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Research article

Assessment of Low-Cost Tide Gauges to Meet GLOSS 1-cm Precision and Accuracy Standards: A Case Study in Pramuka Island, Indonesia

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Abstract

The expansion of the tide gauge network along the coast is essential for better monitoring of sea-level dynamics. Owing to climate change, the urgency has been exacerbated, especially during the last two decades. However, densification remains a challenging task because of the lack of affordability of the sensor, especially in the Global South. Further, the precision and accuracy requirements of 1-cm imposed by the Global Sea Level Observing System (GLOSS) is too restrictive, particularly for low-cost tide gauge sensors. Here, we evaluated the performance of a low-cost DIY tide gauge in meeting these standards. Three sets of sea level observations from IR-TIDES, a DIY tide gauge sensor observed in 2016 and 2018, were subjected to a performance test in terms of precision and accuracy in comparison with a global tide model and two neighbouring established tide gauges. All three datasets were estimated to have an 8-cm standard deviation as a metric for the precision level. In terms of accuracy, the IR-TIDES datasets had a standard deviation of 25 cm and a correlation coefficient of 0.616. Overall, IR-TIDES demonstrated sufficient precision while still lacking accuracy, partially meeting the GLOSS quality standard. These findings could strengthen the confidence level of a low-cost DIY tide gauge, especially for use as a backup and redundant sensor for an established tide gauge station after addressing the limitations.

Keywords: tide gauges; sea level observation; quality control; van de Casteele test.

1. Introduction

A tide is a periodic dynamical movement of the sea surface, influenced by the Sun–Earth and Moon–Earth systems of gravitational attraction, according to Newtonian Law. This movement is expressed as a wave with an amplitude and phase (De Lavergne *et al.*, 2019). The expression of tide as wave resulting in two differing tidal regimes (period of one high and one low tide) of 12.4 hours and 24.8 hours, a half and a full lunar day, respectively. Measuring tides is a well-known observation method dating back to the 18th century (Pytharouli *et al.*, 2018). Over the last half of the century, various methods for observing tides have been developed, including the use of tide poles, mechanical floaters, pressure sensors, acoustic sensors, and radar sensors (Adrianto *et al.*, 2019; Guaraglia & Pousa, 2014; Mehra *et al.*, 2009; Míguez *et al.*, 2005, 2012; Xu *et al.*, 2019). These advancements lead to a wide-range of application: in the topic of geodesy and hydrography (Tamisiea *et al.*, 2014; Wöppelmann *et al.*, 2006), climate change (Church & White, 2006; Fenoglio-Marc *et al.*, 2012; Nadzir *et al.*, 2022; Simons *et al.*, 2023; Wöppelmann & Marcos, 2016; Zerbini *et al.*, 2017), coastline changes (Cazenave & Nerem, 2004; Simarmata *et al.*, 2023; Toimil *et al.*, 2018), shipping safety monitoring (Menéndez & Woodworth, 2010), detecting tsunami occurrences after earthquake (M. A. Merrifield *et al.*, 2005; Satake *et al.*, 2013), and climate mode data assimilation (Becker *et al.*, 2016). Several prominent institutions have measured and predicted tidal coefficients from a ‘mature’ tide gauge station such as the National Oceanic and Atmospheric Administration (NOAA) and the National Ocean Service (NOS) of the USA (Agnew, 1986; Doodson, 1957).

