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SATELLITE SAR INTERFEROMETRY FOR MONITORING DAM DEFORMATIONS IN PORTUGAL

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Abstract. *The paper offers three examples of satellite SAR interferometry (InSAR) application for monitoring dam deformations: Paradela, Raiva and Alto Ceira, all of them in Portugal. Dam deformations were estimated using several sets of ERS and Envisat C-band SAR data by PS-InSAR method that offers accuracy of a millimeter per year at monitoring man-made structures. The results show potential of InSAR but also summarize limits of C-band InSAR in these particular cases and can be handful to recognize applicability of new Sentinel-1 data (since 2014) for continuous monitoring of dam deformations. While Alto Ceira dam lies in SAR radar shadow and was represented by only one observable point, and the movement detected (in satellite line-of-sight direction) appears to fit with geodetical measurements. Raiva and Paradela dams were represented by sufficient number of points feasible for PS-InSAR processing. Deformations at slope near to Raiva dam and slow linear movements of the center of Paradela dam were detected.*

1 INTRODUCTION

InSAR (Synthetic Aperture Radar Interferometry) is a method established in 1990s[1,2] to monitor areas of subsidence or landslides. Since 2001[3], its advantages have been used for monitoring urban areas or man-made constructions, not monitoring the whole area, but only the most quality points.

Monitoring of dams using InSAR is not yet a widespread application, but several applications can be found: Svartevatn earthfill dam in Norway[4], achieving reasonable results from ERS ascending track despite of layover, while no results from the descending track due to the dam/surrounding geometry. For long-term monitoring of La Pedrera dam in Spain[5], three datasets with different spatial resolution were used, and monitoring results were compared to in-situ measurements. Also, the huge Three Gorges dam in China was monitored by InSAR[6], where both temperature and water-level effects were clearly detected. The significant impact of water levels has been also found and described in case of Plover Cove dam in Hong-Kong[7].

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2 INSAR FOR MONITORING DEFORMATIONS

The InSAR principle lies in the measurement of the distance between the satellite and a point on the Earth surface, using the radar phase information. By subtracting the distance measured on two different days, we get information about the movement of the point. However, the method is not so simple due to more causes:

1) the phase is always measured in the (-π,π) radians interval that corresponds with the period of radar wavelength, which is always in the order of centimeters (≅3 cm for X-band, ≅5-6 cm for C-band, > 20 cm for L-band), so the detected information about movement is always smaller than the wavelength and can be ambiguous - if the movement gets larger in the direction of satellite line-of-sight (LOS), the phase of the radar wave jumps to another period. Detection of such phase jumps involves advanced algorithms using enough number of interferograms, for example Permanent Scatterers method (PS-InSAR)[3].

2) the satellite is in a different position in each date of acquisition (the distance is known as spatial/perpendicular baseline), and the phase difference is influenced by the product of the baseline and the height of the point on the Earth surface (or the difference between the real height and the modelled one). Thus, it is necessary to distinguish between phase contributions due to physical movement of observed point and due to stereoscopic effect of height difference (this is often possible precisely using PS-InSAR).

3) radar ray may get delayed during its pass through atmosphere, and the difference of the delay between different parts of the monitored construction may be high enough to be mistaken with deformation in some cases.

4) the radar signal received by the satellite is the sum of the reflection of all the scatterers within a resolution cell, which varies generally between 1x1 m (e.g. TerraSAR-X) to 25x5 m (e.g. Envisat) or more. If the whole cell moves uniformly (ideally together with the surrounding resolution cells), the deformation can be monitored, but if the structure of the resolution cell changes between two acquisition dates (vegetation, ploughed soil etc.), the pixel does not contain a useful information (this is known as decorrelation or low coherence). Due to shorter wavelength and therefore better accuracy, man-made constructions are preferably monitored with X-band or C-band data. However, vegetated slope or ploughed soil may be monitored with L-band, as the L-band radar rays penetrate through the lower vegetation to reach the ground.

The PS-InSAR methodology is based on processing a set of data (at least 20 scenes are recommended) and from it, linear deformation rate is estimated together with height change (with respect to a used external digital elevation model - DEM) and possibly with other effects, such as dilation due to temperature changes or movement due to water level change. Unmodelled phase contributions are considered as phase noise and decreases the estimated coherence (quality) of the observed point, known as PS point.

