Extending the Corsica facilities up to SWOT swath

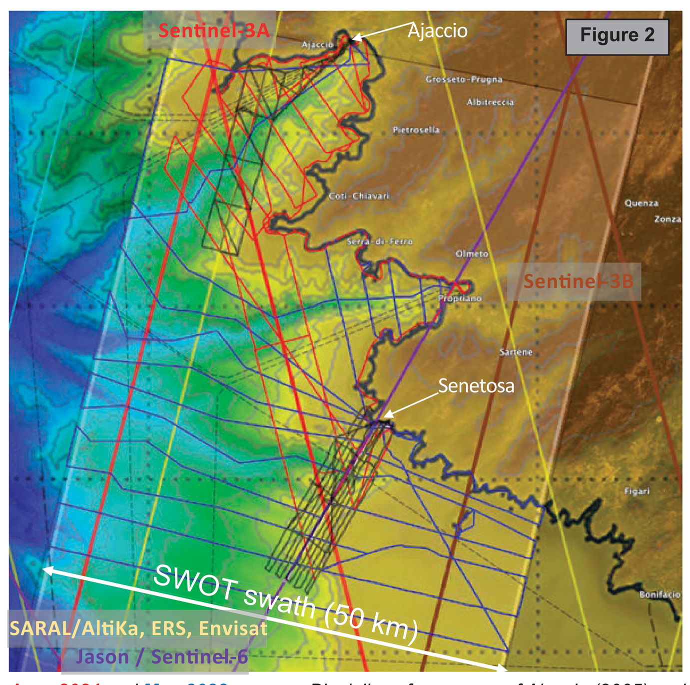
P. Bonnefond[1], O. Laurain[2], M. Calzas[3], C. Drezen[3], L. Fichen[3], A. Guillot[3], T. Guinle[4], N. Picot[4]
[1]Observatoire de Paris/SYRTE, Paris, France / [2]OCA/Geoazur, Sophia-Antipolis, France / [3]DT-INSU, La Seyne sur mer & Plouzané, Toulouse, France / [4]CNES, Toulouse, France

Abstract
Initially developed for monitoring the performance of TOPEX/Poseidon and follow-on Jason legacy satellite altimeters, the Corsica geodetic facilities that are located both at Senetosa Cape and near Ajaccio have been developed to calibrate successive satellite altimeters in an absolute sense. In anticipation of SWOT, a first phase of extension of the reference surfaces of the Corsica site was carried out in June 2021 (378 nautical miles) and the second in May 2022 (508 nautical miles). The measurements were carried out simultaneously using the instruments developed by DT-INSU as part of FOAM project (CalNaGeo and Cyclopée), which showed very good consistency (a few mm on average and ~20 mm standard deviation). GNSS processing using different software (track, MIT, differential mode / GINS, CNES, iPPP mode) and using the GPS and Galileo constellations jointly or separately have been analyzed. The high degree of consistency, both at instrumental level and at instrumental level, demonstrates the great maturity acquired thanks to the synergy of the FOAM group. We present the different phases of processing and preliminary results of the resulting reference surface ("geoid") covering the whole SWOT right swath of pass #001 (60 km along-track and 50 km across-track).
Preliminary Calibration and Validation results of KaRIn altimeter are also presented.

Reference surface («geoid») mapping with GNSS instruments

Campaigns description

Evolution of the Corsica facilities:
- **Extension/unification of the reference surfaces**
  - Junction of the historical Senetosa and Ajaccio references surfaces following the Sentinel-3A ground track (measurements in June 2021, 378 nautical miles)
  - Extend and densify the reference surface in preparation of SWOT (measurements in May 2022, 508 nautical miles)
- **Preliminary results**
  - Measurements using **CalNaGeo and Cyclopée**: a **very good consistency** (few mm in average / 20 mm standard deviation)



June 2021 and May 2022 surveys. Black lines for surveys of Ajaccio (2005) and Senetosa (1999) reference surfaces (bathymetry in background)

GNSS processing

2021	cngc/track		cngc/ippp		cycl/track		cycl/ippp	
	Mean (mm)	σ (mm)	Mean (mm)	σ (mm)	Mean (mm)	σ (mm)	Mean (mm)	σ (mm)
cngc/track	/	/	/	/	/	/	/	/
cngc/ippp	0.7	18.1	/	/	/	/	/	/
cycl/track	14.5	24.0	14.2	30.6	/	/	/	/
cycl/ippp	33.2	27.0	34.5	27.8	18.8	19.2	/	/