Monitoring sea level is becoming increasingly important, and many measurement systems have near-real-time transmission capability that allow them to send, collect, and list the received sea level signals as a centralised tide gauge network. This allows for real-time monitoring of sea level changes across a wide area. Among the first ones was the Permanent Service for Mean Sea Level (PSMSL) (Woodworth, 1991), SHOM and RONIM project by France on early 1990s (Míguez *et al.*, 2008), the BODC initiative by the UK, Flanders Marine Institute-maintained VLIZ, and University of Hawai’i-led UHSLC data centre (Caldwell *et al.*, 2001). The Global Sea Level Observing System (GLOSS) was formed in 1985 by the Intergovernmental Oceanographic Commission (IOC) to coordinate, combine, and provide oversight of all these initiatives from various countries (IOC, 1990; Legler *et al.*, 2015; M. Merrifield *et al.*, 2009). Indonesia, as the biggest archipelagic country in the world, has intensified its effort to build and extend the tide gauge network in the republic during the last couple years (Schöne *et al.*, 2011). As of 2023, Indonesia has over 200 operational tide gauges, primarily focused on providing early warnings for tsunami. However, this focus leads to an imbalanced distribution across the archipelago, with a concentration in areas vulnerable to tsunamis, leaving other coastal regions with sparser data for sea level monitoring purpose (Nadzir *et al.*, 2023). However, the usage of Indonesian tide gauge network could be considered under-utilised, where a number of studies are limited onto a single number of tide gauge (Arifin *et al.*, 2021; Fitriana *et al.*, 2019, 2022; Ichsari *et al.*, 2020; Richasari *et al.*, 2019).

Despite continuous progress in tide gauge technology, a mixture of meteorological and astronomical factor with different mathematical natures (stochastic and deterministic, respectively) that constitute the tidal signal has made the minimization of error and bias in tide gauge record difficult to compute (Chelton & Enfield, 1986). Thus, their level of precision cannot be optimised, even with modern tide gauges. Additionally, a large proportion of global tide gauges have been found to be insufficiently accurate for sea-level studies because of limitations in their observation technology (Míguez *et al.*, 2022). One way to resolve this precision problem is by using the radar method, essentially multiplying the measurement frequency such that the stochastic error can be further cancelled out. Previous studies in Liverpool (Woodworth & Smith, 2003), Africa (Woodworth *et al.*, 2007) and France (Miguez *et al.*, 2008) have shown promising results for the incorporation of radar-based gauges to supplement older tide gauges. Other obstacles hindering the extension of global tide gauge networks include geography, budget, and manpower. The use of instrumentation at a considerably lower cost could be a solution, as demonstrated in the USA and Liverpool (Giardina *et al.*, 2000; Knight *et al.*, 2021).

To address the need for high-precision tide gauges in Indonesia, particularly in meeting the 1-cm GLOSS standard for sea level monitoring, this study evaluated the accuracy and precision level of a low-cost tide gauge instrument. To perform the test, we used an on-site check approach with Pulau Pramuka as the test site. The choice of Pulau Pramuka stems from the existence of mature tide gauges at neighbouring locations (Kolinlamil and Sunda Kelapa) as standard reference gauges. This experiment aimed to evaluate the precision and accuracy of a low-cost tide gauge (IR-TIDES) within the scope of the 1-cm requirement from GLOSS. Additionally, we aimed to elucidate the occurrence of systematic instrument errors in IR-TIDES under field conditions.

2. Data and Methods

A pier on the Pramuka Island in northern Jakarta was selected as the test site for this study. The pier is located at 5.745S and 106.612E, as shown in Figure 1 and is indicated by a red pin. This location was chosen for several reasons, including ease of access and minimal disturbance. Additionally, it was selected because of its proximity to existing operational tide gauge stations at Kolinlamil and Sunda Kelapa, which were used as reference stations for this study.

Figure 1. Pulau Pramuka test site.

The IR-TIDES instrument used in this study was developed by the authors in mid-2015, with a radar sensor as the main equipment used to measure the water level by reflecting a signal off the water surface and measuring the roundtrip travel time. Additionally, the instrument was equipped with GPRS-based telemetry to serve as a connection to the outside world. The default measurement setting of the IR-TIDES was to observe 20 consecutive data points every 5 min, which were chosen to balance the data resolution, battery life, and transmission load. Several other options can be chosen during the setup process. The output of IR-TIDES is a txt file with three columns: date (in DD/mm/YYYY format), water level in centimetres, and time in HH:MM:SS format in Western Indonesian Time (Waktu Indonesia Barat/WIB). On this research, three different datasets with different time interval and setting were used as listed in Table 1.

Table 1. Data from IR-TIDES used on this research.

