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Routine monitoring of hydraulic infrastructures using the European Ground Motion Service and other satellite radar sensors

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Abstract

Ensuring the safety and operational efficiency of hydraulic infrastructures is paramount, considering the widespread consequences

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that damages can inflict on people, communities, and the environment. To mitigate risks and prevent significant losses, continuous surveillance is vital. While some damages might appear minor, they can jeopardize the complete operational reliability of dams, leading to substantial economic losses, especially in energy production and related activities. The rapid growth in 20th-century infrastructure development globally has made security monitoring a necessity for numerous civil structures. Rigorous inspection programs, particularly for reservoir dams, are essential for safeguarding citizens and their properties. However, individually monitoring each dam is often impractical due to the associated costs and time constraints, potentially posing safety risks. Fortunately, satellite-based differential radar interferometry (DInSAR) offers an effective and cost-efficient remote sensing solution. Multi-temporal Interferometric Synthetic Aperture Radar (MT-InSAR) techniques, particularly utilizing Persistent Scatterers, have proven successful in monitoring various infrastructures, natural phenomena, and geological activities. MT-InSAR provides precise measurements without the need for fieldwork, utilizing historical SAR image archives dating back to the 1990s. Technological advancements, such as the Sentinel-1 C-band with a six-day revisit time until the end of 2021, have enhanced monitoring capabilities. Additionally, commercial radar images in the X-band and the development of multi-interferometric InSAR techniques have opened new avenues for monitoring. This study showcases the adaptation and application of MT-InSAR for monitoring dams and large ponds constructed with loose materials. By assessing vertical displacements and consolidation rates, the technique identifies potential issues, aiding in further field investigations. Case studies involving dams and large reservoirs in Andalusia illustrate the effectiveness of satellite radar interferometry in monitoring their structural stability from space as a routine practice.

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Keywords: InSAR; Dam monitoring; Satellite radar interferometry; EGMS; PAZ; Sentinel-1.

1. Introduction

Global trends are changing rapidly the needs and requirements of water supply systems in the world, especially in regions where droughts are increasing in the last decades [1-2]. Dams are essential for the provision of water and energy and need to be urgently adapted to ongoing changes. Dam construction and management is one of the main adaptation strategies to climate change. Dams are critical infrastructures whose failure has high economic and social consequences. These infrastructures have an associated risk that must be properly managed through a continuous and updated process [3-4]. The rapid variations in factors driving dam risks are likely to make traditional surveillance programs no longer appropriate for long-term dam safety management [5-7].

The widespread aging of dams and some recent collapses worldwide have highlighted the importance of developing effective monitoring strategies to identify structural health problems before they become critical and endanger public safety. Moreover, the rapid pace of development has led to the establishment of many linear-shaped structures such as reservoir dams. Spatial steadiness and operational security of these man-made facilities are becoming the focus of attention since their abnormal deformation may indicate risks developing within or around these structures. We should not forget the latest catastrophes in Spain, such as the failure of the Tous dam in Valencia in 1982, leaving 25 people dead or the Aznalcóllar disaster, with the rupture of a mining waste basin in the Doñana Natural and National Park, causing a major ecological disaster. There is a need, therefore, for reliable and secure monitoring and management systems adapted to dam and manager needs. New systems should integrate the best available technologies to ensure reliability, efficiency, and profitability in social and economic dimensions.

