Waveform re-tracking analyses with Fuzzy Logic on altimetry satellite data in Natuna Waters

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Abstract. Waveform re-tracking analyses have been proven to increase the accuracy of sea surface height (SSH) estimation from satellite altimeters specifically in coastal areas. However, each re-tracking algorithm has its strengths and weaknesses so that no dominant algorithm can be applied to any water condition. The study purpose was to obtain the best SSH estimation from altimeter satellite data using waveform re-tracking analyses with fuzzy logic system. The fuzzy logic system was used to select the best SSH values from the results of waveform re-tracking analyses. The data used in this study were level-2 SGRD data from Jason-2 and Jason-3 in Natuna Waters in 2016-2018. Waveform re-tracking with fuzzy logic system can reduce standard deviation of SSH up to 23.3 cm from the on-board (oceanic) algorithm standard deviation. The highest Improvement Percentage (IMP) value from each observation track was constantly generated by re-tracking with fuzzy logic system up to 70.3%. The result of this study showed that this analysis can produce SSH values with the best accuracy in each track observation.

1. Introduction

Indonesia which contains of 17,504 islands (most of them are small islands) has a high level of vulnerability to a sea level rise [1][2][3]. Therefore, it is necessary to monitor sea level (surface) dynamic data regularly and accurately. Traditionally, sea level high data were monitored using tide gauge equipment. However, the number of tide gauge stations is too little to cover Indonesian waters and coastline.

Radar altimeter satellites have been widely used to monitor the dynamic of sea surface high (SSH). The main advantage of using satellite altimeter data is that SSH detection can be done during the day or night time in all weather conditions without data loss due to cloud cover [4]. Altimeter satellites are also capable to produce SSH data with high accuracy up to 2-3 cm specifically in deep water region [5]. The signal received by the satellite altimeter is called a waveform which is used to determine the time when the microwaves emitted by the satellite touch the sea surface and returned back to the satellite. The time is then converted to the SSH estimation [6]. The form of a waveform in the deep sea is generally in an ideal (normal) shape and produces a good SSH estimation using a standard algorithm (oceanic algorithm) [5][7][8]. The ideal waveform is also called Oceanic-waveform or Brown waveform. However, in coastal waters where disturbance of signal reflection from the land will produce complex waveforms and SSH estimations become less accurate [9][10][11][12]. Therefore, to increase the accuracy of SSH estimation by altimeter satellite especially in shallow marine waters and coastal areas, it is necessary to reprocess the altimeter satellite data through the retracking waveform processes [7][13][14][15][16].
Retracking is a method of reprocessing or recalculating the altimeter data, which is to redefine the leading edge points of each form and waveform characteristics [17]. Previous research proved that the use of waveform retracking analysis had been able to improve the accuracy of SSH estimation especially in coastal waters and shallow seas [10][13][16][18][19]. In recent years, many initiatives had been carried out to provide accurate SSH results (such as PISTACH and PEACHI Products) and new retracking in coastal areas. Some of these researches focus on the coastal area of about 10 km from the coastline. However, within a distance of >10 km from the coastline, the results of retracking analyses altimetry data were still inaccurate due to the complex nature of the coastal topography and the influence of the land [13]. The retracking algorithm that is suitable for each waveform is also different depending on the water conditions [13][18][20]. That causes no dominant retracking method to produce better SSH estimations, therefore, we need a system that is able to integrate all the best retracking methods on each waveform along the track observation.

Fuzzy system is a branch of artificial intelligence system that is able to interpret vague statements into logical statements. This system forms a rule set as a guideline for expertise to classify and provide conclusions from certain conditions [21]. Fuzzy system has been widely used to make decisions from several rules that cannot be represented in binary form [22]. [23] suggested to combine several retracking algorithms to handle various forms of waveform using fuzzy logic. Evidenced by using a fuzzy expert system that was applied to the incorporation of several retrackers to determine the value of SSH produced better results than that of conventional retracking [20][24]. Therefore, in this study the fuzzy system was used to choose the best retracking method based on waveform characteristics and SSH statistical characteristics of the entire research trajectories. This study aimed to obtain the best SSH accuracy for coastal and shallow areas by modifying waveform retracking using the fuzzy system of Jason-2 and Jason-3 data at Natuna and its surrounding waters and to calculate the level of accuracy of the retracking results using the fuzzy system.

