Satellite altimeter is the space observing technique for the oceans. During the past two decades, observations from satellite altimeters have demonstrated dramatic descriptions of sea level variability with higher spatial resolution than tide gauges. Nowadays, satellite altimeter measurements have been continuously available since 1991, through the TOPEX/Poseidon, ERS1, ERS2, Geosat Follow-on, Jason-1, Jason-2 and ENVISAT missions. In this paper, sea level anomaly data retrieval and reduction were carried out using the Radar Altimeter Database System (RADS). In RADS data processing, the 2008 updated environmental and geophysical corrections were applied. The corrections were performed by applying specific models for the satellite altimetry mission in RADS. Measurement from this technique has revolutionized our knowledge of the ocean, through studies in sea level, ocean circulation and climate variability. At this moment, satellite altimeter has provided its capability in measuring the global mean of sea level with precision around 2cm and the sea level trends can be resolved better than 1 mm/yr.

Key words: Satellite Altimetry, Sea Level Anomaly

1. Introduction

The Southeast Asian region is characterized by its unique geographical and geophysical settings. It shares continental and archipelagic parts. The archipelago consists of thousands of islands. The entire area is located in the boundaries between two continents, Asia and Australia, and between two major oceans, Pacific and Indian Oceans. Most of Southeast Asian countries are bordered by sea and a large number of populations inhabit low lands in coastal areas.

Due to the afore mentioned facts, better knowledge of sea level behavior in this region becomes important. There are several factors that may cause the sea level height to vary from time to time, i.e. local processes, ocean circulation change, global and regional climate change, and geological processes. Furthermore, long term sea level height variations are a valuable indicator of global climate change.

During the past centuries, coastal tide gauges have provided the main technique to measure sea level change. However, there are two main problems faced in monitoring regional sea level changes by using tide gauge in the region:
Only few tide gauge stations provide long records.
Uneven geographical distributions because the tide gauge stations are usually installed at coastal area and there are no long term records from the deep ocean. An alternative to overcome those problems is to measure the sea level from space, i.e. satellite altimetry technique.

Satellite altimetry technology provides good potential as a complementary tool to the traditional coastal tide gauge instruments in monitoring sea level change in Malaysian seas. It is the space observing technique for the oceans. Observations from satellite altimeters during the past two decades have provided dramatic descriptions of sea level variability with higher spatial resolution than tide gauges. Since the past two decades a number of satellite altimeters were launched. The lists of satellite altimeter missions are as follows:

- Geosat from 1985 until 1990
- ERS-1 from August 1991 until April 1996
- Topex-Poseidon from January 1993 until August 2002
- GFO from September 2001 until September 2008
- ERS-2 from May 1995 until August 2003
- Jason-1 from January 2002 until now
- Envisat1 from April 2003 until now
- Jason-2 from June 2008 until now

2. Satellite Altimeter Missions

Satellite altimeter measurements have now been continuously available since 1991, through the TOPEX/Poseidon, ERS1, ERS2, Jason-1, Jason-2 and ENVISAT missions. Measurements from these instruments have revolutionized our knowledge of the ocean, through studies in sea level, ocean circulation and climate variability.

In 1992 TOPEX/Poseidon satellite altimetry mission was launched and its mission was ended in 2002. Since then it was replaced by Jason-1. Both satellite missions provide the most precise altimetry data when compared to others. Although satellite altimetry records are still quite short compared to the tide gauge data sets, this technique appears quite promising for sea level change problem because it provides sea level measurement with large coverage. A precision around 2cm of measurement global change can be obtained and the sea level trends can be resolved better than 1 mm/yr (Omar et al., 2006).