InSAR (Interferometric Synthetic Aperture Radar) is a geomatic technique used to measure and monitor the Earth's surface. It relies on processing two SAR images to detect surface deformation over large areas with high spatial density. InSAR faces challenges due to changes in scattering properties and radar angle, limiting its applicability. However, time series SAR interferometry, also known as multi-interferogram techniques, has emerged to overcome these limitations. This method utilizes Persistent Scatterers (PS) with stable backscattering characteristics to create long time series of SAR images, enabling accurate deformation measurements. Despite atmospheric and topographic effects impacting measurements, DInSAR (Differential Interferometry) is a powerful tool for describing deformation patterns in geosciences. SAR sensors provide day-and-night imagery independently of weather conditions, making them valuable for Earth Observation. Various space agencies operate SAR missions, each with different wavelength bands affecting interference properties. Sentinel-1 is a notable civilian sensor designed for large-scale surface deformation monitoring, providing free and open data. The availability of SAR data depends on the operating sensors, revisiting time, data acquisition policy, and baselines, affecting the feasibility of InSAR for deformation monitoring. In recent years, satellite radar interferometry has significantly improved using large stacks of SAR images over the same area, enabling the identification of stable reflectors called persistent scatterers (PS). PS allow precise ground displacement measurements (millimeter accuracy) and are found on man-made structures and stable natural reflectors. MT-InSAR algorithms, such as Persistent Scatterer InSAR (PSI) and Small BASeline (SBAS) approaches, overcome atmospheric artifacts and model deformation. PSI assumes a time-dependent model for each PS, while SBAS uses short time interval interferograms to minimize decorrelation. Both techniques achieve uncertainties of around ~1 mm/year. All measurements are made in the satellite line of sight (LOS) relative to a reference point or area, enabling the development of time series of deformation. Ongoing research examines the accuracy, potential, and limitations of these methods for various applications. For more details, refer to Crosetto et al., Osmanoglu et al., Ho Tong Minh et al., and Xue et al. [8-11].

The European Ground Motion Service (EGMS) is a comprehensive geodetic monitoring initiative that employs advanced remote sensing techniques to observe and analyze ground movements across European regions [12]. By employing state-of-the-art multi-temporal InSAR methodologies, EGMS offers timely and reliable detection of early signs of geodetic phenomena, including subsidence, landslides, and other ground instabilities [13]. The service aids decision-makers and local authorities in implementing proactive measures to mitigate potential risks and safeguard critical infrastructure and natural resources. As a complementary component to existing geodetic and geological monitoring systems, EGMS enhances the overall understanding of ground motion dynamics, supporting comprehensive risk management strategies and fostering the safety and resilience of communities and environments across Europe.

Recently, we have initiated a research project aimed at monitoring the structural health of dams and large ponds located in the Andalusia region, southern Spain, using space-based technology. The project aims to create an integrated monitoring system incorporating modeling and artificial intelligence (AI) for effective anomaly detection. The primary objectives of this project include the development and implementation of a next-generation monitoring and management system for hydraulic infrastructures, with a focus on enhancing security and reducing incidents through improved early warning systems. Additionally, the project seeks to optimize infrastructure efficiency and preventive maintenance, leading to increased profitability by reducing the costs associated with in-situ control instrumentation. Furthermore, the research aims to enhance maintenance efficiency across all phases of the infrastructure's lifecycle.

To develop this project, we are making use of multi-temporal InSAR technology to analyze ground deformation over these hydraulic infrastructures. The European Ground Motion Service (EGMS) is firstly utilized as a starting point for our project to promote its usage and secondly, to provide a historical analysis from 2014. Subsequently, it is being complemented with ad-hoc multi-temporal InSAR processing, extending the temporal series up to the latest acquisitions from Sentinel-1, as well as other X-band satellite sensors such as TerraSAR-X and PAZ. Additionally, high-resolution digital elevation models are being derived using UAVs to enhance the InSAR processing results. This work presents an initial status of the project, outlining the methodology, satellite data, and preliminary outcomes.

2. Study areas

Several embankment dams and large ponds are proposed to be studied in this project, all of them located in Andalusia (southern Spain) (Fig. 1). For several reasons, dam managers, as the main public institutions responsible for the management and surveillance of these infrastructures have shown their interest in their monitoring.

Fig. 1. Location of the studied dams and large ponds in Andalusia (southern Spain).

3. Data and Method

In this section, we present the different data sets and describe the processing methodology.

