An Evaluation of Low-Cost GNSS-R Technique for The Precise Measurement of Water-Level Fluctuations Utilizing a Height Displacement Tool

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Abstract

The problem of sea-level rise, mainly caused by global warming, requires ongoing and comprehensive monitoring through various observation methods. Satellite-based and ground-based surveying techniques are commonly used to monitor sea-level changes. The Global Navigation Satellite System (GNSS) serves as a valuable tool in this context. Besides providing accurate positioning data, GNSS supports both direct and indirect monitoring of environmental conditions through signal propagation in the atmosphere, which aids in modeling ionospheric and tropospheric dynamics. Moreover, analyzing multipath data—often considered as an error source—can reveal valuable insights into the surroundings of GNSS receivers. Recently, GNSS-Reflectometry (GNSS-R) has emerged, utilizing multipath effects to gather data on the Earth's surface's physical properties. This study compares the GNSS-R performance of both geodetic-grade and low-cost GNSS receivers by utilizing a ComNav SinoGNSS N2 as geodetic-grade receiver and antenna and a Septentrio Mosaic-x5 low-cost receiver with ArduSimple AS-ANT2B low-cost antenna, both established near above the pond located in ITU Ayazaga Campus. In order to simulate potential variations in water-levels, including tidal fluctuations, the elevations of the antennas were systematically adjusted using a height displacement tool. Subsequently, it was investigated whether the changes in the antenna height were detected by both the geodetic receiver and the low-cost receiver, and the GNSS-R antenna height determination performance of the low-cost receiver/antenna system was revealed. As a conclusion, the discrepancies in antenna height change measurements ranged from 1.4 cm to 3.7 cm for the geodetic receiver, and from 0.7 cm to 5.0 cm for the low-cost setup. Overall, the average height difference for the geodetic-grade receiver was 2.5 cm, while the average height difference for the low-cost receiver was 3.3 cm.

1. Introduction

The phenomenon of sea-level rises, predominantly attributed to global warming, necessitates ongoing and comprehensive monitoring efforts. Various methodologies exist for sea-level observation, including satellite-based and ground-based techniques. Among the former, satellite altimeter missions are recognized for their effectiveness, while ground-based approaches generally utilize tide-gauge stations to assess sea-level fluctuations. It is crucial to recognize that the impact of global warming extends beyond sea-level rise, influencing a multitude of related phenomena, including snow and ice thickness, soil moisture content, and atmospheric conditions within the troposphere. This interconnectedness allows researchers to extract valuable information regarding multiple environmental variables from a single geosensor established at any designated location. In this context, the Global Navigation Satellite System (GNSS) emerges as a effective technological framework. In addition to providing accurate position data, GNSS facilitates the indirect and direct acquisition of information pertaining to various environmental phenomena. Specifically, the propagation of GNSS signals through the atmosphere enables modeling of the ionospheric and tropospheric conditions. Furthermore, the analysis of multipath data —typically considered a significant source of error that reducing positioning accuracy— can also yield insights into the environmental characteristics surrounding the GNSS receiver. In the last decade, an advanced technique known as GNSS-Reflectometry (GNSS-R) has emerged, leveraging the multipath characteristics inherent in GNSS. This innovative approach enables the acquisition of data regarding the physical properties of the Earth's surface through comprehensive terrestrial and satellite-based observations.