Data Name	Data Timespan	Sampling Interval
PASUT	21 July 2016 – 29 August 2016	20 data every 5 min
GELOMBANG	05 August 2018 – 15 August 2018	1024 data every 30 min
PASUT PRAMUKA	01 August 2018 – 14 August 2018	20 data every 5 min

To assess the accuracy and precision of the low-cost tide gauge, we adapted and adjusted methodologies from previous studies (Míguez *et al.*, 2005; Woodworth & Smith, 2003). These processes involves several steps: i) Pre-processing: averaging process with simple mean and outlier detection using 3-sigma method, used as the first parameter of precision, ii) standard deviation approximation from the dataset calculated with Equation 1 to quantify the data's spread as the second parameter of precision; iii) normalisation (de-meaning) process and standard deviation (STD) and median absolute deviation (MAD) estimation (Passaro *et al.*, 2018) using Equation 2, comparing it against the reference gauges and a tidal model as an estimation of accuracy level; iv) visualisation between IR-Tides and reference tide gauges and a tidal model to help identify potential discrepancies and; v) scatterplot visualisation, otherwise known as van de Casteele inspection (Lennon, 1968; Miguez *et al.*, 2008), of the IR-TIDES against the reference gauges as well as linear regression computation to identify the existence of systematic error across the tidal range. A visual representation of this process is shown in Figure 2. To clarify, the precision used in this research is defined as how good the repeated measurements of one object are to each other, whereas accuracy refers to how well the measurements compare to one referenced 'true' value. The three reference datasets (mature tide gauges and the global tidal model) employed in this study are listed in Table 2.

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2} \tag{1}$$

$$MAD = \sigma\sqrt{2}erf^{-1}\frac{1}{2} \approx 0.67449\ from\ \sigma \tag{2}$$

Table 2. Reference Data used on this research.

Data_Name	Coordinate	Data Timespan	Source
TPXO9v4a	5.745S ; 106.612E	01 January 2016 – 31 December 2018	OSU
Kolinlamil	6.107S ; 106.883E	01 January 2016 – 31 December 2018	BIG
Sunda Kelapa	6.125S ; 106.810E	01 January 2016 – 31 December 2018	BIG

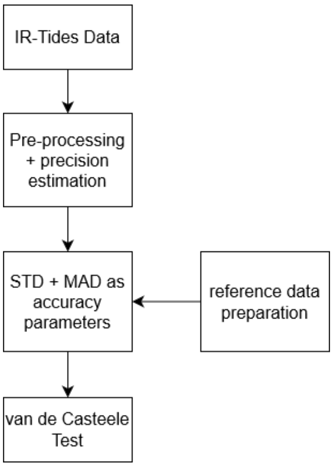

Figure 2. Workflow of the study.

The van de Casteele test indicated the occurrence of an offset at different elevations as an approximation of the systematic error of the tide gauge across the tidal range. In practice, it is visualised as a diagram, where the difference between IR-TIDES H' and reference tide gauge H ($\Delta H = H - H'$) is placed as the x-axis against the reference gauge as the y-axis (H). The use of the van de Casteele diagram was found to be beneficial for calibrating both the established gauge sensor and the DIY low-cost sensor (Miguez *et al.*, 2008). This step concludes the process, after which precision, accuracy, and systematic error are approximated.

3. Results and Discussion

3.1. Precision level of IR-TIDES

The results of preprocessing show that from the three datasets, less than 1% of the data are considered outliers, with 3-sigma as the threshold (Table 3). Meanwhile, 93.31% of the data were retained after 3-scaled MAD outlier search. This indicates that IR-TIDES has robust observation consistency and availability between the two different measurement settings. Additionally, a comparison of the two measurement frequency settings of IR-TIDES, as shown in Figure 3, revealed that while the second setting (1024 data every 30 min) has a larger number of outliers, it has a larger percentage of retained data.

Table 3. Number of retained data after pre-processing.

