PASS-SWIO

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

Final Report

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Acronyms

Acronym	Definition	Further Details
BNGRC	Bureau Nationale de Gestion des Risques et des Catastrophes	National Office for Risk and Disaster Management, Madagascar https://bngrc.gov.mg/
CCI	Climate Change Index	ESA CCI+ is a series ESA programmes to establish satellite data based indices for Essential Climate Variables
CMEMS	Copernicus Marine Environment Monitoring Service	marine.copernicus.eu
CSRS-PPP	Canadian Spatial Reference System - Precise Point Positioning	Canadian resource supporting online processing of GNSS location data. https://webapp.geod.nrcan.gc.ca/geod/tools-outils/ppp.php
DGM	Direction Générale de la Météorologie	Malagasy Met Office http://www.meteomadagascar.mg/
EO	Earth Observation	-
ESA	European Space Agency	www.esa.int
EUMETSAT	European Meteorological Satellite Agency	www.eumetstat.int
FTM	Institut Geographique et Hydrographique National, Madagascar	National geographic and hydrographic agency
GNSS-IR	Global Navigation Satellite System interferometric reflectometry	
IHO	International Hydrographic Organization	https://iho.int
NOC	National Oceanography Centre	https://noc.ac.uk/
POLTIPS	Tidal Prediction Software	Developed at the National Oceanography Centre, UK
RMS	Root Mean Square	

Acronym	Definition	Further Details
SatOC	Satellite Oceanographic Consultants Ltd	Project Partner http://www.satoc.eu/
SHOM	Service hydrographique et océanographique de la marine	A French public administrative establishment under the supervision of the Ministry of the Armed Forces https://www.shom.fr/index.php/en
TASK	Tide gauge data processing and analysis software	Developed at the National Oceanography Centre, UK
WIOMSA	West Indian Ocean Marine Science Association	https://www.wiomsa.org

1. Introduction

The Portagauge and Satellite Sea Level Monitoring System for the Southwest Indian Ocean (PASS-SWIO) project was funded by the European Space Agency (ESA) under the EO4Society programme. It aimed to establish a sea level monitoring system for Madagascar, based on the deployment of a low-cost relocatable tide gauge (Portagauge), which uses a radar gauge alongside Global Navigation Satellite System interferometric reflectometry (GNSS-IR) technology, combined with the analysis of satellite altimeter sea level data to provide validation and wider scale knowledge on sea-level variability.

This final report provides a summary of main activities, issues impacting the project, highlights of results, and lists the main outputs and recommendations.

2. Project Overview

The PASS-SWIO project kicked-off on 5th May 2022, and the Final Review meeting was held on 3rd May 2024. The project timescale was extended from 12 to 24 months due to delays in the manufacture (caused mainly by delays in obtaining parts due to COVID19) and the time required for shipping and released of the Portagauge from customs in Madagascar. There was also a short delay to travel due to unrest around national elections in Madagascar.

The PASS-SWIO project aimed to establish a sea level monitoring system for Madagascar based on the installation and deployment of a low-cost relocatable tide gauge (Portagauge).

The project partners worked closely with Direction Générale de la Météorologie (DGM) who took responsibility for the local maintenance and operation of the Portagauge and were trained to carry out the data processing and analysis of tide gauge and satellite altimeter data. The Portagauge was installed at the port of Toamasina in June 2023 and was donated to DGM at the end of the ESA-funded project.

Discussions were held with key stakeholders to review the project and agree a Road Map for the sustainable long-term implementation of a national sea level monitoring system for Madagascar, which can serve as model for other island states and coastal countries in the Southwest Indian Ocean (SWIO) region and beyond.

2.1. Scientific and Technical Objectives

The main objective of the PASS-SWIO project is to implement and evaluate a low-cost sea level monitoring system for the Madagascar coast, which combines data from relocatable in situ tide gauges with satellite altimeter sea level measurements and analyses. If the evaluation is positive, then this approach can provide a model for application in similar developing island states and coastal nations with limited existing capability and resources.

Scientific/Technical objectives for PASS-SWIO were:

- Provision, shipment, installation and operation of a NOC Portagauge to provide a minimum of 6 months sea level measurement at an agreed location in Madagascar.
- Processing of the NOC Portagauge data and historical Madagascar tide gauge data to provide quality controlled sea level time series data.
- Processing of satellite altimeter data to provide co-located along-track time series of Total Water Level Envelope data for the Madagascar coast.
- Cross calibration of in-situ and satellite sea level data.
- Analysis of tide gauge and satellite data to provide a report on characteristics of sea level variability at the Madagascar coast (tidal, seasonal and inter-annual characteristics).
- Training of staff from the DGM to operate and maintain the Portagauge, and to carry out the data processing (including quality control) and analysis.
- A road map for the sustainable implementation of a national sea level monitoring system for Madagascar.
- The end goal is to provide a model for a sea level monitoring system for developing island states and coastal nations, based on low-cost tide gauges and satellite data.

These objectives were addressed under four technical work packages:

WP1000 – User Engagement & Capacity Building

WP2000 – Portagauge Manufacture, Installation & Operation

WP3000 – Sea Level Data Processing

WP4000 – Sustainable Implementation Road Map

Figure 1 provides an overview and detail on flow between the tasks. The activities of the four technical work packages are described in detail in Section 3.

