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Accuracy investigation of GNSS-reflectometry for sea level monitoring on Horseshoe Island, Antarctica: preliminary results of the Turkish permanent GNSS station (TUR1)

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Abstract: Antarctica is called a natural laboratory and is highly important for investigating climate change and its evolution over time. Sustainability is a critical concern due to the challenges posed by glacier melting and rising sea levels due to global warming. According to the Intergovernmental Panel on Climate Change, since the industrial age, the global mean sea level has risen by about 20 cm as a result of the increase in the average world temperature by 1 °C. Therefore, long-term observations by satellite-based techniques in and around Antarctica are of great importance for monitoring the impacts of climate change. In the last two decades, the Earth has been monitored by satellite-based remote sensing systems with high temporal and spatial resolution. Nowadays, Global Navigation Satellite System (GNSS) signals are increasingly being used in climate change studies. In this context, Türkiye's first GNSS stations were successfully installed during the fourth Turkish Antarctic Expedition (TAE-IV) on Horseshoe Island, Antarctica, within the scope of a project by the Scientific and Technological Research Council of Turkey (TÜBİTAK) titled "Monitoring the troposphere and snow depth/thickness in the Antarctic region with GNSS meteorology and GNSS-reflectometer methods". These stations have been monitoring atmospheric water vapor and changes in snow/sea levels since February 24th, 2020. In this study, one of the permanent GNSS Station (TUR1) signals was analyzed using GNSS-reflectometry (GNSS-R) in order to monitor the sea level changes on Horseshoe Island. Sea level changes of around 1 m in this region, due to the tidal effect, were observed using GNSS-R and compared with ultrasonic distance measurement sensor results for validation. The first results for monitoring sea levels obtained from the TUR1 GNSS Station demonstrated that sea levels in the region can be monitored using GNSS-R with an accuracy of 3–4 cm and correlation of 0.91.

Key words: Antarctica, sea level change, climate change, GNSS-reflectometry

1. Introduction

The continent of Antarctica is renowned for having an extremely unique climate and acts as a critical component in maintaining the Earth's heat balance through the oceans. Moreover, its importance lies in its ability to allow the examination of the effects of global warming and tracking these effects over time.

Average temperature of the Earth has increased by approximately 1 C° (Masson Delmotte et al., 2021) since the industrial revolution (1850s). It was reported in the 6th Intergovernmental Panel on Climate Change Evaluation Report, between 1901 and 2018, that the global mean sea level (GMSL) has risen by 0.20 m as a result of glacier melting, especially in the polar regions. It is estimated that this value will increase by approximately four times in the next century. As a result, communities living in coastal areas, which constitute approximately 28% of the world's population (of which 11% live in areas that are approximately 10 m below sea level), will be seriously affected by coastline changes, groundwater contamination with saltwater, intensified and more frequent flooding, and serious coastal hazards like erosion and island and habitat loss (Werner and Simmons, 2009; Cazenave et al., 2010; Nicholls and Cazenave et al., 2010; Church and White, 2011; Pörtner et al., 2019; Adebisi et al., 2021). Therefore, improving sea level forecast accuracy is of high priority among scientists, policy makers, and all other relevant stakeholders (Adebisi et al., 2021). Uncertainty

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in the GMSL emerges as a major challenge in climate change forecasting (Church and White, 2011). In terms of historical sea level data, a high amount of accuracy is needed to predict future climate change and its effects and increases in the global ocean temperature need to be clearly demonstrated.

Monitoring of changes in the sea level can be done by various methods. The first of these is the measurements performed with tide gauge stations, which is the traditional method, and the other is using a satellite altimeter. However, although the number of tide gauge stations has increased in the last decade, their spatial distribution is still insufficient, especially in Antarctica (Adebisi et al., 2021). The satellite altimeter method, which has emerged in the last 30 years, closes the tide gauge gap, and works globally. However, the use of a satellite altimeter on the coasts is limited due to the change in the waveform on the coasts and the inadequacy of the correction techniques (Quartly et al., 2019). Despite their limitations, sea level monitoring with tide gauges is an effective method for long-term coastal sea level observation (Adebisi et al., 2021).

According to the locations of the tide gauge stations in the Antarctic region, the stations' spatial resolution is approximately 2000 km. Considering the effect of the Antarctic continent on the Earth's climate system, this number is quite insufficient. Increasing the spatial resolution of the stations that determine the local sea level changes will increase the accuracy of the predictions made for the future.