The L-band ocean scatterometer concept based on multistatic principles was initially put forth by Hall and Cordey (1988). Subsequently, the idea of GNSS-based altimetry was first introduced by Martin-Neira (1993). Due to the high dielectric constant of water, electromagnetic waves, including GNSS signals, experience minimal energy loss as they are reflected from the surface of the water. Consequently, the variations in sea-level can be accurately obtained by conducting GNSS-R altimetry processes using GNSS stations situated near water bodies. Many studies have been conducted using the GNSS-R technique to monitor variations in sea-level (Treuhaft et al., 2001), (Germain et al., 2004), (Löfgren et al., 2011), (Stosius et al., 2011), (Larson et al., 2013), (Löfgren et al., 2014), (Lee et al., 2019), (Selbesoğlu, 2023), (Hatipoğlu and Kayıkçı, 2025), (Wang et al., 2025). Treuhaft et al. (2001) conducted a measurement of the surface elevation of crater lake, which has a more stable surface, achieving a precision of 2 cm through the GNSS-R analysis of observation data collected with 1-second intervals. Löfgren et al. (2011) compared the local sea-level data obtained from the GNSS-R based sea-level and tide-gauge with measurements from two different gauges located 18 km and 33 km away from the GNSS station, which has an additional left-hand circularly polarized (LHCP) antenna. The results indicate a root-mean-square error (RMSE) value of approximately 4

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cm. Larson et al. (2013) also obtained sea-level change using only right-hand circularly polarized (RHCP) antenna data from the GNSS station, which included additional LHCP data mentioned in the previous study. They found a slightly larger RMSE value (4.8 cm) compared to the tide-gauge data. In their study, Lee et al. (2019) demonstrated that GNSS-R based sea-level changes exhibit a strong correlation with traditional tide-gauge records, with correlation coefficients ranging from 0.94 to 0.97 for two GNSS stations. The standard deviations of the differences between the sea-level changes obtained from GNSS-R and those from tide-gauge data range from 7.1 to 11.1 cm. In a region with more variable sea-levels such as Antarctica, Selbesoğlu (2023) found a correlation of 0.91 between sea-level changes measured by GNSS-R and tide-gauge data.

So far, geodetic grade receivers have been used in the above-mentioned studies; however, low-cost GNSS receivers have emerged nowadays, capable of providing sufficiently accurate results. Furthermore, the literature includes investigations into GNSS-R applications utilizing these low-cost GNSS receivers (Unwin et al., 2013), (Ichikawa et al., 2019), (Fagundes et al., 2021), (Chen et al., 2023). Fagundes et al. (2021) conducted a comparative analysis of sea-level altimetry retrievals utilizing a low-cost GNSS-R device alongside independent measurements from a co-located radar tide-gauge, which encountered two malfunction periods resulting in substantial data gaps. The robust stability of the GNSS-R altimetry results facilitated the detection of inadvertent miscalibration steps (10 cm and 15 cm) in the radar gauge post-maintenance, ultimately yielding a correlation of 0.989 and a RMSE of 2.9 cm in daily means after mitigating the effects of the gauge's malfunctions. Chen et al. (2023) found RMSE of approximately 16 cm for 80-hours of sea-level measurements by using low-cost GNSS devices.

This study conducts a comparative analysis of geodetic-grade and low-cost GNSS receivers, both of which have been documented in the literature as effective tools for detecting changes in sea-level. The aim of this research is to investigate whether the changes in antenna height can be determined by the GNSS-R technique. Thus, the monitoring of sea-level changes with a fixed GNSS antenna positioned on the shore will be questioned. Furthermore, this study compares the GNSS-R performance for detecting water-level variation with using both geodetic-grade and low-cost GNSS antennas. The antenna heights of both receivers were changed at the same time using a height displacement tool. Selbesoglu et al. (2022) investigated the height of a GNSS antenna positioned at three different heights by using height displacement tool on an aluminum rooftop, with differing by 5 cm. The results show that the GNSS-R technique can determine the antenna height change with an RMSE of 0.5 cm. Additionally, the statistical values indicated that the GNSS-R technique provides sufficient accuracy for detecting changes in height of 1 cm or more, particularly when the reflective surface material is aluminum or another material with high reflectance capabilities. In this study, unlike the mentioned study, a low-cost antenna was also utilized, and the surface of the pond area at the ITU campus (Figure 1) was selected as the reference surface.

