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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 few millimeters 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 to 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 (Massonnet et al, 1993, Werner et al, 1993) to monitor areas of subsidence or landslides. It offers evaluation of temporal displacements over large areas within millimetric sensitivity using specific processing of satellite radar images. Since 2001 (Ferretti et al, 2001), its advantages have been used for monitoring urban areas or man-made constructions, by processing time series of selected well reflecting points (e.g. constructions) instead of monitoring whole area that would be biased by presence of vegetation.

Monitoring of dams using InSAR is not yet a widespread application, but several applications can be found: Svartevatn earthfill dam in Norway (Voege et al, 2012), achieving reasonable results from ERS satellite despite of inappropriate geometry of surrounding slopes with regards to satellite line of sight (LOS) causing layover in radar image. For long-term monitoring of La Pedrera dam in Spain (Tomas et al, 2013), 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 (Wang et al, 2011), 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 (Lazecky et al, 2013).

2. InSAR for Monitoring Deformations

The InSAR principle lies in the measurement of so-called phase (portion of radiation wave) of radar beam reflected from a point on the Earth surface back to the satellite radar (SAR); information about the movement of the point comes by difference of measured phase between two different times of acquisitions. However, the method is not so simple due to more causes:

1) the phase is always measured in the ($-\pi$, π) radians interval that corresponds to the period of radar wavelength, which is always in the order of cm (~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 LOS (that is generally 20-45° from nadir), 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 (PS-InSAR) (Ferretti et al, 2001), and sufficient density of high quality points.

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 beam 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 contains also noise contribution (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 should 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 thermal dilation or movement due to water level change. Unmodelled phase contributions are considered as phase noise and decrease the estimated coherence (quality) of the (PS) point.

It should be noted that the radar only measures the movement in its LOS where the phase is affected by both vertical and horizontal movements of the point. Because of characteristics of the satellite orbit, the measurement can be performed from two (ascending and descending orbit) tracks observing an object from two sides. If two different satellite orbit tracks are used for monitoring and the target is visible on both of them, it is possible to get a 3D movement vector, however, usually the accuracy in each component is different. In the presented study cases of Portuguese dams, only tracks from single orbit were available. Here the evaluation of dam movement can be based on assumption that the direction of the movement is known - the amount of movement in that direction is recomputed from LOS based on the radar sensitivity (typically around 90% for vertical movements, but only up to 30% for horizontal movements; depending on LOS angle).

3. Case Study: Raiva Dam

The Raiva dam is a concrete dam with a length of 200m, 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 (Melo et al, 1992). The resolution of the radar is approximately 4-5 m in the direction parallel to the dam body and 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).

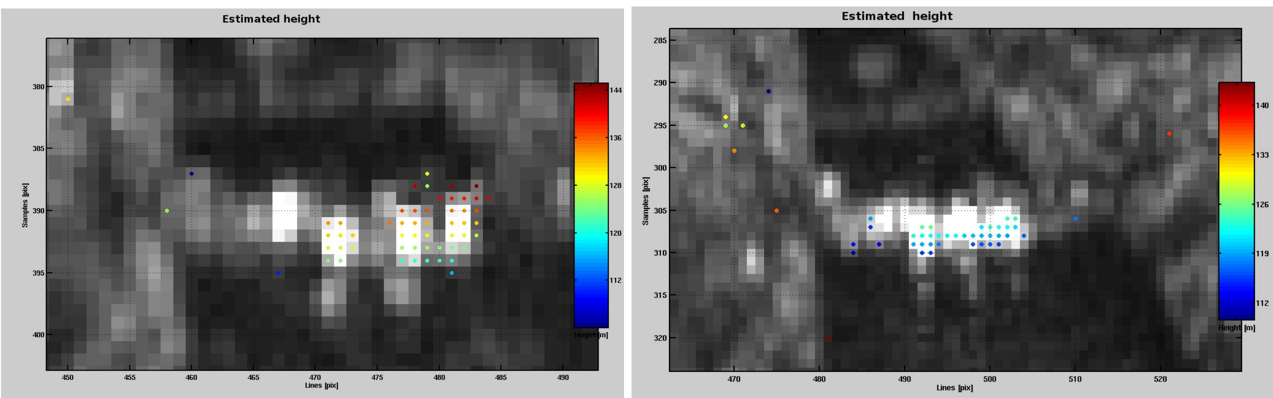

Figure 1 - The dam as seen from the radar, track 44 (left) and track 316 (right). Color represents the estimated height. Downstream is to the top, North is to the right. The dam is monitored from top, i.e. it is visible that the PS points at the bottom of the image correspond to the bottom of the dam.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

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 geometrical configuration), 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. Figure 2 displays 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.

