An assessment of a coastal altimetry data product in the Indonesian Waters

Jonson Lumban-Gaol1*, Danu Adrian1, Stefano Vignudelli2, Robert. R. Leben3, I Wayan Nurjaya1, Takahiro Osawa4, Parluhutan Manurung5, Risti Endriani Arhatin1

1Department of Marine Science and Technology, Faculty of Fisheries and Marine Science, Bogor Agricultural University, Indonesia.
2Consiglio Nazionale delle Ricerche, Istituto di Biofisica, Area Ricerca CNR San Cataldo, 56127 Pisa, Italy.
3Colorado Center for Astrodynamics Research, Colorado University, Boulder, CO 80309-0431, USA.
4Center for Remote Sensing and Ocean Sciences, Jalan Jenderal Sudirman, Udayana University, Bali Indonesia.
5The Indonesian Geospatial Information Agency (BIG), JalanRaya Jakarta - Bogor Km 46, Cibinong 16911, Indonesia.
*e-mail: jonson_lumbangaol@yahoo.com

Abstract. We analyzed the percentage of valid coastal altimetry Jason-2 X-TRACK-SLA data by Center for Topographic Studies in Sea and Hydrosphere (CTOH) and the waveforms from the Sensor Geophysical Data Record (SDGR) that are distributed by NOAA National Ocean Data Center around the Indonesian waters. In general, the percentage of valid data after the first point of the shoreline is greater than 90%. The percentage of valid data in steeper waters (86%) is higher than sloping waters (34%). The waveform types formed in coastal waters are peaky and Brown. However, spatially there is a difference where in a steep coast at a distance of > 5 km from the coastline the type of waveform is identified Brown, while on the sloping coast the brown type is found at a distance > 10 km. The SLA time series indicate seasonal variations in which the SLA is negative during the Southeast Monsoon (May-October) and positive during Northwest Monsoon (November-April).

1. Introduction
Indonesia is an archipelagic nation consisting of nearly 14,000 islands with a total coastline length exceeding 90 thousand kilometers. The Indonesian coastal and deep seas area highly dynamic environment with many physical processes, such as Indonesian Throughflow [1], equatorial origin Rossby and Kelvin waves [2;3], seasonal upwelling [4;5], sea level rise (SLR) and their variability [6]. Altimetry satellite data can be used for this related study; however, as it has been mentioned before, monitoring coastal waters circulation with altimetry is still a challenging issue because of the numerous constraints [7].

Global SLR is one of the impacts of global climate change and causes inundation of many small islands and coastal area in Indonesia. The scientific research indicates that global sea levels have been rising at a rate of 3.5 millimeters per year since the early 1990s, and the rate of increase varies considerably in different locations. As sea level is expected to rise further in the future (0.5 to 1 meter by 2100 and possibly more) [8]. The Sea level rise trend in South East Asia Seas including Indonesia
Sea level change has been estimated from tide gauge measurements, collected over the last century. Recently, approximately 100 units of tide gauges were installed in Indonesia. This amount is certainly not adequate to cover the length of the Indonesian coastline of about 90,000 km. Thus, it is really required to have sea level information that is complete and accurate both spatially and temporally to collect data of sea level. To monitor the dynamics of sea level along the coastlines will be needed more than 400 units of tide gauges. The satellite altimeter data can be used as a complementary tool for covering the lack of sea-level data from tide gauge in Indonesian coastal waters.

Traditionally, sea level change has been estimated from tide gauge measurements, collected over the last century. Recently, approximately 100 units of tide gauges were installed in Indonesia. This amount is certainly not adequate to cover the length of the Indonesian coastline of about 90,000 km. Thus, it is really required to have sea level information that is complete and accurate both spatially and temporally to collect data of sea level. To monitor the dynamics of sea level along the coastlines will be needed more than 400 units of tide gauges. The satellite altimeter data can be used as a complementary tool for covering the lack of sea-level data from tide gauge in Indonesian coastal waters.

Sea level measurement by satellite altimetry has been done since the early 1990s: ERS-1, Topex/Poseidon, ERS-2 GFO Jason-1 and ENVISAT, Jason-2, etc. Radar altimetry has been developed to monitor the sea level with high accuracy. However, despite the many satellite instruments showing some ability to measure sea level, it is still hard to provide accurate altimeter-derived measurement of sea level in the coastal area.