2. Materials and Methodology

2.1 Study Area

The present study was conducted in the pond area situated within the Istanbul Technical University (ITU) Ayazağa Campus. To align with the aims of the research, a specific section of the pond surface was evaluated, characterized by an azimuth angle ranges based on receiver location. On January 22, 2024, Signal-to-Noise Ratio (SNR) data of GPS, GLONASS, and GALILEO satellite systems at L1 frequency were collected with 1 Hz sampling over a four-hour period and used in the study. In order to obtain 2 different height differences (10 cm each), 4 hours of observations were performed at 3 different antenna height (AH) represented at Figure 2a. The data acquisition utilized a ComNav SinoGNSS N2 receiver alongside a Septentrio Mosaic-x5 low-cost GNSS receiver with ArduSimple AS-ANT2B low-cost antenna. Following the data collection, SNR values were derived from the RINEX file. The selection of azimuth and elevation angles ranged from 260° to 320° and 5° to 16°, respectively, based on the analysis of the Fresnel zone map corresponding to the locations of the receivers (Figure 2b). The determination of elevation and azimuth angles was conducted in accordance with the signal strength correlated to the elevation angle, as noted by Larson et al. (2008). To evaluate the accuracy of GNSS-R techniques in measuring changes in water-level, GNSS receivers were positioned on a displacement tool and systematically shifted at predefined intervals. Changes along the vertical axis were executed manually via a screw mechanism integrated into the height displacement tool (Figure 3), and the height differences were meticulously measured and recorded using a steel tape.

2.2 Methodology

The GNSS-R method identifies alterations in the Earth's surface elevation by utilizing reflected radio waves instead of the more conventional direct signals. A low-order polynomial function was employed to derive the signal-to-noise ratio (SNR) to detect direct and reflected signals. As noted by Larson and Nievinski (2013), the SNR was converted from decibel-Hertz to a linear scale (volts/volts), firstly. A software developed by Roesler and Larson (2018) to visualize GNSS-R reflection regions, signal frequencies, and track variations in the height of a reflecting surface using the GNSS-R method. The reflection area of the signal surrounding the GNSS station was used to detect the relevant elevation and azimuth angle. Subsequently, the spectral peak frequency was identified using the Lomb-Scargle periodogram (LSP) method, which is a widely recognized technique for determining periodicity (Larson and Nievinski, 2013). Additionally, Wang et al. (2021) developed a software based on the algorithm from Roesler and Larson (2018) that employs a bimodal Gaussian Mixed Model to compute a weighted average height. The selection of satellite elevation and azimuth angles for the GNSS-R process is made to detect the upper and lower limits of reflected signals. As the elevation angle increases, the reflection area diminishes and approaches the antenna (Larson et al., 2013). At low elevation angles, specifically between 0° and 25°, there is significant interference from both directly received and reflected signals. The strength of the reflected signal, influenced by the incident angle and surface reflection characteristics, can be described using reflection (Fresnel) coefficients. The properties of the surface materials are determined by their electric permittivity and magnetic permeability (Špánik and Hefty, 2017). For low elevation angle observations, especially below 25° (Larson et al., 2013), the multipath effect has a more significant effect on the SNR than in higher elevation angle observations. Therefore, the SNR of low-elevation GNSS signals can be utilized to examine the surface environment.

SNR data was utilized to analyze changes in water-level. The multipath oscillations present in the detrended SNR data can be estimated through the following Equation (1):

