Studying Dynamic Ocean Topography in Indonesia Sea Based on Satellite Altimetry

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Abstract. Dynamic Ocean Topography is a part of sea surface variabilities derived from Sea Surface Topography as a time-dependent component. The Dynamic Ocean Topography height in this study was determined using the geodetic method of instantaneous sea level height measurement from satellite altimetry technology. In the territory of Indonesia seas, a picture of the long-wavelength phenomenon from the Dynamic Ocean Topography ranges from 0-2.5 meters with three distribution zones of low, medium, and high value. At the same time, the correlation with the positive value of Steric Sea Level Rise was obtained in almost all parts of Indonesia except for the area in the southern part of Java Island around Longitude 1070E and in the Pacific Ocean region, where that is thought to be caused by the existence of several permanent marine high-frequency physical phenomenon but with an indefinite period which usually acts as a dominant time-independent component of the Sea Surface Topography. The results are expected to be used to study the characteristics of the Indonesian seas for scientific and engineering purposes.

Keywords: DOT, SLA, Steric SLR, Altimetry, Indonesia

1. Introduction
Indonesia is an archipelagic region that has extraordinary natural resources, in this case, especially in the ocean area, which requires further studies to optimize its benefits and preserve the environment. Optimum utilization of natural resources and efforts to mitigate the impact of disaster factors on water areas are now crucial. To achieve those goals, it is necessary to study various things related to the sea. Here, we study the sea surface variability in the territory of Indonesia by a geodetic method using satellite altimetry technology that measures the instantaneous sea level height relative to the ellipsoid reference surface. From the vertical distance or height measurements between the satellite position on the orbital trajectory and the instantaneous sea water surface level, we can obtain the Sea Surface Height (SSH). Since the ellipsoid surface is a geometric reference surface, we need to convert it into a geoid physical reference surface with geoid undulation to get Sea Surface Topography (SST) as physical height, which can then be used to study the physical properties of the ocean.
The SST value, which represents almost all seawater motion phenomena, is described into Dynamic Ocean Topography (DOT) as a time-dependent component (e.g., caused by current, wind, wave, and tidal) and Dynamic Topography (D.T.) as a time-independent component [1] [2]. Until now, there has been no research that explicitly discusses DOT in the territory of Indonesia. The DOT value can be obtained using SST information derived from the SSH value by assuming that the D.T. value is minimal compared to the DOT value to be ignored [3] [4]. The DOT value is then compared with the Steric Sea Level Rise (Steric SLR) value from each observation position. Steric sea level is the variation of the ocean volume due to density changes (expansion and contraction of water masses) through ocean salinity (allosteric) and ocean temperature (thermostatic) variations [5]. The steric SLR value here is derived from the Sea Level Anomaly (SLA) value at each observation position from [6] [7] as a subtraction result between SSH and its mean value (Mean Sea Surface Height/ MSSH). Using altimetry satellite data from Jason 1-2, Topex Poseidon, Envisat, and GFO-1 from 1992 to 2018 in this research, we hope to get long-wavelength patterns (minimum 18.6 years) of DOT and Steric SLR as one of the components of sea-level variability in Indonesia.

2. Method and Data

Various literature has described the method of determining the instantaneous sea level, geometric height relative, to the geometric ellipsoid surface using satellite altimetry technology [8][9]. Since the first altimetry satellite series was launched in 1972, it has more than 3 decades of altimetry data that can be used to study sea level. Several institutions organize various altimetry satellite databases; one of the databases used in this study is the RADS Data Center from T.U. Delft [9] consist of several altimetry data processing strategies [10] [11] [12]. This study uses satellite data from Jason 1-2, Topex Poseidon, Envisat, and GFO-1 [figure 1] with consideration of the long duration of data coverage and good spatial coverage for Indonesia territory, so that long-term patterns of Indonesian sea surface cycles are expected to be detected, through data interpolation per radius 5 km and the same strategy as [7] [13] for the entire Indonesian sea area.

