Derivation of Sea Level Anomaly Based on the Best Range and Geophysical Corrections for Malaysian Seas using Radar Altimeter Database System (RADS)

Ami Hassan Md Din[a,*], Sahrum Ses[a], Kamaludin Mohd Omar[a], Marc Naeije[b], Omar Yaakob[c] and Muhammad Faiz Pa'suya[a]

[a]GNSS & Geodynamics Research Group, Infocomm Research Alliance, Faculty of Geoinformation & Real Estate, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia.
[b]Faculty of Aerospace Engineering, Delft University of Technology, Kluyverweg 1, 2629 HS Delft, The Netherlands.
[c]Marine Technology Centre, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia.
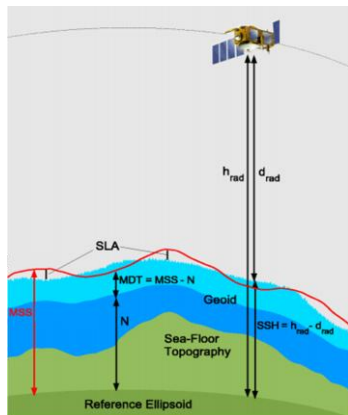
*Corresponding author: amihassan@utm.my

Abstract

The utilization of satellite altimeter data sets from previous and present satellite altimeter missions is imperative to both oceanographic and geodetic applications. The important parameter that can be derived from satellite altimeter is sea level anomaly, while it is also fundamental for sea level monitoring, geoid determination and current circulations study. This paper presents an effort to determine sea level anomaly for Malaysian seas from six satellite altimeter missions; TOPEX, JASON1, JASON2, ERS1, ERS2 and ENVISAT. The best range and geophysical corrections for Malaysian seas were also investigated in this study by evaluating two state of the art corrections available for 9 years of TOPEX satellite altimeter (from January 1993 to December 2001). Sea level data retrieval and reduction were carried out using the Radar Altimeter Database System (RADS). The comparison of near-simultaneous altimeter and tide gauges observations showed good agreement with the correlations are higher than 0.87 at Tioman Island, Langkawi Island and Kota Kinabalu. This paper introduces RADS and deals with determination of sea level anomaly using the best range and geophysical corrections in Malaysian seas.

Keywords: Sea Level Anomaly; Range Correction; Geophysical Effect; Satellite Altimeter; Radar Altimeter Database System (RADS)

Abstrak

Penggunaan data satelit altimeter yang terdahulu dan hinggalah yang terkini adalah penting untuk aplikasi oseanografi dan geodetik. Parameter terpenting yang boleh diperolehi dari satelit altimeter adalah anomali paras air laut , di mana parameter ini juga menjadi data asas bagi pemantauan paras air laut, penentuan geoid dan kajian peredaran arus. Kertas kerja ini membincangkan kaedah untuk menentukan anomali paras air laut bagi perairan Malaysia daripada enam misi satelit altimeter; TOPEX , JASON1 , JASON2 , ERS1 , ERS2 dan ENVISAT . Pembetulan bagi jarak dan geofizikal yang terbaik bagi peraiaran Malaysia telah diuji dalam kajian ini dengan menilai dua jenis pembetulan yang terkini untuk data dari satelit altimeter TOPEX (tempoh masa bermula dari Januari 1993 hingga Disember 2001). Sistem Pengkalan Data Radar Altimeter (RADS) telah digunakan untuk tujuan pengumpulan dan pemprosesan data aras air laut. Perbandingan antara data cerapan altimeter dan tolok pasang surut menunjukkan hubungan yang baik di antara kedua-dua teknik di mana nilai korelasi lebih daripada 0.87 di Pulau Tioman , Pulau Langkawi dan Kota Kinabalu. Penulisan ini memperkenalkan RADS dan berkaitan dengan penentuan anomali paras air laut dengan menggunakan pembetulan jarak dan geofizikal yang terbaik untuk perairan laut Malaysia.

Kata kunci: Anomali Paras Air Laut; Pembetulan Jarak, Kesan Geofizikal; Satelit Altimeter; Sistem Pengkalan Data Radar Altimeter (RADS)

◼1.0 INTRODUCTION

NASA's satellite altimeter program was originally started at the 1969 Williamstown Conference. An altimeter was actually used to scan the Moon by Apollo 14. The first dedicated altimeter mission was GEOS-3 (April 1975 to December 1979), with a measurement precision of 25 cm in the second (s) averages. Technological improvements increased this measurement precision for 1 s averages to about 5 cm for the SEASAT altimeter, which was operated from July to October 1978. Further improvements have resulted in better than 5 cm precision on the presently operational (since March 1985) GEOSAT altimeter [1].

Satellite altimeter measurements have now been continuously available since 1991, through the ERS1, TOPEX/Poseidon, ERS2, GEOSAT Follow-on, JASON1, JASON2, ENVISAT, CRYOSAT2 and SARAL missions. Measurements from these instruments have revolutionized our knowledge of the ocean, through studies in sea level, ocean circulation and climate variability. More details on altimetry and its applications can be found in Fu and Cazenave [2001].

Although satellite altimeter records are still quite short compared to the tide gauge data sets (For sea level anomaly determination case), this technique appears quite promising especially for the sea level study because it provides sea level measurement with large coverage. A precision of about 1 mm/year of measurement global change can be obtained [2]. Six satellite altimeter missions were used to derive sea level anomaly in this study; TOPEX, JASON1, JASON2, ERS1, ERS2 and ENVISAT. Details for each characteristic and orbit of satellite missions are described in Table 1.

