Original Article

e-ISSN: 2581-0545 - https://journal.itera.ac.id/index.php/jsat/

Received 03rd June 2024
Accepted 12th December 2024
Published 10th January 2025

Open Access

DOI: 10.35472 /jsat.v8i2.1851

Regional Validation Coastal Sea Level Anomaly Estimation from Altimetry Satellite and Tide Gauges Data using Fuzzy Inference System: A Case Study Around Natuna Seas

Rizki Dimas Permana*[a], Jonson Lumban Gaol[b] , Febri Dwi Irawati[c] , Tefur Nur Rohman [a], Rizty Maulida Badri[c]

[a] *Marine Environmental Science Study Program, Institut Teknologi Sumatera (ITERA), South Lampung, Lampung 35365, Indonesia*

[b] *Department of Marine Science and Technology, Bogor Agricultural University, Bogor 16680, West Java, Indonesia*

[c] *Data Science Study Program, Institut Teknologi Sumatera (ITERA), South Lampung, Lampung 35365, Indonesia*

** Corresponding E-mail: rizki.permana@sll.itera.ac.id*

Abstract: The validation of waveform retracking analyses with Fuzzy Inferences system, which was previously developed to optimize the estimation of sea surface height (SSHs), particularly in coastal locations, is presented in this study. The fuzzy inference system has been tested and validated in the Natuna Sea, Indonesia, where altimetry waveforms varied based on water conditions. Validation was performed by comparing the waveform retracking result of Jason-3 data with in-situ tide gauge data and geoid. The validation of waveform retracking data for sea level anomaly (SLA) estimate against tidal data demonstrates that the waveform retracking with a fuzzy inference system is more accurate than previous approaches. Waveform retracking with fuzzy inference system is able to produce an average temporal correlation of 0.75-0.89 and RMSE between 0.15-0.17 m. The waveform retracking combined with a fuzzy inference system can improve SLA estimation accuracy in nearshore up to 4 km from the coastline. The results indicate that retracking with fuzzy inference system has the potential to be used in other complicated oceans.

Keywords: *altimetry; fuzzy inference; Jason-3; retracking; waveform*

Introduction

Satellite altimetry is one of the most powerful remote sensing techniques for capturing the dynamic of ocean surface from space, especially sea surface height (SSHs). It has a very wide coverage range, high repeat levels, and can receive the data in all weather conditions during the day or night without loss of data due to cloud cover [1], [2], [3]. Satellite altimetry also offers more SSHs data than tide gauge measurements in spatial and temporal coverage [4], [5]. Altimetry is based on radar principle, which transmits radar pulse with designed power to the nadir surface of the sea, and then record the echoes reflected with a particular time resolution. The time series of the received power distribution is referred to as a "waveform." The underlying premise of radar and waveform altimetry concept is explained in further detail in [6].

Over a homogenous surface such as open-ocean, altimetry can deliver SSHs data with high accuracy (cm level) of waveforms which conform to Brown model [7]. Conversely, in heterogeneous surface (e.g. coastal and shallow water), SSHs estimation is commonly not reliable due to land contamination in the waveform of altimeter [8], [9]. However, in the last thirteen years, coastal altimetry researchers have focused their attention on this topic.

Many studies have been conducted to obtain the highest possible accuracy of SSHs data in coastal areas in order to meet the demand for accurate altimetry data in coastal studies. The most widely used protocol for improving altimetric SSHs is to directly downlink the waveforms to the ground and then correct the estimation geophysical parameters like sea surface height, significant wave height, and wind speed called “waveform retracking” [10], [11]. Various algorithm strategies of waveform retracking were carried out, such as the adaptation of a functional curve fitting e.g. [12], [13], [14]), the model used empirical parameters and/or threshold values e.g. [14], [15], [16], [17] , [18], [19], modelling entire waveform e.g. [20], the retracking of sub-waveform e.g. [8], [17], [18], [21], [22]. Several studies even combined multiple algorithms (retrackers) using an expert system to choose the optimal retracker e.g. [14], [23], [24], [25].