Data_Name	STD_Retained	MAD_Retained
PASUT	99.141%	90.157%
GELOMBANG	99.664%	98.666%
PASUT PRAMUKA	99.802%	91.113%

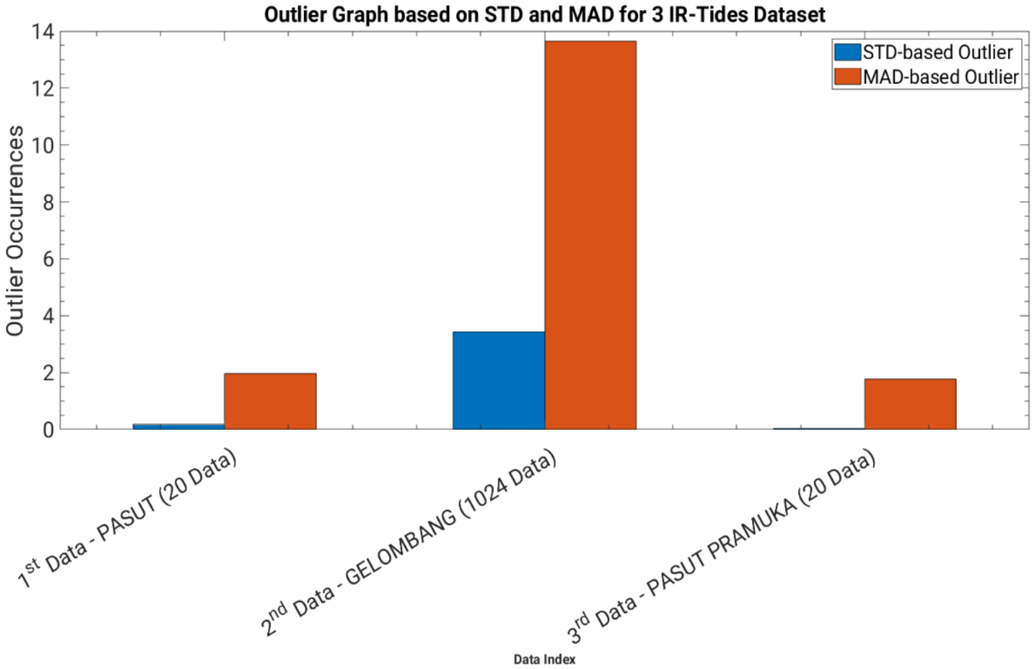

Figure 3. Number of outliers of three IR-TIDES datasets.

Based on Figure 4, which represents the standard deviation and median absolute deviation values of each IR-TIDES dataset, the PASUT (1st) dataset that spans 40 days has STD and MAD values four times larger (~ 8 cm) than those of the GELOMBANG (2nd) and PASUT PRAMUKA (3rd) datasets of ~ 2 cm. Our preliminary analysis indicates a potential relationship between the STD and MAD values and the length of the observation period. Further studies with shorter and longer timespans are required to confirm our results.

The 2- and 8-cm STD and MAD values from the three IR-TIDES datasets were better than the precision level of 12 cm of the Global Navigation Satellite System Interferometry Reflectometry (GNSS-IR) water-level retrieval method (Larson *et al.*, 2017). However, it is worse compared with the result of 1.06 cm from a comparison between two tide gauge in Liverpool (Woodworth & Smith, 2003) and a result of 0.87 cm between float and pressure gauge in Egypt (Salama *et al.*, 2019). IR-TIDES partially met the GLOSS requirement of a 1-cm precision level, at 1 cm lower than the threshold, while having a sufficient level of observation consistency.

