National Oceanography Centre

PASS-SWIO

Portagauge and Satellite Sea Level Monitoring System for the Southwest Indian Ocean

Cross-validation of in situ and satellite altimeter sea level data.

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08/05/24	1.1	Various	Various	Updates in response to ESA review. Additional sections added on validation of Toamasina TG data, and altimeter data from specialised coastal processing. Some additional information on reference levels for sea level measurements.

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1. Introduction

This report describes the methodology and results from the validation and cross-validation of in situ and satellite altimeter sea-level data carried out for the PASS-SWIO project. The following validations and cross-validations have been carried out.

- Quality control and validation of the Toamasina Portagauge data.
- Cross-validation of historical (SHOM) Toamasina tide gauge data against satellite altimeter data (01/01/2010 to 29/03/2022).
- Cross-validation of Toamasina Portagauge radar gauge data against satellite altimeter data (13/06/23 to 31/01/24).
- Cross-validation of Toamasina Portagauge radar gauge data against Toamasina Portagauge GNSS-IR sea-level data (13/06/23 to 31/01/24)
- Validation and assessment of satellite altimeter data produced by a specialised coastal processor.

The objectives of these validation studies are to:

- Establish the accuracy of the satellite measurements of sea-level with respect to the SHOM Toamasina tide gauge measurements.
- Establish the accuracy of the Toamasina GNSS-IR measurements with respect to the Toamasina Portagauge radar gauge measurements.
- Understand the factors contributing to the differences between the different sets of measurements.
- Confirm if a reliable cross-validation can be made between Portagauge radar and satellite altimeter data with a limited period of data (in this case 8 months).

2. Validation and Quality Control of Tide Gauge Data

2.1. Background

An important consideration in selecting Toamasina as the initial deployment site for the Portagauge was the pre-existence (since 2010) of a SHOM-operated radar-based tide gauge in the port, which would facilitate cross-validation of the Portagauge data and provide a means of acceptance-testing the system. Such cross-validation requires the acquisition, quality control and post-processing of the historical Toamasina tide gauge data (2010 onwards) and of the Portagauge data. To promote system longevity beyond the project lifetime, such data processing was to be performed by the Malagasy stakeholder (DGM) using skills acquired through virtual and face-to-face training events delivered in WP1200. Unfortunately, the SHOM tide gauge at Toamasina was offline from March 2022 onwards due to port redevelopment works and remains inoperable until a funding stream can be identified to reinstate the system. As a result, data from the SHOM gauge and Portagauge were not available for validation during a common observing period. Consequently, an alternative means of cross validation was proposed, based upon comparisons of tidal characteristics between the two tide gauge records, since key tidal constituents (derived from classical harmonic analysis) at a location should display temporal stability of amplitude and phase.

2.2. Methodology

Historical Toamasina sea level data from 2010 to March 2022 were downloaded directly from the IOC Sea Level Monitoring Facility website to text files using linux-based commands. These data were reformatted for compatibility with the NOCs' in-house tidal analysis, quality control and data visualisation software, known as TASK (Tidal Analysis Software Kit).

Data from the Portagauge radar sensor for June 2023 to February 2024 were downloaded on site to USB at the tide gauge. These data were reformatted using MS Excel to achieve compatibility with TASK software.

The TASK software comprises a suite of tools that allow users to perform automated quality control tests, data resampling and filtering operations as well as tidal analysis, data visualisation, manual quality control and tidal prediction processes. Whilst some sea level variations (such as tsunamis or storm surges) and instrumental errors are so extreme that they are obviously identifiable in tide gauge records, other variations and errors can be difficult to detect visually, since they are often masked by large tidal fluctuations. Consequently, the TASK software separates the tidal and non-tidal components of a sea level record, using classical harmonic analysis. This makes non-tidal variations and data errors more obvious in the detided time series. Spikes or jumps in the data, timing errors, reference level changes and data gaps in then be corrected in the final dataset.

Both the historical SHOM time series and the Portagauge radar sensor time series were processed in this way, generating the following outputs:

1. Quality controlled time series to validate Portagauge and satellite altimetry

2. Monthly means that will contribute to the global long-term sea level archive at the Permanent Service for Mean Sea Level (PSMSL)
3. Tidal constituents for use with the NOC's POLTIPS tidal predictions software and for cross-validation

Of these, the outputs described in (1) contributed to deliverable D3.1 Datasets, whilst those described in (2) and (3) are additional project by-products that will benefit the global scientific community (in the case of 2) and stakeholders involved in operational coastal monitoring in Madagascar (in the case of 3).

2.3. Results

Despite some data gaps and instrumental errors, the historical SHOM tide gauge record from Toamasina was found to be good quality, capturing tidal variability well across the record and observing many tropical cyclones, with some overtopping of the instrument during extreme sea level events. Similarly, whilst the Portagauge experienced a few initial data gaps due to telemetry teething problems, the time series was found to be of excellent quality, yielding no suspect data during the validation period.

Comparison of the phases and amplitudes of key tidal constituents between the historical SHOM and Portagauge time series (Table 1) displayed good agreement, even though they were derived from different locations within the port and despite the brevity of the Portagauge record compared with that of the SHOM record.

Table 1. Comparison of the phases and amplitudes of key tidal constituents between the Portagauge and historical SHOM tide gauge

	Portagauge		**SHOM tide gauge**	
Tidal Constituent	**Amplitude**	**Phase (°)**	**Amplitude**	**Phase (°)**
O1	0.03421	15.57	0.03553	13.49
K1	0.03014	47.11	0.02736	33.89
M2	0.20734	314.83	0.21001	310.94
S2	0.07805	327.31	0.09235	317.51

3. Cross-validation of historical tide gauge data against satellite altimeter data

3.1. Introduction

For the cross-validation of historical (SHOM) Toamasina tide gauge data against satellite altimeter data the following data sets were used:

- Tide gauge data from the SHOM installed tide gauge, covering 01/01/2010 to 29/03/2022.
- Along-track time series satellite altimeter data from Jason-2, Jason-3 and Sentinel-6a Michael Freilich (MF) (2010-2022), Sentinel-3a (2016-2022) and Sentinel-3b (2018-2022). The source data were the Level 3 along track sea level anomaly data set available through the Copernicus Marine Service. These data were subset and reformatted by NOC and SatOC and are available via the project web site (https://www.satoc.eu/projects/pass-swio/data.html).
- Along-track Level 2 Sentinel-3a satellite altimeter product available via the EUMETSAT Earth Observation Portal, for the period 01/01/2019 to 29/03/22.

3.2. Methodology

Two cross-validation approaches were used, to enable comparison between the historical (SHOM) tide gauge and Portagauge results, as Level 3 data are not yet available for the time the Portagauge was operational.

Along-Track L3 based product

In this approach the satellite altimeter measured sea level anomaly (the measured sea surface height above the mean sea surface, corrected for dynamic atmospheric correction, ocean tide and long wavelength error) was compared against the residual tide gauge water level measurement (measured water level minus the predicted tide).

Python code was used to iterate through the satellite altimeter along-track data and extract data within 200km of the Toamasina tide gauge. Outliers were then removed from these data (sea surface height anomaly greater than 2m, or greater than 3 standard deviations from the mean).

Then tide gauge data closest to the time of the satellite overpass were found and interpolated to the time of the satellite overpass. Correlation and root mean square difference were calculated for each point along track.

This was repeated for all satellite tracks with sections within 200km of the tide gauge location.

The track and along-track location at which the maximum correlation was achieved was identified and a time series generated of altimeter sea level anomaly and tide gauge residual sea level for this point.

Along-Track L2 based product

In this approach the satellite altimeter measured total water level with respect to the ellipsoid, which is the sea surface height anomaly, with model tide (GOT4.1, Ray, 1999) and mean sea surface (DTU21, Andersen et al, 2023) added, is compared against the tide gauge total water level measurement (predicted tide not removed).

The SRAL Level 2 Altimetry Global (version BC005) Sentinel-3a product for relative orbit 083 from 01/01/2019 to 29/03/22 was downloaded from the EUMETSAT Earth Observation Portal. Passes along the same orbit are separated by 27 days, and data from 40 passes were available for this time period.

For each of these 40 satellite Level 2 products, data were selected for the five 1Hz measurements centred on the point of maximum correlation identified in the previous methodology, and the following parameters were extracted:

- Sea surface height anomaly, 1Hz Ku band (ssha_01_ku)
- Geocentric ocean tide height (GOT4.10) (ocean_tide_sol1_01)
- Mean Sea Surface (DTU21) (mean_sea_surf_sol2_01)

The total water level was calculated by adding the tide and mean sea surface to the sea surface height anomaly and averaged over the five 1 Hz products centred on the point of maximum correlation.

Then the tide gauge measurements closest to the time of the satellite overpass were found and interpolated to the time of the satellite overpass. From the resultant time series of paired altimeter and tide gauge total water level measurements, correlation and root mean square difference were calculated.

3.3. Cross-validation results

We present below the results for the Jason series data (from Jason-2, Jason-3, and Sentinel-6a MF satellites) and Sentinel-3a data. Figures 1, 2 and 3 compare satellite data from the L3 along-track time series product. Figure 4 compares satellite data from the L2 satellite product.