![Figure 1. Satellite Altimetry and data sets period for 1992-2018](image)

The DOT studied in this study is one of the components that make up SST (instantaneous sea level height concerning the physical geoid surface) influenced by time. DOT is a superposition phenomenon due to sea waves, tides, the influence of wind, and atmosphere pressure loading [1]. The components that make up SST that are not affected by time are referred to as D.T. The relationship between the two components can be seen in equation (1)

\[ SST(\varphi, \lambda, t) = DOT(\varphi, \lambda, t) + DT(\varphi, \lambda) \]
In this case, the value of the D.T. component is minimal compared to the DOT component, considering that the nature of the D.T. component is sourced from permanent phenomena with unclear periods or scarce high frequencies, thus the value of D.T. can be ignored from equation (1), and we get equation 2

\[ SST(\varphi, \lambda, t) \approx DOT(\varphi, \lambda, t) \]  

(2)

Furthermore, the SST value (sea level height relative to geoid surface, which describes the physical ocean phenomenon) is obtained by reducing the SSH height obtained from altimetry satellite measurements with the geoid undulation value from the global gravitation model at the same position (equation 3).

\[ SST(\varphi, \lambda, t) = SSH(\varphi, \lambda, t) - N(\varphi, \lambda) = (h(\varphi, \lambda, t) - R(\varphi, \lambda, t)) - N(\varphi, \lambda) \]  

(3)

SSH is the ellipsoidal instantaneous sea level height obtained from subtracting the satellite geodetic height relative to the ellipsoid surface with the altimeter measurement range R, N being the geoid undulation (height difference between the ellipsoid and geoid surface), \( \varphi \) is Longitude (degrees), \( \lambda \) is Latitude (degrees) and \( t \) is the observation time (figure 2). The mean value of SSH in a specific time duration is expressed by Mean Sea Surface Height (MSSH), while the mean value of SST is referred to as Mean Dynamic Topography (MDT) which describes global ocean circulation patterns and ocean currents [2].

![Figure 2. Basic Principle of Satellite Altimetry, Sea Surface, Geoid and Ellipsoid](image)

The next step is SLA determination as a deviation between SSH with MSSH, which can be obtained using equation 4 as follow

\[ SLA(\lambda, \varphi) = SSH(\lambda, \varphi) - MSSH(\lambda, \varphi) \]  

(4)

Here the Steric SLR value is then determined from the linear trend of SLA at each observation point.

3. Result and Discussion

In order to study the characteristic correlation between DOT and Steric SLR in Indonesia, in here altimetry satellite data with spatial and temporal optimum coverage for the research area is used in the region -15°S / 90°E to 15°N / 15°E. The altimetry data used here are Jason 1-2, Topex Poseidon, Envisat, and GFO-1 from 1992 to 2018. The selection of these data available in the RADS database system is
based on the duration of the data that has reached more than 2 decades and can be overlapping each other in the determination of Indonesia territory SSH. MSSH determination resulting from collinear adjustments, corrected SSH value, and assimilation of altimetry satellites Jason-1, Topex, Poseidon, GFO-1, and Envisat have a fairly good value with an accuracy of 2.17 cm (MSSH-DTU10) and 3.17 cm (MSSH-CNESCLS13), although it is still not optimal in shallow waters and coastal areas due to noise data. The SLA value is obtained from the SSH reduction (obtained from altimetry satellite measurements) from 1992 through 2018 with the MSSH value, as shown in figure 3. The SLA rate in spatiotemporal variations in the Indonesian region is higher than the global SLA rate of 3.2 mm/year, which ranges from 3.4 mm/year to 5.3 mm/year [7].

Figure 3. Sea Level Anomaly Linear Trend 1992-2018

To determine the SST value, the geoid N undulation value is then needed, since until nowadays in Indonesia have not yet accurate geoid model based on marine gravity data, so in this study, the EGM-2008 global gravity model was used by applying the 360’spherical harmonic degrees to accommodate long-wavelength oceans signals. By eliminating the D.T. value, whose value is minimal compared to the dominance of the DOT value, the SST value will be almost similar to the actual DOT value in the field as described in equation (2) with the results shown in figure 4. The filtering process produces a DOT model that is closer to the global model, for about 0.0166 and 0.0705 meters for the largest sigma radius used (~ 150 km). The application of a smaller sigma radius (~80 km) based on bathymetric conditions, will give smaller residues with in-situ data and increase the RMS value with the global DOT model (0.0225 and 0.0745 meters).