2. Methods

2.1. Data and study site
This research was carried out in the Natuna Waters and its surrounding areas from 103°- 118° East Longitudes and 8° North Latitude - 3° South Latitude. The altimeter path used were 064, 153, 038 tracks for satellite altimeter Jason-2 of cycle 314 and 140, 229, 051 tracks for satellite Jason-3 of cycle 033 (Figure 1). The altimeter data used in this study were SGDR-D Jason-2 and Jason-3 data and global geoid undulation data model (Earth Gravitational Model 2008 (EGM08)) which refers to the World Geodetic System 1984 (WGS84) as a topographical description of the earth's surface.

2.2. Waveform identification and SSH estimation
To identify waveform shape, we used SGDR-D data of Jason-2 and Jason-3 data with 2D and 3D visualization methods. Waveform identification was carried out along the observation track (Table 1) with a house-build Matlab program. Some guidelines to identify a waveform were the thermal noise, leading edges, and trailing edges of a waveform. Thermal noise is the time when the altimeter signal has not reached the sea surface yet. Leading edge is the time when the signal first touches the sea surface (nadir point). While, the trailing edge is a reflection of satellite signals around the leading edge [25]. Waveform was classified into 2 groups i.e., Brown waveform and Non-brown Waveform. Non-brown waveforms were grouped into several classes based on their shapes. Based on the classification of the waveform, the percentage of Brown waveform and Non-brown Waveform was calculated at each track. The percentage was an indicator to determine the error rate of SSH estimation. The higher the percentage of Non-brown Waveform, the SSH estimation on the path becomes more inaccurate.
Figure 1. Study site location. Red lines indicate descending tracks and black lines indicates ascending tracks for Jason-2 dan Jason-3.

Table 1. Observation track coordinates for retracking waveform analyses.

| Satellite | Pass | Latitude                     | Longitude                  |
|-----------|------|-----------------------------|---------------------------|
| Jason-2   | 38   | 3°8'57,2" N - 7°50'18,16" N | 112°58'58,63" E - 114°6'11,12" E |
|           | 153  | 0°58'56,8" S - 7°50'18,16" N | 103°49'29,75" E - 106°57'4,64" E |
|           | 64   | 2°28'2,13" S - 7°50'18,16" N | 106°28'38,29" E - 102°49'3,65" E |
| Jason-3   | 51   | 2°59'12,8" N - 7°50'18,16" N | 112°19'51,18" E - 114°6'11,12" E |
|           | 229  | 2°34'57,4" S - 7°50'18,16" N | 107°5'44,30" E - 109°13'20,19" E |
|           | 140  | 1°40'29,8" N - 7°50'18,16" N | 107°28'24,85" E - 111°10'54,08" E |

After identifying a waveform, we calculated SSH values using the formula developed by [26] as follows:

\[
SSH = \text{altitude} - \text{range}
\]  \( (1) \)

SSH is the sea level in meter (m), altitude is the height of the satellite from the ellipsoid reference (m), and range is the height of the satellite from the sea level (m). The equation used to get the range value is shown in Equation 2 [27]:

\[
\text{range} = \frac{c \left( t_r - t_e \right)}{2}
\]  \( (2) \)

range is the height of the satellite from sea level (m), \( c \) is the speed of light (299792458 m/s) while \( t_e \) and \( t_r \) are the time when the satellite emits microwaves to sea level and the time when the satellite receives reflected waves from the sea surface).
2.3. Waveform retracking

Waveform retracking is a stage of SSH recalculation based on the original shape and characteristics of the waveform. The results of waveform identification were then retracted using several methods such as Oceanic Retracker (on-board retracker method that was already in the SGDR-D data), Offset Center of Gravity Retracker (OCOG) [28], Ice Retracker or Threshold Retracker 30% [17], Threshold (10%, 20%, and 50%) Retrackers developed by [29][30], and the Improved Threshold (10%, 20%, and 50%) developed by [16].

