5th Joint International Symposium on Deformation Monitoring (JISDM), 20-22 June 2022, Valencia, Spain
DOI: http://doi.org/10.4995/JISDM2022.2022.13883

Monitoring embankment dams from space using satellite radar interferometry: Case studies from RemoDams project

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Key words: *dam monitoring; deformation; MT-InSAR; embankment dams; satellite radar interferometry*

ABSTRACT

The monitoring procedures with different geotechnical/structural sensors and classical geodetic techniques including GNSS are the usual practices in most of the dams where these controls are established. Other geomatic techniques such as TLS, GB-SAR and multi-temporal InSAR (MT-InSAR), allow the determination of 3D displacements with the advantage of covering a large number of control points. In particular, MT-InSAR techniques enable the detection of displacements at a very low cost compared to other techniques, and without the need for field work or the installation of special equipment. In addition, they can provide a single source of information on the stability of the dam when monitoring programs are not carried out due to lack of funding, resources or other reasons. These techniques provide measurement uncertainties of the order of 1 mm/year, interpreting time series of interferometric phases of coherent reflectors present in the area, called Persistent Scatterers. In this work, we present the adaptation and application of MT-InSAR techniques to monitor embankment dams, obtaining vertical displacements, characterizing their consolidation rates, and allowing the identification of potential problems surrounding the reservoir that require further field investigation. This study is part of the ReMoDams project, a Spanish research initiative developed for monitoring dam structural stability from space using satellite radar interferometry.

I. INTRODUCTION

After experiencing huge infrastructure development activities in the 20th century, many engineering infrastructures in the world require security monitoring. Detailed inspection plans and monitoring these infrastructures (such as reservoir dams) are critical to ensure the security of citizens and properties. These interventions are usually expensive and time-consuming. In many cases, resource constraints make practically impossible to monitor each infrastructure individually, which may represent a potential safety risk.

Global changes are rapidly transforming the needs and requirements of water supply systems in the world, especially in areas where drought has increased in recent decades (Estrela *et al*., 2012; Forero-Ortiz *et al*., 2020). Dams are an important part of the water cycle infrastructure, which can provide our society with water, energy and food, and need to urgently adapt to the ever-changing environment. The construction and management of dams is one of the main strategies to adapt to climate change. Dams are critical infrastructures, and their failure has high economic and social consequences, although usually very low, there exist related risks that must be properly managed in a continuously updated process (ICOLD, 2003; Fluixá-Sanmartín *et al*., 2018). The rapid changes in the factors leading to dam risks may make traditional monitoring programs no longer suitable for long-term safety management of dams (Bowles *et al*., 2013; USBR, 2016; USACE, 2016).

A reliable and safe monitoring and management system suitable for the characteristics of the dam and the manager's needs is needed. The required system should integrate the best available technology to ensure social and economic reliability, efficiency and profitability.

Monitoring the deformation of large man-made structures is essential to avoid catastrophic infrastructure and loss of life. Many structures that need to be monitored may span hundreds of meters, such as dams, and tens of kilometers, such as dikes and embankments. The widespread deterioration of these man-made structures and some recent collapses (Dam failure, n. d.) highlight the importance of developing effective structural monitoring strategies that can help identify structural problems before they become serious and endanger public safety problem. In addition, the rapid pace of development has led to the establishment of a large number of linear structures, such as reservoir dams. The spatial stability and operational safety of these man-made facilities have become the focus of attention because the deformation implies potential hazards or risks in or around these structures.

Measuring and monitoring the deformation of these man-made objects and structures is the key task of applied geodesy and geomatics. However, although these deformation measurement technologies are undoubtedly very accurate and reliable, they are based on detecting changes in specific points and require prior investment of human resources or special equipment. Deformation monitoring schemes may target different deformation schemes and mechanisms, and therefore may be very different. For example, laser alignment, laser scanning, total station, leveling and inverse plummet are widely used in dam deformation monitoring. These specialized equipments are sometimes integrated with Global Navigation Satellite System (GNSS) for specific surveillance purposes.