The waveform retracking analyses with Fuzzy Inference has been developed by [26] to achieve the best SSHs accuracy from several retrackers. Based on waveform characteristics and SSHs statistical features of the complete study tracks, this method uses a fuzzy system to assess and choose the optimal retracker outcome. Reference [26] reported that the Improvement Percentage (IMP) of waveform retracking with Fuzzy Inference over shallow waters at Natuna Sea, Indonesia constantly outperformed those from single retracker on each track observation there. However, the performance was only based on comparison to the geoidal height data, which emphasize the precision. In this study, the validation of waveform retracking with Fuzzy Inference is performed over regional complicated ocean at Natuna Sea, Indonesia. This includes comparing the retracking results to both geoid and in-situ tides gauge data to determine precision and accuracy. With this validation, the capacity and reliability of retracking with Fuzzy Inference to improve SSHs estimation in a complex region could be identified.

Method / Metode

Study Area

This study was conducted in the Natuna Waters and neighboring areas between 103° and 118° East Longitudes and 8° North Latitude and 3° South Latitude. The satellite altimetery pass were used, pass number 064, 140, 229 for Jason-3. (**Figure 1**). The Natuna Sea is a shallow body of water (<200 m) surrounded by numerous small islands with a high level of topographical complexity. Aside from the intricacy of the water dynamics, the region has several bays and numerous tiny islands, all of which might contaminate the recorded signals in the altimetry footprint, resulting in complex waveform patterns. Reference [25] reported that the waveforms characteristics of altimetry depending on the water condition, the Natuna Sea was complicated and diversified. (i.e. distance from coastline, water depth, and coastal topography).

Data Study

The data utilized in this research are as follows:

1. Data from the Jason-3 altimeter satellites in the form of Sensor Geophysical Data Records version "D" (SGDR-D) the period September 2016 – December 2018 for Jason-3. The data were obtained from the ftp-access.aviso.altimetry.fr/website.
2. Global geoid undulation model data from the Earth Gravitational Model 2008 (EGM08), which can be accessed at http://earthinfo.nga.mil/GandG/wgs84/gravitymod/egm2008.html.
3. Satellite track data for the Jason-3 altimeter satellites. These data were obtained from https://www.aviso.altimetry.fr/en/data/tools/pass-locator.html.
4. Tidal data obtained from the tide gauge stations of the Geospatial Information Agency (BIG) in the Natuna Islands and surrounding areas, specifically the Natuna, Pemangkat, and Tarempa stations for the years 2016-2018.

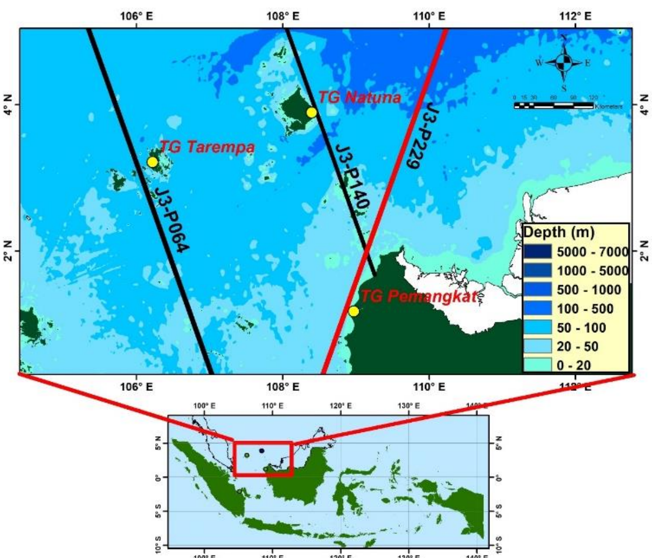

Figure 1. Study site and track altimetery satellite. The black lines represent the ascending tracks, and the red lines represent the descending tracks of the Jason-3 satellites. The yellow dots represent the tide gauge stations.

