Satellite Based Longterm Deformation Monitoring on Dams and its Surroundings

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ABSTRACT:

Surface deformation of dams and its surroundings may endanger infrastructure and even human lives. Satellites monitor single structure displacements and movements of surrounding landscapes at regular intervals. They can help to understand the nature of ground instabilities and formulate an adequate response. Satellite based monitoring ideally complements terrestrial surveying. InSAR (Interferometric Synthetic Aperture Radar) is a technique that allows mapping millimeter-scale deformations of the earth's surface with radar satellite measurements in a very high resolution. In general the precision of InSAR movement measurement is optimized by interferometric time series analyses with an increasing stack of radar acquisitions over time. A precision within the range of few milimeters will then be achievable for each individual measurement. Thousands or even millions of measurement points can be reliably analysed. Detailed movement maps for dams in Kirgizstan and Iraq are created, demonstrating the capacity of the InSAR technique. The Mosul dam in Iraq is well known for standing on unstable soft soil and gypsum. The results show surface movements that may arise from underground instabilities and water pressure of the reservoir. The presented results demonstrate that satellite based interferometric monitoring provides precise and cost-effective information suitable for static risk assessment approaches.

1 INTRODUCTION

SAR-interferometric surface deformation monitoring has gained an increasing interest and acceptance for monitoring purposes. Several operational aspects are addressed by this technique complementing and partially even replacing successively terrestrial surveillance approaches. Surface movements induced by man-made activities such as infrastructure constructions, excavations and underground engineering, or natural disasters (e.g. landslides) can be unexpected and far-reaching, and may endanger infrastructure and even human lives. Satellites monitor wide-area surface movements as well as single structure displacements at regular intervals. They can help to understand the nature of ground instabilities and formulate an adequate response. They may also provide input data into simulation models to better evaluate risks of future surface movements.

The following case studies demonstrate the capacity of InSAR to provide an additional information layer for the determination of long-term deformation trends within a multi-sensorial setup.

2 METHODS

The start of the TerraSAR-X mission in 2007 (details for example in TerraSAR-X Image Product Guide (2015)) was a significant milestone which helped to establish products and geoinformation services based on Earth remote sensing sources on a global scale. In particular, Interferometric Synthetic Aperture Radar (InSAR) techniques profit from a precisely defined satellite orbit tube and precise absolute orbit information. InSAR disciplines like Multi Baseline Interferometric Techniques (such as Persistent Scatter Interferometry (PSI), described by Ferretti et al (2001) and Small Baseline Subsets (SBAS), described by Berardino et al (2002), profit from a precisely defined satellite orbit tube and precise absolute orbit information. The sensor’s high resolution of up to 0.25 m x 1.0 m allows for monitoring of infrastructure elements (e.g. dams) on a large scale. In urban regions a density of 100,000 valid measurement points per square kilometer is typically exceeded. This high level of detail in combination with complementary geospatial information provides added value to a broad range of applications.

In general, urban structures provide a sufficiently high number of valid measurement pixels. In rural areas with dense vegetation on agricultural land, grasslands, forests and plantations, yet, no surface valid movement results can be derived, due to vegetation growth and movement and thus the induced the changes of radar backscattering over time. Infrastructure objects are stable radar backscatter targets, thereby allowing for the allocation of a large number of measurement pixels to create feature layers, as shown in the following paragraphs.

3 CASE STUDY I: KURPSAI DAM

3.1 Overview

The Kyrgyz Republic is currently planning the construction of several hydropower plants. In order to provide important information in case of emergency for monitoring the structures and the surrounding slopes, especially related to seismic activities and landslide hazards, the R&D project MI-DAM will develop a robust, cost-effective and flexible early warning and fragility monitoring system. MI-DAM stands for "MultI-parameter monitoring and real-time risk assessment of hydroelectric DAMs in the Kyrgyz Republic". The project is funded by the German Federal Ministry of Education and Research (BMBF).

