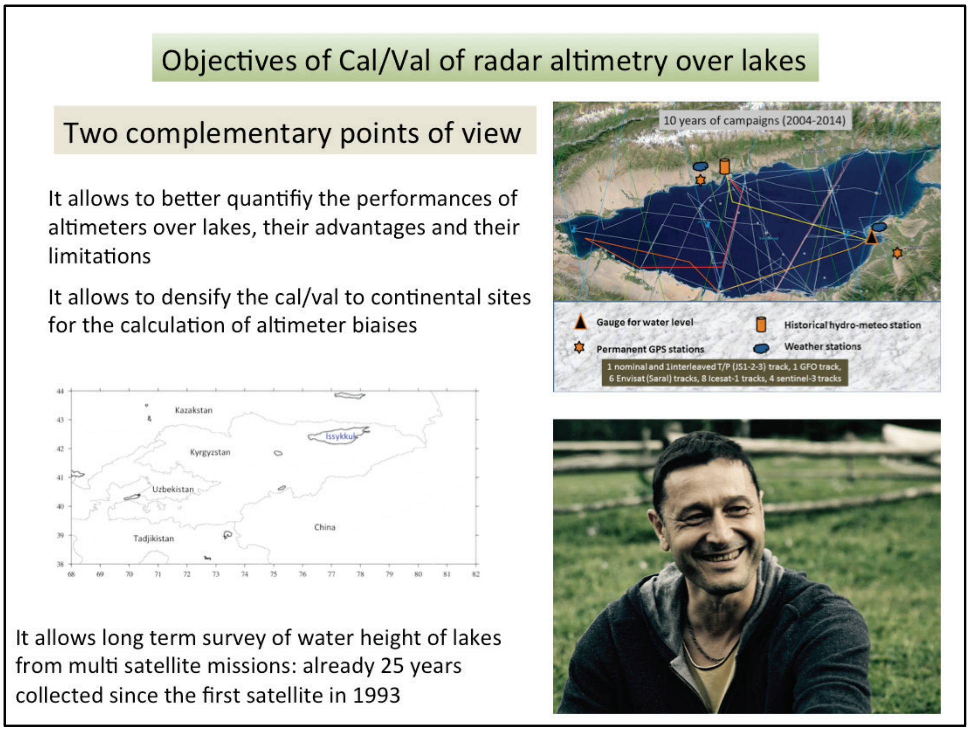
-Extension of FOAM to Saral/AltiKa

-2015 for 4 years

-Extension of FOAM to Sentinel-3A and Jason-3

-2015 for 8 years

-Decision to include the lake Issykkul as a priority cal/val Site for SWOT



Satellite altimetry has been extensively used over the last two decades to calculate the water height variations over the Earth's lakes, rivers, reservoirs and floodplains (Calmant et al. 2008, Frappart et al., 2015, Cretaux et al., 2015, 2016). However over continental waters, this technique is limited by several factors.

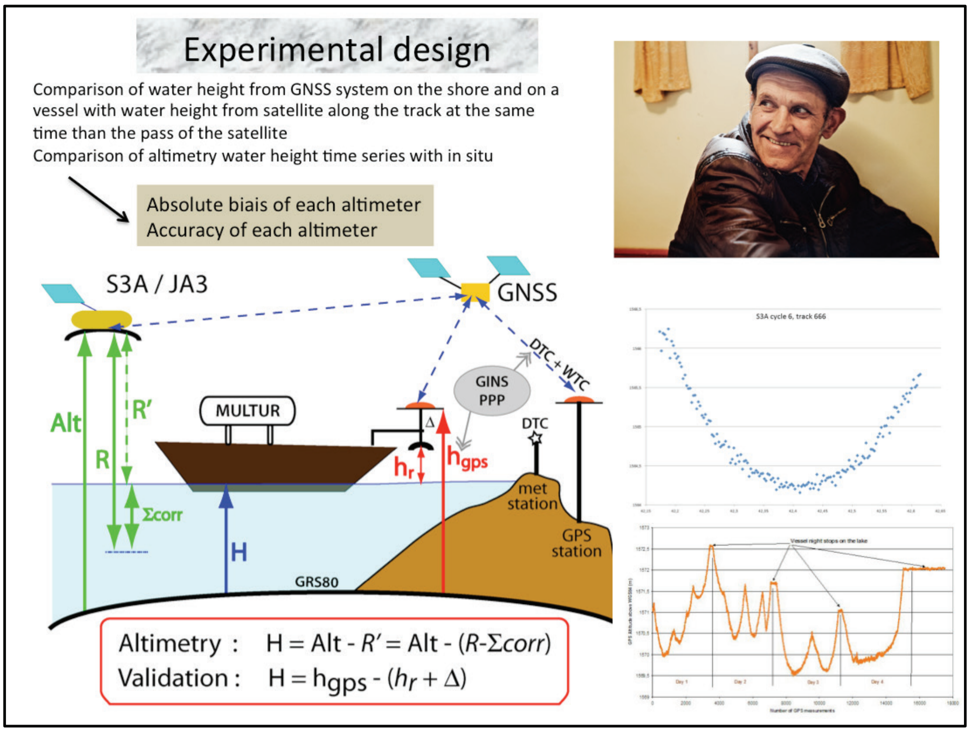
First of all, the onboard retrackers were designed for ocean surfaces, hence the radar echo waveform is not always processed correctly and may provide erroneous range measurements. Moreover, rapidly varying topography or complex terrain may inhibit the retrieval of the correct elevation data. This leads the user community to develop new algorithms (namely "retracking") to better fit these complex waveform echoes. Relative range biases between various retracking have been computed in Crétaux et al. (2009, 2011, 2013, 2018, Bonnefond et al., 2018, Quartly et al., 2020). Other limitation comes from the corrections of range measurements due to the radar propagation in the atmosphere.

Indeed, there is clear evidence that the calibration of satellite altimetry over the ocean does not apply to inland seas (e.g., corrections, retracking, geographical effects). Shum et al. (2003), Cheng et al. (2010), and Crétaux et al. (2009, 2011, 2013, 2018) pointed out that the number and variety of Calibration and Validation (hereafter C/V) sites for altimetry have to be increased in order to have more global distribution and more robust assessment of the altimetry system over different lakes. This allows us to verify whether specific hydrological conditions would lead to a different estimation of the absolute bias of the instruments.