It should be noted that the radar only measures the movement in its LOS and it is not possible to get a 3D movement vector. If two different satellite tracks are used for monitoring, theoretically it is possible to get a 2D movement vector, however, usually, the accuracy in each component is different; the feasibility depends on the configuration of the two tracks and also on the visibility of the construction in each of them. If a movement is known to be vertical, it is possible to convert the LOS movement into vertical (the sensitivity is usually around 90%, i.e. InSAR detects 90% of the real vertical movement). If it is known to be horizontal, it is possible to be converted into horizontal if the movement direction is known. The sensitivity of horizontal movements, however, is only up to approximately 30%, depending on the angle between radar ray and the direction of the movement.

3 CASE STUDY: RAIVA DAM

The Raiva dam is a concrete dam with a length of 200 m, situated in central Portugal, on the Douro river near the Coiço town. The area is monitored using ENVISAT data from two ascending tracks where the orientation of the dam is almost ideal - parallel to the flight direction. The dam is monitored from downstream, i.e. its visible height is 34 m[8]. The resolution of the radar is approximately 4-5 m in the direction parallel to the dam body, while 20-30 m in the perpendicular direction (different for each track).

Data from 2003-2007 (track 44, 20 scenes) and 2003-2005 (track 316, 16 scenes) were processed. Due to longer spatial and temporal baselines and lower number of scenes, track 316 is less suitable for monitoring, however it has slightly better resolution in the direction perpendicular to the dam construction. The dam is subject to a strong radar layover from both tracks, as the PS points on the top of the dam are closer to the radar than the PS points on the bottom side (see Fig. 1). The northern part of the dam is not visible by the radar or the PS points were excluded from the processing due to inappropriate quality (coherence).

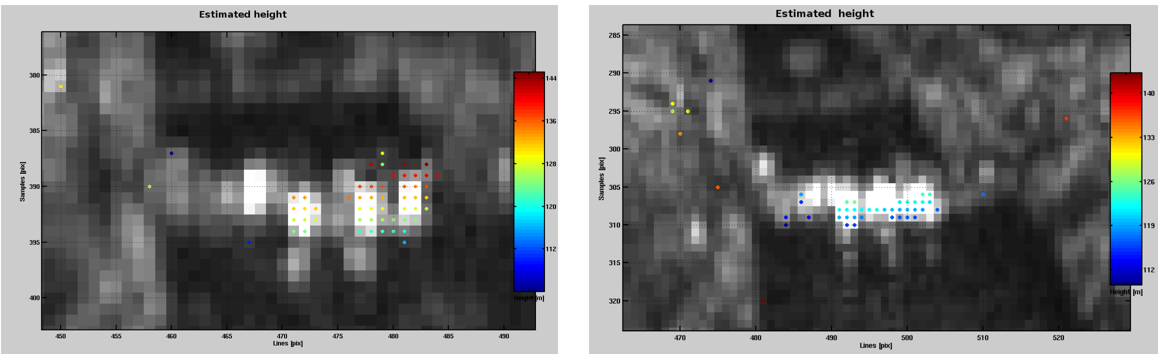

Figure 1: The dam as seen from the radar, track 44 (left) and track 316 (right). Color represents the estimated height. Downstream is to the top, North is to the right. The dam is monitored from top, i.e. it is visible that the PS points at the bottom of the image correspond to the bottom of the dam. High-intensity points are usually considered to be the quality ones.

Within processing, we tried to estimate temperature effects (dilation) and water level effects (possible bending due to water level change) but no consistent results were obtained. We attribute this independency to the location of the dam (mountain valley), its length (only 200 m) and material (concrete). In addition, the sensitivity of the InSAR processing with regard to horizontal movements (as expected both for the dilation and water level effects) is only around 25% even in this almost ideal case (given by the angle between radar ray and the direction of movements), i.e. minimum visible horizontal movement due to these effects would be around 8 mm/ºC or 8 mm/m of water level change.

The southern (left) slope above the dam is known to be unstable[9]. Figures 2-5 display the estimated (linear) deformation velocity both on the dam body and the unstable slope. Unfortunately, due to low quality of PS points, most of the points at the northern part of the dam and most of the points at the slope were excluded during processing. It looks like that the dam is not deformed at all (estimated deformation values are at the limits of the method), and at the slope, the point density is low. Please note that all the disclosed linear deformation values are in radar LOS, as the deformation direction is unknown. If a point is situated in the water, it is considered noisy and not significant. Denoising is planned for near future.