Most altimetry datasets are designed for the deep oceans because land contaminates the return signal of the altimeter. To resolve these issues, there was an effort in the last decade to improve the processing using a set of techniques (e.g., re-tracking, new corrections). One example is the coastal datasets that were corrected regionally through the use of X-TRACK, which is developed by Center for Topographic Studies in the Sea and Hydrosphere (CTOH). Before utilizing the dataset widely, it is necessary to assess the potential of this CTOH data, especially in the Indonesian coastal waters. This study attempts to analyze the potential altimetry Jason-2 data along the coast of Indonesian waters.

2. Methods

2.1. Coastal Altimetry Data

In this study we used the along-track (X-TRACK) satellite altimeter data product, developed by CTOH (http://ctoh.legos.obs-mip.fr/products/coastal-products/), and Sensor Geophysical Data Record (SDGR) that are distributed by NOAA National Ocean Data Center (https://podaac.jpl.nasa.gov/dataset/OSTM_L2_SGDR_D).

SLA projected onto reference tracks with a spatial interval of about 6-7 km between points (1 second) are computed using the X-TRACK software, developed at LEGOS France. The CTOH computes regional along-track sea level anomaly (SLA) products for altimeter Jason-2 missions from 2008-2013. We used Jason-2 data along-track (1 Hz) of Indonesian coastal tracks (figure 1). Sea level data were derived from level 2 of GRD in NetCDF format.
Figure 1. Jason-2 satellite altimetry of track of 2008-2013 in Indonesian waters. The red lines are ascending pass and black lines are descending pass.

2.2. Sea Surface Height (SSH) measurement

Satellite observations of sea surface height are available along the ground-tracks of Jason-2 satellite altimetry missions. Measurement of SSH was performed with various corrections in order to obtain actual distances between a satellite and sea level, as the following [17]:

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

where \((R_{cor})\) is the corrected range, \((R_{obs}) = \frac{ct}{2}\) is the computed range from travel time \(t\) observed and \(c\) is the speed of the radar pulse neglecting refraction.

Altimeters measure the distance between the sea surface and the satellite. The height, \(h\), of the sea surface above references ellipsoid is given as:

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

where \(H\) is the height of the spacecraft determined through orbit determination. Atmospheric disturbances are corrected, among others: the effects of the ionosphere \((\Delta h_{iono})\), wet troposphere \((\Delta h_{wet})\), dry troposphere \((\Delta h_{dry})\), the bias condition of the sea \((\Delta h_{ssb})\), tidal correction value \((h_{tides})\), and dynamic atmospheric corrected value \((h_{atm})\). The actual sea surface height is a superposition of these geophysical signals and the dynamic sea surface height, \(h_{D}\) such that [10]:

$$SSH(h) = h_{D} + h_{geoid} + h_{tides} + h_{atm}$$

The sea surface high anomaly \((h_{sla})\) determined as:

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

2.3. Data processing and analysis

The altimeter satellites were originally designed to observe offshore waters so that the raw data produced around the coast was very limited in both quality and quantity. Therefore, various studies have been conducted to improve the quality and quantity of altimeter data around the coast. One of
them is the Altimeter-Based Investigations in Corsica, Capraia and Contiguous Areas (ALBICOCCA) research project in the Northwest Mediterranean Sea. Through this project developed Additional developments lead to the X-TRAC tool. With this tool, new classical GDR processing is done to produce coastal altimeter data [19].

The approach is to use more detailed models for responding to the high frequency of tidal and atmospheric responses, reducing satellite orbit errors and increasing mean sea surface resolution. The application of x-track tool is expected to improve the quality of altimeter products i.e.: SSH, MSSH, SLA in coastal areas [19]. A more complete explanation of data processing and analysis can be found in the User Handbook of CTOH Along-Track Sea Level Anomalies regional products (X-TRACK).

3. Results and discussion

3.1. Potential coastal altimeter data

Figure 2 shows the percentage of along-track available valid data from the Jason-2 missions 2008 - 2013 period in Indonesian coastal waters and adjacent seas. The along-track valid data indicate that the availability are greater than 90%, except one near shore points from the coastal line. The average percentage of valid data on the first footprint from the coastline in shallow water such as the Java Sea (34%) is lower than the coastal in the deep sea (86%) such as the eastern Indian Ocean (figure 2b).

