Long term variation of sea level anomaly (September 1992-January 2017) in the Indonesian sea from multi-mission satellite altimetry data

Dina A. Sarsito¹, Kosasih Prijatna¹, Dudy D. Wijaya¹, Nur Fajar T¹, Ivonne M. Radjawane², Wiwin Windupranata³ and Brian Bramanto¹

¹ Geodesy Research Group, Faculty of Earth Sciences and Technology, Bandung Institute of Technology, Jl. Ganesha 10 Bandung, Indonesia
² Oceanography Research Group, Faculty of Earth Sciences and Technology, Bandung Institute of Technology, Jl. Ganesha 10 Bandung, Indonesia
³ SSKWPL, Faculty of Earth Sciences and Technology, Bandung Institute of Technology, Jl. Ganesha 10 Bandung, Indonesia

E-mail: dsarsito@gd.itb.ac.id

Abstract. Sea level anomaly (SLA) is one of the oceanic parameters that play a crucial role in the ocean dynamics. In the Indonesian region, spatio-temporal characteristic of SLA is significantly affected by local topographic features of the region. In this research, we investigate long-term variation of SLA over the region based on Topex/Poseidon, Jason-1 and Jason-2 data, during the period of Sept 1992 to January 2017. After removing some geophysical effects, time series of SLA values at each point of the collinear tracks are analyzed. The result show the long term MSSH in Indonesia area have increase from western part of Indonesia to eastern part with range -40 m to 80 m. The long term SST in Indonesia have almost same trend with the deviation from geoid undulation full degree with short wavelength type, and this phenomena represent the local effect such as shallow bathymetry and close sea. And for long term SLA, Indonesia shows positive value that the anomaly increasing with variable from western part to eastern part of Indonesia from 2.5 mm/year until 7 mm/yr.

1. Introduction

Sea level anomaly (SLA) is deviation between time independent sea surface height (SSH) with respect to the mean sea surface height (MSSH) using ellipsoid as a mathematical reference surface. The variability of SLA is affected by geographical setting each area and play a crucial role in dynamic of ocean and can give important information for geoid computation in geodetic research and ocean circulation-sea level rise study [1] tidal modeling in physical oceanography and environmental research. In this research, we will use altimetry data to study SLA, to get better understanding of the SLA phenomena in Indonesia, an archipelagic zone, that lay on equatorial area that have many type of ocean circulations. Since 1992 until 2017, SLA is derived using various type of altimetry data and gave promising accuracy. Archiving, Validation and Interpretation of Satellites Oceanographic data (AVISO), Physical Oceanography Distributed Active Archive Center (PO.DAAC), European Meteorological Satellite (EUMETSAT), and National Oceanic and Atmospheric Administration (NOAA) are the agencies that distribute altimetry data. The mirror of all satellite altimeter missions data...
can also be derived from Radar Altimeter Database System (RADS) [2] [3] that is developed by Delft Institute for Earth-Oriented Space Research (DEOS) and the NOAA Laboratory for Satellite Altimetry, that consist of validated and cross-calibrated sea level data. To get better understanding about SLA implications to geodetic and oceanographic studies in the Indonesian area, in this research, we study long-term SLA based on 30 years of sea-level data (more than 1 full period of 18.6 year) derived from multi-mission of satellite Altimetry collected in Radar Altimeter in the research coverage area -15S/90E to 15N/150E. The estimation method to determine the SLA in here is purely a geometric-geodetic strategy by estimate the cross over value and interpolate it in radius 5 km. The investigation area for full degree (n = 2190) and short wavelength (with degree n = 180) period of signal is chosen in Indonesia area.

2. Methods

2.1. Sea Level Surface and Satellite Altimetry

In studying sea surface, there are several types of surfaces that are used as reference (Figure 1). The choice of surface type used depends on the usage requirements as well as the necessary analysis. The reference datum used there are 2 types, namely geoid as the real potential field and ellipsoid as the mathematical reference field of the earth's surface. When using geoid as reference surface, it can be obtained Instantaneous Sea Surface Height (ISSH) or often called Sea Surface Height (SSH) and MSSH (Mean Sea surface Height). The difference between ISSH and MSSH is referred to as Sea Level Anomaly (SLA) (Equation 1). Whereas if the ellipsoid surface is used as a reference it will be obtained Dynamic Topography (DT) and Mean Dynamic Topography (MDT). In addition to the above, there is a type of sea surface that is also used as a reference that is Sea Surface Topography (SST) which is the difference between ISSH with geoid undulation (N) (Equation 2).