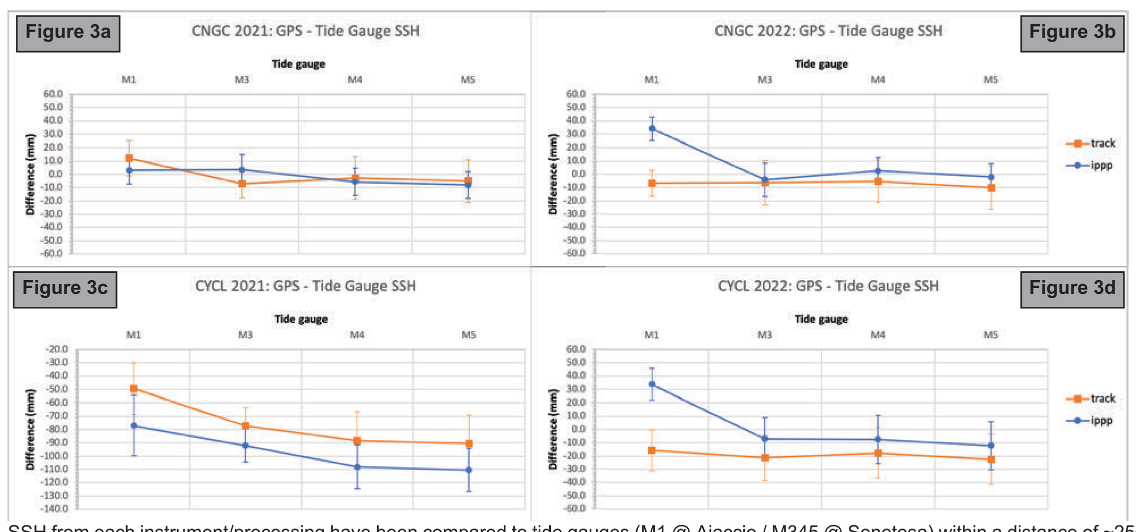
2022	cngc/track		cngc/ippp		cycl/track		cycl/ippp	
	Mean (mm)	σ (mm)	Mean (mm)	σ (mm)	Mean (mm)	σ (mm)	Mean (mm)	σ (mm)
cngc/track	/	/	/	/	/	/	/	/
cngc/ippp	-2.7	18.3	/	/	/	/	/	/
cycl/track	2.3	23.0	4.9	29.2	/	/	/	/
cycl/ippp	-6.7	26.1	-4.0	22.8	-9.1	19.1	/	/

same instrument / different processing
different instrument / same processing
different instrument / different processing

GNSS data from the 2 instruments (CalNaGeo [cngc] and Cyclopée [cycl]) were processed with 2 kind of processing:
- **track**: Using TRACK software from MIT (differential mode only using GPS data, no clear improvement when adding Galileo data) **-> need a fix receiver in vicinity of the mobile one (less than few tens of km)**
- **ippp**: Using GINS software, from GRGS/CNES (Precise Point Positioning mode with integer ambiguity fixing, using both GPS and Galileo data improves the precision) **-> no need of a fix receiver**

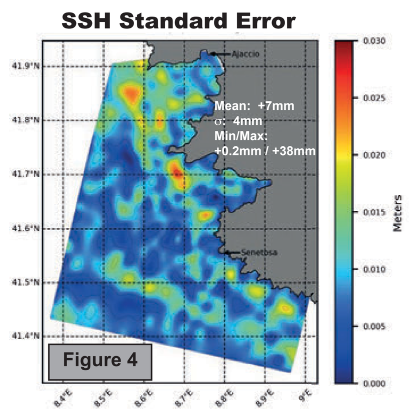
-> Comparisons of the 2 processing modes for each instrument show a very good agreement (few mm in average / ~20 mm standard deviation) -> ippp having a similar precision it could allow to process GNSS data everywhere (even very far from the coast)
-> Comparisons of the 2 instruments with the same processing mode also agree well but exhibit larger biases (up to 34.5 mm) and larger standard deviations (up to 27.8 mm). The larger biases and standard deviations for Cyclopée (cycl) in 2021: This is mainly because the sonic altimeter was not compensated for air temperature and the GNSS antenna had not the geodetic quality.