In the past few years, international researchers have made great efforts to find an effective method to monitor the deformation of man-made structures. However, dam monitoring is still a difficult task. As far as dams are concerned, due to the high risks they represent, the supervision work is supervised by the competent national bodies. The main goal of public supervision is to ensure that the safety level of dams and auxiliary structures is uniform, so as to ensure that they do not pose a threat to life, property or the environment. The rapid development of space technology in recent decades has enabled to detect the displacement of the earth's surface from space with high accuracy, which has brought unexpected results to earth observation and related research. This progress has been made due to the development of microwave images obtained through synthetic aperture radar (SAR) mounted on satellites and multi-temporal interferometry (MTI or MT-InSAR) technology. MTI has the potential to support the development of new and more effective methods for monitoring and analyzing the health of dams, and to increase redundant monitoring at low cost to support and assist early warning systems. With the help of SAR interferometry, specific dams can be monitored to identify and investigate suspiciously displaced targets on a monthly (ERS, Envisat and Radarsat data) or weekly (TerraSAR-X, COSMO-SkyMed, PAZ and Sentinel-1) time scales. As a result, timely detection of potential problems can help mitigate their impact on structural health and reduce infrastructure repair costs. In addition, there are two main characteristics that make interferometric technology attractive to the scientific community. The first is that it provides a high-resolution two-dimensional representation of the deformation from 10 s to more than 200 s kilometers. The second is the high accuracy of the deformation that can be measured (up to 1 mm/year) (Hooper *et al*., 2012). In addition, in some cases, the data can be analyzed retrospectively to obtain past deformation information.

In this paper, we present some case studies of the monitoring of embankment dams. They belong to ReMoDams project, a research Spanish initiative devoted to the application of MT-InSAR techniques for monitoring dam structural stability from space using satellite data.

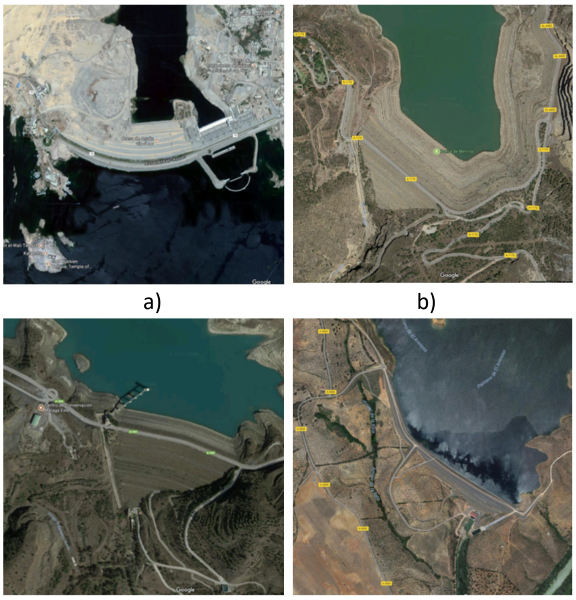
II. Study area – Test sites

With the aim of remote monitoring of their structural health from space using satellite radar interferometry, four dams were selected. One of them (The Aswan High Dam) is located in Egypt and the others (Benínar, La Viñuela and El Arenoso dams) in southern Spain (Figure 1).

a) b)

Figure 1. Location maps of the study areas: a) Egypt; b) Spain. (Source: Google Maps).

The Aswan High Dam (Egypt) (Figure 2a) is one of the major artificial structures ever built. This dam, which construction finished in 1979, has 3600 m in length and is 1000 m wide at the base. It is a rockfill dam that forms an artificial lake (Lake Nasser) covering, at maximum capacity, an area of 5250 Km^2, storing a water volume of 135 Km^3. Nasser Lake was created as a result of the construction of the Aswan High Dam across the waters of the Nile between 1958 and 1970. It is located in a very active tectonic area mainly because of the complexity of its fault system. The safety of dams during earthquakes is extremely important because the failure of such structures may have disastrous consequences on life and property. Therefore, different factors must be considered as part of a site assessment.



a) b) c) d)

Figure 2. a) The Aswan High dam; b) The Benínar dam; c) La Viñuela dam; d) El Arenoso dam. (Source: Google Maps).

