Internal solitary waves propagation speed estimation in the northern-part of Lombok Strait observed by Sentinel-1 SAR and Himawari-8 images

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Abstract. Remotely sensed data, both Synthetic Aperture Radar (SAR) and optical sensors, significantly contribute to the study and understanding internal solitary wave (ISW) dynamics in the ocean. Pairs of SAR and optical sensors were analyzed to estimate the ISW propagation speed in the northern-part of Lombok Strait. ISW propagation speed estimation used an image from Sentinel-1 SAR and three image pairs of Himawari-8 on 29 October 2018 with a time difference of 409 minutes. Sentinel-1 wide-swath imagery (250 km x 400 km) from two adjacent scenes can provide information on multiple ISW packets evolution in the northern-part of Lombok Strait. ISW propagation speed estimation on Sentinel-1 SAR image using the simple estimation by measuring the interpacket distance and dividing by the semidiurnal tidal period. The high temporal resolution of the optical sensor from Himawari-8 can estimate the ISW propagation speed using two different approaches. ISW propagation speed estimation from Sentinel-1 and Himawari-8 showed almost similar values. Sentinel-1 estimation results are 2.69 m.s\(^{-1}\) (Lombok Strait) and 1.30 m.s\(^{-1}\) (northern-part area), Himawari-8 results are 2.52 m.s\(^{-1}\) (Lombok Strait) and 1.27 m.s\(^{-1}\) (northern-part area). ISW propagation speed variability in the northern-part of the Lombok Strait shown in this study.

Keywords: Himawari-8, internal solitary waves, Lombok Strait, propagation speed, Sentinel-1

1. Introduction
Lombok Strait, a famous place for the intensive internal solitary waves (ISW) generation observed by satellite images and the large wave-amplitude observed by in-situ data [1]. Intensive ISW generation in this strait is obtained from the combination of the strong tides and the water stratification over the irregular topography. Spectacular images of the ISW radar signatures and in-situ data over the Lombok Strait are shown [1]. Lombok Strait has an important role in the interocean water exchange over the Indonesian Seas, known as Indonesian Throughflow (ITF) [2]. The central and the northern-part of the strait has a deep channel with the depth up to 1400 m. The northern-part of the Lombok Strait has a unique characteristic on the bathymetry and the tides. Mixed tides with the predominantly diurnal cycle
are the tidal characteristic in the northern part of the Lombok Strait [3]. Lombok Strait ISW characterized by strong energy propagation and large amplitude [1]. They're always heading north and south away from the sill in the southern part of the strait, indicating that they're the result of interactions with the barotropic tide and the sill. Despite their power and evident scientific and social significance, little is understood about the waves' propagation near the crest area particularly in the transit area from the depth to the shallow water in the north near Kangean Island.

Remotely sensed data, both Synthetic Aperture Radar (SAR) and optical sensors, significantly contribute to the study and understanding of ISW dynamics in the ocean. SAR can detect slight changes that occur on rough sea surfaces in a range of wavelengths of several centimeters to decimeters [4], while the optical sensors can detect the ISW pattern in the sea surface using the near-specular reflectance pattern sun-glint areas [5]. SAR is the most commonly used instrument for monitoring ISW from space. It operates all weather, day and night operation and a wide range of up to 250 km. At the same time, the optical sensors for the sun-glint imagery provide the ISW observation for the large areas monitoring with the high temporal resolution. The surface manifestation of ISW in the remote sensing data can estimate the critical ISW parameters such as wavelength, first crest length, soliton numbers, inter packet distances, direction and the propagation speed [6]. This study focuses on ISW propagation speeds estimation in the northern part of Lombok Strait using two different sensors from SAR (Sentinel-1) and optical (Himawari-8). Estimation of ISW propagation speed using SAR and optical satellite images in the Andaman Sea has been investigated [7], the study used two methods, Multiple Images Comparison (MIC) and Tidal Time Period (TTP), to estimate the ISW phase speed. Sentinel-1 and Himawari-8 are the best combinations for comprehensive analysis of ISW propagation speeds. SAR images are the standard tool for ISW observation that has been proven theoretically [8]. Himawari-8, with an optical sensor with an advantage of 10-minutes temporal resolution, is expected to be a more accurate comparison for the propagation speed estimation from SAR image.

Sentinel-1 is an advanced mission instrument C-band operation of the satellites European Remote Sensing (ERS) 1/2 that has a better temporal resolution than previous missions. Sentinel-1 observation of ISW in the Lombok Strait has been observed [9-10]. The high temporal resolution images from the geostationary satellite Himawari-8 with 10 minutes period were used to compare the ISW propagation speed estimation results from Sentinel-1 SAR image in the northern part of the Lombok Strait. This study aims to compare the ISW propagation speed estimation results between Sentinel-1 SAR images and Himawari-8 images.