Comparison @ Tide Gauges



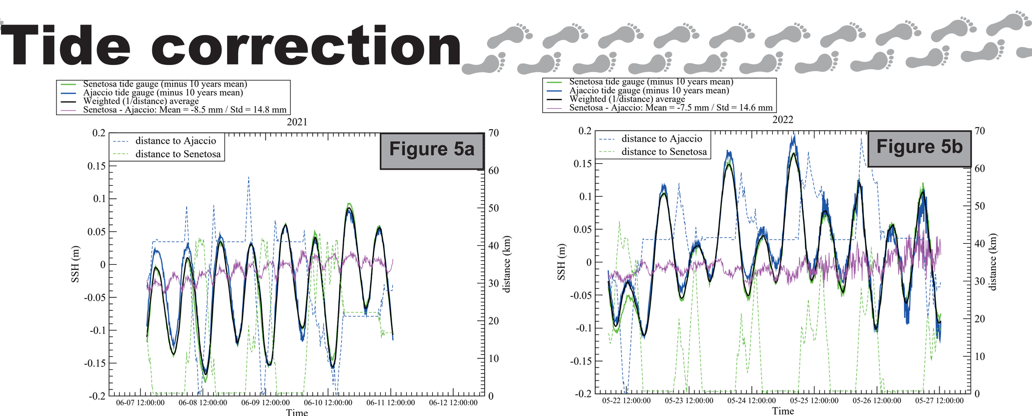
SSH from each instrument/processing have been compared to tide gauges (M1 @ Ajaccio / M345 @ Senetosa) within a distance of ~250 m. Note that the comparisons were made during all the nights long (3 sessions in 2021 and 5 in 2022) at Senetosa while for only about 1h (3 sessions in 2021 and 1 in 2022) at Ajaccio.
The error bars in Figure 3 correspond to the standard deviation that ranges from ~10 mm up to ~20 mm. The standard deviation increases a little for all instruments when using the ippp mode for processing but this mode do not exhibits significant bias. The standard deviation is also higher for Cyclopée (cycl) compared to CalNaGeo (cngc), notably in 2021 for the previously exposed reason.
A weighted mean, by the number of data, have been computed for all Senetosa tide gauges for each instrument/processing/year to be able to obtain «non biased ssh» and then compute the final solution (see «Weighted average of individual solutions»). The values the applied biases are below (values in brackets correspond to the standard deviation):
cngc/track/2021: -3.9 (10.3) mm cngc/track/2022: -7.4 (10.6) mm cngc/ippp/2021: -6.7 (16.1) mm cngc/ippp/2022: -0.4 (16.2) mm
cycl/track/2021: -89.4 (16.3) mm cycl/track/2022: -20.2 (17.9) mm cycl/ippp/2021: -109.1 (21.5) mm cycl/ippp/2022: -9.3 (18.7) mm

Weighted average of individual solutions



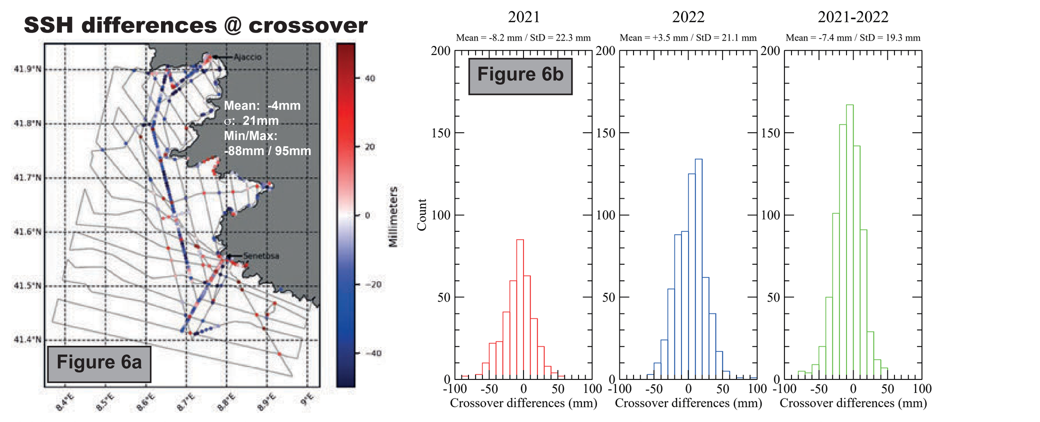
After applying the bias listed in «Comparison @ Tide Gauges», the final GNSS SSH have been computed using a weighted average of individual solutions (instrument/processing). The weights used come from the standard deviation at Senetosa tide gauges of individual solutions (see values in brackets in «Comparison @ Tide Gauges»).
Figure 4 shows the standard error of this averaging illustrating that the individual solutions are sometimes «far» from each other (high standard error), for example in the gulf of Ajaccio. This needs further investigation, but the overall distribution of the standard error (see Figure 7b) is mainly in between 0 and 10 mm illustrating a very good consistency of all individual solutions (see also «GNSS processing».

Tide correction



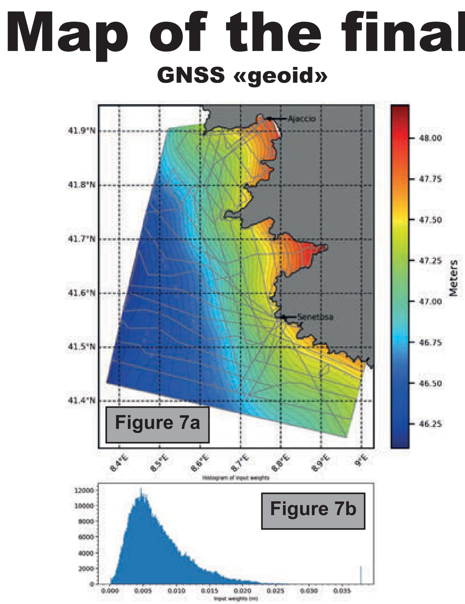
The GNSS SSH being surveyed not at the same time (and even in 2 different years, 2021 and 2022), these SSH needs to be corrected from tides. We computed a tide correction based on Ajaccio and Senetosa tide gauges SSH. This correction is a simple weighted average (1/(distance to tide gauge)) of Ajaccio and Senetosa SSH (black lines on Figures 5a and 5b). On Figures 5a and 5b, the magenta line shows the difference in term of SSH signal beween Ajaccio and Senetosa: (i) the mean (~-8 mm) illustrates a potential datum inconsistency or a constant difference during the considered periods (e.g. Dynamic Atmospheric Correction difference), (ii) while the standard deviation illustrates potential tide gauge measurement errors or more likely SSH differences due to physical signals (e.g. Dynamic Atmospheric Correction differences).
The tide correction are computed relatively to the mean over 10 years (2013-2023) for each site (Ajaccio and Senetosa). The mean SSH for Ajaccio and Senetosa is respectively 48.5150 m and 48.1679 m. The difference between both SSH mean is 0.3471 m and should physically corresponds to the geoid difference between the 2 locations.