Benínar dam (Almería, Spain) (Figure 2b) is located on the Grande de Adra River, in the Andalusian municipality of Benínar, in the Almería province. Today, the village of Benínar is submerged under the waters of the reservoir and administratively depends on Berja Town Hall. The dam whose construction finished in 1983 was built with loose materials, with distinct profile inclined impervious core, and rockfill shoulders. It has a height of 87 m and a length of 400 m; the reservoir has a volume of 68,2 hm^3. Its catchment area (521 km^2) affects the provinces of Granada and Almería on its eastern and western boundaries. Population water supply and irrigation are the main use of this dam. According to water flow records and geotechnical studies, this dam has always had water leakage issues since it was constructed.

La Viñuela dam (Málaga, Spain) (Figure 2c) is located on the Guaro River in the municipality of La Viñuela and stores inflows from the hydrographic network of the region of La Axarquía. It was built to supply water to the region and to improve irrigation. The basin of La Viñuela reservoir has a surface of 119 km^2, an average yearly rainfall of 893 mm, and an average yearly contribution of 25 hm^3. It is an embankment dam of mixed plant, having a crest length of 460 m and heights of 90 and 96 m over riverbed and foundations, respectively. The reservoir has a capacity of 170 hm^3. Its construction finished in 1989. The main purposes of this dam are to supply drinkable water to the urban centers of the eastern Costa del Sol, between Málaga and Nerja, the irrigation of 8000 ha of subtropical and extra-early horticultural crops, and potentially, to supply the city of Málaga.

El Arenoso dam (Cordova, Spain) (Figure 2d) is located in the Arenoso riverbed, a tributary of the Guadalquivir on the right bank, in the Andalusian municipality of Montoro, province of Cordova. Its reservoir has a capacity of 166,97 hm^3 and an area of 764,12 ha. It is an embankment dam, with a central clay core, slates, and greywacke shoulders. The core is covered downstream by a filter material, and upstream by a transition material. It also has a cofferdam with a similar section and materials, which remains leaning against the dam's body. The dam has a maximum height of 80 m, a crest length of 1481 m, and a coronation width of 11,30 m. The construction of the dam increased the water available in the Guadalquivir which improved the economic and social development of the Guadalquivir basin. Its construction finished in May 2008.

III. Data and Methods

A. *Insar data*

For this study, we used different satellite SAR data. In this paper, we present the results of medium resolution C-band SAR data (~5,7 cm wavelength) that come from the European satellites ERS-1/2, Envisat, and Sentinel-1A/B. ERS-1/2 SAR and Envisat ASAR that have been used to reconstruct historical time series of deformation in the different dams where they were available. ERS-1/2 SAR data allow us to monitor the deformation in the period 1992-2000 and Envisat in 2002-2010. In the case of Sentinel-1A/B satellites, the -1A started the mission in 2014 and -1B in 2016. When both satellites -1A and -1B are combined, they offer a 6-days revisit time. All the SAR data are in SLC format, and in the case of Sentinel-1A/B we used the

Interferometric Wide (IW) swath mode. Table 1 summarizes the different data sets used for each test site.

B. *Methods*

InSAR relies on the processing of two SAR images of the same part of the earth's surface. These images are obtained from two slightly shifted passes of the SAR antenna at different times (repeated-pass interferometry), or from two antennas being placed on the same platform and separated perpendicularly to the flight path (single-pass SAR interferometry). However, despite the many successes of InSAR, the applicability of this technology is limited by the problems caused by the time-varying scattering characteristics of the earth's surface and the incidence angle in the direction of the radar's line of sight. This especially makes the detection of slow deformation processes challenging to detect with the standard InSAR techniques.

In the late 1990s, it was noticed that certain radar targets maintained stable backscatter characteristics for months or years, as well as the phase information from these stable targets (hereinafter referred to as "Persistent scatterer" or PS) can be used, even for a long period of time, profiting from a SAR scene archive in existence since 1991 (ERS-1) which allows the establishment of long time series of SAR images. This led to the development of time-series SAR interferometry methodology, or also known as multi-interferogram technology (MTI or MT-InSAR). Because of their ability to overcome the limitations of conventional InSAR, they are becoming more and more popular being considered currently as standard deformation measurement tools.