Figure 1 shows the results from a cross-validation between sea level anomaly (tidal signal removed) from the Jason-series satellites (Jason-2, Jason-3 and Sentinel-6a MF) against historical (SHOM) Toamasina tide gauge sea level residual (tidal signal removed), for 2010 to early 2022. L3 along-track time series satellite data from three tracks were processed and data from relative orbit 094 were found to provide the highest correlation. The central panels show the variation of correlation and root mean square difference along the track of relative orbit 094, allowing the point of highest correlation to be identified. The bottom panel shows the time series of tide gauge and altimeter data sea level anomaly at the point of highest correlation.

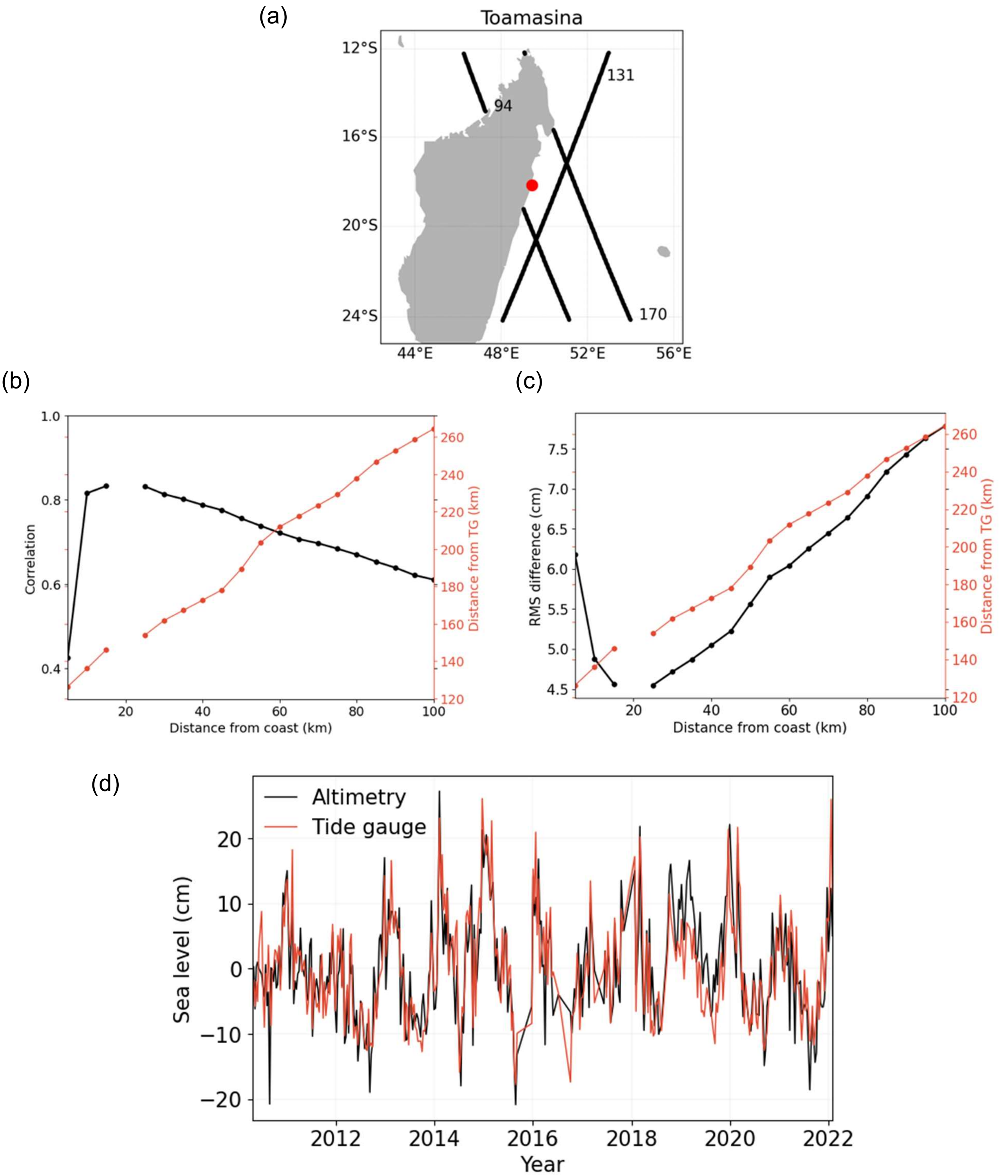

Figure 1. Results from cross-validation of satellite altimeter sea level anomaly against Toamasina tide gauge residual – for Jason series satellite data (including Sentinel-6a-MF). (a) Jason series satellite orbits close to Toamasina. (b) Correlation against distance from coast (relative orbit 094). (c) Root Mean Square against distance from coast (relative orbit 094. (d) time series of altimeter sea level anomaly and tide gauge residual sea level at point of highest correlation (relative orbit 094).

Figure 2 shows the results from a cross-validation between sea level anomaly (tidal signal removed) from Sentinel 3a against historical Toamasina tide gauge sea level residual (tidal signal removed), for 2016 to early 2022. L3 along-track time series satellite data from seven tracks were processed and data from relative orbit 083 were found to provide the highest correlation. The central panels show the variation of correlation and root mean square difference along the track of relative orbit 083, allowing the point of highest correlation to be identified. The bottom panel shows the time series of tide gauge and altimeter data sea level anomaly at the point of highest correlation.

Figure 3 shows the results from a cross-validation between sea level anomaly (tidal signal removed) from Sentinel 3b data against historical Toamasina tide gauge sea level residual (tidal signal removed), for 2019 to early 2022. L3 along-track time series satellite data from nine tracks were processed and data from relative orbit 197 were found to provide the highest correlation. The central panels show the variation of correlation and root mean square difference along the track of relative orbit 197, allowing the point of highest correlation to be identified. The bottom panel shows the time series of tide gauge and altimeter data sea level anomaly at the point of highest correlation.

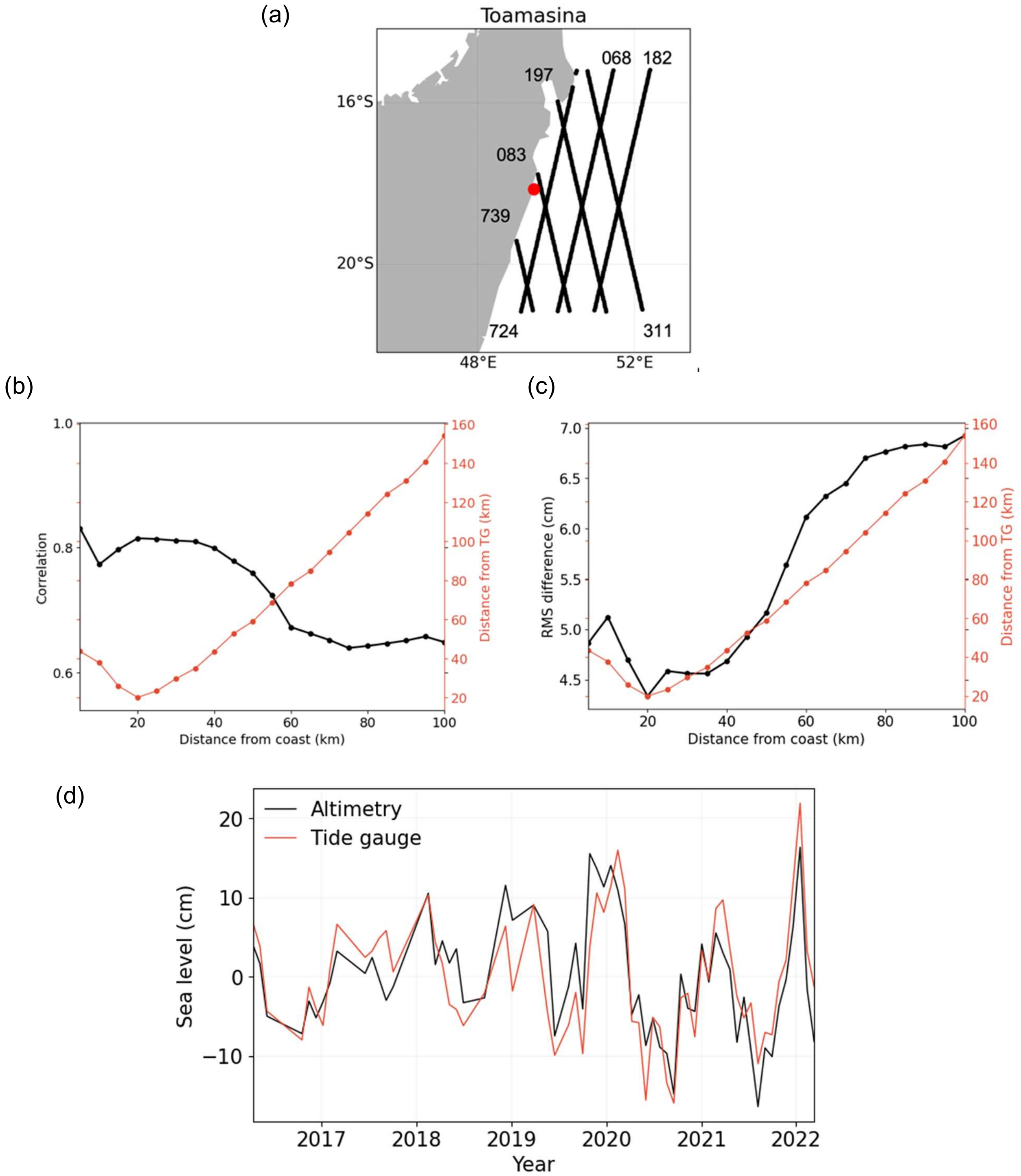

Figure 2. Results from cross-validation of satellite altimeter sea level anomaly against Toamasina tide gauge residual – Sentinel-3a satellite data. (a) Sentinel-3a satellite orbits close to Toamasina. (b) Correlation against distance from coast (relative orbit 083). (c) Root Mean Square against distance from coast (relative orbit 083). (d) Time series of altimeter sea level anomaly and tide gauge residual sea level at point of highest correlation (relative orbit 083).