Meanwhile, ERS satellites launched and operated by the European Space Agency, were the first missions acquiring commercially available microwave radar data, offering new opportunities for all-weather remote sensing applications. Both ERS satellites were launched into a sun-synchronous orbit at an inclination of 98° 52’ and an altitude between 782 and 785 km (J.P. Dumont et al., 2006).
The next mission of satellite altimetry after ERS was ENVISAT. The main objective of the ENVISAT Altimetry Mission is to ensure the continuity of the altimetric observations started with the ERS-1 satellite in 1991 and continued by ERS-2, launched in 1995. The science mission objectives are similar to that of ERS but the length of the altimeter record will exceed 15 years and will permit to examine changes on inter-annual to decadal time scales of:

- global and regional sea level
- dynamic ocean circulation patterns
- significant wave height and wind speed climatology
- ice sheet elevation, sea-ice thickness

Figure 1: An example of Topex Phase A/ Jason1 Track – 10 days repeated orbit

Figure 2: An example of ERS2 Track-35 days repeated orbit
3. Principle of Satellite Altimetry

Generally, radar altimetry is among the simplest of remote sensing techniques. Two basic geometric measurements are involved. Firstly, the distance between the satellite and the sea surface is determined from the round-trip travel time of microwave pulses emitted downward by the satellite’s radar and reflected back from the ocean. Secondly, independent tracking systems are used to compute the satellite’s three-dimensional position relative to a fixed earth coordinate system. Combining these two measurements yields profiles of sea surface topography, or sea level, with respect to the reference ellipsoid (a smooth geometric surface which approximates the shape of the Earth). Figure 3 shows the principle of satellite altimetry.

An altimeter operates by sending out a short pulse of radiation and measuring the time required for the pulse to return from the sea surface. This measurement is called altimeter range, $R$ gives the height of the instrument above the sea surface. The $R$ from the satellite to mean sea level is estimated from the round-trip travel time by equation 1 (Fu and Cazenave, 2001).

$$R = R' - \sum \Delta R_j$$  \hspace{1cm} (1)

Where,

$R' = ct / 2$: Range computed neglecting refraction based on the free-space speed of light $c$.

$\Delta R_j$: Corrections for the various components of atmospheric refraction and for biases between the mean electromagnetic scattering surface and mean sea level at the air-sea interface.

Figure 4 represents a schematic summary of the corrections that must be applied to the altimeter range measurement $R$ and the relations between $R$, the orbital height $H$.
and the height $h$ of the sea surface relative to an ellipsoid approximation of the equipotential of the sea surface from the combined effects of the Earth’s gravity and centrifugal forces (the geoid) (Fu and Cazenave, 2001).

![Figure 4: The corrections of altimeter range measurement (Fu and Cazenave, 2001)](image)

The range measurement is then converted to the height, $h$, of the sea surface relative to the reference ellipsoid using equation 2.

$$h = H - R$$  \hspace{1cm} (2)

Where,

- $H$ : Orbital height
- $R$ : Altimeter range measurement

The sea surface height obtained from equation 2 is not sufficient for oceanographic application because it is a superposition of geophysical effects. The height $h$, is affected by geoid undulations, tidal height variations and ocean surface response to the atmospheric pressure loading (Fu and Cazenave, 2001). In order to remove the external geophysical effects from the sea surface height, equation 3 is applied.
\[ hd = SSH - hg - ht - ha \]  \hspace{1cm} (3)

Where,

- \( hd \) : Dynamic sea surface height
- \( SSH \) : Sea surface height
- \( hg \) : Geoid undulation
- \( ht \) : Tidal height variations
- \( ha \) : Ocean surface response to atmospheric pressure loading

Satellite altimeters have certain weakness and strength for each system. Nevertheless, the combination between each satellite will be more accurate. For example, Topex/Poseidon-ERS and Jason-Envisat are good examples of how altimetry satellites can operate together. Topex/Poseidon and Jason-1 follow a repeat cycle of ten days designed to monitor ocean variations, so they pass over the same points fairly frequently but their ground tracks are some 315 kilometers apart at the equator-more than the average span of an ocean eddy. On the other hand, ERS-2 and Envisat only revisit the same point on the globe every 35 days but the maximum distance between two tracks at the equator is just 80 kilometers. Figure 5 and Figure 6 show high precision altimetry with satellites working together.

**Figure 5:** ERS-T/P superimposed ground tracks (AVISO, 2008).
Figure 6: Dynamic topography in the Gulf Stream, December 5, 1999. Left: T/P data only. Right: T/P + ERS data. The resolution of the numerous eddies in this ocean current is clearly better (AVISO, 2008).