DOT in this study was analyzed monthly from January to December from 1992 to 2018 and had variations from 0 meters to 2.5 meters. In January, low DOT values ranging from 0 – 1.0 meters were seen in almost all Indian Ocean and the Pacific Ocean at Latitude 10°N from the Philippines to the east. Medium DOT variations with a range of 1.0 – 1.25 meters are seen in the southern region of Bali Island to Timor Island, southern of Banda Sea, south of the Java Sea, and the Pacific Ocean at latitude 0° in northern Papua. High DOT values above 1.25 meters are seen in the Karimata Strait from the northern part of the Riau Islands to the Thai Gulf, where the DOT pattern has decreased again close to 0 meters to the north. High DOT values are also seen in the Pacific Ocean north of latitude 12°N, in the Makassar Strait (between Sulawesi Island and Kalimantan Island), which continues eastward around Bone Bay to the east to Ambon and in the southern region of Papua in the Longitude 138°E -142°E. There are several high DOT values around the west coast of Sumatra Island at Latitude around -5°S and at the southern coast of Java around Longitude 109°E. From February to April, the DOT pattern generally changes throughout Indonesia. Low DOT values between 0-1.0 meters are still seen to dominate the Indian Ocean
region, increasing DOT to a medium value ranging from 1.0-1.25 meters can be seen around Longitude 110°E (at the western part of January middle DOT position in the south of Bali). Those phenomena show that the DOT value increase to the west lasted from January to April for this region.

![Dynamic Ocean Topography - JANUARY](image1)
![Dynamic Ocean Topography - APRIL](image2)
![Dynamic Ocean Topography - JULY](image3)
![Dynamic Ocean Topography - OCTOBER](image4)

Figure 4. Dynamic Ocean Topography 1992-2018

Low DOT values are also still seen in the Pacific Ocean at latitude 10°N, and similarly to the Indian Ocean region, there is an increase in DOT value starting at 1400E Longitude to the east in this zone. In the Pacific Ocean region, at Latitude 12°N to 0°, there is also a broader increase in DOT, reaching a high range of DOT values. The opposite phenomenon happened in the Karimata Strait, in the northern part of the Riau Islands to the southern part of the Thai Gulf; the DOT value decreased to a variation between high and medium values. Meanwhile, in the South China Sea area at the northern Kalimantan Island, there is a flow pattern of increasing DOT to the north and a DOT decreasing value in the northern coast of the Kalimantan Island. High DOT values are still visible in the Makassar Strait (between Sulawesi Island and Kalimantan Island), which are currently interspersed with low DOT values in Tomini Bay and on the coast of the south-west tip of Kalimantan. The high DOT value extends from Bone Bay to the south to reach Bali and West Nusa Tenggara islands and extends from the Halmahera region to the Banda Sea. For the southern region of Papua in the Longitude 138°E to -142°E there is a sharp decrease in DOT close to 0 meters. Some high DOT values are still visible around the west coast of Sumatra at Latitude around -5°S and around the southern coast of Java around Longitude 109°E.

From April to July to October, there is another change in the DOT pattern. Low DOT values between 0-1.0 meters still seem to dominate the Indian Ocean region, but there are increasing DOT values to a
medium level starting at longitude 95°E and high level around longitude 105°E to 120°E. This shows that the increasing DOT value to the west has continued since January for this region. The pattern of increasing DOT values continues to move westward to 90°E. Longitude in October, but high DOT values at Longitude 105°E - 120°E have decreased to a medium level this month. Furthermore, if we look back at the January pattern, there is a decrease in DOT value throughout October to December until it reaches the lowest DOT value in January. For the southern region of Papua, in the range of longitude 138°E - 142°E, there is a sharp decrease in DOT value close to 0 meters for the entire region in July and is seen starting to increase until reach a medium level in October. The DOT pattern in this region increased again from October to January to a high DOT level above 1.25 meters.