The system will continuously monitor the structural conditions of the dams and surrounding slopes. Real-time sensors (Low-Cost GNSS, Fiber Optics, Seismics) will be installed on the dams and slopes for measuring structural deformations and displacements and information will be transmitted in real time to the responsible authorities (e. g. disaster control). To supplement the measurements from locally installed sensors, high-resolution satellite-based radar measurements are used in addition for long-term for monitoring purposes. These provide a dense network of measuring points on the dam and the surrounding terrain. Remote sensing data can provide information on long-term stability behavior of dam structure and surroundings independent of the local accessibility of monitoring objects. The main advantages are the contactless operation, the relative high repetition interval of a few days and the number of achievable measuring points on the object surface. This allows for the detection of spatially and temporal non-uniform movements at structures and to derive e.g. tilt and curvature parameters of the surface.

The pilot monitoring system was installed in 2018 at the Kurpsai dam in the Kyrgyz Republic (see Figure 1) and is currently in the testing phase. The Kurpsai hydroelectric station is located on the Naryn River between the Talas Ala-Too Range and Fergana Range in the Tian Shan mountains and was commissioned in 1976. The dam is part of a sequence of Lower Kama hydropower stations.

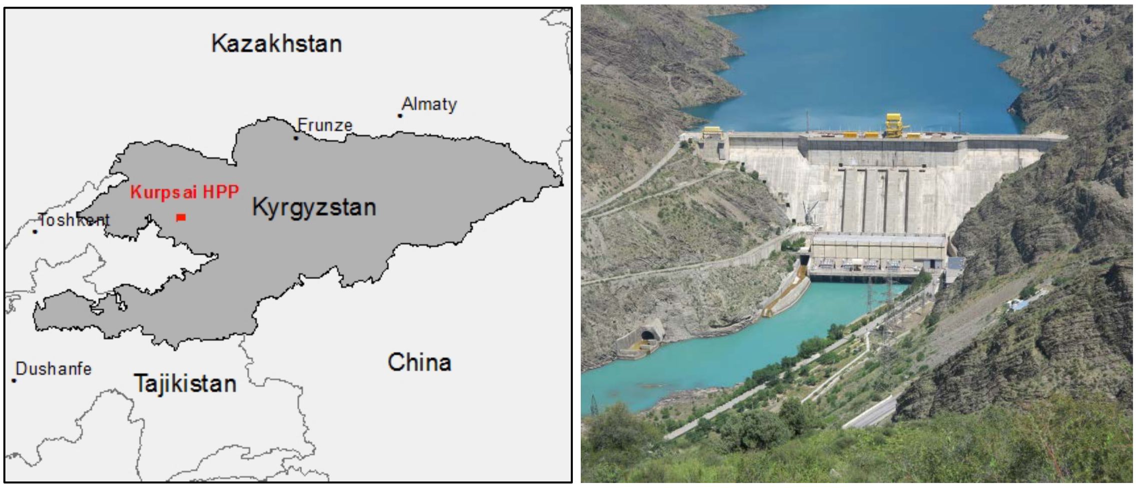

Figure 1. The Kurpsai Hydropower Plant (HPP) and its surroundings (right; Photo © M. Pilz) as well as the location in the Kyrgyz Republic (left).

3.2 SAR acquisitions

The TerraSAR-X (TSX) satellite acquires imagery of Kurpsai Dam area in the highest resolution mode, the so-called Staring SpotLight (ST) with a spatial resolution of approximately 1.0 m x 0.25 m and an footprint coverage of about 5 km x 3 km. TSX is orientated in two different orbits to the area of interest (dam, and adjacent slopes) with different look directions. The latter shall ensure a maximum visibility of the objects and minimum geometric effects (e.g. shading, distortions) in the satellite radar images. Figure 2 shows the area of interest (AOI) fully covered by the ascending and descending TSX footprints.

As it can be seen in Figure 3, surface movements measurements cannot be retrieved for some slope areas. Reasons are layover effects (bright edges) or shadowing effects (dark areas) due to the slanted view of the sensor in combination with strong topography.