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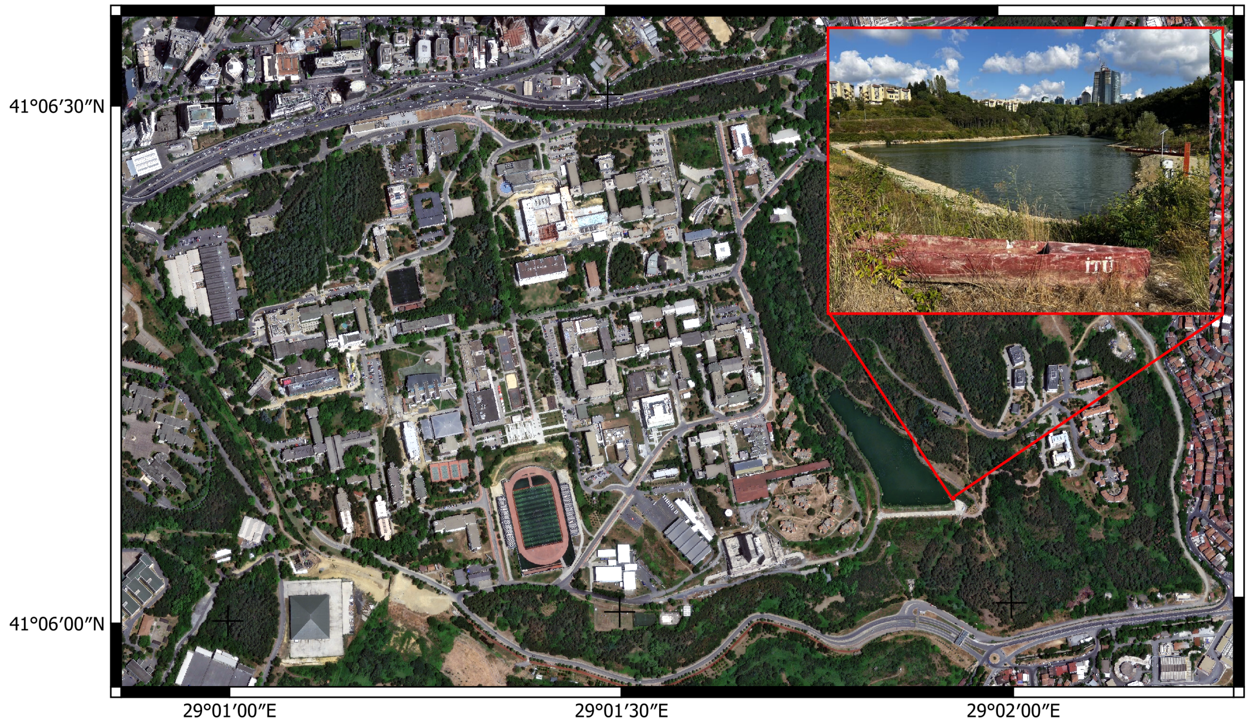


Figure 1. Study area located in ITU Campus.

$$\delta SNR = A(\theta) cos(\frac{4\pi h}{\lambda} sin(\theta) + \Phi); \quad f = \frac{2h}{\lambda} \\ = A(\theta) cos(2\pi f sin(\theta) + \Phi) \tag{1}$$

where h is the antenna height with respect to the reflected surface, λ is the wavelength of the carrier frequency, $A(\theta)$ is the amplitude value varying with the satellite elevation angle, θ is the satellite elevation angle and Φ is the phase difference. If the height of the reflector (h) is assumed to be stable, the frequency of SNR corresponds to the $sin(\theta)$ because λ is a signal-dependent constant value. Water-levels can be calculated using the collected SNR data, which has been detrended and analyzed at specific azimuths and elevations. The frequency (f) is computed from Equation (1) using the detrended SNR values (δSNR). Subsequently, the antenna height (h) relative to the water surface can be obtained using Equation (2).

$$h = \frac{f\lambda}{2} \tag{2}$$

3. Results and Discussion

Prior to initiating the SNR analysis, a quality control assessment of the RINEX observation data from both the low-cost and geodetic setups was conducted. In this context, dilution of precision (DOP) data from the two distinct datasets were acquired and subsequently compared. As can be seen in Table 1, all observations are within the ideal limits when the DOP statistics obtained are considered in the literature (Liu et al., 2013).