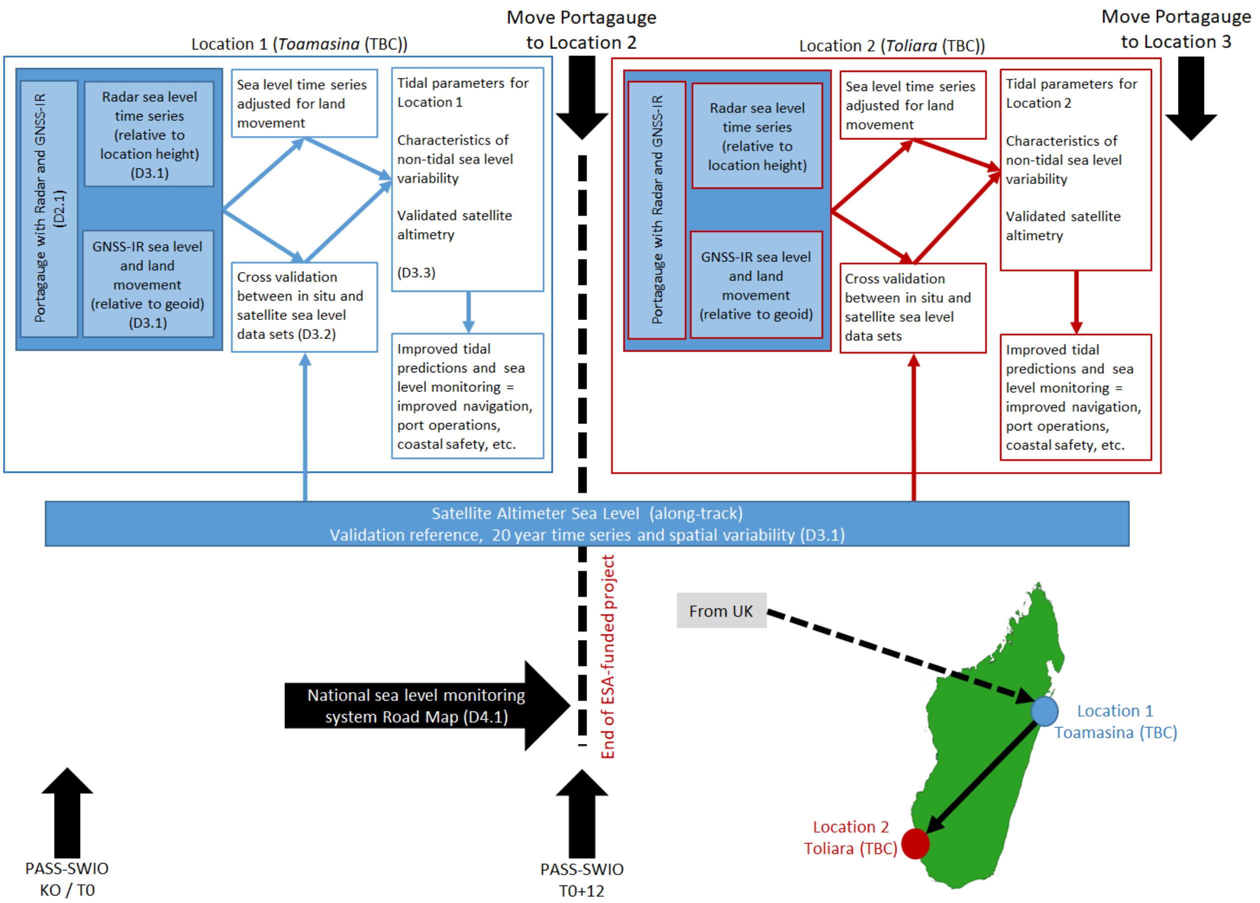

Figure 1. PASS-SWIO Implementation Diagram

3. Summary of Main Activities

3.1. WP1000 User Engagement and Capacity Building

This activity (WP1000) was led by NOC, with support from SatOC.

Training

Table 1 lists the training activities carried out in PASS-SWIO.

The training in the installation and operation of the Portagauge were provided in person to DGM staff during the visit of a NOC engineer to Toamasina, Madagascar, for the installation of the Portagauge on 12-16 June 2023 (Figure 2). A key resource to support this training is the Portagauge Installation Manual, available in both English and French.

Figure 2. DGM, NOC and SatOC staff during the Portagauge installation at Toamasina Harbour, 13 June 2023

Training in tide gauge and satellite altimeter sea level data processing and validation provided through an online training workshop, held over two days, on 12 and 18 October 2023, and through in person training delivered at the DGM offices in Antananarivo, Madagascar, on 13 and 14 February 2024. The objective of this training was to ensure that the Portagauge end users (DGM) are fully trained in the processing of satellite altimeter and tide gauge data, and in cross-validating these data against each other. It covered checking and validation of tide gauge sea level data; processing and submission of

Portagauge GNSS position data, satellite altimeter data accessing and pre-processing, cross-validation of satellite altimeter and tide gauge data, and analysis of sea-level variability from satellite altimeter data.

The data processing and validation required the use of tide data processing applications and python code routines. Training resources are available on the project web page at https://www.satoc.eu/projects/pass-swio/training.html

Table 1. PASS-SWIO training events

Name	Dates	Details	Participants
Portagauge Installation and Operation	12-16/6/23	In person, Toamasina	NOC, DGM, SatOC
Initial Training	10 & 18/10/23	Online. Presentation and exercises	NOC, DGM, SatOC
Second Training	14/02/24	In person at DGM offices, Antananarivo, Madagascar	NOC, DGM, SatOC

User Engagement

It was important to engage with current and potential users of sea level data in Madagascar to understand the main requirements for sea level information and gaps in current data availability. This will help to inform plans for future developments and ensure that they meet key user requirements, complemented existing and planned capability and are sustainable in the long-term, considering availability of resources.

Initial engagement was through a webinar on 14 September 2022. A series of five presentations introduced the PASS-SWIO project, provided context to sea level change in the Southwest Indian Ocean and introduced an online questionnaire. These presentations are available on the project website (https://www.satoc.eu/projects/pass-swio/index.html).

Following the webinar, we shared an online questionnaire, with the objective to understand requirements of users in Madagascar for sea level data, together with relevant background information. The results from 17 individual responses are summarised in a document *User Requirements Survey - Summary of Results,* available on the project website. The responses revealed an interest in sea level data for most of the Madagascar coastline, for a wide range of uses. Problems identified included: sparse data availability, which could be difficult to access; and limited resources in terms of logistical capability, access to IT hardware, and available skills for data analysis.

Finally, in person meetings were held with Madagascar organisations during the PASS-SWIO team visit to Antananarivo, Madagascar, on 12-16 February 2024.

3.2. WP2000 Portagauge Manufacture, Installation and Operation

This activity (WP2000) was carried out by NOC, with the assistance of DGM and SatOC. The main objective was to design and install a relocatable multi-parametric tide gauge system (Portagauge) to ground truth satellite data and provide complementary high frequency observational datasets for Malagasy stakeholders.

Manufacture

The initial component of this work package was to design the Portagauge (both mechanical and electrical aspects - Figure 3), procure the necessary components, assemble them within a bespoke supporting steelwork and test the operation. This was all carried out within NOC's Liverpool offices during May to November 2022. There were some unexpected delays due to COVID19 impacting availability of components, the requirement for design alterations to accommodate additional solar panels and the need to remake some steel framework components. The Portagauge was ready for shipping at the end of November 2022.