Moreover, C/V over lakes surfaces has interesting characteristics with respect to ocean surface. The surface of the reflecting water body is little affected by tide effects, wind waves are reduced, the surface dynamic variability is small and the Sea State Bias (SSB) is very negligible over lakes (Shum et al. 2003, Crétaux et al. 2009, 2011). Finally, for some big lakes, like Lake Issykkul, it is also possible to perform multi mission C/V on a same site (Crétaux et al. 2013).

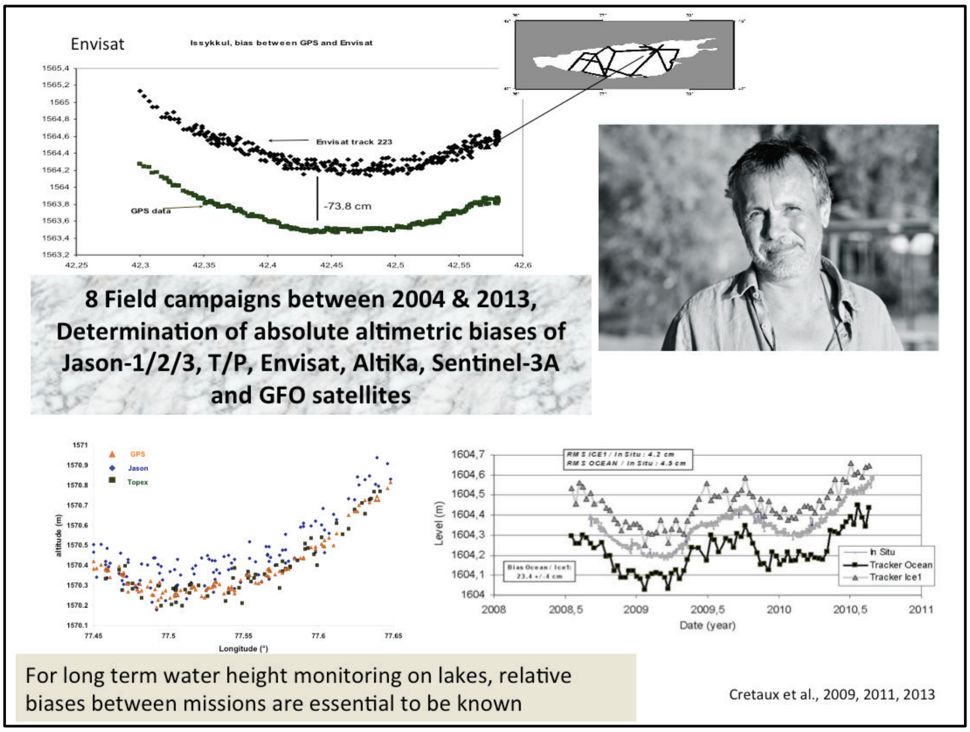
The comparison of altimeter biases of T/P, Jason-1, Jason-2, Jason-3, SARAL/AltiKa and Sentinel3A obtained over lakes and over ocean sites, shows an agreement at better than 2 cm (Cheng et al. 2010, Crétaux et al. 2011, 2018, Bonnefond et al., 2018, Quartly et al., 2020) which indicates that lakes can be relevant sites for multi mission C/V.

Lake Issykkul (Figure) is located in Central Asia, in Kyrgyzstan, and since 2016 (when previous FOAM project was submitted to OSTST) 6 new field campaigns have been carried out in the framework of the FOAM project for the C/V of recent satellite altimetry missions: Jason-3, SARAL/AltiKa, Sentinel-3A and Sentinel-3B.



Since 2016, 6 field campaigns over the lake Issykkul have been carried out in the framework of the FOAM project. Lake Issykkul has been instrumented with a network of different instruments. These instrumentations were deployed in order to better calibrate the tropospheric correction (two weather stations and two permanent GNSS receiver) and to serve as a validation of long term time series of water level calculation from satellite altimetry (one radar to measure the in situ water height of the lake). We also have agreement with the Institute of water problem of Bishkek (IWPB) to collect historical data from in situ instrument to complete the validation dataset. It includes level gauges and weather station.

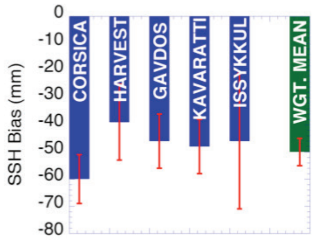
Regarding the principal objective of the experiment, which is to estimate the altimeter absolute bias, we have developed a strategy of field measurements based on GNSS surveys of the lake surface along the altimetry track for each targeted satellite. The principle is to install one or two GNSS antennas on the top of a vessel, and to navigate along the track, with one condition, which is to measure the ellipsoidal altitude all along the satellite track at the exact time of the pass of the satellite (what we call RDV mode). Meanwhile we install a radar on the boat which also measure the GNSS height antenna and allows thus to correct for changing waterline of the vessel when it moves at different velocities. This RDV mode also allows us to cancel errors due to the potential seiche effects, which statistically may occur during the experiment. Through this procedure, if a seiche is observed during the experiment, it is naturally removed in the estimation of the altimeter bias, as both, the GNSS and altimeter measure this seiche instantaneously. This procedure has been applied with success in previous study (Crétaux et al. 2011, 2013, 2018, Bonnefond et al., 2018, Quartly et al., 2020) for the estimation of Jason-1, Jason-2, Jason-3, SARAL-AltiKa, Envisat and Sentinel-3A absolute and relative biases.



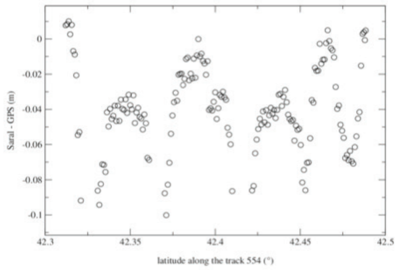
In order to determine the altimeter absolute bias we must calculate the ellipsoidal altitude of the lake along the altimeter track by two means: from altimetry data and from the GNSS receivers installed on a boat which follows the different altimeter tracks during 3-4 days of cruise on the lake. The absolute bias is simply the averaged difference between both estimations along the track. It is obviously also necessary to quantify the error budget of this calculation which originates from both water altitude estimations. So part of the uncertainty is due to altimetry errors, the other part from the GNSS data processing.