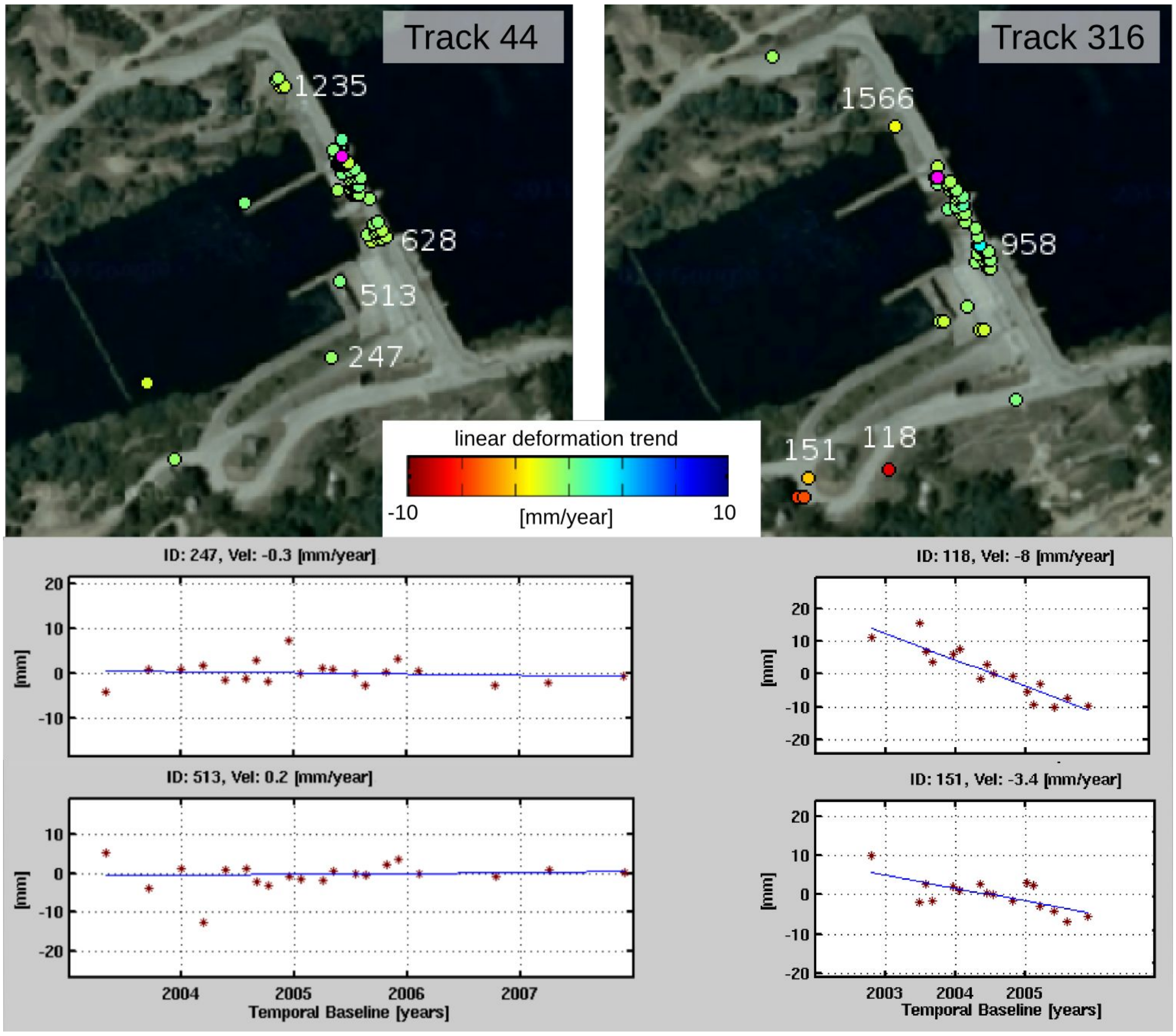

Figure 2 - Estimated linear deformation for track 44 (left) and track 316 (right), without the water-level influence included in the model, with marked distinctive PS points (time series of selected points are below)

In figure 2, no significant movement is visible in case of track 44 (left), however from processing of track 316 (right), movement of the slope is detected (see time series in Fig. 2 right). 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.