For the Karimata Strait to the Thai Gulf region, the DOT value still decreased from high to medium in July and increased to a high level in October. Meanwhile, in the South China Sea area in the north of Kalimantan Island, the flow pattern of increasing DOT value is spreading throughout the region, and in October, the increase of DOT value reaches the same level as the Thai Gulf region. In this region, increasing DOT value is higher to the west towards the Thai Gulf and decreased in the eastern part of the South China Sea from October to January. For the Pacific Ocean region in Latitude 10°N, there is an increasing DOT value to a medium level from April to July and a decline from October to January to a low DOT level. In the Pacific Ocean region at latitude 12°N, there is an increasing DOT value to a high level and an expansion of the coverage area from April to July. In October, there was a decline in the DOT value, although it was still at a high level until January and the narrowing of its area coverage. The same pattern is also seen in this region at latitude 0°. For the Makassar Strait, southern Sulawesi, Halmahera, and the Banda Sea, there are decreasing DOT values from high levels continuously from April-July to October, and an increasing value again occurs in October to January. In general, the value of DOT in Indonesia territory has increased and decreased with a cyclical pattern depending on the zone's position and physical properties. For open sea zones, as is the case with the Indian Ocean and the Pacific Ocean, the pattern of increasing and decreasing of DOT value looks like a continuous cyclical flow, both temporally and spatially. As for other marine areas, although the cyclical flow pattern is visible, several random patterns require further research from the physical factors causing it.

To get a better picture of the correlation between DOT and the SLA value, in this case, is the Steric SLR, then the correlation between DOT value and Steric SLR value is described by extracted from the SLA value for each position shown in figure 3 using profiles along with Longitude 95°E, 107°E, 117°E and 130°E in figure 5. For the longitude 95°E profile, the Steric SLR value looks almost linearly increase from Latitude -10°S to 15°N from 2 mm/year to the highest value of around 5.5 mm/yr. This increasing linear value can be seen considering that the altimetry data obtained for this open area in the Indian Ocean provides minimal noise at the SSH value determination. Steric SLR values in the Longitude 107°E and 117°E profiles are more volatile considering these two altimetry satellite routes pass through various islands. In the longitude 107°E profile, the value of the SLR steric increase in ranges from 3 mm/year to 4 mm/year from the south (Indian Ocean) to the north (south coast of Java Island), then the pattern becomes irregular because it passes through the mainland of Java Island and the shallow Java Sea to the Riau Islands. The steric SLR pattern began to appear again when entering the South China Sea, which experienced a downward trend from south to north, from 4.5 mm/year to 3 mm/year. A similar pattern can be seen in the longitude 117°E profile; the SLR steric value tends to decrease from 5 mm/year to 4 mm/year from the south (Indian Ocean) to the north (south coast of West Nusa Tenggara), then the pattern becomes irregular because it passes through the land of West Nusa Tenggara, the Bali Sea, and Kalimantan Island. The Steric SLR pattern is again seen to experience a slight increase to the north in the range of 4 mm/year to 4.7 mm/year for the North Sula Sea region. For the longitude 130°E profile, since it through mainland Australia, the Steric SLR pattern has only been seen clear at the Latitude -10°S to the north, which has increased for the Banda Sea area from 4 mm/year in the southern part to 6 mm/year in the northern part. The Steric SLR value was again not detected when passing through Papua, and the pattern was seen again from Latitude 2°N to the north, which experienced an increase in the Steric SLR value ranging from 5 mm/year to 6 mm/year, and decreased to 3 mm/year since latitude 12°N up to Latitude 15°N.
In January, the DOT value for the Longitude 95\(^{0}\)E profile showed a positive correlation with the increasing value of the Steric SLR (2.0 – 5.5 mm/year), which DOT value also increased from 0.8 meters to 1.1 meters. In general, a positive correlation pattern is also shown in April (0.8 – 1.1 meters), July (0.9 – 1.15 meters), and October (0.85 – 1.15 meters), with the slightest difference from the DOT value that happened in July. The DOT value pattern at longitude 107\(^{0}\)E profile has a negative correlation for the southern part of Java Island where the SLR Steric value has increased from 3 mm/year to 4 mm/year; that is, in January, the DOT value has decreased slightly from 1 meter to 0.9 meters, further from 1.05
meters to 0.9 meters in April, from 1.1 meters to 0.8 meters in July and from 1.05 meters to 0.8 meters in October. This negative correlation is due to a marine high-frequency physical phenomenon in the area, considering that the zone is an open ocean area. For the southern region of Java Island, there are various marine physical phenomena, including the South Java Current and South Equatorial Current, which are estimated to be D.T. components that may cause this negative correlation. At this same longitude profile, the DOT value pattern shows a positive correlation in the South China Sea region, the DOT value pattern in January experienced a decreasing value from the southern part to the northern part (from 1.4 meters to 1.2 meters), which is consistent with a decreasing Steric SLR value for 4.5 mm/year to 3 mm/year. On the same longitude profile, for April, there was a decrease in the DOT value from 1.2 meters to 1.1 meters, for July although there was a stable value in the range of 1.1 meters, there was a decrease in the DOT value which was in line with the decreasing value of Steric SLR in April at Latitude 5°N to the north, i.e., from 1.15 meters to 0.9 meters. In October, there is a slight difference in this longitude profile, i.e., the stability of the DOT value with a slightly fluctuating value ranging from 1.2 to 1.3 meters while the Steric SLR has decreased. The DOT value pattern at Longitude 117°E shows a positive correlation with the decreasing of Steric SLR value for the southern part of West Nusa Tenggara, where the DOT value decreased from 1.1 meters to 1 meter in January and April, from 1.2 meters to 0.9 meters in April to July and from 1.1 meters to 0.9 meters in October. In this profile for the North Sula Sea area, the DOT value pattern provides a varied correlation value with the increasing value of the Steric SLR. In January, this longitude profile had a negative correlation; there was a decrease in the DOT value from 1.2 meters to 1.1 meters. While in April – July – October, this longitude profile has a positive correlation, namely the increase in DOT values from 6.5 meters to 7 meters in April, from 1.15 meters to 1.25 meters in July, and from 1.1 meters to 1.2 meters in October. For the Banda Sea area, the DOT value pattern at Longitude 1300E profile shows a positive correlation with the increasing value in Steric SLR, i.e., the DOT increasing value pattern in January-April-July-October from 1 meter to 1.1 meters. Meanwhile, for the Pacific Ocean region, all DOT values from January-April-July-October increase from 0.9 meters to 1.3 meters that showed a negative correlation with the decreasing value of Steric SLR. This negative correlation may also cause by various marine high-frequency physical phenomena that act as the dominant component of the time-independent SST constituent variables such as La Nina and El Nino phenomena in this area.