Generally, the percentage of data availability of the X-TRACK-SLA product after the first point from the coastline is greater than 90%. However, the percentage of valid data in deep waters is higher than in coastal waters (figure 2c). The results of this study are consistent with those shown in the Northwestern Mediterranean Sea, the X-TRACK-SLA data significantly increase the number of valid data [18]. The altimeter satellite data around the coast is usually low quality due to land contamination of the satellite footprints, the high frequency ocean response to tidal and atmospheric loading [19].

3.2. Types of waveform

The radar altimeter waveforms provide the range between the satellite and the surface at nadir via two-way travel time of the transmitted pulse, the Significant Wave Height (SWH) via the slope of the waveform leading edge, and the backscattering coefficients which represent the surface roughness and characteristics via the returned power [20]. Figure 3 shows the Jason-2 track 246 waveforms at a distance of 0-5 km, 5-10, and 50-100 km from the southern coast of Java Island.
Figure 2. Top: (a) percentage of data availability for along-tracks data from the Jason-2 missions. Bottom: (b) the blue circles highlight region where the percentage of availability data in coastal shallow waters and the red circles highlight region the coastal deep waters, and (c) Comparison of the percentage of valid data in shallow water coastal (the Java Sea) and deep coastal waters (the eastern Indian Ocean off Southern Java) calculated from the first point up to 100 km from coast line.

The waveform formed near the coast (0-5 km) on track 246 is a peaky type (figure 3a) and more than 10 km is Brown type. Waveform near the coast is strongly influenced by the noise generated by terrestrial and shallow waters [19]. The ideal waveform is the Brown waveform generally formed in the open seas far away from the main land. An average 94% Brown waveform type can be found at a distance of more than 15 km from the shore [21]. However Waveform in the southern coast of Java island at a distance of 5-10 km from the coast is a Brown type (figure 4b). Meanwhile the waveform types in the same distance in the north coast of Java island is peaky (figure 4a) [22], where the depth is shallow with an average depth of 30 meters [23].
The bathymetry in southern coast of Java Island shows that the depth of coastal waters at a distance of 5 km and more from the coast > 500 m. The south coast of Java Island is also directly related to the Indian Ocean so that the water characteristics near the coast it is classified as an deep sea. The ideal Brown waveform type is generally formed in the high seas (figure 4b) [24]. The other factors that may affect signals received by satellite sensors and affect the waveforms are the depth and shape of the water surface, coastal environmental conditions, atmospheric aerosols, buildings (e.g., lighthouses or vessels), and others [25].

Figure 3. Types of Waveform Jason-2 track 242 of cycle 104.

Figure 4. Types of waveform at a distance of 5-10 Km from the coast (a) North coast of Java Island (shallow waters) [21] and (b) South coast of Java Island (deep waters).
3.3. Mean Sea Surface Height (MSSH)
The MSSH is substantially obtained by averaging all valid SSHs at each point along track. It accounts for geoid and Mean Dynamic Topography (MDT). MSSH is estimated at each of the altimeter Jason-2 foot points. Generally, the MSSH increases from offshore to coast. The MSSH in Indonesian waters is shown in figure 5. The MSSH located at each foot points covers in the Indonesian water ununiformly. And it indicates well-known patterns, such as the MSSH is much higher in eastern Indonesia water (western Pacific) than that in eastern Indian Ocean off of south Java.

The highest of MSSH is 80 cm occur in Eastern Indonesia waters off North Papua, and the lowest is -20 cm in Eastern Indian Ocean off Sumatera and Java. This sea-level difference leads to establish the Indonesian Throughflow from the Pacific to the Indian Ocean [24].

![Figure 5. Mean Sea Surface Height [in cm] along the track of Jason-2 missions (2008-2013).](image)

3.4. Sea-Level Anomaly (SLA)
Sea-level anomaly is the difference between the sea-level and the mean sea level for this time of year. For example, we analyzed the SLA time series on the Jason-2 track 064, and cycle-latitude plot (Hovmoller diagram) of SLA along selected track in the southern cost of Java Island (figure 6). The sea-level displays the number of months/cycles each year experiencing positive or negative anomalies. The SLA is negative during the Southeast Monsoon (SEM) period from June to October, meanwhile positive SLA occurs during the Northwest Monsoon (NWM) period from November to March. This seasonal change of SLA expresses a response of sea surface to reversal monsoon winds system. During the SEM period, the wind-driven Ekman transport in the southern cost of Java is toward offshore causing sea-level decreases. In contrary, during the NWM near the coastal area of southern Java Ekman transport toward the coast that pills up surface water near the coastal region.

