Monitoring of Mosul dam through SAR data

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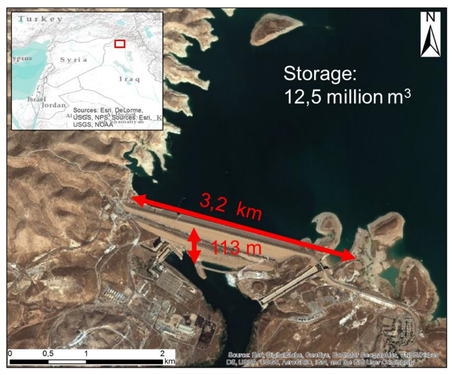
ABSTRACT

Monitoring of dams is a necessary practice to ensure the safety of the infrastructure itself but also guarantee the stability of the water reservoir and the surrounding areas. In fact, the longevity of the structure is strongly connected to any event which causes possible damages and, in the worst scenario, ends on the dam failure. Hence, the detection of the deformation affecting not only the dam but also the surrounding basin is essential to prevent catastrophic situations and plan all the necessary maintenance interventions. The use of satellite Synthetic Aperture Radar (SAR) data was proposed to detect the deformation affecting an emblematic case, where the traditional techniques could not temporary be applied: the Iraqi Mosul dam. This structure is affected by dangerous deformation caused by the erosion of the highly water-soluble gypsum layer where the foundation lays. The importance of these techniques emerged recently because safety and logistic conditions did not allow to monitor the dam applying the traditional geodetic techniques. In such cases, Advanced Differential SAR Interferometry constitutes a reliable diagnostic tool of dam structural health to avoid any extraordinary failure that may lead to loss of lives. Sentinel-1 and Cosmo-SkyMed data revealed the hazards that threaten the dam and the surrounding area, showing the sliding of a small portion of the basin boundary and some sinkholes located in front of the dam. Furthermore, strong non-linearity influenced the temporal evolution on deformation.

INTRODUCTION and OBJECTIVE

The dam of Mosul, is the biggest dam in Iraq. It is located along the river Tigris, 35 km north from the city of Mosul. It consists of 113 m tall and 3.4 km long earth-fill embankment-type, with a clay core. This structure is affected by dangerous deformation caused by the erosion of the highly water-soluble gypsum layer where the foundation lays. To preserve the dam stability after its construction, multiple grouting projects have taken place in the last decades (Kelley, 2007).
Space-borne SAR data were used to analyse the stability of the Mosul dam by Milillo et al. (2016) but results mainly focused on the structure. Here, Sentinel-1 and COSMO-SkyMed data were considered to identify the ongoing deformation of the Mosul dam but also the surrounding areas. Also, a possible connection with the variation of the water level on the basin and its seasonality was deepen.



1.Localization of the Mosul dam.
2. Formation of underground cavities, causing the dam instabilities. Grouting injections were adopted as consolidation.

DATA AND METHODS

Several datasets of SAR data, with different ground resolution, were analysed:

- ✓ **Sentinel-1** data, 15 m ground resolution, (59 ascending data from October 2014 to February 2017; 74 descendig data from October 2014 to February 2017);
- ✓ **COSMO-SkyMed** data, 3 m and 1 m ground resolution respectively (61 Stripmap ascending data from December 2012 to July 2015; 11 Spotlight descending data from June 2016 to December 2016).