Ultrasonic sensors in modern tide gauge stations measure vertical distance to the water surface. Therefore, it is not possible to carry out measurements without the installation of scaffolding, especially in places where the magnitude of the tide is high. For the Antarctic continent, this structures increase the cost of the stations to be established due to the logistics costs and it contradicts the principle of interfering as little as possible with the natural structure of the continent.

In space-based positioning, position information is determined with the integration of space (satellite), ground, and user units. Users determine their position instantly by processing directly retrieved electromagnetic signals from navigation satellites to the GNSS receiver. However, some of the signals retrieved by the GNSS antennas are reflected or scattered from Earth surface. This is one of the main sources of error (multipath) for GNSS measurements (Jumaah et al., 2018; Wen et al., 2020). In recent years, applications such as monitoring the sea level, detecting glacial/snow level changes, and estimating soil moisture have been carried out with a bistatic remote sensing technique called GNSS-reflectometry (GNSS-R).

Using reflected signals, GNSS signals have been used to monitor the physical characteristics of the Earth's surface since the early 1990s. Hall and Cordey (1988) first proposed a scattering principle based on multistatic principles. Based on this hypothesis, the GNSS reflected height determination technique was developed in 1993 (Martin Neira, 1993). Over the years, a multitude of studies have been conducted to reveal the accuracy and effectiveness of using reflected GNSS signals for various purposes, including but not limited to soil moisture analysis, vegetation growth, and monitoring sea and ice levels. For instance, Small et al. (2010) conducted a study that focused on using reflected GNSS signals to monitor soil moisture. The results of the study showed that GNSS-R could be used to derive soil moisture measurements with a correlation coefficient higher than 0.8. GNSS-R has also been used to derive changes in sea and ice levels based on GNSS data, and numerous studies have demonstrated its effectiveness (Larson et al., 2013a; Larson et al., 2013b; Löfgren et al., 2014; Tabibi et al., 2020; Selbesoğlu, 2023). Geremia-Nievinski et al. (2020) investigated the use of GNSS-R for monitoring sea levels. They analyzed GNSS data from a network of receivers located in Antarctica for tidal analysis and showed that estimation of the sea level using GNSS-R was compatible with that of the tide gauge sensor, with a correlation coefficient of 0.90 and an RMSE of 15.4 cm. A study conducted by Zheng et al. (2021) demonstrated the potential of using a multi-GNSS instead of only Global Positioning System (GPS) signals to further improve the accuracy of sea level monitoring. Furthermore, many studies have demonstrated the versatility of using reflected GNSS signals for sea level monitoring and the potential of GNSS-R as a tool for monitoring changes in the physical structure of the Earth's surface (Liu et al., 2017; Beşel and Kayıkçı, 2022; Selbesoğlu, 2023). Since it is important to increase the resolution of monitoring the sea/ice level and atmospheric water vapor in Antarctica, Türkiye's first permanent GNSS stations (TUR1 for the sea and TUR2 for glacier change observations) were successfully installed during the 4th Turkish Antarctic Science Expedition on Horseshoe Island (February–March 2020), where the temporary Turkish base is located. Apart from the GNSS receivers, these stations have ultrasonic sensors to validate sea/ice level results. Approximately 6 months of GNSS data from the times when the GNSS receiver and ultrasonic sensor were working together were evaluated to investigate GNSS-R accuracy for sea level determination. This study highlights that the use of multi-GNSS signals instead of only GPS signals can lead to improved accuracy in sea level monitoring. Therefore, one of the main objectives of the present study was to reveal the performance of the GNSS-R using TUR1 GNSS Station observations based on the multi-GNSS approach in Antarctica.

2. Materials and methods

Employing conventional methods for detecting sea levels can be difficult due to the challenging terrain and the existence of large ice sheets that form due to the severe weather conditions in the western Antarctic Peninsula. To monitor the Earth's surface features in these challenging conditions, GNSS-R technology, which makes use of reflected radio waves rather than direct signals, appears to be a promising tool.

In this context, two permanent GNSS stations that can operate off-grid, one in the coastal zone (TUR1) and the other near the glacier (TUR2) in the interior, were installed on Horseshoe Island (Figure 1) during the 4th Turkish Antarctic Science Expedition. In this study, analyses of the sea level changes were carried out based on TUR1 GNSS Station observations (Figure 2).

