VALIDATION OF IN-SAR TECHNOLOGY TO CONTROL DEFORMATION AND MOVEMENTS IN CONCRETE DAMS

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ABSTRACT

Space-borne Synthetic Aperture Radar Interferometry (InSAR) has been generally used to monitor wide-area to local scale ground motions with up to millimetre accuracy or to generate medium to very high-resolution digital elevation models.

As far as dams are concerned, InSAR has been applied for monitoring deformations in embankment dams and this method offers accuracy in vertical displacements. However, it has never been tested yet to measure planimetric displacements in concrete dams.

In this sense, two concrete dams (La Aceña Dam and El Atazar Dam) placed in the North of Madrid have been analysed with InSAR for a time range of 2 years to valid this technology and the results are promising. The movement detected with InSAR fits with pendulum measurements under a 1.5-3 mm of error.

Comparing both, it can be said that InSAR provides millimetric data that is consistent with the settlement patterns expected. Thus, the methodology can give reliable data with little variation and high temporal and spatial resolution for dams.

This methodology is an innovative method to improve the inspections and maintenance processes. By using processing techniques to a series of a radar images over the same region, InSAR technology may be useful as hot spot indicator of relative deformations structures over large areas and different time period (including past eras) making possible to monitor the health of dams.

Finally, the application of InSAR will undoubtedly keep growing because it improves the security standards during the maintenance of dams and must be taken into consideration.

1. INTRODUCTION AND OBJETIVES

Observing the Earth from the space is experimenting big changes and a continuous improvement of the obtained information, both in terms of the spatial components (new satellites and better observation sensors which results in better spatial, temporal and spectral resolution), as well as in applications that increases the value of the information captured by satellites.

The availability of systematic and high-quality Earth observation datasets, the freedom to access them (without limitation of use or monetary) opens a wide range of possibilities of developing value-added applications for many sectors, including safety and explotation of dams.

One of the applications of satellite observation in the dams's field is the detection of millimeter movements through InSAR techniques (Synthetic Aperture Radar Interferometry). By applying the InSAR technique it is possible to detect vertical displacements in large dams of loose materials and monitor slopes nearby the reservoirs. However, it has not been possible to show the feasibility of the InSAR technique for the calculation of planimetric deformations in concrete dams.

The aim of this paper is to validate the InSAR technique for measuring radial displacements in concrete dams by comparing the measurements obtained with InSAR techniques and the traditional measurements obtained with auscultation devices in two concrete dams located in Spain (La Aceña and El Atazar), which are part of the Supply System of Canal de Isabel II (CYII).

2. SAR INTERFEROMETRY

The SAR technology has been recognized as a promising tool to obtain cartographic information because it uses active sensors and clouds are transparent on that electromagnetic spectrum, which ensure a guaranteed acquisition of the area of interest (AOI). In particular, the SAR image interferometry demonstrated its capacity to give supplementary information regarding compared with traditional optical sensors.

Now-a-days, SAR interferometry is one of the most promising applications when it comes to radar image processing due to its application on infrastructure monitoring and topographic information (ground deformations, subsidence, accurate Digital Elevation Models, bridges and viaducts control, etc) That is the reason why there is a substantial amount of papers describing from the theoretical point of view each of the necessary processes to generate numerical models of terrain elevations with this technique .

The SAR interferometry principle is based in the comparison between two images of the same scene. They can be taken by two spatially separated antennas or by two time-separated frames taken with a single antenna (this option was used for this study case). To compare both images, there are some considerations that must be taken:

First, there are orbital disturbances (the satellite does not follow exactly the same orbit in each observation), so the waves reflected by the terrain travel different paths.

This signal path difference can be quantified by measuring the phase difference of the waves. The height of each point also introduces a path difference in the waves observed in the two images. Therefore, the phase difference of the observed waves from each of the orbital positions is used to derive the altimetric information.