4. Case Study: Alto Ceira Dam

The construction of Alto Ceira dam 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. 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 concrete crackings, since the first filling of its reservoir. Several geodetic studies (e.g. EDP, 2012) have revealed that this behaviour is related to the swelling process of the concrete that was used for the construction.

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. SAR images from ERS (42) and ENVISAT (21) satellites, acquired from the track no. 180 between 1992-1998 and 2003-2009 respectively, were used.

For the evaluation of InSAR potential to detect dam body deformation under unfavourable conditions, 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 consists of three geodetic networks (EDP, 2012). According to levelling data, the upward movement with the extreme of +16.8 mm is present near the the left margin (NPIII), since the reference epoch in 1989. 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. 3) if there are no huge data gaps present (ERS case).

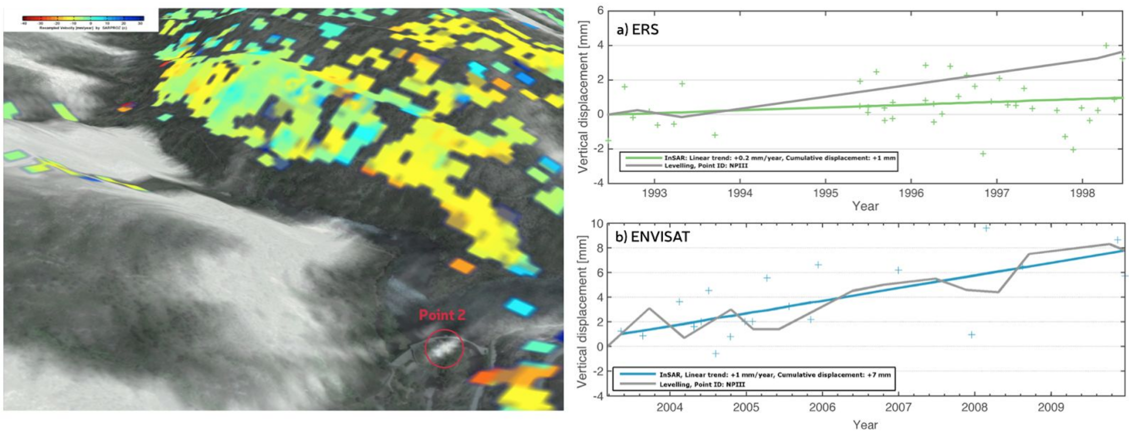

Figure 3 - Example of Envisat Quasi-PSInSAR slope stability analysis superimposed on reflectivity map (left), PS-InSAR estimated deformation time series over Point 2 (right) from a) ERS and b) Envisat vs. levelling data of corresponding geodetic point coded NPIII

5. Case Study: Paradela Dam

Paradela dam was monitored blindly, i.e. without any reference knowledge. Applying SARPROZ (Perissin, 2015) 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 with the rate of less 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. 4, including graphs of linear deformation estimated at two selected points, located at close positions within datasets of both tracks.