The TUR1 GNSS Station (with a CHC P5E receiver and a C220GR antenna), which logs observations with

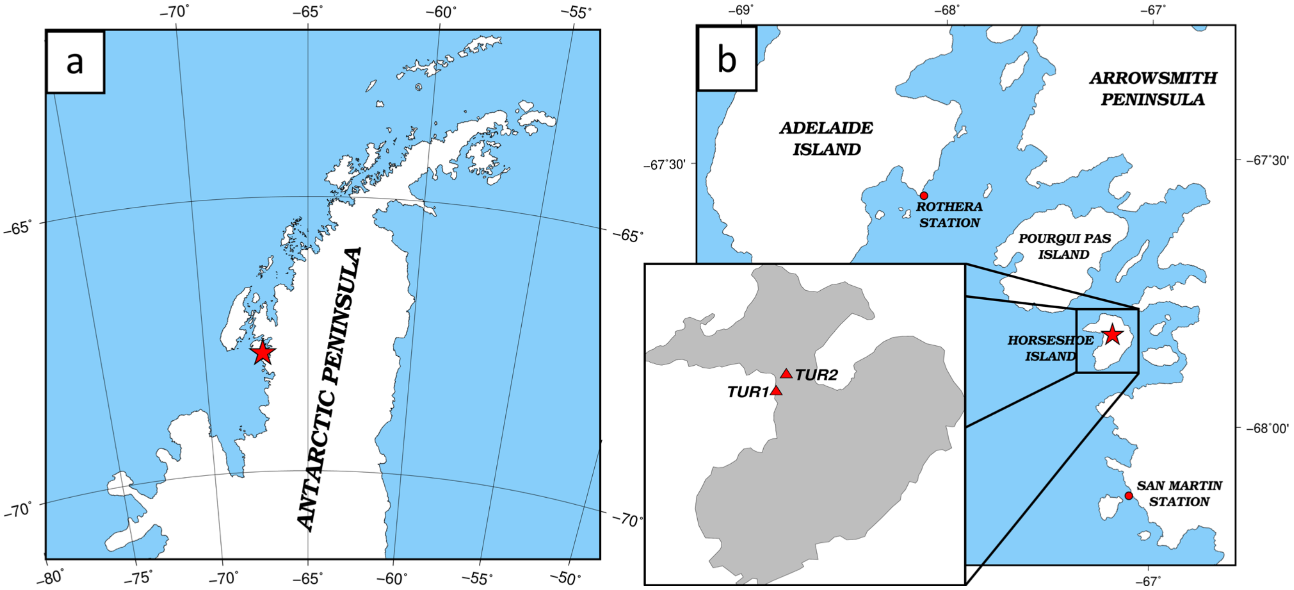

Figure 1. a) Location of Horseshoe Island in the Antarctic Peninsula, b) Location of TUR1 and TUR2 stations on Horseshoe Island.