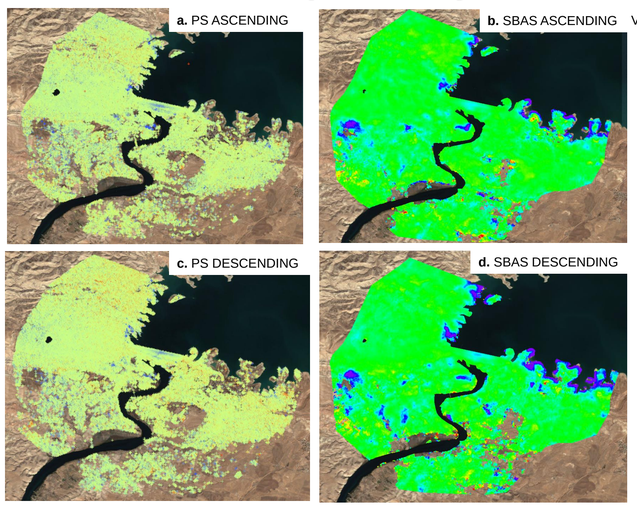
Multi-temporal Differential InSAR techniques, **PS** and **SBAS**, allowed to retrieve the evolution of deformations affecting the Mosul dam and the surrounding areas. Ascending and descending time-series obtained with Sentinel-1 data were combined to obtained the *vertical* and *east-west* components of the deformations.

The behavior of the evolution of deformation and eventual seasonal effects were searched identifying for each pixel, the **function** which **best fit** the measured deformation.

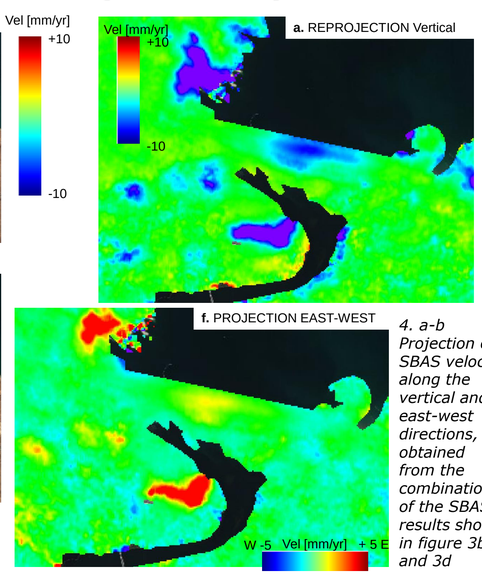
Furthermore, **statistical parameters** were calculate on the **amplitude** of the different stacks of data, and combine to evaluate the variation of the water level on the basin and define the connection with the ongoing deformation.

RESULTS

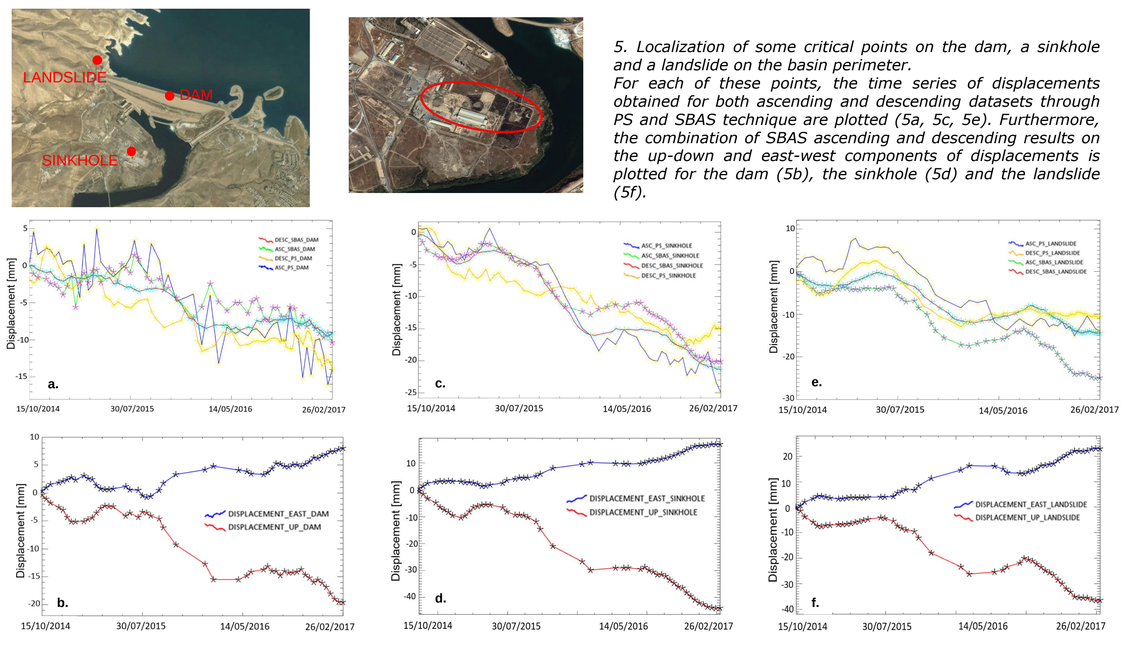
Sentinel-1 Multi-temporal analysis: PS and SBAS (2014-2017)