\[ SLA = SSH - MSSH \]  \hspace{1cm} (1)  
\[ SST = SSH - N \]  \hspace{1cm} (2)

\[ N(\lambda, \theta) = \frac{GM}{r(\lambda, \theta)} \sum_{n=2}^{N_{max}} \sum_{m=0}^{n} \left( C_{nm}^* \cos m\lambda + S_{nm}^* \sin m\lambda \right) P_{nm}^* \sin \theta \]  \hspace{1cm} (3)

**Figure 1.** Sea surface types and principle of satellite altimetry  
(modified from [5])

N values in the ocean can be obtained in various ways, i.e. marine/sub-bottom gravimetry, airborne gravimetry, satellite gravity or Global Geopotential Model (GGM). For the area of research that has not been organized geoid model local/regional, then N obtained from GGM by using Equation 3.
Where \((r, \lambda, \theta)\) is the radius-longitude in the sphere system, \(G\) is the gravitational constant, \(M\) is the mass of the globe of the fingers radius \(R\), and \(\overline{\math{C}^r}, \overline{\math{S}^r}, \text{ and } \overline{\math{P}^r}\) is a fully normalized coefficient and associated Legendre's polynomials with degree \(n\) and order \(m\).

The combination of altimetry satellite technology (dedicated to determining sea-water dynamics) with positioning satellites (GNSS) allows for the measurement of the height difference (vertical distance) of the satellite up to the surface of seawater (Figure 1). The vertical distance \(R_{\text{obs}}\) is obtained by measuring the travel time back \(t\) of the electromagnetic waves emitted by the satellite based on Equation 4

\[
R_{\text{obs}} = c * 0.5t
\]

Where \(c\) is the speed of light in a vacuum. \(R_{\text{obs}}\) still contains errors as well as bias that must be corrected first. The correction is adjusted to the source of the orbit \(H_{\text{ell}}\), the satellite instrument \(\text{corr}_{\text{ins}}\), the propagating media (ionosphere \(c_{\text{ion}}\), wet troposphere \(c_{\text{tw}}\), dry troposphere \(c_{\text{td}}\)) and the reflecting medium of sea state bias \(c_{\text{SSB}}\), while the geophysical bias derived from ocean tide \(c_{\text{ot}}\), loading tide \(c_{\text{lt}}\), solid earth tide \(c_{\text{set}}\), pole tide \(c_{\text{pt}}\) and atmospheric tide \(c_{\text{ib}}\). Furthermore, the SSH value is obtained by reducing the satellite heights to the \(H_{\text{ell}}\) ellipsoid with the vertical distance \(R_{\text{obs}}\) along with the error correction and the bias in equation 5

\[
SSH = H_{\text{ell}} - R_{\text{obs}} - c_{\text{ion}} - c_{\text{tw}} - c_{\text{td}} - c_{\text{ins}} - c_{\text{SSB}} - c_{\text{ot}} - c_{\text{lt}} - c_{\text{set}} - c_{\text{pt}} - c_{\text{ib}}
\]

2.2. Radar Altimeter Database System (RADS) and strategy of altimetry data processing

Radar Altimeter Database System (RADS) where carried out in here for data retrieval and reduction as the archiving and processing system initiative by TU-Delft, NOAA and Altimetrics LLC [6] [8]. This system was re installed in ITB at 2016 in the frame of ITB-UTM-DEOS collaboration as the continuation the 2005 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 altimetry data base are consist of all radar altimetry mission data in the timeline from 1992 until early 2017 that portrayed in Figure 2 and RADS system layout is in Figure 3 below:

![Figure 2. Timeline of modern radar altimetry mission [5] [6]](image-url)
Strategy for altimetry data processing in here are by merging all choices satellite altimeter missions using collinear track to normal reference point and every footprint is calculated before interpolated for nearby points in radius 5 km surrounding cross over points (Figure 4) that modified from [7],[8] and [9]. The value are calculated on daily solution and collected per month to get monthly solution.

Table 1 is summary of corrections and models that applied at RADS for this research, in which specific models are used for correcting each satellite altimetry missions in RADS and an updated geophysical and environmental corrections were also applied. The sea level data have been corrected from error and bias as mention before.

Table 1. Corrections and models applied for altimeter processing in RADS

| Correction / Model       | Description                                                      |
|--------------------------|------------------------------------------------------------------|
| Orbit/Gravity Field      | EIGEN GL04C                                                      |
| Dry Troposphere          | Atmospheric pressure grids; ECMWF (Model)                        |
| Wet Troposphere          | All satellites                                                   |
| Ionosphere               | NIC08                                                            |
| Inverse Barometer        | IB (Model, Local Pressure)                                       |
| Dynamic atmosphere       | All satellites: MOG2D                                             |
| Solid Earth Tide         | Applied (Elastic response to tidal potential)                    |
| Ocean Tide               | GOT4.8                                                           |
| Load Tide                | GOT4.8                                                           |
3. Results and Discussion
The research coverage area is between -15S/90E to 15N/150E with 110 points of observation are chosen nearby the crossover position between satellite altimetry tracks in Figure 5, with Topex/Poseidon, Jason-1 and Jason-2 data from 1992-2017.