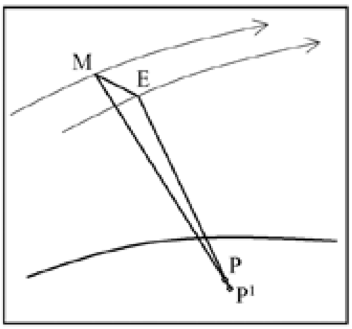

Figure 1 : Geometry of the SAR interferometry. Source: Own

When the point on the floor moves forms P to P1 (Figure 1) between the two collected frames, the phase difference or interferometric phase $\Delta\Phi_{Int}$ is:

$$\Delta\Phi_{Int} = \Phi_E - \Phi_M = \frac{EP - MP}{\lambda} + \frac{EP^1 - EP}{\lambda} + \Phi_{Atm} + \Phi_{Noise} = \Phi_{Topo} + \Phi_{Mov} + \Phi_{Atm} + \Phi_{Noise} \quad \text{...(1)}$$

Where Φ_E = principal phase image; Φ_M = secondary phase; E = sensor position in the principal image; M = sensor position in the secondary image; EP = distance from P to E; MP = distance from M to P; EP^1 = distance from E to P^1; λ = radar wavelength; Φ_{Topo} = topographic phase component; Φ_{Mov} = displacement phase component; Φ_{Atm} = atmospheric phase component; Φ_{Noise} = noise phase component.

DEM Generation

If there is no deformation between two phases ($\Phi_{Mov} = 0$), the atmospheric phase component is negligible ($\Phi_{Atm} \cong 0$) and the noise phase is smaller than the topographic phase component ($\Phi_{Noise} << \Phi_{Topo}$), then it is possible to obtain information topographic information from Φ_{Topo}, obtaining the DEM of the AOI.

The precision in the altimetric calculation depends on the spatial separation between the orbits of each image used in the interferometry process. With 100 m of separation, 2π phase transition means a height difference of 100 m. It is possible to use wider spatial separation, but the noise would increase and the coherence decrease, so the next processing step (unwrapping) would be more difficult.

Terrain displacements control (DInSAR)

If there is a DEM of the AOI, then it is possible to calculate the topographic phase component Φ_{Topo} and subtract it from the interferometric phase $\Delta\Phi_{Int}$, resulting the Differencial Interferometric phase (DInSAR):

$$\Delta\Phi_{D\text{-}Int} = \Delta\Phi_{Int} - \Phi_{Topo} = \Phi_{Mov} + \Phi_{Atm} + \Phi_{Res\_Topo}\ \Phi_{Noise} \quad \text{...(2)}$$

Where $\Phi_{Res\_Topo} =$ residual topographic error component due to the DEM used.

If both Φ_{Atm} y Φ_{Res_Topo} are negligible and the noise phase component is smaller than the terrain movements ($\Phi_{Noise} << \Phi_{Mov}$), then from Φ_{Mov} is possible to obtain information about the terrain movements, making a deformation map.

In this case, the precision in the movement calculation does not depend on the spatial separation. 2π phase transition means a 5.7 cm movement. It must be said that the atmospheric and noise components are not taken into consideration.

The interferometric process is similar for both cases, only during the unwrapping the phase variations are understood as heights or as distance.

PSI (Persistent Scatterer Interferometry)

PSI represents a specific class of the Differential Interferometric Synthetic Aperture Radar (DInSAR) techniques. Such techniques exploit the information contained in the radar phase of at least two complex SAR images acquired in different times over the same area, which are used to form an interferometric pair. The repeated acquisition of images over a given area is usually performed with the same sensor or sensors with identical system characteristics.

With appropriate data processing and analysis procedures, PSI technique separates Φ_{Mov} from the other phase components. The analysis calculates the coherence of each pixel and estimates the deformation velocity in those pixels with more quality. Finally, the deformation between the two images of the interferogram is evaluated by eliminating the atmospheric phase component. Furthermore, it is also possible to preselect the stable pixels by analyzing amplitude instead of coherence.

To get a high coherence feature (value from 0 to 1) that ensures the reliability of results, a consider number of scenes is needed.

3. SENTINEL 1 SATELLITE

The European Space Agency (ESA), through the Copernicus programme, has the most ambitious Earth observation satellite constellation in history, designed to provide accurate and up-to-date information, to improve environmental management, understand and mitigate the effects of climate change and guarantee citizen security.

