Observing Dam's Movements with Spaceborne SAR Interferometry

26

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Abstract

Advantages of satellite synthetic aperture radar (SAR) interferometry techniques are demonstrated in three cases of monitoring: Charvak Dam (Uzbekistan) using SAR data from Envisat satellite, Three Gorges Dam (China) using data from Cosmo-SkyMed satellite constellation and Plover Cove Dam (Hong Kong) using dataset from TerraSAR-X satellite. Subsidence of dam bodies and seasonal dilation can be observed together with movements correlated with water level changes. The topic of separation between dam deformations and seasonal movements is discussed. Data have been processed using advanced multitemporal processing techniques implemented in Sarproz. These techniques show high potential for continuous monitoring of both dam deformations and surrounding slope instabilities.

Keywords

Insar • Dam deformations • Sarproz • Terrasar-X • Cosmo-Skymed • Envisat

26.1 Introduction and Methodology

Water reservoirs help society by providing water needed for irrigated agriculture and by regulating river flow. However due to significantly increased amount of water, areas around dams are affected by hydro-geological and other changes, often endangering dam stability by increased seismic activity or slope deformations (Bláha and Horský 2011). Systems monitoring deformations of dams or their surroundings are not sufficient for every dam in terms of accuracy and temporal control. Using satellite SAR Interferometry (InSAR) techniques, these deformations can be monitored within whole imaged area (several km^2), in mm precision, or theoretically even better. Almost whole world is covered by archived InSAR-capable satellite data since 1991 (since ERS-1).

Presented results are based on processing of focused SAR data using advanced multitemporal methods of SAR Interferometry: Persistent Scatterers Interferometry (PSI) (Ferretti et al. 2000) and Quasi-PSI (QPSI) (Perissin et al. 2007a). PSI method is capable of utilizing large dataset of SAR images for accurate evaluation of deformation trend of selected points that have strong and very stable scattering characteristics, i.e. persistent scatterers. QPSI method relaxes such selection to include less stable points and differs from PSI by three main modifications (Wang et al. 2011):

(1) SAR images in PSI are connected in a star-like graph with the center in "Master" image, while QPSI uses a

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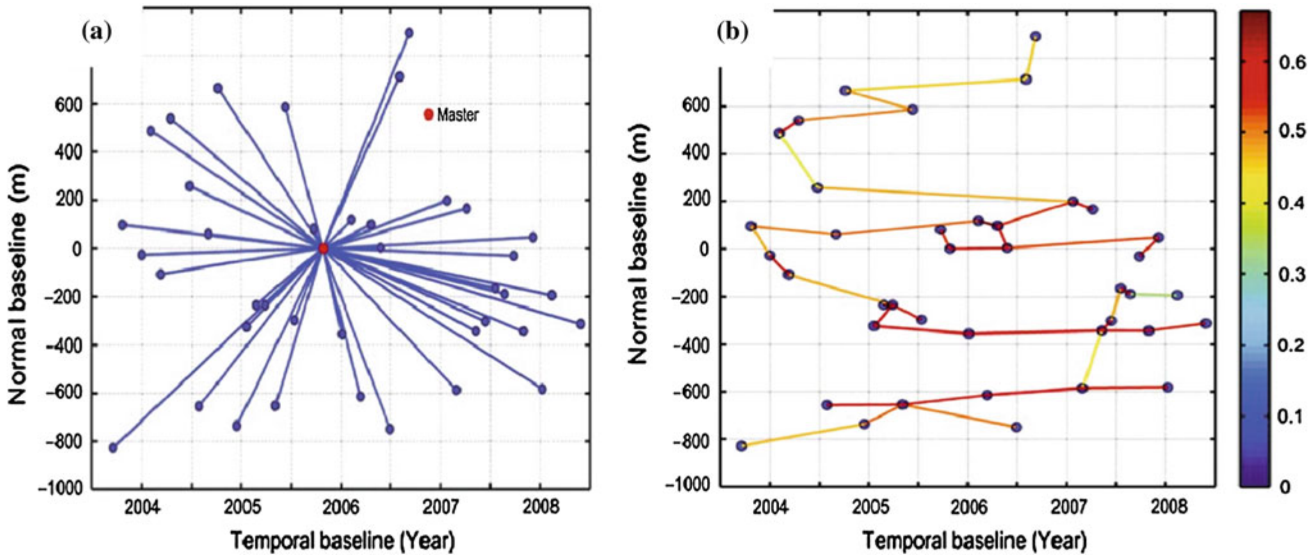