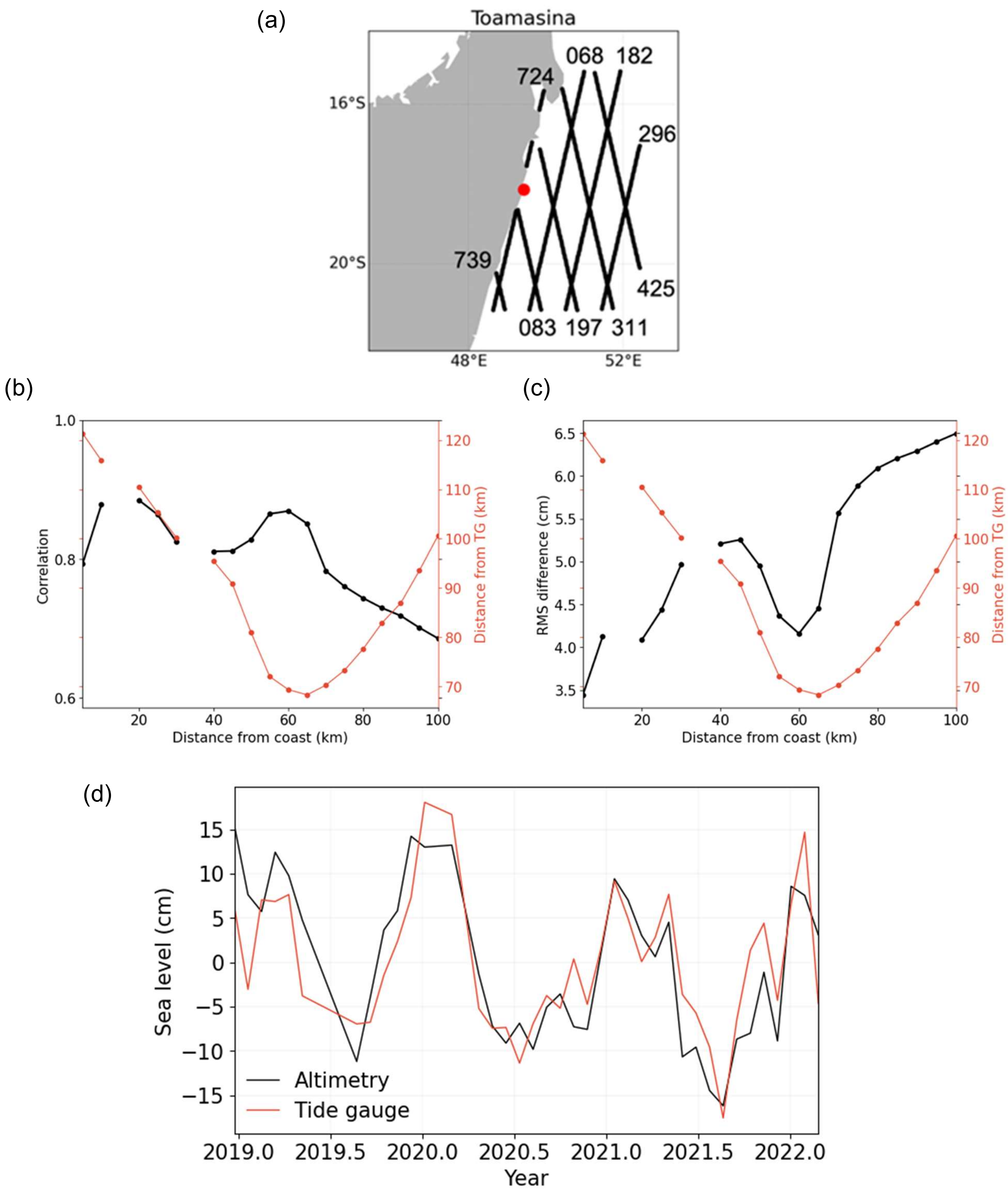

Figure 3. Results from cross-validation of satellite sea level anomaly against Toamasina tide gauge residual – Sentinel-3b satellite data (a) Sentinel-3b satellite orbits close to Toamasina. (b) Correlation against distance from coast (relative orbit 197). (c) Root Mean Square against distance from coast (relative orbit 197). (d) Time series of altimeter sea level anomaly and tide gauge residual sea level at point of highest correlation (relative orbit 197).

Finally, Figure 4 shows the results from a second cross-validation between Sentinel-3a data against historical Toamasina tide gauge data, for 2019 to early 2022. This comparison is based on measurements in the L2 satellite product, rather than the L3 along-track time series products used for Figures 1-3 and compares total water level rather than sea level residual. The figure shows the time series of tide gauge and altimeter total water level at the point of highest correlation identified in the analysis presented in Figure 2. An offset of 10.28m was found between the two data sets, and so 10.28m has been added to the satellite measured total water level. The satellite measurements are made every 27 days, at the same time of day, and the contribution of the tidal signal in the total water levels can be seen. This results in a higher range of water levels (0.4m to 1.2m), than seen in the earlier figures (-0.2m to +0.2m).

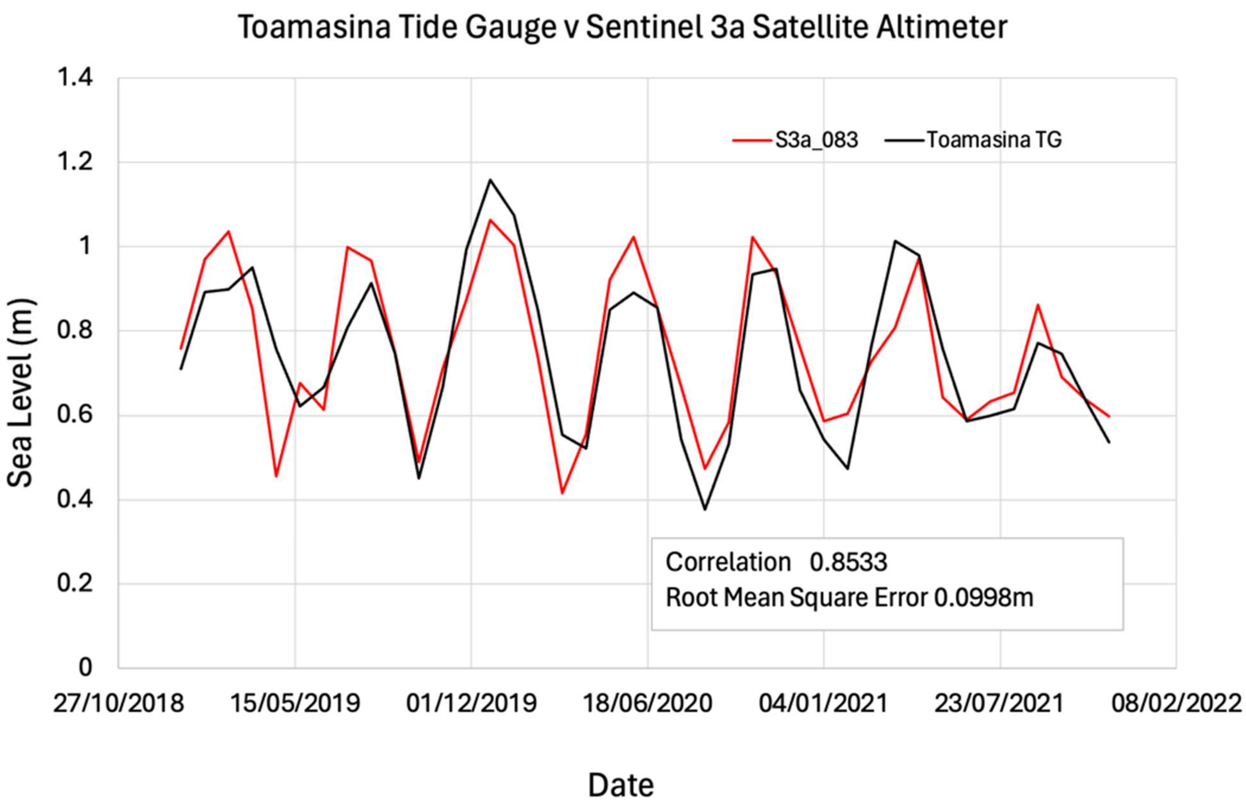

Figure 4. Time series of Sentinel-3a altimeter and tide gauge total water level from relative orbit 083, at the point of maximum correlation identified in Figure 2.