The Copernicus program has several satellite fleets to cover different missions. In this study case, as radar information is needed, the fleet used was Sentinel-1.

This mission is made up of a constellation of two twin satellites that acquires synthetic radar images in the C-band. Sentinel-1 is in a near-polar, sun-synchronous orbit, so it has an ascendant direction (from South hemisphere to North hemisphere) or descendent direction if it travels the other way. Because radar data is not affected by atmospheric or daylight conditions, the monitoring of the earth's surface is constant.

The Sentinel-1A was launched on April 3, 2014 and its twin Sentinel-1B on April 25, 2016. Each of them has 12 day repeat cycle and 175 orbits per cycle for a single satellite. Both Sentinel-1A and Senitnel-1B share the same orbit plane with a 180 ° orbital phasing difference. With both satellites operating, the repeat cycle is 6 days.

- Altitude: 693 km. Inclination: 98.18º. Period: 98.6 min. Cycle: 12 days.
- Ref. tube derivation: ± 100 m. Dual polarization (VV + VH or HH + HV)
- Interferometric Wide Swath mode (IWS): 240 swath, 5 m x 20 m resolution, single-look

Azimuth Angle

When the Sentinel 1 satellite advances, it sends lateral impulses and gets images of the Earth´s surface that is on the right side of its flight direction. Consequently, Sentinel 1 is able to measure displacements in the perpendicular direction to its path. Therefore, since Sentinel 1's orbit is polar, only those dams with its face oriented to the East (for the ascending case the azimuth is ± 349.9824º) or the West (for the descending case the azimuth is ± 189.3563º) can be considered