MT-InSAR is an extension of conventional DInSAR, which aims to solve the problems caused by decorrelation and atmospheric delay. These techniques involve processing multiple SAR acquisitions simultaneously on the same area to correct for uncorrelated phase noise terms, thereby reducing errors related to distortion estimation. MT-InSAR is a collective term used in the InSAR community to distinguish between a single interferogram DInSAR and the second-generation InSAR technology. The first of these methods appeared in 1999 as the Permanent Scatterer algorithm (PSInSAR™) (Ferretti, 2001). The interferogram is the core of all MT-InSAR technology, and the main driving force for its development is the need to overcome the error in the signal phase value introduced by atmospheric artifacts. These limitations can be resolved by using the phase behavior in time to select the pixels with minimal decorrelation noise. Then, the undistorted signal is estimated through a combination of time series modeling and filtering. MT-InSAR algorithms are divided into two categories, the first is Persistent Scatterers InSAR (PSI or PS-InSAR), and the second is the more general Small BASeline (SBAS) method. Each of these methods is designed for a specific type of scattering mechanism.

The main spaceborne medium resolution C-band SAR sensors used for deformation monitoring include ERS-1/2, Envisat, and Sentinel-1 from ESA (Europe), and Radarsat-1/Radarsat-2 from CSA (Canada). Among all these sensors, Sentinel-1 is the first (civilian) sensor specially designed for large-area surface deformation monitoring, being their data completely open for any user/application. Modern spaceborne SAR sensors can provide a spatial resolution of about 1 meter or lower. In high-resolution X-band SAR data (TerraSAR-X, TanDEM-X, COSMO-SkyMed, PAZ, ICEYE, and Capella), even small dams are covered by a large number of pixels. These data are being tested for structural health monitoring (SHM) applications, and the results are very satisfactory. The new generation of high-resolution radar images acquired by SAR sensors and the development of advanced MTI algorithms can retrieve the deformation time series and velocity maps from a stack of SAR images acquired at different times in the area. In recent years, our ability to use MTI technology for high-precision deformation monitoring has been enhanced and is related to engineering infrastructure. With the advent of even more advanced MT-InSAR processing technology that combines both PS and SBAS methods, these sensors have been used to monitor the deformation of a series of natural and man-made structures, including large structures such as dams and dikes. Several tests carried out with different types of structures have helped to establish a standard procedure for structural monitoring using interferometric techniques, and it can be concluded that although the temporal and spatial resolution of the C-band is relatively coarse (Sentinel-1 greatly improves this state), it can be used to monitor major structures, including dams. Obviously, it was quickly discovered that the geometric resolution of satellite images (X-band with 0.5-1 m) did not match the size of typical defects, such as in concrete dams (0.01-0.5 m). Therefore, it is not possible to use SAR satellite images to identify problems such as cracking and raveling; however, the only spaceborne sensor that can help structural inspections by measuring deformation is the synthetic aperture radar. Several tests conducted by research and working teams have shown the potential of C-band SAR interferometry technology in dam monitoring (Sousa *et al*., 2016; Lazecky *et al*., 2017; Delgado-Blasco *et al*., 2017). The application of radar interferometry technology may potentially reduce in millions of euros the operating costs of monitoring structure tasks, while providing more detailed and frequent monitoring, which will inevitably lead to better security conditions.

Regardless of the method used, all measurements are made in the satellite LOS and are relative to a reference point or area. Once the data are analyzed, it is possible to develop the movement history (deformation time series) of the entire region of interest. This is achieved by sequentially calculating the relative displacement between a single radar target and the reference point throughout the analysis period. Therefore, deformation is relative in time and space. A lot of research has been conducted to study the accuracy, potential, and limitations of this technology in a variety of applications. Xue *et al*. (2020) and Ho Tong Minh *et al*. (2020) offer a review of these multi-interferogram algorithms. Table 2 summarizes the different MT-InSAR methods and software used in this study with the different data sets.

IV. Result and Discussion

In the case of The Aswan High Dam, we performed both PS-InSAR and SBAS processing as well as the combination of them using StaMPS-MTI software with Envisat descending images. Figure 3 shows a subsidence zone in the central part of the dam with a mean LOS velocity around -3 mm/year at the crest. In addition, it has also been detected a slope subsiding in the east bank 1 km north of the dam. The analyzed period is from 19/12/2003 to 03/09/2010.