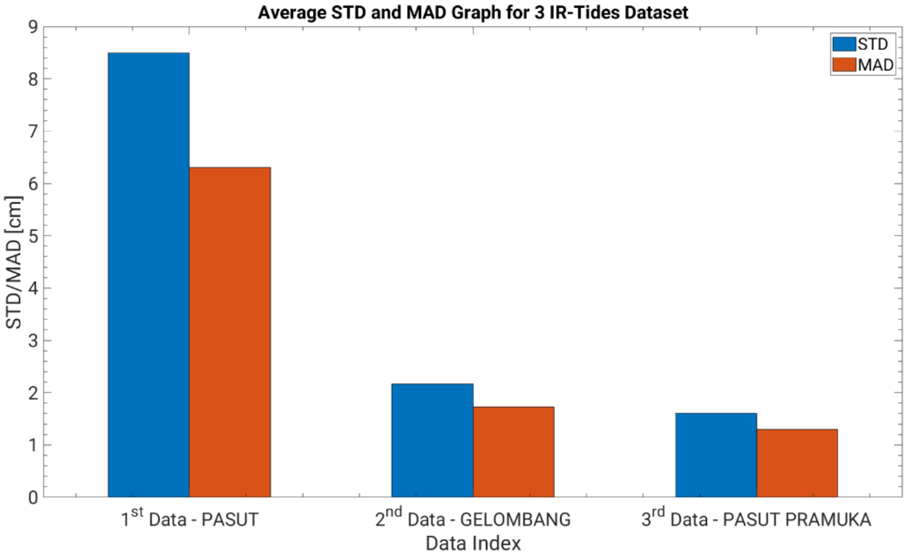

Figure 4. STD and MAD of three IR-TIDES datasets.

3.2. Accuracy level of IR-TIDES compared with reference datasets

The accuracy level of IR-TIDES was assessed by comparing it with the reference datasets. A comparison with the TPXO9v4a model as the 1st reference model, as indicated in Table 4 and Figure 5, showed a difference of approximately 30 cm in STD and an average difference of 20 cm. Table 4 also shows a comparison with the Sunda Kelapa and Kolinlamil tide gauge stations, which were slightly better than the TPXO9v4a results because of the lower STD and MAD values. This performance improvement can be attributed to the fact that tidal models are typically unable to resolve the long wavelength and secular parts of the tidal force (Míguez *et al.*, 2022). Additionally, the correlation coefficient estimation revealed that the IR-TIDES datasets showed medium agreement with the reference datasets. The IR-TIDES performances are marginally worse compared with those of different water level retrieval method, e.g., GNSS-IR with 11.6 cm and 6 cm STD (Larson *et al.*, 2017; Nadzir & Kusche, in preparation), another TG pairs of 3.3 cm STD (Pérez *et al.*, 2014), and altimetry of 15.8 cm STD (Nadzir & Kusche, in preparation).

Table 4. Number of retained data after pre-processing.

Data_Name	**STD_TPXO [cm]**	**MAD_TPXO [cm]**	**STD_KOLIN [cm]**	**MAD_KOLIN [cm]**	**STD_KLP [cm]**	**MAD_KLP [cm]**
PASUT	34.555	27.456	NaN	NaN	37.487	30.528
GELOMBANG	25.743	12.345	25.352	11.853	25.185	11.761
PASUT PRAMUKA	29.804	21.366	30.031	22.254	30.312	22.404

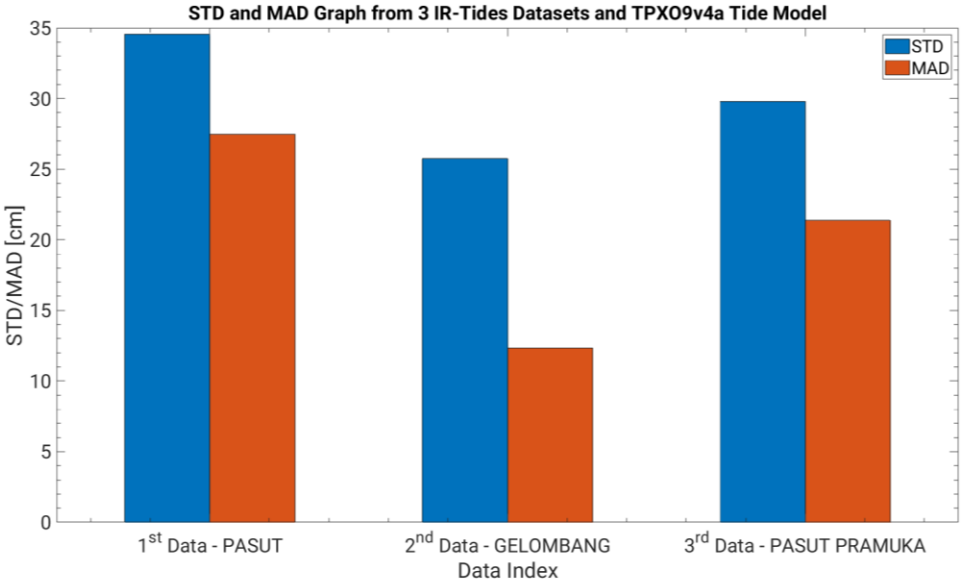

Figure 5. STD and MAD of three IR-TIDES datasets compared to TPXO9v4a.