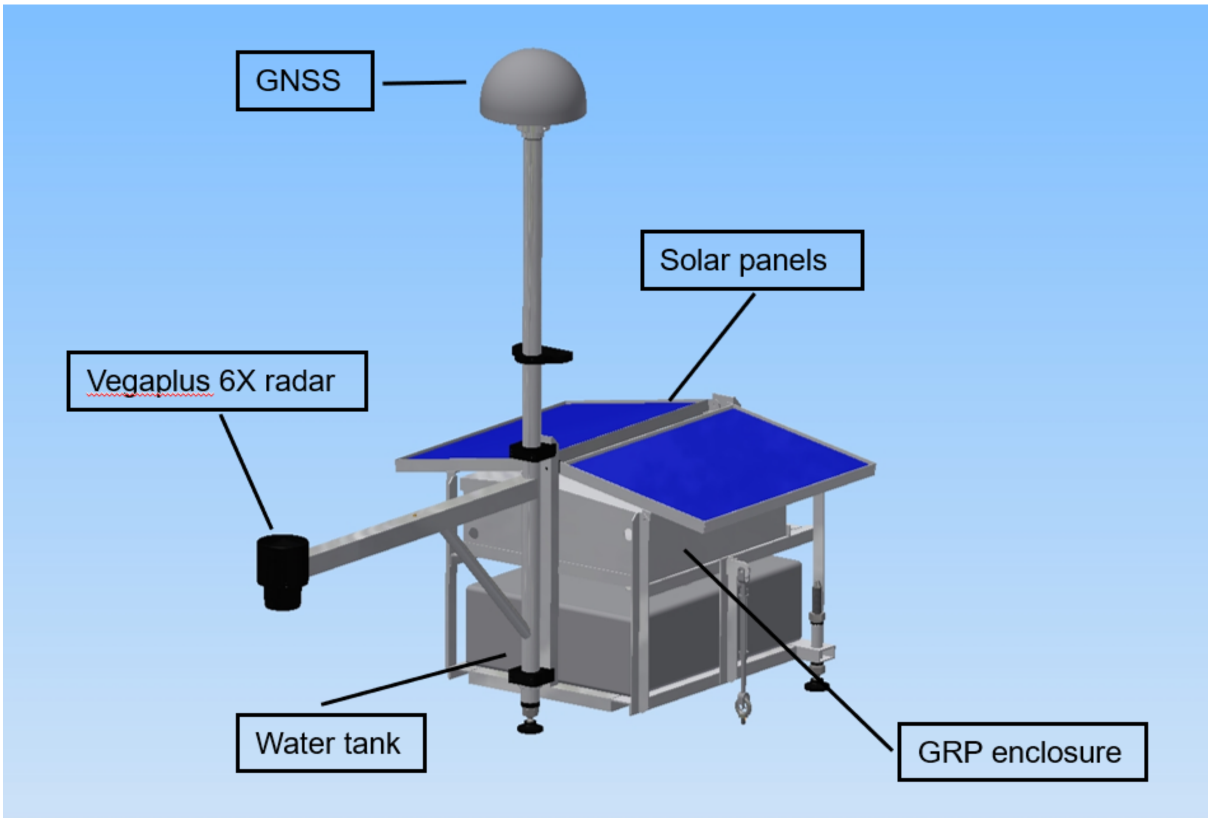

Figure 3. Computer-Aided Design of Portagauge

Transport and Installation

There was some difficulty in obtaining dates and quotes for shipping to Madagascar, as available services are very infrequent, which created an additional delay in the project. The Portagauge was transported by sea to Madagascar, in a specially designed packing crate, arriving in Toamasina (via Mauritius) on 18/02/23. It was further delayed by being held in customs for 10 weeks until 22/03/23.

The Portagauge was delivered to the care of DGM at Toamasina on 03/05/23 and installed by NOC and DGM staff on 13/06/23. The installation was trouble free and the instruments confirmed to be working according to expectations after initial switch on. DGM staff reported that the instruction manual was clearly written and easy to follow.

Following initial installation and successful transmission of data in the first few weeks, we experienced difficulties with data transmission via the mobile data network. A global mobile data SIM card was purchased in the UK and provided with the Portagauge, however after success in making an initial data connection it failed to reconnect. After several attempts to reset the connection the global SIM card was replaced with a local SIM card, which restored the data connection. There were also some technical problems with the router, which resulted in a loss of the local Wi-Fi connection. This was solved by a physical reset. All data were recovered by copying to a USB memory drive.

Figure 4 and Figure 5 show the location of the Portagauge within the harbour and in the overall context of Madagascar and the installed Portagauge in Toamasina Port.

Figure 4 Location of Toamasina Port and the site of the Portagauge (yellow stars)

Figure 5 The Portagauge deployed at Toamasina, Madagascar

Operation

The Portagauge has been operating continuously since 13/06/23. Local DGM staff have visited the Portagauge on a number of occasions to investigate the problem related to the data transmission via the mobile network and attempt fixes recommended by NOC. No other issues in operating the Portagauge have been reported, although it was noted that it would be useful to have a small laptop or tablet to use when connecting to the Portagauge on these visits.

3.3. WP3000 Sea Level Data Processing

This activity (WP3000) was carried out by NOC, and SatOC, with the assistance of DGM.

The Data Sets are fully described in the PASS-SWIO Deliverable D3.1 *Data Set and Report for Tide Gauge and Satellite Data.*

Portagauge Radar Sea Level Data

The NOC Portagauge provides sea level measurements via a Vegapuls 6X radar sensor. This is set to provide one measurements of sea level every minute.

The raw sea level measurements have been quality controlled and reformatted using the TASK (Tidal Analysis Software Kit) processing software. This has produced a primary results file which provides the harmonic tidal constituents, a TASK format .t2k (text) file of quality controlled one minute sea level measurements, and daily average and monthly average sea level measurements data files (tidal signal removed).

The quality control process confirmed that the Portagauge radar data are of excellent quality and had no suspect data points (Figure 6). A comparison of the tidal constituents derived from this relatively short period data set showed good agreements with constituents derived from the SHOM tide gauge which was previously located nearby. DGM have been trained to carry out the routine data quality control and processing using the TASK software.

Processed and validated sea level data from the Portagauge Radar gauge are available from 10:04 13/06/23 to 05:30 25/04/24. Data are still being recorded at the time of writing.

Figure 6. Portagauge Sea Level Data on TASK application (June to September 2023). In the top panel the green line gives the recorded sea level, and the blue line the tidal prediction. The magenta line in the bottom panel gives residual sea level (recorded minus tidal prediction).

GNSS Data

The GNSS instrument in the NOC Portagauge is a Trimble Alloy GNSS receiver. The GNSS receiver receives direct GNSS signals to provide a precise location measurement, and indirect signals reflected from the sea surface.

The direct and reflected GNSS signals have been processed using the Canadian online system CSRS-PPP (https://webapp.geod.nrcan.gc.ca/geod/tools-outils/ppp.php) to generate daily mean files for location and sea-surface height. DGM staff have been trained on the processing of the GNSS data using this system

Sea surface height data are provided referenced to the ellipsoid, so can be used to connect the sea level measurements provided by the satellite data to the sea level measurements from the Portagauge.

The precise positioning data are of interest to the Madagascar national mapping and hydrographic agency (FTM).

Processed GNSS data from the Portagauge are available from 13 June 2023 to 29 April 2024. Data are still being recorded at the time of writing.

Satellite Altimeter Data

Three sets of satellite altimeter data have been used in the PASS-SWIO project.

1. CMEMS L3 satellite altimeter data, subset and reformatted to an along-track time series – for validating against historical tide gauge data and analyses of sea level variability.

Along-track time series of sea surface height anomaly data were used for validating satellite sea level measurements against historical Toamasina Tide Gauge data and for analyses of sea level variability.

The source product for these data was the SEALEVEL_GLO_PHY_L3_MY_008_062 product, downloaded from the Copernicus Marine Service, for the following satellites and time periods:

- Jason-1, Jason-2 and Jason-3: 2002-2022
- Sentinel 3A 2016-2022
- Sentinel 3B 2018-2022

These data were subset by NOC and SatOC to within a latitude and longitude range around Madagascar (36°-56° E, 8°-30° S), and then processed into a reduced netcdf format.

2. Reprocessed Sentinel-3A and Sentinel-3B data – for assessing potential improvements from coastal processors.

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. The satellite altimeter data used for this study 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

3. EUMETSAT non-time critical L2 and L2P for validating Portagauge data.

Standard EUMETSAT Altimeter L2 products for the Sentinel 6A MF (the latest in the "Jason Series" satellites), Sentinel-3A and Sentinel-3B were used for cross validation against the NOC Portagauge data. This was necessary because the CMEMS L3 along-track product is not yet available.