Sentinel-1A/B ascending images were processed using a classical PS-InSAR approach using SARPROZ. The stability of the dam is confirmed in the period 01/05/2015 - 26/10/2021 showing LOS velocities lower than –3 mm/year (Figure 4). To investigate the expected theoretical subsiding behavior due to the material consolidation through time a preliminary calculation of stress-strain modeling of the dam has been performed using Limit Equilibrium Method (LEM) and Finite Element Method (FEM). It has been done along the wider section on the river axis since it is the most unfavorable due to the hydraulic load. According to this model, a possible vertical deformation of 22.8 cm is obtained. This estimated settlement is caused by the secondary consolidation or fluency from 1970 to present without considering the settlement during the construction of the dam or other external influences from other sources such as the power plant attached to the dam.

Table 1. C-band SAR data sets used in this study. The number of images for each stack, the orbit direction (ascending or descending) as well as the time span are indicated

Dam	ERS-1/2	Envisat	Sentinel-1A/B	
Aswan	---	31 descending 19/12/2003 - 03/09/2010	319 ascending 01/05/2015 - 26/10/2021	
Benínar	22 descending 06/06/1992 - 31/10/2000	32 ascending 02/12/2002 - 29/06/2010	192 ascending 10/11/2014 - 07/03/2019	188 descending 16/11/2014 - 01/03/2019
La Viñuela	24 descending 05/02/1992 - 28/01/2000	27 ascending 21/03/2003 - 01/08/2008	309 ascending 03/10/2015 - 24/02/2021	303 descending 16/03/2015 - 24/02/2021
El Arenoso	---	---	194 ascending. 03/03/2015 - 28/02/2019	188 descending 16/11/2014 - 01/03/2019

Table 2. C-band SAR data sets used in this study. The number of images for each stack, the orbit direction (ascending or descending) as well as the time span are indicated

Dam	ERS-1/2	Envisat	Sentinel-1A/B	
Aswan	---	PSI+SBAS; StaMPS-MTI	PSI SARPROZ	
Benínar	PSI+SBAS; StaMPS-MTI	PSI+SBAS; StaMPS-MTI	PSI; SARPROZ	PSI; SNAP-StaMPS
La Viñuela	PSI+SBAS; StaMPS-MTI	PSI+SBAS; StaMPS-MTI	PSI; SARPROZ	PSI; SARPROZ
El Arenoso	---	---	PSI; SARPROZ	PSI; SARPROZ

a) b)

Figure 3. a) Mean LOS velocity derived from Envisat ASAR data over The Aswan High dam (2003-2010); b) Location of a possible landslide 1 km north of the dam (red pixels in the center of the image).

Figure 4. Mean LOS velocity derived from Sentinel-1A/B ascending data over The Aswan High dam (2015-2021).

For the case of Benínar dam, we processed C-band images from ERS-1/2, Envisat, and Sentinel-1A/B ESA satellites, covering a period of more than 25 years, that is, from 1992 to 2019. The ERS-1/2 (06/06/1992-31/10/2000) and Envisat (03/12/2000-29/06/2010) data sets were processed using a combination of these two MT-InSAR methods PSI and SBAS using StaMPS-MTI software. The ascending Sentinel-1A/B data set (10/11/2014-07/03/2019) was processed using a PSI analysis with SARPROZ software (Perissin, 2022) while the descending one (16/11/2014-01/03/2019) was processed with SNAP-StaMPS using a PSI analysis.