3.1. Satellite Data

In our research, we utilize Copernicus Sentinel-1A/B C-band synthetic aperture radar (SAR) data provided by the European Space Agency (ESA) and the European Commission (EC). These twin satellites, Sentinel-1A and -1B, offer SAR images with a short revisit time of 12 days. When their data are combined, the revisit time is reduced to 6 days, but only in the period 2016-end of 2021, where Sentinel-1B ended its mission. In line with Copernicus's policy, these data are freely and openly accessible. We use the SAR data in Interferometric Wide (IW) swath mode using Terrain Observation with Progressive Scan, allowing for wide area coverage with an image size of 240 km x 170 km. For our analysis, we selected SAR images with vertical polarization (VV) and processed independent sets of Sentinel-1A/B data acquired along ascending and descending orbits. The spatial resolution for these single-look complex (SLC) IW images at the incidence angles is 3.4 m x 22 m (range x azimuth), with a ground sampling of 3.3 m x 13.9 m (range x azimuth). In addition, we also use PAZ and TerraSAR-X X-band data with HH polarization and the following image modes: Stripmap with a spatial resolution of 1.76 m x 3.01 m (range x azimuth), Spotlight with a spatial resolution of 1.18 m x 1.46 m (range x azimuth), and high-resolution Spotlight with a spatial resolution of 0.6 m x 1.05 m (range x azimuth).

3.2. UAVs Data

High-resolution DEMs are being provided using UAV photogrammetry. For that, we use a DJI Mavic 3 Multispectral UAV with a 20MP 4/3 CMOS RGB camera, four 5 MP multispectral cameras, sunlight sensor, RTK module for centimeter-level positioning, 43-minute max flight time, 200-hectare coverage in one flight, fast charging, and O3 transmission up to 15 km.

3.3. Multi-Temporal InSAR

Firstly, in this project, we use the products from the European Ground Motion Service (EGMS) to conduct an initial inventory of the movement of dams, large reservoirs, and surrounding areas. The Basic and Calibrated products provide excellent information about the stability of these study areas. While the product updates are currently available up to December 31, 2021, there are plans to extend the temporal series annually in the future. EGMS employs and processes Sentinel-1 data at full resolution, utilizing a 6-day revisit time whenever possible and processing both ascending and descending images. The Basic products include maps of mean deformation in the Line-of-Sight (LOS) direction and temporal series using the first date as the temporal reference and a virtual point as the spatial reference, representing the average of all measurement points within a stable zone located within each burst. The Calibrated products are particularly noteworthy as they produce the same outputs as the Basic products but are adjusted to the movement of permanent GNSS stations across Europe. Both Basic and Calibrated products are offered at a full resolution of 14 x 4 m. Finally, the system provides Ortho products, which deliver maps of mean deformation and temporal series in vertically and east-west decomposed directions. These Ortho products are generated with a 100 x 100 m grid and serve as a global indicator of the deformation field but are not suitable for infrastructure monitoring purposes due to the width of the grid.

In addition to the products from the European Ground Motion Service (EGMS), this project involves multi-temporal processing using PS-InSAR with the SARPROZ software [14]. SARPROZ is a comprehensive and versatile software designed for processing and analyzing synthetic aperture radar (SAR) data, particularly for interferometric SAR (InSAR) applications. Developed by Daniele Perissin, SARPROZ offers a wide range of tools and functionalities for advanced InSAR processing and geodetic applications. It enables the creation and analysis of time series from multi-temporal SAR data, allowing users to monitor ground displacements over extended periods. The topographic phase component is removed using the different DEMs as SRTM 1-arcsec, Copernicus 30 m, and high-resolution UAVs-derived.