Data Analysis

This study retracked waveforms using Fuzzy Inference modified by [25]. It evaluated SSHs estimations of several retrackers (i.e. MLE4, Ice, Threshold, and Improved Threshold) based on outputs of defuzzyfication process in Fuzzy System, which utilized several variables (i.e. determination coefficient between the waveform sample and the ideal waveform, difference value from the retracked SSH from the mean sea surface (MSS), and difference of successive SSH. Detailed descriptions about the system can be found in [25].

The output of waveform retracking with Fuzzy Inference System was evaluated by comparison with world global geoid EGM08 and in-situ tide gauges data. The comparison with EGM08 was used to check data precision, whereas the comparison with in situ tide gauge was used to examine both precision and accuracy.

SSH results from waveform retracking are converted to sea level anomaly (SLA) and compared to tide gauge data. T Tide Harmonic Analysis Toolbox is used to remove tidal signals from sea level altimeter and tide gauge data in order to obtain the original value of sea level [27]. T Tide is a FORTRAN program that is commonly used for doing harmonic analysis of oceanic tides. However, the code is ancient and difficult to understand and alter. Rich Pawlowicz, Steve Lentz and Bob Beardsley have updated the program with the language in Matlab, and combined many other additional components. At present the program can be trusted to conduct tidal harmonic analysis (**Figure 2**).

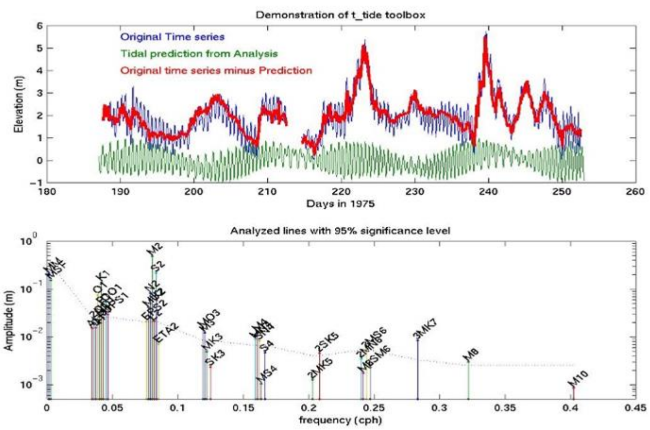

Figure 2. T_tide Program.

T Tide Harmonic Analysis Toolbox is a matlab program that includes the t tide.m function package, the t example.mat data sample, and the t demo.m execution program. The matlab code required to run the T tide correction function to remove the tidal signal from the tide gauge data and the sea level altimeter is shown below. where sea level anomaly by tide gauge data were the data input.

Comparison to Geoid Data

Comparison to geoid data was conducted by the computation of the IMP. It was determined by calculating the standard deviation (SD) of the difference between the SSHs dataset and the geoid data dataset [17], [28] using the following equations(1-2):

$$\sigma_{Ocean\ (\text{or}\ Retracking)} = \left(\frac{1}{N}\sum_{i=1}^{N}(x_i-\bar{x})^2\right)^{\frac{1}{2}} \quad (1)$$

$$IMP = \frac{\sigma_{Ocean} - \sigma_{Retracking}}{\sigma_{Ocean}} \times 100\% \quad (2)$$

where, σ is the standard deviation. N is the number of data points in the SSHs data set. x_i is value of the i^{th} point in SSHs data set (from respective retracker), and $\bar{x}$ is the mean value of SSH data set.

Validation to Tide Gauge Data

SLA data from waveform retracking were checked against in-situ tidal anomaly data at three station locations: Natuna Station, Pemangkat, and Tarempa. The results of SLA data validation from wave retacking with tidal data were carried out by calculating the correlation coefficient (r, Equation (3), Emery and Thomson 2004) and root mean square error (RMSE, Equation (4), Willmott 1982). As in:

$$r = C^2_{x.y}/(S_x S_y) \quad (3)$$

$$RMSE = \sqrt{\frac{\sum(xi-yi)^2}{N}} \quad (4)$$

where :

$C^2_{x.y}$: The value of covariance between the variables *x* (SLA Altimeter) and y (in-situ data)

S_y : Standard deviation of SLA retracking results

x : SLA from satellite

y : SLA from tide gauge

where, *x* is the SLAs resulting from waveform retracking, *y* is the tide gauge data, is co-variant, S_x and S_y are the standard deviations and *N* is the number of data

Results And Discussion

In this section, evaluation of waveform retracking using Fuzzy Inference with geoid data (Section A) and tide gauge data (Section B) are performed. The performances are compared to existing retrackers in the SGDR-D product (i.e. MLE4 and Ice).

