Sea-level variations from co-located tide gauge and GNSS stations using GNSS-Reflectometry in Indonesia

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Abstract. Sea level variation is an important key for hazard mitigation in the coastal region to study climate change. In the last decade, reflected GNSS signals have been used in many applications, such as snow, sea level, and ocean storm monitoring. In this research, we use GNSS-Reflectometry co-located with a tide gauge station to monitor sea-level variations. We use the Signal Noise to Ratio (SNR) data to derive sea-level height from GNSS. One-month comparison of sea-level variations has been made from a tide gauge and a GNSS measurement in Barus, North Sumatra Indonesia. The results have a mean bias of about 2 cm with a root mean square error of 11 cm and a correlation coefficient value of 0.90. Our result demonstrates that the GNSS-Reflectometry technique is potential to provide a new approach to monitor sea-level changes that complement the existing tide-gauge networks in Indonesia.

1. Introduction

The sea-level height and its variation are playing a central role to study climate change. In the last century, sea-level observations have been measured primarily with tide gauge sensors [1] such as pressure, radar, floating bubble. These methods resulted in measurement relative to a benchmark on the land or Earth’s crust [2] and resulted in sea-level height and its variation which were affected by both sea-level and land surface changes since the measurements are related to a benchmark on the land as a reference. The land surface change can be measured using Global Navigation Satellite Systems (GNSS) [3, 2]. Sea-level height in the global reference frame such as the International Terrestrial Reference Frame (ITRF) can be derived by combining the GNSS and tide gauge observations [4, 5].

The use of reflected GNSS signal for remote sensing of the ocean has been introduced by Martin-Neira [6]. The Global Navigation Satellite System-Interferometric Reflectometry (GNSS-IR) technique in this study called GNSS-Reflectometry is a technique to monitor in situ sea-level using reflected GNSS signal from the geodetic GNSS instrument and provides continuous weather-independent sea-level information and vertical land motions [7]. This reflected GNSS signal is recorded in the receiver as a signal-to-noise ratio (SNR). The vertical distance from the water surface as reflected medium can be estimated by analyzing the frequency of SNR data. The water levels from SNR data have been demonstrated by many researchers [8-11] and the accuracy results are comparable to traditional tide gauges. The analysis of SNR data has been applied in several applications such as tsunami and hurricane [12], detecting storm surge [13], sea-level monitoring [7-10], quantification of shallow sediment compaction [14], measuring snow accumulation [15], a study in permafrost area [16, 17], etc.
In this research, we examined a one-month data set from a co-located tide gauge and GNSS station in Barus Harbour, North Sumatra Indonesia (Figure 1). We investigated the potential capability of GNSS data to monitor sea-level change to complement the existing tide-gauge networks in Indonesia.

Figure 1. The location of co-located tide gauge and GNSS station in the southern part of North Sumatera, Indonesia facing Indian Ocean.

2. Data and method
This study used the tide gauge data from Barus tide gauge station as a part of the Indonesian sea-level monitoring system (http://ina-sealevelmonitoring.big.go.id) [18] and GNSS data from CBRS station as a part of the Indonesian Continuously Operating Reference System (Ina-CORS). The GNSS station is installed on the top of the tide gauge station (Figure 2). We used a one-month tide gauge and GNSS data in December 2020. The interval of observations was 1 minute and 30 seconds for tide gauge and GNSS data, respectively. We match both time series in the time variable and calculate the different biases using equation 1.

\[
\Delta SL = SL_G - SL_{TG}
\]  

which \(\Delta SL\) is a different bias, \(SL_G\) is sea-level from GNSS, and \(SL_{TG}\) is sea-level from TG.

Figure 2. Pictures showing the condition of Barus tide gauge station and GNSS monument [19].
Figure 3. The schematic diagram of height in GNSS-Reflectometry. TGR is tide gauge reference height. SLH is sea level height. RH is reflector height. Robs is observation from radar sensor. h R is radar sensor height with respect to TGR. h_G is GNSS station height with respect to TGR.

Figure 4. The reflection zone of Barus TG with the elevation 5 -15 (https://gnss-reflections.org/rzones)[20].

Figure 3 shows the schematic diagram of how to calculate sea-level height from GNSS-Reflectometry. Reflector height was estimated based on the gnssrfl python code from online repository of Larson [21]. First, information about the reflector zone from the TG location was required. We used a reflector zone code from https://gnss-reflections.org/rzones [20]. Figure 4 shows the reflection zone for Barus TG. The result of the reflection zone of Barus TG shows a good reflection zone area. The reflected GNSS signals can be achieved from four quadrants.

3. Result and discussions
In this section, we discussed the main results of our comparison of the two sea-level systems at Barus Harbour. The first analysis is sea-level estimation from TG and GNSS and the second is a comparison of the two sea-level results. The comparison plot of sea-level height from the two systems shows in Figure 5. The solid black line is sea-level from the TG system and the colored circles are estimated result of sea-level from each GNSS signal frequency. Over the whole of one month, we obtained 3655 individual GNSS water level estimates.
Figure 5 One-month sea-level height from tide gauge and GNSS-reflectrometry. Solid black line is tide gauge observation, colored circles are estimate sea-level from each GNSS signal frequency, G for GPS, R for GLONASS and E for Galileo.

Within 3665 observation data, we obtained the mean different bias was about 0.02 m with the standard deviation was 0.11 m (Figure 6a). The standard deviation of the different biases is similar to the results obtained by Larson [9]. Larson used 10 years data for this comparison. Comparing to the standard deviation with two conventional tide gauges, which can be achieved until sub-centimeter [22], our standard deviation result was much larger. However, the coefficient correlation between GNSS and TG sea levels was 0.90. This value indicated that the GNSS sea-level was very close to the in situ sea-level from tide-gauge station. The histogram of bias difference is shown in Figure 6 b.

Figure 6. Scatter plots of TG and GNSS sea level. (a): Comparison of sea-level height as measured by tide gauge and GNSS; colored circles are the estimation of sea-level from each GNSS signal frequency; G for GPS, R for GLONASS and E for Galileo. (b) Histogram of sea-level bias was calculated using GNSS – TG; vertical red line is the mean bias, and vertical black lines are 95% confidence level.

4. Conclusion
In this research, the sea-level from GNSS data and TG station have been investigated from one-month observation data. The result shows that GNSS sea-level had a good agreement with the TG sea-level,
with mean bias difference was about 0.02 m [-0.11, 0.11] and the coefficient correlation was 0.90. This result indicated that the GNSS sea-level is the potential to provide a new approach to monitor sea-level changes to complement the existing tide-gauge networks in Indonesia and used to support the climate change research with the longest GNSS data.

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