4. Results and conclusions

As an example of the Calibrated products from EGMS, Figs. 2 and 3 show the deformation maps for large ponds and dams. In particular, Fig. 2a and 2b show the mean LOS velocity and time series for the ascending and descending tracks at full resolution for Cadimo pond in the province of Jaén visualized at ±5 mm/year interval. On the other side, Fig. 3a and 3b show the mean LOS velocity maps and time series for the ascending and descending orbits in the case of Vadomojón dam in the province of Córdoba visualized ±10 mm/year interval and, finally, Fig. 3c and 3d show the same maps visualized at ±20 mm/year interval for Siles dam in the province of Jaén. A landslide can be denoted on the right margin of this dam. In all of these cases, the deformation pattern is perfectly registered by the multi-temporal InSAR technique showing subsidence in the central part of the dam with LOS velocity values up to -25 mm/year. These results provide an example of the inventory maps obtained for each dam and large pond where the historic deformation from 2014 up to the end of 2021 is provided as an initial stage in the project.

Fig. 4 shows the results of the processing of almost 1 year of high-resolution Spotlight PAZ data with 1-m resolution using SARPROZ. The multi-temporal PS-InSAR method shows a higher density of measured points with high temporal coherence. In both the ascending and descending tracks, the slight subsidence pattern in the central part of the dam body is detected with a mean LOS velocity close to -4 mm/year.

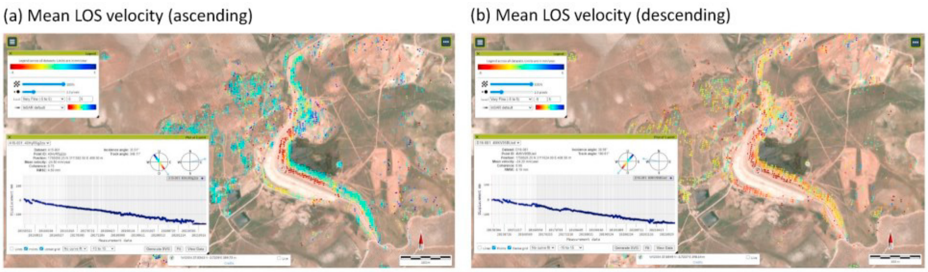

Fig. 2. Mean LOS velocity for the ascending and descending tracks for Cadimo pond (a and b). Source: EGMS.

Fig. 5 shows an example of a high-resolution DEM obtained with a resolution of 10 cm over the Vadomojón dam using photogrammetry with UAVs. Similar DEMs will be derived for other dams and ponds.

Finally, Fig. 6 shows the results of the multi-temporal PS-InSAR processing using SARPROZ for the Siles dam located in the province of Jaén with Sentinel-1A/B data from 2014 until the end of 2022. In this case, the cumulative LOS displacement shows a non-linear behavior in the deformation history of the central part of the dam for the ascending and descending tracks. In the same way, the landslide located at the right margin of the dam is clearly visible.

Similar studies have been carried out by different authors where the effectiveness of multitemporal InSAR techniques for the monitoring of this type of infrastructures and the analysis of deformations over time has been demonstrated [15-19].