Evaluation with Geoid Data

Table 1 summarizes the temporal mean of IMPs on each track over the experimental region. The results show that Fuzzy improves the precision (up to 60%) from standard algorithm (MLE4) indicated by positive value of IMPs for all tracks. IMP value for OCOG, Threshold 50%, and improve threshold 50% is always minus that means the algorithm cannot improve accuracy SSH by standard algorithm.

Table 1. Statistics of waveform retracking performance across observation paths for the Jason-3 satellite for the period September 2016 – December 2018 (cycle = 22–106). (IMP=improvement percentage; STD=standard deviation; SR=success rate). The best retrackers are shown in bold.

Pass Number Jason-3	Retracker	STD (cm)	IMP %	SR %
229	Ocean	21.7	0.0	95.7
	Fuzzy sistem	**10.3**	**36.7**	**100**
	Ice	37.9	-130.9	100
	Threshold 10%	13.5	18.1	100
	Threshold 20%	23.1	-33.2	100
	Threshold 50%	89.9	-495.1	100
	Improved Threshold 10%	12.7	18.8	100
	Improved Threshold 20%	19.9	-19.2	100
	Improved Threshold 50%	57.5	-252.4	100
	OCOG	184.7	-999.9	100
140	Ocean	59.9	-	87.7
	Fuzzy sistem	**32.3**	**38.5**	**100**
	Ice	102.8	-58.4	100
	Threshold 10%	37.2	15.0	100
	Threshold 20%	54.1	10.4	100
	Threshold 50%	193.9	-191.3	100
	Improved Threshold 10%	59.4	-3.7	100
	Improved Threshold 20%	68.3	-8.9	100
	Improved Threshold 50%	187.9	-182.2	100
	OCOG	272.3	-437.2	100
064	Ocean	39.2	-	90.8
	Fuzzy sistem	**10.2**	**60.0**	**100**
	Ice	29.4	21.1	100
	Threshold 10%	15.1	40.4	100
	Threshold 20%	19.4	37.3	100
	Threshold 50%	57.6	-27.9	100
	Improved Threshold 10%	18.7	33.7	100
	Improved Threshold 20%	22.0	32.0	100
	Improved Threshold 50%	57.5	-34.4	100
	OCOG	163.0	-506.0	100

Retracking with fuzzy system can reduce SSH standard deviation up to 25.6 cm for Jason-3 from the on-board (standard) retracker deviation. The mean of IMPs from Fuzzy over all tracks (38,5%) even outperforms the Ice retracker (36,7%). This suggests that waveform retracking using Fuzzy could provide good quality of SSHs estimation both in open-ocean and coastal. In other experimental region of Great Barier Reef Australian Seas, Idris et al lso reported that IMPs of Fuzzy outperforms the other single retrackers [29].

When evaluated on each track, the precision of Fuzzy is always superior, shown by lower IMPs on two tracks of four cases (**Table 1**) than Ice retracker. This suggests that SGDR Ice retracker is also reliable and should offer precision SSHs, especially over the bays (passed by track 140 and track 064 of Jason-3), which are usually dominated by peaky waveforms.