Two satellites from the GPS, GLONASS, and Galileo systems were selected based on their extended signal durations received by both geodetic and low-cost GNSS receivers. A comparative analysis of the SNR values for these satellites was conducted. It was determined that SNR values for L1 satellite signals

	Geodetic			
	GDOP	PDOP	HDOP	VDOP
Mean	1.11	0.99	0.51	0.84
Max.	1.40	1.20	0.70	1.00
Min.	1.00	0.90	0.40	0.70
	Low-cost			
	GDOP	PDOP	HDOP	VDOP
Mean	1.07	0.95	0.50	0.80
Max.	2.60	2.20	1.40	1.80
Min.	0.90	0.80	0.40	0.70

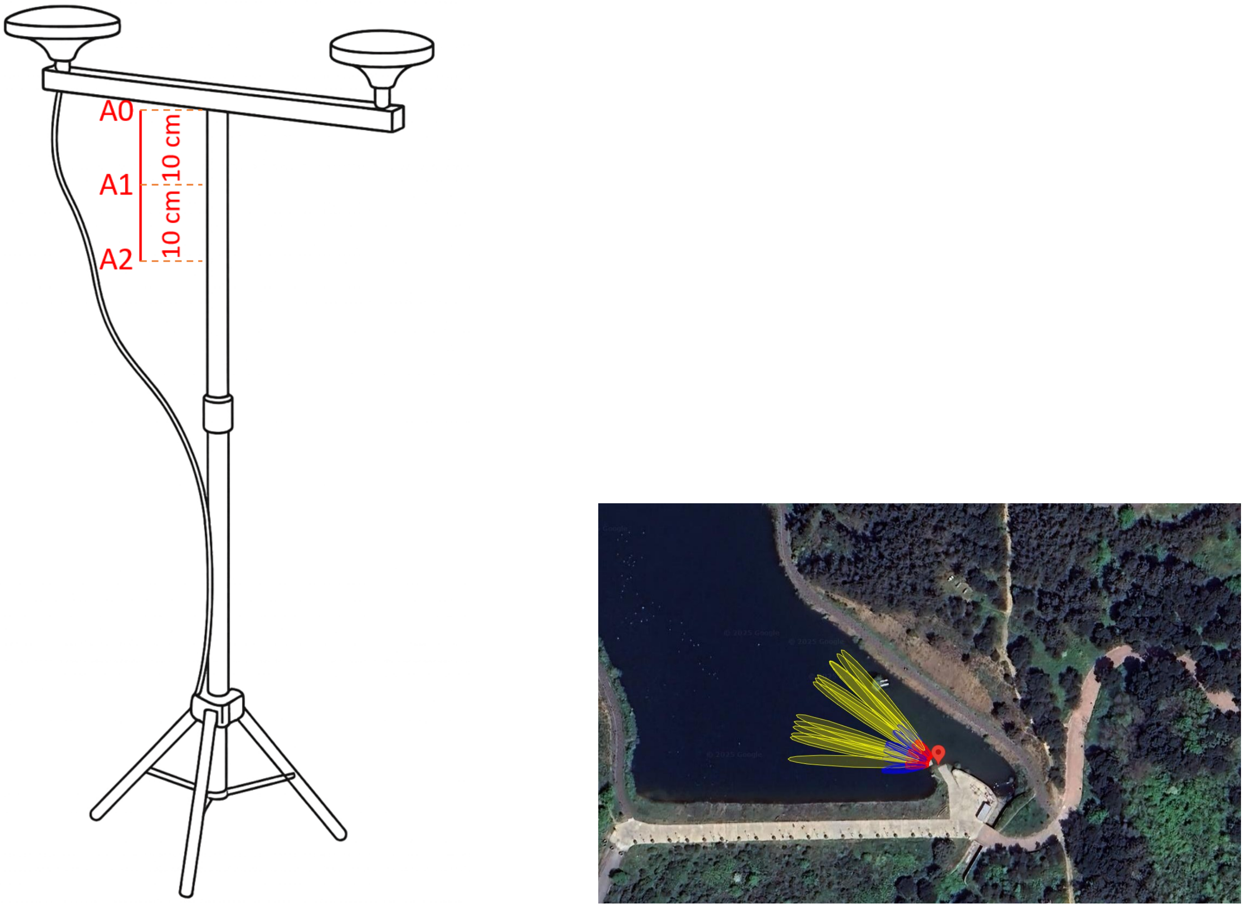
Table 1. The DOP values obtained as a result of the field study.