4. Altimeter Data Processing

In this study, sea level data retrieval and reduction were carried out using the Radar Altimeter Database System (RADS), the archiving and processing initiative of TUDelft, NOAA and Altimetrics LLC (Naeije et al, 2008). This system was installed in Malaysia at UTM in 2005 in the frame of the SEAMERGES project, an EU funded project (AUNP) that aimed for knowledge, methods and data exchange related to satellite altimetry, InSAR and GPS (www.deos.tudelft.nl/seamerges). The complete RADS system layout is portrayed in Figure 7 below:

Figure 7: Overview of the Radar Altimeter Database System RADS (Naeije et al., 2008)
In RADS data processing, the 2008 updated environmental and geophysical corrections were applied. The sea level data have been corrected for orbital altitude, altimeter range corrected for instrument, sea state bias, ionospheric delay, dry and wet tropospheric corrections, solid earth and ocean tides, ocean tide loading, pole tide, electromagnetic bias and inverse barometer correction. The corrections were done by applying specific models for each satellite altimetry missions in RADS. These corrections have been summarized in Table 1. As shown in Table 1, the guidelines of the ‘standard recipe’ for consistency have been followed. In this study, combinations of Topex and Jason1 satellites were used to derive sea level data from RADS. These satellites were chosen because they gave more accurate data compared with other satellites.

Table 1: Corrections applied for sea level data extraction in RADS

<table>
<thead>
<tr>
<th>Correction</th>
<th>TOPEX</th>
<th>Jason-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbit</td>
<td>GGM02C gravity (ITRF2000)</td>
<td>EIGEN CG03C gravity</td>
</tr>
<tr>
<td>Dry Troposphere</td>
<td>ECMWF Model</td>
<td>ECMWF Model</td>
</tr>
<tr>
<td>Wet Troposphere</td>
<td>Radiometer Measurement</td>
<td>Radiometer Measurement</td>
</tr>
<tr>
<td>Ionosphere</td>
<td>Smoothed dual-freq value</td>
<td>Smoothed dual-freq value</td>
</tr>
<tr>
<td>Inverse Barometer</td>
<td>MOG2D Model</td>
<td>MOG2D Model</td>
</tr>
<tr>
<td>Solid Earth Tide</td>
<td>Applied</td>
<td>Applied</td>
</tr>
<tr>
<td>Ocean Tide</td>
<td>FES2004</td>
<td>FES2004</td>
</tr>
<tr>
<td>Load Tide</td>
<td>FES2004</td>
<td>FES2004</td>
</tr>
<tr>
<td>Pole Tide</td>
<td>Applied</td>
<td>Applied</td>
</tr>
<tr>
<td>Sea State Bias</td>
<td>BM3/BM4 model</td>
<td>BM3/BM4 model</td>
</tr>
<tr>
<td>Geoid/Mass Height</td>
<td>CLS01 MSS Height</td>
<td>CLS01 MSS Height</td>
</tr>
</tbody>
</table>

Furthermore, because of factors such as orbit error and inconsistency in the satellite orbit frame, the sea surface heights (SSH) from different satellite missions need to be adjusted to a ‘standard’ surface. This is called crossover adjustment for multi-satellite missions.

Besides that, editing criteria for the computation of fully-corrected sea surface height (SSH) anomaly (orbit - range - environmental corrections - mean sea surface) are also needed to be applied consistently for all satellites missions. There are three sources of editing criteria that can be used when deriving the altimeter data in RADS:

- limits on the environmental corrections used to correct the range
- limits on altimetric parameters independent of range
- flag bits generated by the data processing chains
In the RADS data processing, we can easily specify the limits on the corrections and other variables associated with the corrected SSH anomaly values. If any variable exceeds the minimum or maximum limits, or any editing flag bit is set, the SSH anomaly is discarded from further analysis. However, the editing criteria using flag bits generated by the data processing chains were not used in this study.