Table 1 Characteristics of Satellite Altimeter Mission (Summarized from [3])

MISSION	TOPEX	JASON1	JASON2	ERS1	ERS2	ENVISAT
Launch Date	10/08/ 1992	07/12/ 2001	22/06/ 2008	17/07/ 1991	21/04/ 1995	01/03/ 2002
Agency	NASA/ CNES	NASA/ CNES	NASA/ CNES	ESA	ESA	ESA
Type	Ocean Altimetr	Ocean Altimetr	Ocean Altimetr	Multi-sensor	Multi-sensor	Multi-sensor
Synchroniz ation	Non Sun-synchron ous	Non Sun-synchron ous	Non Sun-synchron ous	Sun-synchron ous	Sun-synchron ous	Sun-synchron ous
Sense	Prograde	Prograde	Prograde	Retrogra de	Retrogra de	Retrogra de
Altitude (km)	1336	1336	1336	800	800	800
Inclination (deg)	66	66	66	98.5	98.5	98.5
Period (mn)	112	112	112	100	100	100
Orbits per Day	12.8	12.8	12.8	14 + 11/35	14 + 11/35	14 + 11/35
Repeat Cycle (days)	10	10	10	35	35	35

◼2.0 RADAR ALTIMETER DATABASE SYSTEM (RADS)

Satellite altimeter data has been distributed through agencies like NOAA, AVISO, EUMETSAT and PO.DAAC. In addition to these agencies, the Delft Institute for Earth-Oriented Space Research (DEOS) and the NOAA Laboratory for Satellite Altimetry has been collaborating in the development of Radar Altimeter Database System (RADS). The RADS is established in a harmonized, validated and cross-calibrated sea level database from all satellite altimeter missions. In RADS, users able to access to the most present range and geophysical

corrections and also can produce their own altimetric products based on their particular interest [4].

In the frame of RADS, the DEOS is developing a database that incorporates validated and verified altimetry data products. Besides, the database is also consistent in accuracy, correction, format and reference system parameters. The capability of such a database will attract users with less satellite altimeter expertise like advisory councils, water management authorities and even high schools [5]. This system also fulfills the need of scientists and operational users to have value-added sea level data readily at one's disposal [6]. Currently, RADS enables users to extract the data from several present and past satellite altimeter missions like GEOSAT, ERS1, ERS2, ENVISAT, TOPEX/Poseidon (T/P), JASON1, JASON2, CRYOSAT2 and SARAL.

In Universiti Teknologi Malaysia (UTM), the RADS system has been installed since 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). Several universities and research group from France and the Netherlands (Europe representative), and Malaysia, Indonesia, and Thailand (South East Asia representative) are participating in this geodetic education and geodetic research project. The main goal of the SEAMERGES project is to accomplish the knowledge transfer, expertise and technology from Europe to South East Asia to locally enable the geodetic research at higher-level and to initiate the implementation of these technologies in the water management and risk assessment applications. It also aims at encouraging the scientific cooperation and collaboration among the different South East Asia countries.

◼3.0 SEA LEVEL ANOMALY DERIVATION

The basic principle of satellite altimeter is based on the simple fact that time is a distance. The distance between the satellite and the sea surface is measured from the round-trip travel time of microwave pulses emitted downward by the satellite radar, reflected back from the ocean, and received again on board. Meanwhile, the independent tracking systems are used to compute the satellite's three-dimensional position relative to a fixed Earth coordinate system. By combining these two measurements yields profiles of sea surface height, or sea level, with respect to the reference ellipsoid [2].

However, the situation is far more complex in practice. Several factors have to take into account such as instrument design, calibration, validation, range corrections (ionosphere, troposphere and sea state bias), geophysical corrections (tides, geoid and inverse barometer), reference systems, precise orbit (satellite height) determination, different satellites with different sampling characteristics, and so on.

Figure 1 presents the schematic diagram of satellite radar altimeter system and its principle. By using a similar notation to [1], the corrected range $R_{corrected}$ is related to the observed range R_{obs} as:

$$R_{corrected} = R_{obs} - \Delta R_{dry} - \Delta R_{wet} - \Delta R_{iono} - \Delta R_{ssb}$$

Where,

$R_{obs} = c\,t/2$ is the computed range from the travel time t observed by the on-board ultra-stable oscillator (USO), and c is the speed of the radar pulse neglecting refraction.
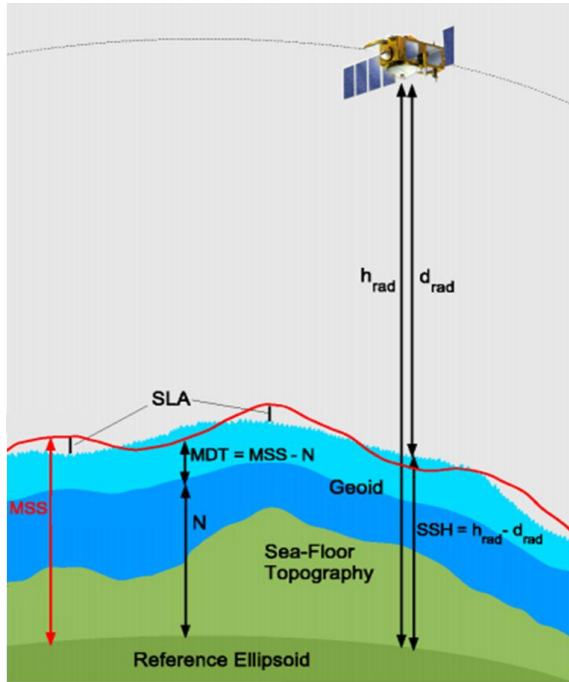
ΔR_{dry} : Dry tropospheric correction