Fig. 26.1 Combination of SAR images: **a** star graph (PSI), **b** MST graph (QPSI)

minimum spanning tree (MST) algorithm to obtain an optimal network of highly coherent interferograms (see Fig. 26.1);

(2) target height and displacement is estimated from a coherence-weighted subset of interferograms in QPSI. Also partially coherent targets are included. Such subset may lead to lower accuracy of estimation of deformation rates;

(3) considering distributed (non-dominant) targets, a spatial filtering is applied to enhance the signal to noise ratio of the interferometric phase.

26.2 Deformations Around Three Gorges Dam (02–08/2011)

Since 1994, the mass of water in the 660 km long reservoir behind Three Gorges Dam (TGD) causes instability of mountain slopes, increasing occurrence of block slides, rockfalls and shallow debris-slides in the upriver areas of the dam (Fourniadis et al. 2007), cumulating into huge landslides in 2003, 2007, 2009.

Deformations were identified using QPSI in the area of Badong, in the height about 400 m above the Yangtze River (Perissin et al. 2007b). Areas close to the TGD body are affected by continuous subsidence in rates over 1 cm/year, as identified by combined QPSI + PSI processing of 40 Envisat ASAR acquisitions from 08/2003–04/2008 (Wang et al. 2011). Deformations in the same locations were also identified by 29 high resolution Cosmo SkyMed stripmap images from 02/2011-08/2011, showing movements of river banks, landslides and relative stretch between up and down river sides (Wang and Perissin 2012)—see Fig. 26.2.

Dam movements of TGD are monitored by high precision leveling and differential GPS: subsidence of the dam basement has ceased, a horizontal displacement of the dam exists in the upriver direction, at 175 m height (Dai and Su 2006). This was also confirmed by InSAR study (Wang et al. 2011): dam is slightly declining in upriver direction and "*slight deformation due to different water levels and temperatures were detected*".

26.3 Deformation Trend of Charvak Dam (2003–2010)

Two different implementations of PSI technique have been applied to process 45 Envisat ASAR images (04/2003–05/2010) over Charvak Dam, using StaMPS Toolbox (Hooper 2008) and SarProz PSI. Both of them show similar results in Fig. 26.3. A continuous deformation throughout the whole Envisat dataset has been found over the dam body, at <5 mm/year in satellite line of sight (LOS), which is 23° from nadir vertically and almost perpendicular to the dam, horizontally. Therefore both vertical and horizontal deformations of the dam are observed here.

Amongst the continuous deformation, also other, non-linear fluctuations were identified. Figure 26.4 demonstrates these residual deformations detected in the relative middle of Charvak Dam body. To minimize processing ambiguities, a potentially stable reference point has been selected ∼600 m from point ID 1542 where no significant atmospheric disturbance is expected. Water of Charvak reservoir is used for irrigation in the region, in summer. More frequent precipitation of May-June was reported in 2005 than in 2004 or 2006 (weatherspark.com).