3.4. Discussion

Table 2 and Figures 1, 2 and 3 present the results of the cross-validation of Toamasina tide gauge data against data produced from the L3 along-track data from the Jason-series satellites (Jason-2, Jason-3 and Sentinel-6a MF), Sentinel-3a and Sentinel-3b. Table 2 gives values for the distance to coast and distance to tide gauge at the point of highest correlation, and the correlation and root mean square difference at these points. Note that these results are based on comparisons of relative sea level, the reference level being the long term mean with the tidal signal removed.

For the Jason series satellites the separation between tracks is larger than for Sentinel 3a and Sentinel 3b (~300 km at this latitude), but each track is revisited once every 10 days. For Sentinel-3a and 3b, the revisit interval is larger (27 days) but the spacing between tracks is less (100km at this latitude). Thus we receive more measurements (almost three times more) in a given period from Jason-3 than from Sentinel 3a and 3b.

For the Jason series satellites, the point giving the highest correlation was found to be on track 094, 146km from the Toamasina tide gauge and 14.8km from the coast. For Sentinel 3a, it was track 083, 19.9km from Toamasina, and 18km from the coast, and for Sentinel 3b, it was track 197; 81km from Toamasina and 48km from the coast.

Although these points of closest correlation vary significantly in terms of distance to Toamasina and to the coast, we find very similar results in terms of correlations between the tide gauge and altimeter data of 0.82 to 0.83, and root mean square differences (4 to 5cm).

These results can be compared to similar validation studies at European locations for the recent HYDROCOASTAL study, which gave standard deviation of differences of 7 to 9 cm for locations off the southern Spanish Coast, with correlations of 0.56 to 0.70 (HYDROCOASTAL 2023).

Table 2. Results from cross-validation between historical (SHOM)Toamasina Tide Gauge Data and Along-track Altimeter Data. Residual sea levels (without predicted tide) from the tide gauge are compared against sea surface height anomaly data (with ocean tide, dynamic atmospheric correction and long wavelength error removed) from the satellite altimeters.

Satellite(s)	**Relative Orbit No**	**Distance to Coast (km)**	**Distance to Tide Gauge**	**Correlation**	**RMS (m)**	**No of points**
Jason series	094	14.8	146.0	0.8312	0.0422	365
Sentinel-3a	083	18.0	19.9	0.8224	0.0443	62
Sentinel-3b	197	48.0	81.0	0.8267	0.0494	39

Thus, these results indicate very good agreement between the satellite and tide gauge measurements, even though the separation between the satellite measurement and tide gauge can be large (up to 146km). Indeed, the correlation between the satellite and tide gauge measurements stays higher than 0.6 along the entire path length considered, for all three satellites. These results suggest a low natural variability in sea level at this location on the East Madagascar coastal region and provide confidence that the altimeter data provide an accurate measurement of sea level close to the East coast of Madagascar.

A further cross-validation, based on L2 Sentinel-3a data, was carried out to compare the results from validations based on L2 and L3 satellite products, and using total water level instead of residual sea level after the predicted tide was removed. This second approach was applied as it was the methodology used to cross-validate data from the Portagauge against L2 satellite data. L3 data are not yet available for the time the Portagauge was operational. As noted in the previous section, an offset of 10.28m was found between the two data sets, and so 10.28m was added to the satellite measured total water level. It was also noted that the contribution of the tidal signal in the total water levels can be seen, which results in a higher range of water levels (0.4m to 1.2m), than seen in the validation against residual water levels (-20cm to +20cm). The correlation between the tide gauge and satellite total water level measurements was 0.8522, and the root mean square error was 9.98 cm.

4. Cross-validation of Portagauge radar gauge data against satellite altimeter data

4.1. Introduction

In this section we validate the Toamasina sea level measured by the Portagauge radar gauge against satellite altimeter data. The along track time series L3 data are not yet available for the time period that the data are available from the Portagauge, so instead the L2 along-track satellite products available via the EUMETSAT Earth Observation Portal were used for the validation, and the method applied for L2 product as described in section 2.2 was adopted. The data sets used were:

- Tide gauge data from the PG1 Portagauge, installed by NOC and DGM at Toamasina port in June 2023. These data cover 13/06/2023 to 31/01/2024.
- Along-track satellite altimeter data from Sentinel-6a MF, Sentinel-3a and Sentinel-3b. The source data were the reprocessed L2 satellite altimeter product available via the EUMETSAT Earth Observation Portal.

4.2. Methodology

Satellite altimeter data (Sentinel-6a-MF, Sentinel-3a, and Sentinel-3b) for the relevant orbits and time period were downloaded from the EUMETSAT Earth Observation Portal, as follows.

Sentinel-6a-MF

Poseidon-4 Altimetry Level 2 High Resolution (baseline version F08) - Sentinel-6 - Reprocessed Product:

- Relative Orbit 094 and 131
- Dates: 01/06/23 to 31/01/24

Data from the reduced measurement product were selected by latitude (within 19.2° S to 20° S), and the following parameters extracted:

- Sea surface height anomaly, 1Hz Ku band (ssha)
- Geocentric ocean tide height (GOT4.10) (ocean_tide_sol1)
- Mean Sea Surface (DTU18) (mean_sea_surf_sol2)

Sentinel-3a, Sentinel-3b

SRAL Level 2 Altimetry Global (version BC005) - Sentinel-3 – Reprocessed Product:

- Relative Orbits 041 and 362
- Dates: 01/06/23 to 31/01/24

Data from the reduced measurement product were selected by latitude (within 18.3° S to 18.8° S), and the following parameters extracted:

- Sea surface height anomaly, 1Hz Ku band (ssha_01_ku)
- Geocentric ocean tide height (GOT4.10) (ocean_tide_sol1_01)
- Mean Sea Surface (DTU21) (mean_sea_surf_sol2_01)

The total sea level was then calculated by adding the ocean tide and mean sea surface to the sea surface height anomaly. Measurements were averaged over five 1Hz data points (an along track distance of 28 km). Because of the limited time period available, it was decided to use points at which satellite tracks from two different relative orbits cross over for the validation, so that satellite data from two orbits at the same location (but separated in time) could be used, thus doubling the number of measurements available for the validation. Figures 1a, 2a and 3a show the locations of the orbits and crossover points. Portagauge sea level measurements for the nearest minute to the satellite pass were then extracted and matched against the respective satellite measurement.

The Portagauge radar water level measurement is calculated relative to the radar reference level, 10m below the radar reference plane, itself 0.196m below the benchmark on the Portagauge radar arm. We do not have a cross reference from the radar benchmark to a second reference benchmark at Toamasina.

4.3. Cross-validation results

Figures 5, 6 and 7, and Table 2 illustrate the results for Sentinel-6a-MF, Sentinel-3a and Sentinel-3b.

The Toamasina Portagauge sea level measurements used here are the absolute measurements referred to the radar reference plane and include tidal variability. Also, the satellite data have the ocean tide and mean sea surface corrections added. As a consequence, these measurements are made against different reference planes, and a significant offset was found between the satellite mean sea level and the Portagauge mean sea level. This difference between the respective mean sea levels has been removed in Figure 5, 6 and 7, and is given in Table 2.

