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EXPERIENCE IN DEPLOYING RADAR CORNER REFLECTORS FOR INSAR MONITORING

This work aims to analyze the effectiveness of corner reflectors deployment designed in various for InSAR monitoring by the Sentinel-1 satellite. Method. The accuracy of determining the spatial movements of the surface by the InSAR method in the places where the corner reflectors are deployed depends on their size, as well as the signal-to-clutter ratio on the radar images. Therefore, it is necessary to assess the backscattering intensity on radar images for the selected territory before installing the corner reflector. In places where corner reflectors are to be deployed, an increase in backscatter should be at least 10 dB. The orientation of the corner reflectors was performed based on Sentinel-1 satellite orbit parameters, which were obtained from the Heavens Above web resource. The analysis of the backscatter intensity time series on radar images was carried out using the online platform EO Browser. Results. The effectiveness of deployment and monitoring of trihedral triangular corner reflectors measuring 0.5 m and 1 m was studied. The research results made it possible to generalize the experience of deploying temporary corner reflectors and use them to design reflector structures for permanent monitoring using radar sensing. The maximum autonomy and constant value of the effective scattering area of the triangular corner reflector is ensured thanks to the equipped protective screen that prevents atmospheric precipitation from entering the reflector. Unlike three-sided corner reflectors, which are oriented to the ascending or descending orbit of the satellite, the circular four-sided corner reflector provides an increase in the intensity of backscatter on radar images taken from different orbits and different satellites. The circular quadrilateral reflector, which was deployed for continuous monitoring, is characterized as a universal reflector for all possible sensors that will conduct radar imaging. Scientific novelty and practical significance are in the confirmation of the effectiveness of the use of ground corner reflectors to increase the intensity of backscattering on radar images. Tested and improved designs of reflectors can be used when creating a network for constant monitoring, which will ensure millimeter accuracy in determining the spatial movements of the earth's surface and engineering structures by the InSAR method.

Key words: InSAR, trihedral corner reflector, quadruple reflector, radar cross section, Sentinel-1, EO Browser

Introduction

During the last decade, the satellite radar interferometry method (InSAR) has become widely used as a geodetic tool for solving various problems of geotechnical monitoring with millimeter accuracy. This level of accuracy is achieved due to the use of sensors that provide medium and high resolution, as well as the technique of processing time series of radar images (Multi-Temporal SAR). The two most common methods for processing long-time series of images are the Small Baseline method (SBAS) and the Persistent Scatterer method (PSInSAR).

Problem formulation. The result of processing a series of radar images by the PSInSAR method is a time series of vertical movements of the earth's surface only for those pixels that have a constant and sufficiently high signal amplitude. Such pixels in the image, dominating among others, are called permanent scatterers. It has been found that the number of permanent scatterers in images of an urban area can reach several hundred per square kilometer, while in non-built-up or vegetated areas there are much fewer or no permanent scatterers at all [Huang and Zebker, 2019].

The absence of artificial or natural objects that provide the high intensity of the reflected signal can be balanced by installing passive corner reflectors. Due to its properties, which provide strong backscatter and maintain a stable position, corner reflectors are broadly used as coherent terrestrial targets for geodynamic monitoring using the InSAR method. The usage of corner reflectors is especially relevant for the areas where long-term monitoring by satellite radar methods is envisaged. Therefore, to ensure reliable results of InSAR monitoring of the earth's surface and infrastructure objects, it is necessary to install corner reflectors.

Reflector shapes. Corner reflectors of various shapes and designs are used for SAR monitoring [Doerry, 2014]. However, the most commonly used form that provides effective signal reflection is a passive reflector with three orthogonal plates. A trihedral reflector allows less accurate orientation compared to other forms of reflectors. It is noted [Doerry and Brock, 2012; Garthwaite, 2017] that the orientation of the reflector within an accuracy of 4° in azimuth and in the vertical plane does not have a significant effect on the backscatter level. The shape of the reflector plates affects the value of its radar cross section (RCS – is the ratio of backscatter power to the power density received by the target). In practice, trihedral triangular, rectangular, and pentagonal reflectors are used. Even though the RCS of a triangular trihedral reflector (corner reflector) is the smallest, it is used more often than other ones. This is due to its structural rigidity and relative simplicity of manufacture.

The size of the reflectors is determined by the length of the internal orthogonal edges. It is known the usage of corner reflectors with sizes from 0.33 m [Dheenathayalan et al., 2017; Kelevitz et al., 2022] to 5 m [Schwerdt et al, 2018]. Large reflectors are commonly used for radiometric calibration of satellite radar. The most common use of reflectors with 1-2 m inner leg length. The purpose of corner reflector installation is to ensure the required level of RCS at a given point of a radar image. This value is directly proportional to the size of the corner reflector and inversely proportional to the wavelength of the satellite's radar [Collilieux et al., 2020].