Figure 1 Principle of Satellite Altimeter

ΔR_{wet} : Wet tropospheric correction
ΔR_{iono}: Ionospheric correction
ΔR_{ssb} : Sea-state bias correction

The range measurement is then converted to the height, *h* of the sea surface relative to the reference ellipsoid and given as:

$$h = H - R_{corrected} = H - (R_{obs} - \Delta R_{dry} - \Delta R_{wet} - \Delta R_{iono} - \Delta R_{ssb})$$

Where,

    H :   The height of the spacecraft determined through orbit determination

As a result, the sea surface height accuracy is directly related to the accuracy of the orbit determination. Fortunately, the orbit accuracy has improved from tens of meters on the first altimeters to about 1 cm on the most recent satellites [7]. After the (satellite-specific) range corrections have been applied, the resulting sea surface heights vary spatially between ±100 m with temporal variations up to ±10 m [4].

The main focus of satellite altimeter field is to study the dynamic sea surface height signals related to oceanographic processes, which are normally on the sub meter scale. In order to study/isolate these, it is necessary to remove the dominant geophysical contributors to sea surface height variations, which can be divided into three main components such as geoid, tide and dynamic atmosphere corrections.

The geoid correction gives the largest contribution to the measured sea surface height. The geoid is an equipotential of the gravity field; if the ocean were at rest, the sea surface would exactly follow the geoid. By removing the permanent geoid signal and referencing the sea surface height to a given geoid model, the sea surface height is reduced to meter scale [4].

Meanwhile, the tide correction is the dominant contributor to temporal sea surface height variability. Ocean tides are the largest tidal component, but the correction also accounts for solid earth tides, loading tides, and pole tides. Last but not least is the dynamic atmospheric correction, which corrects the sea surface height variations due to the time varying atmospheric pressure loading. This correction normally involves a static response (inverse barometer) of the ocean to atmospheric forcing for low-frequency signals (longer than 20 days) combined with a correction for dynamic high-frequency variations (shorter than 20 days) in sea surface height [4].

The actual sea surface height, *h* obtained is not sufficient for oceanographic application because it is a superposition of geophysical signals. In order to remove the external geophysical signals from the sea surface height, the equation below is applied. It noted that these are corrections for genuine geophysical signals, but they act like corrections to the range.

$$h_D = h - h_{geoid} - h_{tides} - h_{atm}$$

Where,

    h_D : Dynamic sea surface height
    h_{geoid} : Geoid correction
    h_{tides} : Tide correction
    h_{atm} : Dynamic atmosphere correction

The next step is to combine the range and geophysical corrections into a combined set of corrections. By combining the range and geophysical corrections using this convention, the dynamic sea surface height, h_D, is derived from the height, *H*, of the spacecraft, and the range, R_{obs} given as:

$$h_D = H - R_{obs} - \Delta h_{dry} - \Delta h_{wet} - \Delta h_{iono} - \Delta h_{ssb} - h_{geoid} - h_{tides} - h_{atm}$$

Where all corrections are sea surface height corrections and, i.e., $\Delta R_{wet} = -\Delta h_{wet}$, etc.

By applying the geophysical corrections, and particularly the geoid correction, the sea surface height, h_D height values are typically reduced from ranging up to 100 m to range up to a few meters [4]. Normally, for sea surface height variation study, it is often more convenient to refer the sea surface height to the mean sea surface height rather than to the geoid, thus creating the sea level anomalies h_{sla} , given as:

$$h_{sla} = H - R_{obs} - \Delta h_{dry} - \Delta h_{wet} - \Delta h_{iono} - \Delta h_{ssb} - h_{MSS} - h_{tides} - h_{atm}$$

Subtraction of the mean sea surface conveniently removes the temporal mean of the dynamic sea surface height and creates sea level anomalies that, in principle, have zero mean. This is so, because mean sea surfaces are normally computed by averaging altimetric observations over a long time period and preferably combining data from several exact repeat missions. When removing the temporal mean, also the temporal mean of the corrections is removed and only the time-variable part of the correction is then a concern [4].

■4.0 MULTI-SATELLITE ALTIMETER PROCESSING IN RADS

In this study, multi-mission satellite altimetry data has been processed using Radar Altimeter Database System (RADS). RADS processing uses Ubuntu as operating system. The details procedure to derive sea level anomaly in RADS can be summarized as illustrated in Figure 2. For the estimation of the satellite altimeter biases, a global analysis in which the difference with respect to the TOPEX reference frame. The

TOPEX reference frame is modelled by 5 spherical harmonic coefficients constituting a constant bias, shifts in Z, X, and Y
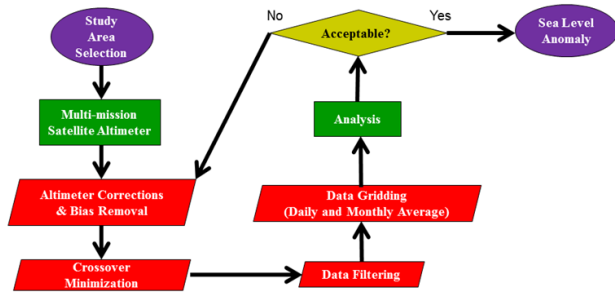

Figure 2 Overview of altimeter data processing flows in RADS

directions and a difference in flattening based on as much coincident data as possible [8].