Construction works of the dam were initiated in 1974 and concluded in 1983, although it was not finally put into service until 1988, following various projects to waterproof the base. Nowadays, after 32 years since its construction, it is clear that this dam has not satisfied expectations due to severe leakage that has occurred through the reservoir bottom. The complex and unfavorable geological characteristics, together with an initial concept that made little effort to integrate the possibilities of surface and groundwater resources, gave rise to this failure. In early 1991, the authorities revised the initial focus of the regulatory project and took action to tap the water that was escaping into the underlying carbonate aquifer into which the reservoir water is draining (García-López *et al.*, 2009). Figure 5 shows the mean LOS velocity maps for ERS-1/2 and Envisat data sets. The results indicate a subsiding zone in the central part of the dam with a mean LOS velocity in the order of -3/-5 mm/year in all periods (ERS-1/2: 1992-2000, Envisat: 2002-2010 and Sentinel-1A/B: 2014-2019) (Figure 5). This behavior is partially coherent with the dam typology (earth fill) but the expected attenuation in time is not observed. Currently, mathematical modeling of the dam is being performed to investigate the expected theoretical subsiding behavior due to the material consolidation through time. The obtained results must be validated/compared to this stress-strain analysis to know if the measured satellite deformation matches the expected one for this kind of dam. In the same way, some investigations are being carried out to get information from field measurements over the dam as well as other geotechnical monitoring systems which may help to prove the effectivity of this remote sensing technique.

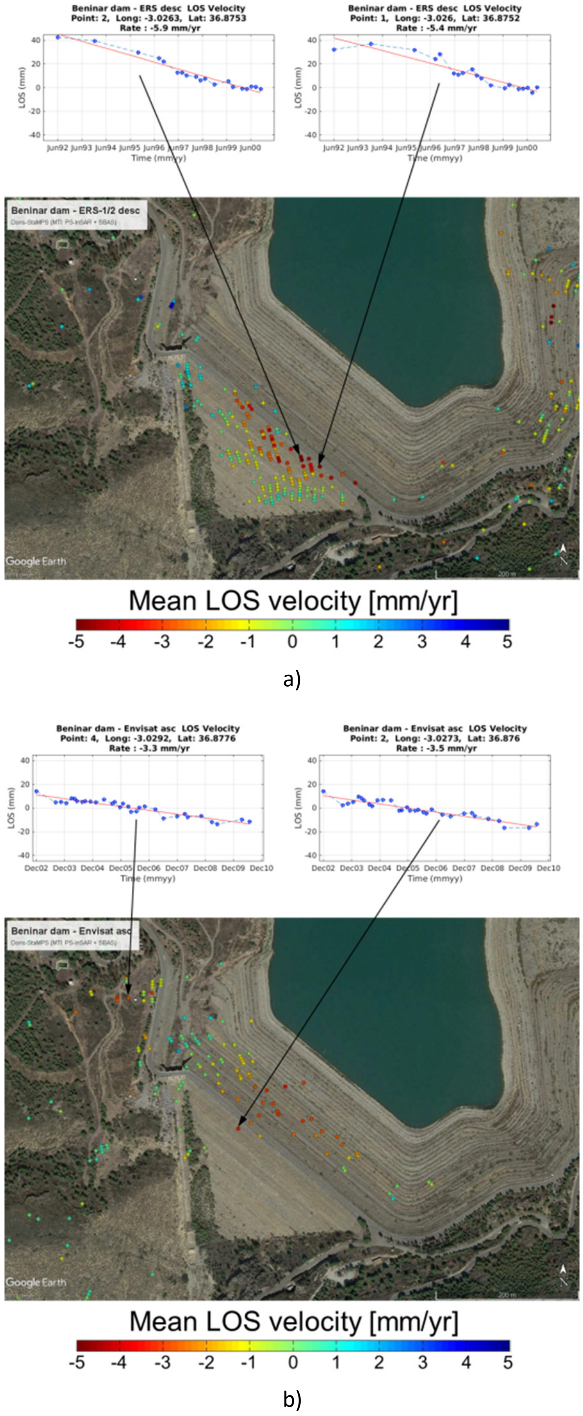


Figure 5. Mean LOS velocity maps over the Benínar dam: a) ERS-1/2 desc (1992-2000); b) Envisat asc (2000-2010).