For example, in order to achieve the theoretical accuracy of determining vertical movements less than 1 mm, using the InSAR method in the C-band (λ=5.5466 cm), it is necessary to ensure an increase in the signal-to-clutter ratio up to 30 dB [Bányai et al., 2020]. Thus, for practical applications of SAR images obtained by the Sentinel-1 satellite (C-band), the required size of the triangular corner reflector should be within 0.8-1.7 m [Garthwaite, 2017; Ferretti, 2014].

The purpose of this study is to analyze the effectiveness of deploying corner reflectors of various sizes and designs for InSAR monitoring by the Sentinel-1 satellite with an average C-band wavelength.

Methods

When designing the position of the corner reflector, it is advisable to preliminarily evaluate the intensity of backscatter in radar images for the studied area [Struhár et al., 2021]. The selection of the location for the deployment of the corner reflector should ensure an increase in the intensity of backscatter by at least 10 dB. This will allow to achieve the accuracy of measuring along the line of sight less than 1 mm [Garthwaite, 2017].

Since the main task of the corner reflector is to reflect the wave sent from the radar back to the satellite, it is important to correctly orient it during installation for effective operation. To do this, determine the ephemerids of the satellite's orbit, which will conduct the acquisition: the maximum altitude of the satellite above the horizon and its azimuth at this moment. The parameters of the Sentinel-1A satellite orbit were determined according to the Heavens Above online resource (http://www.heavens-above.com). The input data for the calculation were the reflector installation coordinates, the date of the observations, and the name of the satellite (identification number Sentinel-1A – 39634). The obtained ephemerides were used to orient the reflector in the vertical and horizontal planes according to the method described in the work [Tretyak et al., 2023].

All corner reflectors were oriented according to the described method. This made it possible to increase the backscatter of the signal in SAR images in the places of reflector deployment. Estimation of backscatter intensity level can be performed directly from radar images using special software. However, for this purpose, we consider it appropriate to use EO Browser (https://www.sentinel-hub.com/explore/eobrowser/). EO Browser is an online platform that provides access to remote sensing data, including SAR data obtained by Sentinel-1 satellite. The advantages of using EO Browser are fast access to data without the need to download images; the possibility of platform usage at the design stage as well as for further monitoring and evaluation of the corner reflector effectiveness;

convenient tools for estimating statistics of backscatter level changes for linearly polarized and cross-polarized data.

Results

This paper presents the description, deployment method, and monitoring results of four corner reflectors. The first two reflectors (0.5 m and 1 m triangular corner reflectors) were installed temporarily as test samples. Based on the experience gained and the known research results, which are highlighted in scientific works and reports, two corner reflectors were designed for continuous monitoring: 1 m trihedral triangular corner reflector, and 1 m quadruple corner reflector.

1. A triangular 0.5 m corner reflector (Fig. 1), is made of 3 mm-thick aluminum sheets. It is securely fixed to the concrete base and has a mechanism for inclination angle adjusting in a range from 0° to 15°.

Fig. 1. Triangular corner reflector with 0.5 m inner leg length

The reflector was installed temporarily, for the period from March 17, 2023 to September 30, 2023. The determined parameters for the orientation of the corner reflector: azimuth 99°; the elevation angle for the reflector's boresight - 48°. The relation between the boresight angle and elevation of the lower plate of the reflector is equal 35.3°. Thus, vertical position installation is made by adjustment of 12° inclination of the lower plate of the corner reflector to the horizon. In this way, the orientation onto the descending orbit of the Sentinel-1 satellite was made.

Fig. 2 shows the graph of the change in backscatter (dB) of the vertically polarized signal of the Sentinel-1 satellite. The graph represents the statistics for the reflector installation point over the last two years.

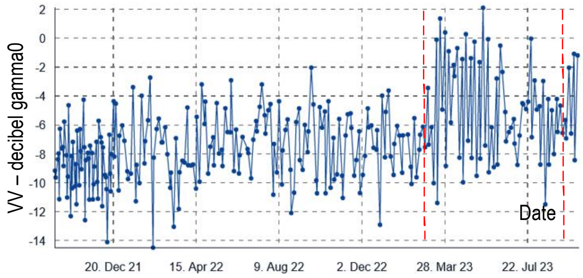

Fig. 2. Backscatter intensity time series for the location of corner reflector (0.5 m). The time span on the timeline is 2 years (30.09.21-30.09.23). The period of the corner reflector deployment (17.03.23-30.09.23) bounded by red dashed lines

The backscatter time series for the point where the reflector was deployed was obtained from the EO Browser. Therefore, the graph represents the backscatter value from all available radar images obtained over the given area. A sharp change in the amplitude between consecutive values occurred due to a change in the orientation of the satellite's radar by 180° when it passes an ascending or descending orbit.