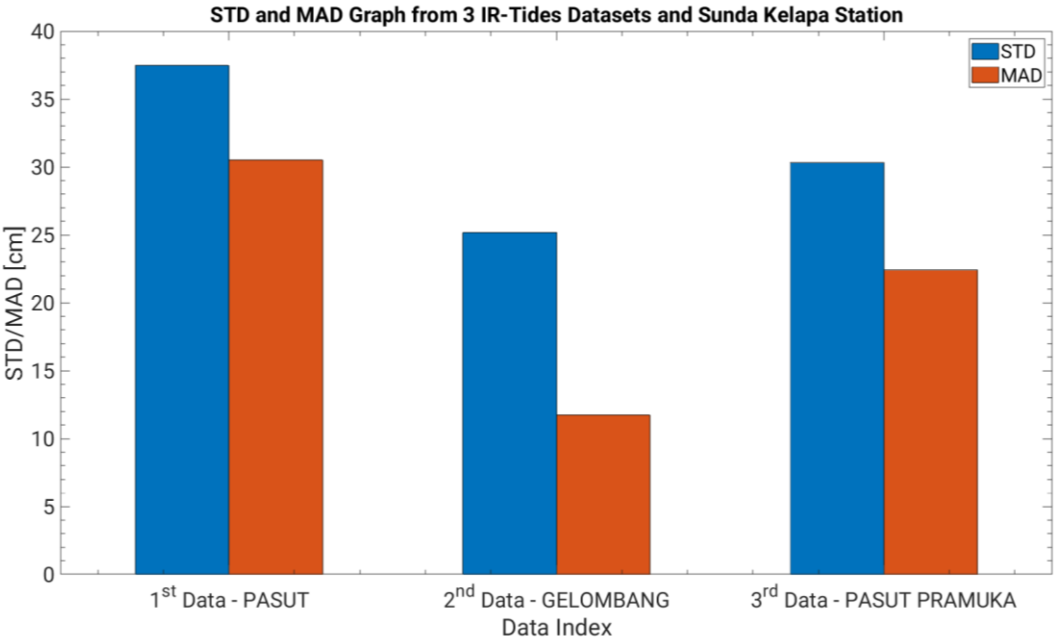

Figure 6. STD and MAD of three IR-TIDES datasets compared to Sunda Kelapa tide gauge.

In the case of the individual dataset accuracy level evaluation, it was found that the GELOMBANG dataset slightly edges the PASUT PRAMUKA dataset, as shown in Figure 6. This is similar to the precision level results, which indicate that the second measurement setting (1024 data points every 30 min) is more robust than the first setting. However, IR-TIDES falls short of fulfilling the GLOSS 1-cm requirement by a slight STD and MAD value. This finding indicates that a low-cost DIY tide sensor, albeit with consistent observations, must be developed to replicate the performance of conventional tide-gauge sensors (Fagundes *et al.*, 2021; Giardina *et al.*, 2000).

3.3. Time Series Visualisation and Van de Casteele Test

One of the main applications of tide gauges is near real-time tidal monitoring and observation. This necessitates the seamless and smooth operation of the tide gauge. IR-TIDES, shown in Figure 7 as a blue dot scatterplot, demonstrates good visual agreement compared with the reference datasets, in lieu of an apparent difference in the magnitude of the water level. This could be attributed to a lack of power, telemetry errors (Pytharouli *et al.*, 2018), and differences in location between observations that lead to different tidal phases between observation locations (Lase & Nadzir, on review). In contrast, the agreement between IR-TIDES and the reference datasets outlined the possibility of employing IR-TIDES as a redundancy at a more mature tide gauge station.

