The Retracked Sea Levels from SARAL/AltiKa Satellite Altimetry: the Case Study around the Strait of Malacca and the South China Sea

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Abstract
This paper examines the quality of retracked sea surface heights (SSHs) from SARAL/AltiKa satellite altimetry over the Strait of Malacca and the South China Sea. The SSHs are retrieved from retracked SSHs taken by MLE-4, Ice-1 and Ice-2 retrackers which is provided in the Sensor Geophysical Data Records that has been optimized for coastal oceans. Based on the analysis of data availability, SARAL/AltiKa data coverage is excellent beyond 5 km from the coastline after removing the outliers, which can provide ≥82% of data for both regions. However, this value is somewhat lower when they are close to the coast due to the impact of land and coastal sea states to the altimetric signals. The Ice-1 retracker appears superior in providing SSHs data for the regions when compared to those of the Ice-2 and MLE-4 retrackers. In comparison with geoid height, the Improvement of Percentage (IMP) of Ice-1 retracker (35%) is higher when compared to Ice-2 retracker (27%) over the Strait of Malacca. In contrast, over the South China Sea, Ice-2 retracker has higher IMP (43%) than those of Ice-1 retracker (39%). Comparison with tide gauge stations indicates that the retracked SSHs from Ice-1 retracker are more accurate than the other retrackers.

1. Introduction

Satellite altimetry is a mature discipline over the open ocean that provides accurate measurement about the ocean geophysical information of sea surface height (SSHs), significant wave heights (SWHs), and wind speeds (Gommenginger et al., 2011). However, as the satellite altimeter approaches the coastal area, the altimeter data become unreliable due to rapid changes in measured surface between land and ocean (Idris and Deng, 2012). With the previous generation of radar altimeters, which operated with Ku-band (e.g. Jason-1, Jason-2 and Envisat), the coastal water is poorly observed within ~10 km from the coastline around the Marginal Seas, i.e. South China Sea and Taiwan Strait (Kuo et al., 2012). The new generation of SARAL/AltiKa satellite altimetry, which is operated with Ka-band, is beneficial for coastal observations as it provides higher spatial resolution (up to 40 Hz, or ~188 m along the satellite track) than the present Ku-band (20 Hz, or ~300 m along the track) altimetry. The SARAL/AltiKa has much smaller size (~5.7 km) of footprint than the Jason-2 (~10 km; Idris et al., 2014 and Prandi et al., 2015), thus making it excellent in data coverage (~99%) over the coast (Prandi et al., 2015). It also enables coastal observations much closer to the coast (Vincent et al., 2006). The high-rate measurement offered by SARAL/AltiKa mission should benefit various coastal applications including the study for understanding the sea surface current system and its mesoscale variability. Thus, the exploitation of SARAL/AltiKa altimetry is needed for accurate mapping of coastal sea levels. Global calibration for SARAL/AltiKa data has been conducted by Centre National d'Etudes Spatiales (CNES), Indian Space Research Organisation (ISRO) and many other researchers (e.g., Valladeau et al., 2014 and Strachan and Vidale, 2013). However, there are limited researches which focused on the validation over the Strait of Malacca and the South China Sea. The regional validation is important because of the ocean characteristics which is significantly different from one ocean to the other (e.g. the Pacific and Atlantic Oceans). In this paper, we examine the quality of sea surface heights (SSHs) from SARAL/AltiKa Sensor Geophysical Data Record (SGDR) product over the Strait of Malacca and the South China Sea. The SSHs are derived from various retracking solutions (e.g. MLE-4, Ice-1 and Ice-2). Waveform retracking is a

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ground post-processing method to optimize the parameters estimation (i.e. the power of amplitude, epoch, and slope of leading edge and trailing edge) from the measured waveforms (Gommenginger et al., 2011). The MLE-4 is a standard ocean retracking solution which is developed to fit the returned waveforms to the theoretical Brown model (Brown, 1977 and Deng and Featherstone, 2006). It is also well-known as a physical-based retracker. The Ice-1 and Ice-2 retrackers, which are based on the statistical features of the waveforms, are mainly developed for the observation of inland water and sea ice (Davis, 1997 and Lee et al., 2010). The Ice-1 retracker is based on Offset Center of Gravity retracking algorithm (cf. Lee et al., 2010), and the Ice-2 retracker is based on the Brown (1977) model that optimize waveforms from continental ice sheet interior (Resti et al., 1999). The remainder of the paper is organized as follows: Section 2 describes the data and study area; Section 3 shows the derivation of SSHs; Section 4 discusses the comparison of retracked SSH with geoid height and tide gauge data; and Section 5 is the conclusion and future recommendations.