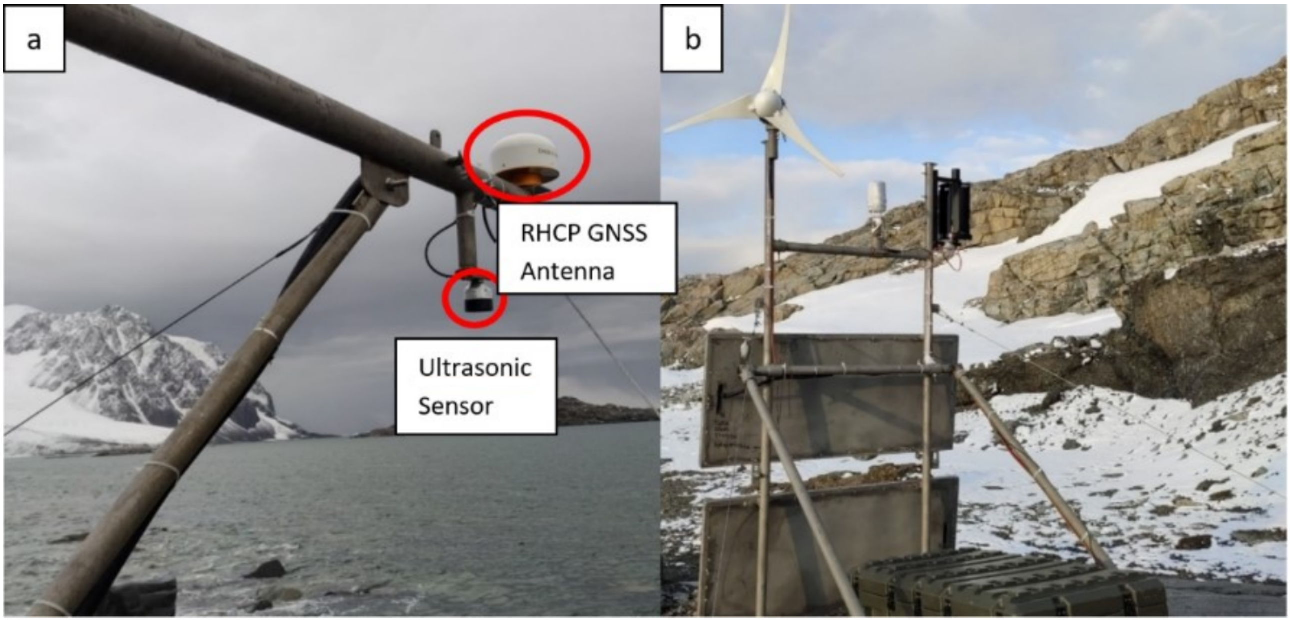

Figure 2. a) GNSS and ultrasonic sensor of the TUR1 station, b) Energy system, receiver, and meteorological sensor of the TUR1 station (67°49′ S, 67°14′ W).

a cut-off elevation angle of 0° and recording interval of 5 s, was installed to estimate sea level and tropospheric water vapor in Antarctica. The TUR1 Station is situated in the coastal region of Horseshoe Island, equipped with a Campbell Scientific ultrasonic sensor (Logan, UT, USA) which has a resolution of approximately 0.25 mm and accuracy of 1 cm. Energy for the TUR1 Station is supplied by 2 solar panels and 2 wind turbines, and the excess energy is stored in batteries. The batteries, receivers, and dataloggers for the sensors are located in the military case with thermal insulation.

The signals reflected from the Earth's surface are typically considered as noise and errors in geodetic positioning studies. However, in the case of GNSS-R, these reflected signals produce specific oscillations in the received signal power, which are reflected in the signal-to-noise ratio (SNR) values as a unique pattern. Using this feature, the vertical distance can be determined between the antenna and the surface where the signal is reflected (Figure 3). In this approach, there is no need to make any changes on the receiver, no need for an additional antenna or orientation to the study area, or place any structures like scaffolding on the shore (except pillar or tripod for GNSS antenna). It is sufficient that the GNSS antenna is at any location where the signals reflected from the sea can reach the receiver.

Monitoring the variations in the sea level can be carried out with L1 frequency to detect the reflections of the GNSS signals from the sea surface. In studies using reflected signals, the SNR is used instead of carrier phase information, which is used to determine the position. Due to the distance between the receiver-satellite and the gain pattern of the antenna, the SNR data is affected by long-period variations. If these long-period variables with a low elevation angle (<30°) are eliminated using low-order polynomials, only the multipath effect remains (Larson et al., 2013b). The multipath effect is derived from the propagation delay, y, between the direct incoming signal and the reflected signal, as shown in Eq. (1):

$$y = 2H_R \sin\theta. \qquad (1)$$

Here, H_R is the height between the reflected surface and the antenna phase center, and θ is the elevation angle of the satellite with respect to the horizontal plane. When the surface is stable, the instantaneous phase value $\Phi = k\,y$, ($k = 2\pi/\lambda$, λ is the wavelength of the GNSS carrier signals) $4\,\pi\,H_R / \lambda$ is obtained from a constant value obtained by multiplying the variable sin θ (Auber et al., 1994).

If the y differentiates with respect to time:

$$y' = 2\,H_R\,\theta'\cos\theta + 2\,H'R\sin\theta. \qquad (2)$$

Eq. (2) can be stated as the sum of the dynamic satellite and dynamic surface terms. The angular delay rate can be defined as follows:

$$\mathring{y} = 2\,H_R + 2\,H'_R\tan\theta/\theta'. \qquad (3)$$

The first term of Eq. (3) is the reflected height value, and the second term is the height-rate correction. These two unknowns are solved iteratively. In order to obtain the height time series, first the H_R values are estimated with the Lomb-Scargle periodogram (LSP), then the H'_R value and the $\tan\theta/\theta'$ value are found. These values are removed from the time series drawn a priori, and the resulting product time series is obtained (Larson et al., 2013b).