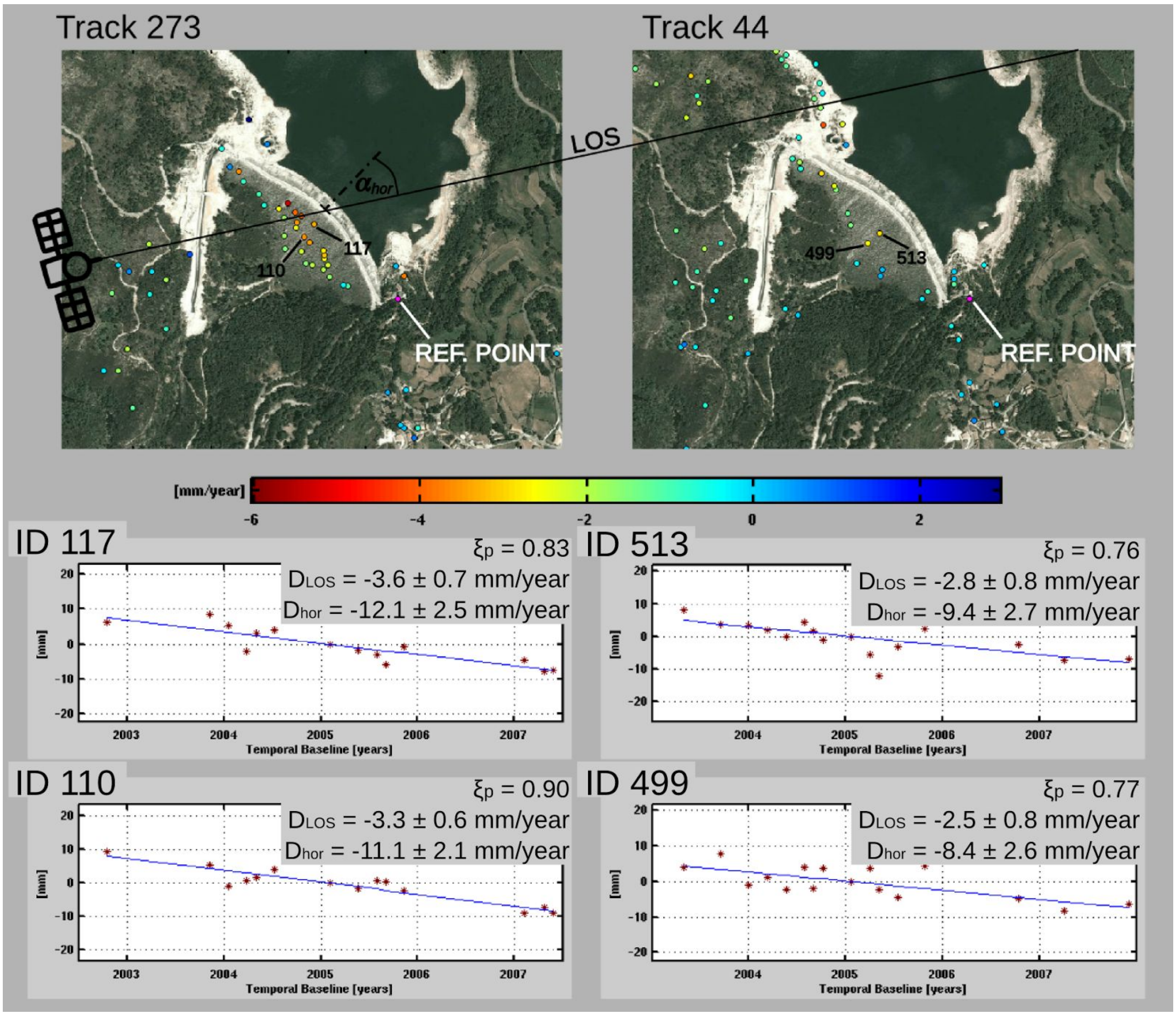

Figure 4 - Linear LOS deformation trend of Paradela dam estimated using SARPROZ PS-InSAR processing of Envisat ASAR data of track 273 (left) and track 44 (right)

The radar signal is always affected by various minor sources (Hanssen, 2001). Neglecting them in model estimations leads to noise-like character of phase residuals affecting accuracy of deformation estimations. A temporal coherence (Wang et al, 2010) parameter ξ_p describes the quality of the fit between linear deformation model and phase measurements. From temporal coherence value, standard deviation of linear deformation trend v[mm/year] estimations $\delta_{\Delta v}$ can be extracted using adapted Eq. 1 (Wang et al, 2010). 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 the 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 (Lazecky et al, 2015), where θ_{inc} is incidence angle of satellite LOS from vertical direction (for case of Envisat ASAR, θ_{inc} = 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 α_{hor} = 34° as values D_{hor} in lower part of Figure 4 where minus sign means inclination towards the reservoir.

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. 4 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 of ERS/ENVISAT is not appropriate for monitoring of local movements of dams. 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 knowledge of the vector describing orientation of (major) deformation (or without images from both ascending and descending tracks that would allow decomposition of detected movements into 3D vector). It is also recommended to maintain proper comparison of geodetical measurements with PS-InSAR results.

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