In figures 2-3 (track 44), no significant movement is visible, however in figures 4-5 (track 316), movement of the slope is detected. Note that identified high-quality PS points are different. Within the accuracy of the method, i.e. within few mm, there is nothing happening at the dam. On the slopes, movements are possible, however the point density (or coherence) is low; the results for the two tracks do not verify one another, but they both present stable behaviour of the dam.

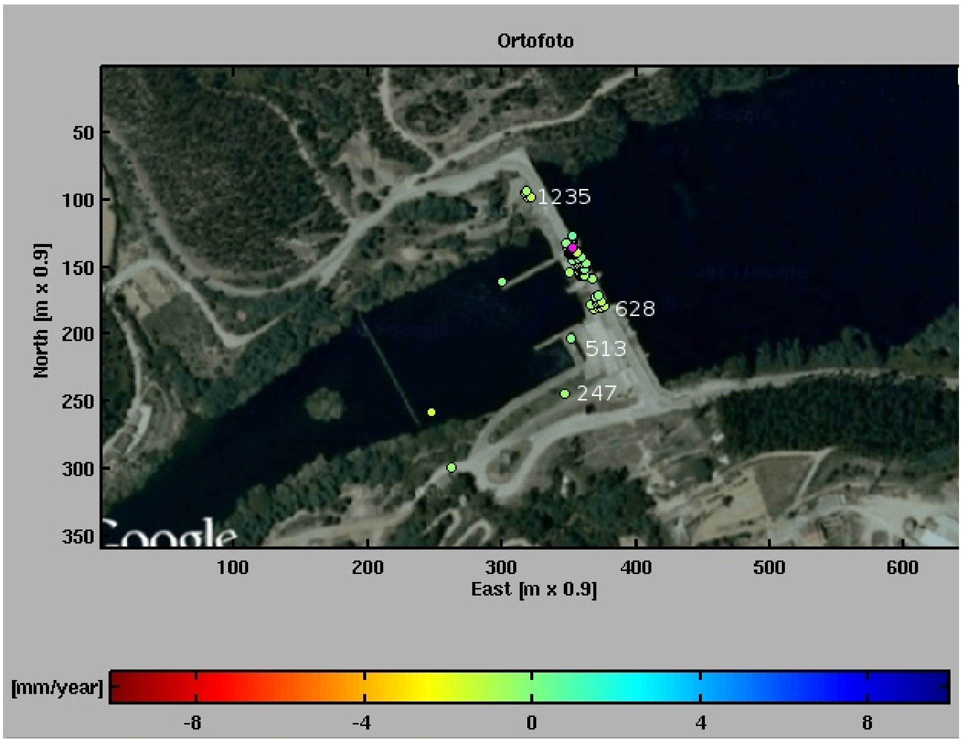

Figure 2: Estimated linear deformation for track 44 (without the water-level influence included in the model), with marked distinctive PS points (time series to be found below)

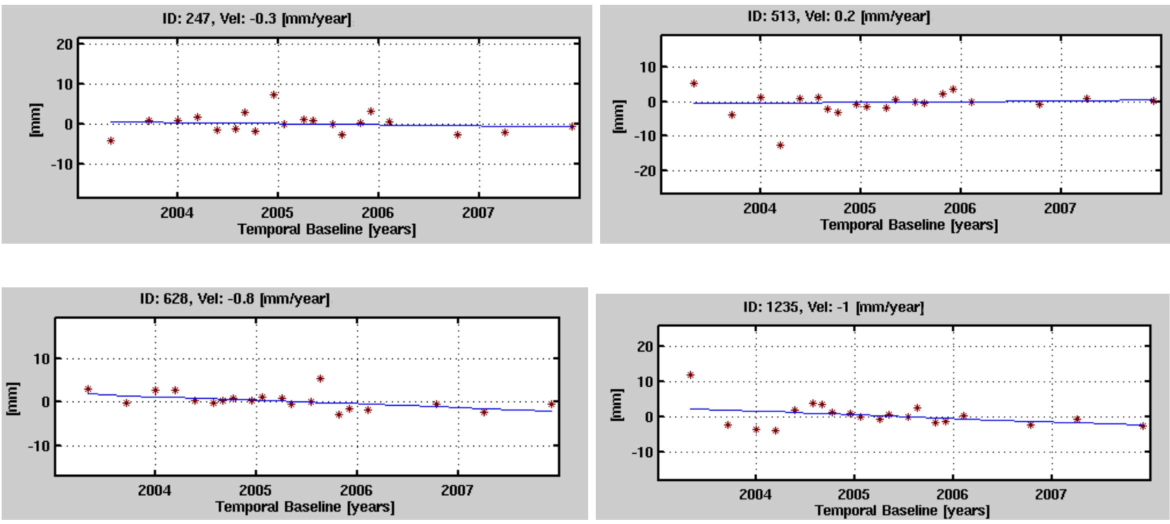

Figure 3: Time-series of the estimated deformations for distinctive PS points (track 44)