The difference of sea-level between the SEM and NWM period in the southern of Java Island is approximately 80 cm. Generally during NWM period, monthly mean of sea-level height in Indonesian waters increases such as in south Java waters, Makassar Strait, and Banda Sea [5, 26-27]. The SLA changes in the southern cost of Java Island are strongly influenced by the monsoon winds in the Indonesian waters [28-29]. During the SEM period the easterly monsoon winds blow along southern coast of Java and produces Ekman transport toward offshore, which then generate coastal upwelling. This causes sea level to drop due to an offshore Ekman transport [4,5].
4. Conclusion
The altimetry data of X-TRACK-SLA from CTOH product in Indonesian coastal waters showed that more than 90% of recorded SLA data are valid for 5 years of the Jason-2 missions. In general, the percentage of valid data in steeper coastal waters is higher than the sloping coastal waters. It shows that coastal altimetry data are potential to be used for coastal dynamics and sea level variability studies in the Indonesian coastal waters. The type of waveform formed in Indonesian coastal waters is a type of peaky and Brown type. The waveform type in Indonesian coastal waters is not only affected by distance from a coast but also influenced by water depth. The variability of SLA anomaly in Indonesian coastal waters exhibits large seasonal change that is influenced by monsoon winds system. Negative SLA occurs during the SEM period, while positive SLA is during the NWM period.

Acknowledgments
I wish to extend my appreciation to the Directorate General of High Education and Research and Technology for the funding support with grant No. 1667/IT3.1/PN/2018, and IPB staff mobility program. Altimetry data used in this study were developed, validated, and distributed by the CTOH/LEGOS, France. Anonymous reviewers provided useful suggestions.