After retracking the waveform, we calculated the SSH based on the retracted waveform data. The results of the waveform retracking analyses were a range correction values calculated by subtracting the gate value from the midpoint position of the leading edge position of the retracked waveform to the midpoint position of the leading edge on-board waveform [27]. Calculation of retracted range correction results is showed at the equation 3 and 4.

\[
d_r = c \times \frac{\Delta G_d}{G_507} \times \frac{(G_r - G_o)}{2} \quad (3)
\]

\[
R_r = R + d_r \quad (4)
\]

Where \(d_r\) is the height correction of the satellite and corrected sea surface (m), \(c\) is the speed of light (3 x 10^8 m/s), \(\Delta G_d\) is the time interval for one gate for Jason Satellite (3,125 ns), \(G_r\) is the observation gate at the leading mid-point edge from the retracked results, \(G_o\) is the on-board observation gate of Jason Satellite (32), \(R\) is the range of satellite measurement results (m), and \(R_r\) is the range of retracking results (m).

Corrections to geophysical and atmospheric disturbances were also carried out to obtain the true range values (equation 5).

\[
R_{corr} = R_r - \Delta h_{dry} - \Delta h_{wet} - \Delta h_{iono} - \Delta h_{ssb} - h_{tides} - h_{atm} \quad (5)
\]

Where, \(R_{corr}\) is the corrected range (m), \(R_r\) is the range of retracked result (m), \(\Delta h_{dry}\) and \(\Delta h_{wet}\) are the correction of the dry and wet troposphere (m), \(\Delta h_{iono}\) is an ionosphere correction (m), and \(\Delta h_{ssb}\) is a correction of sea surface shape (m), whereas \(h_{tides}\) and \(h_{atm}\) are tidal corrections and dynamic atmospheric corrections (m).

After the corrected range was calculated, then we calculated the SSH value of the retracked waveform using the equation developed by [31] as described in equation 6.

\[
SSH_{retracking} = altitude - R_{corr} \quad (6)
\]

Where, \(SSH_{retracking}\) is the sea surface height after retracking (m), \(altitude\) is the satellite height from ellipsoid reference (m), \(R_{corr}\) is the corrected range (m).

2.4. Waveform retracking modification using fuzzy logic system

This study used a fuzzy system to evaluate the most optimal retracker in estimating sea level height in coastal areas. Fuzzy system is a system that uses a collection of fuzzy function members, rules, disguised logic, and the results are described [21]. The basic framework of a fuzzy system is built based on 3 stages i.e., fuzzification, inference (if then rule), and defuzzification.

Fuzzification was used to divide or change non-fuzzy variables (numeric variables) into fuzzy variables (linguistic variables). The fuzzification process was preceded by determining the membership function. In this study the type of membership function used was the triangular type [32]. We used 3 membership functions in this study i.e., \(R^2\), \(dSSH\), and \(diff\) (Figure 2). \(R^2\) is the coefficient of determination between the retracked waveform shape and the ideal waveform. \(dSSH\) is the SSH difference value from the retracked result and the value of mean sea surface, while \(diff\) is the difference between the SSH value of the retracked waveform and the SSH value of the next retracked waveform.
IF then rule is the basis of expertise in fuzzy systems represented in the form of implication function equation [22]. The structure of the equation used in this study was as follows:

- If $R^2$ is good; and $dSSH$, and $dif1$ are small, then Ranking=high
- If $R^2$ is good; and $dSSH$, and $dif1$ are large, then Ranking=low
- If $R^2$ is poor; and $dSSH$, and $dif1$ are small, then Ranking=high
- If $R^2$ is poor; and $dSSH$, and $dif1$ are large, then Ranking=low
- If $R^2$ is none; and $dSSH$, and $dif1$ are small, then Ranking=high

Defuzzyfication is the final stage of a fuzzy system to convert fuzzy-based outputs into numeric variables (crisp). Defuzzyfication using the centroid method with a range of values from 0-10. Output values of 0-9 represent SSH values with low quality, while output values 9-10 are SSH values with high SSH quality [23]. [23] stated that the greater the value of defuzzyfication, the better the resulting SSH value would be.

SSH output values with high ranking were made into the final SSH results, while SSH values with low ranking were processed again using other methods (Figure 4). The fuzzy system was automatically choose based on predetermined rules (expertise) so that it would get the best SSH value at each point of measurement of the satellite altimeter.