In the case of La Viñuela dam, we used C-band radar data from the European satellites ERS-1/2, Envisat, and Sentinel-1A/B. The ERS-1/2 (02/05/1992-28/02/2000) and Envisat (21/03/2003-01/08/2008) data sets were processed using StaMPS-MTI (PSI + SBAS). The ascending and descending Sentinel-1A/B images (2015-2021) were processed using the standard PSI analysis using SARPROZ. Mean LOS velocity maps for ERS-1/2 and Envisat were derived from StaMPS-MTI processing. Both results correspond to the combined (PSI+SBAS) processing. In the case of ERS-1/2, a subsidence pattern can be clearly detected with maximum subsidence around -7 mm/year on the crest of the dam. In the Envisat period, the subsidence pattern is lower, with maximum subsidence in the order of -4 mm/year. The standard deviations of the LOS velocity are quite low, in the order of ±1 mm/year. The standard PSI approach from SARPROZ with the linear model assumption for the deformation estimates confirmed that the investigated area of the dam's body is prone to subsidence of up to -5 mm/year (LOS velocity) in the whole monitoring period of Sentinel-1 (2015-2021) (Figure 6).

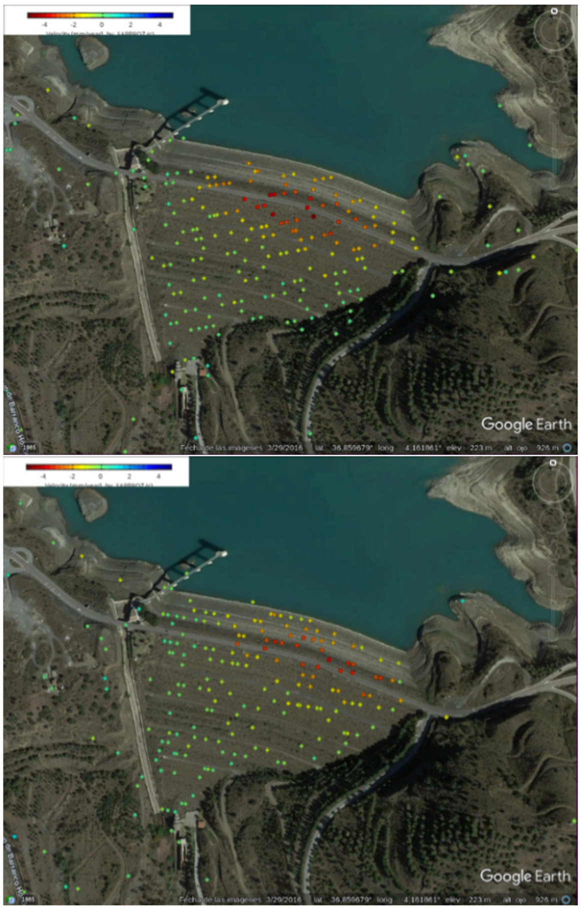


Figure 6. Mean LOS velocity maps over La Viñuela dam in the period 2015-2021. Top: ascending. Bottom: descending.

Finally, in the case of El Arenoso dam, we selected and processed two independent sets of Sentinel-1A/B SAR images acquired along ascending and descending orbits. The ascending set is composed by 194 (03/03/2015-28/02/2019) and the descending one by 188 (16/11/2014 – 01/03/2019) SAR images. The processing was done using the standard PSI technique using SARPROZ. Figure 7 shows the mean LOS velocity maps for both ascending and descending data sets. The general picture is quite similar. According to the depicted patterns, both tracks indicate the presence of a subsiding sector in the crest of the dam reaching linear values of the order of -8/-10 mm/year which represents cumulative displacement in the LOS direction up to about -40 mm in 4 years.