Data for the period 13/06/23 to 31/01/24 were downloaded from the EUMETSAT Earth Observation portal / EUMETSAT Data Store.

Validation of Satellite Altimeter and Tide Gauge Data

A series of validation activities were carried out to assess the quality of the Portagauge data sets, and to cross-validate satellite altimeter measurements of sea level against in-situ measurements. The results of these assessments are described in the deliverable D3.*2 PASS-SWIO Validation Report*.

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

Satellite data for 2010-2022 were cross validated against historical tide gauge data from the original SHOM tide gauge at Toamasina. Residual sea level measurements were compared (sea level minus mean sea level and minus tidal variability). Figure 7 shows the results for data from one track of the Jason series satellites. Table 2 summarises the results for all the data.

They show a high correlation between the satellite and tide gauge residual sea levels of greater than 0.8 and a root mean square difference of 4.2 to 4.9 cm. Thus, 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).

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)
Jason series	094	14.8	146.0	0.8312	0.0422
Sentinel-3a	083	18.0	19.9	0.8224	0.0443
Sentinel-3b	197	48.0	81.0	0.8267	0.0494

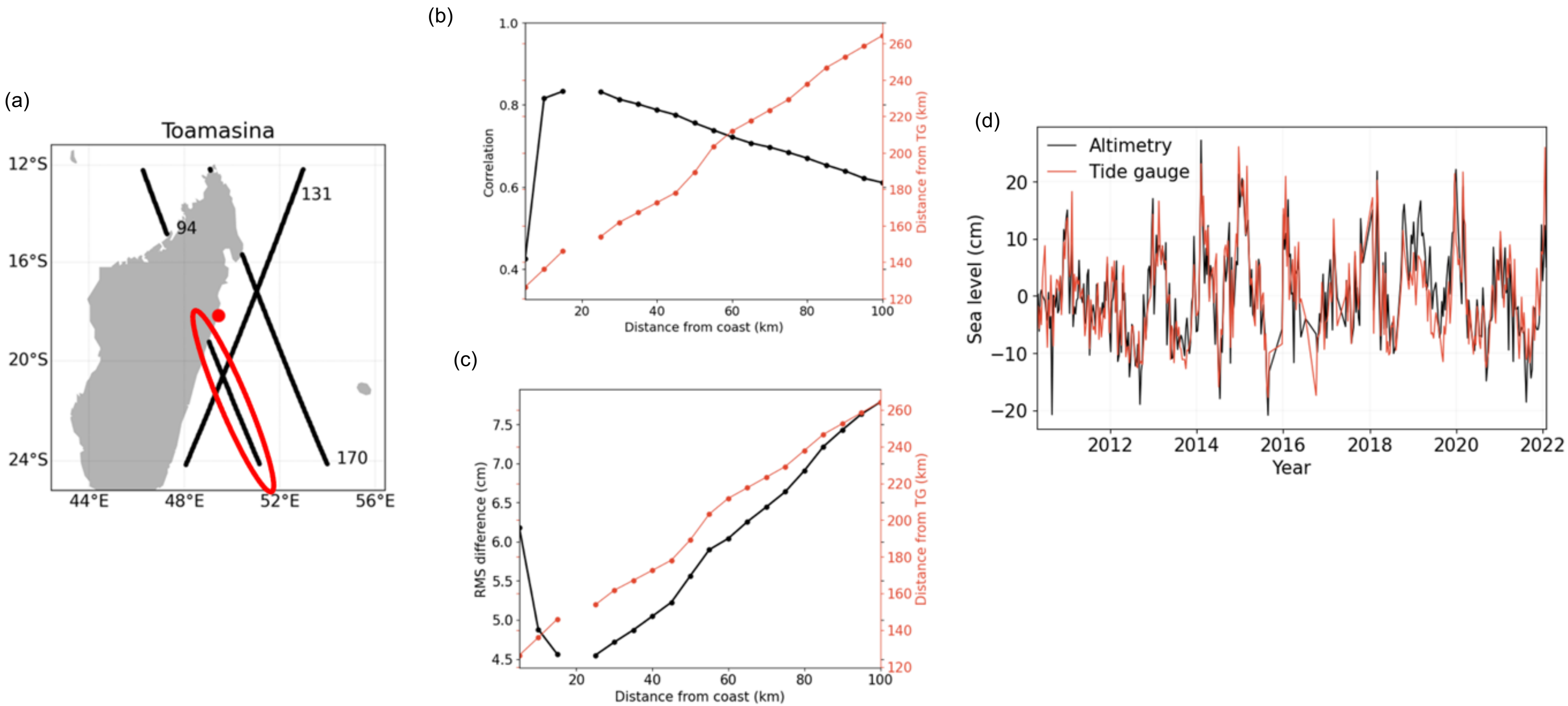

Figure 7. Results from cross-validation of satellite altimeter sea level anomaly against Toamasina tide gauge residual – for Jason series satellite data. (including Sentinel-6a-MF). (a) Jason series satellite orbits close to Toamasina. (b) Correlation against distance from coast (relative orbit 094). (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).

2. Cross-validation of Portagauge radar gauge data against satellite altimeter data
   For the cross validation of Portagauge data, total water level measurements from the Portagauge radar and along track satellite L2 data products were compared. The data sets covered the period 13/06/23 to 31/01/24. Figure 8 illustrates the result from Sentinel 6a-MF data.
   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. The track numbers are indicated in column 2 in Table 3, and the distances from the cross over points to the nearest coastline and to the Portagauge at Toamasina are indicated in columns 3 and 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 of between 18.45m and 20.15m was found between the satellite mean sea level and the Portagauge mean sea level (Table 3, column 7).

Despite the relatively short time scale and limited number of data points, the results in Table 3 (columns 5 and 6) show a high correlation (0.89 to 0.97) and low RMS (5.7 to 9.8cm).

Table 3 summarises the results for all the satellites. Due to the limited time period for which Portagauge data were available for this comparison (8 months), only a relatively small number of data points are available for the validation.