2.5 Accuracy improvement calculation on retracked SSH

Improved SSH accuracy of retracked waveform results was calculated using the Improvement Percentage (IMP) formula based on [16] method which was developed by [14]. IMP was generated from the difference in oceanic retracker's standard deviation to the geoid with the standard deviation of the retracking method. The formula for calculating IMP is as follows.

$$IMP = \frac{\sigma_{ocean} - \sigma_{retracker}}{\sigma_{ocean}} \times 100\%$$

where IMP is a percentage of improvement in units (%) and $\sigma_{ocean}$ is the standard deviation of the on-board SSH difference with geoid undulation (m) while $\sigma_{retracker}$ is the standard deviation of the SSH retracking difference with geoid undulation (m). A positive IMP value indicated that there was a significant improvement in SSH accuracy and retracking result can be used, whereas if the IMP was negative, it indicated that the results of retracking were no better than the on-board SSH data [33].

Figure 2. Membership function in fuzzy logic tracking system. (a) $R^2$ membership function, (b) the $dSSH$ and $dif1$ membership functions.
3. Result and discussion

3.1. Waveform identification

The results of the waveform identification patterns for all tracks of Jason-2 and Jason-3 altimeter satellites in Natuna Waters and its surrounding contained a high variability. The difference in the waveform shapes were strongly influenced by the presence of land and the level of water depth passed by the altimeter satellite and this was similar to the finding of [33][34]. The majority percentage of waveforms in Natuna waters, in general, were in the form of Brownish waveform (ideal waveform) of about 95.5% from all observation points. However, in the coastal areas of both the western coast of Kalimantan, northern coast of Sumatra, and in the Natuna islands, each observation track was generally dominated by a non-Brownwaveform. In general the average percentage of non-Brown-waveform in Natuna waters was about 4.46%. The highest percentage of non-Brown-waveform was found on the Jason-3 pass 140 of about 10.1% of all waveform data in one track, while the lowest percentage of non-Brown-waveform was found on the Jason-3 pass 229 track of 1.0% (Table 2). A Brown-waveform describes the ideal form of the signal received back by satellites and will produce a very high accurate
of SSH estimate, while non-Brown-waveform is a form of waveform that experiences noise (noise) from several factors such as the presence of land and water depth thus resulting inaccurate SSH estimate [7][14]. In a non-Brownform waveform identified by standard (oceanic) algorithm, an "alt echo type" would automatically be set for the waveform pattern and the retracked (oceanic retracked) would provide a “NaN” values for its SSH estimation.

Table 2. Percartage of non-brown waveform in Natuna Waters and its surrounding.

| Satellite | Pass | Track length (km) | Total waveform | Total Brown waveform | Total non-Brown waveform | Percentage of non-Brown waveform |
|-----------|------|-------------------|----------------|----------------------|--------------------------|----------------------------------|
| Jason-2   | 38   | 520               | 1877           | 1826                 | 51                       | 2,72 %                           |
|           | 153  | 976               | 3516           | 3236                 | 280                      | 7,96 %                           |
|           | 64   | 1144              | 4123           | 4023                 | 120                      | 2,91 %                           |
| Jason-3   | 51   | 538               | 1945           | 1905                 | 40                       | 2,06 %                           |
|           | 229  | 1157              | 4174           | 4134                 | 40                       | 1,00 %                           |
|           | 140  | 648               | 2470           | 2220                 | 250                      | 10,1 %                           |
| Average   |      | 830,5             | 3017           | 2890                 | 130                      | 4.46%                            |

The non-Brown-waveform pattern in Natuna waters had very high variations both in coastal waters and waters near small islands (Figure 4). Some waveform patterns in coastal waters were closely similar to the Brown-waveform pattern but there were still some noises (additional peaks) at the leading edge and the trailing edge (Figure 4a). The waveform in waters near small islands had a peaky pattern, peaky with noise, leading at the end with noise, and brown with peaky echoes (Figure 4b). This results in changes in the position of the leading edge of each waveform and the pre given gate was not appropriate to cut in the middle of the leading edge so that the estimation of SSH by satellite was inaccurate. According to [7] that waveforms in the form of Brown-waveform can be found at a distance greater than 15 km of coastline and waveforms with peaky form in this study were found at a distance less than 5 km from coastline.

![Figure 4](image)

Figure 4. Three-dimensional satellite waveform altimeter patterns of Jason-2 and Jason-3. Waveform in coastal areas (a) and waveform in waters near small islands (b).