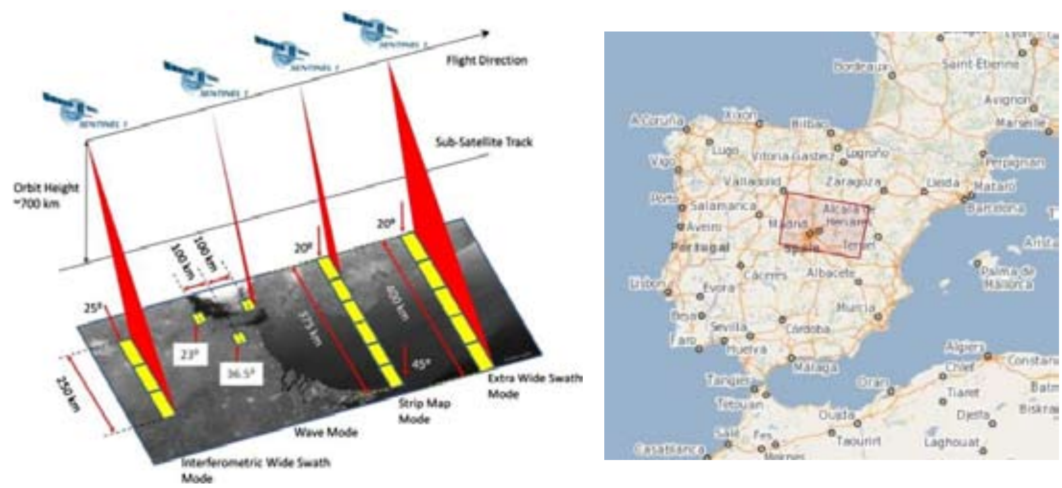

Figure 2 : Sentinel 1 Flight Direction. Source: NASA

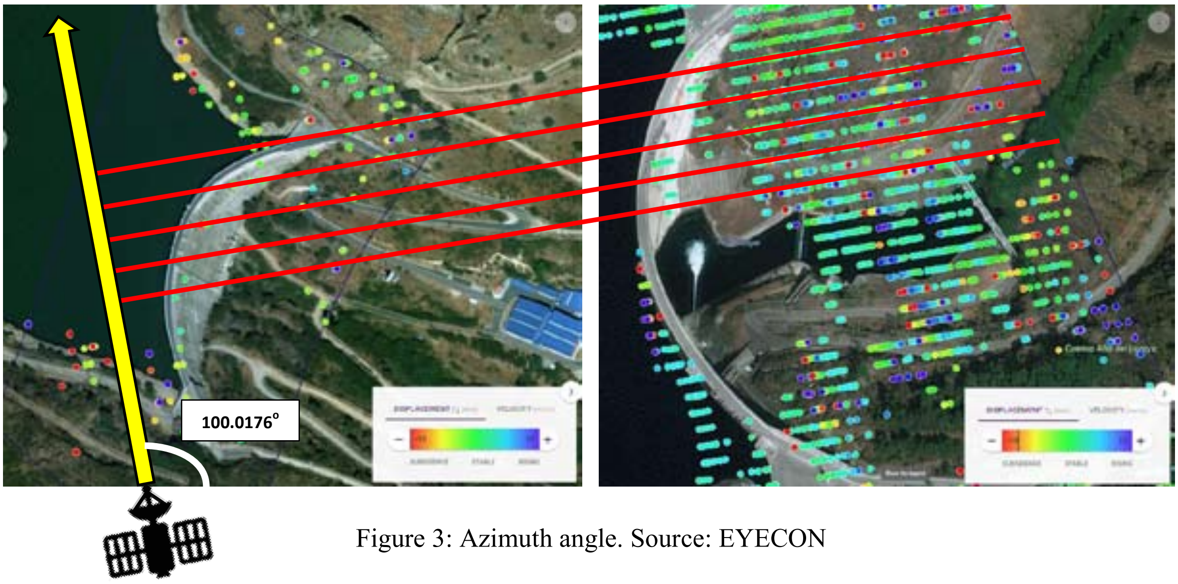

Figure 3: Azimuth angle. Source: EYECON

On the other hand, the measurement of displacement obtained from the DInSAR analysis is in the direction of the satellite. As already mentioned, Sentinel 1 observes the AOI obliquely, so to be able to compare the displacements obtained with DInSAR with those measured by the pendulums, it is necessary to decompose the resulting measure in the axial direction of the dam. The angle between the observation direction and the Earth is 39.19º ascending direction and 39.35º descending direction.

4. DAMS CONSIDERED

La Aceña Dam is located on the Aceña River, a tributary of the Tagus River in central Spain. It is part of the Peguerinos town council in Ávila province. This arch-gravity dam is made of concrete, being a maximum of 68 m height over the foundation. The upstream face is vertical and the downstream face has a 0.4 slope. The dam crest is 1319 m above sea level, 340 m long and 6 m wide. It has two traffic lanes, each 2.25 m wide, and two 0.75 m sidewalks.

The dam has four pendulums, all of them direct (hanging), giving information about the displacements of the dam crest in relation to the two inspection galleries where the reading devices are located. The great slenderness of this dam amplifies the radial movements caused by the annual cycles of water loading and temperature. These movements are about 35-40 mm. Today the radial movements of La Aceña dam are being monitored using three different technologies: direct pendulums, DGPS and precise angular collimation.

El Atazar Dam is located on the Lozoya River, nearby confluence of the Jarama and Lozoya rivers. It is located near Patones town in the North of Madrid. The dam, made of concrete, has a double curvature concrete arch buttress design and its crest is 873.4 m above sea level. It has a maximum of 141 m height over the foundation and the dam crest is 484 m long and 10 m wide.

The dam has 8 inverted and 2 direct pendulums. The annual radial movements in this case is between 30-35 mm.

Figure 4 : La Aceña and El Atazar Dam rushing out. Source: Canal de Isabel II

5. METODOLOGY AND RESULTS

To measure displacement, PSI method was used and for the points orthorectification it was used the Global SRTM model that produce positional differences respect background image. The selected pixels where those near the Pendulums. The software used to process the SAR images was SNAP (Sentinel Application Platform) from the ESA.

As far as the SPP filter is concerned, La Aceña Dam has been studied with all points filtering (more generic information of the AOI and less spatial accuracy) and El Atazar Dam with local maximum filtering (more spatial accuracy of the AOI).