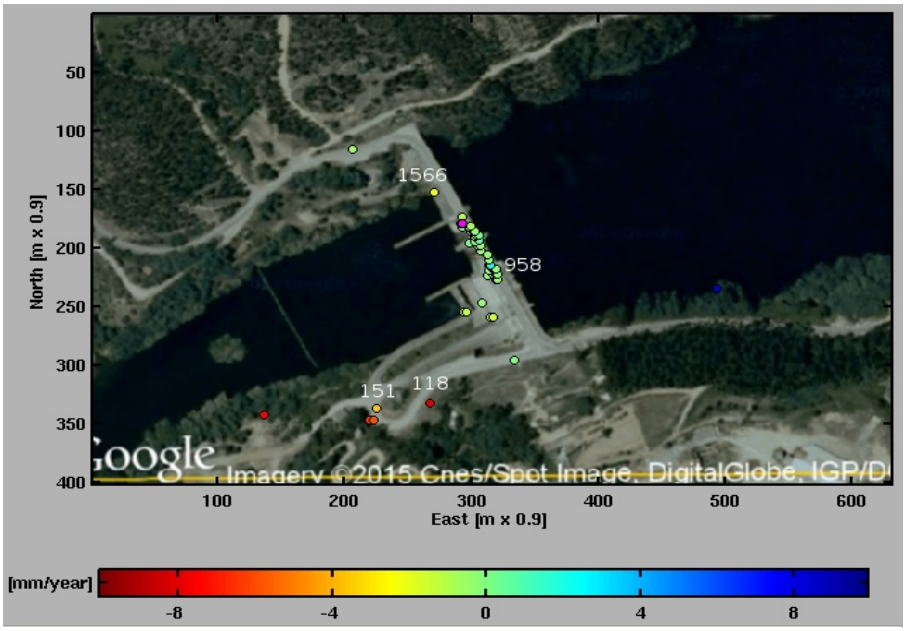

Figure 4: Estimated linear deformation for track 316 (without the water-level influence included in the model), with marked distinctive PS points (time series to be found below)

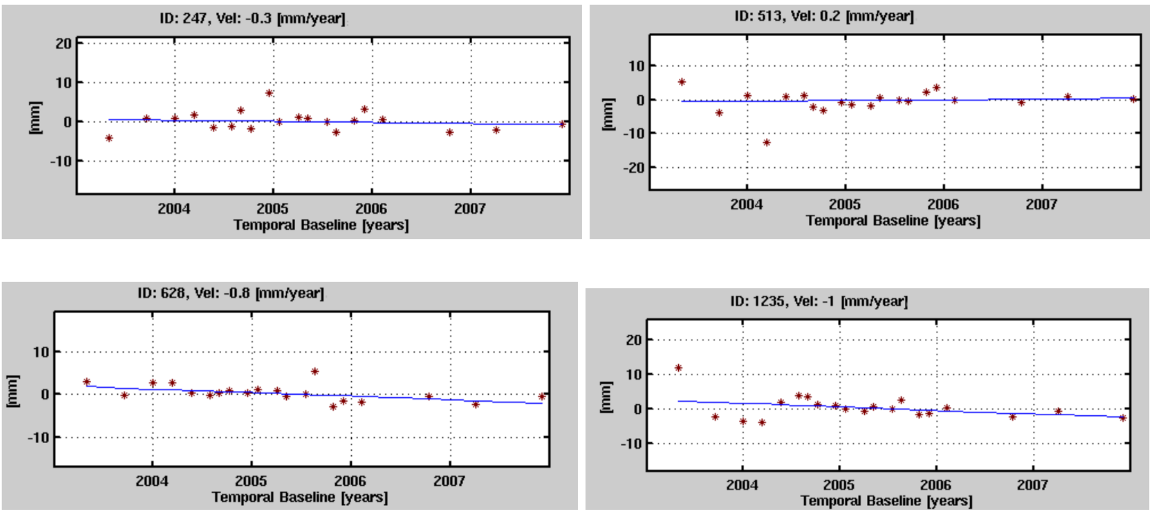

Figure 5: Time-series of the estimated deformations for distinctive PS points (track 316)