SLA Validation of Waveform Retracking Results with Tide Gauge In-situ Data

Evaluation of validation with tide gauge data is performed within 5km band up to 20 km from the land. The temporal correlation and RMSE between retracked SLAs and Natuna tide gauge data are plotted at sample track points of Jason-3 pass 140 (**Figure 3**). The finding shows that within 20km from the land, Ice retracker and Fuzzy system can provide full data, while MLE4 retracker only offer 20% of reasonable data. Beside the data availability, Ice and Fuzzy also present certainly better correlation (up to >0.8) and RMSE (up to <20cm) than available data of MLE4 retracker. This indicates that they could extended accurate SSHs estimation to coastal. However, when compared to Ice retracker, Fuzzy still outperforms at several points in each band shown by darker color.

The result of temporal correlation shows that retracking waveform with fuzzy inference system consistently produces the highest value (>0.75) at each tidal station (**Table 2**). Another method that also produces a fairly high temporal correlation value is a threshold of 10% and an improved threshold of 10% (>0.73) while the Ocean (MLE-4) retracker method at TG I and TG II stations is not able to estimate the SSHA at a distance of less than 20 km. from the mainland so that the mean value of temporal correlation and RMSE is NaN. This is in line with research conducted by Idris et.al which states that the ocean retracker (MLE-4) provides inaccurate estimates of SSHA in waters near the shoreline at a distance of less than 30 km.

Table 2. The average temporal correlation and RMSE values in waters close to the coastline (<20 km) of several retracking methods (TG I = Natuna tide station, TG II = Tarempa tide station, TG III = Pemangkat tide station).

Retracker	Correlation (*r*)			RMSE (m)		
	TG I	TG II	TG III	TG I	TG II	TG III
Ocean	NaN	NaN	0.60	NaN	NaN	0.35
OCOG	0.27	0.44	0.54	1.53	0.51	4.38
Ice	0.49	0.85	0.41	0.76	0.22	3.35
Threshold 10%	0.74	0.84	0.84	0.31	0.22	0.22
Threshold 20%	0.59	0.85	0.30	0.52	0.21	2.11
Threshold 50%	0.44	0.85	0.47	0.87	0.22	4.15
Improved Threshold 10%	0.73	0.84	0.84	0.30	0.22	0.20
Improved Threshold 20%	0.48	0.85	0.27	0.77	0.22	2.14
Improved Threshold 50%	0.43	0.85	0.44	0.84	0.22	3.76
Fuzzy sistem	**0.75**	**0.89**	**0.87**	**0.28**	**0.18**	**0.17**

The average RMSE value between SSHA retracking results with three tidal stations shows that waveform retracking with fuzzy inference systems consistently produces more accurate results than other retrackers (**Table 2**). The value of RMSE at a distance of less than 20 km from the shoreline for retracking waveform with fuzzy inference system is 0.17-0.28 meter. The second best is aimed at Improved Threshold 10% with RMSE is 0.20-0.30 m and Threshold 10% is 0.21-0.31 m. While in other methods the RMSE average is more than 1.0 m which shows that other retrackers do not consistently provide good accuracy at all tide stations. Roscher et.al also reported that the RMSE SSHA for tidal data in coastal areas resulted in a fairly high value between 0.2-1.3 m [9]. This is due to disturbances from the mainland and small islands that distort the altimeter satellite waveform so that the SSHA estimation is inaccurate [8]. The analysis of the average RMSE and the correlation coefficient based on the distance from the shoreline in the waters near the Natuna tidal station is shown in more detail in **Table 3** and **Table 4**.

Retracking waveform with fuzzy inference system is able to produce SSHA data which is quite accurate even at a distance of less than 10 km from the coastline with the smallest RMSE of 0.28 m (**Table 3**) and temporal correlation reaching 0.75 (**Table 4**). Accurate SSHA is characterized by the farther from the mainland, the higher the correlation value and vice versa the lower the RMSE value [9], [30], [31]. This can only be found from the results obtained from retracking the waveform with a fuzzy inference system that consistently displays excellent performance. While the other methods at a distance of 2-10 km showed poor performance with low correlation (<0.5) and high RMSE up to more than 1.0 m.

Table 3. The average RMSE is every 2 km to 10 km from the shoreline in the waters close to the Natuna tide station.