In this study, the sea levels were calculated based on SNR data at certain azimuths and elevations. In order to monitor sea level in the study area where the stations are

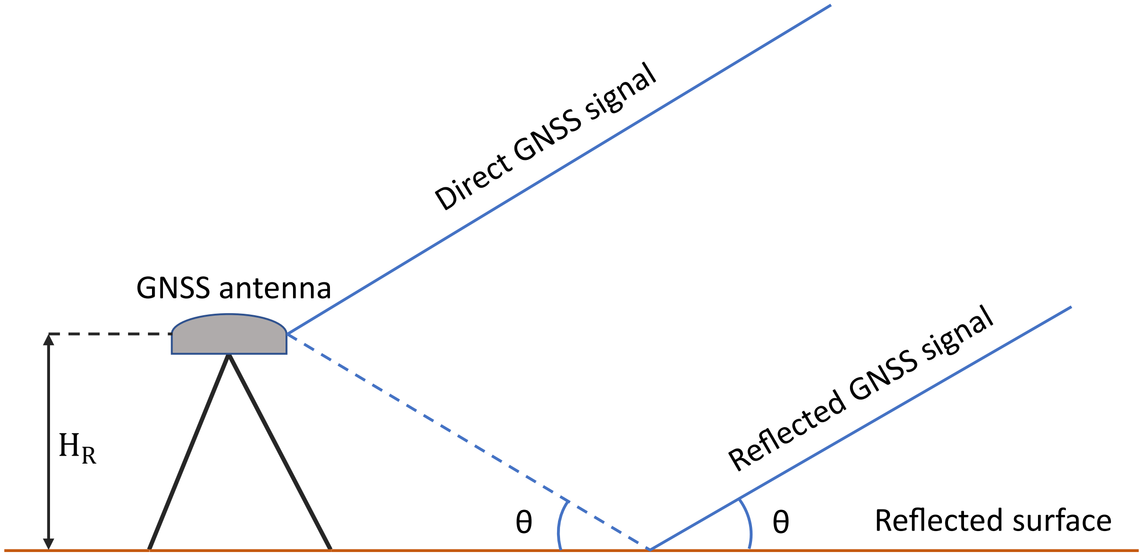

Figure 3. Sketch of the GNSS-R method.

located, data representing the relevant region should be used. For this purpose, the azimuth angle and elevation angle values for the reflected signals from the satellites were determined and signal analysis was performed to obtain the signal peak using the LSP. The processing steps applied are given below in Figure 4.

3. Results

Multi-GNSS sea level results were obtained by SNR analysis, and the time series of all of the navigation systems were merged into a single GNSS SNR time series. For this purpose, 4 different time series were derived, and comparative analyses were performed using the ultrasonic distance sensor data. Sea levels were obtained based on signals within the range of 200°–350° azimuth, and an elevation angle of 10°–20° (Figure 5) around the TUR1 station location.

Figure 6 shows the 4 different sea levels for the 6-h time periods throughout the day estimated by the corresponding LSP produced using the SNR data.

The vertical distances between the reflective surface and the antenna were estimated on day of the year (DOY) 73 0–6 h, 6–12 h, 12–18 h, and 18–24 h, 2020, as 3.58, 4.10, 3.72 and 3.65 m, respectively (Figure 6). According to these values, while the sea level was the lowest between 6 and 12 h, the highest was observed between 0 and 6 h. There was a

