Extending the Corsica facilities up to SWOT swath

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Abstract

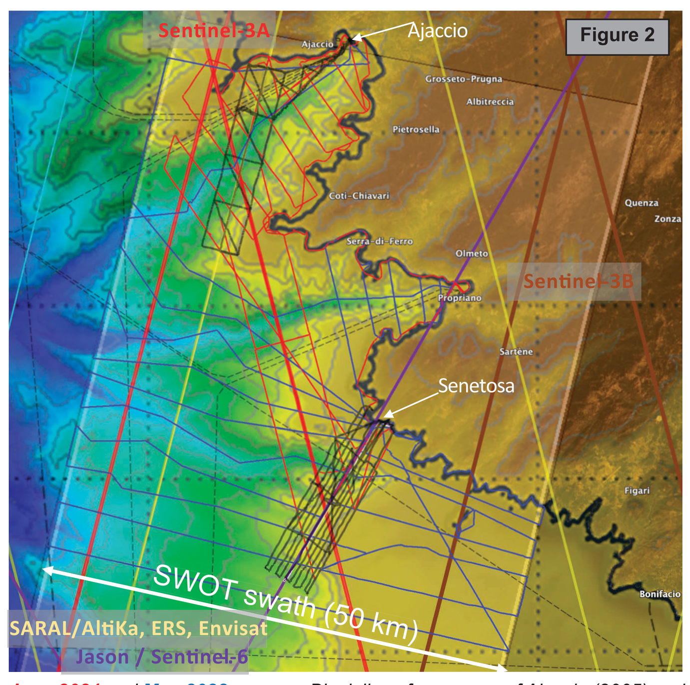
Initially developed for monitoring the performance of TOPEX/Poseidon and follow-on Jason legacy satellite altimeters, the Corsica geodetic facilities that are located both at Senetosa Cape and near Ajaccio have been developed to calibrate successive satellite altimeters in an absolute sense. In anticipation 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 processing 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 using the derived reference surface ("geoid") covering the whole SWOT right swath of pass #001 (60 km along-swath and 50 km across-swath).
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	3.3	18.1	/	/	/	/	/	/
cycl/track	16.6	23.8	13.8	28.5	/	/	/	/
cycl/ippp	31.7	28.8	28.0	26.0	15.4	20.1	/	/

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	-3.0	19.6	/	/	/	/	/	/
cycl/track	1.2	22.9	4.3	27.5	/	/	/	/
cycl/ippp	-24.5	28.7	-21.7	22.8	-26.1	20.6	/	/

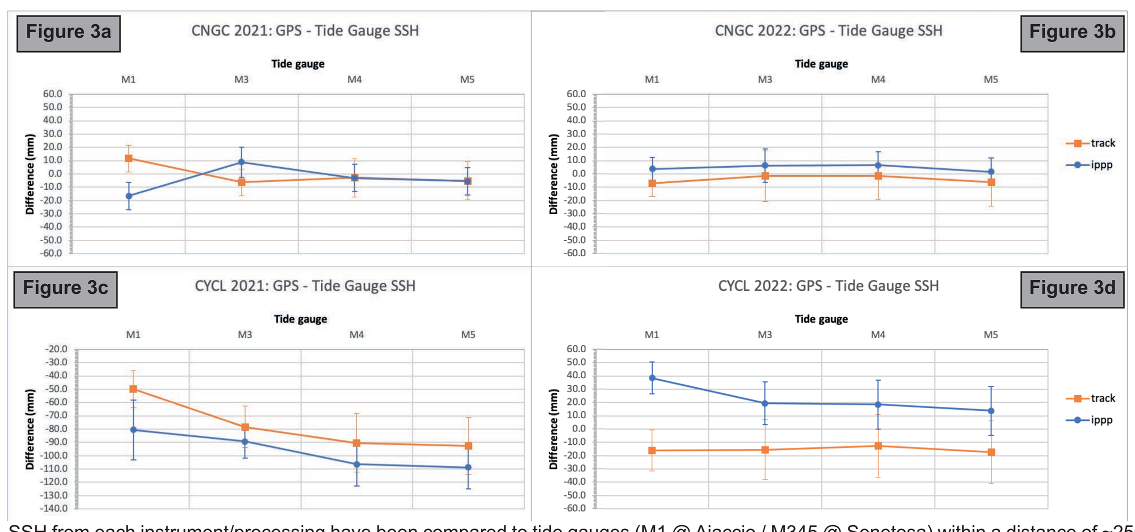
same instrument / different processing
different instrument / same processing
different instrument / different processing

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 of 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 28.0 mm**) and larger standard deviations (**up to 28.8 mm**). The larger biases and standard deviations are 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.