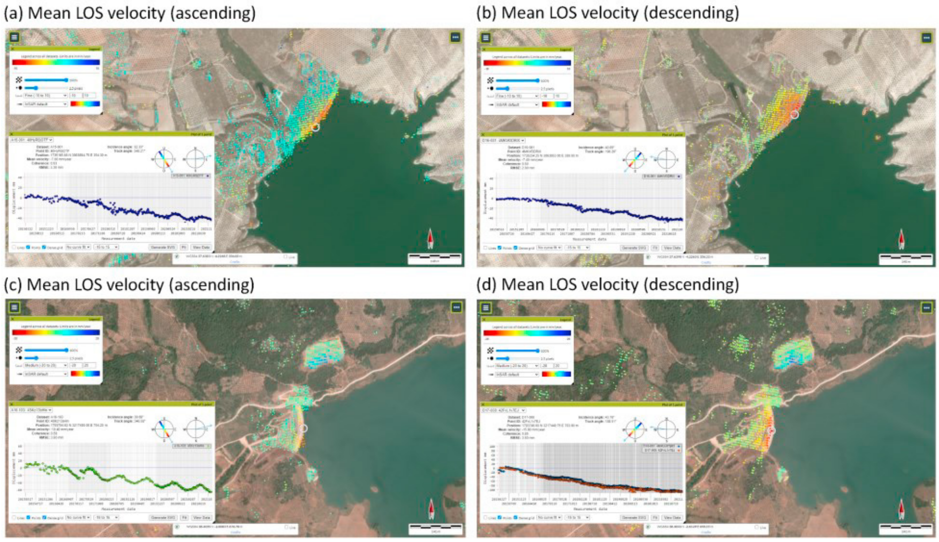

Fig. 3. Mean LOS velocity for the ascending and descending tracks for Vadomojón dam (a and b) and Siles dam (c and d). Source: EGMS.

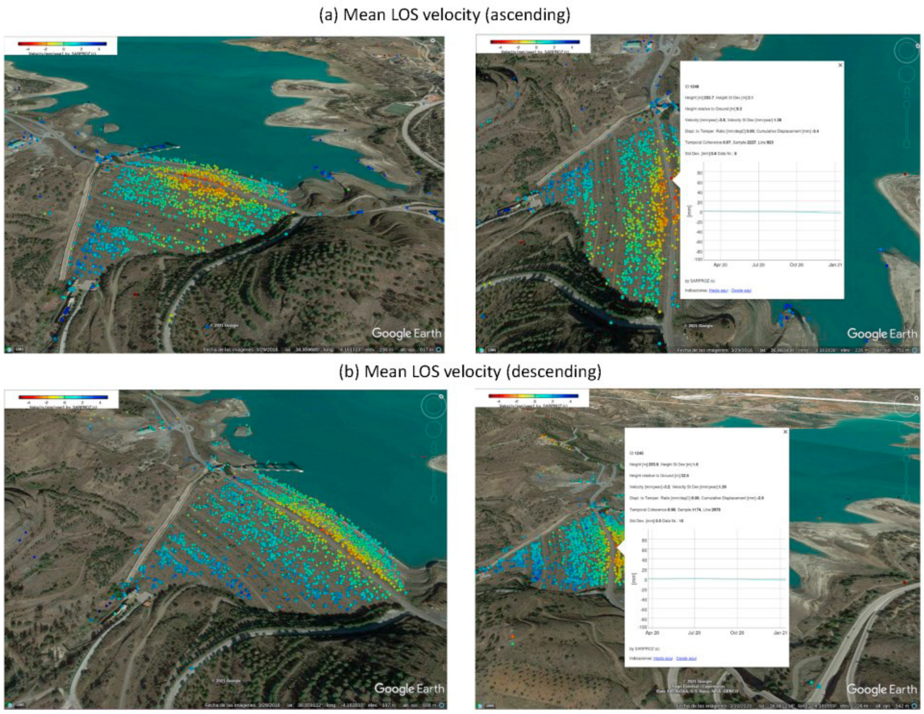

Fig. 4. Mean LOS velocity for the ascending and descending tracks for La Viñuela dam using high-resolution Spotlight PAZ data.