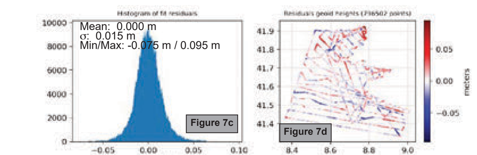
Estimation of precision @ crossover



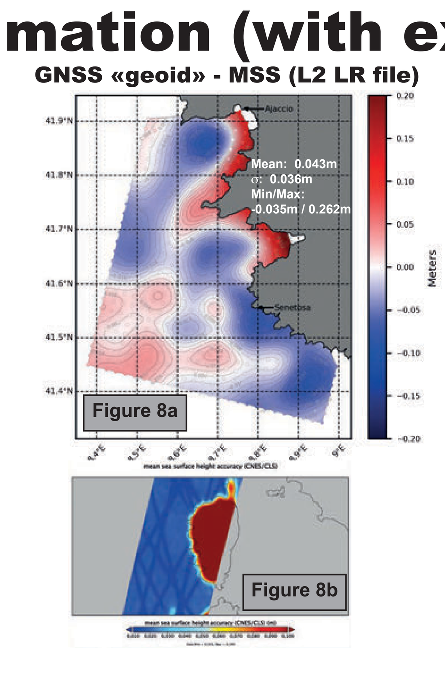
Differences of SSH (corrected from tides) have been computed at crossover locations of the surveyed tracks (grey lines in Figure 6a). Figure 6a illustrates the geographical distribution with the statistics of the whole crossover data set (yearly respective histogram and statistics are given in Figure 6b). The global standard deviation (21 mm) is coherent with the precision estimation illustrated in «GNSS processing». The mean (-7.4 mm) for 2021-2022 illustrates a very good consistency between the 2 surveys.
These crossover differences have been applied to the SSH to produce the final SSH series. Details on crossover computations, crossover correction method, as well as GNSS processing strategy can be found in:
Bonnefond, P., Laurain, O., Exertier, P., Calzas, M., Guinle, T., Picot, N. and the FOAM project Team (2022). Validating a new GNSS-based sea level instrument (CalNaGeo) at Senetosa Cape, Marine Geodesy, https://doi.org/10.1080/01490419.2021.2013355

Map of the final solution and precision estimation (with external references)