2. Data and Study Area

The experimental region is over the regions of the Strait of Malacca and the South China Sea (Figure 1). The areas are chosen for several reasons. First, it consists of peninsulas, shallow seas, and small islands that exhibits various topographic features, including coastal plains, beaches, estuaries, oceans and islands. The geographical features around this area produces complicated waveform patterns when it enters the altimeter footprints. Second, the climate of the regions are made up of contributions from various weather system causing distinct diurnal rainfall, and tropical cyclones frequently pass over the region (Strachan and Vidale, 2013). Since altimetric waveforms can be affected by heavy rain associated with cyclones, the data selected in this area can capture diverse waveform pattern due to the temporal variability of coastal sea states. The high resolution of SARAL/AltiKa data in 40 Hz from SGDR product were retrieved from the Archiving, Validation, and Interpretation of Satellite Oceanographic ftp site (ftp://avisoftp.cnes.fr). The improved data from MLE-4, Ice-1 and Ice-2 retracking algorithms were utilized to derive improved SSHs above a reference ellipsoid. The SARAL/AltiKa data were retrieved from cycles 1-14. These correspond to February 2013-July 2014. Hourly tide gauge data obtained from Department of Survey and Mapping Malaysia was utilized with the same time period with altimeter data for validation purpose. Hourly data from two tide gauges stations; Langkawi and Bintulu, were chosen to validate data over the Strait of Malacca and the South China Sea, respectively. The tide gauge stations are shown in Figure 1.

3. Derivation of Sea Surface Height

The SSHs above a referenced ellipsoid can be extracted as (Andersen and Scharroo, 2011).

$$SSH = H - (R_{obs} - R_{retracked} - \Delta R_{wet} - \Delta R_{dry} - \Delta R_{iono} - \Delta R_{ssb}) - h_{ot} - h_{solid} - h_{pole} - h_{load} - h_{iny} - h_{hf}$$

Equation 1

where H is satellite altitude, R_{obs} is observed range, $R_{retracked}$ is range corrections from retracking algorithm, R_{dry} is dry tropospheric correction, R_{wet} is wet tropospheric correction, R_{iono} is ionospheric correction, R_{ssb} is sea state bias correction and h_{ot} is ocean tides, h_{solid} is solid earth tides, h_{pole} is pole tides, h_{load} is tidal loading, h_{iny} is inverse barometer height correction, and h_{hf} is high frequency fluctuations. The correction of $R_{retracked}$ are from the MLE-4, Ice-1 and Ice-2 retracking algorithms, R_{dry} and R_{wet} are based on the European Centre for Medium-Range Weather Forecasts, R_{iono} is from the Global Ionospheric Map, R_{ssb} is from the Hybrid sea state bias (SSB) and h_{ot} is from the FES2004 model. These corrections are provided in the SGDR product.

4. Analysis of Sea Surface Height Data Availability

This section examines SARAL/AltiKa data availability by computing the data percentage over the experimental regions and the minimum distance of the data from the coastline. Table 1 and Figure 2 show the percentage of SARAL/AltiKa SSHs availability over the regions that are computed from the on-board satellite tracking system (Zieger et al., 1991 and Fu and Cazenave, 2001), the MLE4, the Ice-1 and the Ice-2 retrackers.