Table 2: Editing limits on environmental corrections

<table>
<thead>
<tr>
<th>Correction</th>
<th>Dry Tropo(m)</th>
<th>Wet Tropo(m)</th>
<th>Ionosphere(m)</th>
<th>Inverse Barometer(m)</th>
<th>Solid Tide(m)</th>
<th>Ocean Tide(m)</th>
<th>Load Tide(m)</th>
<th>Pole Tide(m)</th>
<th>Sea State Bias(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum</td>
<td>-2.1</td>
<td>0.050.0</td>
<td>0.04</td>
<td>1.0</td>
<td>1.0</td>
<td>5.0</td>
<td>0.5</td>
<td>0.1</td>
<td>1.0</td>
</tr>
<tr>
<td>Minimum</td>
<td>-2.4</td>
<td>-0.6</td>
<td>-0.4</td>
<td>-1.0</td>
<td>-1.0</td>
<td>-6.0</td>
<td>-0.5</td>
<td>-0.1</td>
<td>-1.0</td>
</tr>
</tbody>
</table>

Table 3: Editing limits on altimetric parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Latitude (deg)</th>
<th>Longitude (deg)</th>
<th>SSH Anomaly(m)</th>
<th>1-Hz Cssw (m)</th>
<th>Sww (m)</th>
<th>1-Hz Csw (m)</th>
<th>Wind Speed (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum</td>
<td>15.0</td>
<td>125.0</td>
<td>5.0/5.5</td>
<td>0.05/0.09</td>
<td>3.0</td>
<td>0.34/0.5</td>
<td>30.0</td>
</tr>
<tr>
<td>Minimum</td>
<td>0.0</td>
<td>95.0</td>
<td>-4.5/-5.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>-5.0</td>
</tr>
</tbody>
</table>

Table 2 and Table 3 present the limits used in this study. In most instances the same values apply to all satellites missions. However, the differential values in the table cells are separated by a ‘/’.

5. A Case Study for Satellite Altimeter Data Processing

This section discusses the comparison of sea level using satellite altimeter and tide gauge data. Then, the data was used to validate the results from a combination of Topex and Jason-1 data (Satellite Altimeter) and tide gauge data. Two 1° × 1° areas were chosen for the comparison, where the altimeter tracks were nearby to tide gauge locations (Figure 8).

The tide gauge data was taken from Department of Survey and Mapping Malaysia (DSMM). In Malaysia, the Department of Survey and Mapping Malaysia (DSMM) is the main government agency in Malaysia responsible for the acquisition, processing, archiving, and dissemination of sea-level data. To date, there are 12 tidal stations along the coast of Peninsular Malaysia (West Malaysia) and 9 tidal stations along the coast of Sabah and Sarawak (East Malaysia).
The result of the comparison of sea level trend using satellite altimeter and tide gauge data are given in Figure 9 and Figure 10.

**Figure 8:** Selected $1^\circ \times 1^\circ$ areas nearby to tide gauge stations

**Figure 9:** Plot of sea level rise at Kota Kinabalu tide gauge and altimeter data
Figure 10: Plot of sea level rise at P. Tioman tide gauge and altimeter data

Linear trend for Topex/Jason1 (Altimeter) and tide gauge measurements were evaluated over the same period at each area in order to produce comparable results. We can see, similarity in the pattern of sea level variations indicated good agreements between tide gauge and altimeter data. Refer to Table 4, it indicates that the differences of linear trend between tide gauge and altimeter data were considered small, around -0.03 mm/year. These results basically encourage us to estimate the rate of sea level trend at South China Sea using altimeter data.

Table 4: Comparison of sea level trend between tide gauge and altimeter data

<table>
<thead>
<tr>
<th>LOCATION</th>
<th>DATA</th>
<th>TIDE GAUGE (mm/yr)</th>
<th>ALTIMETER (mm/yr)</th>
<th>DIFFERENT (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>K. Kirabalu</td>
<td>1993 - 2008</td>
<td>2.33</td>
<td>2.36</td>
<td>0.03</td>
</tr>
<tr>
<td>P. Tioman</td>
<td>1993 - 2008</td>
<td>2.36</td>
<td>2.39</td>
<td>0.03</td>
</tr>
</tbody>
</table>

This study used the altimeter data from Topex and Jason-1 over South China Sea covering the area of $2^\circ$ N $\leq \phi \leq 7^\circ$ N and $104^\circ$ E $\leq \lambda \leq 114^\circ$ E, starting from January 1993 until April 2008. The sea surface height (SSH) data have been corrected using RADS. The geophysical effects on the sea surface height have been modeled and removed from the sea level height in order to get the corrected sea level. The corrected height is called as sea level anomaly. Table 5 shows the statistics of sea level anomaly for TOPEX and Jason-1 after correcting for sea level height.