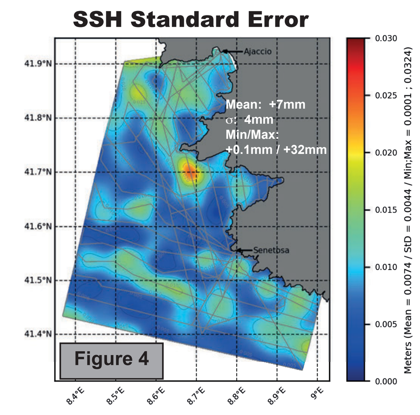
Comparison @ Tide Gauges



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 does not exhibit 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: -4.1 (10.3) mm   cngc/track/2022: -3.4 (10.6) mm   cngc/ippp/2021: -4.2 (14.3) mm   cngc/ippp/2022: +4.5 (18.1) mm
cycl/track/2021: -91.4 (16.3) mm   cycl/track/2022: -15.1 (17.9) mm   cycl/ippp/2021: -107.4 (21.6) mm   cycl/ippp/2022: +16.7 (23.4) mm

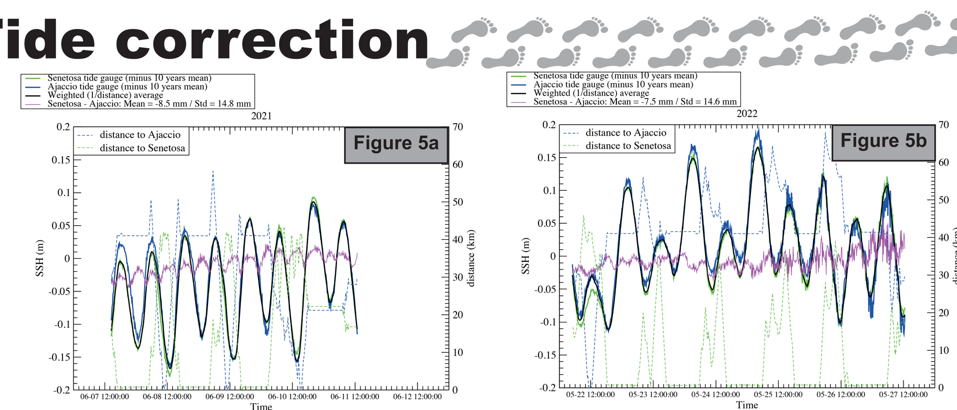
Weighted average of individual solutions

SSH Standard Error



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».