4 CASE STUDY: ALTO CEIRA DAM

The construction of Alto Ceira dam began in 1939 and was completed in 1949. The dam is located in Coimbra district, Portugal and severs the Ceira River in order to increase the water in the reservoir of Santa Luzia dam for hydroelectric development. The Alto Ceira dam has been built as a concrete arch dam, with the height above foundations of 36.5 m and the crest length of 85 m. The structure of the dam exhibited an abnormal behaviour, characterized by the horizontal upstream displacements and upward vertical deformations together with the concrete crackings, since the first filling of its reservoir. Several geodetic studies[10] have revealed that this abnormal behaviour is related to the swelling process of the concrete that was used for the construction. Due to the high recovery costs of the existing structure, the

Electricidade de Portugal (EDP) decided to build a new dam about 200 m downstream of the existing structure, with the same purpose, serving as a reservoir and passing the accumulated water through the tunnel to Santa Luzia reservoir, situated about 7 km away[11,12]. The tunnel suffered of a problematic rupture in January 31, 2015 flooding the downstream populations, damaging the local infrastructure and, conversely, highlighting the vital importance of continuous remote sensing techniques, such as InSAR[3,13,14], that can help to identify structural problems before they become critical and endanger public safety.

The experimental application of PS-InSAR methodology over the old structure of Alto Ceira dam aims to perform a deeper knowledge about the performance of the technique under the difficult environmental conditions (mountain surroundings), while evaluating unequally sampled historical ERS/Envisat data with low coherence and low spatio-temporal resolution (Fig. 6). SAR images from ERS (42) and ENVISAT (21) satellites, acquired from the track no. 180 between 1992-1998 and 2003-2009 respectively, were used. By the detailed look on the reflectivity maps (Fig. 7), only two small reflections from the dam body are visible.

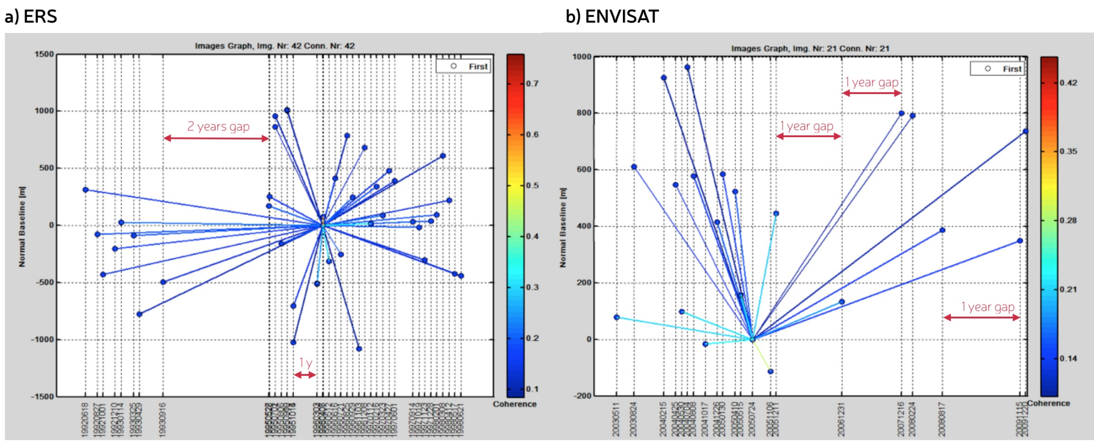

Figure 6: Images graph of a) ERS and b) ENVISAT dataset.