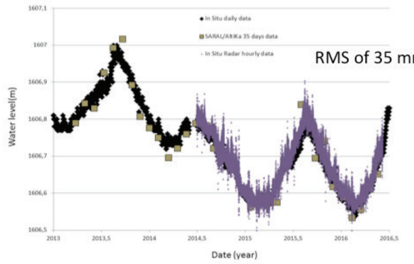
For tropospheric correction we have used the weather stations data combined to the permanent GNSS receiver. It has allowed to use more precise dry and wet tropospheric correction and also to determine the level of errors made when using the models available in the GDRs (it is sub centimeter for dry tropospheric correction and centimeter for wet tropospheric correction, Cretaux et al., 2013).

Cal/Val on SARAL/AltiKa (field campaign in 2014)



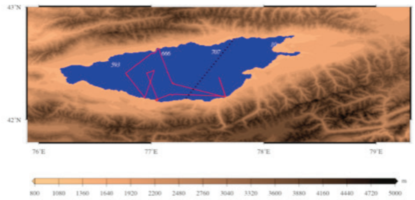
- 52 +/-24 mm

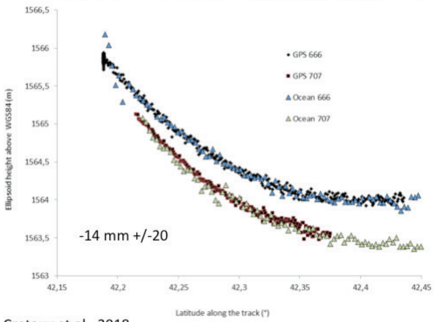


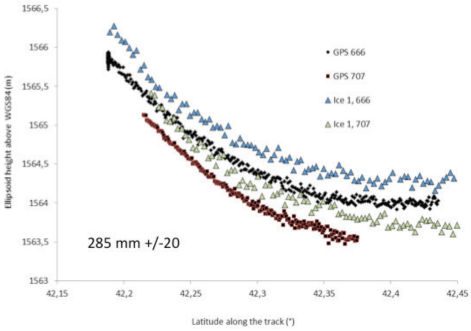


Bonnefond et al., 2018

Campaigns of 2016-2017: Sentinel-3A absolute bias

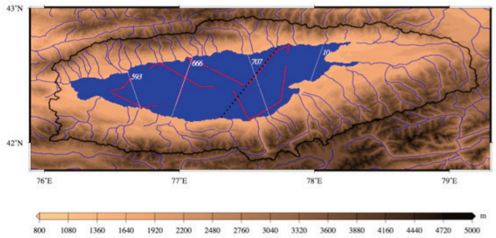




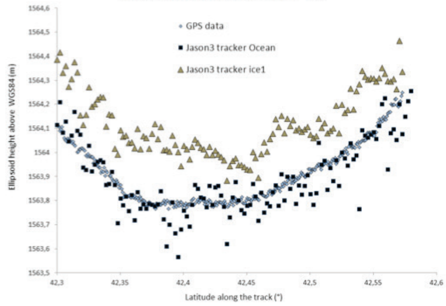


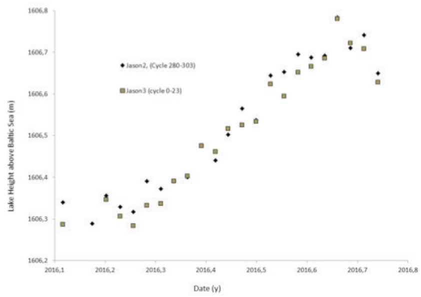
Cretaux et al., 2018

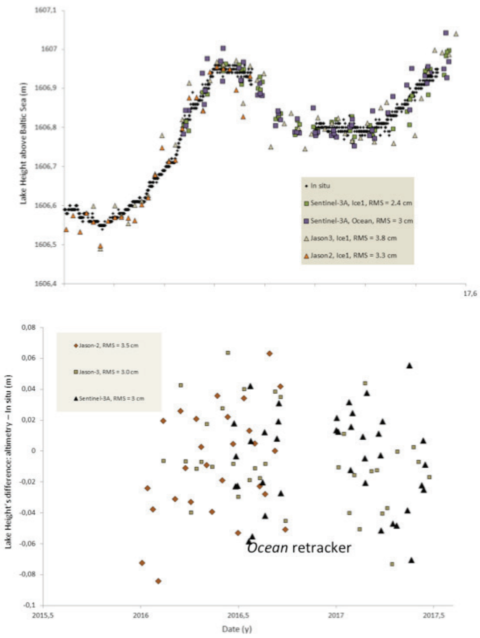
Campaigns of 2016-2017: Jason-3 absolute and relative biases