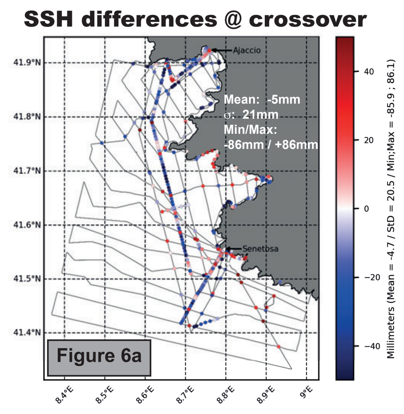
Tide correction

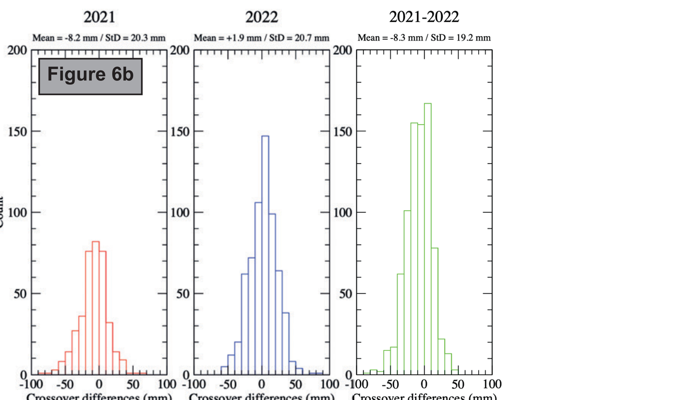


The GNSS SSH being surveyed not at the same time (and even in 2 different years, 2021 and 2022), these SSH need to be corrected from tides. We computed a tide correction based on Ajaccio and Senetosa tide gauges SSH. This correction is a simple weighted average (1/(distance to tide gauge)) of Ajaccio 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 is 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

SSH differences @ crossover

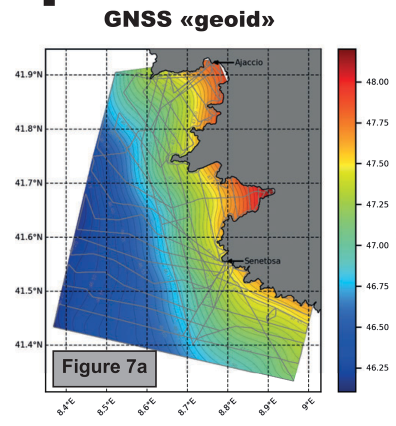


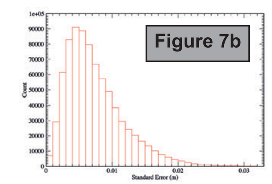


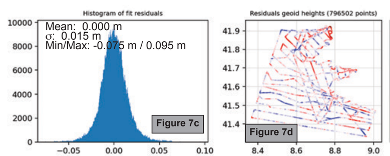
Differences of SSH (corrected from tides) have been computed at crossover locations of the surveyed tracks (grey lines in Figure 6a). Figure 6a illustrates the geographical distribution with the statistics of the whole crossover data set (yearly respective histogram and statistics are given in Figure 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)

GNSS «geoid»





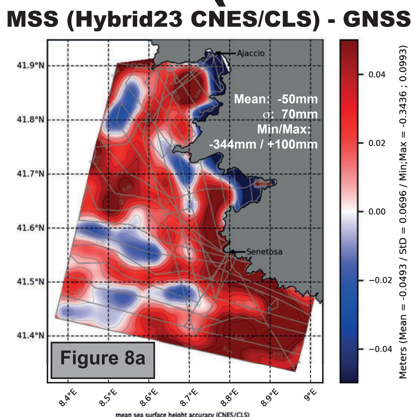


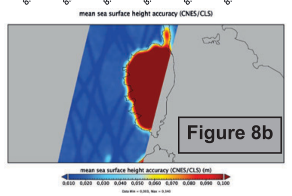
The final SSH (corrected from tides and crossover differences) have been mapped and gridded using python verde (v1.8.0) library and notably the BlockReduceMean with a "reducing" scale of 1km (~low-path filter) and gridding spacing of 100m:
Uieda, L. (2018). Verde: Processing and gridding spatial data using Green's functions. Journal of Open Source Software, 3(29), 957. doi:10.21105/joss.0095
The residuals of the fit shown in the histogram are mostly gaussian with very few outliers outside ±3s (45 mm). Their geographical distribution (Figure at right of the histogram) does not exhibit strong localized patterns (except maybe in the Gulf of Ajaccio).
A map using the final grid (~100 m resolution) is given in Figure at left and is used in the next steps for deriving the altimeters' SSH biases (see next slides)
.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": 0.3514 m

This gives a difference of only -4.3 mm illustrating very small potential individually or sum-up remaining errors that can come from:

- GNSS "geoid" error,
- error in vertical references (tide gauges positioning) and/or
- difference in ocean dynamics between the 2 sites (including MSL rise).