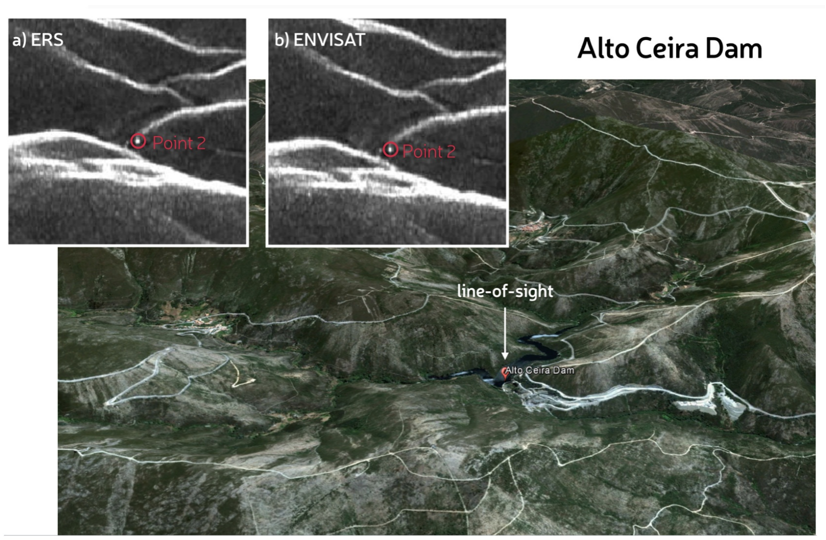

Figure 7: Reflectivity maps generated from the set of SAR images acquired by a) ERS and b) Envisat satellite. Point No. 2 (marked red) with the higher intensity was selected for the extraction of the deformation signal through PS-InSAR approach

For the evaluation of InSAR potential to detect dam body deformation under unfavourable conditions (environment, dataset statistics), PS-InSAR derived time series of a deformation signal from point no. 2 were compared to the levelling data from point coded NPIII. The levelling data were obtained from the Geodetic Observing System (GOS) implemented in the old Alto Ceira structure that is consisting of three geodetic networks[10]. The triangulation and polygon network to control the horizontal movements and a levelling line (formed by the 13 observed points, 7 reference points and 4 waypoints) that allows for monitoring of the vertical movements. The analysis of the geodetic measurements for the horizontal displacements reveals that the crest's points near the right bank present a greater movement in 2009 in the sense of downstream towards the upstream (60.2 mm) and points near the left bank present a greater movements in 2004 in the sense of right bank towards the left bank (40.4 mm). For the vertical displacements observed by the last levelling campaign in 2012, geodetic analysis shows that the points observed in the dam's crest near the right bank (NPVI) have the upward movement of up to +39.7 mm and similarly the upward movement with the extreme of +16.8 mm is present near the left margin (NPIII), since the reference epoch in 1989. The centre of the dam's crest (NPIV) suffers of a smaller movement with +9,7 mm in the same period. Analysis of the PS-InSAR observations showed that with the proper inspection methods for performing interferometry, similar increasing tendency (Point 2) was detected and it is correlated with the levelling data (NPIII) (Fig. 8) if there are no huge data gaps present (ERS case).

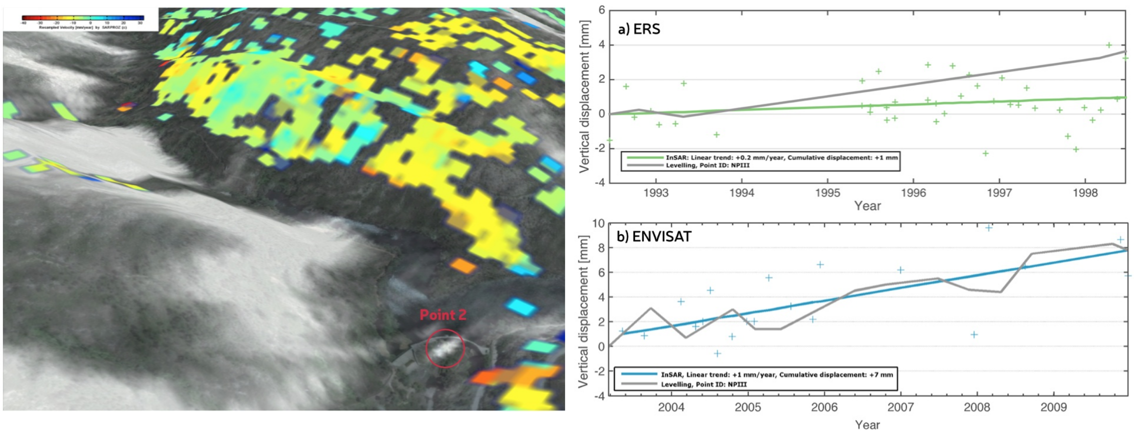

Figure 8: left) Example of Envisat Quasi-PSInSAR[13] slope stability analysis superimposed on reflectivity map, right) PS-InSAR estimated deformation time series over Point 2 from a) ERS and b) Envisat vs. levelling measurements from corresponding geodetic point coded NPIII