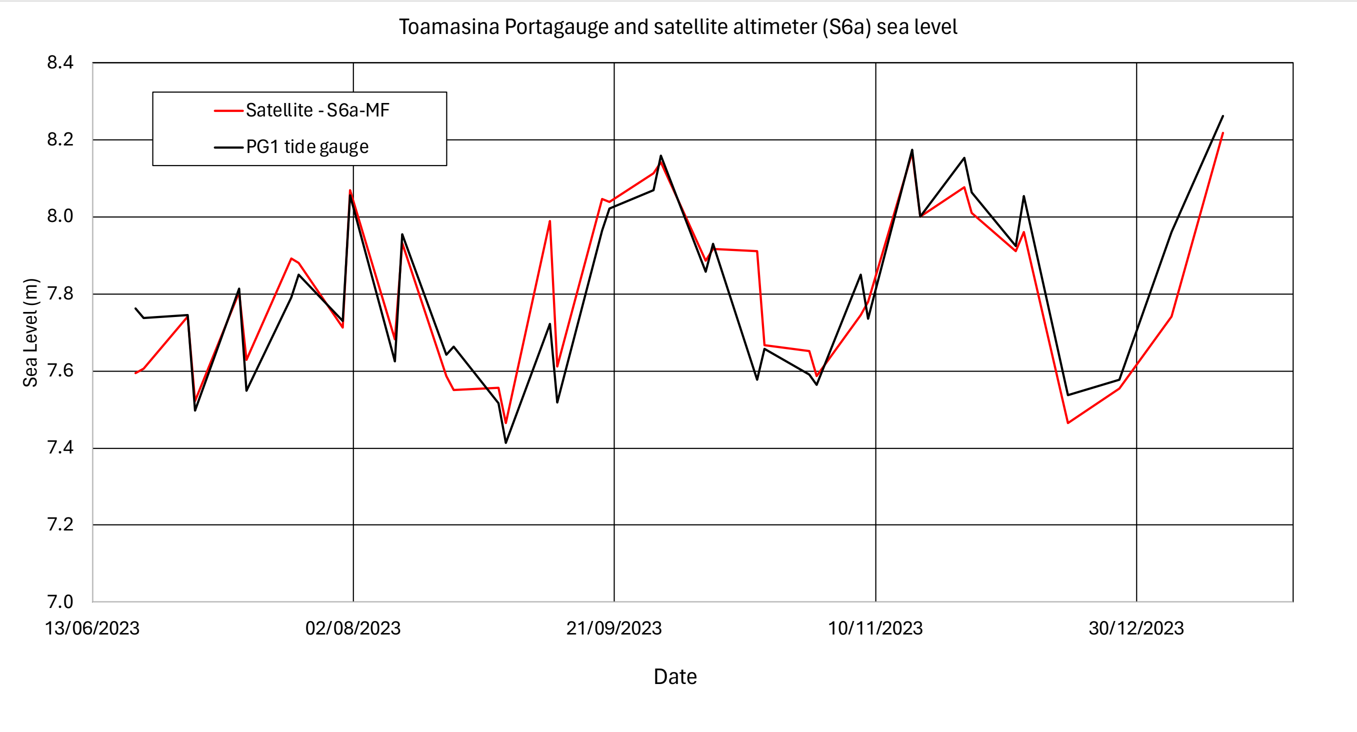

Figure 8. Cross-validation between Toamasina Portagauge and satellite altimeter (S6a-MF) sea level. The baseline for the satellite altimeter sea level has been adjusted to match the Portagauge sea level. The satellite measurements are at the crossover points between relative orbits 094 and 131.

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. The track numbers are indicated in column 2 in Table 3, and the distances from the cross over points to the nearest coastline and to the Portagauge at Toamasina are indicated in columns 3 and 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 of between 18.45m and 20.15m was found between the satellite mean sea level and the Portagauge mean sea level (Table 3, column 7).

Despite the relatively short time scale and limited number of data points, the results in Table 3 (columns 5 and 6) show a high correlation (0.89 to 0.97) and low RMS (5.7 to 9.8cm).

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

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

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. Figure 9 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. There is an offset between the GNSS-IR and the Portagauge radar water levels of 11.7346 m. 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.

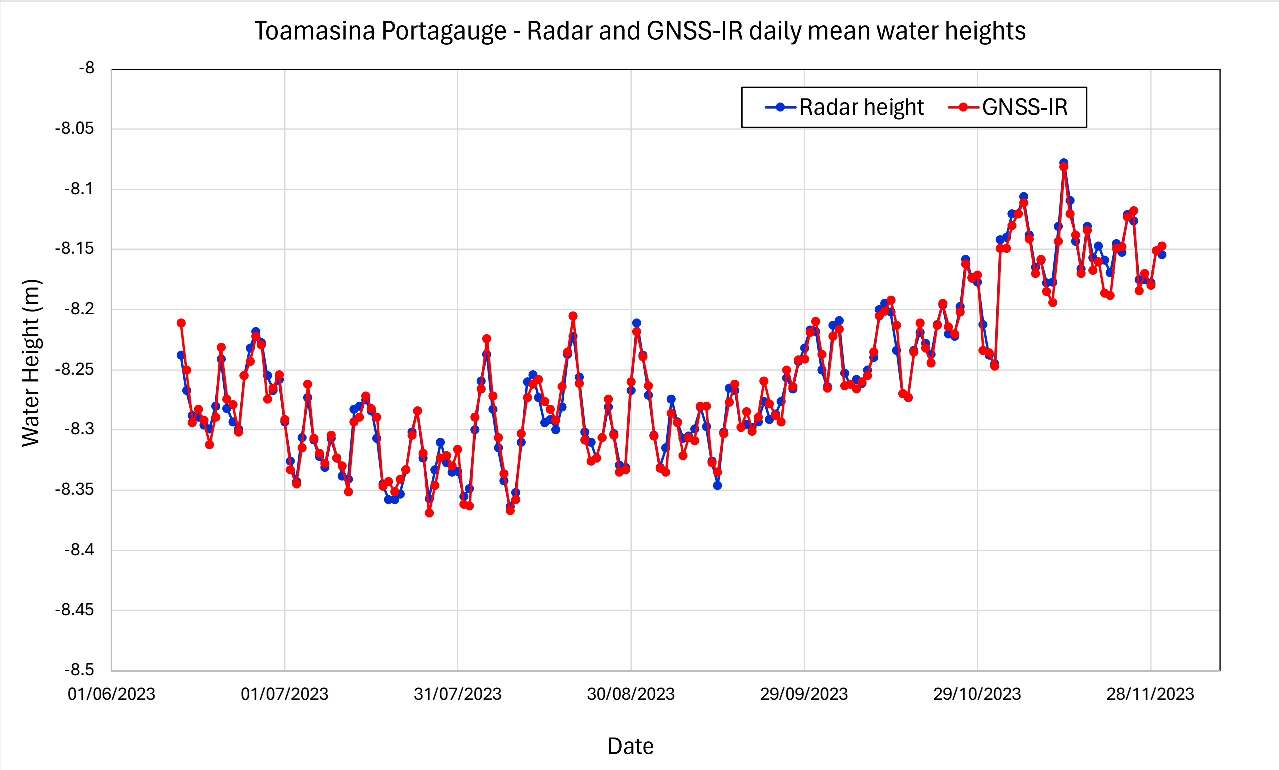

Figure 9. Daily mean water height measurements from the Toamasina Portagauge radar sensor and GNSS IR.

4. 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. 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, 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, with the average difference between consecutive measurements of uncorrected sea surface height steady at about 5cm from 5-20km from the coast (see Figure 10).

It was 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. The results of this study are provided in the PASS-SWIO Technical Note: *Technical Note on the Analysis of Sentinel-3 Altimeter Data at the Coast of Madagascar*, which is available on the project website.

5. Conclusion

From the above validation studies, it was concluded 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, and that 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 results also demonstrate that the Portagauge could be deployed in 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.