Since the TOPEX and JASON satellites can give better accuracy compares to the ERS and ENVISAT satellites, the so-called dual-crossover minimization analysis were performed, in which the orbit of the TOPEX and JASON satellites was held fixed and ERS and ENVISAT satellites were adjusted simultaneously [9]. In this case, the crossovers were only performed between ERS-ENVISAT and TOPEX-JASON satellites.

The area used for the crossover minimization is much larger than the area under investigation to have sufficient crossover information to estimate the smoothness (1 cycle per orbital revolution) orbit error function fits. The timeframe covered by individual crossovers is limited to 18 days to reduce the risk of eliminating real oceanic signal and, with that, the sea level trend [8]. All satellite altimeter missions were merged and then gridded to sea level anomaly grids on a daily basis. Gridding involved both temporal and spatial weighing. Subsequently the daily solutions are collected per month and a monthly average is calculated.

This method aims to equalize the final monthly altimeter solution with the monthly tide gauge solution. It appeared that this methodology (daily to monthly altimeter results) improves the correlation and the sea level pattern between monthly-solutions of altimeter and tide gauge. The best range and geophysical corrections for Malaysian seas have been applied in RADS processing and details criteria to choose the corrections were discussed in Section 5.0.

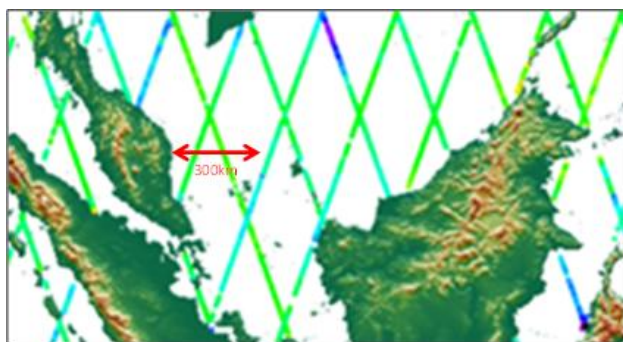# ■5.0 ANALYSIS OF RANGE AND GEOPHYSICAL CORRECTIONS FOR MALAYSIAN SEAS

Figure 3 Sample of coastal region within 300km for investigating the best range and geophysical corrections

In this study, the researchers have been tried to find the best range and geophysical corrections for Malaysia region. In this section, range and geophysical corrections are investigated with a focus on coastal regions (Figure 3). For each correction, an investigation of the accuracy will be given, by evaluating two state of the art corrections available for 9 years of TOPEX satellite altimeter (from January 1993 to December 2001). Table 2 shows the two most recent state of the art corrections for TOPEX and these are the corrections that have been used for this investigation.

Table 2 The two state of the art range and geophysical corrections available in the RADS

CORRECTION	OBSERVATION OR MODEL
Dry Troposphere	ECMWF (Model)
	NCEP (Model)
Wet Troposphere	Radiometer Measurement
	NCEP (Model)
Ionosphere	Radiometer – Smoothed Dual Frequency
	JPL GIM (Model)
Dynamic Atmosphere	IB (Model, Local Presure)
	MOG2D (Model)
Tides	FES2004 (Model)
	GOT4.8 (Model)
Sea-state Bias	BM4 (Model)
	CLS NON-PARAM (model)

Before analysing each range and geophysical corrections for TOPEX, standard deviation of range is also important to take into account. In this study, the interpretation of standard deviation of range (in cm) from 9 years of TOPEX has been performed by estimating averaged in 2 km bins as a function of the distance to the coast (in km) as illustrated in Figure 4. In general, the standard deviation of range for TOPEX is around 2-3 cm in the deep ocean. However, the range observations are degraded closer than 30km to the coast.
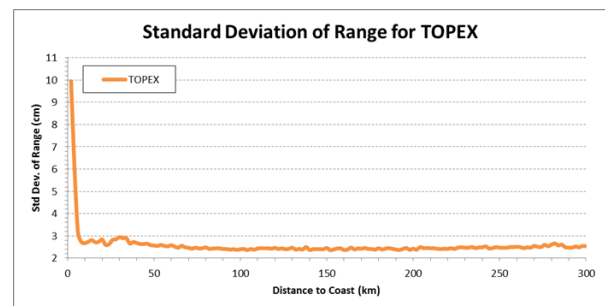

Figure 4 Standard deviation of range (cm) for TOPEX as a function distance to the coast (km)

5.1 Dry Troposphere Correction

The correction for dry troposphere is by far the largest adjustment that must be applied to the range. The vertical integration of the air density is closely related to the pressure, and the dry troposphere correction is for most practical purposes approximated using information about the atmospheric pressure at sea level (or sea level pressure, SLP) and a refractivity constant of 0.2277 cm^3/g[4].The formula for the dry troposphere
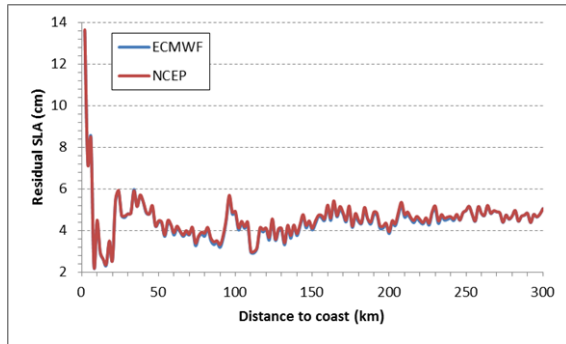
Figure 5 The standard deviation of residual sea level anomaly variation (in cm) from 9 years of TOPEX observations corrected using the ECMWF and NCEP based dry troposphere correction and then shown as a function of the distance to the coast (in km)

Figure 6 The residual sea level anomaly variation (in cm) applying the wet troposphere correction from the on-board radiometer and interpolated NCEP estimates averaged in 2 km bins as a function of the distance to the coast (in km)

corrections are discussed in details by [10] and are given in units of cm as:

$$\Delta h_{dry} \approx -0.2277\ P_0\ (1 + 0.0026\ \cos 2\phi)$$

Where, P_0 is the SLP in hecto-Pascal (hPa) and the coefficient in the parenthesis is the first order Taylor expansion of the latitude (ϕ) dependence of standard gravity evaluated at the location of observation to account for the oblateness of the Earth.