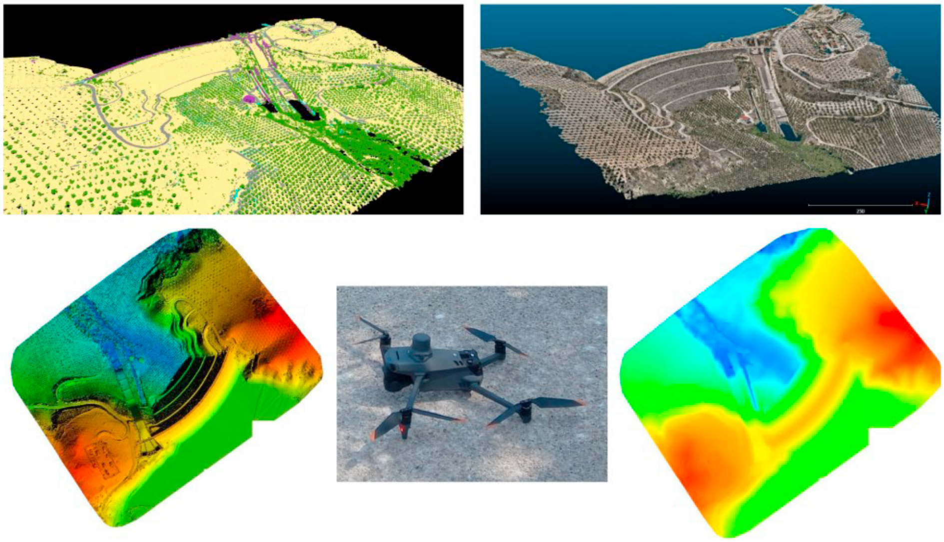

Fig. 5. 3D views of a high-resolution DEM derived for Vadomojón dam using a DJI Mavic 3 Multispectral UAV.

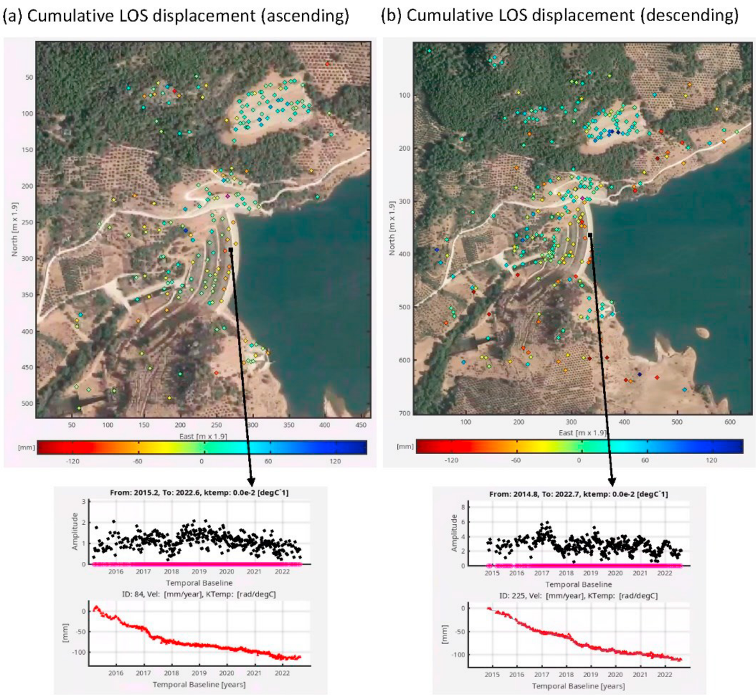

Fig. 6. Cumulative LOS displacements for the ascending (a) and descending (b) tracks over Siles dam processed with SARPROZ.

In conclusion, this study presents the current status of a research project aimed at exploring the applicability of multi-temporal InSAR techniques for monitoring hydraulic infrastructures. Several dams and large ponds of interest to their managers have been selected for analysis. The European Ground Motion Service (EGMS) was used as the initial tool to assess the behavior of these structures from 2014 until the end of 2021, providing an initial inventory of their movements. In addition, PS-InSAR processing was conducted for each structure using Sentinel-1A/B data and, when available, X-band data and high-resolution digital elevation models. This project will continue to analyze these infrastructures with interferometric techniques, developing mathematical models to describe their movements. In the second phase, the project will integrate various technologies, including topographic auscultation and geotechnical devices, into a pilot case with the aim of creating management-oriented models for monitoring and predicting movements in these infrastructures. Additionally, artificial intelligence (AI) will be introduced for early detection of anomalies.

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