The results of waveform classification based on their shape were divided into 8 classes (Figure 5). The waveform in Natuna waters was dominated by the class of brown waveform (Figure 5a). While the
other class was a type of non-Brown waveform with a pre-given gate (red line) located after the leading edge and there were many peaks in the trailing edge in which oceanic (standard) retracker would produce inaccurate SSH estimates (Figures 5b, 5d, 5h). Waveform in the form of peaky noise reflected no signal that intersects with the pre-given gate which would produce an estimation of SSH as “NaN” (no data) (Fig. 5c, 5e, 5f, 5g). A “NaN” value resulted an empty data of SSH estimation. In this study, we found approximately 234.3 km of empty data (no SSH values) in Natuna waters. The empty (vacant) data were then re-analyzed (retrack) again using other retracker methods to obtain a more accurate SSH estimate.

The classified waveform is then retracked to get an accurate estimation of SSH value. Each waveform has a specific retracking algorithm that is specific for an accurate SSH estimation. This is because the ability of each retracking method in determining LEP (leading edge point) on each waveform is different [13]. The method with LEP that fits right across the leading edge waveform will provide an accurate SSH estimate [28].

The results of retracking in the non-Brown class with increasing leading edge waveform showed that the LEP results of ocean retracker and OCOG were far from the midpoint of the leading edge while the LEP result of a 20% Threshold was precisely cut at the midpoint of the leading edge waveform (Figure 6a). As for the peak echoes class, the LEP result of Ice retracker was closest to the midpoint of the leading edge waveform compared to other methods (Figure 6b). This showed that the Threshold 20% method provided an accurate estimate of the non-Brown class with increasing leading edge waveform while the most suitable method for the peak echoes class was Ice retracker. The difference in retracking methods
that were suitable for each waveform class and the variety of waveform classes in a waters would be more difficult to get the best SSH value. Therefore, it was necessary to make a system to choose the best estimation of the SSH value of each waveform using the fuzzy logic system.

Figure 6. The results of determining the position of leading edge point (LEP) on each retracking method on two samples of waveform classes (a) non-Brown with increasing leading edge (b) Peak echoes.

3.2. Retracking waveform performance with fuzzy logic system

The performance of retracking waveform with the fuzzy logic system was tested based on the value of standard deviation (STD), improvement of percentage (IMP), and compared with the result of other retracking methods. The STD value was obtained from the difference in the value of SSH retracking results by geoid undulation (EGM 08). A small STD value indicated an SSH pattern that approaches the geoid pattern so that it was more accurate and vice versa. The IMP value was calculated from the percentage between the standard deviation of the SSH difference between on-board (oceanic retracker) and geoid and the standard deviation of the SSH difference between the retracked SSH and geoid divided by the standard deviation of the SSH difference between on-board and geoid.

The results of this study indicated that retracked waveform with a fuzzy system was able to produce the highest quality SSH values compared to other methods. It was proven in all track observations, SSH estimation results from retracking waveform with fuzzy system showed the smallest standard deviation (STD) compared to other methods (Table 3). The retracking method was considered successful if it produced an SSH estimate with a STD value that was smaller than the STD ocean (on-board) retracker. Retracking with fuzzy system can reduce SSH standard deviation up to 23.3 cm for Jason-2 and 7.9 cm for Jason-3 from the on-board (standard) retracker deviation with an average STD reduction from all tracks of 7.3 cm. The highest reduction in STD SSH was 23.3 cm on the satellite Jason-2 pass 064 while the lowest was 1 cm on the Jason-2 pass 153. The lower STD showed the less SSH estimation noise produced so that the SSH estimate quality would be more accurate [23].
Table 3. Statistic performance for retracking waveform across all observation tracks for Jason-2 and Jason-3 satellites (IMP = improvement percentage; STD = standard deviation; SR = success rate). The best retracking was shown in bold letters.