In this study, the two most widely used models for dry troposphere corrections are analysed: the European Centre for Medium-Range Weather Forecasts (ECMWF) and the U.S. National Centers for Environmental Prediction (NCEP).

Figure 5 shows the standard deviation of residual sea level anomaly variations applying the dry troposphere correction based on ECMWF and NCEP as a function of the distance to the coast. Nine years of TOPEX data have been used and averaged in bins of 2 km as a function of the distance to the coast in order to analyse the quality and differences between the corrections in coastal regions. By comparing the standard deviation of the residual sea level anomaly signal while leaving all other corrections unchanged evaluates the two models. A lower standard deviation of residual sea level anomaly will indicate that the correction removes more "signal," indicating that the correction is more efficient (better).

Figure 5 illustrates that it is basically impossible to tell the two curves (ECMWF and NCEP model) apart indicating that the two models have removed the same amount of signal and are presumably of same accuracy. The investigation also confirms that there is only very minor differences (<3 mm) between these two corrections. The increase in residual sea level anomaly closer to the coast is due to increased sea level variability in shallow water depth and not related to the corrections.

5.2 Wet Troposphere Correction

The wet troposphere correction is related to water vapour in the troposphere, and cloud liquid water droplets. The water vapour dominates the wet tropospheric correction by several factors, and the liquid water droplet from small to moderate clouds is generally smaller than one centimetre [11].
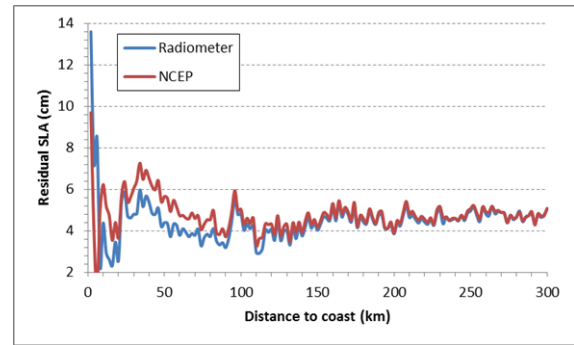
The wet troposphere correction can be derived by using the equation as (in units of cm):

$$\Delta h_{wet} \approx 636(cm^3/g)\int\sigma_{vap}\ (z)dz$$

Which, σ_{vap} is a vertical integration of the water vapour density in grams per cubic centimetres (g/cm^3). The equation has been simplified by replacing the altitude dependent temperature T of the troposphere with a constant temperature. More advanced formulas can be referred in [12].

Figure 6 illustrates the standard deviation of sea level anomaly for wet troposphere corrections using on-board radiometer and interpolated NCEP model. As before, 9 years of TOPEX data have been averaged in 2km bin with respect to the distance to the coast. It clearly illustrates that in the deep ocean there is virtually no difference between the two corrections. But, overall analysis shows that the on-board radiometer reduces the sea level anomaly variability slightly more than the interpolated NCEP correction especially 100km to the coast.

5.3 Ionosphere Correction

The refraction of electromagnetic waves in the earth's ionosphere is directly connected to the free electrons and ions at altitudes above approximately 100 km. At this altitude, high energy photons emitting from the sun are able to strip atomic and molecular gasses of an electron. At lower altitudes, up to about 300 km, NO^+ and $O_2^{\ +}$ are the most prevalent types, while at higher altitudes, stretching even far above the altitude of the satellite altimeters, can easily be found H^+, O^+, $N^{+,}$ and He^+ [13].

The interaction between the electromagnetic waves and the ions makes the waves to slow down by an amount proportional to the electron density in the ionosphere. Hence, the total delay obtained on the satellite altimeter radar pulse along its path through the ionosphere is proportional to the number of electrons per unit area in a column extending from the earth's surface to the satellite altimeter. This columnar electron density count is known as the Total Electron Content (TEC). The TEC unit, or TECU, equals 10^{16} electrons/m^2 [4].

The ionosphere correction (the negative of the delay) is also inversely proportional to the square of the radar frequency can be summarized by:
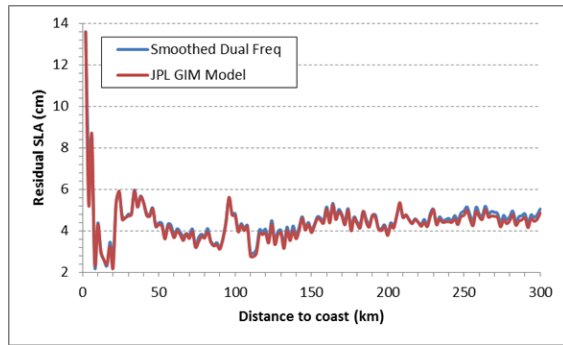
$$\Delta h_{iono} = -k\text{TEC}\ /\ f^2$$

Figure 7 The residual sea level anomaly variation (in cm) applying the ionosphere correction from the dual-frequency altimeter and the interpolated JPL GIM estimates averaged in 2 km bins as a function of the distance to the coast (in km)

Where, k is a constant of 0.40250 m GHz^2/TECU. At the Ku-band frequency of approximately 13.6 GHz, this means that the ionospheric delay amounts to about 2 mm for each TEC unit [14].