Absolute bias with *Ocean* 28 mm +/-40
Offtset with *Ice1* 206 mm +/-30







Accuracy of sentinel-3A and Jason-3

Absolute bias Summary

Ocean retracker

Jason-3 : **28 mm +/-40**

Sentinel-3A : **-14 mm +/-20**

Saral : -**52 mm +/-24**

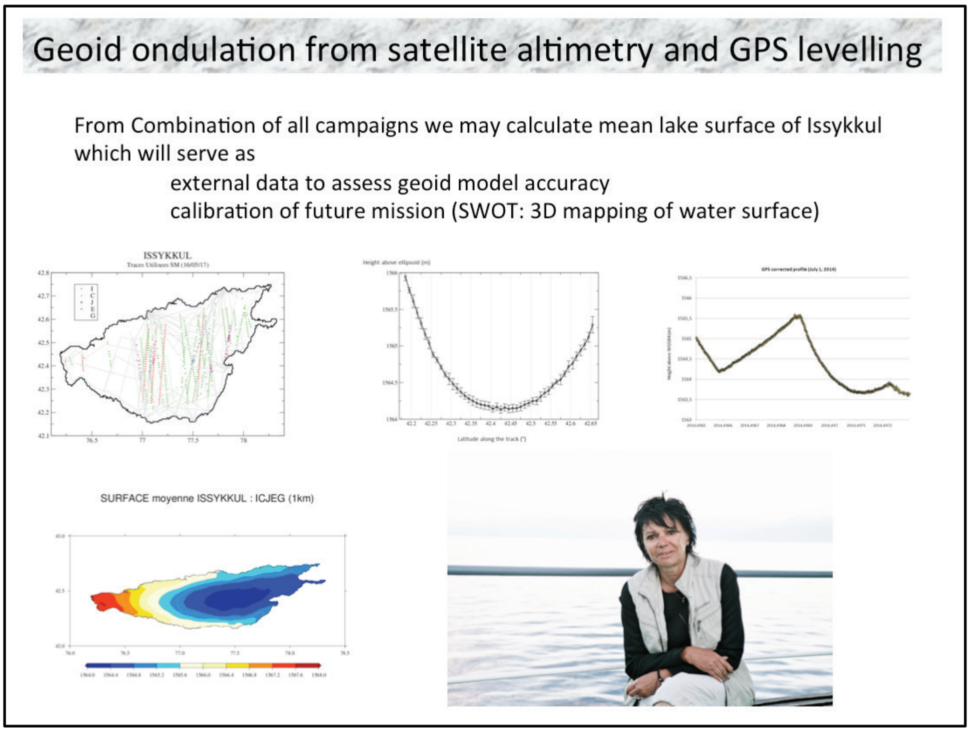
Ice-1 retracker

Jason-3 : **206 mm +/-30**

Sentinel-3A : **285 mm +/-20**

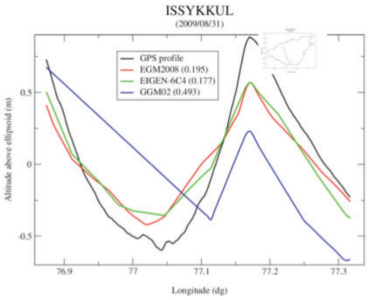
Saral : **34 mm +/-20**

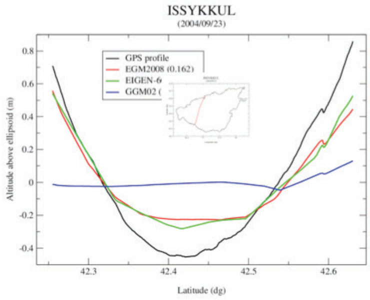
(Bonnefond et al., 2018, Cretaux et al., 2018)

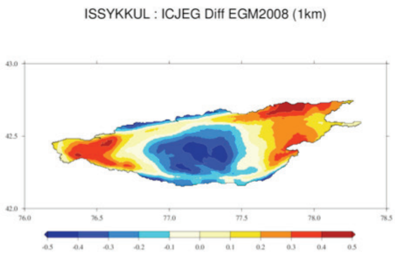


Recently we also have calculated mean lake surface (MLS) of 22 big lakes in the world, using the lake Issykkul as a test case for validation of this calculation. It was an objective of the previous project. Currently, lake water level inferred from satellite altimetry is provided with respect to an ellipsoid. Ellipsoidal heights are converted into orthometric heights using geoid models interpolated along the satellite tracks. However, the spatial resolution of the current geoid models does not allow capturing short wavelength undulations that may reach decimeters in mountaineering regions or for like the lake Issykul. Assuming that MLS mimics the local undulations of the geoid, our study have shown that over a large set of lakes including the Lake Issykkul (next slide), short wavelength undulations of the geoid in poorly sampled areas can be derived using satellite altimetry. Moreover, MLS can serve as a validation dataset for the future mission SWOT (Surface Water and Ocean Topography) which will measure and map water heights over the lakes with a high horizontal resolution of 250 by 250 meters. The full methodology is described in Berge-Nguyen et al., 2020. It has been validated using the GNSS field campaign over the lake Issykkul and also using the mean profile along the ICESAt-2 tracks. The MLS calculated over the lake Issykkul has a precision of about 5 cm.

Geoid ondulation: comparison with models





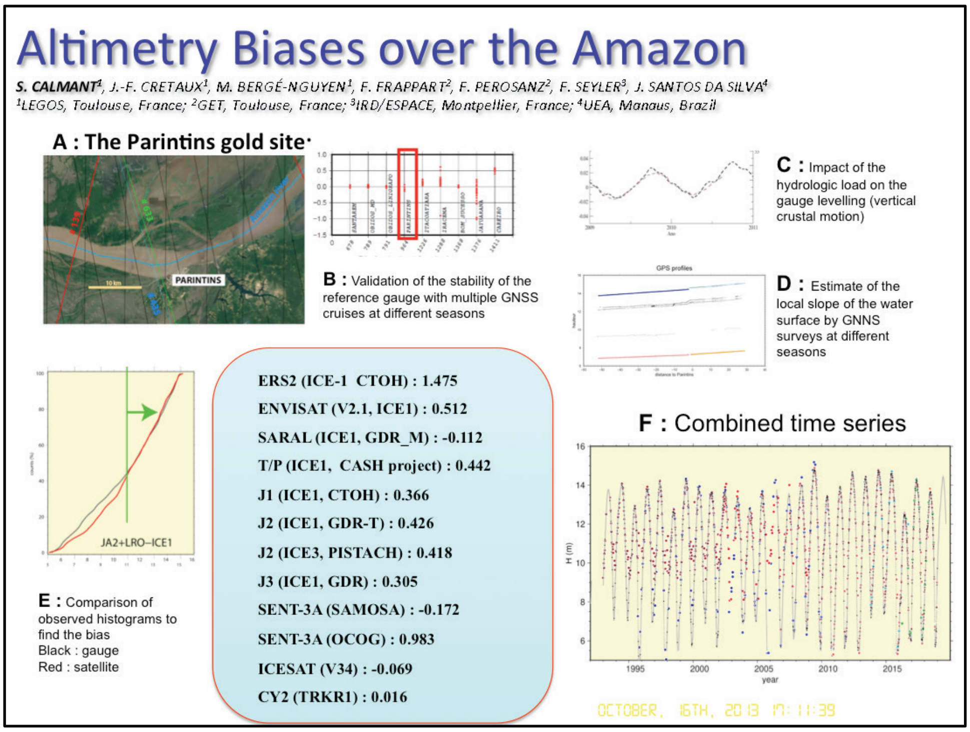


Conclusions & perspectives

Last 15 years: cooperation with IWPH

- 15 field work for calibration of 8 altimeters
- Installation of 2 permanent GPS receivers
- Installation of a permanent lake gauge 5 scientific publications

Ready for C/V of current and future missions (S6/Jason-CS, SWOT...)