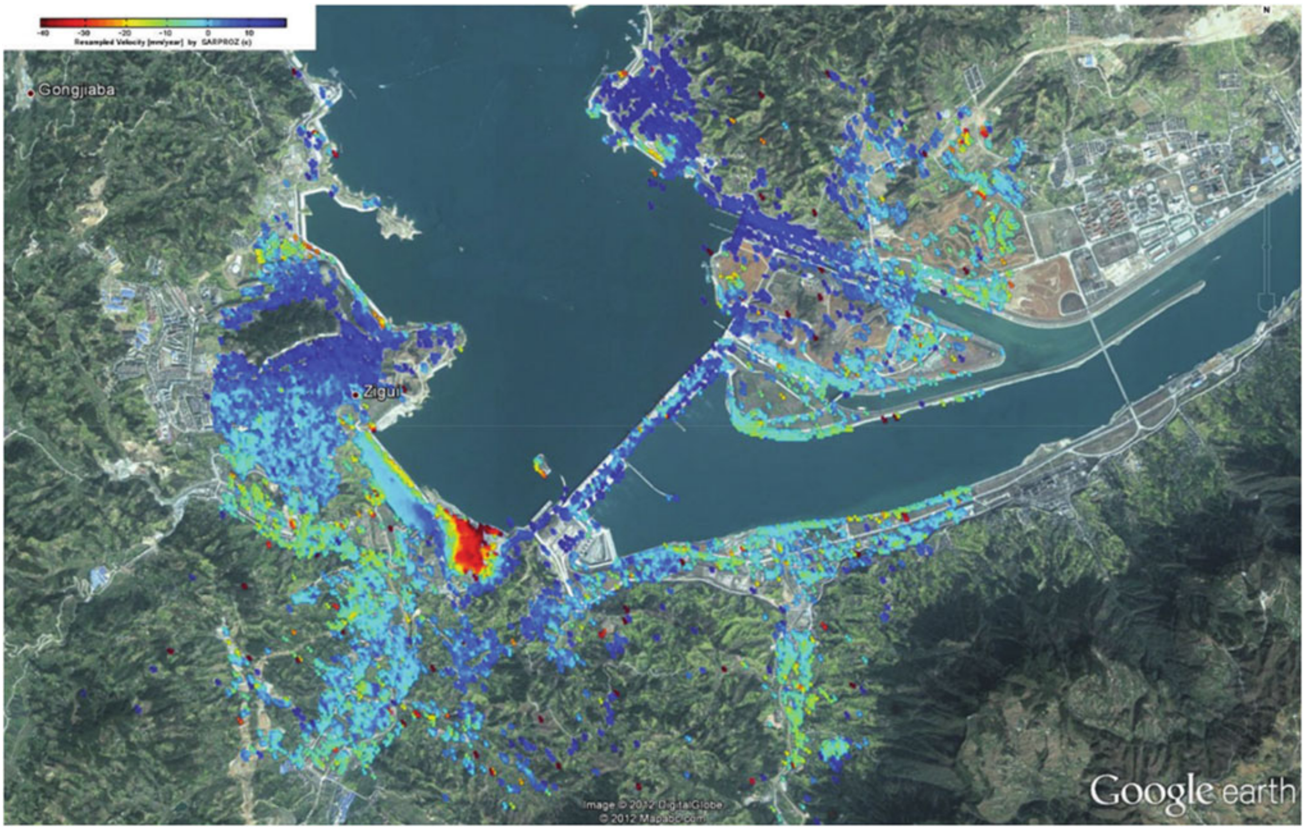


Fig. 26.2 PSI processing result: linear deformation trend over TGD area, using 29 Cosmo SkyMed data from 02–08/2011. (Wang and Perissin 2012)

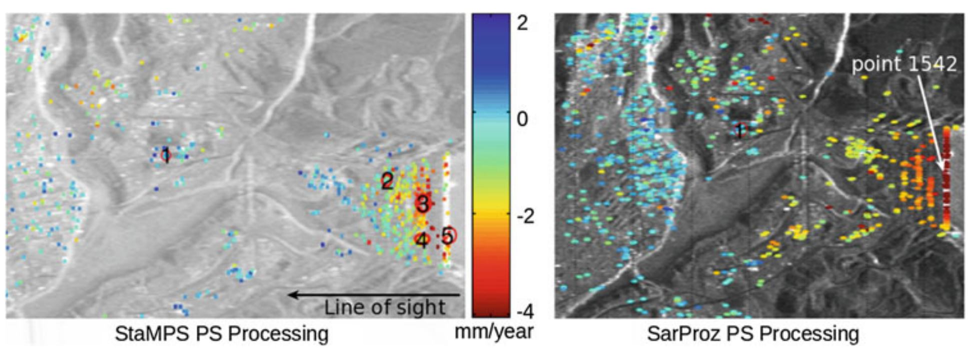


Fig. 26.3 PSI processing results of Charvak dam using implementations of: StaMPS (*left*) and SarProz (*right*). Point ID 1 is selected as reference point. (Abdullaev et al. 2013)