We can see from the graph that the average level of backscatter is close to -8 dB. This value is slightly higher than the intensity of backscattering for an undeveloped area which varies in the range (-10; -15 dB). This is due to the presence of artificial structures (buildings, fences) at a distance of several tens of meters from the place of the reflector installation.

At the end of March 2023, we observed an increase in the intensity of backscatter to the level (-2; +2 dB), which corresponds to the deployment period of the corner reflector (March 17, 2023). A small corner reflector (0.5 m) in combination with a sufficiently high background backscatter provided an intensity increase of only 8 dB. In addition, during the period of operation of the reflector from June to September 2023, the graph shows two moments of rapid decrease in the level of backscattering. They are associated with periodic flooding of the reflector after summer rains.

The experience of using this reflector allowed us to draw the following conclusions. Sheet aluminum with 3 mm thickness provides the necessary rigidity of the reflector structure and preserves its geometric parameters. The light weight of the product, corrosion resistance, and low cost are favorable to use the aluminum. Despite the compact dimensions of the 0.5 m corner reflector, which is convenient for engineering objects and structures, it does not create sufficient backscatter in SAR images. At the same time, the idea of using compact reflectors should not be rejected. The large size of the reflector can be compensated by several small reflectors, arranging them into an array of convenient configuration [Kelevitz et al., 2022]. It is crucial to provide a system to prevent flooding of the corner reflector. In its absence, the reflector will be filled with water or snow every now and again, which sharply reduces the efficiency of its work. The simplest way to organize such a system is to create drainage in the form of perforations on the lower plate of the reflector [Garthwaite et al., 2015].

2. The triangular 1 m corner reflector (Fig. 3), is made of galvanized steel sheets with a thickness of 0.55 mm. It was installed temporarily for conducting additional research for the period 17.03.2023-01.07.2023.

Fig. 3. Triangular corner reflector with 1.0 m inner leg length

It was located a few tens of meters from the previously described reflector. Therefore, the orientation parameters for the Sentinel-1 satellite, which made acquisition from a descending orbit, were the same (azimuth 99°; boresight elevation angle 48°). In fig. 4 shows the time series of changes in the intensity of backscattering at the place of installation of the reflector over two years (15.07.2021-15.07.2023)

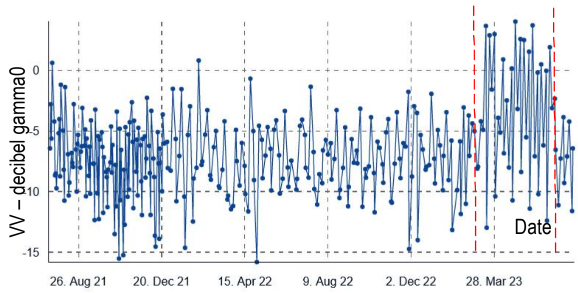

Fig. 4. Backscatter intensity time series for the location of corner reflector (1.0 m). The time span on the timeline is 2 years (15.07.21-15.07.23). The period of the corner reflector deployment (17.03.23-01.07.23) bounded by red dashed lines

The average value of backscatter for the investigated period is -8 dB. The graph clearly shows the period of the corner reflector installation, which provided an increase in intensity up to +4 dB. The achieved backscatter intensity is a good indicator for a 1 m corner reflector, but with an average background scattering value of -8 dB, it may not be sufficient to ensure the necessary accuracy of determining vertical movements by the InSAR method. The obtained results are an example of the necessity for a preliminary assessment of the backscattering level for the territory at the stage of choosing the reflector's position.

The experience of using this reflector confirmed the possibility of implementing a structure made of galvanized metal with a thickness of 0.55 mm. At the same time, one must consider additional works to create a frame that will provide the necessary geometric parameters, in particular, the orthogonality of the planes. As it was in the previous reflector, the need for a drainage system remains.

3. A triangular 1.0 m corner reflector for permanent use (Fig. 5) is made taking into account previous experience. Material – 3 mm thick aluminum sheet; the edges are additionally reinforced with

aluminum corners. The reflector was installed on a concrete pad. The peculiarity of this corner reflector is the protective screen made of plexiglass, which completely covers the working face of the reflector (directed on the satellite) and prevents rainwater, snow, dirt, and foreign objects from getting inside. Due to the presence of a protective screen, maximum autonomy of the reflector is ensured.