3.3 InSAR processing and conditions

3.3.1 Persistent Scatterer Interferometry

The Persistent Scatterer Interferometry (PSI) technique was chosen for the interferometric processing of the TSX repeat pass scenes separately for each data stack. We used a semi-automated processing chain for interferometric SAR analysis and subsequent post-processing with the objective of providing movement measurement values and time series for as many high quality backscatter points within the AOI. The PSI processing of the TSX data stacks was carried out using the Interferometry software from Gamma Remote Sensing Research and Consulting AG. The processing includes the estimation of displacements in Line of Sight (LOS) direction. In addition, the height errors of initial digital height model (DEM) as well as atmospheric effects during the acquisition time are estimated. The global height model WorldDEM™ from Airbus with 12 m spatial resolution was chosen for the initial topographic correction of the interferograms.

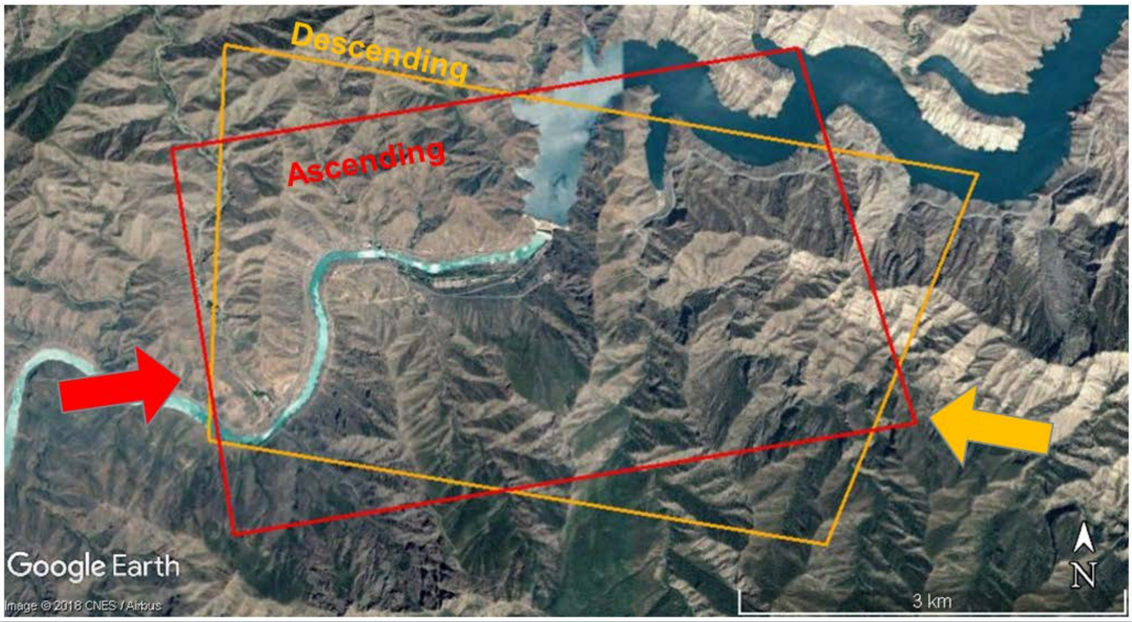

Figure 2. Spatial coverage of Kurpsai dam (in the image center) and its surroundings by two different TSX ST acquisition footprints resulting from different viewing directions (see arrows).

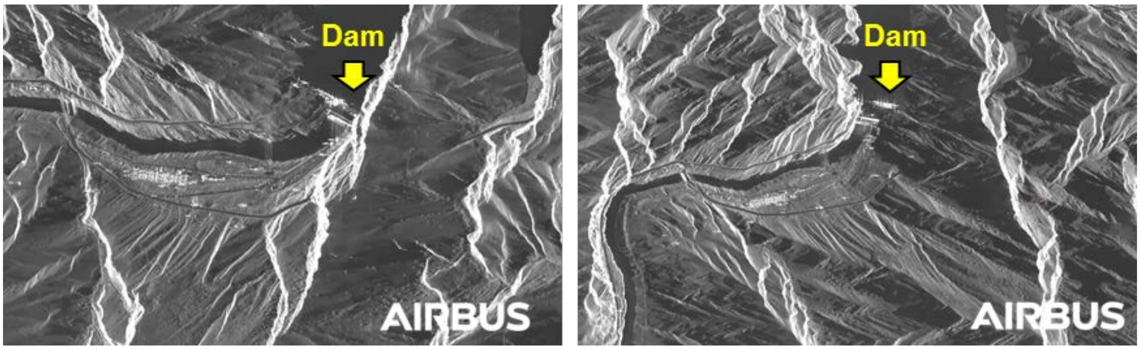

Figure 3. Subset of non-geocoded TSX ST radar mean intensity image in ascending (left) and descending (right) (© DLR e.V. 2017-2018 and © Airbus Defence and Space GmbH 2019).