3.a-d Results of the multi-temporal processing of the Sentinel-1 ascending dataset with the PS technique (3a) and SBAS technique (3b) and the PS and SBAS techniques applied to the descending dataset (3c and 3d).



4. a-b Projection of SBAS velocity along the vertical and east-west directions, obtained from the combination of the SBAS results shown in figure 3b and 3d



5. Localization of some critical points on the dam, a sinkhole and a landslide on the basin perimeter. For each of these points, the time series of displacements obtained for both ascending and descending datasets through PS and SBAS technique are plotted (5a, 5c, 5e). Furthermore, the combination of SBAS ascending and descending results on the up-down and east-west components of displacements is plotted for the dam (5b), the sinkhole (5d) and the landslide (5f).

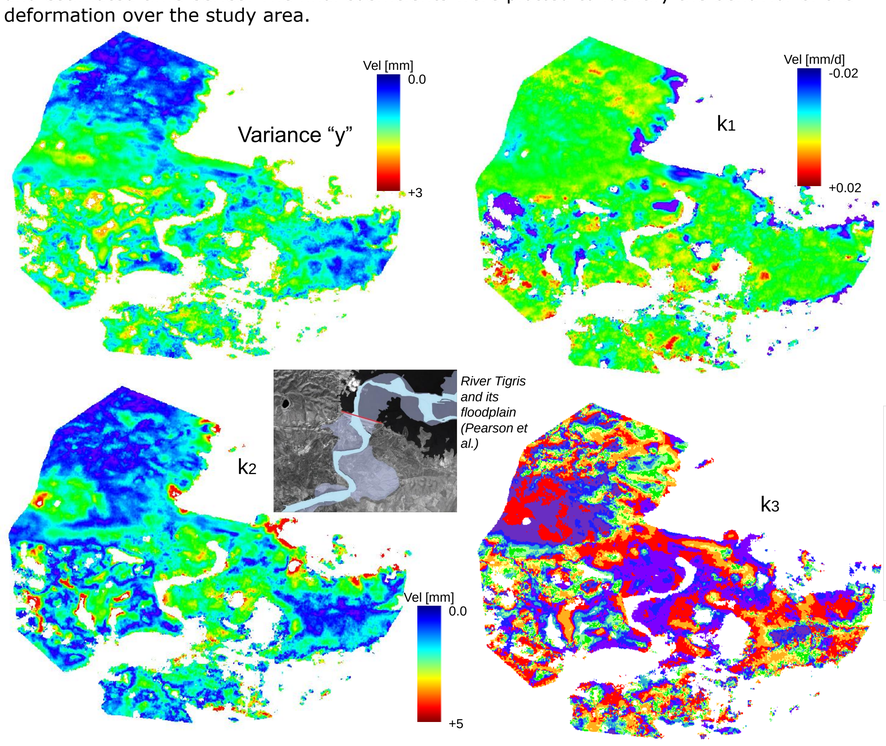
Sentinel-1 time series behavior

As a strong seasonal influence was noticed on the vertical component of displacement, the time-series of each pixel was fitted with the following function:

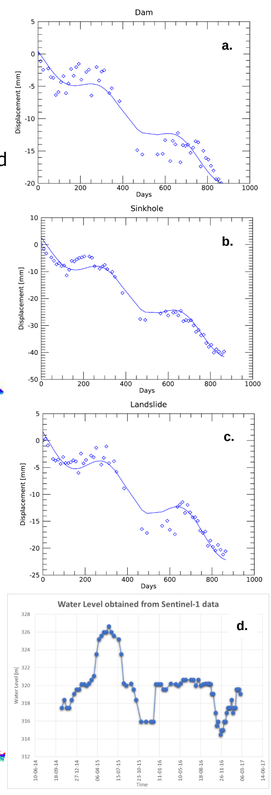
$$y = k_0 + k_1 x + k_2 \sin(k_3 + \frac{2\pi}{T} t)$$

y: variance between the observed and the fitted function
K0: constant
K1: linear coefficient
K2: amplitude of oscillation
K3: initial phase

For each pixel, the fitting function was obtained minimizing the variance between the observed and estimated time-series. The final coefficients were plotted to identify the behavior of the deformation over the study area.



6. Results of the fitting coefficients obtained from the variance minimization. The variance 'y' was used as a degree of confidence to mask the other parameter maps. k1 represents the entity of linear component of vertical displacements; k2 is the amplitude of the oscillation, giving information on the influence of the seasonal behavior; k3 is the initial phase of the oscillation, showing the spatial propagation of the oscillations and its timely delay.

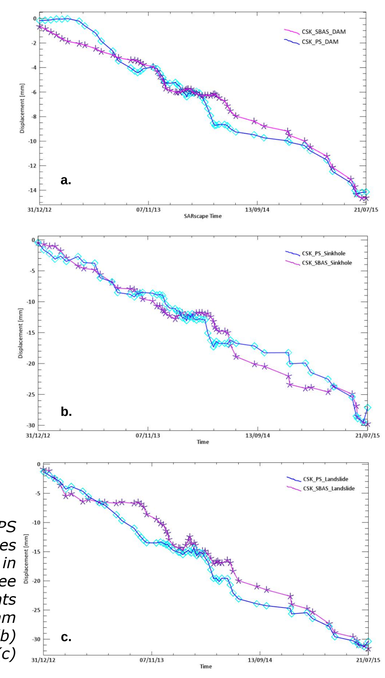


7. Examples of the fitting results obtained for the fitting functions of three points selected on the dam (a), the sinkhole (b) and the landslide (c). The fourth plot represent the water level on the basin, obtain from the amplitude variation of Sentinel-1 data (d).

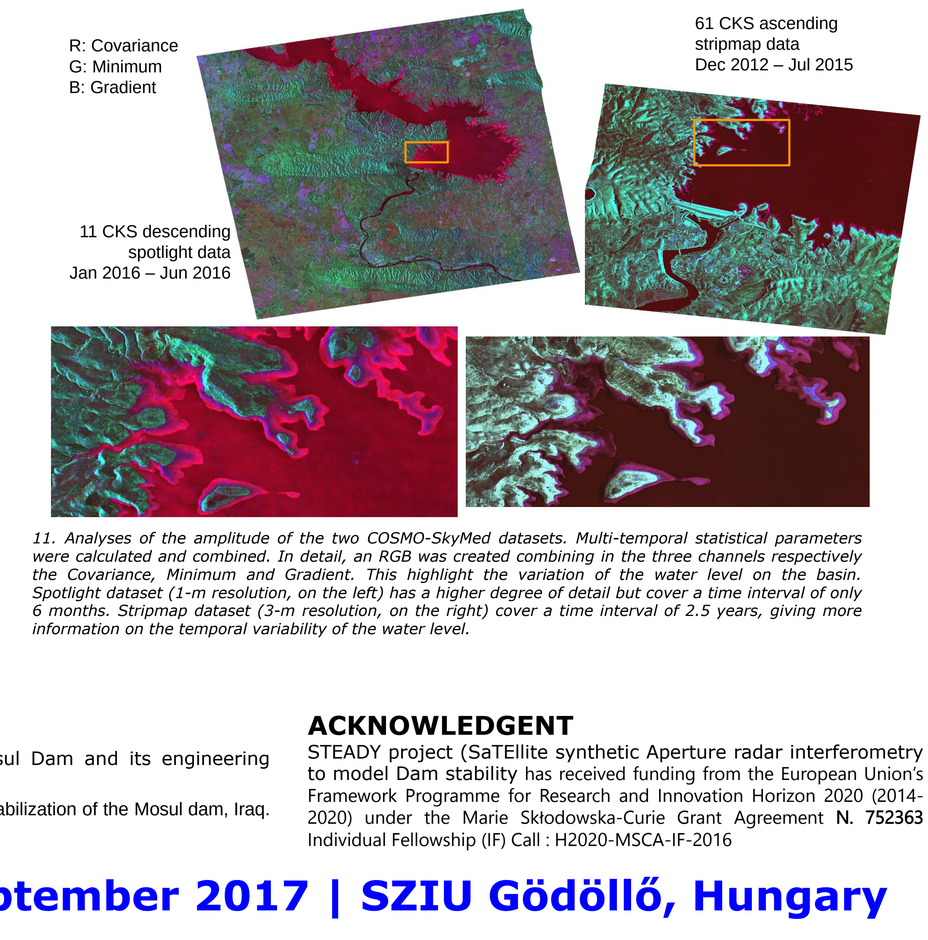
COSMO-SkyMed Multi-temporal analysis: PS and SBAS