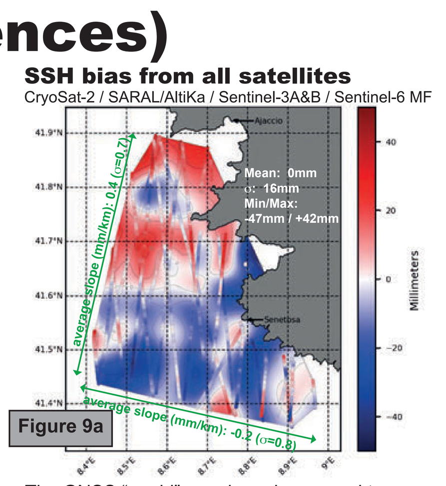


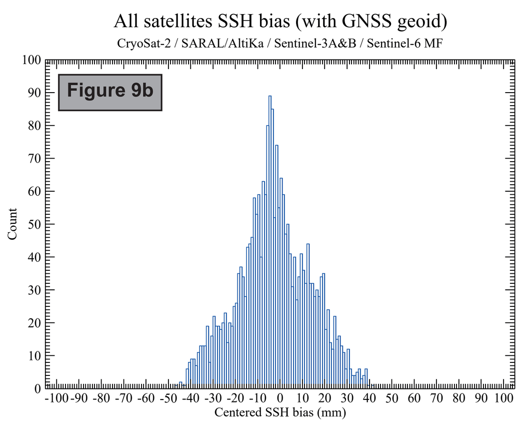


The final SSH (corrected from tides and crossover differences) have been mapped and gridded using python verde (v1.8.0) library and notably the BlockMean feature that allows to use input weights and propagate the uncertainty:
Uieda, L. (2018). Verde: Processing and gridding spatial data using Green's functions. Journal of Open Source Software, 3(29), 957. doi:10.21105/joss.0095
The input weights come from the standard error computed previously (see Figure 4) and their statistical distribution are given in Figure 7b. The residuals of the fit shown in Figure 7c are mostly gaussian with very few outliers outside ±3σ (45 mm). Their geographical distribution given in Figure 7d does not exhibit strong localized patterns (except maybe in the Gulf of Ajaccio).
A map using the final grid (~50 m resolution) is given in Figure 7a and is used in the next steps for deriving the altimeters' SSH biases.
We must note that "geoid" may be inappropriate and is an in between a Mean Sea Surface (MSS) and a Mean Dynamic Topography (MDT). However, in this area, the ocean dynamics being small with little temporal variations we can approximate it to the geoid.
As a result, we can compare for example the geoid difference between Ajaccio and Senetosa derived from our GNSS "geoid" to the one derived from mean SSH determined over 10 years (see "tide correction"):
Ajaccio - Senetosa from 10 years SSH average: 0.3471 m
Ajaccio - Senetosa from GNSS "geoid": 0.3342 m
This gives a difference of only 12.9 mm illustrating very small potential remaining errors that can come from: (i) GNSS "geoid" error, (ii) error in vertical references (tide gauges positioning) and/or (iii) difference in ocean dynamics between the 2 sites (including MSL rise).



A first validation can be performed by comparing to the MSS given in the SWOT LR L2 files (CNES/CLS 2015) and the differences are given in Figure 8a.
Even if the overall standard deviation is relatively small (3.6 cm), it clearly reveals very high differences (up to ~30 cm) in the coastal areas where the geoid is rapidly changing. The differences also looks very correlated with the canyons of the gulfs (see Figure 2). The relatively flat differences in the south-east of Senetosa also correspond to a «plateau» in the geoid. Figure 8b gives the geographical distribution of the CNES/CLS MSS accuracy and clearly shows the degradation in the coastal areas. Note the clear pattern of satellites tracks where the accuracy is the best (notably ERS-1&2, Envisat, SARAL/AltiKa ground track #130 and TOPEX, Jason, Sentinel-6 ground track #085, see Figure 2)
This comparison clearly shows the need of improving the MSS in coastal areas and that was the aim of our 2021&2022 surveys with GNSS instruments.





Standard deviation for individual satellites:

SARAL/AltiKa (pass 130): 15.2 mm
Sentinel-3A (pass 741): 10.8 mm
Sentinel-3A (pass 044): 10.8 mm
Sentinel-3B (pass 157): 03.1 mm
Sentinel-6 MF (pass 085): 08.4 mm
CryoSat-2 (all passes): 17.5 mm