were primarily analyzed within GNSS-R applications for elevation angles up to 50°. Consequently, the comparison of SNR values was constrained to the signals and measurement data of GNSS receivers. When the Table 2 is examined, the SNR values obtained from the geodetic GNSS receiver exhibit fluctuations ranging from 42.01 to 48.74 for the selected satellites. In contrast, the low-cost GNSS receiver demonstrates SNR values between 41.58 and 49.65. These observations suggest that the SNR values produced by the low-cost system are within the anticipated limits for GNSS-R studies.

		Geodetic		Low-cost	
Sat. ID	DOY	Mean	Std. Err.	Mean	Std. Err.
G15	22	43.95	0.03	44.26	0.04
G20	22	42.01	0.02	41.58	0.02
R01	22	43.23	0.03	45.66	0.03
R11	22	48.74	0.03	49.65	0.02
E24	22	43.87	0.03	43.18	0.03
E34	22	42.09	0.04	42.67	0.04

Table 2. The obtained mean SNR values for selected satellites.

As outlined in the methodology section, the conversion of the SNR values to water-level variations necessitates the prior determination of antenna heights (AH). These heights, which denote the vertical distance between the antenna and the reflecting



(a) (b)

Figure 2. (a) Antenna height changes by using the height displacement tool; (b) GNSS-R Fresnel zones (Elevation angle: Yellow: 5°, Blue: 10°, Red: 15°)

surface, are established through the LSP method. The averaged values of the antenna heights, azimuth angles, and elevation angles derived from the LSP technique are presented in Table 3. As an illustration of LSP, Figure 4 presents the periodogram derived from the SNR data obtained at position A0 of the low-cost receiver.

Table 3 presents the average height of the geodetic receiver at base A0 as 4.706 m, while the corresponding heights at base A1 and A2 are recorded as 4.592 m and 4.469 m, respectively. Considering that the height differences between these locations are maintained at a constant 10 cm, the antenna height measurements detailed in Table 4. Table 4 illustrates the antenna height differences of the geodetic-grade receiver as 1.4 cm for A0-A1, 2.3 cm for A1-A2, and 3.7 cm for A0-A2. In a similar manner, the base heights for the low-cost receiver were determined to be 4.688 m for A0, 4.581 m for A1, and 4.438 m for A2. Furthermore, the differences in antenna height is 0.7 cm for A0-A1, 4.3 cm for A1-A2, and 5.0 cm for A0-A2. As a result of the analyses performed, based on the antenna heights obtained in Table 4, the average difference value in determining the change in antenna height with the geodetic receiver was found to be 2.5 cm and 3.3 cm with the low-cost receiver.

Löfgren et al. (2011) emphasized a RMSE value of 4 cm, while Lee et al. (2019) observed standard deviation values ranging from 7.1 to 11.1 cm in comparisons between tide-gauge data and geodetic-grade GNSS-R. Furthermore, Chen et al. (2023)

Geodetic			
	Antenna Height (m)	Elevation Angle (°)	Azimuth Angle (°)
A0	4.706	13.787	289.262
A1	4.592	12.737	292.923
A2	4.469	12.012	312.448
Low-cost			
	Antenna Height (m)	Elevation Angle (°)	Azimuth Angle (°)
A0	4.688	15.656	289.160
A1	4.581	15.318	286.961
A2	4.438	12.299	313.901

Table 3. The average AH, elevation angle and azimuth angle for both geodetic and low-cost receiver.