| Jason-2 Pass Retracker | STD (cm) | IMP % | SR % | Jason-3 Pass Retracker | STD (cm) | IMP % | SR % |
|------------------------|----------|-------|------|-------------------------|----------|-------|------|
| Ocean                  | 10.9     | -     | 81.0 | Ocean                   | 16.1     | -     | 93.7 |
| Fuzzy sistem           | 6.1      | 40.5  | 100  | Fuzzy sistem            | 8.3      | 47.8  | 100  |
| Ice                    | 8.3      | 15.9  | 100  | Ice                     | 10.5     | 34.2  | 100  |
| Threshold 10%          | 18.1     | -65.9 | 100  | Threshold 10%           | 18.1     | -12.8 | 100  |
| Threshold 20%          | 7.7      | 29.3  | 100  | Threshold 20%           | 9.1      | 43.1  | 100  |
| Threshold 50%          | 9.3      | 14.1  | 100  | Threshold 50%           | 14.3     | 10.6  | 100  |
| Improved Threshold 10% | 18.9     | -73.5 | 100  | Improved Threshold 10%  | 14.8     | 7.70  | 100  |
| Improved Threshold 20% | 7.9      | 27.3  | 100  | Improved Threshold 20%  | 9.8      | 38.6  | 100  |
| Improved Threshold 50% | 10.2     | 6.29  | 100  | Improved Threshold 50%  | 15.7     | 1.84  | 100  |
| OCOG                   | 23.2     | -113.0| 100  | OCOG                    | 38.3     | -139  | 100  |
| Ocean                  | 33.0     | -     | 90.8 | Ocean                   | 9.2      | -     | 95.7 |
| Fuzzy sistem           | 9.7      | 70.3  | 100  | Fuzzy sistem            | 7.3      | 21.0  | 100  |
| Ice                    | 20.6     | 37.3  | 100  | Ice                     | 27.5     | -198  | 100  |
| Threshold 10%          | 71.9     | -117  | 100  | Threshold 10%           | 37.9     | -320  | 100  |
| Threshold 20%          | 27.4     | 16.9  | 100  | Threshold 20%           | 35.3     | -293  | 100  |
| Threshold 50%          | 11.5     | 65.1  | 100  | Threshold 50%           | 8.1      | 12.0  | 100  |
| Improved Threshold 10% | 52.8     | -59.9 | 100  | Improved Threshold 10%  | 38.9     | -198  | 100  |
| Improved Threshold 20% | 29.2     | 11.2  | 100  | Improved Threshold 20%  | 36.3     | -320  | 100  |
| Improved Threshold 50% | 12.0     | 63.4  | 100  | Improved Threshold 50%  | 8.8      | 4.63  | 100  |
| OCOG                   | 69.8     | -111  | 100  | OCOG                    | 37.3     | -303  | 100  |
| Ocean                  | 7.6      | -     | 82.0 | Ocean                   | 13.0     | -     | 87.7 |
| Fuzzy sistem           | 6.6      | 13.1  | 100  | Fuzzy sistem            | 8.0      | 39.5  | 100  |
| Ice                    | 51.7     | -576  | 100  | Ice                     | 33.0     | -144  | 100  |
| Threshold 10%          | 131.3    | -999  | 100  | Threshold 10%           | 26.0     | -98   | 100  |
| Threshold 20%          | 74.9     | -880  | 100  | Threshold 20%           | 29.0     | -116  | 100  |
| Threshold 50%          | 33.5     | -339  | 100  | Threshold 50%           | 40.0     | -202  | 100  |
| Improved Threshold 10% | 118.8    | -999  | 100  | Improved Threshold 10%  | 23.0     | -72   | 100  |
| Improved Threshold 20% | 78.3     | -924  | 100  | Improved Threshold 20%  | 25.0     | -85   | 100  |
| Improved Threshold 50% | 27.9     | -265  | 100  | Improved Threshold 50%  | 34.0     | -157  | 100  |
| OCOG                   | 66.4     | -768  | 100  | OCOG                    | 92.0     | -586  | 100  |

Figure 7 showed an example of analyses of the Jason-2 satellite SSH estimate patterns of all retracking methods. Based on the SSH pattern, the SSH retracking waveform estimation results showed that all methods followed the geoid pattern (Figure 7b). However, at a distance of 0-20 km from the coastline and shallow waters (<50m) the SSH estimate from the ocean retracker did not succeed in providing the SSH estimate (the SSH estimate was invalid or produced a NaN value). This indicated that the waveform shape in this area was dominated by the non-brown waveform pattern so that it could
not be estimated well by an ocean retracker (Figure 7a). Inaccurate estimation of SSH would fluctuate to the geoid profile and if the waveform was observed, there were still be forms that were non-Brown waveform with pre-given gate that did not cut right on the leading edge [14][16].

![Figure 7](image.png)

**Figure 7.** Example of a comparative analysis of SSH pattern results from retracking waveform from Jason-2 satellite data in Natuna waters. (a) SSH pattern of all retracking methods at a distance of 20 km from the coastline. (b) SSH pattern along the observation track from Jason-2 pass 038 satellite data in Natuna waters.