Table 1: The mean percentage of SSH data availability over the Strait of Malacca and South China Sea from different retrackers

Regions	Percentage of data availability (%)			
	On-board retracker	MLE-4 retracker	Ice-1 retracker	Ice-2 retracker
Strait of Malacca	82	85	89	86
South China Sea	87	88	90	89

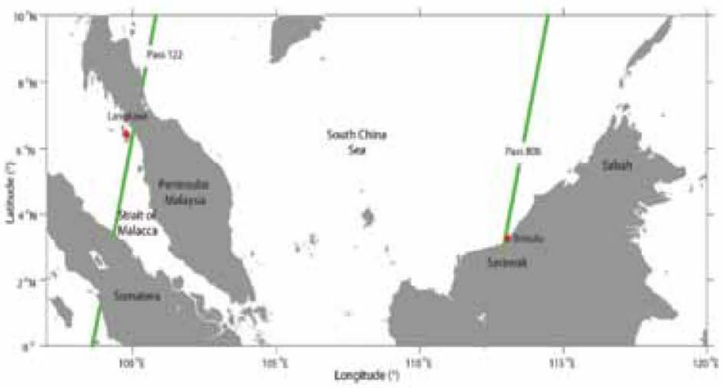

Figure 1: The study area covers the South China Sea and the Strait of Malacca. Red marks and green lines indicate the tide gauge stations and the SARAL/AltiKa ground passes, respectively. They are used for validation purposes (see Section 4)

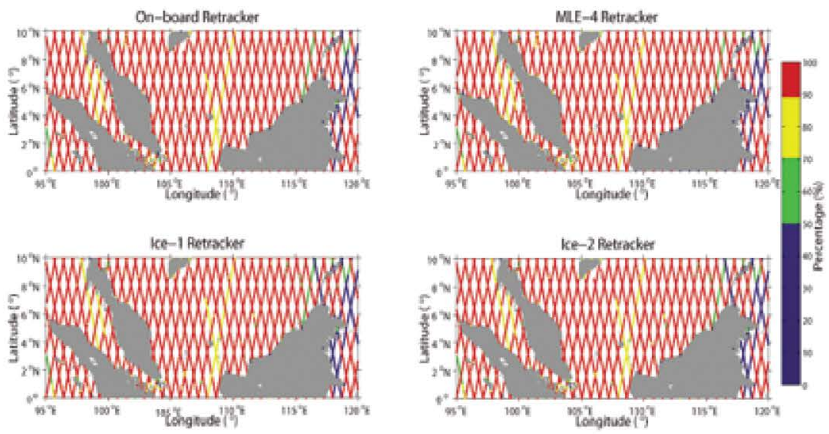

Figure 2: Percentage of SSHs data availability derived from on-board tracker, MLE-4, Ice-1 and Ice-2 retrackers

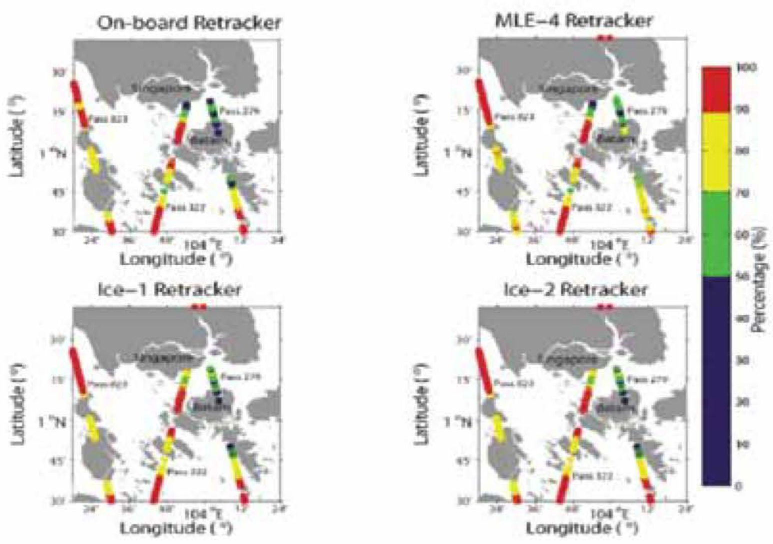

Figure 3: Percentage of SSHs data availability around Batam derived from on-board retracker, MLE-4, Ice-1 and Ice-2 retrackers