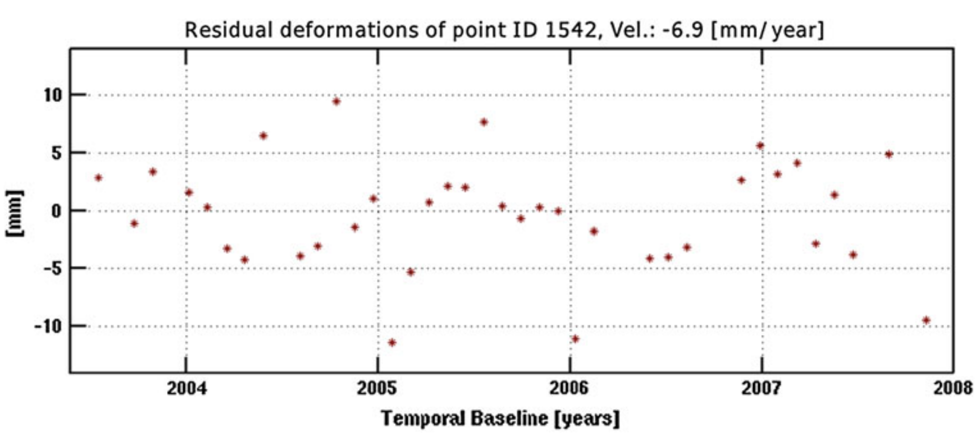


Fig. 26.4 Residual deformations of point ID 1542 at Charvak Dam, SarProz PSI processing of Envisat images (subset of 2003–2008)

26.4 Deformation Types of Plover Cove Dam (2008–2012)

Plover Cove Dam is a 2 km long marine dam formed mostly by sand and gravel earthfill. Monitoring has been performed using SarProz PSI processing of 62 TerraSAR-X and 11 TanDEM-X stripmap acquisitions of 10/2008–09/2012, with line of sight inclined by $\theta_{inc} = 37.3°$ from nadir facing almost perpendicularly to the main dam body (Lazecký et al. 2013). Using highly sampled dataset with external data about current temperature, water level of reservoir and tidal movements of surrounding bay, different dam deformations could have been analysed.

Very shallow motion has been detected from PSI InSAR. Linear deformation trend doesn't exceed 4 mm/year in LOS. Dam bank closer to reservoir side is subsiding slightly faster (averagely 1–2 mm/year in LOS faster) than the other side. Yet, cumulatively the subsidence doesn't exceed 1.5 cm in LOS during observed period of 10/2008–06/2012, which corresponds to max 1.2 cm in vertical direction.

On the other hand, the dam is relatively significantly affected by another motions, caused by water pressure from reservoir and also minor motions caused by tidal changes were detected. These motions have periodical character and don't cause permanent changes such as subsidence. However the range of these motions in LOS (D_{LOS}) is overwhelming subsidence trend of the dam—for example during 2010, the water level has been increased by around 8 m, causing $D_{LOS} = \sim 1.5$ cm over majority of points on the dam structure. As can be observed from results of correlation analysis (based on comparison between interferometric phase values corrected for height and linear trend and official