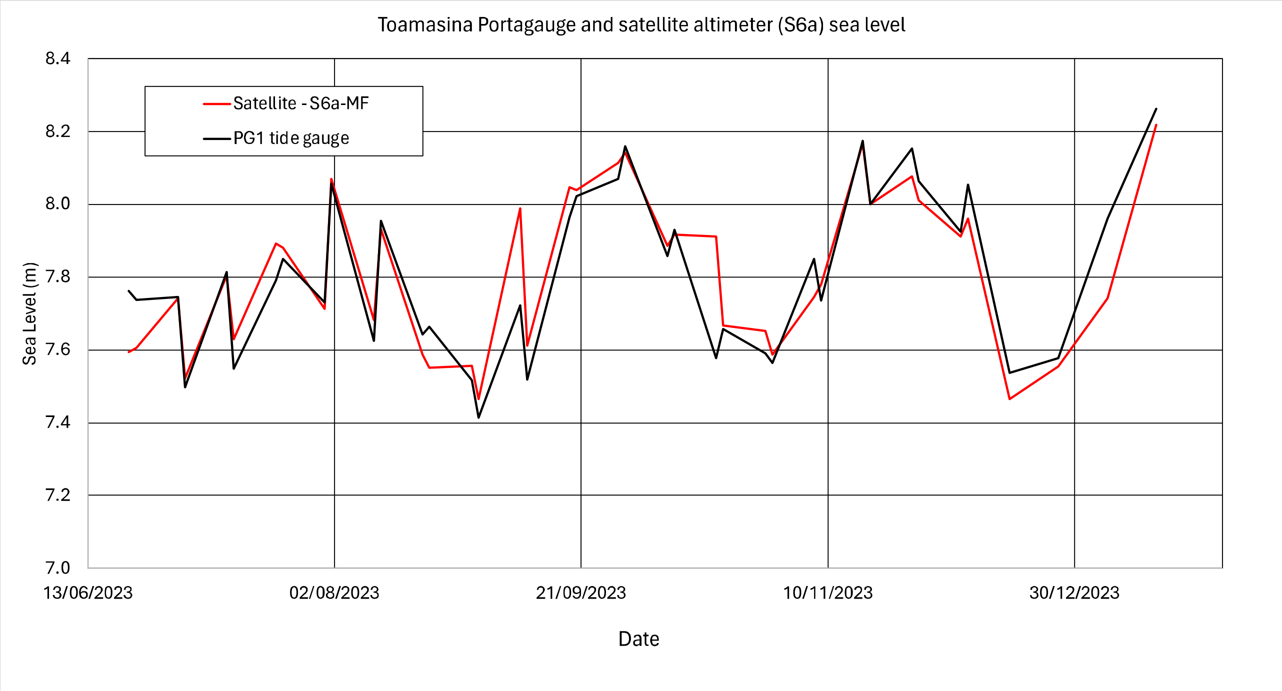

Figure 5. Cross-validation between Toamasina Portagauge and satellite altimeter (S6a-MF) sea level. The baseline for the satellite altimeter sea level has been adjusted to match the Portagauge sea level. The satellite measurements are at the crossover points between relative orbits 094 and 131.

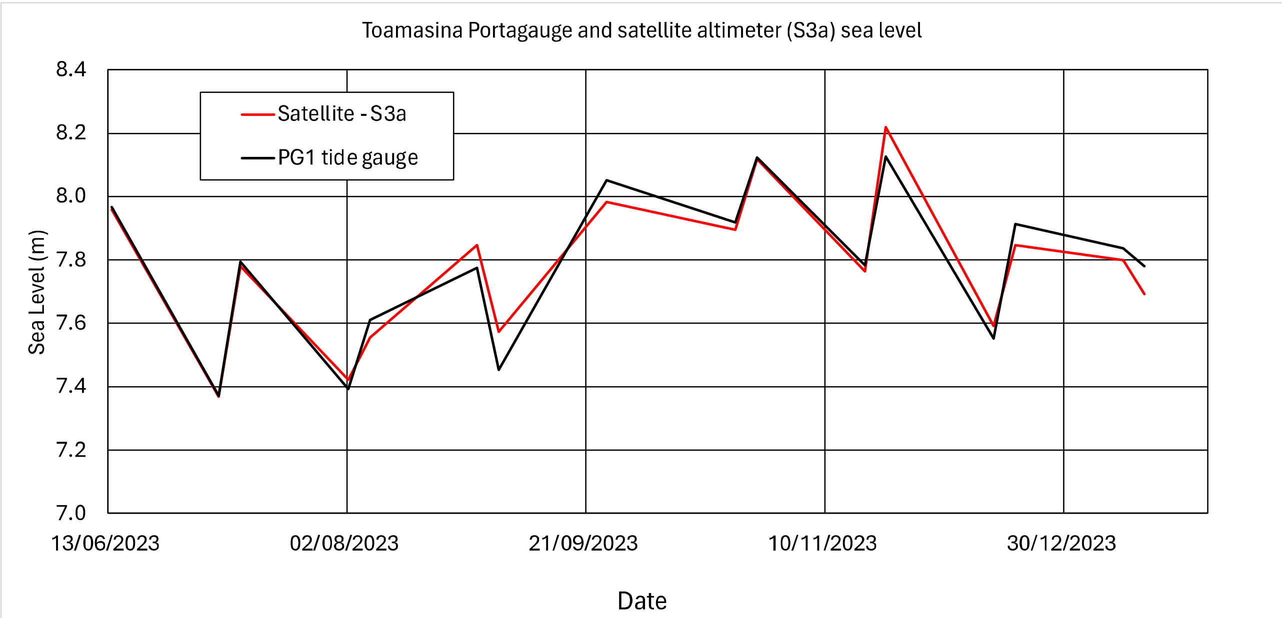

Figure 6. Cross-validation between Toamasina Portagauge and satellite altimeter (S3a) sea level. The baseline for the satellite altimeter sea level has been adjusted to match the Portagauge sea level. The satellite measurements are at the crossover points between relative orbits 362 and 041.

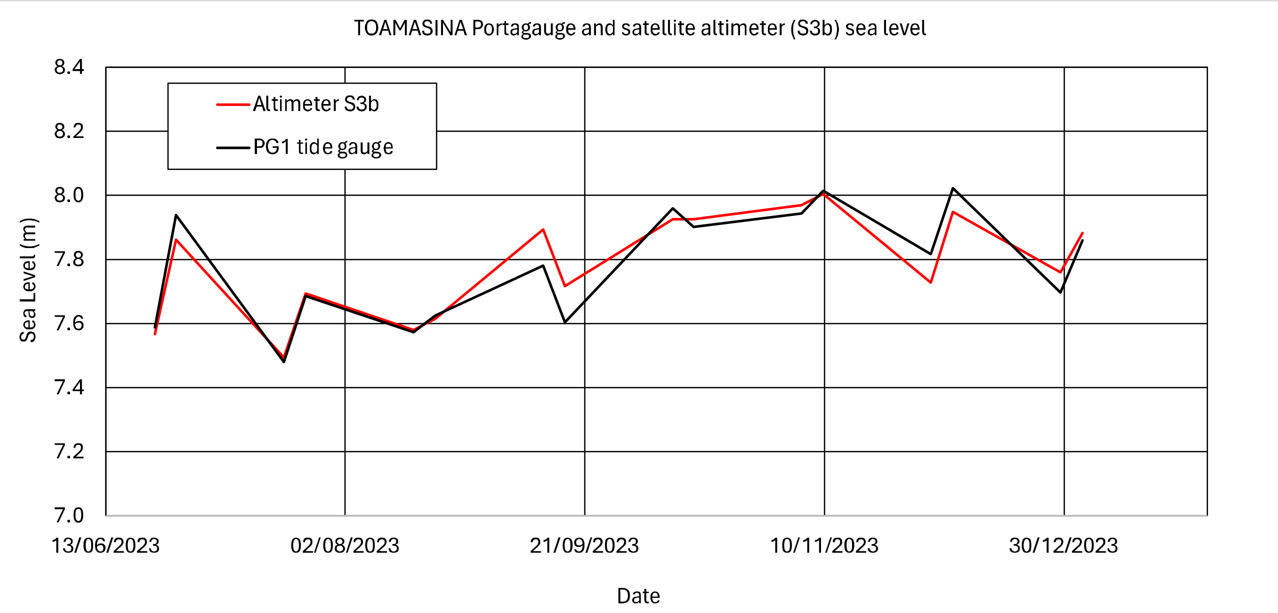

Figure 7. Cross-validation between Toamasina Portagauge and satellite altimeter (S3b) sea level. The baseline for the satellite altimeter sea level has been adjusted to match the Portagauge sea level. The satellite measurements are at the crossover points between relative orbits 098 and 034.

4.4. Discussion

Table 3 summarises the results of the cross validation of satellite data from Sentinel-6a-MF, Sentinel-3a and Sentinel-3b data against Toamasina Portagauge radar data. The table gives values for the distance to coast and distance to Portagauge at the point of highest correlation, and also the correlation and root mean square difference at these points.

Table 3. Results from cross-validation between Toamasina Portagauge radar data and satellite altimeter data. Total measured sea level from the Portagauge were compared against sea surface height anomaly data (with ocean tide and mean sea surface added) from the satellite altimeters.

Satellite(s)	Relative Orbit Nos	Distance to Coast (km)	Distance to Tide Gauge (km)	Correlation	RMS (m)	Offset applied to satellite data (m)	No of points
Sentinel-6a	094 / 131	106	273	0.8987	0.0976	18.66	40
Sentinel-3a	724 / 083	42	61	0.9703	0.0571	18.45	16
Sentinel-3b	098 / 034	92	93	0.9225	0.0638	20.15	16

Due to the limited time period for which Portagauge data are available (8 months), only a relatively small number of data points are available for the validation. Nonetheless, the results show a high correlation (0.89 to 0.97) and low RMS (5.7 to 9.8cm).

The use of crossover points means that the distance between the satellite measurements and the tide gauge was larger than the analysis in Section 2 (273km in the case of Sentinel-6-MF), perhaps resulting in a larger RMS difference between the Portagauge and satellite sea level measurements than seen in the analysis in Section 2.

The offset applied to the satellite data varied from 18.66 to 20.45m. As noted above these results are based on comparisons of total water level.

5. Cross-validation of Portagauge radar gauge data against GNSS-IR data

5.1. Methodology

For cross-validating GNSS-IR sea levels against radar gauge sea levels, both instruments within the Portagauge platform installed at Toamasina, daily mean sea levels were calculated with ocean tide removed for data from 13/06/22 to 30/11/22.