5 CASE STUDY: PARADELA DAM

Paradela dam was monitored blindly, i.e. without any reference knowledge. Applying SARPROZ[14] PS-InSAR to Envisat images from overlapping ascending tracks 273 (14 images from 10/2002-05/2007) and 44 (16 images from 05/2003-12/2007) using closely corresponding reference point, the results show very similar behaviour, however for different PS points. In both datasets the dam is defined by several high-intensity stable points. These stable points are showing some (rather small) deformation trend in rate of not more than 2 mm/year on the lower part of the dam and up to ~5 mm/year on the upper part of the dam in satellite LOS. The situation is described in Fig. 9, including graphs of linear deformation estimated at two selected points, located at close positions within datasets of both tracks.

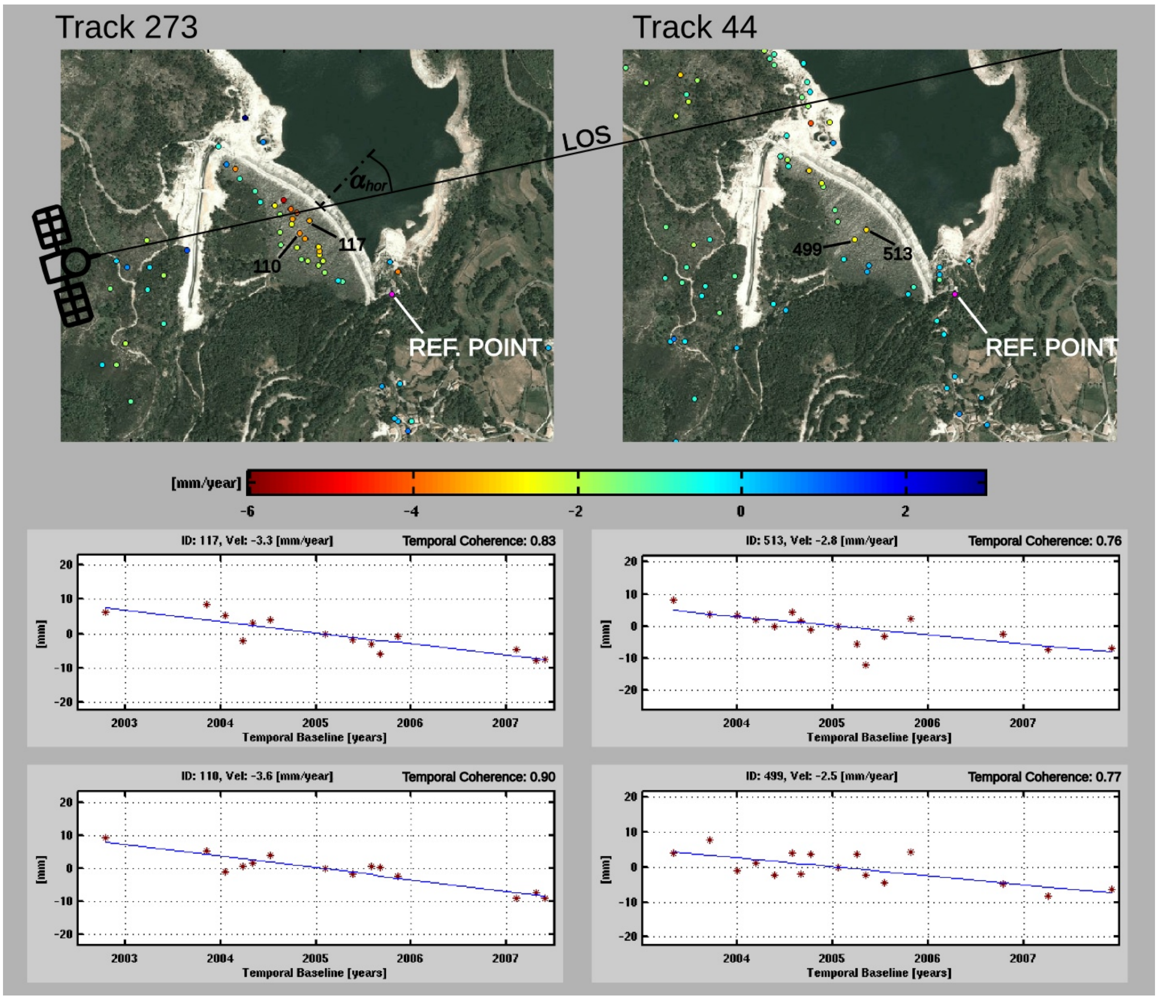

Figure 9: Linear LOS deformation trend of Paradela dam estimated using SARPROZ PS-InSAR processing of Envisat ASAR data of track 273 (left) and track 44 (right)