For the creation of interferometric TSX pairs within a data stack, maximum geometric baselines related to a selected master scene were approx. 300 m.

3.3.2 2D Decomposition

Since the original motion measurement is done LOS direction and thus only one-dimensionally, no 3D motion vector can generally be determined with the described approach without auxiliary information.. The combination of ascending and descending PSI results allows for a 2D decomposition of the measured LOS movements into vertical (M_V) and East-West directed horizontal (M_{EW}) movement values (see Figure 4). The north-south motion component cannot be detected due to the polar orbit of all radar satellites and its side looking direction, i.e. the radar sensor is almost blind for movements in this direction. The 2D decomposition step is essential in order to determine the correct movement absolute values and directions at the Kurpsai dam and the surrounding slopes of the AOI.

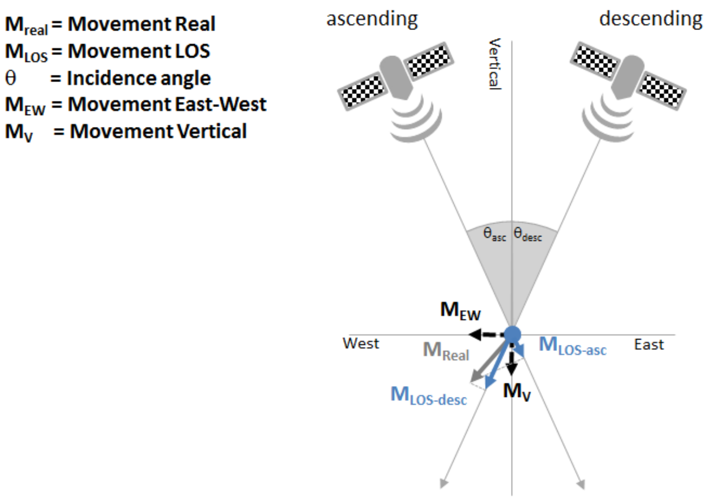

Figure 4. Schematic illustration of the ascending and descending acquisition geometry as an example of a movement with vertical and horizontal component. (© Airbus Defence and Space GmbH 2019).

3.4 First Results

In the result of an initial PSI analysis using 41 TSX ascending scenes (acq. between 11/2017 and 02/2019) and 39 TSX descending scenes (acq. between 11/2017 - 01/2019), we obtain for each data stack a large number of measurement PSI points. In the area of non-vegetation slopes and the dam itself, the number of PSI points is about 55,000 per square kilometer in both results (see Figure 5).

Figure 5. Overview about the location of measurement points (red points) at the dam and its immediate surroundings as result of the descending PSI analysis (© DLR e.V. 2017-2018 and © Airbus Defence and Space GmbH 2019).

Figure 6 shows the mean LOS movement velocities estimated by descending TSX ST data for the AOI. As a result, local movement zones on the slope south of the Naryn River are be clearly detected (red-colored points in Figure 6). Figure 7 shows an example of a measured time series of the LOS movements for a single PSI point located in a landslide zone. The measured LOS velocity on the selected point is about -50 mm/year and can be interpreted as downhill movement. At the Kurpsai dam crest, only minimal movements with a typical seasonal signal component are measured. Further analysis, i.e. the 2D Decomposition of the ascending and descending results will show which LOS movements are caused by vertical and/or horizontal East-West movements.

In the following phase of the project the results are used in combination with GPS measurements for the determination of the motion dynamics at the dam and at the surrounding slopes. The results will be used as input for subsequent modelling of the dam's and slopes' motion behaviour. The final goal is to simulate potential landslides and stronger seismic events and to evaluate their risks with respect to the dam's structural health.