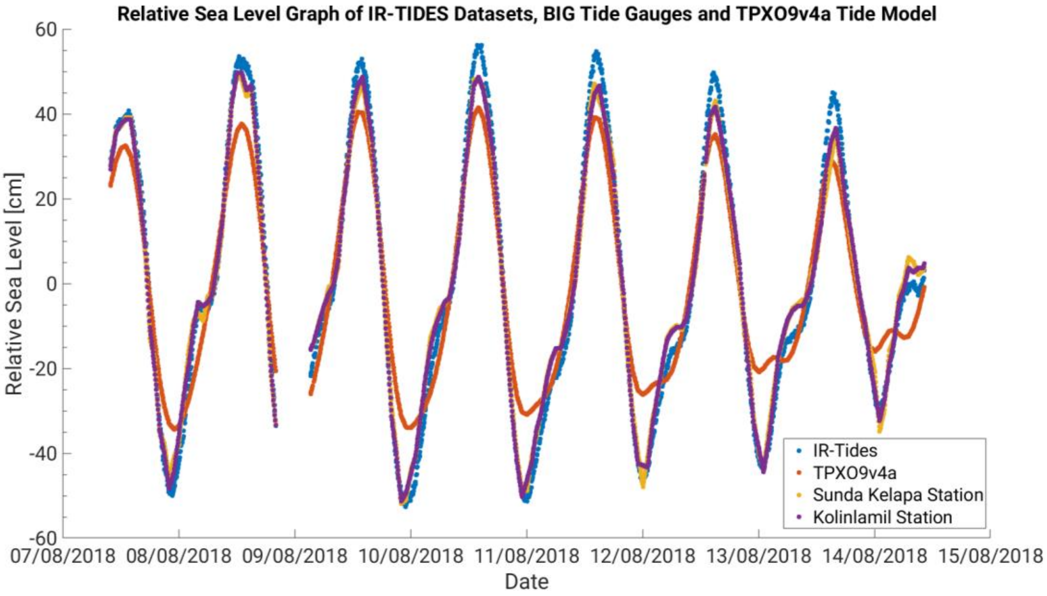

Figure 7. Time series between 3rd IR-Tides data with reference datasets.

The Van de Casteele test performed on the IR-TIDES datasets with both the Kolinlamil and Sunda Kelapa stations showed which type of error dominated the data. Figure 8 shows that the slope goes from left to right (from negative to positive values). This is evidence that the tide gauge in question observed the water level with differing minimum-to-maximum ranges, called scale errors (Miguez *et al.*, 2008). The magnitude of the scale error is proportional to the slope, as shown in Figure 9. Subsequently, the scale error could be used to correct the DIY tide gauge sensor as $H^* = H - \Delta s$. The computation and implementation of this scale-error correction could be further explored and refined for both the DIY low-cost tide gauge and different sea-level observation methods with the ultimate goal of precision-accuracy level improvement.

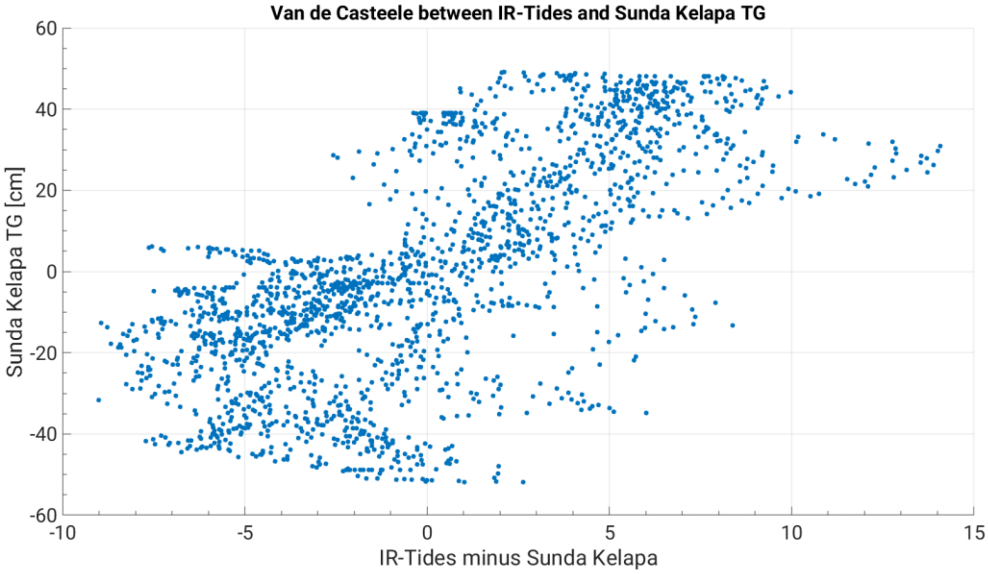

Figure 8. de Casteele test on Sunda Kelapa station.