5.2. Cross-validation results

Figure 8 compares the daily mean sea level measurements (with tide removed) from the radar sensor and sea level calculated from the reflected GNSS signals (GNSS-IR). The correlation between the two data sets is 0.9901, and the root mean square error is 9.187mm.

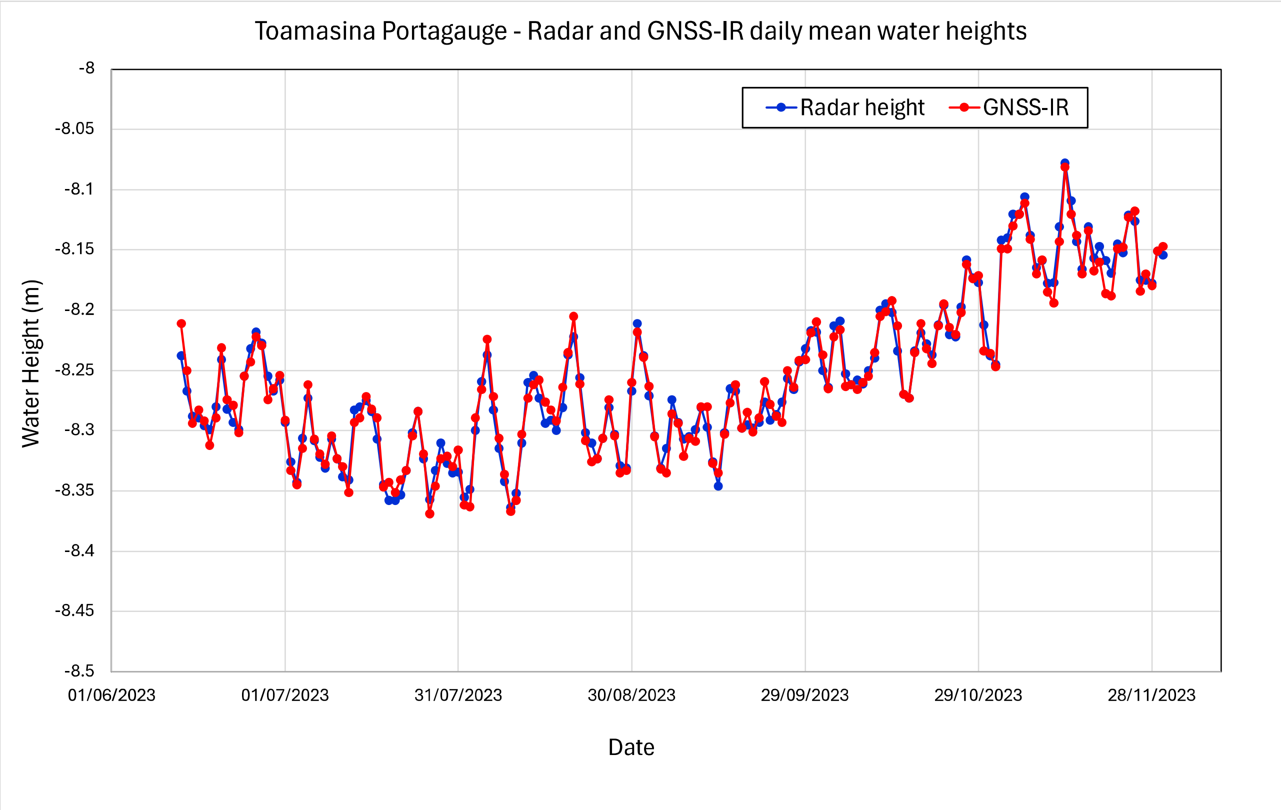

Figure 8. Daily mean water height measurements from the Toamasina Portagauge radar sensor and GNSS-IR.

5.3. Discussion

These results show very good agreement between GNSS-IR and tide gauge daily means. This is perhaps surprising as the location of the Portagauge in Toamasina harbour has a very limited field of view for GNSS signals reflected from the sea surface. Even the small segment that does look out over open water is often also interrupted by shipping (Figure 9).

There is an offset between the GNSS-IR and the Portagauge radar mean water levels of 11.7346m. A detailed explanation of why this exists is given in Annex 1 of this report.

The reference level for GNSS-IR data is WGS84, and the measured height of the GNSS (at the Antenna Reference Point) is -4.3213m with respect to WGS84 (IGS20). That therefore gives the zero level for the Portagauge sea level measurements, with respect to WGS84, of -16.0496m.

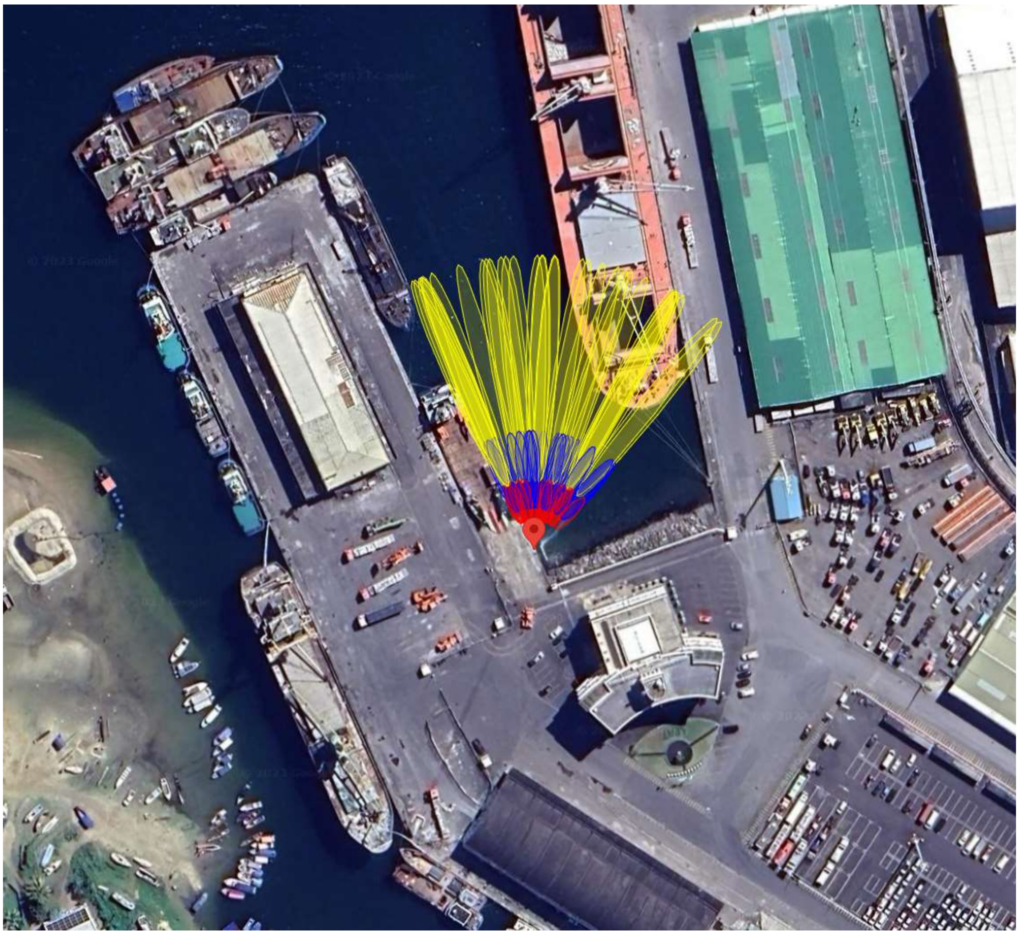

Figure 9. Field of view for GNSS_IR measurements in Toamasina harbour.

6. Reference Levels for Tide Gauge and Satellite data

6.1. SHOM Tide Gauge and NOC Portagauge

The GNSS data discussed in Section 5 can be used to provide a cross reference between the satellite and Portagauge measurements of total water level. Information from SHOM (Fraboul, 2024) indicates that the SHOM Toamasina tide gauge water level measurements are referenced to a level that is 8.997m below the reference ellipsoid. We have estimated a mean water level for the SHOM tide gauge (with respect to the reference level) of 0.76m, and for the Portagauge of 7.85m. Therefore, the mean sea levels with respect to the ellipsoid for the SHOM tide gauge and the NOC Portagauge are -8.2370m and -8.1996m respectively (see

Table 4), a difference of 3.74cm.

Table 4. Reference levels and mean recorded levels for the SHOM tide gauge and NOC Portagauge at Toamasina.