References
[1] Gordon A L, Susanto R D and Vranes K 2003 Cool Indonesian Throughflow as a consequence of restricted surface layer flow Nature 425(824)
[2] Meyers G, Bailey R J and Worby A P 1995 Geostrophic transport of Indonesian Throughflow Deep Sea Research Part I: Oceanographic Research Papers 1163-1174.
[3] Sprintall J, Gordon A L, Murtugudde R and Susanto R D 1997 A semiannual Indian Ocean forced Kelvin wave observed in the Indonesian seas in May Journal of Geophysical Research: Oceans 2000 105 17217-17230
[4] Wyrtki K 1962 The upwelling in the region between Java and Australia during the south-east monsoon Marine and Freshwater Research 217-25
[5] Susanto R D, Gordon A L and Zheng Q 2001 Upwelling along the coasts of Java and Sumatra and its relation to ENSO Geophysical Research Letters 28 599-1602
[6] Strassburg, M.W., Hamlington, B.D., Leben, R.R., Manurung, P., LumbanGaol, J., Nababan, B., Vignudelli, S. and Kim, K.Y. 2014. Sea level trends in South East Asian Seas (SEAS). Climate of the Past Discussions, 10:4129-4148.
[7] Roblou L, Lamouroux J, Bouffard J, Lyard, F, Le Hénaff M, Lombard A, Marsaleix P, De Mey, P and Birol F 2011 Post-processing altimeter data towards coastal applications and integration into coastal models In Coastal altimetry Springer Berlin Heidelberg pp 217-246
[8] Church J A W and N J W 2011 Sea-level rise from the late 19th to the early 21st century Surv. Geophys. 32(4-5) 585–602
[9] Wassmann R, Hien N X, Hoanh C T and Tuong T P 2004. Sea level rise affecting the Vietnamese Mekong Delta: water elevation in the flood season and implications for rice production Climatic Change 66(1-2) 89-107
[10] Förster H, Sterzel T, Pape C A, Moneo-Lain M, Niemeyer I, Boer R and Kropp J P 2011 Sea-level rise in Indonesia: on adaptation priorities in the agricultural sector Regional Environmental Change 11 893-904
[11] Saiy A R and Aziz Y 2009 Sea level rise in South Kalimantan, Indonesia: an economic analysis of adaptation strategies in agriculture EEPSEA, IDRC Regional Office for Southeast and East Asia, Singapore, SG
[12] Manurung, P, Leben, R R, Vignudelli S, and Lumban-Gaol J 2014 Reconstruction of sea level change in Southeast Asia waters using combined coastal sea level data and satellite altimetry data APN science bulletin: global environmental change 4 23-29
[13] Leben R R, George H B, and Benjamin R E 2002 Operational altimeter data processing for mesoscale monitoring Mar. Geod. 25 3-18
[14] Ablain M, Legeais J F, Prandi P, Marcos M, Fenoglio-Marc L, Dieng H B, Benveniste J and Cazenave A 2017 Satellite altimetry-based sea level at global and regional scales Surveys in Geophysics 38(1) 7-31
[15] Carton J A, and Chao Y 1999 Caribbean Sea eddies inferred from TOPEX/POSEIDON altimetry and a 1/6° Atlantic Oceanmodel simulation J.Geophys. Res. 104: 7743–7752.
[16] Andersen and Scharroo 2011 Range and geophysical correction in coastal region: and implication for mean sea surface determination Coastal Altimetry S Vignudelli et al Editor Springer Berlin
[17] Vignudelli, S Kostianoy A G, Cipollini P, and Benveniste J 2011 (Eds) Coastal Altimetry Springer Berlin/Heidelberg Germany
[18] Bouffard J, Roblou L, Birol F, Pascual A, Fenoglio-Marc L, Canet M, Morrow R and Menard Y 2011 Introduction and assessment of improved coastal altimetry strategies: case study over the Northwestern Mediterranean Sea In Coastal altimetry (297-330) Springer, Berlin, Heidelberg.
[19] Roblou L, Lyard F, Le Henaff M, and Maraldi C 2007 X-TRACK, a new processing tool for altimetry in coastal oceans Geoscience and Remote Sensing Symposium IGARSS 2007 IEEE International 5129-5133
[20] Lee H, Shum C K, Emery W, Calmant S, Deng X, Kuo C Y, Roessler C and Yi Y 2010 Validation of Jason-2 altimeter data by waveform retracking over California coastal ocean Marine Geodesy 33(S1) 304-316
[21] Deng X. 2004. Improvement of Geodetic Parameter Estimation in Coastal Regions from Satellite Radar Altimetry [thesis] Perth (AU) Curtin University of Technology
[22] Hakim M R, Nababan B and Panjaitan J P 2016 Accuracy improvement on sea surface height estimation based on waveform retracking analyses of Jason-2 satellite in Java Sea Jurnal Ilmu dan Teknologi Kelautan Tropis 7 771-790
[23] Ningsih N S, Yamashita T, and Aouf L 2000 Three-dimensional simulation of water circulation in the Java Sea: influence of wind waves on surface and bottom stresses Natural Hazards
[24] Deng X and Featherstone W E 2006 A coastal retracking system for satellite radar altimeter waveforms: application to ERS-2 around Australia *Journal of Geophysical Research: Oceans* 111(C6)

[25] Chelton D B, Ries J C, Haines B J, Fu L L and Callahan P S 2001 Satellite altimetry *International geophysics* 69

[26] Radjawane I M and Azminuddin F 2016 Seasonal and semi-annual variability of sea surface height in Makassar Strait *Journal of Physics: Conference Series* 739(1) p012067

[27] Gordon A L and Susanto R D 2001 Banda Sea surface-layer divergence *Ocean Dynamics* 52(1) p2-10

[28] Bray N A, Hautala S, Chong J and Pariwono J 1996 Largescale sea level, thermocline, and wind variations in the Indonesian Throughflow region *Journal of Geophysical Research: Oceans* 101(C5) 12239-12254

[29] Lumban-Gaol J, Leben R R, Vignudelli S, Mahapatra K, Okada Y, Nababan B, Mei-Ling M, Amri K, Arhatin R E, and Syahdan M 2015 Variability of satellite-derived sea surface height anomaly, and its relationship with Bigeye tuna (*Thunnus obesus*) catch in the Eastern Indian Ocean *European Journal of Remote Sensing* 48 465-477