![Figure 5. Altimetry tracks and point distribution](image)

The next step is to calculate MSSH at all points of observation as shown in Figure 6.

![Figure 6. Indonesian MSSH from 1992-2017](image)
The observed pattern is that in the western part of Indonesia it is worth -40 meters which rises gradually eastward to the highest value close to 80 meters for the northern region of Papua. For the central part of Indonesia the value ranges from 30 meters to 60 meters, where there is a significant increase of 70 meters for the northern part of Sulawesi which is interspersed with a lower MSSH gap of 50 meters in Halmahera double subduction area and rises again next to east after the Halmahera archipelago.

To get a clearer picture of the phenomenon of MSSH, we use the geo-undulation value of GGM EGM-2008 using 2 degree types, i.e. full wavelength n = 2190 and long wavelength n = 180 and calculate the SST value for both types of wavelengths used. Figure 7 shows a cross-section at latitude 0° that passes through various islands in the study area and at latitude -10° over more open oceans. These latitudes are selected to obtain a clear picture of the effect of land crossing the altimetry satellite path. The disconnected line for MSSH and SST indicates that the data passes through the land area, whereas the GGM undulation data does not experience a data gap as it passes through the mainland. For both cross sections, it is apparent that the MSSH value has a value that is not significantly different from the geoid undulation value of both full wavelength and long wavelength types with a maximum value of 5 meters, where this deviation appears in the transition region between the sea-land. For SST both for full wavelength and long wavelength types are seen to have a pattern that is close to the difference in GGM geoid undulation values of both wavelength types. This shows the effect of the dominant local effect (high frequency/short wavelength local phenomenon). Visible deviation of GGM difference model can reach 10 meters, especially for narrow/closed seawater area.

**Figure 7.** MSSH, SST and GGM EGM-2008 (n = 2190 and n = 180)
The next step is to know the SLA for all observation points, with sample stations in Figure 8 representing 110 observation stations. The point of 037 South China Sea representing the western part of western Indonesia has a positive linear trend of 4.99 mm/year, while for the southern latitude 065 point (Indian Ocean) also shows a linear trend of 4.38 mm/yr. For the eastern part of Indonesia the northern latitude is represented by the 055 (North Pacific Ocean) point which has a positive linear trend of 5.49 mm/year and the point 089 (Arafura Sea) in southern latitude with a linear trend value of 5.78 mm/year. In general, the Indonesian territory experienced a rising sea level trend represented by a positive SLA with variations in each region.

SLAs for all observation stations can be seen in Figure 9 and the SLA range (difference between maximum and minimum SLA values in the same station) in figure 10.
Indonesia’s territory as a whole has a positive trend value of about 2.5 mm/year in the west (station: 076 and 094) and eastward increments with gradually increased values up to 7 mm/year in the northern region of the Pacific Ocean. The highest SLA is located in this section (station: 025, 026, 027 and 028) which is the open sea area. For shallow sea or closed sea areas, the SLA value changes are relatively small, this is probably due to the quality of altimetry data coverage is not as good for open sea areas, where much noise is still present in the data. Phenomenon SLA can also be seen from the range in figure 10, the average for all regions with data hose from 1992-2016 is seen on average around 50-75 cm, except for southern Java (station 084) and western part of Sumatra (station 067) with a value of 90 cm and a higher value reaching above 100 cm between Papua-Australia (stations: 075, 090, 091, 107 and 108). This anomaly happens due to the effect of the land being cut off by the narrow and not too deep so it affects the altimetry data when reflected back to the satellite.

4. Conclusion
In this study, we can recognize that the long term MSSH in Indonesia area have increase from western part of Indonesia to eastern part with range -40 m to 80 m. This MSSH majority pattern have almost same pattern with geoid undulation from GGM with full degree n = 2190 and degree n =180, except for the transition area between land and sea. The long term SST in Indonesia have almost same trend with the deviation from geoid undulation full degree with short wavelength type, and this phenomena represent the local effect such as shallow bathymetry and close sea. And for long term SLA, Indonesia shows positive value that the anomaly increasing with variable from western part to eastern part of Indonesia from 2.5 mm/year until 7 mm/yr. The range between the highest and the lowest SLA in each station shows an 50-75cm in average for Indonesia. Several SLA - anomaly range happened in close sea and shallow sea. The long term MSSH, SST and SLA in Indonesia shows variability that indicate not only the geographical variation but also the other oceanography phenomena, that still need more investigation to get better understanding the causes and impacts of SLA.

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