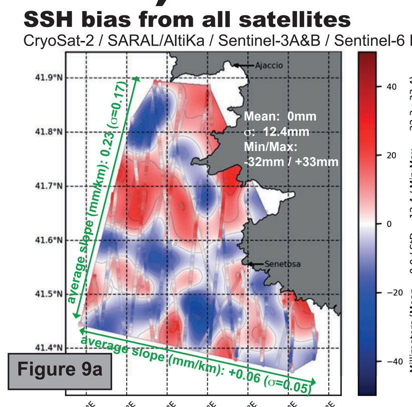
MSS (Hybrid23 CNES/CLS) - GNSS «geoid»

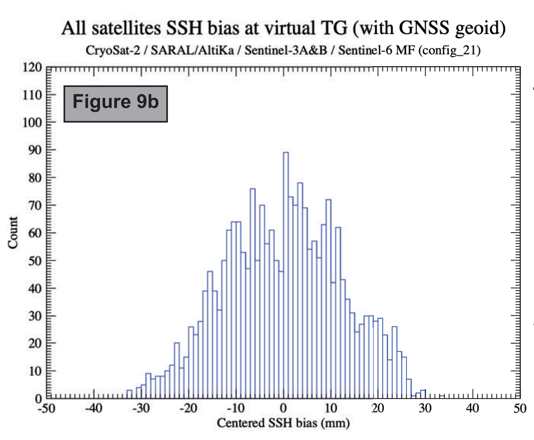




A first validation can be performed by comparing to the Hybrid MSS (CNES/CLS 2023) and the differences are given in Figure 8a.
Even if the overall standard deviation is not so high (~7 cm), it clearly reveals very high differences (up to ~35 cm) in the coastal areas where the geoid is rapidly changing. 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.

SSH bias from all satellites
CryoSat-2 / SARAL/AltiKa / Sentinel-3A&B / Sentinel-6 MF





Standard deviation for individual satellites:

SARAL/AltiKa (pass 130):	09.6 mm
Sentinel-3A (pass 741):	09.2 mm
Sentinel-3A (pass 044):	15.4 mm
Sentinel-3B (pass 157):	05.2 mm
Sentinel-6 MF (pass 085):	10.9 mm
CryoSat-2 (all passes):	12.8 mm
All satellites (all passes):	12.4 mm

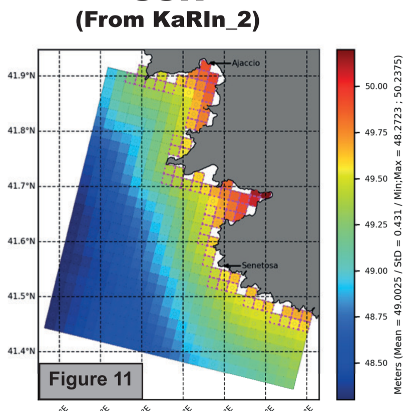
The GNSS "geoid" map have been used to compute the SSH bias for each altimeter overflying the area and for all the available cycles (from 2010 to 2022). The missions used are:
CryoSat-2, SARAL/AltiKa, Sentinel-3A&B and Sentinel-6 MF
For each satellites a mean bias has been computed along-track from all 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 (12.4 mm) and consistent with all the error estimations (see "GNSS processing", "Comparisons @ Tide gauges", and "Estimation of precision @ crossover").
Figure 9a clearly shows some patterns (and for some they correspond to those of Figure 8a) but the slopes over the whole area are very small (+0.23 mm/km along-swath and +0.06 mm/km across-swath),

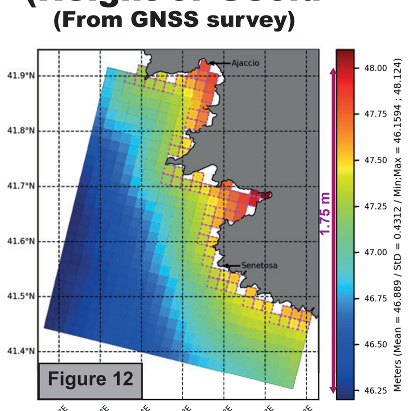
SWOT SSH bias from L2 LR Version C (Science Phase)