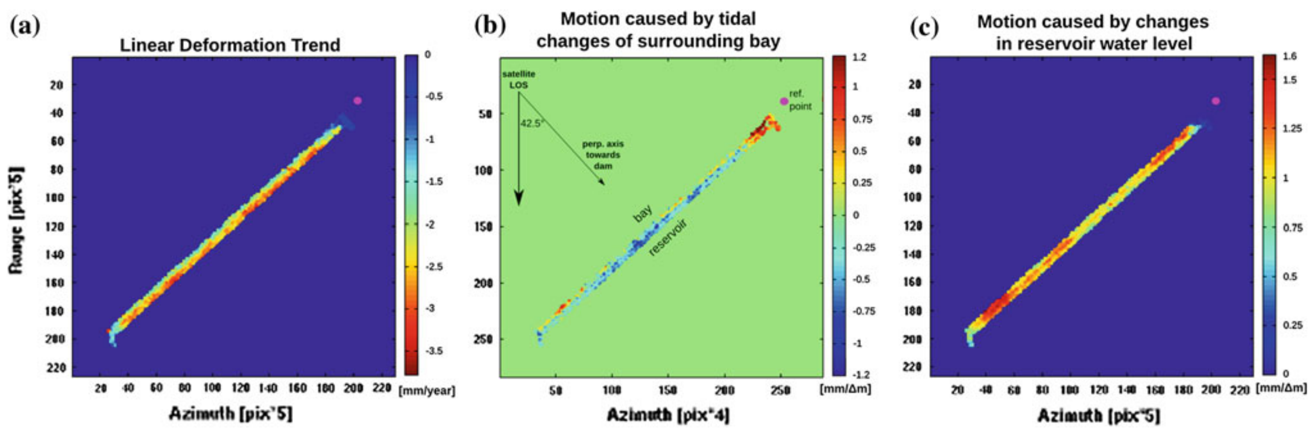
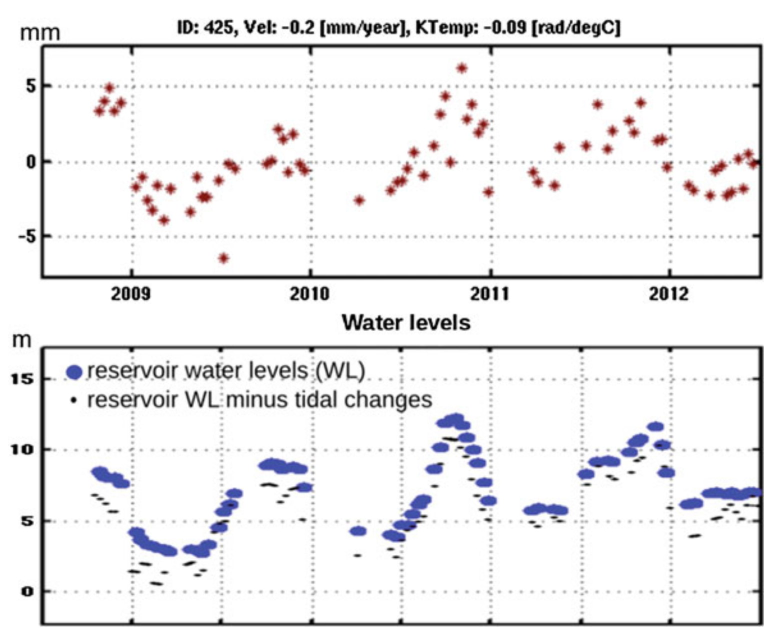


Fig. 26.5 Identified deformations of Plover Cove dam from InSAR processing of TerraSAR-X dataset from 10/2008-09/2012; values are in LOS direction: **a** Linear deformation trend (down to −3.9 mm/year), **b** Motion caused by tidal changes ([−1.2; 1.2] mm/Δm), **c** Motion caused by water level changes (0–1.6 mm/Δm)

Fig. 26.6 Comparison between residual deformations of selected point on the Plover Cove dam (*upper*) and water level data from Plover Cove reservoir (*lower*)