The radar signal is always affected by various minor sources[15]. Neglecting them in model estimations leads to noise-like character of phase residuals affecting accuracy of deformation estimations. A temporal coherence[16] parameter ξ_p describes the quality of fit between linear deformation model and phase measurements. From temporal coherence value, a standard deviation of linear deformation trend v[mm/year] estimations $\delta_{\Delta v}$ can be extracted using adapted Eq. 1[16]. Other input parameters for the Eq. 1 are radar wavelength λ [mm] (in case of Envisat ASAR, λ=56.2 mm), number of interferograms M and variance of temporal difference of SAR images from reference date $\delta_{\Delta t}^2$. For track 273, M=13, $\delta_{\Delta t}^2$=1.772 year, while for track 44, M=15, $\delta_{\Delta t}^2$= 1.525 year.

$$\delta_{\Delta v}=\sqrt{\left(\frac{\lambda}{4\pi}\right)^2 \frac{\sqrt{2}\cdot\sqrt{-\log(\xi_p)}}{M\,\delta_{\Delta t}^{\;2}}} \tag{1}$$

If the physical movement of the dam can be expected to be horizontal, perpendicularly to the dam body, i.e. in angle of α_{hor} from LOS direction, and if the vertical deformation is not assumed and will be neglected for sake of simplicity, the rate of deformation D_{hor} may be derived from LOS direction value using Eq. 2[17], where θ_{inc} is incidence angle of satellite LOS from vertical direction (for case of Envisat ASAR, $\theta_{inc} \simeq 21°$).

$$D_{hor} = \frac{D_{LOS}}{\sin\theta_{inc} \cdot \cos\alpha_{hor}} \tag{2}$$

Therefore, supposing strictly horizontal deformation of selected points in direction perpendicular to the dam orientation, information about their linear deformation trend can be extracted from LOS deformation rates D_{LOS} using parameter $\alpha_{hor} \simeq 34°$ as values D_{hor} in Table 1 where minus sign means inclination towards the reservoir.

ID	track	ξ_p	D_{LOS} [mm/y]	D_{hor} [mm/y]
110	273	0.83	-3.6 ± 0.7	-12.1 ± 2.5
117	273	0.90	-3.3 ± 0.6	-11.1 ± 2.1
499	44	0.77	-2.5 ± 0.8	-8.4 ± 2.6
513	44	0.76	-2.8 ± 0.8	-9.4 ± 2.7

Table 1: Horizontal deformation trend estimated for selected points

Generalizing the provided information, PS-InSAR estimations show the top-center part of Paradela dam to be slowly inclining towards the reservoir, linearly in time. This conclusion should be further investigated by comparison with other data. The phase residuals plotted in Fig. 9 show rather small distortion. Approach to correlate these residuals with water levels as well as with temperature changes has been performed. The rate of correlation was very small, changes comparable to noise-like signal, thus neglected.

7 CONCLUSIONS AND RECOMMENDATIONS

The monitoring possibility of InSAR and quality of PS points highly depends on the orientation of the dam w.r.t. the satellite flight direction. It is known that sensitivity of satellite-based InSAR for horizontal deformations in the N-S direction is very low. The accuracy also depends on the SAR image resolution and radar wavelength.

The number of images used for described case studies is rather low and their resolution not appropriate for dam monitoring. To deal with the noise incorporated in the time series and to increase the overall accuracy of the estimated parameters, the usage of large dataset of frequently acquired high resolution SAR data (e.g. TerraSAR-X, COSMO-SkyMed) is suggested. Thanks to their high sensitivity, it should be also possible to precisely estimate the influence of various deformation sources, such as water level or temperature changes.

Regarding the orientation of detected deformations, it is not possible to unambiguously decompose estimated linear deformation rate into vertical or horizontal directions without other data (e.g. by combination with descending track or using knowledge from geodetical measurements) or without knowledge of vector describing orientation of major deformation. Another possibility is application of both ascending and descending tracks, allowing decomposition of detected movements into 3D vector. It is also recommended to maintain proper comparison of geodetical measeurements with PS-InSAR results.

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