4. Conclusion
The SSH and MSSH value obtained from altimetry satellite measurement results and using information from the EGM2008 global gravity model makes it possible to derive the SST value that describes the pattern of ocean dynamics. MSSH determination resulting from collinear adjustments, corrected SSH value, and assimilation of several altimetry satellites have a fairly good value with an accuracy of 2.17 cm (MSSH-DTU10) and 3.17 cm (MSSH-CNESCLS13), although it is still not optimal in shallow waters and coastal areas due to noise data. One of the constituent variables of SST, which has a time-dependent nature, is DOT. The DOT value is then used to study the phenomenon of ocean dynamics for scientific and engineering purposes and mitigate socio-economic hazards. The filtering process produces a DOT model that is closer to the global model, for about 0.0166 and 0.0705 meters for the largest sigma radius used (~ 150 km). The application of a smaller sigma radius (~80 km) based on bathymetric conditions, will give smaller residues with in-situ data and increase the RMS value with the global DOT model (0.0225 and 0.0745 meters). The results of the 1992-2018 altimetry satellite measurements monthly DOT values were obtained for all parts of Indonesia, which are generally divided into 3 main parts, namely areas with low DOT between 0 - 1.0 meters for the Indian Ocean open sea area in western Indonesia, then areas with high DOT above 1.25 meters, namely in the South China Sea, Karimata Strait and northern part of the Pacific Ocean. Meanwhile, other areas of Indonesia sea areas are fluctuating zones that move in the range of low DOT, medium DOT to high DOT, i.e., from 0 to 2.5 meters.
To get better figures of the correlation between DOT and the SLA value, in this case, the Steric SLR, each position at Indonesia sea is described by both correlations. The positive correlation between the DOT value and the Steric SLR value is obtained in almost all parts of Indonesia except in the southern
part of Java Island for the nearby Longitude $107^\circ$E profile and in the Pacific Ocean region, where this is thought to be caused by the existence of marine high-frequency physical phenomena that are permanent but with an uncertain period, which usually acts as the dominant component of the time-independent SST constituent variables, namely D.T. For the southern region of Java Island, there are various marine physical phenomena, including the South Java Current and South Equatorial Current, while for the Pacific Ocean region, there are La Nina and El Nino phenomena, which are estimated to be D.T. components that cause this negative correlation considering the two zones are open sea area.

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