A « Gold site » has been built at Parintins (Amazon). Over there, all existing and past mission cross the river within 15 km of Parintins

Main steps were :

B : Gauge stability was confirmed by the little spread of the reference levels found by the kinematics surveys (combining water level given by the floating GNSS and the reading at the gauge, after correction of the hydrologic load)

C : Level the gauge (GNSS static + cinematic surveys) and use a level dependent reference value (crustal displacement +/- 4 cm from GRGS GRACE solutions, after testing all other solutions)

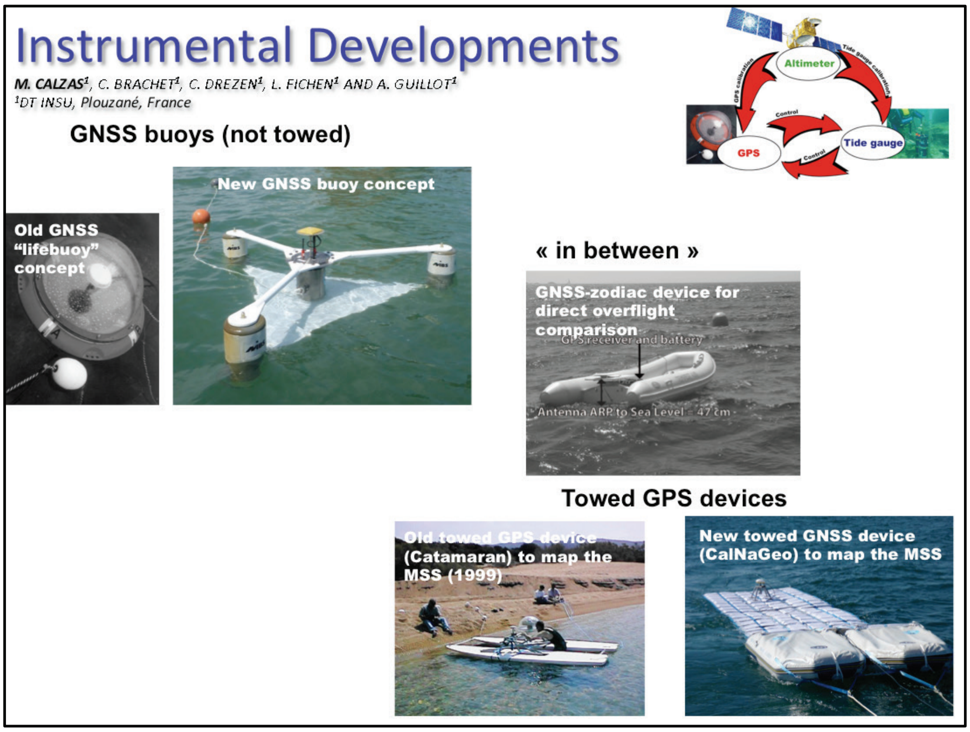
D : Satellite measurements have been corrected for the slope of the water surface to account for the distance to the gauge that can vary for each cycle, even for Exact Repeat missions (even more for Geodetic Missions). Slope was determined by GNSS cruises at various seasons (12-17 mm:km)

E : bias of each hand made time series, corrected for B,C,D has been estimated by fitting histograms rather than the series themselves to reduce the overweighting of most frequent levels. Only the part right of the green line is considered (limit being mission dependent) to exclude ranges with many erroneous sat values

F : after being corrected, all the series are combined into a long, consistent (*) multi-mission series from 1992 to present day, including Geodetic Missionsmissions.

This Gold Site will be maintained operational for the future missions, including SWOT since a nadir track passes right over the gauge

(*) this study detected residual errors in multi-mission series published on various web sites



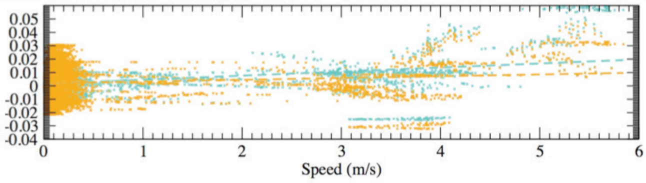
GNSS buoys have undergone many different developments since their first use in 1994 at Harvest (Born et al., 1994) after the launch of TOPEX/Poseidon. The most recent developments (Watson et al., 2011; Testut et al. 2010) raise the antenna relative to the water level while minimizing the tilt to avoid loss of lock caused by waves. This type of design allows very precise definition of antenna heights, but does not allow smooth movement to cover large areas. On the other hand, by using boats (at Lake Issykkul or Vanuatu for example) it is possible to cover large areas, but with the difficulty of estimating the antenna height due to speed dependence, fuel consumption or other factors (Bouin et al., 2009a,b; Crétaux et al., 2011&2013).

The key point in the absolute calibration process is that the relationship between the sea surface height from altimetry data and that from in situ measurements is mainly affected by the geoid slope between the position of the altimetry measurement offshore and that of the tide gauges very close to the coast. This slope is a few cm/km on average and, for example, a specific GNSS campaign was carried out in 1999 to determine a geoid map about 20 km long and 5.4 km wide centred on the T/P and Jason satellite ground track No. 085 at the Senetosa Cape site (Bonnefond et al., 2003b).

From our 20+ years of experience with the GNSS buoy in Senetosa (Corsica), we have identified two main problems with the concept based on a "lifebuoy" type buoy: firstly, during the trip from the tide gauge to the calibration point at sea, many locking losses are encountered which degrade the accuracy of the GNSS solution, secondly, in strong sea state conditions, the buoy tilts strongly leading also to satellite losses. We have therefore designed a new system based on a zodiac integrating both the antenna and the receiver (Bonnefond et al. 2015). Such a system allows minimizing locking losses and a relatively high speed operation (~7 knots) in order to use the same system both for altimeter calibration at overflight but also for local geoid extension. Unfortunately, tests at different speeds showed a strong dependence of the waterline on sea state which is difficult to model for a centimeter accuracy.