Figure 7 presents the standard deviation of residual sea level anomaly as a function of the distance to the coast while applying two different ionospheric corrections: based on the dual-frequency altimeter measurements and the JPL GPS ionosphere maps. At this comparison, the differences are minimized. In general, the dual-frequency ionosphere and JPL GIM model applies well to the coastal region. The temporal variation of the ionosphere correction is only a few mm in most places. Therefore it is hard to determine which correction model reduces the variability of the sea level anomaly the most and both seem to be performing equally accurate in coastal regions.

5.4 Sea-state Bias Correction

The correction of sea-state bias (SSB) compensates for the bias of the satellite altimeter range measurement toward the troughs of ocean waves. This bias is believed to occur from three inter-related effects: an electromagnetic (EM) bias, a skewness bias, and an instrument tracker bias [4]. The SSB was originally modelled as a simple percentage of the SWH (e.g., Δh_{ssb} = -0.04 SWH), explaining that, with increasing SWH, altimeter ranges longer or more below the mean sea surface within the altimeter footprint. The SWH represents the average height of the 1/3 highest waves considered [15].

The SSB signal also relies on the wind field and the different wave types. Therefore, a more advanced parametric model comprising four parameters has been introduced to describe the SSB correction ([16], [17]). The model is generally referred to as the BM4 model:

$$\Delta h_{ssb} = \text{SWH} \, (a_1 + a_2 U + a_3 U^2 + a_4 \text{SWH})$$

Where, U is the wind speed derived from the backscatter coefficient. This formula gives the total SSB correction including all the three contributions to SSB mentioned above, as all of these are dependent on the SWH.

In order to evaluate the BM4 parametric and the non-parametric sea-state bias model in the coastal zone, Figure 8 illustrates the standard deviation of residual sea level anomaly variation from 9 years of TOPEX observations applying the BM4 and the CLS non-parametric SSB model. Overall analysis
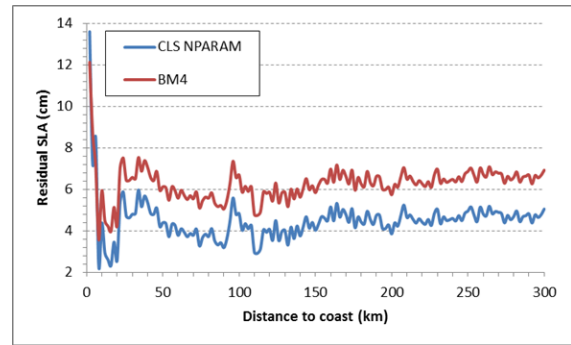

Figure 8 Standard deviation of residual sea level anomaly variation from 9 years of TOPEX observations applying the BM4 and the CLS non-parametric SSB model

shows that the CLS Non-parametric SSB reduces the sea level anomaly variability more than the BM4 correction everywhere both in the deep ocean and coastal area.

5.5 Ocean Tide Correction

The correction of ocean tide is by far the correction that reduces the temporal sea surface height variance the most. In an analysis of collinear differences of sea surface heights variations, [18] discovered that the ocean tides were contributing for more than 80% of the total signal variance in most areas.

Besides the ocean tide signal, in fact the tidal correction includes correction for a few smaller tidal signals: the loading tide, the solid earth tide, and the pole tide. The sum of the tidal corrections can be written as:

$$\Delta h_{tides} = \Delta h_{ocean\ tide} + \Delta h_{load\ tide} + \Delta h_{solid\ earth\ tide} + \Delta h_{pole\ tide}$$

However, only the ocean tide has been investigated in coastal regions in this study. The solid earth and pole tide correction are independent of coastal regions and normally it can be derived using closed mathematical formulas [4].

In order to investigate the ocean tide correction in coastal zones, Figure 9 shows the standard deviation of residual sea level anomaly variation applying the FES2004 and GOT4.8 ocean tide models. It clearly illustrates, that in the deep ocean and coastal region there are a significant difference in the models, and here GOT4.8 is clearly reducing more sea level anomaly variability signal than FES2004.
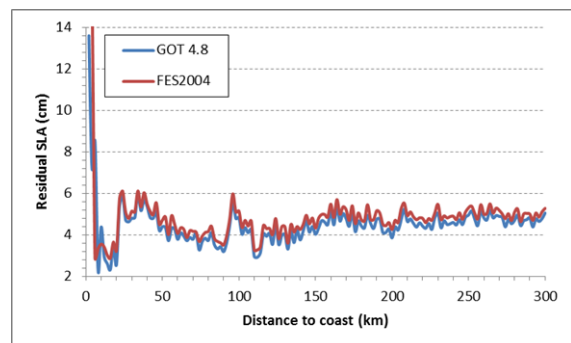

Figure 9 Standard deviation of residual sea level anomaly variation from 9 years of TOPEX observations applying the FES2004 and GOT4.8 ocean tide models
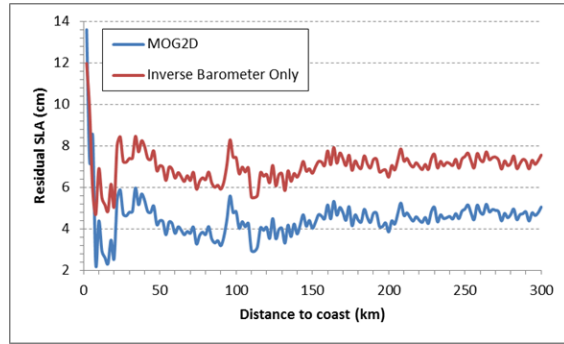
5.6 Dynamic Atmosphere Correction

Figure 10 Standard deviation of residual sea level anomaly variation (in cm) applying the inverse barometer correction and the MOG2D

The ocean reacts roughly as a huge inverted barometer, coming up when atmospheric pressure is low, and down when the pressure rises. The sea surface height correction due to variations in the atmosphere, is divided into low-frequency contribution (periods longer than 20 days), and a high-frequency contribution (periods shorter than 20 days) [4].