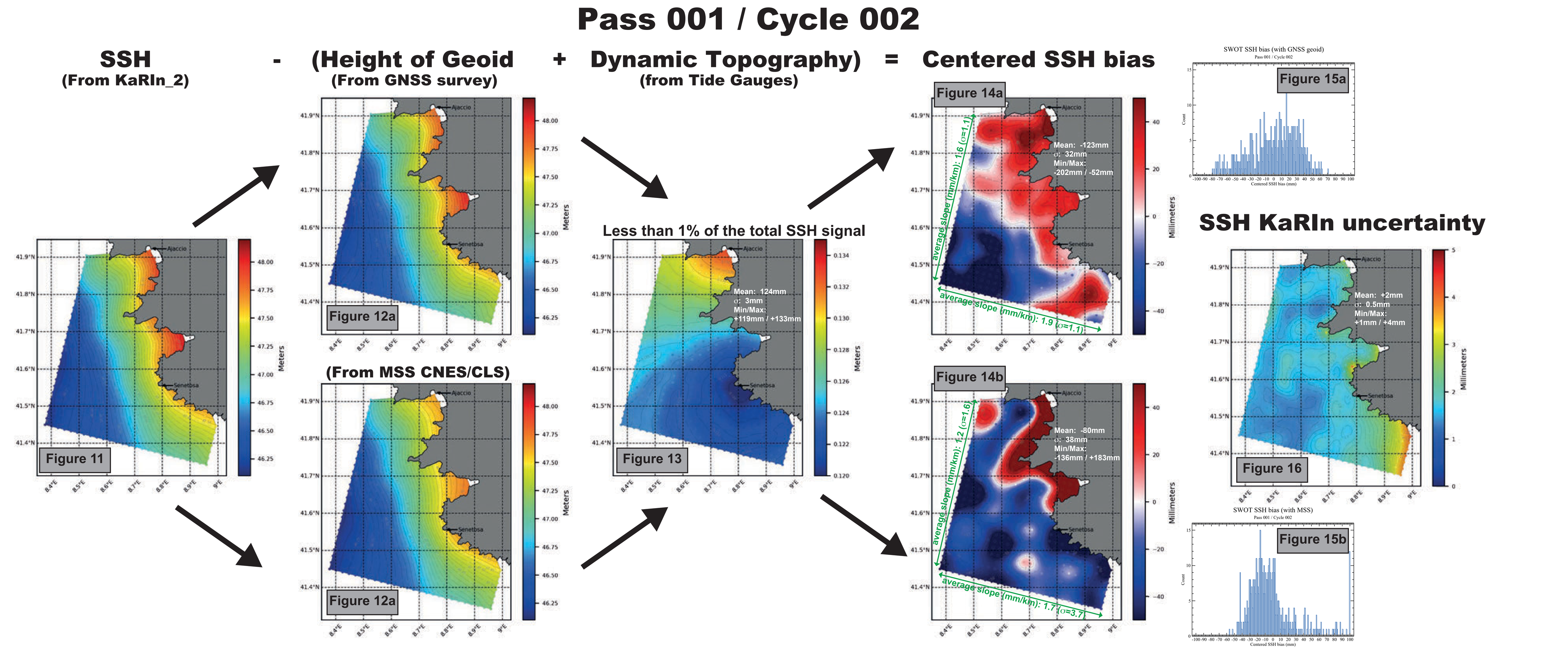
All satellites (all passes): 16.3 mm

The GNSS "geoid" map have been used to compute the SSH bias for each altimeter overflying the area and for all the available cycles. The missions used are: CryoSat-2, SARAL/AltiKa, Sentinel-3A&B and Sentinel-6 MF
For each satellites a mean bias has been computed along-track from all cycles time series using a moving window of ~300 m width and step (no overlap). The mean for each pass has been removed to "center" the SSH bias allowing to cumulate all the missions and then map the geographical distribution (Figure 9a). The overall standard deviation is relatively small (16.3 mm) and consistent with all the error estimations (see "GNSS processing", "Comparisons @ Tide gauges", and "Estimation of precision @ crossover"). However, this standard deviation is mainly dominated by the CryoSat-2 one (17.5 mm) that needs to be further investigated but most probably due to the small number of cycles (low repetitivity of 369 days).
Figure 9a clearly shows a north-south pattern but the slope is very small (~0.4 mm/km), this also needs to be further investigated.

SWOT SSH bias from L2 LR (Science Phase)

Method and results

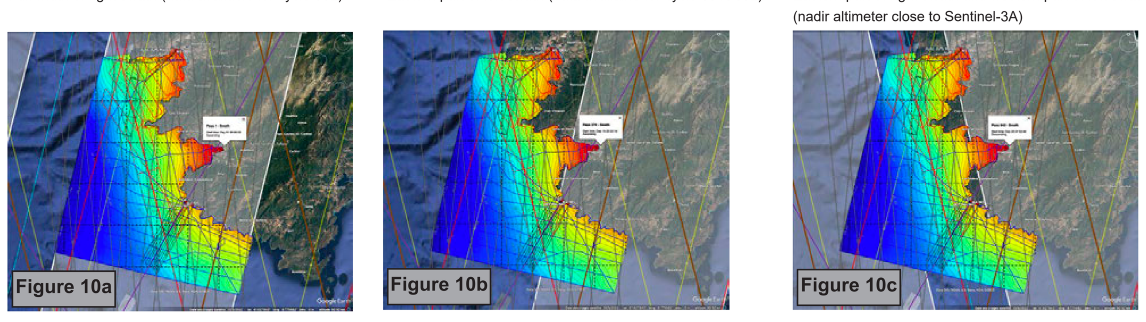
Pass 001 / Cycle 002



Pass 001:
Full width of right swath (data available for cycle 002)

Pass 279:
Eastern part of left swath (data available for cycle 001&002)

Pass 542:
Eastern part of right swath and western part of left swath (no data for cycle 001&002) (nadir altimeter close to Sentinel-3A)



3 SWOT passes overflight the Corsica facilities during the Science Phase and their description are given respectively in Figure 10a,b,c
The general method is illustrated on the left and corresponds to the classical closure equation for Absolute SSH bias determination:
SSH bias = (SSH from altimeter) - (In situ SSH)
The in situ SSH being measured at tide gauge locations (Ajaccio and Senetosa), it needs to be "transfered" to the SWOT data locations that are evenly distributed on a fix geographical grid every 2 km for LR L2 files used in this study): in every Figures these data locations are plotted by colored circles. This transfer has 2 components:
- The geoid difference is derived either from our GNSS "geoid" (Figure 12a) or from the MSS (CNES/CLS 2015) given in the L2 LR file (Figure 12b). Differences between both have been detailed in the "GNSS «geoid» - MSS (L2 LR file)" section. The strong coastal patterns in SWOT SSH bias using the MSS (Figure 14b) comes from the high uncertainty in the coastal zone.
- The SSH "Dynamic Topography" is derived from tide gauges (Figure 13): (i) by removing the geoid height at tide gauges locations and then (2) by applying a simple weighted average (1/(distance to tide gauge)) of Ajaccio and Senetosa SSH (as done for the "Tide correction"). The signal is very small (~3 mm standard deviation) and mostly an offset at the temporal scale of one overflight.