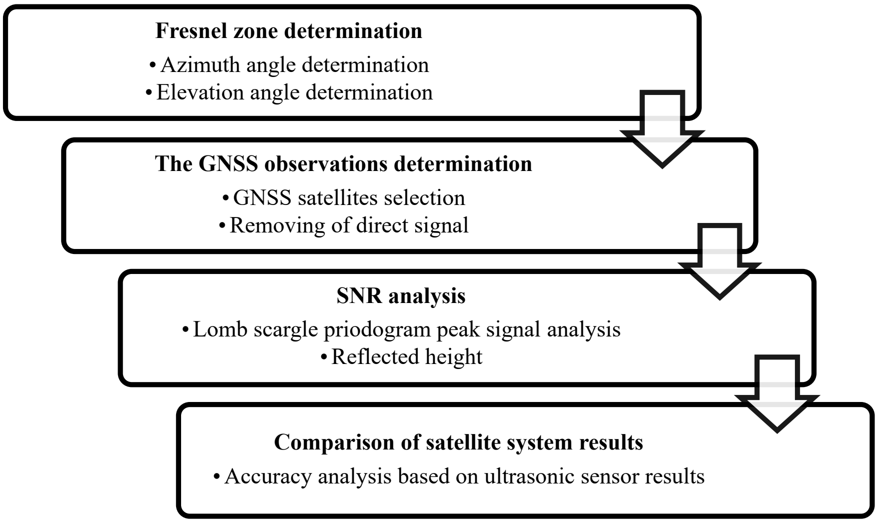

Figure 4. GNSS-R sea level monitoring work flow chart.

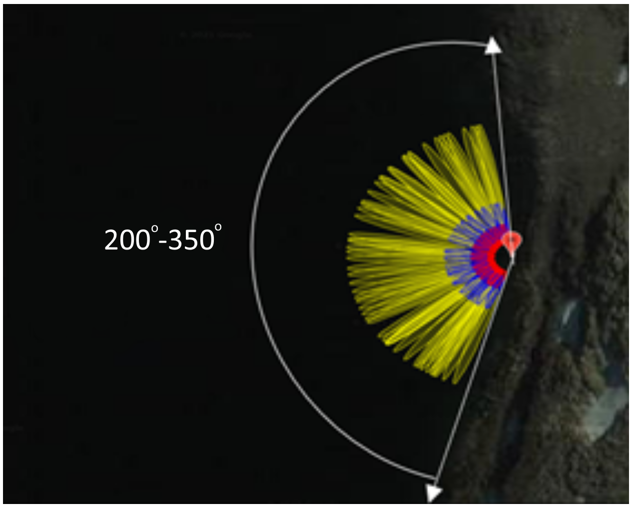

Figure 5. Fresnel zone map of the TUR1 station (elevation angle: 10°, 20°).