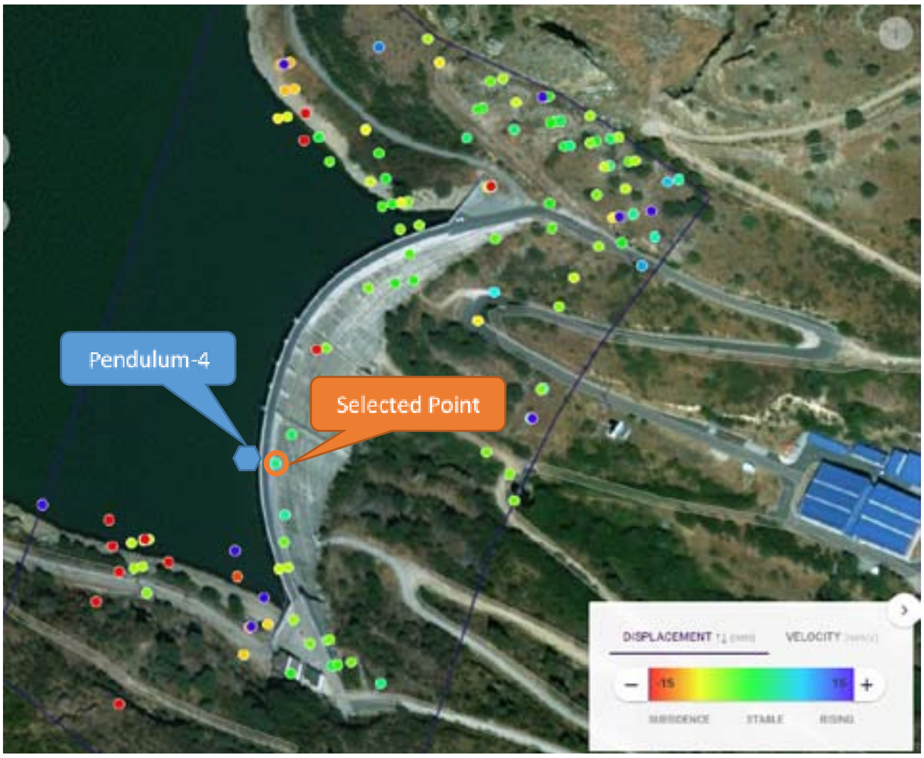

Figure 5 : Displacement comparison between DInSAR and Pendulum in La Aceña Dam

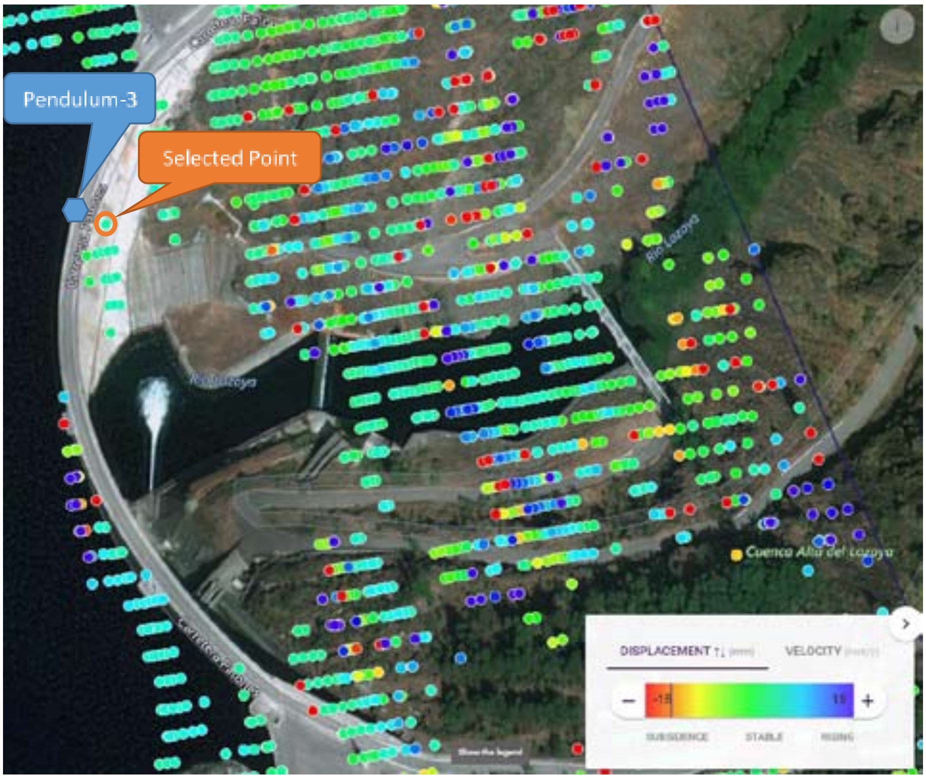

Figure 6 : Displacement comparison between DInSAR and Pendulum in El Atazar Dam

La Aceña

For the DInSAR study, the Aceña dam was analyzed from 02/08/2017 to 09/09/2019 and the coherence feature given was 0,75. In this case, the orbit direction used was ascendant. Among all the points within the area of interest, one of them (1286 m) has been selected for the analysis due to its closeness to Pendulum 4 Base 1(1287.91 m).