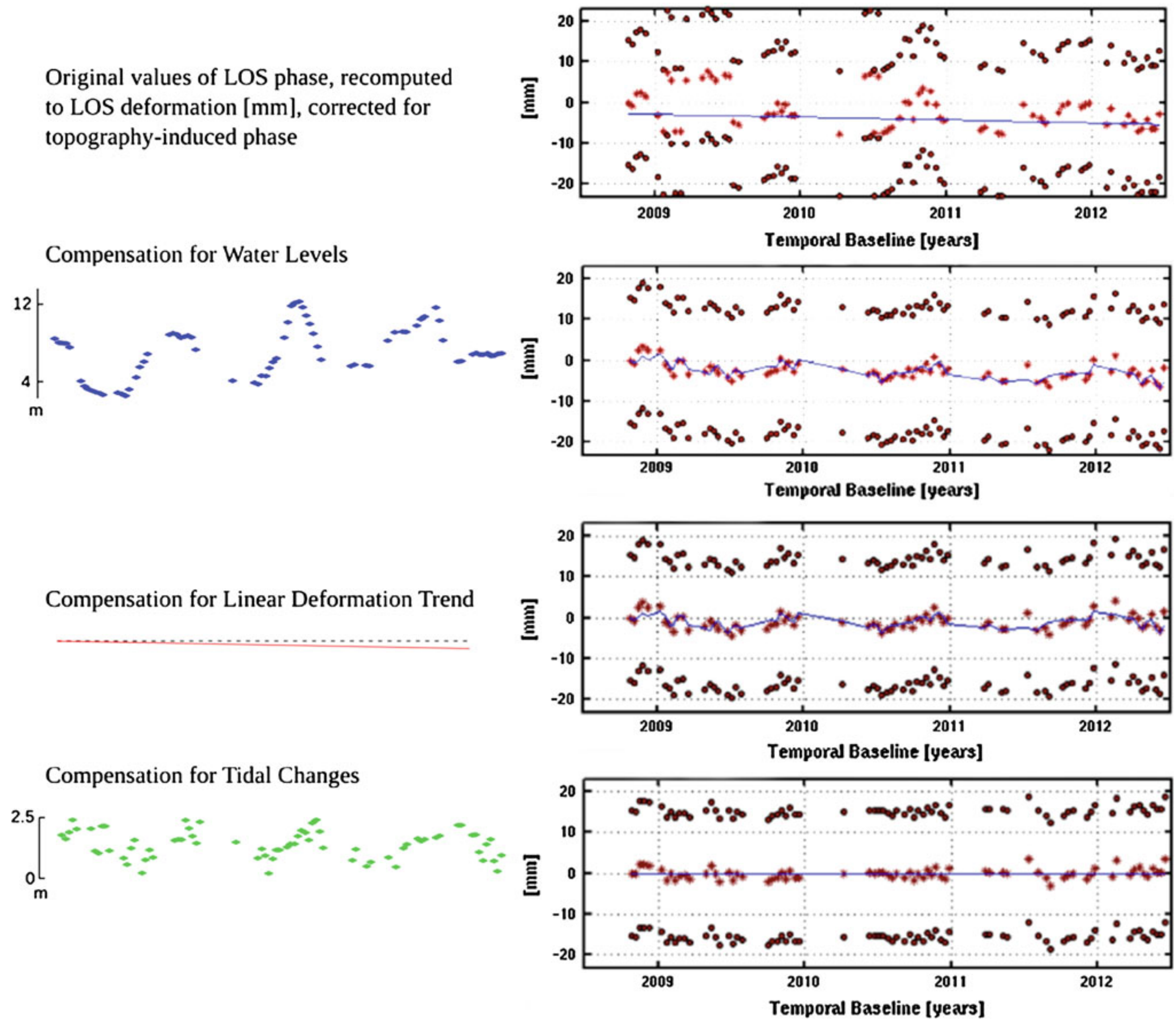


Fig. 26.7 Compensation for sources of motions demonstrated on selected point on Plover Cove dam

data of water levels and tidal changes), the direction of tidal changes influence is opposite to influence by water levels, in most of processed points—with exception for several points on the side to the sea which might have been affected directly by the sea water. It can be expected that the induced motion is mainly horizontal and perpendicular to the dam (which is angle $\alpha_{dam} = 42.5°$ from LOS horizontal direction). If this assumption is correct, all the D_{LOS} values can be recomputed to approximately conform values of horizontal motion of the dam, D_{dam}, by neglecting other motion directions—see Eq. 26.1, based on (Cumming and Zhang 1999).

$$D_{dam} = \frac{D_{LOS}}{\sin \theta_{inc} \cdot \cos \alpha_{dam}} \quad (26.1)$$

In the end, $D_{dam} = D_{LOS} \cdot 2.238$. However, since there are no reference data available to appropriately validate these assumptions, following values remain in satellite LOS direction only.

Three main significant motions of the dam are shown in Fig. 26.5. In addition to figured sources, also temperature affects motions of metallic objects over the dam. These motions were neglected as insignificant—thermal expansion can affect several areas in rate of up to only 0.17 mm/Δ°C (Lazecký et al. 2013), according to PSI estimations. A correlation between non-linear deformations of the dam and changes of water levels in reservoir can be seen in Fig. 26.6, showing example on selected dam PS point near to the entrance of the dam. Another point was selected in order to demonstrate correction of estimated models of phase contribution in Fig. 26.7. After correction, residuals show no periodical motion and could have been caused by errors due to different delay of radar pulses transmission through atmosphere (due to weather conditions and including water vapor) or they can represent non-linear motions due to mentioned (or another) sources affecting the dam. These residuals are not significant and show no temporal trend.

26.5 Conclusions

InSAR techniques can be recommended for monitoring movements of dams and surrounding slopes and, due to its very high sensitivity, it can precisely estimate influence of various deformation sources, such as pressure of water in dammed reservoir. Using appropriate dataset, in terms of temporal and spatial resolution of data as well as orientation of satellite line of sight towards the dam, it is possible to accurately identify dam movements, both continuously graduating as well as periodical. Good results are acquired also in case of Plover Cove dam in Hong Kong that is area characteristic for its inconvenient high moisture and rain clouds.

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