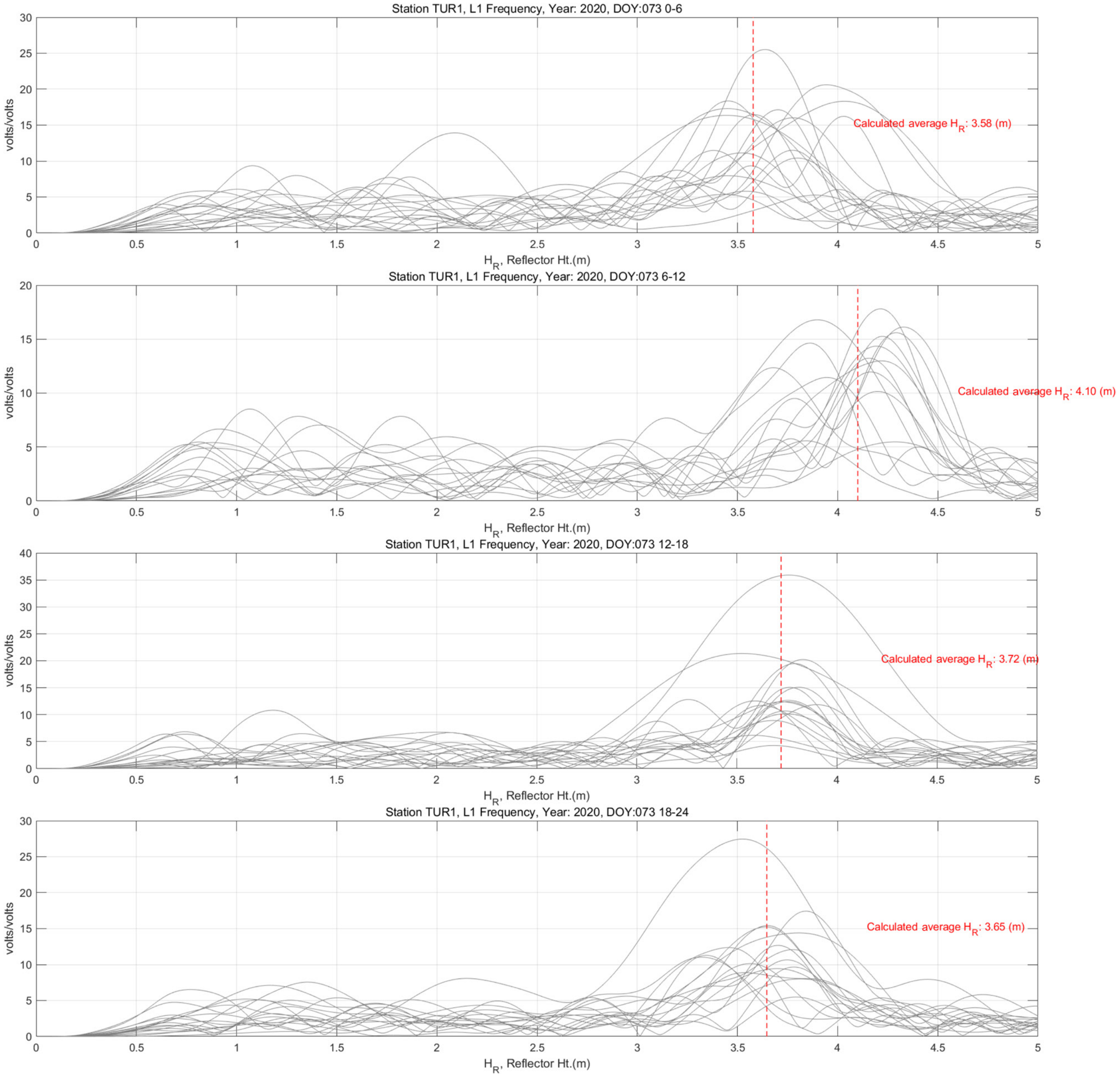

Figure 6. A 6-hour LSP chart of the 2020 73. Day of the year (DOY) of the TUR1 station data.

difference of approximately 50 cm between the minimum and maximum sea levels. In Figure 7, it is seen that the sea levels obtained with GNSS-R and the ultrasonic sensors are compatible. A correlation of 91% was found between the sea levels obtained with GNSS-R and the ultrasonic sensor. In the figure marked with red, it is seen that the difference between the antenna and the sea level decreased considerably and exhibited a different behavior compared to the other time periods. The reason for this is that the sea in the region is completely covered with ice and snow during the winter.

The photographs taken with the camera trap set up at the TUR1 Station are given in Figure 8, where it can be seen that in July–August, the sea was completely frozen. Thus, the data for this time period were excluded from the comparative analysis of the sea level with GNSS-R and the ultrasonic sensor. A time-based comparison is given in Figure 7, only for the sake of clarity of the results. According to the results, the integration of all of the currently available navigation satellite systems (GPS, GLONASS, GALILEO and BeiDou) was observed to significantly enhance precision and accuracy. The