2. Materials and Methods

2.1. Sentinel-1 SAR image

The Sentinel-1 mission that operates with C-bands imaging (wavelength 3.8 - 7.5 cm) has four imaging modes with different resolutions (reaching 5 m) and coverage (up to 400 km), provides dual polarization capability, improvement of the revisit times and rapid product delivery. Sentinel-1 provides more improvement from the previous mission of C-band SAR Earth Observation of ESA’s. Precise measurements of spacecraft position and attitude are available for each observation data. Sentinel-1 is a radar imaging mission that provides continuous weather imaging throughout the day, day and night that operates at a central frequency of 5.405 GHz and an angle of 200 - 450 [11].

This study used two scenes from Interferometric Wide swath mode to acquire data with a 250 km swath at 5 m by 20 m spatial resolution for a scene. Interferometric Wide mode records the target in three sub-swaths using Terrain Observation with Progressive Scans SAR (TOPSAR). This technique can produce homogeneous images throughout the swath. The swath range (Figure 1) is suitable for the ISW monitoring over the Lombok Strait areas. Sentinel-1 SAR Level-1 Ground Range Detected (GRD) images are collected from Alaska Satellite Facility (ASF) Website (https://search.asf.alaska.edu).
2.2. Himawari-8
Himawari-8, the latest generation satellite belonging to the Japanese Meteorological Agency (JMA), is equipped with more sophisticated optical sensors, with better radiometric, spectral, and spatial resolution, than other satellites in previous geostationary orbits. Himawari-8 with the principal payload, Advanced Himawari Imager (AHI), has 16 observation bands with a spatial resolution of 500 m or 1 km in the visible and near-infrared bands, respectively, and 2 km for the infrared band. The visible band at 640 nm is the band that provides the best ability (spatial resolution 500 m) as a tool for estimating the ISW propagation speeds in the Lombok Strait. Himawari-8 detects the ISW surface manifestation in the sun-glint area related to the Sun/sensor locations that move meridionally with the season, and this observation requires a relatively cloud-free scene. ISW parameters estimation using Himawari-8 has been shown in the previous studies [12-13]. Himawari-8, with a revisit time of 10 minutes, can estimate the ISW phase speed more realistically without the assumption of the tide. Pairs of Sentinel-1 SAR images and Himawari-8 provide a comprehensive analysis of ISW propagation speeds in the northern part of the Lombok Strait.

2.3. Data Analysis
The first method is using Sentinel-1 SAR images. Two scenes from a high-resolution GRD level-1 product were merged using the 'Mosaicking' menu in the Sentinel Application Platform (SNAP) software. Merging the two scenes aims to get a more broad study area. Sentinel-1 has two different scenes recorded with a time difference of almost a minute to be combined for two adjacent scenes. The advantage of using two scenes combinations makes it possible to observe ISW in the Lombok Strait further to determine the propagation speed variations. After mosaicking (Figure 2(a)), the propagation

Figure 1. Map of the study area. Yellow rectangles represent two scenes of the Interferometric Wide swath from the Sentinel-1 SAR images.
speed was estimated by dividing the inter-packet distance (Figure 2(b)) with the semidiurnal tidal period in the study area.

![Figure 2](image)

**Figure 2.** (a) Sentinel-1 SAR image from mosaicking two scene result in the Lombok Strait areas acquired 29 October 2018. (b) Extracted ISW first crest pattern from the Sentinel-1 image (red lines) overlapping with the bathymetric relief in the northern part of Lombok Strait. The red marked ‘A’ – ‘C’ represents the ISW packet ID for Table 1 references. Yellow lines are the inter-packet distance.

Himawari-8 can estimate the ISW propagation speeds by two methods, using semidiurnal tidal period and 10-minutes period. Three images from the Himawari-8 red band (640 nm) with a spatial resolution of 500 m and ISW detected were used to estimate the ISW propagation speed in the northern-part Lombok Strait (Figure 3).

![Figure 3](image)

**Figure 3.** Himawari-8/AHI red band (640 nm) images recorded on (a) 29 October 2018 12:40 WITA (local time), (b) 29 October 2018 12:50 WITA, and (c) 29 October 2018 13:00 WITA.
ISW propagation speed in Himawari-8 images was estimated using the semidiurnal tidal period by dividing the inter-packet distance in one image as in the Sentinel-1 image. The advanced technique from Himawari-8 is ISW propagation speed estimation using 10 minutes. This technique uses the overlay of three ISW first crest feature extractions which is then calculated by dividing the inter-crest distances and the travel time (Figure 4(a)). The last method uses pairs of Sentinel-1 and Himawari-8 images with a time difference of 409 minutes, known as Multiple Image Comparison (MIC) [7]. This technique uses the overlay of the ISW first crest feature extractions from Sentinel-1 and Himawari-8, which is then calculated by dividing the inter-crest distances and the time difference (Figure 4(b)).

Figure 4. (a) Extracted ISW first crest pattern from the Himawari-8 images (blue lines) overlapping with the bathymetric relief in the northern part of Lombok Strait. (b) Pairs of extracted ISW patterns from Sentinel-1 and Himawari-8. The red marked ‘A’ – ‘C’ represents the ISW packet ID for Table 1 references. Yellow lines are the inter-packet distance.