Outliers have been removed from the computation based on 3 standard deviation methods (David, 1985). Based on the results in Table 1 and Figure 2, in general, SARAL/AltiKa has high ($\geq$82%) percentage of data for all retrackers over both regions. Results in Table 1 show that the Ice-1 retracker has the highest data percentage with 89% and 90% for the Strait of Malacca and South China Sea, respectively. It is followed by Ice-2 retracker with 86% and 89%, and the MLE4 retracker with 85% and 88%. Figure 3 shows the spatial plot of data availability (in percentage) around Batam.This is the most complicated areas in the Strait of Malacca, which consists of many small islands and shallow water. Along pass 823, the data percentage exceeds 70% for all retrackers. Along pass 322, the percentages near Singapore are $\leq$50% for the on-board tracker and MLE-4 retracker, while the values are $\geq$70% for the Ice-1 and Ice-2 retrackers. Although over complex regions such as around Batam (Figure 3), in general, the percentage of data availability is still high. This is due to the advantageous of small (5.7 km) footprint of SARAL/AltiKa that contributes to improving the spatial resolution and segregating type of surface in transition zone such as coastal areas and sea ice boundaries. The results in Figure 1, Figure 3 and Table 1 suggest that in the case of the South China Sea and Strait of Malacca, the standard ocean retracking solution (i.e. MLE-4) is less reliable than those of the retrackers that meant for the inland water/sea ice (i.e. Ice-1 and Ice-2). However, it is observed that the percentage of all retrackers is low ($\leq$50%) over the eastern part of Sabah. This may be due to the complex topography of the region, which consists of many small islands, sandbanks and shoals, thus affecting the altimetric observation. Research is currently ongoing to identify the reason for the low data coverage over the said region. Examples of SARAL/AltiKa retracked SSHs from the on-board satellite tracker, MLE-4, Ice-1 and Ice-2 retrackers along passes 823, 322 and 279 within 20 km from the coastline are shown in Figure 4 (see Figure 3 for the location of the passes). From the limited examples that are shown in Figure 4, retracked SSHs from all retrackers can reach up to 3 km for pass 823, 5 km for pass 322 and 1 km for pass 279. However, noisy profiles were observed within 5 km from the coast. Over pass 279, large SSH variations are observed along the satellite track because the data are located at narrow coastal water between Singapore and Batam Island. In this area, land contamination and inaccurate data corrections affect the altimetric measurements, thus resulting in noisy SSH data. Figure 5 shows the minimum distance of SARAL/AltiKa data from the coastline that is computed from several passes. Figure 5 indicates that SARAL/AltiKa retracked SSHs becomes available within 3 km from the coast. This is overwhelmingly better than the performance of Jason-2 mission, which can generally provide data beyond ~5-10 km from the coast (Deng and Featherstone, 2006 and Idris and Deng, 2012). It is noted that the analysis of data availability and minimum distance only takes into consideration of the number of valid datasets after the removal of outliers. It is not validated with other independent in-situ data. Therefore, further study is crucial to identify the accuracy and reliability of the datasets with respect to in-situ data such as tide gauge. Based on the results in Figure 5, the performance of retrackers is different for different satellite passes. For examples, the three retrackers have the same level of performance with the minimum distance to the coast of ~1 km for pass 36. This is in contrast to pass 421, where MLE-4 retracker is only available at ~3 km beyond the coast, while Ice-1 retracker is available at ~1 km. Our close inspection has seen that the Ice-1 retracker performs much better than other retrackers of along passes 421 and 851 over the South China Sea. The Ice-1 retracker is a statistical-based retracker that does not rely on the physical shape of the waveform, while the MLE4 and Ice2 retrackers are physical-based retrackers that fits the waveform to the theoretical Brown shape. The Ice-1 retracker is based on offset centre of gravity algorithm, which is well adapted to the rapidly changing surface (Gommenginger et al., 2011) like continental sea area (e.g. South China Sea). These suggest that the performance of retrackers varies depending on the coastal characteristics.