Validation	Location	Reference level wrt ellipsoid	Mean recorded sea level	Mean sea level wrt ellipsoid
SHOM TG	Toamasina	-8.997m (±0.051m)	~0.76m	-8.2370m
Portagauge (PG1)	Toamasina	-16.0496m	7.85 m	-8.1996m

6.2. Satellite Total Water Level Validations

As discussed in Section 3, the SHOM tide gauge total water level data for Toamasina were validated against Sentinel 3A data, at a point 19.9km from Toamasina. An offset of -10.28m was found between the satellite data and the tide gauge data (satellite lower than tide gauge). The satellite data are directly referenced against the ellipsoid, whereas the SHOM tide gauge reference level is 8.997 beneath the ellipsoid at Toamasina. Therefore, we have a discrepancy between the recorded total of (10.28 – 8.997) = 1.283m

As discussed in Section 4, total water level data from the Portagauge at Toamasina were validated against Sentinel 3A, 3B and Sentinel 6A data. Offsets between the satellite and Portagauge total water levels of 18.45, 20.15 and 18.66m were found. Again, the satellite water levels are directly referenced against the ellipsoid, whereas the Portagauge data reference level is 16.0496m below the ellipsoid. When corrected for the tide gauge corrections to the ellipsoid, final discrepancies in the satellite total water levels of 2.4m, 4.1m and 2.6m were found.

Table 5 summarises the results.

Possible causes of these discrepancies include:

- Errors in the tidal model at the location of the satellite altimeter data measurement.
- Errors in the mean sea surface model at the location of the satellite altimeter data measurement.
- A difference in the mean sea surface between the location of the tide gauge at Toamasina and the location of the satellite altimeter data measurement.

Table 5. Results from cross validations of satellite and tide gauge (TG) total water levels (twl), adjusted to reference against the ellipsoid (WGS84)

Satellite	Location of validation	Distance to TG (km)	Offset: TG-satellite mean total water level (m)	TG reference level wrt to ellipsoid (m)	Discrepancy: Satellite wrt ellipsoid – WGS84 (m)
S3a L2 (SHOM)	Track 083	19.9	10.28	-8.237	-1.283
S3a L2 (PG1)	724 / 063 crossover	61	18.45	16.0496	-2.404
S3b L2 (PG1)	098/034 crossover	93	20.15	16.0496	-4.1004
S6a L2 (PG1)	094 /131 crossover	146	18.66	16.0496	-2.6104

Again, we do not have a reference level for the Portagauge radar data, though we note that the reference level for Portagauge sea level measurements is set to be 10m below the radar reference plane, which is 0.196m below the benchmark on the radar arm. The satellite altimeter data total water levels are relative to the reference ellipsoid (WGS84). Thus, the difference offsets between the tide gauge and satellite mean water levels will again be made of various components, as follows:

- The difference between the Tide Gauge reference level and the reference ellipsoid at the location of the Tide Gauge in Toamasina.
- Errors in the tidal model at the locations of the satellite altimeter data measurement.
- Errors in the mean sea surface model at the locations of the satellite altimeter data measurement (different for each satellite).
- A difference in the mean sea surface between the location of the tide gauge at Toamasina and the locations of the satellite altimeter data measurement (different for each satellite).

In summary these results give confidence that a data set over a limited period (in this case 8 months) can be used to validate altimeter data against a temporary tide gauge. However, it is recommended for future deployments that levelling is carried out to establish a reference to a local benchmark. Note that the precise positioning available from the GNSS instrument is available for use in this process.

7. Assessment of satellite altimeter data generated by specialised coastal processing.

PASS-SWIO carried out a study to assess satellite altimeter data processed through the SARvatore for Sentinel-3 service with settings specific for coastal processing (Cotton and Shaw, 2023). The satellite altimeter data were from Sentinel 3A and Sentinel 3B orbits 362 and 041 in the vicinity of Toamasina, for the years 2020 and 2021. Data from the standard EUMETSAT processing were compared against data processed with specific coastal settings (including the SAMOSA+ retracker) using the SARvatore for Sentinel-3 service on the ESA Altimetry Virtual Laboratory, on EarthConsole (https://earthconsole.eu/altimetry-virtual- lab/) with funding provided by ESA Network of Resources Sponsorship.

An assessment of along-track data found that the coastal processing was able to retrieve more valid data within 5km of the coast than the standard processing (Figure 10), but that at distance greater than 5km of the coast, along track "noise" (a measure of random error) was similar from the two processing approaches (Figure 11), with the average difference between consecutive measurements of uncorrected sea surface height steady at about 5cm from 5 – 20km from the coast.

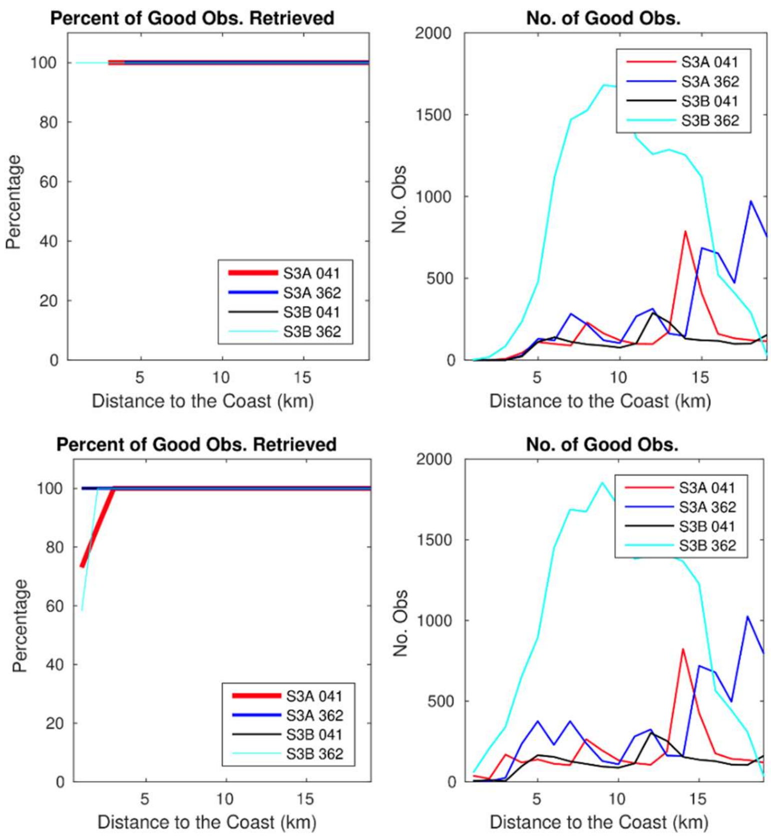

Figure 10. Percentage of "good observations" (left) and total number of "good observations" (right) retrieved from (top) the standard EUMETSAT/ESA L2 product, and (bottom) the specialist coastal processor.

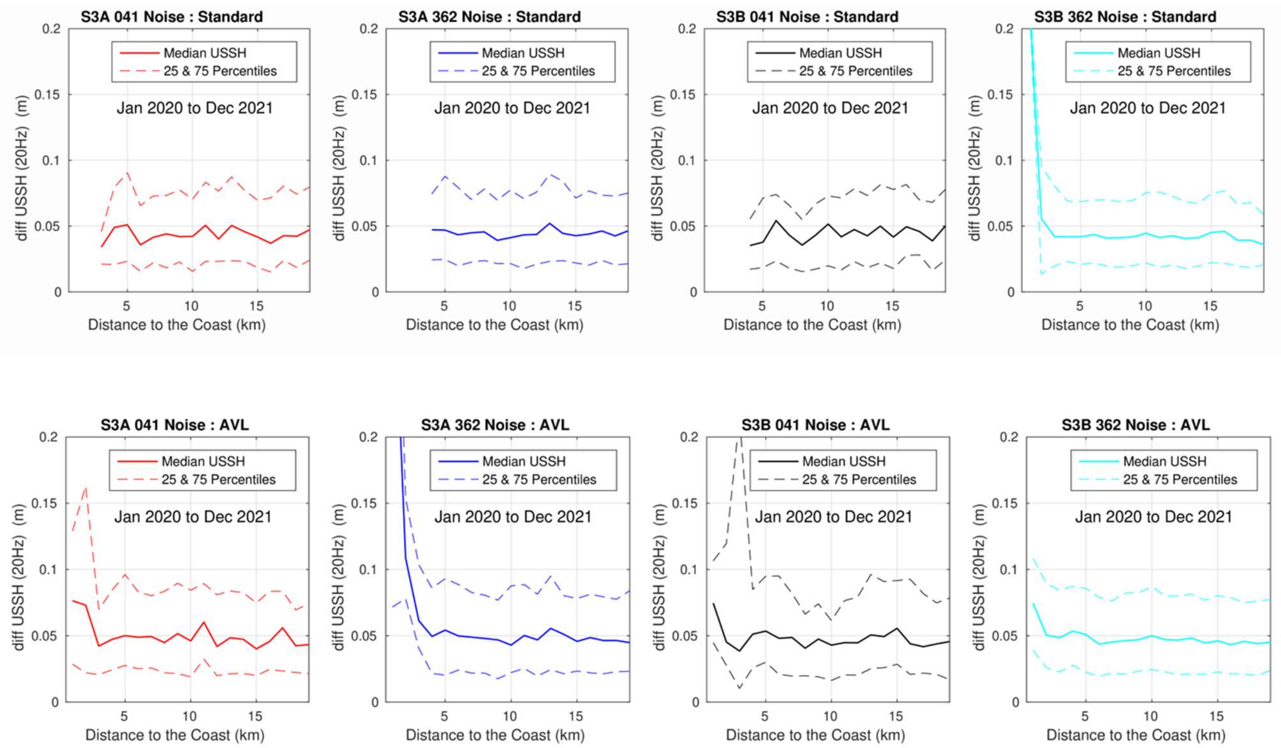

Figure 11. Along-track "noise" in sea-surface height, calculated as the difference between consecutive measurements of uncorrected sea surface height (USSH). Top Row – along track noise in USSH against distance to the coast, from the standard EUMETSAT/ESA L2 product for tracks S3A 041, S3A 362, S3B 041 and S3B 362. Bottom row - along track noise in USSH against distance to the coast, from the specialised coastal processor ("AVL").