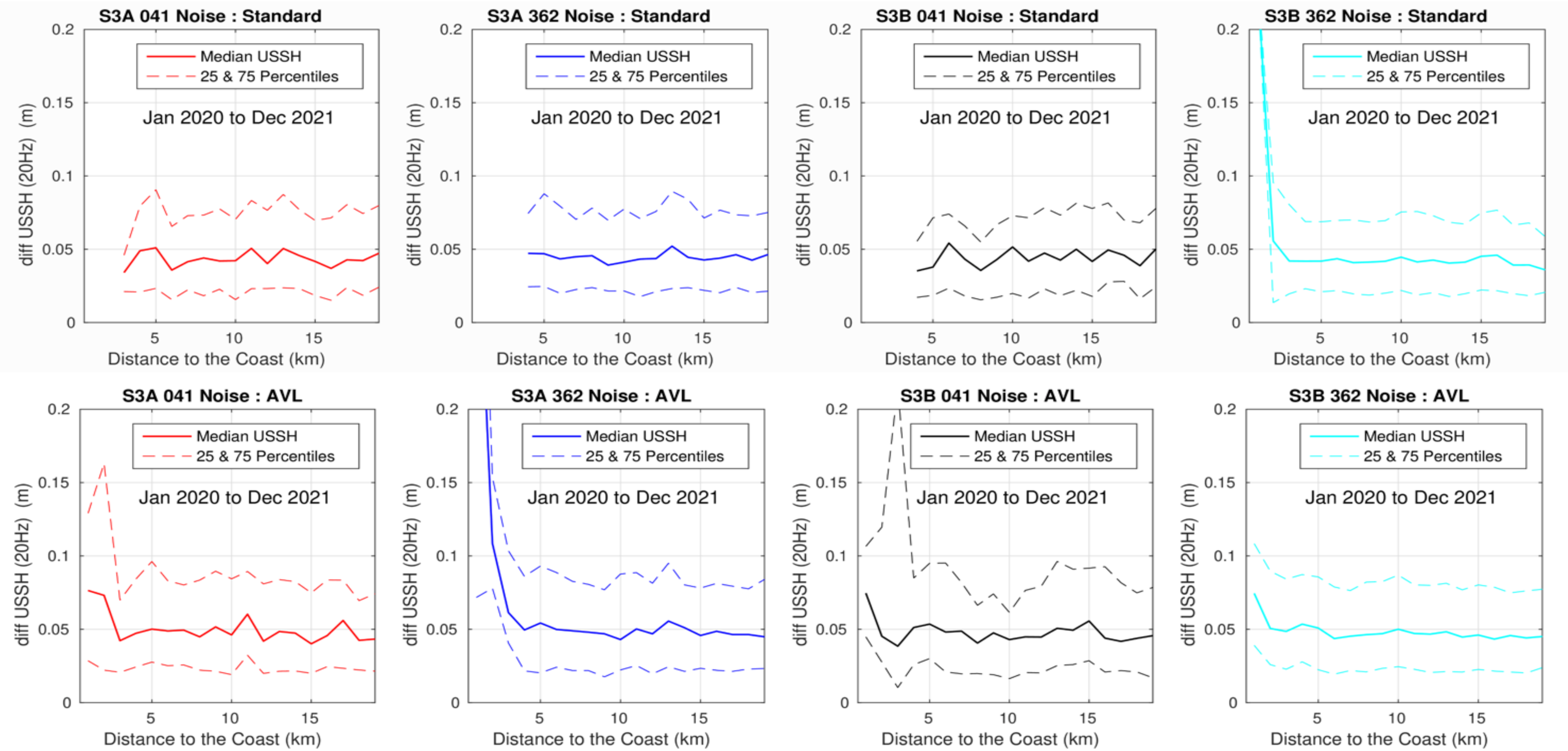

Figure 10. Along-track "noise" in sea-surface height, calculated as the difference between consecutive measurements of uncorrected sea surface height (USSH). Top Row – along track noise in USSH against distance to the coast, from the standard EUMETSAT/ESA L2 product for tracks S3A 041, S3A 362, S3B 041 and S3B 362. Bottom row - along track noise in USSH against distance to the coast, from the specialised coastal processor ("AVL").

Sea Level Variability Analysis

An analysis of characteristics of sea level variability for the Madagascar coastal region was carried out. Analysis of tidal characteristics was based on tide gauge and tide model data. Satellite Altimeter data were processed and analysed to provide analyses of seasonal and inter-annual variability (including long-term trends). The objective of the overview is to identify regions where the patterns of variability are coherent, and where they are different, to support the identification of future tide gauge locations in the development of a sea level monitoring system for the Southwest Indian Ocean.

The results of this analysis are provided in PASS-SWIO deliverable D3.3 *Sea Level Variability Report*.

1. Tidal Variability

Tidal parameters vary around the coast of Madagascar. The tidal range varies from 4m in the northwest coast to less than 1m on the east coast.

Tidal parameters for locations around the Madagascar coast were extracted from the POLTIPS model (NOC, 2024) and used to analyse tidal variability around the coast of Madagascar.

The largest tidal range (4.03m) is for Mahajanga in the northwest, this range decreases for locations to the south on the west coast (Morondava 3.91m; Toliara 2.96m). The tidal range is much lower on the east coast: 0.72m at Toamasina and 0.55m at Mananjary. Note that these tidal ranges are not referenced against a local datum, but against a nominal mean sea level.

2. Non-Tidal Variability

Long term trends in sea level also vary around the coast of Madagascar, from 3.9 $mmyr^{-1}$ in the northwest to 2.1 $mmyr^{-1}$ in the southeast (Figure 11). From analysis of 20 years' altimeter data, the sea level at the Madagascar coast is estimated to have risen by 42 – 780 mm over that time period. These trends calculated from satellite altimeter data are expressed relative to a mean sea level, so do not include any changes in the land at the coast (for instance vertical land movement and erosion), which should be investigated.

The seasonal cycle in sea level is mostly caused by variations in ocean circulation driven by the different monsoon seasons. The amplitude of the semi-annual cycle was under 2cm, and 6-10cm for the annual cycle, largest at the southwest coast. It is much lower than the tidal range, even for the east coast. This is more important for oceanographic investigations and unlikely to be an important practical consideration for most coastal applications.

3. Extreme Events

In terms of extreme events, the storm surge associated with tropical cyclones can be up to 2m. The impact of storm surges can be felt at all locations on the Madagascar coast, but analysis of historical storms indicates the northeast coast and central west coast are most at risk.

Madagascar is also subject to risk from Tsunami. The maximum runup from the 26/01/04 Indian Ocean Tsunami was 5.4m at Betanty in the south.