Example for processing with cycle 002

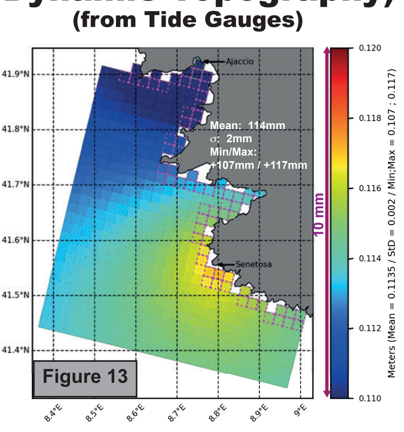
Pass 001 / Cycle 002

SSH (From KaRIn_2) - **(Height of Geoid** (From GNSS survey) + **Dynamic Topography)** (from Tide Gauges) = **Centered SSH bias**

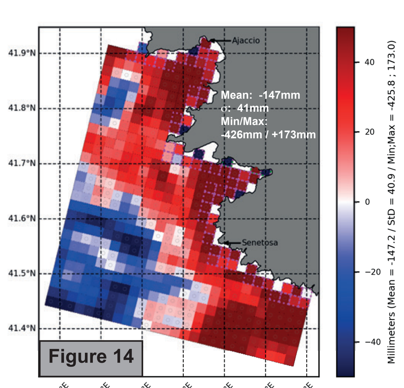




~99% of the total SSH signal (1.75 m)
From geoid slope



~1% of total signal (10 mm)
(main tidal signal removed)



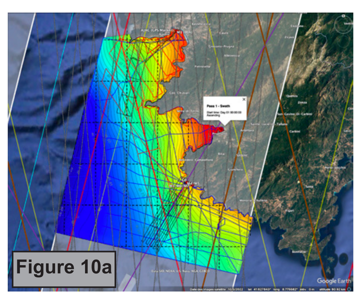
Pixels surrounded in magenta are flagged as "bad_not_usable" in ssh_karin_2_qual variable:

- All located within 4km from the coast
- ~70 over a total of 475 over the whole area (~15%)

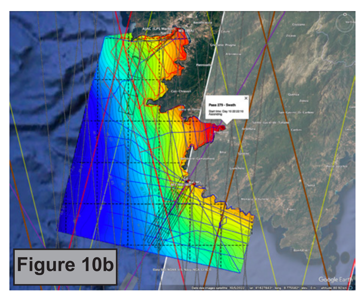
They are all removed from the study

All SWOT passes over Corsica facilities

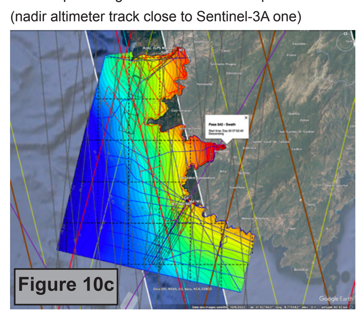
Pass 001:
Full width of right swath



Pass 279:
Eastern part of left swath



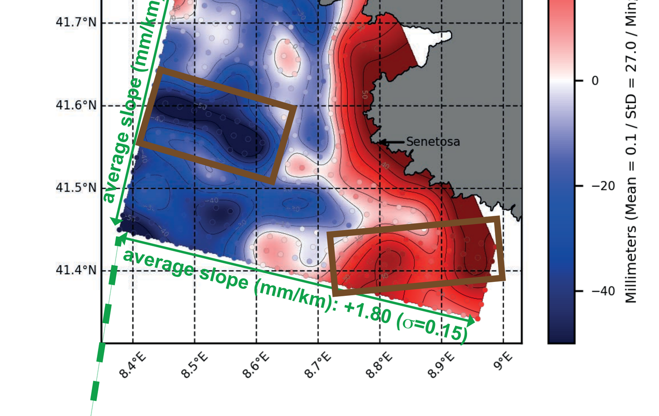
Pass 542:
Eastern part of right swath and western part of left swath (nadir altimeter track close to Sentinel-3A one)



Mean SWOT SSH bias over cycle 002 (August 2023) to 014 (April 2024)

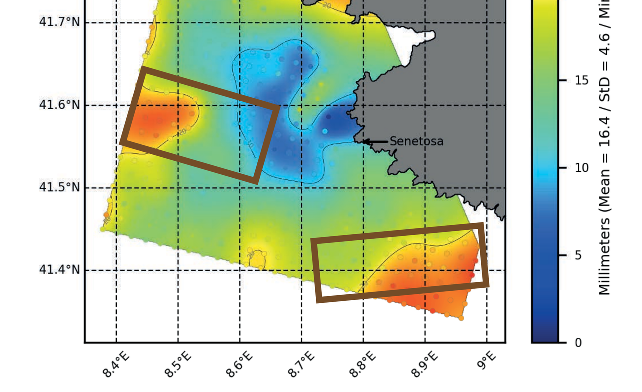
GDR: cycles 002-005 / IGDR: cycles 007-014