3. Results and Discussion

Lombok Strait, one of the ITF out-flow in the southern-part of the Indonesian seas, connected the Makassar Strait to the Indian Ocean directly and separates the islands of Bali and Lombok. This strait is characterized by the strong currents that combined with the rough topography in the sill area (southern-part of the strait) cause this strait famous by intensive internal-wave generation. The northern-part of the Lombok Strait has a unique characteristic on the bathymetry and the tides. The northern-part of the strait has a deep channel with the depth up to 1400 m. The tidal characteristic in the northern-part of the Lombok Strait are mixed tides with the predominantly diurnal cycle [3].

The support of the Sentinel-1 SAR data availability that can reach areas in the Lombok Strait, the analysis area is widened to the northern part of the Lombok Strait through Kangean Island. This study focuses on the Lombok strait area and the northern-part of the strait (6° – 10°S and 115° – 117.5°E) to determine the ISW propagation speed evolution after propagating through the bathymetric variations in the northern part of the strait.

The estimated ISW propagation speeds in the northern-part Lombok Strait using different methods are given in Table 1 with the water depths range where the ISW packet was detected. The northern-part Lombok Strait has a complex bathymetry that increases approximately 1400 m in the strait area near the Kangean Island that decreases approximately 500 – 400 m. ISW propagation speed using Sentinel-1 is
2.69 m.s\(^{-1}\) (A to B) in the Lombok Strait and 1.30 m.s\(^{-1}\) (B to C) in the northern part of the strait (near Kangean Island). Himawari-8 estimation result is 2.52 m.s\(^{-1}\) (A to B) in the Lombok Strait and 1.27 m.s\(^{-1}\) (B to C) in the northern part of the strait using the tidal period estimation. The ISW propagation speed estimation using 10 minutes period is 2.78 m.s\(^{-1}\) (A) in the Lombok Strait and 1.85 m.s\(^{-1}\) (B and C) in the northern part of the strait. ISW propagation speed estimation using the semidiurnal tidal period from Sentinel-1 and Himawari-8 showed almost similar values. However, the result shows decreasing ISW propagation speed when the ISW propagates in the shallow water in the northern part of the strait. This decrease in ISW propagation speed is also confirmed by the estimation results using 10 minutes period. Estimation result using MIC methods using pairs of Sentinel-1 and Himawari-8 feature extraction shows the difference in the propagation speed value in packet A. The ISW propagation speed estimation using MIC methods is 1.98 m.s\(^{-1}\) (A) in the Lombok Strait, 1.55 m.s\(^{-1}\) (B), and 1.57 m.s\(^{-1}\) (C) in the northern part of the strait. ISW propagation speed estimation results from this study are consistent with the previous investigation result in the Lombok Strait areas [1, 14-16].

Table 1. ISW propagation speeds estimation measured at different locations from two different satellite sensors.

| Satellite sensor | Date and Time (local time) | ISW packets ID | Depth Range (m) | Propagation Speed (m.s\(^{-1}\)) |
|------------------|---------------------------|----------------|----------------|----------------------------------|
| Sentinel-1       | 29 Oct 2018 05:52         | A              | 700 - 1400     | Tidal estimation: 2.69           |
| Sentinel-1       | 29 Oct 2018 05:53         | B              | 1000-500       | 10-mins periods: 2.69            |
| Sentinel-1       |                           | C              | 400            | Pairs: 1.30                      |
| Himawari-8       | 29 Oct 2018 12:40         | A              | 1400           | Tidal estimation: 2.78           |
| Himawari-8       | 29 Oct 2018 12:50         | B              | 500-400        | 10-mins periods: 2.52            |
| Himawari-8       | 29 Oct 2018 13:00         | C              | 400            | Pairs: 1.85, 1.55, 1.57          |

Standard deviation of the three methods used in this study was 0.44 for the ISW packet (A) in the Lombok Strait and 0.33 for the ISW packets (B and C) in the northern part of the Lombok Strait. The standard deviation results indicate that the ISW propagation speed estimation results in this study are considered stable with a constant pattern of estimation results and no other influencing factors. Standard deviation is used to determine the distortion of the three methods results used in this study, because the comparison of estimates using these three methods was first analyzed in the Lombok Strait. Previous research only used SAR data that could not reach the Kangean island area, whereas there was a change in bathymetry that occurred in the northern part of the Lombok Strait.

4. Conclusion
ISW propagation speed estimation using the semidiurnal tidal period from Sentinel-1 and Himawari-8 showed almost similar values. However, the result shows decreasing ISW propagation speed when the ISW propagates in the shallow water in the northern part of the strait. This decrease in ISW propagation speed is also confirmed by the estimation results using 10 minutes period. Estimation result using MIC methods using pairs of Sentinel-1 and Himawari-8 feature extraction shows the difference in the propagation speed value in packet A and confirms the decreasing propagation speeds in the northern part of the strait.

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