It was therefore concluded that data from the specialist coastal processor (SAMOSA+) were not found to provide more accurate sea surface height data than those from the standard L2 EUMETSAT/ESA product (SAMOSA2 retracker) in the range 5-10km from the coast. However, the specialised processing does provide data in near coastal locations (within 5km of the coast) where the standard product does not.

8. Summary and Conclusions

The validation analysis presented in this report has shown:

- Measurements of sea level anomaly from: Jason-2, Jason-3 and Sentinel-6a Michael Freilich (MF) (2010-2022); Sentinel-3a (2016-2022); and Sentinel-3b (2018-2022), Level 3 data validated against SHOM Toamasina tide gauge sea level residual show a root mean square error of 4 to 5cm.
    - These results show a high level of agreement between the satellite and tide gauge data, even though the measurement points were up to 146km apart.

    - These results also suggest a low natural variability in sea level at this location in the Madagascar coastal region and provide confidence that the altimeter data provide an accurate measurement of sea level close to the Madagascar coast.

- Taken over 27 months (01/01/2020 to 29/03/2022), measurements of total water level from the Sentinel-3a Level 2 product validated against SHOM Toamasina tide gauge sea level show a root mean square error of 9.98cm and a correlation of 0.8533. There was an offset of 10.28m between the satellite and tide gauge total water level measurements.
    - These results suggest that the approach using Level 3 along-track time series data is to be preferred, if these data are available. This then avoids the problem of the offset between the two data sets and any error related to the tide and mean sea surface models.

- Over a period of 8 months (13/06/2023 to 31/01/2024), measurements of total sea level from the Sentinel-6a MF, Sentinel-3a and Sentinel-3b satellites validated against Portagauge tide gauge sea level show root mean square error of between 5 to 10cm.
    - These results give confidence that a data set over a limited period (in this case 8 months) can be used to validate altimeter data against a temporary tide gauge.
    - There is an offset of between 18.45 to 20.15m between the satellite altimeter and Portagauge sea level measurements. The potential components to this offset are known but have not been established in detail.

- Comparison between the GNSS-IR and radar gauge daily mean sea levels (both instruments on the Portagauge installed at Toamasina) show a very high level of agreement (root mean square error of 9.2mm). This demonstrates that the GNSS-IR instrument is able to provide an accurate measurement of water level, even when it has a severely restricted field of view.

Together these findings help us to conclude that

- A relatively short-term deployment (6-8 months) of the NOC Portagauge can provide sufficient data for a reliable cross-validation against satellite altimeter data.
- The Portagauge can be used as a basis for providing reliable sea level data to support the development of a national sea level measuring capability.
- The Portagauge could be deployed as part of calibration / validation programmes to provide reference sea level values for validation of altimeter measurements. For this purpose, it could be installed at new favourably located reference sites on a temporary (~6 months) or longer-term basis.

9. References

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Annex 1: Calculation of Reference Levels for Portagauge GNSS-IR measurements

It was noted in Section 5 that there is an offset of 11.7346m between the mean water levels recorded by the Portagauge radar gauge, and those from the GNSS-IR measurements. This annex provides an explanation for the difference between the Portagauge Radar and GNSS-IR reference levels.

The reference level for Portagauge radar sea level measurements (TGZ in Figure 12) is set to be 10m below the radar reference plane, which is 0.196m below the benchmark on the radar arm (“Marker” in Figure 12).

The GNSS-IR measurements are reflector heights (RH) relative to the antenna, and the sea surface height is the RH subtracted from the range between the GNSS antenna to tide gauge reference point, measured at 11.8026 m (see Figure 12).

The RH are in reality measured relative to an electronic Antenna Phase Centre (APC), which has been calculated for position measurements, but not for GNSS-IR measurements. These two phase centres have been seen from experiments to be different.

If we correct for the positioning APC with respect to the Antenna Referencing Point (ARP), the difference becomes 11.7423m. However, because we do not have a precise location for the IR APC we instead adjust to the GPS daily values and this gives us the 11.7346m with an RMSE of 0.06 (number of points 38595). Comparing with other sites using the same antenna the bias is possibly around 12 cm.

PORTAGAUGE (PASS-SWIO)

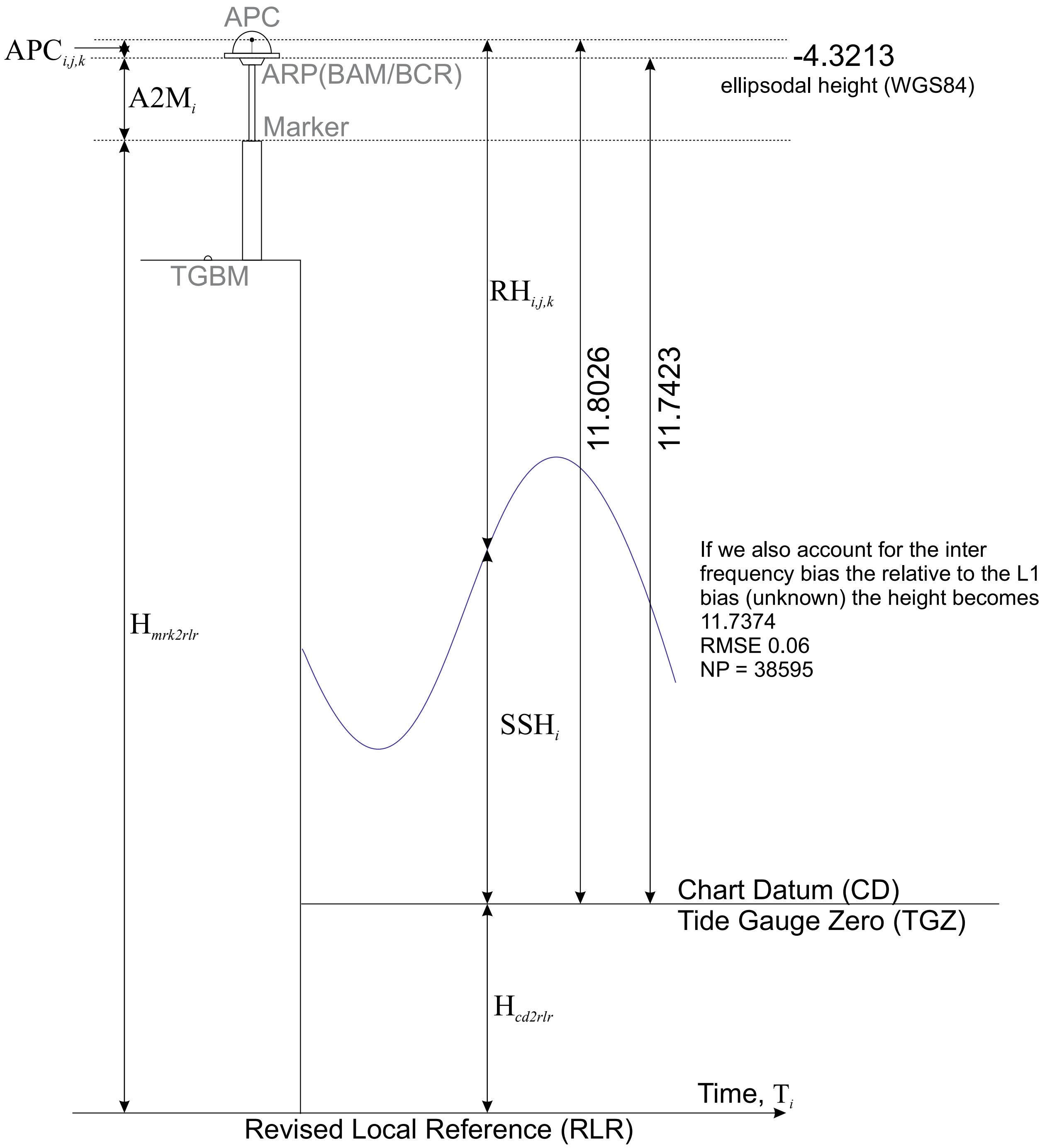

Figure 12. Calculation of reference levels for Portagauge GNSS-IR measurements. All measurements are in metres. APC – positioning Antenna Phase Centre, $APC_{i,j,k}$ - IR Antenna Phase Centre, TGBM - Tide Gauge Benchmark, BAM – Bottom of Antenna Mount, BCR - Bottom of Chokering, RH - Reflector Height with respect to GNSS antenna, SSH -Sea Surface Height.

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