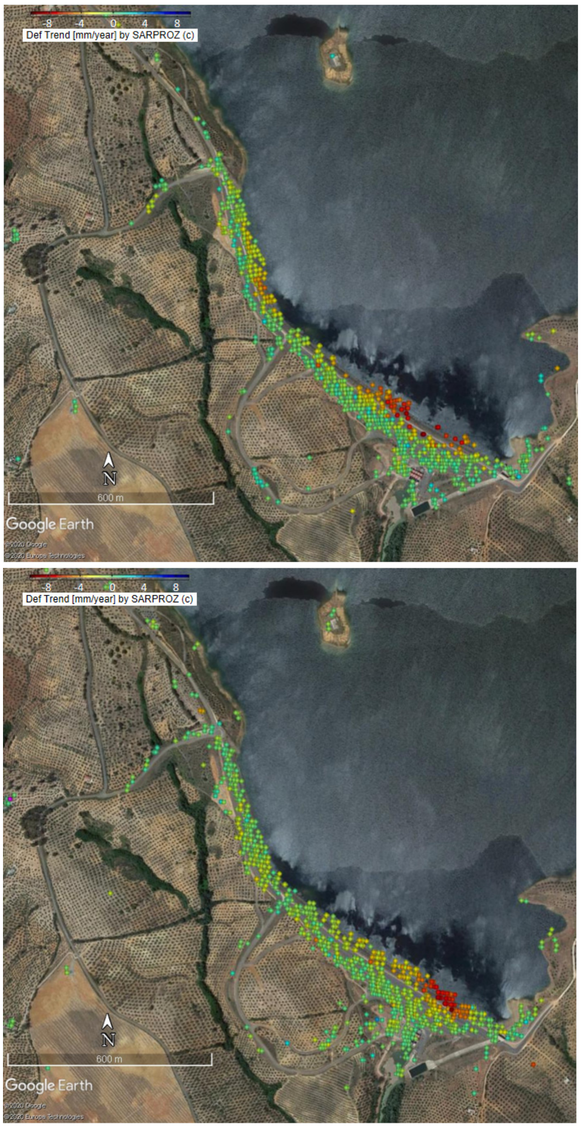


Figure 7. Mean LOS velocity maps over El Arenoso dam in the period 2015-2019. Top: ascending. Bottom: descending.

V. Conclusions

In this work, we present the applicability of satellite radar interferometry for deformation studies in civil engineering, in particular, for monitoring embankment dams. Different case studies are presented in the framework of ReMoDams project, a Spanish research initiative to monitor dam infrastructures from space using satellite radar interferometry, such as The Aswan High dam in Egypt, and Benínar, La Viñuela and El Arenoso dams in southern Spain. Today, MT-InSAR can be considered a consolidated technique whose effectivity for deformation studies has been proved in many cases. For infrastructure monitoring, if there is SAR data available of the study area, the technique is demonstrated to be of high value at a very low cost as compared with classical geodetic monitoring techniques. In case of other geotechnical or geodetic data are available, they can be successfully complemented.

We also show the potential of SAR long time series scenes and the MT-InSAR technique for deformation monitoring in some important infrastructures such as dams. To our best knowledge, this study represents the first attempt to monitor the presented dams using this technology. The MT-InSAR results indicate different deformation periods in all the analyzed dams with rates of subsidence in the LOS direction of -10 mm/year maximum.

This is an ongoing project that will be extended in the future analyzing more SAR data provided from these medium resolution C-band SAR images and incorporating high-resolution X-band data to increase the potential of the technique. Continuous processing of InSAR information could be successfully integrated in regular structural monitoring programs as a component of the implementation of early warning systems.

VI. Acknowledgements

ERS-1/2 and Envisat data sets were provided by the European Space Agency (ESA). Sentinel-1A/B data were freely provided by ESA through Copernicus Programme. Data have been processed by DORIS (TUDelft), StaMPS (Andy Hooper), SARPROZ (Copyright (c) 2009-2020 Daniele Perissin), and SNAP (ESA). The satellite orbits are from TUDelft and ESA, as well as from the ESA Quality control Group of Sentinel-1. Research was supported by: (a) ESA Research and Service Support for providing hardware resources employed in this work, (b) ReMoDams project ESP2017-89344-R (AEI/FEDER, UE) from Spanish Ministry of Economy, Industry and Competitiveness, POAIUJA-2021/2022 and CEACTEMA from University of Jaén (Spain), and RNM-282 research group from the Junta de Andalucía (Spain), (c) ERDF through the Operational Programme for Competitiveness and Internationalisation - COMPETE 2020 Programme within project «POCI-01-0145-FEDER-006961», and by National Funds through the FCT – Fundação para a Ciência e a Tecnologia (Portuguese Foundation for Science and Technology) as part of project UID/EEA/50014/2013, (d) The Ministry of Education, Youth and Sports from the National Programme of Sustainability (NPU II) project «IT4Innovations excellence in science - LQ1602» (Czech Republic), and (e) Slovak Grant Agency VEGA under projects No. 2/0100/20.

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