The SWOT SSH (Figure 11) is taken directly from the ssh_karin_2 variable that is the "Fully corrected sea surface height measured by KaRIn" (which uses a meteorological model for the effects of the wet troposphere on range delays and sigma0 atmospheric attenuation). We added the Solid Earth, pole and loading tides to be comparable to tide gauges measurements that are only relative to these crustal effects. Figure 16 gives the SSH Karin uncertainty (ssh_karin_uncert variable) as determined from ground processing (see handbook for more details) which appears to be very small but higher in coastal areas and on the farthest side of the swath (eastern part on the map).

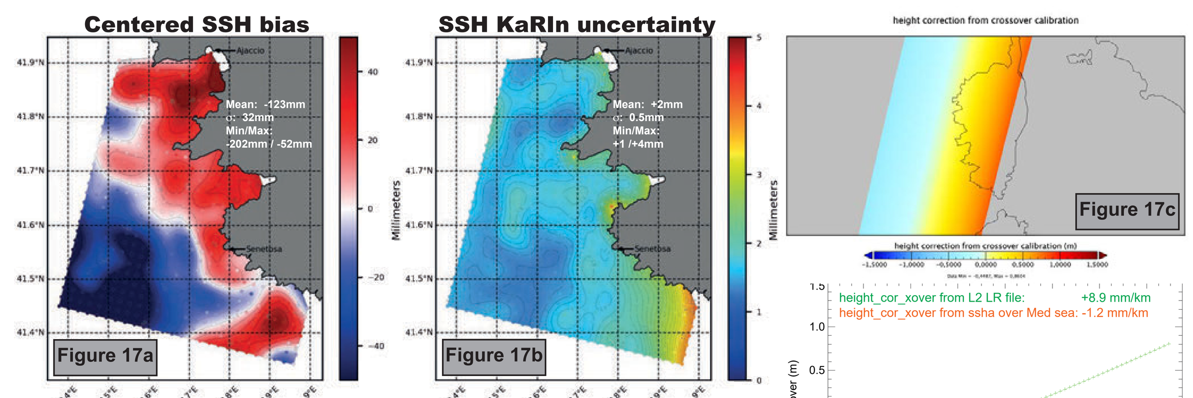
The SSH bias derived from our GNSS "geoid" is given in Figure 14a and shows a spatial standard deviation of 32 mm. This standard deviation is higher than the one derived in Figure 9a (16.3 mm) but this is for a single overflight while in Figure 9a it corresponds to a mean over all the cycles available: in comparison, the SSH bias time series of a nadir altimeter (e.g. Sentinel-6 MF) has a temporal standard deviation of ~30 mm, comparable then to the spatial standard deviation of 32 mm for SWOT.
Even if the patterns look strong, we must note that it only represents a small slope of (1.6 mm/km along-track and 1.9 mm/km across-track direction). This slope is higher than the one derived from Figure 9a (0.4 mm/km along-track and -0.2 mm/km across-track direction) but this is again only for a single overflight. When using the MSS (Figure 14b), the slopes are comparable to the one using our GNSS "geoid" (Figure 14a) but with higher standard deviations (σ) notably in the across-track direction (mainly due to the high uncertainty in the coastal zone).

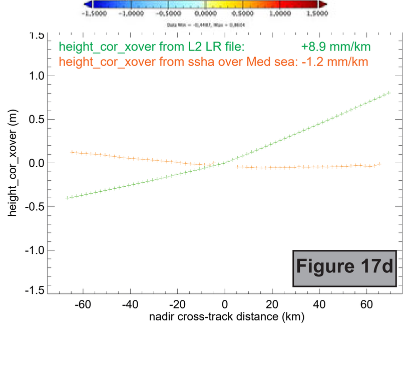
In conclusion, this very preliminary result illustrates the high potential of the Corsica facilities to give insight of the SWOT measurement accuracy.
More to come as soon as more cycles can be analyzed.

height_cor_xover OR NOT height_cor_xover

Definition from handbook: height_cor_xover: Height correction to ssh_karin and ssh_karin_2 computed from a combination of crossovers between KaRIn/KaRIn measurements and KaRIn/nadir altimeter measurements on different passes within a temporal window surrounding the SSH measurement. This correction provides an estimate of residual errors that have not been removed with use of ancillary attitude and calibration data during processing. This correction is not applied in forming ssh_karin, ssh_karin_2, ssha_karin, or ssha_karin_2. The value of height_cor_xover should be added to the value of ssh_karin, ssh_karin_2, ssha_karin, and/or ssha_karin_2 by the user **if it is to be applied.**