8. PS results obtained from the 3-m resolution stripmap dataset of COSMO-SkyMed

9. SBAS results obtained from the 3-m resolution stripmap dataset of COSMO-SkyMed



10. Comparison of PS and SBAS time-series of displacement, in line-of-sigth, for three significant points selected on the dam (a), the sinkhole (b) and the landslide (c)



11. Analyses of the amplitude of the two COSMO-SkyMed datasets. Multi-temporal statistical parameters were calculated and combined. In detail, an RGB was created combining in the three channels respectively the Covariance, Minimum and Gradient. This highlight the variation of the water level on the basin. Spotlight dataset (1-m resolution, on the left) has a higher degree of detail but cover a time interval of only 6 months. Stripmap dataset (3-m resolution, on the right) cover a time interval of 2.5 years, giving more information on the temporal variability of the water level.

DISCUSSIONS AND FUTURE DEVELOPMENTS

- •The availability of ascending and descending **Sentinel-1** data allowed to identify the ongoing deformations affecting the Mosul dam and the surrounding area. Several sinkholes could be highlighted and also the sliding of a portion of the basin;
- •It was possible to combine the results obtained from two tracks and obtain the **vertical** and **east-west** component of deformation;
- •The evolution of deformation is strongly connected with the **geology** of this area (Kelley, 2007) which supports the obtained results;
- •The **non-linear behavior** of the deformation trend were identified and mapped, highlighting the area affected by oscillations;
- •An important influence of the **basin water level** was supposed. Further investigate are required to precisely define the correlation with deformations and possibly identify the geological unit properties;
- •Ascending COSMO-SkyMed data showed a displacement trend consistent with Sentinel-1 results. The high resolution of these data help on distinguishing **several sinkholes** in front of the dam but also close to the dam left abutment. The non-linear behavior of the deformations need to be deepen;
- •The high resolution of COSMO-SkyMed data could help on obtaining a detailed information on the **water level** as it was seen from the preliminary results obtained from the multi-temporal features extracted from the **amplitude** of stripmap and spotlight data.
- •Future developments will be focus on deepen:
- ✓The structure behavior;
- ✓The subsoil erosion and the influence on the groundwater flow

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Milillo P., Bűrgmann R., Lundgren P., Salzer J., Perissin D., Fielding e., Biondi F., Milillo G., 2016. Spae geodetic monitoring of engineered structures: the ongoing destabilization of the Mosul dam, Iraq. Scientific Reports 6, doi: 10,1038/srep37408.

ACKNOWLEDGENT

STEADY project (SaTEllite synthetic Aperture radar interferometry to model Dam stability has received funding from the European Union's Framework Programme for Research and Innovation Horizon 2020 (2014-2020) under the Marie Skłodowska-Curie Grant Agreement N. 752363 Individual Fellowship (IF) Call : H2020-MSCA-IF-2016