5. Comparison of Retracked Sea Surface Heights with Geoid Heights and Tide Gauge

In this section, the quality of retracked SSHs are assessed by comparing the retracked SSHs with geoid heights. In comparison with geoid height, the standard deviation of difference (STD) between geoid and retracked SSHs, and the improvement of percentage (IMP) are computed within 30 km from the coastline after removing the outlier using 3 standard deviation methods. The geoid height is based on the Earth Gravitational Model (EGM2008 and Pavlis et al., 2012). The IMP is computed relative to MLE-4 retracker as it is the standard retracker for the ocean. The IMP can be computed as (Hwang et al., 2006).

$$IMP = \frac{\sigma_{MLE4} - \sigma_{retracked}}{\sigma_{MLE4}} x\ 100$$

Equation 2

Where σ_{MLE4} is the STD between MLE-4 retracked SSHs and geoid height, and $\sigma_{retracked}$ is the STD between Ice-1 (or Ice-2) retracked SSHs and geoid height, respectively. A small STD and a high IMP indicates that the retracker is reliable. Table 2 shows the value of STDs and IMPs of Ice-1 and Ice-2 retracked SSHs over the regions. Over the Strait of Malacca, Ice-1 retracker shows better precision (IMP of 35% and STD of 104 cm) than those of Ice-2 retracker (IMP of 27% and STD of 117 cm).

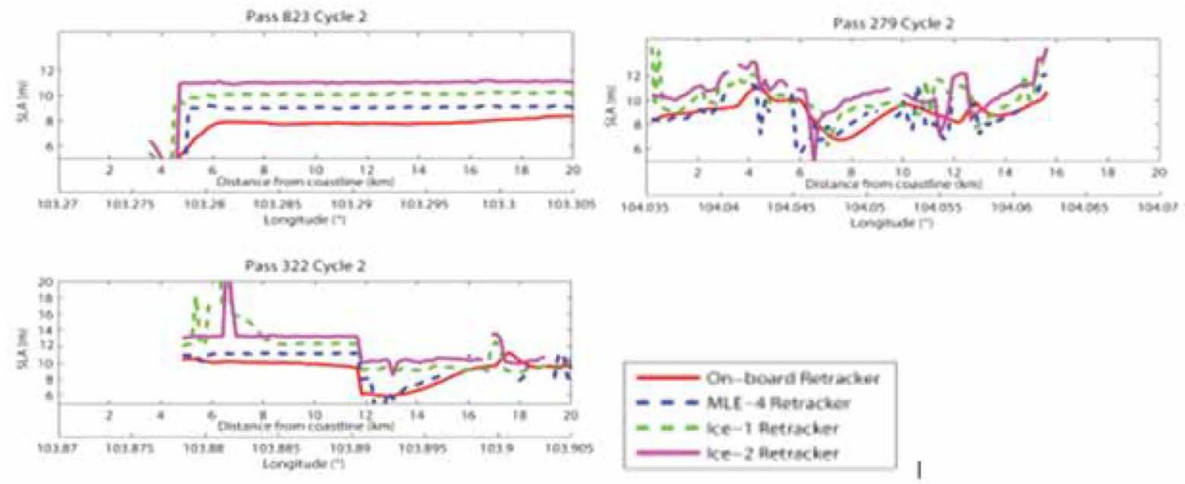

Figure 4: SSHs profiles from passes 823, 322 and 279. An arbitrary constant of 1 m, 2 m and 3 m was added to MLE-4, Ice-1 and Ice-2 retracked SSHs, respectively for visual clarity. No constant value was added to the on-board retracked SSHs

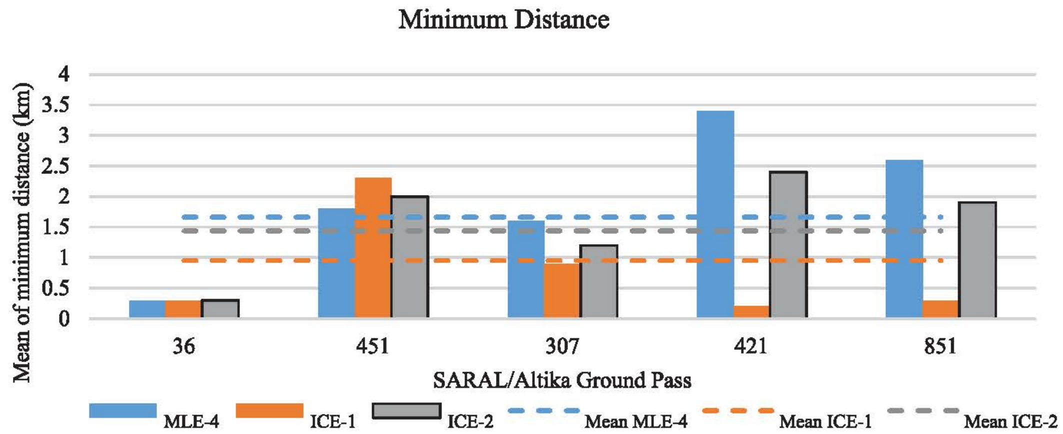

Figure 5: Minimum distance of MLE-4, Ice-1 and Ice-2 retracked SSHs over the Strait of Malacca (passes 36 and 451) and South China Sea (passes 307, 421 and 851)