Antenna Height Changes (cm)			
	Steel Tape	Geodetic	Differences
A0-A1	10	11.4	1.4
A1-A2	10	12.3	2.3
A0-A2	20	23.7	3.7
	Steel Tape	Low-cost	Differences
A0-A1	10	10.7	0.7
A1-A2	10	14.3	4.3
A0-A2	20	25.0	5.0

Table 4. The antenna height change differences values obtained by using GNSS-R.

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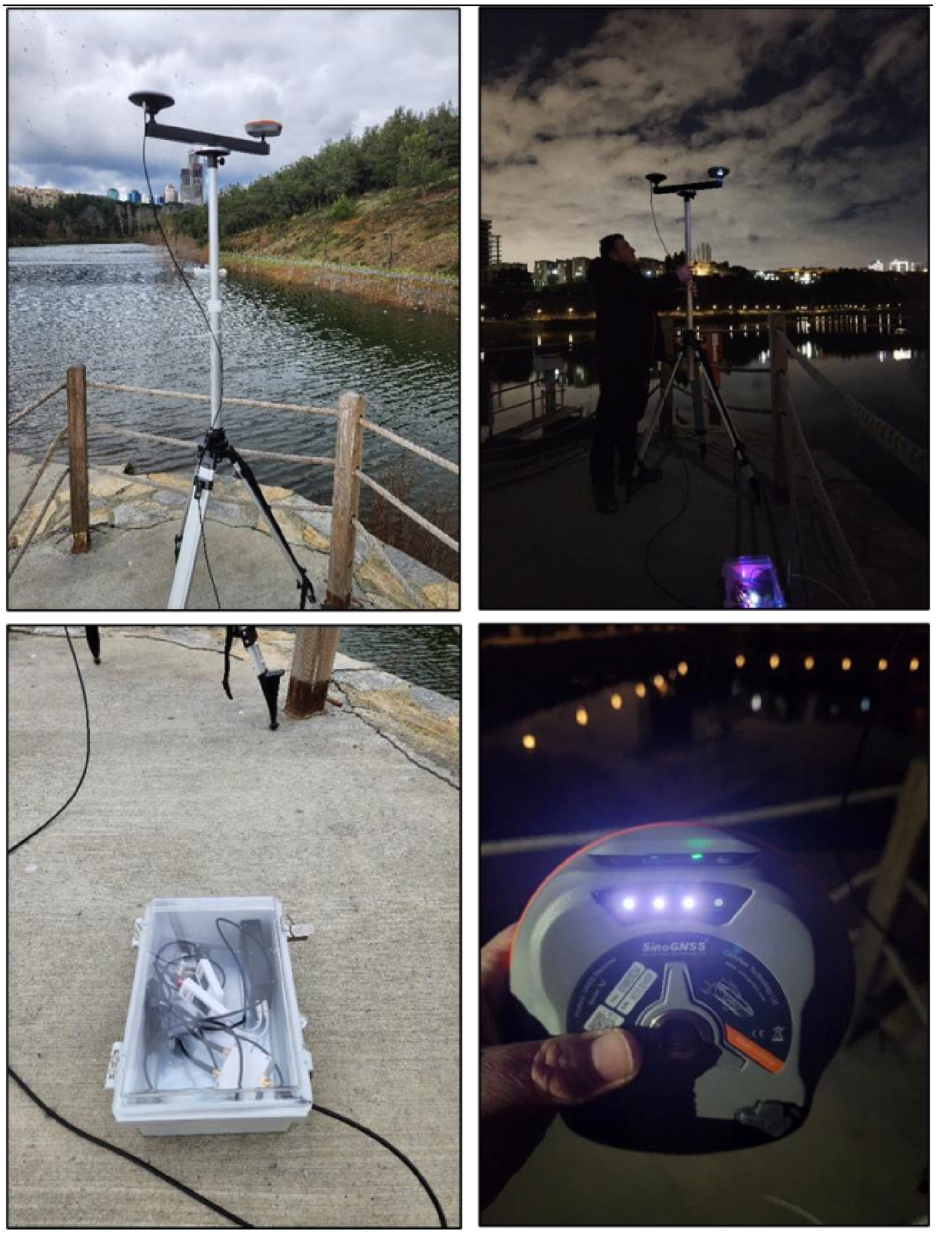

Figure 3. Instrument set up for GNSS-R measurements.