The SSH pattern from the analysis of the retracking waveform analysis using the fuzzy system and other retracking methods was presented in Figure 7a. From this result it can be seen that waveform retracking using fuzzy systems and other retracking methods was able to estimate SSH in places where ocean retrackers were not able to estimate SSH (NaN results). Threshold and ice methods produced SSH estimation results with patterns that had followed geoid and had low fluctuations, but the estimation results were still over estimates from the on-board SSH value. Whereas in the OCOG method and improved threshold, it can be seen that the SSH estimation pattern produced high fluctuations. This showed that the estimation results of the method had a lot of noise and were inaccurate [18]. SSH estimation generated by the waveform retracking method using a fuzzy system (blue) on the Jason-2 satellite for a finer and non-fluctuating pattern compared to other retracker methods and did not over estimate or under estimate on-board SSH values.

SSH estimation from the retracked waveform with the fuzzy system on Jason-3 satellite also provided the best pattern compared to other retracting methods (Figure 8). Therefore, both the Jason-2 and Jason-3 retracking waveform satellites with fuzzy systems were very reliable as a method to estimate SSH accurately. Besides being able to be applied to two different satellites retracking waveform, a fuzzy system also provided an accurate SSH estimation in offshore, nearshore (<5 km from the coastline), and in shallow waters (<50 m deep).
Figur 8. Example of a comparative analysis of SSH pattern results from retracked waveform from Jason-3 satellite data in Natuna waters. (a) SSH pattern of all retracking methods at a distance of 35 km from the coastline. (b) SSH pattern along the observation track from Jason-3 pass 051 satellite data in Natuna waters.

Waveform retracking with fuzzy system produced the highest percentage of IMP compared to other methods with the improvement value up to 70.3% for Jason-2 and 47.8 for Jason-3. This showed that the waveform retracking using a fuzzy system was able to improve more data with better quality compared to other methods. Waveform retracking with a fuzzy system could improve the quality of SSH in which others previously methods could not improve SSH estimates such as the Jason-3 pass 140 and Jason-2 pass 153. On these tracks, all retracking methods such as (ice, ocean, threshold, and improve threshold) showed a negative IMP result meaning that SSH estimations of the retracking results were no better than the on-board retracked SSH estimate, whereas after using the fuzzy SSH system the result showed a positive IMP of 39.5% for Jason-3 pass 140 and 13.1% for Jason-2 pass 153. On other tracks of Jason-2 pass 038 and pass 064 and Jason-3 pass 051 and pass 229, Threshold and Improved Threshold methods showed significant IMP values, however, retracking waveforms with fuzzy systems produced the highest IMP values on each track.

The results indicated that retracking with the fuzzy system can improve the percentage of data near coastline, with percentage up to 70.3%. However, the standard MLE4 (Ocean) retracker only produced ~30% of data near coastline. Similar to waveform retracking studies in Southeast Asia [35] that MLE-4 retrack was only able to provide <20% of data in coastal areas and using CAWRES (Coastal Altimetry Waveform Retracking Expert System) it was able to provide an improvement percentage of up to 80%.

Based on the results of the STD analysis, the SSH and IMP patterns showed that the waveform retracking with the fuzzy system succeeded in providing SSH estimation results better than other retracking methods such as OCOG, Ice, Ocean, Threshold, and Improve Threshold. The expertise system of fuzzy logic was able to optimally choose the value of SSH with rule set based on the statistical characteristics of all retracking methods at each waveform point [23]. Therefore, it can produce an SSH estimate with the best accuracy in each track of an observation.
4. Conclusion
Waveform shapes in Natuna waters were dominated by Brown-waveform pattern with a percentage of 95.5%. Non-brown waveform patterns were found in coastal waters and close to small islands with an average percentage of 4.5% (130 waveforms) on each track. Waveform classification based on its shape was divided into 8 classes; each waveform class has a certain suitability on retracking method. Retracking waveform with a fuzzy system consistently produced the best SSH estimation across the entire observation tracks. Retracking waveform with fuzzy system can reduce SSH standard deviation up to 23.3 cm for Jason-2 and 7.9 cm for Jason-3 from standard on-board retracker deviation and produced the highest IMP percentage compared to other methods with improvement values up to 70.3% for Jason-2 and 47.8% for Jason-3. Retracking waveform with a fuzzy logic system is potential to be applied in coastal areas, waters close to small islands, and for other satellite altimeters.

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