Fig. 5. Triangular corner reflector with 1.0 m inner leg length and antiflood protective screen, deployed in Berezhany

The corner reflector was deployed on October 10, 2023, on the territory of the practice base of the Institute of Geodesy (Lviv Polytechnic National University) in the city of Berezhany. It is oriented towards the ascending orbit of the Sentinel-1 satellite for constant monitoring of the territory by the InSAR method. The co-location of the GNSS station on the training building will provide additional data for the interpretation of SAR monitoring results. Fig. 6 presents a graph of the change in the intensity of backscattering at the place of the reflector installation over two years (13.11.2021-13.11.2023).

Before installing the reflector in a permanent place, the level of backscattering in this area was previously analyzed. The absence of structures or other objects near the place of installation ensured a low level of backscatter intensity. According to the data for the last two years (Fig. 6), the average level of backscatter was -13 dB. After the deployment of the corner reflector on October 10, 2023, the intensity increased to +3.7 dB. From the graph, we can see not only a confident increase in the backscatter intensity by 15 dB but also the stability of these values in consecutive images. Due to the protective screen, these values are expected to remain consistently high in the future.

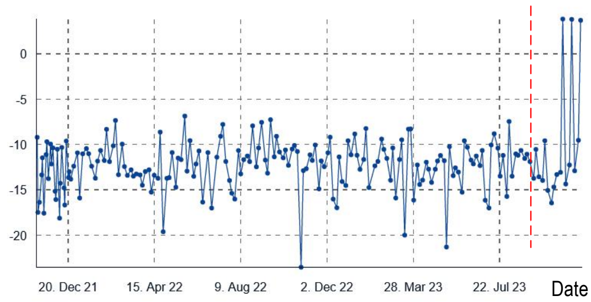

Fig. 6. Backscatter intensity time series for the location of 1.0 m corner reflector in Berezhany. The time span on the timeline is 2 years (13.11.21-13.11.23). The date of the corner reflector deployment (10.10.23) is marked by a red dashed line

4. Trihedral corner reflectors, which consist of three planes of a simple shape (triangle, rectangle, quarter circle), can be combined into more complex configurations. Such kind of reflectors combine two, four, eight or more trihedral reflectors in order to increase the radar cross section and improve its "visibility" from different directions.

The quadruple corner reflector (Fig. 7) consists of four adjacent quarter-circle trihedral reflectors. It was designed as a universal reflector for all possible sensors that will conduct SAR monitoring. Unlike trihedral corner reflectors, which have limited bandwidth and are oriented to the ascending or descending orbit of the satellite, the quadruple reflector provides an increase in backscatter intensity on radar images taken from different flight directions.This reflector is made of a 3 mm thick aluminum sheet and additionally reinforced with aluminum corners. The length of the inner edge of the reflector is 1 m. Perforations in the vertical plates of the reflector were made to increase the wind resistance. The diameter of the holes is selected according to the recommendations of [Garthwaite et al., 2015] and is 5 mm, which does not exceed 1/6 of the X-band radar wavelength.

A quadruple corner reflector was installed on the Tereble-Ritska HPP dam on July 15, 2023 for constant radar monitoring. In fig. 8 presents a graph of the change in the backscattering intensity at the place of the reflector's installation over a year (15.11.2022-15.11.2023)

Fig. 7. The quadruple corner reflector with 1.0 m inner leg length, deployed at the dam of Tereble-Ritska HPP: a) view 1; b) view 2

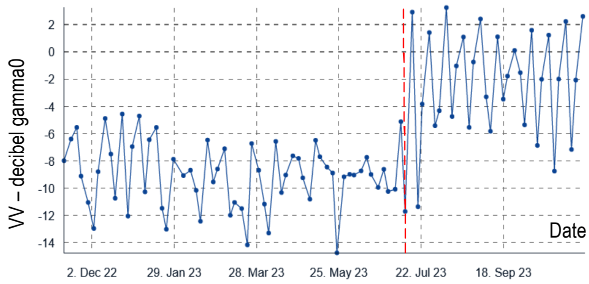

Fig. 8. Backscatter intensity time series for the location of quadruple corner reflector (1.0 m) at the dam of Tereble-Ritska HPP. The time span on the timeline is 1 year (15.11.22-15.11.23). The date of the corner reflector deployment (15.07.23) is marked by a red dashed line

Differences in the design of a quadruple corner reflector from common trihedral corner reflectors are reflected in the results of the intensity of back-scattering at the place of its deployment. From the graph, we can see that after installing the quadruple reflector, the intensity of backscattering increased in all radar images. This is explained by the effective reflection of the signal in all directions over the given territory. As a result of the deployment of the reflector on the HPP dam, the backscatter intensity, which was in the range (-14; -4 dB), has increased and varies within (-8; +2 dB). The maximum value reaches 3.2 dB.