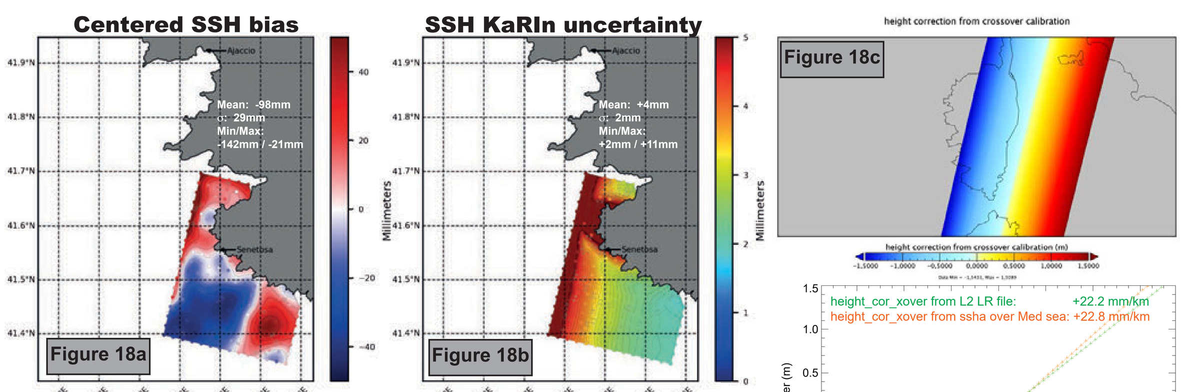
Pass 001 / Cycle 002 (NOT corrected with height_cor_xover)

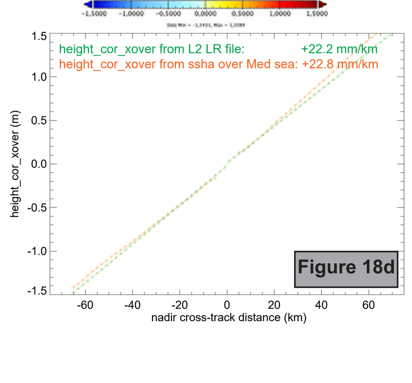




For this pass and cycle, the height_cor_xover looks bad (+8.9 mm/km from L2 LR file / -1.2 mm/km from ssha over Med sea, Figure 17d) and **should not be applied** (this is most probably due to a bug in processing that makes it incorrect for each first pass of each 28 passes flow => to be discussed with the project team). Moreover, the slope looks very close to zero for the right swath so that we do not see any clear cross-track slope in the ssh bias.
The flag (height_cor_xover_qual) indicates that the correction is bad (2) which is coherent.

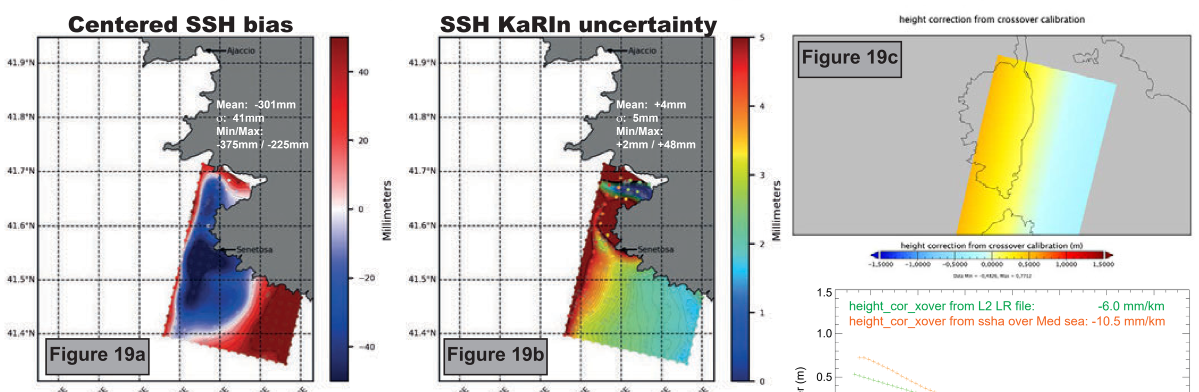
Pass 279 / Cycle 001 (corrected with height_cor_xover)

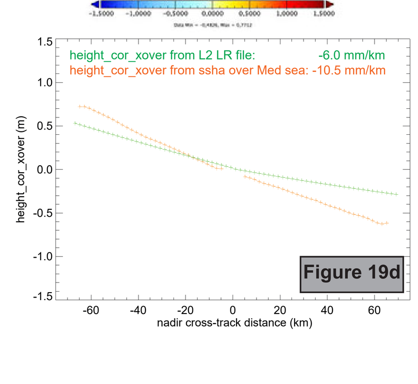




For this pass and cycle, the height_cor_xover looks correct (+22.2 mm/km from L2 LR file / +22.8 mm/km from ssha over Med sea, Figure 18d) and **should be applied.**
However, it looks like there's a remaining cross-track slope in the ssh bias.
The flag (height_cor_xover_qual) indicates that the correction is bad (2) which is not coherent (correction needs to be applied).

Pass 279 / Cycle 002 (corrected with height_cor_xover)





For this pass and cycle, the height_cor_xover looks not very good (-6.0 mm/km from L2 LR file / -10.5 mm/km from ssha over Med sea, Figure 19d) but **should be applied** (if not it will lead to a strong cross-track slope). However, it looks like there's a remaining cross-track slope in the ssh bias (the one from ssha over Med sea should improve it).
The flag (height_cor_xover_qual) indicates that the correction is bad (2) which is not coherent (correction needs to be applied).