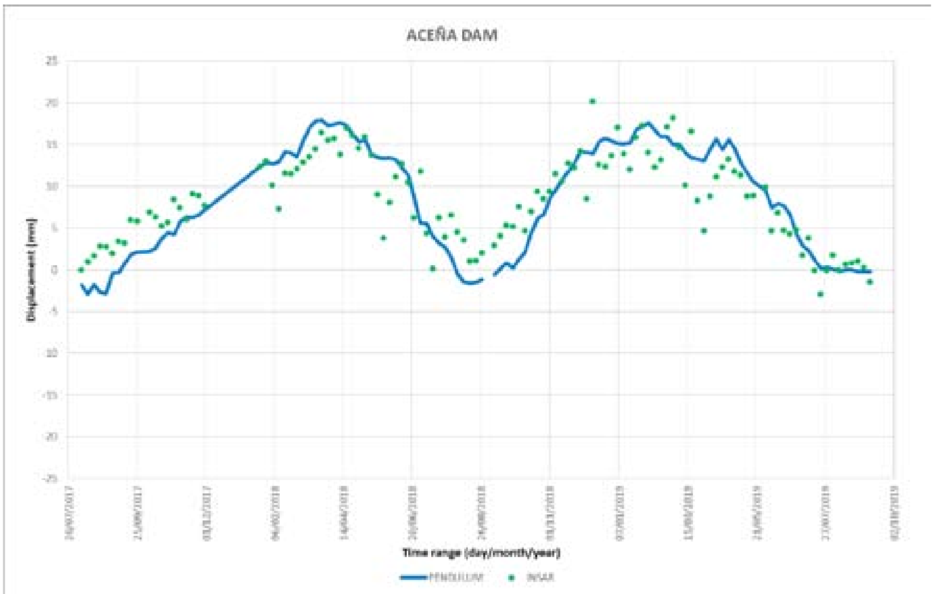

Figure 7 : Displacement analysis in La Aceña Dam

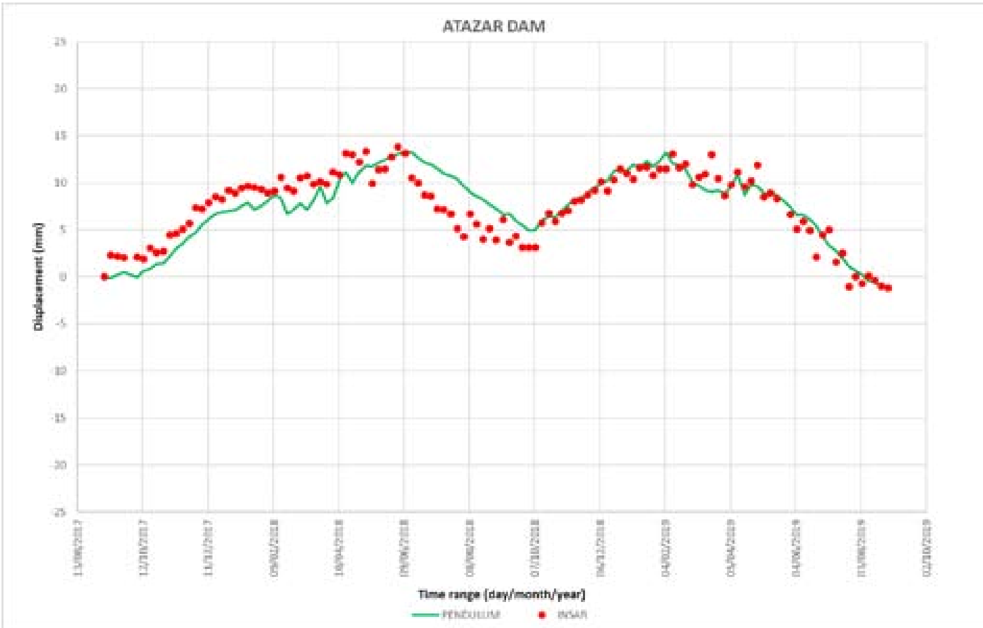

Figure 8 : Displacement analysis in El Atazar Dam

El Atazar

For the Atazar´s DInSAR study, the time range goes from 07/09/2017 to 28/08/2019 and the coherence feature given was 0,75. For this case, the orbit direction used was ascendant too. Among all the points within the area of interest, one of them (846.15 m) has been selected for the analysis due to its closeness to Pendulum 3 Base 2 (847 m).

6. COMPARATIVE AND PRECISION OBTAINED

In order to compare the accuracy of the DInSAR technology against the results obtained with the pendulums (considered as real movements), Root Mean Square errors (RMS) were calculated as follows:

$$\varepsilon = \sqrt{\frac{\sum(l_{Pendulum} - l_{SAR})^2}{n}}$$

The root mean square error of DInSAR radial movements was calculated for two periods in each dam:

- Atazar: (a) September 2017 to October 2019 (complete period); b) October 2018 to October 2019 (period that seems to fit better)
- Aceña: (a) August 2017 to September 2019 (complete period); b) October 2017 to September 2019 (period that seems to fit better)

The results are shown in Table 1. For both dams, Period b) shows a lesser error than in the whole period.

Table 1 : Errors in radial movements measured with DInSAR

Radial movements	RMS (ε) period a)	RMS (ε) period b)
ACEÑA DAM	3.18 mm	2.81 mm
ATAZAR DAM	1.92 mm	1.13 mm

7. CONCLUSIONS

- The DInSAR technique is valid to measure radial displacements in concrete dams and its accuracy is of the order of at least 1-3 mm.
- From the dam exploitation point of view, it is demonstrated that DInSAR can be used as another auscultation technique to study the tendency of displacements in the dam.