Instrumental Developments: CalNaGeo

Two models of the GNSS-carpet (CalNaGeo) has been developed:



Differences (in m) between CalNaGeo and tide gauges sea level as a function of speed during the campaign in Corsica. It illustrates the negligible dependence of the waterline as a function of speed (less than 3 mm/(m/s))

Table 1. Linear trend of SSH differences (CalNaGeo – Tide gauges) as a function of velocity

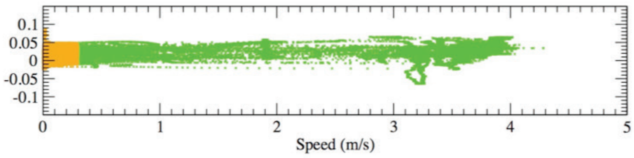
	Bias @ 0 m/s (mm)	Slope (mm/(m/s))	Number of data
M3&M5	+2.77 ± 0.09	+2.56 ± 0.07	7861
M3&M5 (0<V<4)	+3.48 ± 0.07	+0.06 ± 0.07	7597
M3&M5 (0.5<V<4)	+5.73 ± 1.0	+0.86 ± 0.34	980

To avoid the dependence of the waterline to sea state and speed (planning effect), the Technical Division of INSU (DT INSU) has explored, at our request, another approach to build a mobile GNSS for sea surface mapping that can be towed at high speed. The basic idea is therefore to force the antenna reference point to stay at the sea surface level, by putting a GNSS antenna on a floating carpet (CalNaGeo). The results obtained during a test campaign carried out at the Senetosa site (Corsica) have shown a very high stability of the waterline line (better than 3 mm/(m/s) over the range 0-6 m/s and almost zero in the 0-4 m/s range. The only negative point of this instrumentation is the size of the instrument and the time required to deploy it. Nevertheless, it remains for the moment the most powerful instrument to achieve centimeter accuracy on sea level height in both static and dynamic applications.

Instrumental Developments: Cyclopée

Concept: measuring in real time, simultaneously with GNSS measurements, the position of the antenna above sea level. This makes possible to avoid the need to calibrate the boat's attitude, in order to obtain centimeter precision, and thus to simplify the measurement campaign by making the direct and simple use of a boat possible.

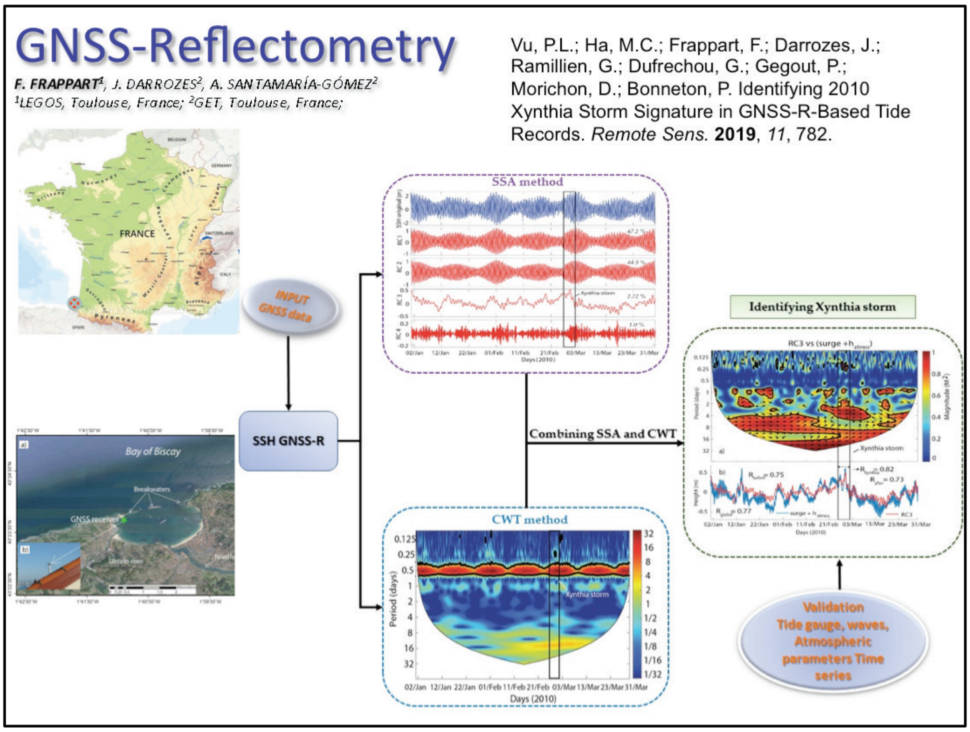
Left: picture of the system named "Cyclopée" (acoustic radar and GNSS antenna mounted on a stabilizer arm) at the front of the boat during the campaign on the Gironde river in October 2018. Right: photo of the electronic box containing the data acquisition and control/ visualization system.



Differences (in m) between Cyclopée and CalNaGeo as a function of speed during the campaign on the Gironde river in October 2018. It illustrates the negligible dependence of the waterline as a function of speed.

The use of vessels as a GNSS antenna support would be much more efficient and practical compared to CalNaGeo. This would allow higher speeds to be achieved and reduce the amount of useful equipment. However, its use is relatively rare in GNSS precision measurement operations, as vessels generally have poor stability. They are indeed subject to significant roll and pitching and have the unfortunate characteristic of planning over at a certain speed. All these parameters greatly modify the previously determined position of the GNSS antenna above the water level, and thus alter the final accuracy of the results obtained. Numerous studies (Zilkowsky et al, 1997, Clarke et al, 2005, etc...), have been carried out by precisely calibrating the attitude of a boat according to various parameters (speed, turn, sea conditions, boat load, etc...) which allows to know precisely the position of the GNSS antenna above the water. These calibrations are particularly long, complex, expensive, and do not always allow obtaining accuracy of the order of a centimeter.