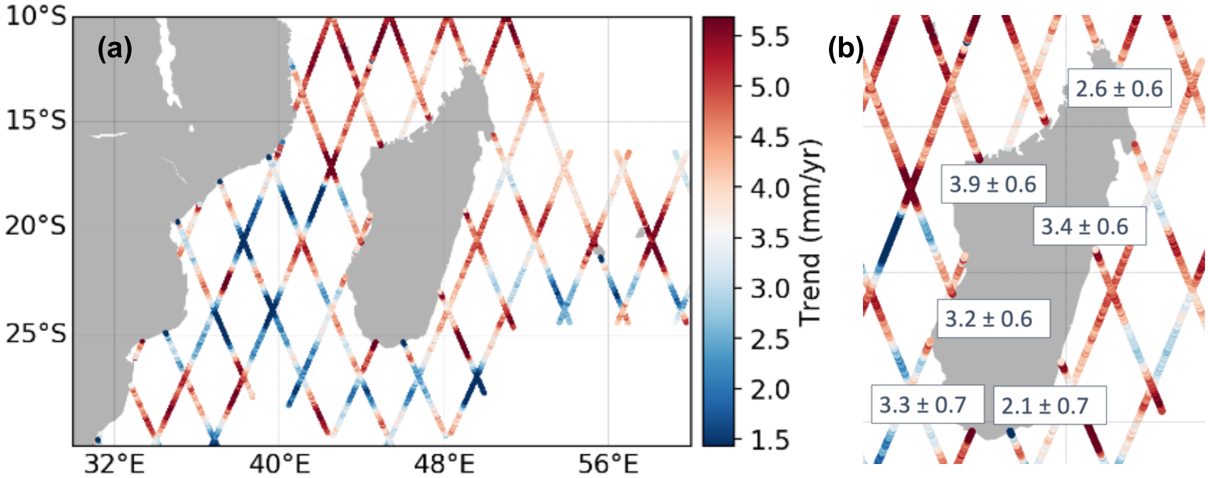

Figure 11. (a) Annual increase in sea level (2000-2020) calculated from satellite altimeter data (Jason-1, Jason-2, Jason-3), (b) Zoom of right panel to Madagascar coast. Inset values are annual increase within 3km of the coast, calculated for the ESA CCI+ sea level project (Cazenave et al., 2022)

4. Conclusions

It was concluded that the major factors of variability in sea level for Madagascar were the differences in tidal range on the west and east coasts, and the impact of storm surges on the northeast and central west coasts. Infrastructure, logistical and security requirements are also key considerations in identifying suitable locations, with only the six major international ports meeting the necessary conditions (Toamasina, Toliara, Antsiranana, Mahajanga, Nosy Be and Ehoala). These ports are relatively evenly distributed around the Madagascar coast, and so a programme that places the Portagauge at these ports will allow measurement of key characteristics of sea level variability around the coast of Madagascar.

3.4. WP4000 Sustainable Implementation Road Map

This activity (WP4000) was carried out by SatOC and NOC. The objective was to work with Malagasy agencies to define a road map to establish a long-term, sustainable, national sea-level monitoring system for the country. Major tasks were:

- To summarise requirements for a Madagascar sea level monitoring capability, based on inputs from WP1000 and further discussions with stakeholders
- Plan future Portagauge deployments in Madagascar, considering:
  - Key characteristics of sea level variability (tidal, and non-tidal)
  - Coastline sections displaying similar variability characteristics (tidal and non-tidal)
  - Important port and harbour locations, requirements for regional coverage, and understanding of logistical aspects (transport, suitable installation locations, local support for gauge maintenance and operation).
- Generate an Implementation Road Map with recommendations to establish a long-term, sustainable, national sea-level monitoring system for Madagascar in liaison with key stakeholder agencies

The deliverable for this activity is D4.1 *Implementation Road Map*.

4. Issues Impacting the Project

A small number of issues impacted the progress of PASS-SWIO, delaying the project completion.

There were some delays in the design and build of the Portagauge at NOC, including:

- Initial problems with the availability of certain key components, which was due to the impact of the COVID19 pandemic on supply chains
- Some revisions were required to the initial design to incorporate additional solar panels.
- There was an issue with the welding of the framework.

Shipping to Madagascar from the UK is infrequent and slow. The shipping had to wait for availability of suitable transport, and then once on its way, the transport was held up in both Northern Europe and Mauritius.

There was a 10-week delay in releasing the Portagauge from Customs in Madagascar to DGM.

Early in the project there was a change in key personnel at DGM, where a new Director of Research was appointed. There was a short delay before the new appointee was contacted and was able to confirm the project could continue as planned.

There were problems with data transmission to the UK, which was interrupted due to a problem with the SIM card set up. This was eventually overcome by replacing the SIM with a locally purchased card.

The final visit to Madagascar had initially been planned to take place late in 2023, but it was delayed due to potential unrest during national elections in November 2023.

As a consequence of these issues the project duration was extended from 12 to 24 months.

5. Project Deliverables

The formal project deliverables are listed below. All are available through the project website: https://www.satoc.eu/projects/pass-swio/

5.1. Reports, Documents

- D1.1 PASS-SWIO Training Material
- D2.2 Portagauge installation and operation instructions (in English and French)
- D3.1 Data Set and Report for Tide Gauge and Satellite Data
- D3.2 Validation Report
- D3.3 Sea Level Variability Report
- D4.1 Implementation Road Map
- D5.3 Executive Summary Report
- D5.4 Final Report (this report)
- D5.5 Communications Package
- D5.7 Final Presentation

5.2. Data Sets

The PASS-SWIO data sets are listed below and available on the project data set webpage at https://www.satoc.eu/projects/pass-swio/data.html

Toamasina Portagauge Radar Gauge data (13/06/23 - 25/04/24)

- Primary Results File - *HA_053_000001_007603_GS_02_PR.txt*
- Time Series Results File - *HA_053_000001_007603_GS_02_TS.t2k*
- Daily mean sea level File - *HA_053_000001_007603_GS_02_DM.txt*
- Monthly mean sea level File - *HA_053_000001_007603_GS_02_MM.txt*

Toamasina Portagauge GNSS data (13/06/23 - 29/04/24)

- Quality controlled daily mean sea level: *PG1_GNSS_swio_daily.txt*
- Quality controlled daily mean GNSS position: *SWIO00MDG_IGS20.neu*

Historic Toamasina SHOM Tide Gauge data (01/01/2010 – 29/03/2022)

- Time Series File - *HA_112_000001_058741_GS_02_TS_Toamasina.t2k*

Satellite altimeter data
Along-track time series of sea surface height anomaly, available as a zip file containing:

- Jason-1, Jason-2 and Jason-3: 2002-2022
- Sentinel 3A 2016-2022
- Sentinel 3B 2018-2022

There is one file per satellite track. The naming convention is *sss*_cmems_p*oooo*.nc, where *sss* is satellite series (s3a, s3b or j1j2j3) and oooo is relative orbit number, e.g. s3a_cmems_p0012.nc, j1j2j3_p0222.nc.

5.3. Training material

The PASS-SWIO training material for tide gauge and satellite altimeter data processing and validation is listed below and is available from the Training section of the project website at https://www.satoc.eu/projects/pass-swio/training.html

- Checking and Validation of Tide Gauge sea level data
- Processing and Submission of Portagauge GNSS position data
- Satellite altimeter data: Accessing and pre-processing
- Satellite altimeter data: Validation and analysis of sea level variability

6. Results Highlights

6.1. Portagauge Installation and Operation

The NOC Portagauge was successfully installed on 13/06/23, and to date has provided 10 months validated and processed sea level and location data. Its capability as a fully autonomous accurate and reliable tide gauge, with radar and GNSS measurement capacity, was clearly demonstrated.