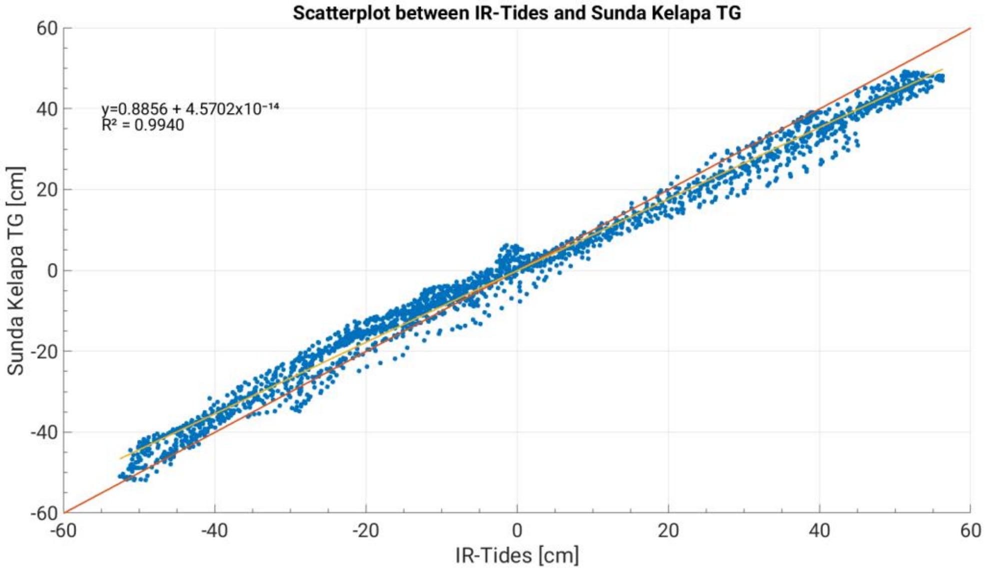

Figure 9. Scale error computation on Sunda Kelapa station.

The above results demonstrate that IR-Tides achieved a better data spread (precision level) than GNSS-IR, but its accuracy level falls short of the GLOSS- 1-cm standard. Nonetheless, it shows promise as a redundant sensor for operational tide-gauge stations. Further research and development to address these limitations would be beneficial for the densification of tide gauge stations with affordable sensors.

4. Conclusion

The advancement of low-cost and accurate tide gauges is fundamental for improving sea level monitoring, particularly in resource-limited regions. This study presents a DIY low-cost tide gauge called IR-TIDES that demonstrated robust observation consistency. While IR-TIDES offers promising performance in terms of data consistency as its precision parameter, its current accuracy level of sub-decimetre STD and MAD falls short of the GLOSS 1-cm requirement. Despite this limitation, IR-TIDES has the potential to be utilised as a redundant sensor (4th sensor) for mature tide gauge stations, especially after applying scale error correction using the de Casteele test. Further exploration of data acquisition systems is needed to improve the accuracy level of IR-TIDES or to investigate alternative designs that could fulfil the GLOSS standard.

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Author Contributions

Conceptualisation: Nadzir, Z.A, Adil, I.; **methodology**: Nadzir, Z.A, Adil, I; **investigation**: Nadzir, Z.A; **writing—original draft preparation**: Nadzir, Z.A; **writing—review and editing**: Nadzir, Z.A, Adil, I; **visualisation**: Nadzir, Z.A. All authors have read and agreed to the published version of the manuscript.

Conflict of interest

All authors declare that they have no conflicts of interest.

Data availability

Data is available upon Request.

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