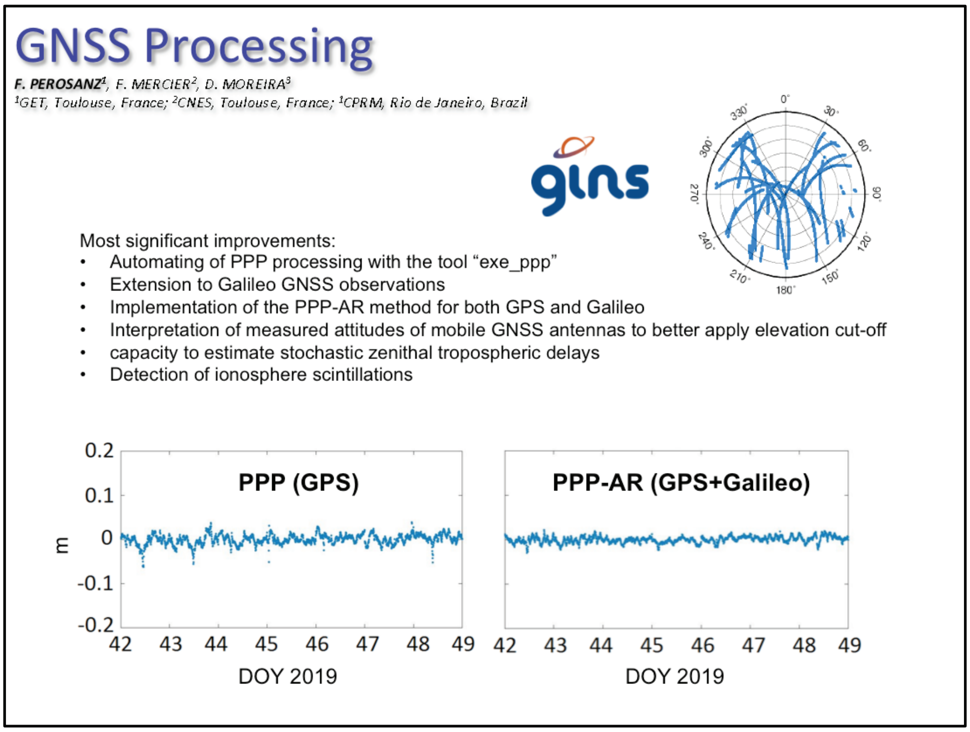
Thus, the idea of measuring in real time, simultaneously with GNSS measurements, the position of the antenna above sea level is particularly interesting: this would make it possible to avoid the need to calibrate the boat's attitude, in order to obtain centimeter precision, and thus to simplify the measurement campaign by making the direct and simple use of a boat possible. A first prototype, named Cyclopée, with a data control/visualization interface contained in a waterproof box (see Figure) was used during a multi-instrument campaign on the Gironde in October 2018.



In this study, three months of records (January–March 2010) that were acquired by a geodetic Global Navigation Satellite Systems (GNSS) station from the permanent network of RGP (Réseau GNSS Permanent), which was deployed by the French Geographic Institute (IGNF), located in Socoa, in the south of the Bay of Biscay, were used to determine the tide components and identify the signature of storms on the signal to noise ratio (SNR) during winter 2010. The Xynthia storm hit the French Atlantic coast on the 28th of February 2010, causing large floods and damages from the Gironde to the Loire estuaries. The Global Navigation Satellite Systems-reflectometry (GNSS-R) technique can be used for the monitoring of sea surface variations. At monthly to interannual time-scales, SSH variations are mostly derived from the processing of the Signal-to-Noise Ratio (SNR) acquired by a geodetic GNSS receiver. SSH variations are mostly derived from the processing of the Signal-to-Noise Ratio (SNR) recorded by a geodetic GNSS receiver. SNR data records from the Socoa geodetic station (south west of France) were used to determine the SSH variations from January to March 2010 in the Saint Jean de Luz Bay. Blind separation of the tide components and of the storm signature was achieved while using both a singular spectrum analysis (SSA) and a continuous wavelet transform (CWT). A correlation of 0.98/0.97 and root mean square error (RMSE) of 0.21/0.28 m between the tide gauge records of Socoa and our estimates of the sea surface height (SSH) using the SSA and the CWT, respectively, were found. Correlations of 0.76 and 0.7 were also obtained between one of the modes from the SSA and atmospheric pressure from a meteorological station and a mode of the SSA. Particularly, a correlation reaches to 0.76 when using both the tide residual that is associated to surges and atmospheric pressure variation.

Vu, P.L.; Ha, M.C.; Frappart, F.; Darrozes, J.; Ramillien, G.; Dufrechou, G.; Gegout, P.; Morichon, D.; Bonneton, P. Identifying 2010 Xynthia Storm Signature in GNSS-R-Based Tide Records. *Remote Sens.* **2019**, *11*, 782:

https://doi.org/10.3390/rs11070782



A precise GNSS tracking of buoys or boats is mandatory in most of the experiments of this proposal.

The objective of the GNSS processing WP is to provide the best support to the users of the project for the computation of high precision and accuracy GNSS solutions

The most significant evolution of the processing capabilities are:

- The automating of PPP GNSS data processing using the tool "exe_ppp" and the GINS CNES software
- Extension to Galileo GNSS observations
- Implementation of the PPP with Ambiguity Resolution method for both GPS and Galileo data
- Interpretation of measured attitude of mobile GNSS antennas to better apply elevation cut-off
- capacity to estimate stochastic zenithal tropospheric delays
- Detection of ionosphere scintillations to better understand processing issues in tropical regions

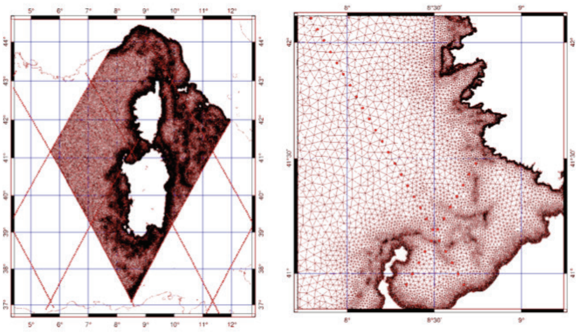
These figures represent the UP component solution of a static station estimated every measurement epoch (like for a mobile) during 7 days using two different strategies. The left plot shows the classical PPP solution based on GPS data while the right plot shows the PPP with Ambiguity Resolution solution using both GPS and Galileo observations. This illustrates the interest of the new capabilities of the GNSS data processing tools.