For the low-frequency contribution, the classical inverse barometer correction is used to account for the presumed hydrostatic response of the sea surface to changes in atmospheric pressure [19]. One hecto-Pascal increase in atmospheric pressure depresses the sea surface by about 1 cm. Consequently, the instantaneous correction to sea level can be computed directly from the surface pressure and in units of cm as:

$$\Delta h_{ib} \approx -0.99484 \ (P_0 - P_{ref})$$

Where, P_0 can be determined from the dry troposphere correction. P_{ref} is the global "mean" pressure (reference pressure). Traditionally a constant global value of 1,013.3 hPa has been used as this value is the average pressure over the globe [4].

Analysis of evaluating the inverse barometer correction and the MOG2D dynamic atmosphere correction in coastal regions is shown in Figure 10. Again, the standard deviation of residual sea level anomaly from 9 years of TOPEX data applying the two models is shown. The figure reveals that MOG2D removes considerably more sea level anomaly variability in deep ocean and coastal regions compared with the traditional inverse barometer corrections.

■6.0 ALTIMETER DATA PROCESSING VERIFICATION: ALTIMETER VERSUS TIDE GAUGE

This section discusses several sample areas of the verification of sea level anomaly that has been derived using RADS. The final parameters applied for multi-mission altimeter processing in RADS were shown in Table 3. In this study, the comparison of sea level using satellite altimetry and tidal data was done by choosing 0.25° × 0.25 ° bins, where the altimeter tracks were nearby to tide gauge locations. The tidal data were taken from Department of Survey and Mapping Malaysia (DSMM). Tioman Island, Langkawi Island and Kota Kinabalu areas were chosen for the study areas as illustrated in Figure 11. The period

Table 3 Corrections and models applied for altimeter processing in RADS

Correction/Model	Editing (m)		Description
	Min	**Max**	
Orbit/ Gravity field			All satellites: EIGEN GL04C ERS: DGM-E04/D-PAF
Dry troposphere	-2.4	-2.1	All satellites: Atmospheric pressure grids
Wet troposphere	-0.6	0.0	All satellites: Radiometer measurement
Ionosphere	-0.4	0.04	All satellites: Smoothed dual-freq, ERS/POSEIDON: NIC08
Dynamic atmosphere	-1.0	1.0	All satellites: MOG2D
Ocean tide	-5.0	5.0	All satellites: GOT4.8
Load tide	-0.5	0.5	All satellites: GOT4.8
Solid earth tide	-1.0	1.0	Applied (Elastic response to tidal potential)
Pole tide	-0.1	0.1	Applied (Tide produced by Polar Wobble)
Sea state bias	-1.0	1.0	All satellites: CLS non parametric ERS: BM3/BM4 parametric
Reference	-1.0	1.0	DTU10 mean sea surface height
Engineering flag			Applied
Applied reference frame biases (cm)			JASON1: -4.8, ERS1: +3.4, ERS2: +7.3, ENVISAT: +5.2 JASON2:+15.9 TOPEX: Reference frame

Figure 11 Selected study areas for comparison of altimetry and tidal data; Tioman Island, Langkawi Island and Kota Kinabalu

of the data comparison starts from 1 January 1993 up to and including 31st December 2011.

The details results of the comparison are shown in Figure 12 and Figure 13 respectively. The analysis of the sea level anomaly is focused on the pattern and the correlation between altimetry and tidal data. The linear trend for altimeter and tide gauge measurements was evaluated over the same period in each area in order to produce comparable results. In Figure 12, the similarity in the pattern of sea level from altimeter and tide gauge indicated good agreements at Tioman Island, Langkawi Island and Kota Kinabalu accordingly.

Based on the correlation results in Figure 13, correlations between monthly values of tide gauge and altimetry data in all selected areas are higher than 0.87. These results mean that the altimeter processing did well in this study and the altimetry data has a good potential for sea level anomaly determination using RADS.
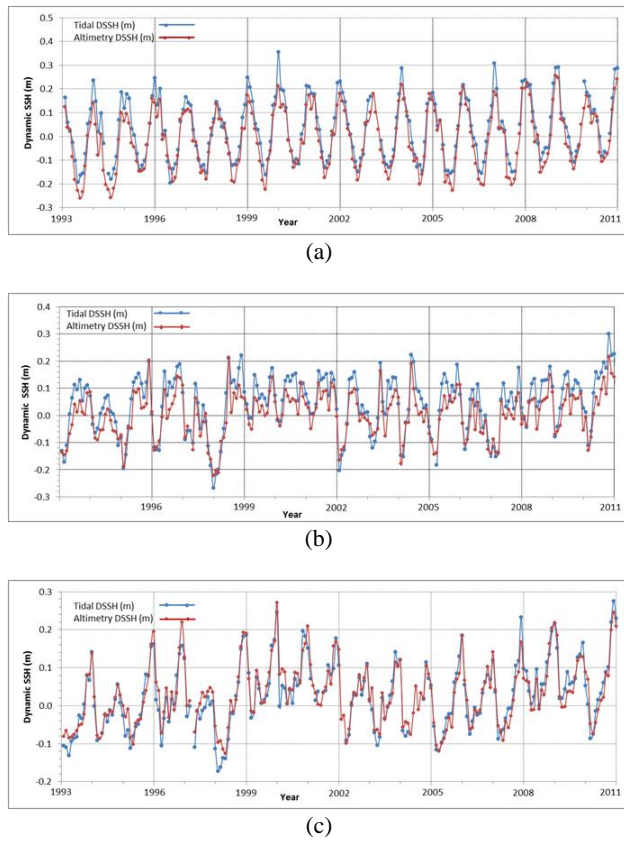
(a)