The quadruple reflector has a flat bottom face that is attached to a horizontal base. This design will not fill with rainwater. To avoid snow accumulation, a protective dome was installed over the reflector.

Scientific novelty and practical significance

The presented results confirm the effectiveness of using corner reflectors to increase the intensity of backscatter on SAR images. Tested and improved designs of reflectors can be used when developing a network for continuous monitoring. This will ensure millimeter accuracy in determining the spatial movements of the earth's surface and engineering structures by the InSAR method.

Conclusions

Unlike natural reflectors of radar signal, artificial corner reflectors can be purposefully installed in locations where information about spatial movements is required.

It was established that a triangular trihedral 1 m corner reflector reliably increases the intensity of backscatter by 10 dB. According to the theory, this makes it possible to achieve the accuracy of vertical movement determination of 1 mm by the InSAR method. Such theoretical calculations require experimental studies based on long-term monitoring of reflectors, which will be the subject of further research.

The autonomy of the reflector of this design is easily ensured by installing a protective screen that prevents water, snow, and dirt from collecting in the corner reflector.

The application of a triangular 0.5 m corner reflector does not provide the necessary level of backscattering intensity. However, the use of an array of several compact reflectors can be effectively used in areas with limited space, such as engineering facilities and structures.

It has been practically confirmed that the quadruple corner reflector is a universal tool for increasing backscatter intensity, at the point of its deployment, for the maximum number of sensors that conduct SAR acquisition from different orbits.

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ДОСВІД РОЗГОР×АННЯ НАЗЕМНИХ КУ×ОВИХ ВІДБИВАЧІВ ДЛЯ СУПУ×НИКОВОГО РАДІОЛОКАЦІЙНОГО МОНІ×ОРИНГУ

Мета цієї роботи – аналіз ефективності розгортання наземних кутових відбивачів різних розмірів та конструкцій для проведення радіолокаційного моніторингу супутником Sentinel-1. Методика. ×очність визначення просторових рухів поверхні методом InSAR у місцях розгортання кутових відбивачів залежить від їхнього розміру, а також співвідношення сигнал-шум на радіолокаційних знімках. ×ому при проектуванні положення кутового відбивача попередньо виконано оцінку інтенсивності зворотного розсіювання вибраної території на радарних знімках. В місцях розгортання наземних кутових відбивачів прагнули забезпечити збільшення зворотного розсіювання не менше ніж на 10 dB. Орієнтування кутових відбивачів виконувалось на основі даних про параметри орбіти супутника Sentinel-1, які отримано з веб-ресурсу Heavens Above. Оцінку зміни рівня інтенсивності зворотного розсіювання на радіолокаційних знімках проводили із застосуванням онлайн-платформи EO Browser. Результати. Досліджено ефективність розгортання та моніторингу тригранних трикутних кутових відбивачів розміром 0,5 м та 1 м. Результати досліджень дали змогу узагальнити досвід розгортання тимчасових кутових відбивачів та використати його для проектування конструкцій відбивачів для постійного моніторингу засобами радіолокаційного зондування. Максимальна автономність та постійне значення ефективної площі розсіювання трикутного кутового відбивача забезпечена завдяки обладнаному захисному екрану, що перешкоджає потраплянню атмосферних опадів всередину відбивача. На відміну від тригранних кутових відбивачів, які зорієнтовані на висхідну або низхідну орбіту супутника, круговий чотиригранний кутовий відбивач забезпечує підвищення інтенсивності зворотного розсіювання на радіолокаційних знімках, зроблених з різних орбіт та різними супутниками. Круговий чотиригранний відбивач, який було розгорнуто для постійного моніторингу, характеризується як універсальний відбивач для усіх можливих сенсорів, що проводитимуть радіолокаційне знімання. Наукова новизна та практична значущість полягають у підтвердженні ефективності використання наземних кутових відбивачів для підвищення інтенсивності зворотного розсіювання на радіолокаційних знімках. Апробовані та удосконалені конструкції відбивачів можуть бути використані при створенні мережі для постійного моніторингу, що дозволить забезпечити міліметрову точність визначення просторових рухів земної поверхні та інженерних споруд методом InSAR.

Ключові слова: InSAR, тригранний кутовий відбивач, чотиригранний відбивач, ефективна площа розсіювання, Sentinel-1, EO Browser

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