Tides and Dynamic Atmospheric Correction

F. LYARD[1], M. CANCET[2], L. TESTUT[1,3],
[1]OMP/CNRS/LEGOS, Toulouse, France; [2]NOVELTIS, Toulouse, France; [3]LIENSs, La Rochelle university, France

Objectives

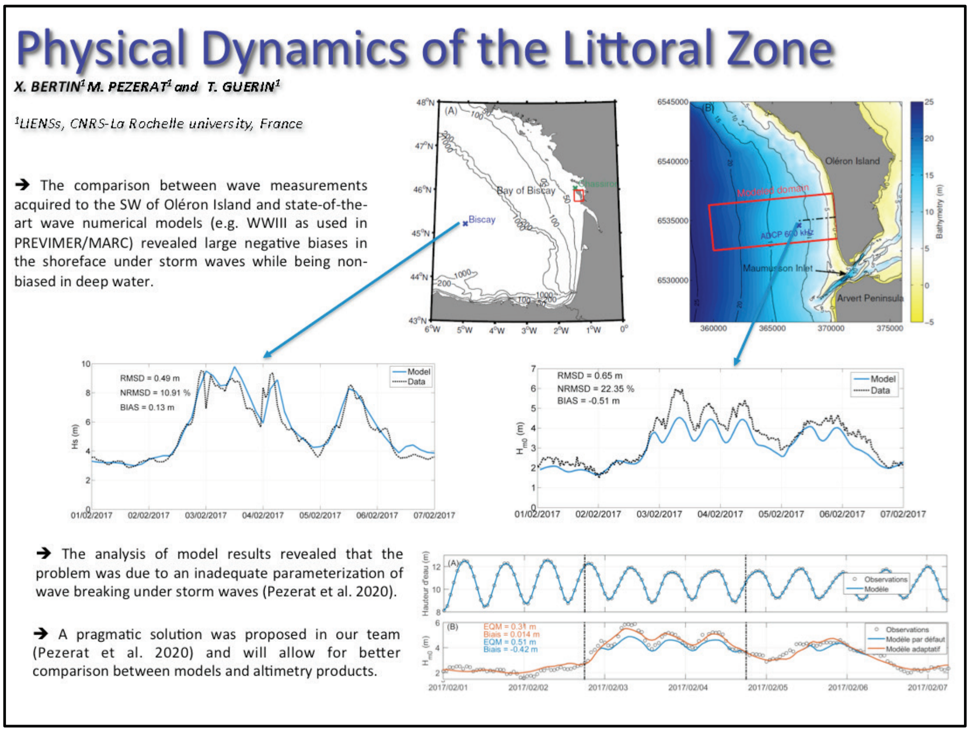
Due to the non-colocation of in situ and remote observations, altimetry calibration requires to complete the sea surface dynamics gap between satellite observation and in situ measurements in order to remove the subsequent uncertainties or misfits. A major difficulty is the land-based implementation of in situ gauges, where short-scale dynamics impact the local observations. Beside this challenge, the existing and forth-coming altimetry missions are now requesting to upgrade the calibration methodology toward spatially-extended capabilities.



High frequency model grid around Corsica (left) and zoom (right) in on the main calibration region (T/P-Jason tracks, close to Senetosa site). The unstructured grid is dedicated to tides, storm surge and ocean waves with a resolution of about 25m at the tide gauge sites.

T-UGOm simulations of tides and storm surges will cover the 1992-2024 period to provide improved high frequency corrections for the coastal altimetry data processing and the connection with in situ measurements. The very-high-resolution model will be imbricated in the LEGOS global storm surge configuration and tidal boundary conditions will be extracted from the MED-2019 RegAT (Regional Atlas for Tides) atlas implemented by NOVELTIS for CNES in 2019 or from direct satellite altimetry analysis. Atmospheric forcing will be taken from the ECMWF re-analysis products at the best time/space resolution. Sensitivity to the meteorological forcing formulation (i.e. bulk formula against wind stress deduced from the ocean wave model) will be examined. A high resolution and precise bathymetry has been built with special care for the regions surrounding the tide gauge location in order to guarantee a proper dynamical connection between the satellite data and the in situ data, especially when resolving ocean waves setup at shorelines.

The WW3 model will be run to infer the ocean waves impact on sea level during strong waves events at the calibration sites. In a second step, large-scale sea surface patterns, extracted from available ocean circulation in the Western Mediterranean Sea, will be used to infer the sea level variations due to the circulation variability. The circulation variability can be a significant term in the calibration error budget, especially for the regional calibration technique. We will investigate the possibility of using normal mode decomposition to separate the baroclinic circulation sea surface variability from the barotropic one. The benefit of using such information will be assessed.



Field observations:

A field campaign was carried out to the SO of Oléron Island (central part of the Bay of Biscay, France) in February 2017 and a current profiler ADCP mounted with a pressure transducer allowed measuring the sea-state associated with storm Kurt by a mean water depth of about 10 m. At the peak of the storm, Significant wave heights (SWH) reached 6.0 m, with a strong tidal modulation, suggesting that the sensor deployed more than 3 km from the shore was located in the surfzone.

Numerical modelling:

The sea-state associated with Kurt was hindcast in the NE Atlantic Ocean using the spectral wave model WaveWatchIII, forced by wind fields originating from the CFSR reanalysis. Model/data comparison in deep water (Biscay Buoy) revealed a good comparison, with normalized errors of the order of 10%. Close to shore, a large negative bias reaching 50% on SWH can be observed. The analysis of source terms in the model revealed that this problem was due to the default parameterization for wave dissipation by breaking, which is inadequate for storm waves at gently sloping shorefaces. This parameterization being used in most operational wave models wolrdwide, it is likely that storm waves and associated storm surge are underestimated close to shore. We proposed an adaptive parameterization for wave dissipation by breaking which account for the beach slope and allows for much improved predictions.

Implications:

Beside improved predictions for coastal models under storm conditions, this study will also allow for better comparisons between numerical models and SWH estimates derived from altimetry products, with are nowadays possible close to shore with recent missions such as Sentinel3.

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