- An auscultation technique independent of atmospheric conditions, which allows remote control of dam movements in extreme climatic situations (no visibility, inability to access the dam, etc.) or exceptional conditions (communications failure, cyber-attacks, etc.) is a strategic issue for the dam´s safety.
- Although DInSAR is a technique that does not replace traditional auscultation, it can be useful when there are no auscultation systems: mining rafts or dams under construction. In addition, as images of past eras can be examined, the construction of dams that are already under the exploitation phase can be analysed.
- The DInSAR technique is an emerging technology so, as uncertainty is reduced in certain parameters (incidence angles, distances, atmosphere, brightness, algorithms, etc.), results will be more accurate.
- In general, DInSAR brings you the opportunity to monitor worldwide dams at low cost. Only when the spatial resolution is high (1x1m), the image cost is increased.
- The DInSAR methodology is recommended for those dams whose face is oriented perpendicular to the satellite's orbit.
- The DInSAR technique requires a minimum number of images to reduce noise errors and obtain high coherence. The frequency of measures is lower than the one offered by traditional auscultation.

REFERENCES

Furukawa, Y., & Ponce, J. (2010). Accurate, dense, and robust multiview stereopsis. In IEEE Transactions on Pattern Analysis and Machine Intelligence (Vol. 32). https://doi.org/10.1109/TPAMI.2009.161 re from motion (Vol. 426).

Villanueva, J. R. E., Martinez, L. I., & Montiel, J. I. P. (2019). DEM Generation from Fixed-Wing UAV Imaging and LiDAR-Derived Ground Control Points for Flood Estimations. Sensors.

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https://sentinel.esa.int/web/sentinel/missions/sentinel-1/satellite-description/orbit

Informes de la Construcción, Vol. 62, 519, 47-53, julio-septiembre 2010.