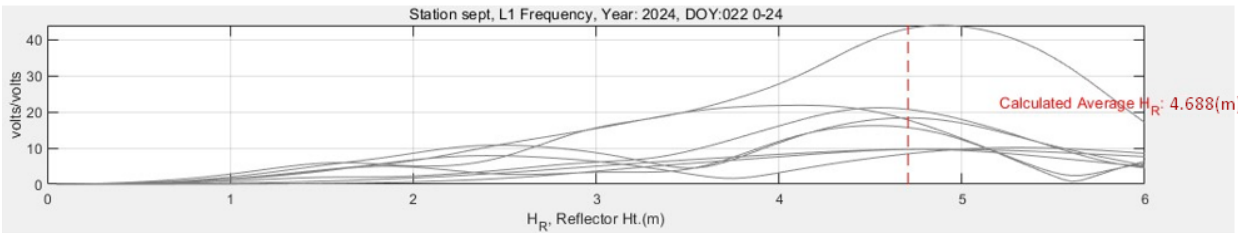

Figure 4. Lomb Scargle Periodogram for low-cost receiver.

utilized a low-cost receiver and found an RMSE value of 16 cm. It is noteworthy that the RMSE and standard deviation values reported in these offshore studies appear to be larger when juxtaposed with the mean antenna height differences of 2.5 cm and 3.3 cm calculated in this study using both low-cost and geodetic receivers, suggesting that the receivers and methodology used in this study allow significant determination of sea-level change.

4. Conclusions

This research undertakes a comparative analysis of geodetic-grade and low-cost GNSS receivers, both of which are recognized in scholarly literature as effective instruments for detecting changes in water-level by using GNSS-R method.The primary objective of this study systematically compares the performance of GNSS-R in detecting water-level variations between geodetic-grade and low-cost GNSS. To simulate potential variations in water-levels, the antenna heights of both receivers were concurrently modified using a height displacement tool. The obtained antenna heights were evaluated and compared between geodetic receivers and low-cost systems to determine whether low-cost GNSS-R data has a significant counterpart. In addition, the investigation of the feasibility of employing the GNSS-R technique to ascertain variations in antenna height was done. Consequently, this inquiry are critically evaluated the efficacy of monitoring water-level fluctuations with a fixed GNSS antenna positioned along the shoreline.

In order to enable a meaningful comparison, the study started with a quality control assessment of raw observation data collected with two different quality GNSS receivers. The DOP values obtained from both geodetic and low-cost receivers were compared, showing that both sets provided data of ideal quality. Then, the qualities of GPS, GLONASS and Galileo signals collected by two different receiver/antenna sets were examined and compared in terms of SNR values. The results indicated that the low-cost set was able to achieve sufficient SNR values. Following this, the antenna heights from three different bases (A0, A1, A2) were determined by processing the SNR values of signals between 260° and 320° in azimuth—representing the water surface—and at elevation angles between 5° and 16° using the LSP method for both two receiver set. The variations in antenna height measurements for the geodetic receiver ranged from 1.4 cm to 3.7 cm, while the low-cost setup showed discrepancies between 0.7 cm and 5.0 cm. In reviewing the existing literature on the subject, it is noteworthy that the RMSE and standard deviation values reported in offshore studies tend to be larger when compared to the mean antenna height change differences of 2.5 cm and 3.3 cm calculated in this study using both low-cost and geodetic receivers. This suggests that the receivers and methodology utilized in this study effectively allow for a significant determination of sea-level change.

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