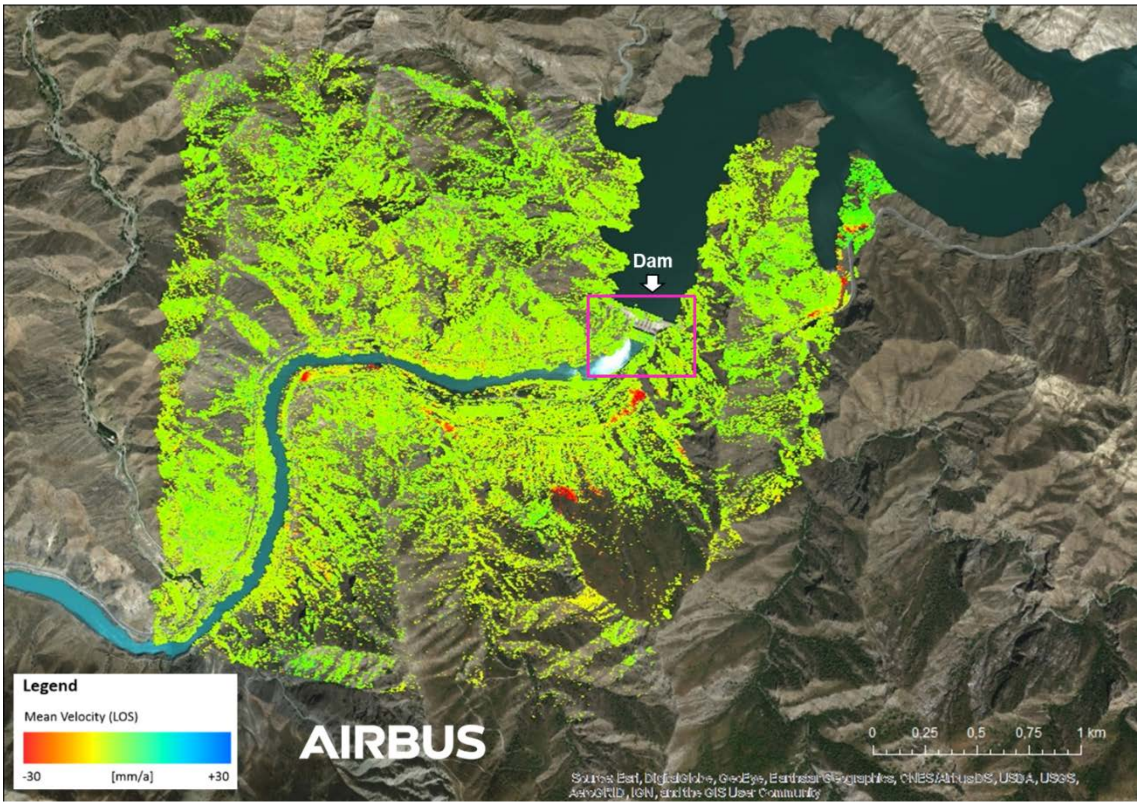

Figure 6. Mean movement velocities (mm/year) in LOS direction resulting from descending TSX ST images for the period of 11/2017 - 11/2018 in Kurpsai dam region (© DLR e.V. 2017-2018 and © Airbus Defence and Space GmbH 2019).

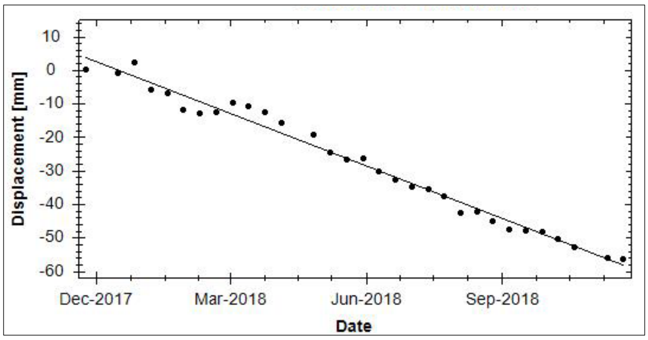

Figure 7. Time series of the LOS movement of a PSI point in a landslide slope zone of the descending TSX analysis 11/2017 - 11/2018 (© DLR e.V. 2017-2018 and © Airbus Defence and Space GmbH 2019).