Table 5: Statistics of sea level anomaly from satellite altimeter

<table>
<thead>
<tr>
<th>Point No.</th>
<th>Satellite</th>
<th>Min (m)</th>
<th>Max (m)</th>
<th>Mean (m)</th>
<th>StdDev (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>922415</td>
<td>Topex</td>
<td>-0.221</td>
<td>0.221</td>
<td>0.026</td>
<td>9.3</td>
</tr>
<tr>
<td>587236</td>
<td>Jason1</td>
<td>-0.638</td>
<td>0.806</td>
<td>0.013</td>
<td>11.2</td>
</tr>
</tbody>
</table>
As mentioned above, because of factors such as orbit error and inconsistency in the satellite orbit frame, the sea surface heights (SSH) from different satellite missions need to be adjusted to a ‘standard’ surface. In this study, the SSH from the Topex mission is used as a standard surface in the stage of integrated data processing because of its highly accurate orbit. That is called as crossover adjustment for dual-satellite missions. Table 6.8 shows the statistics of crossover differences before and after crossover adjustment.

**Table 6:** Statistics of crossover differences between Topex and other satellite before and after crossover adjustment

<table>
<thead>
<tr>
<th>Satellite</th>
<th>No. Point</th>
<th>Before Adjustment</th>
<th>After Adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Min (m)</td>
<td>Max (m)</td>
</tr>
<tr>
<td>Jason-1</td>
<td>587,236</td>
<td>-0.635</td>
<td>0.806</td>
</tr>
</tbody>
</table>

The results before crossover adjustment in Table 6 show that there is a systematic bias between Topex and Jason-1 data. It is just because there exists an inconsistency between Topex and Jason-1 orbit frames. The systematic bias has been eliminated after crossover adjustment. Table 6 also shows that compared to the Standard Deviation crossover differences of ±11 cm before crossover adjustment, an improved accuracy of ±9 cm has been obtained after crossover adjustment. It means that the goal of unifying dual-satellite altimeter data in the frame of Topex was achieved in this study.

Topex altimetry data (NASA/CNES Agency) were analyzed at South China Sea from January 1993 to July 2002 (cycle 11 – cycle 363). Meanwhile, Jason-1 data (NASA/CNES Agency) were taken from August 2002 to April 2008 (cycle 21- cycle 230). For each satellite mission the average over each cycle and over the entire South China Sea of the corrected sea surface heights (SSH) above mean sea surface model CLS01 MSS was computed and a simple regression model was fitted to the results.

The time series of mean sea level were derived from the averages of monthly altimeter data. The sea level time series of South China Sea is given in Figure 11. Plot of sea level time series of South China Sea depicted that the rise of mean sea level was clearly visible from the altimeter. The rate of sea level rise obtained from Topex/Jason1 in South China Sea was about 1.99 mm/year. It also shows that the short-term periodic circulation of mean sea level was revealed at the open South China Sea.

**Figure 11:** Plot of sea level time series of South China Sea using Topex/Jason1
6. Conclusion

Satellite altimetry technology provides a means as a complementary tool to the traditional coastal tide gauge instruments in measuring long term sea level height. Especially for the Malaysia region where the tide gauge stations are still limited both in number and geographical distribution, this technology is able facilitate the demand of sea level change information at almost every part of the area. The comparison of near-simultaneous altimeter and tide gauges observations showed good agreement, and therefore both techniques are competitive. This information is important to study alternative energy extraction and environmental issues related to flood investigations and global warming.

7. References