SWOT mean SSH bias over cycles 002-014



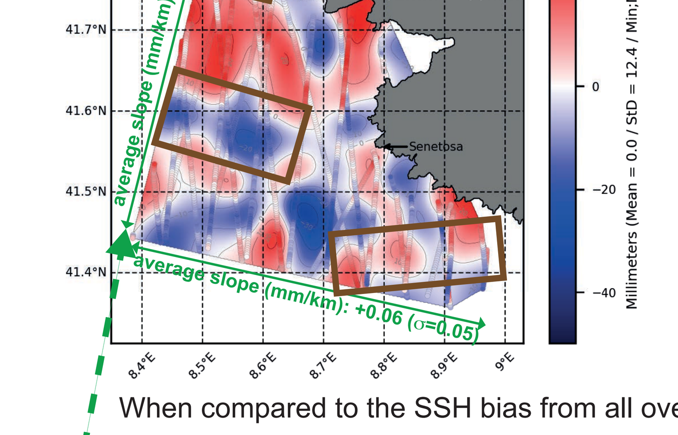
- A small standard deviation (27 mm) over the whole area
- **Some patterns at the ~10 km scale**
- Coastal red pattern mostly due to mapping

SWOT σ SSH bias over cycles 002-014



Small (16.4 mm) dispersion of the SSH bias over the studied cycles
Higher dispersion in some areas (e.g. Gulf of Ajaccio) -> stronger "ocean dynamic" ?

SSH bias from all nadir satellites over 12 years (2010-2022)
CryoSat-2 / SARAL/AltiKa / Sentinel-3A&B / Sentinel-6 MF



When compared to the SSH bias from all overflying nadir satellites, **some of these patterns looks to be common with SWOT** (but with lower amplitude: dispersion of 12.4mm compared to SWOT one of 27.0, due to a smallest time period (8 months / 12 years))

- Along-swath slope is small (0.45mm/km)
- Across-swath slope is higher (1.80mm/km) but mainly due to strong West-East patterns (south of Senetosa)

- For comparison, using all nadir satellites:
- Along-swath slope is very small (0.23mm/km)
- Across-swath slope is also very small (0.06mm/km)

=> no clear along-swath or across-swath slopes in the reference surface GNSS "geoid"

CONCLUSIONS

3 SWOT passes overflight the Corsica facilities during the Science Phase and their descriptions are given respectively in Figure 10a,b,c. Only analysis of pass #001 (full swath width) is given in this study.
The general method for one cycle (002) 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 from our GNSS "geoid" (Figure 12).
- 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 small (~2 mm standard deviation for cycle 002 but up to 10 mm for some cycles) 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.

The SSH bias derived from our GNSS "geoid" for cycle 002 is given in Figure 14 and shows a spatial standard deviation of 41 mm. This standard deviation is high but this is for a single overflight and includes **pixels flagged as "bad_not_usable"**.

When averaged over cycles 002-014 (**and without "bad" pixels**), this spatial standard deviation decreases to 27 mm (Figure 15).

Even if **some patterns look strong (surrounded in maroon)**, we must note that the slopes over the whole area are small (0.45 mm/km along-swath and 1.8 mm/km across-swath). These slopes are higher than the ones derived from Figure 9a (0.23 mm/km along-swath and +0.06 mm/km across-swath), mainly due to the time averaging (8 months for SWOT / 12 years for all nadir satellites). The **surrounded maroon patterns** look also correlated with stronger "ocean dynamic" (Figure 15) and needs longer periods for a better averaging. To a lesser extent, they also appears in Figure 9a probably indicating some deficiencies in the GNSS "geoid" only surveyed at the same period of the year in 2021&2022.

In conclusion, this preliminary result illustrates the high potential of the Corsica facilities to give insight of the SWOT measurement accuracy