4 CASE STUDY II: MOSUL DAM

Another example of a satellite based InSAR monitoring of a dam is shown in Figure 8. The Mosul dam was built in the early 1980s. With a length of 3.65 km and the crest elevation of 341 m, the Mosul dam is the largest dam in Iraq. The purpose of the dam is to generate hydroelectricity and provide water for downstream irrigation. The dam is well known for its instability as the riverbed is made of unstable soft soil and gypsum, a mineral that dissolves as water runs through it. The structure has to be cemented daily in order to keep water from seeping through. Airbus Defence and Space monitored the dam from April 2015 to April 2016.

The measured movements (see Figure 8) result from interferometric SBAS processing of 32 TerraSAR-X repeat pass scenes, acquired in High-Resolution Spotlight (HS) mode at a spatial resolution of 1 m and a repeat cycle of 11 days. The acquisitions were recorded from a descending orbit with an incidence angle of approximately 27°. More information can be found in Airbus Defence and Space (2017, 2019)

5 CONCLUSIONS

The paper presents two case studies on hydropower dams. In both studies a satellite based surface deformation measurement technique (InSAR) has been used to determine the object's long-term movement behavior at its surface. It is demonstrated that the remotely sensed approach can be used to generate deformation patterns with a high spatial resolution. The results can be used as input for subsequent modelling and risk assessment methods. Advantages to terrestrial surveillance are: independency of local accessibility, very high number of measurement points, long-term availability, large scale coverage and determined costs on a moderate level. Drawbacks are the relatively low temporal resolutions (several days), the limited sensitivity of the system for horizontal movements in North-South direction and the complex acquisition geometry. Thus, the strength of satellite based infrastructure monitoring is the precise detection of long-term deformation trends complementing in-situ instrumentation.

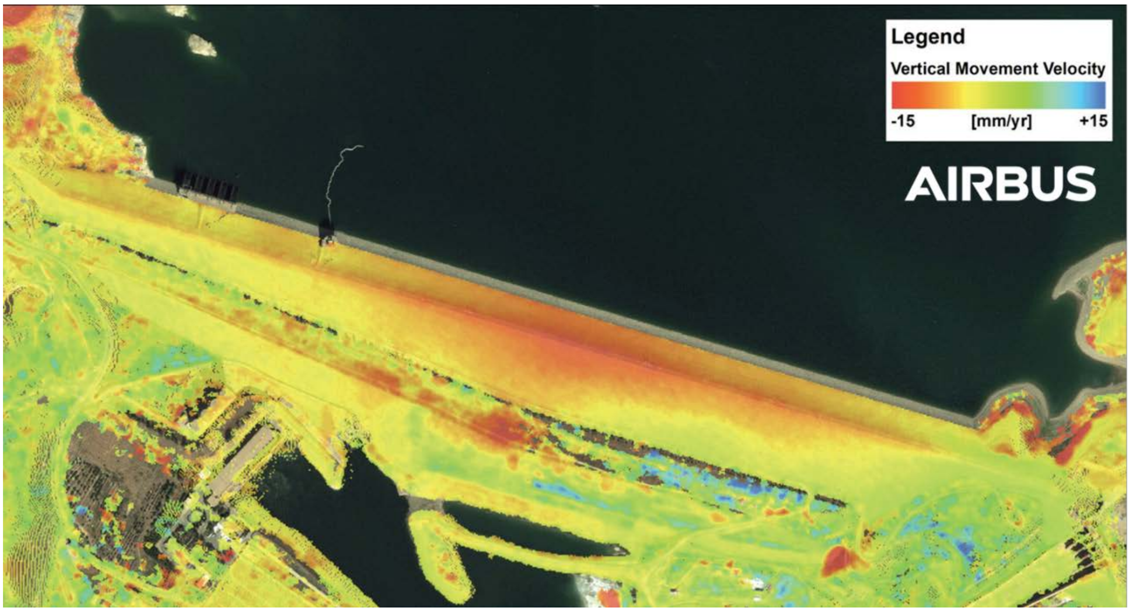

Figure 8. Mosul dam in Iraq: Vertical movement velocities between 04/2015 and 04/2016 (© DLR e.V. 2015-2016 and © Airbus Defence and Space GmbH 2016).

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