Table 2: IMPs and STDs of Ice-1 and Ice-2 retrackers computed within 30 km from the coastline over Strait of Malacca and South China Sea (The highest IMP value is indicated in bold)

Regions	STD (cm)		IMP (%)		No. of Samples
	Ice-1	Ice-2	Ice-1	Ice-2	
Strait of Malacca	104	117	**35**	27	79,326
South China Sea	98	91	39	**43**	127,661

Table 3: The mean temporal correlation and RMS error of retracked SSHs with respect to tide gauges. The mean was computed within 60 km from tide gauge station (The highest correlation and the smallest RMS error are indicated in bold)

Retrackers	Pass 122 near Langkawi		Pass 808 near Bintulu	
	Correlation	RMS (cm)	Correlation	RMS (cm)
On-board	0.34	28	0.53	20
MLE-4	0.51	21	0.77	17
Ice-1	**0.73**	**16**	**0.82**	**14**
Ice-2	0.71	20	0.81	16

However, different results were observed over the South China Sea where the Ice-2 retracker shows better precision than those of the Ice-1 retracker. This again indicates that the performance of retracker depends on coastal sea states and topography. Since the values were calculated for complicated regions within 30 km from the coastline, high noise level in the dataset can be observed. Our further reading also found that over California coastal ocean (Lee et al., 2010), some of the STD values exceed 1 meter. The validation of SARAL/AltiKa SSHs with tide gauge data are computed for two passes (122 and 808) near Langkawi and Bintulu tide gauge stations (see Figure1). To enable comparison between both datasets, non-tidal SSHs have been derived by removing the major tidal constituent such as M2, S2, K1 and O1. Mean difference between both datasets also has been removed to synchronize the high datum because the altimeter reference height is based on ellipsoid WGS84 and tide gauge reference height is based on local mean sea level (MSL) as referred to Peninsular Malaysia Geodetic Vertical Datum (PMGVD and Ses and Mohamed, 2009) . This process is required to standardize the height reference to allow the comparison. The mean of temporal correlation and of root mean square (RMS) error are summarised in Table 3. They are computed within 60 km from the tide gauge stations. Results in Table 3 show that the temporal correlation of Ice-1 retracker are superior ($\geq$0.73) than those of the on-boards, i.e. MLE-4 and Ice-2 ($\leq$0.82) retrackers over both regions. This suggests that, on average, the Ice-1 retracker explains $\geq$73% of tide gauge total variance while the other retrackers describe only $\leq$81%. Concerning the RMS error, Ice-1 retracker has the smallest value (16 cm for Langkawi and 14 cm for Bintulu) when compared to the other retrackers. This suggests that the Ice-1 retracker has a better accuracy when compared to the other retrackers.

6. Conclusion and Recommendation

Based on the results of this paper, the SARAL/AltiKa can provide high-quality SSH data coverage for the regions of the Strait of Malacca and the South China Sea. Off the coast (beyond 5 km), the percentage of data availability is $\geq$80%, but the accuracy of the dataset with respect to independent in-situ data is yet to be counted when getting closer to the coast (within 3 km), the percentage reduces due to land interference and difference in coastal sea states. The results of IMP and STD indicate that the Ice-1 retracker produces precise SSHs over the Strait of Malacca when compared to the other retrackers. However, in the case of the South China Sea, the Ice-2 retracker appears feasible in terms of the spatial variance. The analysis of temporal correlation and RMS error with tide gauge suggests that the Ice-1 retracker produces accurate SSHs when compared to those of the other retracked SSHs. Research is currently ongoing to validate the retracked SSHs with other tide gauge stations around Malaysian coastal water.

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