Distance from The Land	Mean of RMSE (m)				
	Ocean	OCOG	Ice	TH 10 %	Fuzzy System
2 km	NaN	3.47	1.90	0.59	0.60
4 km	NaN	3.30	1.42	0.47	0.46
6 km	NaN	2.68	1.24	0.41	0.39
8 km	NaN	2.68	1.38	0.40	0.36
10 km	NaN	2.69	1.68	0.37	0.28

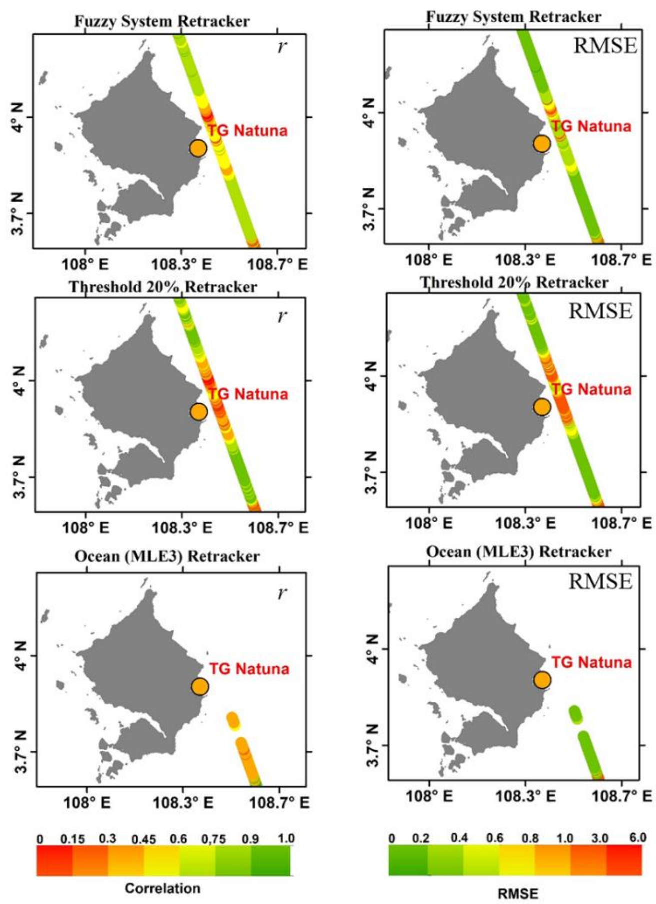

Figure 3. Spatial plot of temporal correlation values (left) and RMSE (right) between retracking SSHA and tidal in situ data in Natuna waters close to the shoreline.

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Table 4. The average Corellation is every 2 km to 10 km from the shoreline in the waters close to the Natuna tide station. (TH= Threshold, ITH= Improved Threshold).

Distance from The Land	Mean Of Corellation				
	Ocean	OCOG	Ice	TH 10%	Fuzzy System
2 km	NaN	0.30	0.23	0.43	0.44
4 km	NaN	0.24	0.33	0.52	0.56
6 km	NaN	0.23	0.45	0.61	0.60
8 km	NaN	0.29	0.44	0.59	0.62
10 km	NaN	0.19	0.40	0.62	0.75

The results of the validation at the three tidal stations showed that the SSHA pattern that was most incompatible with the tidal pattern was found at the Natuna tide station (Figure 4a) and had the lowest correlation of 0.74 and the highest RMSE of 0.28 m. This is because around the Natuna tidal station is surrounded by many small islands which causes the water conditions to be more complex than other tidal stations. At the Tarempa and Pemangkat tidal stations, the SSHA pattern of the retracking waveform with a fuzzy inference system looks very similar to the tidal pattern and has a fairly high correlation of 0.89-0.91 m and a low RMSE of 0.15-0.16 m (Figure 4b and Figure 4c). This shows that in these waters the retracking wave from the fuzzy system is very reliable.