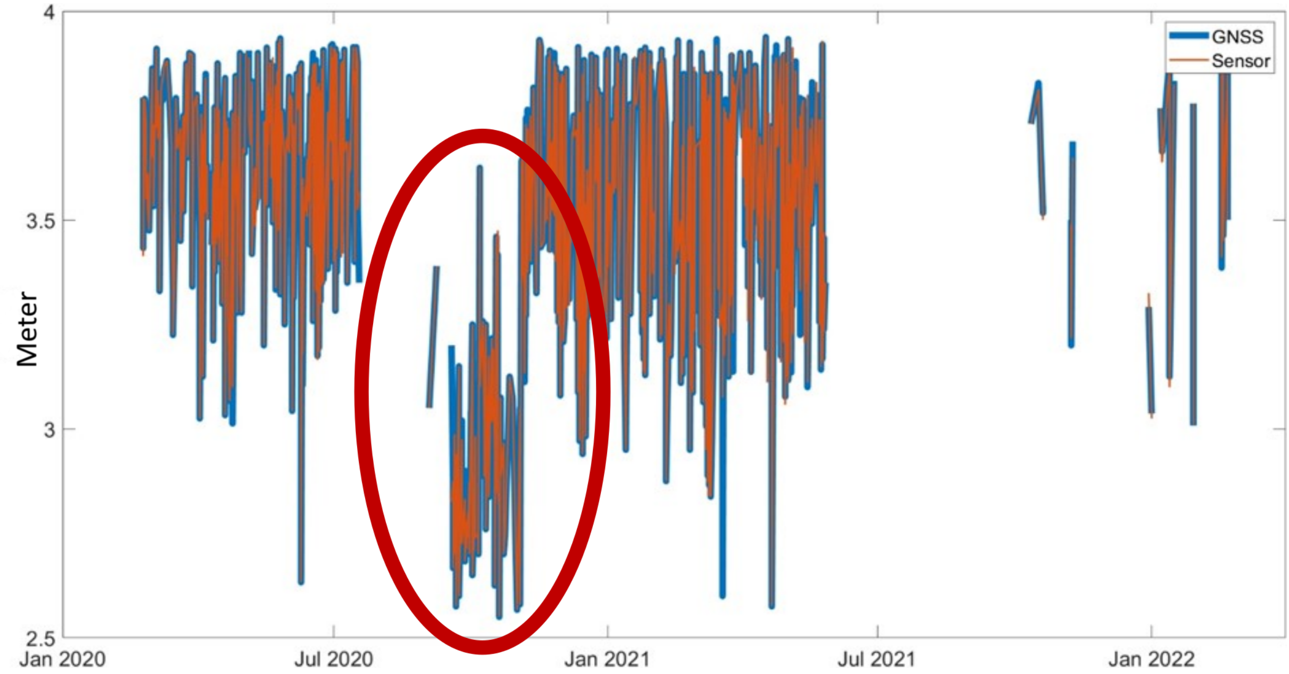

Figure 7. Comparison of GNSS-R and ultrasonic sensor sea levels.

Figure 8. Image of the July 20th, 2020, TUR1 station.

statistical analysis highlighted a 2-cm average difference between the multi-GNSS and GPS-only solutions (Table). In a region with a tidal fluctuation of approximately 1 m, the difference obtained from comparing the GNSS-R and ultrasonic sensor results showed that the GNSS-R results are compatible with those of conventional methods. The conclusions derived from the information provided strengthen the concept that GNSS-R can be successfully

Table. RMSE of the sea level determination with GNSS-R.

	GPS+GLO+GAL+BEI	GPS+GLO+GAL	GPS+GLO	GPS
RMSE (m)	0.032	0.034	0.049	0.052

employed for the effective monitoring of long-term sea level trends in the Antarctic region.

4. Discussion

Global warming has played an important role in increasing the GMSL in the last century. In recent years, GNSS-R has been widely used for satellite-based sea level monitoring studies. In these studies, the comparative analysis of tide gauge data and GNSS-R sea level observations has shown that correlations between 0.90 and 0.99 can be achieved (Zheng et al., 2021; Selbesoğlu, 2023). The sea level monitoring study with the TUR1 Station was carried out using the GPS, GLONASS, Galileo, and BeiDou navigation satellite systems. Furthermore, signal analyses were made with different satellite systems and the results were produced by taking the average of the level changes obtained from these satellites. With the use of all of the GNSS satellite systems, the number of reflected signals increased, and the standard deviation values of the results improved. The standard deviation obtained was 3.2 cm based on all of the systems. In addition, it was observed that sea level changes around 1 m due to the gravitational force of the moon. The gravitational force of the moon continues to be the main cause of tides in both summer and winter. However, the intensity and patterns of the tides in Antarctica vary seasonally due to the interaction of tidal impacts with a variety of local factors, including ice cover, ocean currents, and the temperature. Despite the fact that these are broad patterns, it is crucial to keep in mind that exact tidal patterns might change depending on a location specifics within Antarctica and the local oceanographic circumstances. In these analyses, predictions were performed in 6-h time periods due to the tidal patterns of the sea level in the study area. The acquired standard deviations showed the possibility for sufficient detection and monitoring of fluctuations in the sea level using GNSS-R, despite the fact that tidal effects in the area reach almost 1 m.

5. Conclusion

GNSS-R has emerged as a highly effective technique for studying sea level determination in recent years. In this study, sea level monitoring was conducted using multi-GNSS data from the TUR1 Station. The study revealed that the sea level change can be determined with a standard deviation of 3–4 cm. Notably, analyses evaluating the GNSS satellite systems individually revealed that using all of the systems resulted in improved standard deviations. GNSS-R represents one such approach that holds great promise for ongoing scientific investigations into the effects of climate change in the Earth's polar regions. The ability to use GNSS signals to monitor sea level changes contributes to the development of more effective strategies for mitigating the impacts of sea level rise.

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