(b)

(c)

Figure 12 Sea level comparisons between altimetry – tidal data at Tioman Island (a), Langkawi Island (b) and Kota Kinabalu (c)
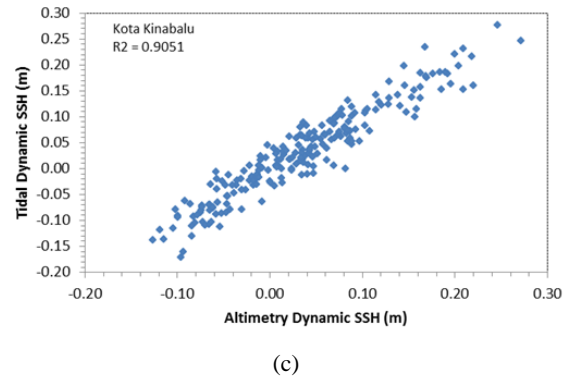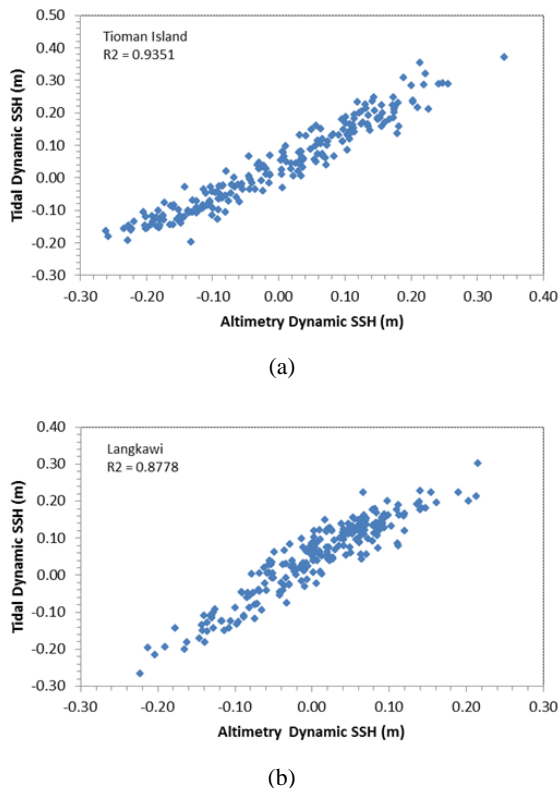

(a)

(b)

(c)

Figure 13 The correlation analysis of Tioman Island (a), Langkawi Island (b) and Kota Kinabalu (c)

■7.0 CONCLUSION

Multi-mission satellite altimeter provides a means as a complementary tool to the traditional coastal tide gauge instruments in measuring long term sea level anomaly, especially in the Malaysia region where the tide gauge stations are still limited both in number and geographic distribution. Through RADS technology, it is able to facilitate the demand of sea level anomaly information on almost every part of the area. The best range and geophysical corrections for deriving sea level anomaly in RADS have been investigated and applied for Malaysian seas in this study. The comparison of near-simultaneous altimeter and tide gauges observations showed good agreement with the correlations are higher than 0.87 at Tioman Island, Langkawi Island and Kota Kinabalu. Therefore both altimeter and tide gauges techniques are competitive. In conclusion, RADS is extremely helpful in both research and education and in operational and commercial exploitation of the radar altimeter data products.

Nomenclature

DEOS	-	Delft Institute for Earth-Oriented Space Research
DSMM	-	Department of Survey and Mapping Malaysia
ECMWF	-	European Centre for Medium-Range Weather Forecasts
ESA	-	European Space Agency
EU	-	European Union
EUMETSAT	-	European Organization for the Exploitation of Meteorological Satellites
GOT4.8	-	Global Ocean Tide 4.8
GPS	-	Global Positioning System
IB	-	Inverse Barometer

InSAR	-	Interferometry Synthetic Aperture Radar
JPL GIM	-	Jet Propulsion Laboratory GPS ionosphere maps
MOG2D	-	2 Dimensions Gravity Waves model
NASA	-	National Aeronautics and Space Administration
NCEP	-	National Centers for Environmental Prediction
NOAA	-	National Oceanic and Atmospheric Administration
PO.DAAC	-	Physical Oceanography Distributed Active Archive Center
RADS	-	Radar Altimeter Database System
SEAMERGES	-	South-East Asia: Mastering Environmental Research with GEodetic Space Techniques
SLP	-	Sea Level Pressure
SSB	-	Sea State Bias
WSH	-	Significant Wave Height
TEC	-	Total Electron Content
USO	-	Ultra Stable Oscillator

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