The ability of the fuzzy inference system to create a rule (ruleset) in evaluating SSHA and choosing the best SSHA has proven to be effective in getting the most accurate estimation results. Idris et.al (2017) also stated that the fuzzy expert system in CAWRES was able to contribute to increasing the accuracy of SSH in coastal areas with correlations reaching 0.77-0.81 and RMSE 0.14-0.19 m. Similarly, research conducted by Idris et.al (2019) which states that in the waters of Southeast Asia, including Indonesia, the CAWRES method is slightly superior to the Ocean Retracker (MLE-4) and Ice-1 methods with a correlation of more than 0.85 and RMSE below 0.1m.

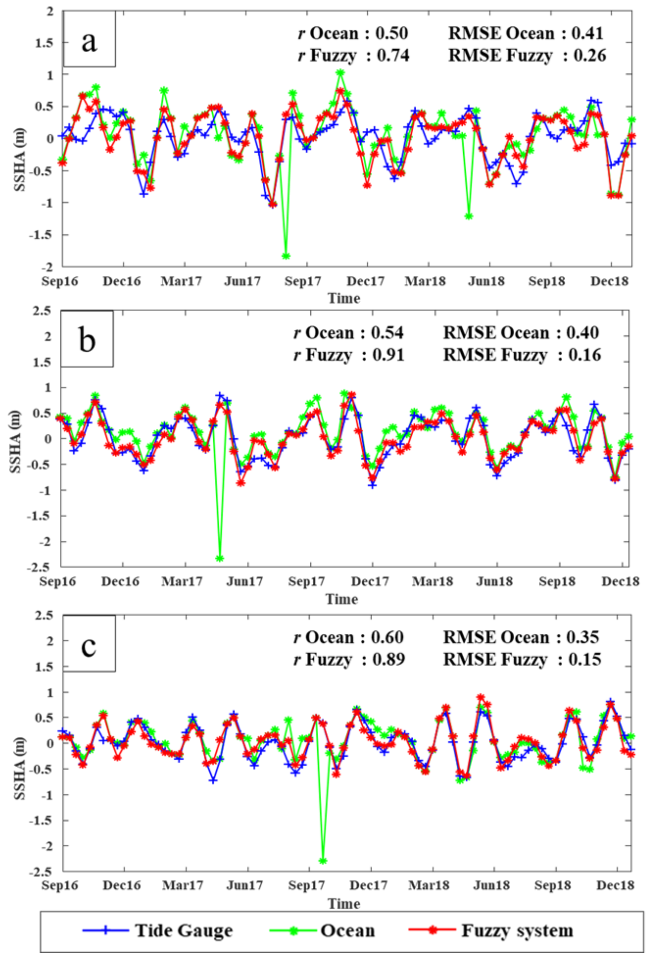

Figure 4. Comparison of SLA resulting from waveform retracking with fuzzy vs ocean retracker inference systems against tidal patterns of time series during 2016-2018 at a distance of less than 20 km from the coastline. (a) Natuna tide station, (b) Tarempa tide station, and (c) Pemangkat tide station.

Conclusions

The result of waveform retracking analyses with Fuzzy Inference over the tested area provide SSHs improvement in terms of accuracy and precision from standard retracker of MLE4. Fuzzy system produce the highest mean of IMP (60%) than the two SGDR retrackers. Validation with tide gauge data indicates that Fuzzy system outperforms the MLE4 and Ice retracker, which records the highest correlation (up to 0.87) and lower RMSE (up to 16cm). Waveform Retracking Analyses with Fuzzy Inference could provide reasonably good SSHs estimation closer to the coastal, with correlation higher than 0.75 and RMSE lower than 22cm within 0-20km from coastline.

SLA validation of the results of waveform retracking against tidal data shows that waveform retracking with a fuzzy inference system is more accurate than other methods. The mean temporal correlation generated from the fuzzy inference system reaches 0.75-0.89 and the RMSE value is between 0.15-0.17 m. Retracking waveform with a fuzzy inference system can improve the accuracy of SSH estimation in coastal areas up to a distance of 4 km from the coastline. Retracking waveforms with fuzzy inference systems have the potential to be applied in other locations both in coastal areas and waters close to small islands and for other altimeter satellites.

Conflicts of interest

There are no conflicts in this research.

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