The installation was successfully carried out over two days, and the Installation Manual was reported by DGM staff to be clear and comprehensive.

The Portagauge radar gauge was found to provide accurate and reliable measurements of sea level and the GNSS instrument accurate and reliable measurements of position. GNSS-IR processing also provided accurate measurements of daily average sea level, which could then be used to cross-reference the radar gauge water levels to the reference ellipsoid.

The solar panels were found to provide charging capability to ensure the battery provided sufficient power for continuous operation throughout the deployment.

There was a problem with data transmission over the mobile data network using the provided global mobile SIM card which in principle could link to any mobile network. In practice a local mobile network SIM card (for the Telma network) was required.

It is recommended to include a levelling exercise against local benchmarks as part of the installation process.

6.2. Capacity Building for Tide Gauge operation and sea level data processing

An important part of the project was to help develop a national capacity within Madagascar to install, operate and maintain the Portagauge, and also to be responsible for data management, validation and processing. In person and online training was delivered to DGM staff and we are confident that DGM now has the capacity to carry out these tasks.

6.3. Sea Level Data Sets for Madagascar Coastal Regions

A number of data sets have been produced for the PASS-SWIO project and are available through the project web site for analysis and applications. These data sets are:

- Toamasina Portagauge Radar Gauge data (13/06/23 - 25/04/24)
- Toamasina Portagauge GNSS data (13/06/23 - 29/04/24)
- Satellite altimeter data
  Along-track time series of sea surface height anomaly, available as a zip file containing:
    - Jason-1, Jason-2 and Jason-3: 2002-2022
    - Sentinel 3A 2016-2022
    - Sentinel 3B 2018-2022

6.4. Validation of Satellite Altimeter and Tide Gauge data

Eight months of Portagauge data have been quality controlled and validated using tidal analysis software. These data were found to be of excellent quality, yielding no suspect data during the validation period. Comparison of key tidal constituents between the historical SHOM and Portagauge time series displayed good agreement, even though they were derived from different locations within the port and despite the brevity of the Portagauge record compared with the SHOM record. This provides confidence in quality of the Portagauge data, and confirms that a relatively short time series can be used to generate accurate tidal constituents

Satellite altimeter and tide gauge data for Toamasina have been carefully cross-validated against each other, for historical tide gauge data (2010-2022) and Portagauge data (June 2023 to February 2024). A high level of agreement has been found between both sets of in situ data and the satellite data. This provides confidence that satellite altimeter data can be used to support analyses of sea level variability in the northeast coastal regions of Madagascar close to Toamasina.

The results are available in the PASS-SWIO report (D3.2), *Cross-validation of in situ and satellite altimeter sea level data*.

6.5. Assessment of Satellite Altimeter Data from Specialised Coastal Processing

Thanks to support from the ESA Network of Resources, PASS-SWIO was able to carry out an assessment of satellite altimeter data from specialised coastal processing, to discover if these data could be useful for coastal applications. It was concluded that data from the specialist coastal processor were not found to provide more accurate sea surface height data than those from the standard product in the range 5-10km from the coast, but that the specialised processing does provide data in near coastal locations (within 5km of the coast) where the standard product does not. The PASS-SWIO *Technical Note on the Analysis of Sentinel-3 Altimeter data at the coast of Madagascar* provides full details.

6.6. Sea Level Variability Analysis

A report has been produced which provides an analysis of characteristics of sea level variability for the Madagascar coastal region. Analysis of tidal characteristics was based on tide gauge and tide model data. Satellite altimeter data were processed and analysed to provide information on seasonal and inter-annual variability (including long-term trends). This analysis enabled the identification of regions where the patterns of variability are coherent, and where they are different, and also to identify regions potentially more at risk from sea level surges due to extreme events. This has been used to support the identification of future tide gauge locations in the development of a sea level monitoring system for the Southwest Indian Ocean.

6.7. Implementation Road Map

The Implementation Road Map provides recommendations to establish a long-term, sustainable, national sea level monitoring system for Madagascar. It also provides a model for a sea level monitoring system for developing island states and coastal nations, based on low-cost tide gauges and satellite data. It was developed with input from Madagascar organisations with an interest in using sea level data for a range of applications. The PASS-SWIO team will continue to work with Madagascar partners to find a way to implement these recommendations.

7. Project Outreach

The PASS-SWIO project has been presented at a number of scientific meetings, including OSTST 2022, 13th Coastal Altimetry Workshop, IUGG 2023, and the Sentinel-3 Validation Team meeting in December 2023. An abstract has also been submitted for presentation at the 30 years Progress in Radar Altimetry Symposium in September 2024. All presentations are available on the project website (https://www.satoc.eu/projects/pass-swio/index.html).

It is planned to develop some of the work for scientific peer review publication. The relatively short time frame of the project did not allow sufficient time for this process to be completed.

8. Project Recommendations

Detailed recommendations are provided in the PASS-SWIO Implementation Road Map. Main points are:

Full Implementation of Portagauge based sea level monitoring system

We recommend the implementation of a rolling programme of installation of the Portagauge at the five remaining Madagascar Ports of National Interest, for a minimum of 6 months at each, with the next two installations on the northwest coast at Mahajanga and Nosy Be.

Madagascar Sea Level Data Management infrastructure

We recommend the establishment of a co-ordinated national data management infrastructure for sea level data, linked to international sea level data measurement systems, to ensure the sea level data are available nationally and internationally. This should include the provision of tidal predictions for the sites where tidal harmonics are available.

Other Recommendations

1. The PASS-SWIO Implementation Road Map should be provided to the relevant Madagascar stakeholder agencies, to the IHO, the Indian Ocean Commission and WIOMSA.
2. The GNSS data should be made available to the FTM for analysis and processed to provide information on Vertical Land Movement at coastal locations. The issue of the low precision of the local geoid model for Madagascar should be addressed.
3. BNGRC and NOC should hold discussions regarding Tsunami warning systems for the Southwest Indian Ocean.
4. Noting that the Esteves and Ballesteros (2021) study, which developed an index of exposure to coastal change, could not include sea level change or geomorphology in their analysis for Madagascar due to lack of comparable data, and the fact that the east coast of Madagascar was assessed to have a very high exposure to coastal change, we recommend a scientific programme to provide improved data on these key parameters.
5. The Pangalanes Canal on the northeast coast of Madagascar (south of Toamasina) is a series of link inland lakes and waterways and provides an important safe transport link instead of the open Indian Ocean which is vulnerable to large swells. However, it is subject to changes in water level following prolonged rain, which can flood coastal villages. There is a Sentinel 3B track that runs along this canal for much of its length, and the use of Fully Focussed SAR altimeter processing to provide accurate water levels could be of interest.

9. References

Ballesteros, C. and Esteves, L.S. (2021) Integrated Assessment of Coastal Exposure and Social Vulnerability to Coastal Hazards in East Africa, Estuaries and Coasts, https://doi.org/10.1007/s12237-021-00930-5

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