Integration of Ground-Based Monitoring Techniques to Control the Behaviour of Medium-Scale Critical Infrastructure: The Case of Arch Dam

M. Corsetti, P.J.V. D'Aranno, F. Giancola, M. Marsella, A. Sonnessa, W. Wahbeh
Sapienza Università degli Studi di Roma
D.I.C.E.A, Dipartimento di Ingegneria Civile e Ambientale
Via Eudossiana, 18, 00184 Roma

A.Meta, L. Testa
MetaSensing BV
Huygensstraat 44, Noordwijk, 2201DK, The Netherlands

G. Solaro, G. Zeni
IREA – CNR, Istituto per il Rilevamento Elettromagnetico dell'Ambiente
Via Diocleziano, 80124 Napoli

Abstract. Among the civil infrastructure systems, the dams are the ones more systematically monitored by means of periodic measurements and fixed sensors installed on the structure soon after the construction. Considering their age and long lifetime, most of the monitoring systems appear presently dated both for the instruments and for adopted the measurement approach. On the contrary, the technological development is providing new perspectives to improve the observational and capability and the accuracy of the dam monitoring system . This work presents an integrated approach based on the use of innovative ground based surveying techniques that may be adopted to control the behavior of arch dams. A field test was conducted to test the performance and the applicability of an Automatic Total Station (ATS), a Terrestrial Laser Scanner and a Ground-Based SAR instrument to collect measurements on the structure and attempt their integration for further monitoring and modeling implementations. The ATS was adopted to establish a set of reference and control points useful also for coregistration and validation of the TLS and GBSAR measurements. The TLS data provide an accurate 3D model of the dam and its abutments to be used for describing the monitoring data in relation to the real geometry of the structure and to improve the structural modeling. The GBSAR, that is able to furnish an overall patterns of the dam displacements at sub-millimeter accuracy, will be adopted to attempt the observation of the horizontal displacements linked to temperature and water level effects variations.
The results obtained are compared to traditional measurements (automatic/manual collimation data) in order to assess if this advanced monitoring techniques proved to be useful for the control of dam displacements in terms of temporal and spatial resolution.

Keywords. Synthetic Aperture Radar (SAR), FastGround-based SAR (FastGBSAR), Health monitoring of dams

1 Introduction

A Synthetic Aperture Radar (SAR) is an active microwave sensor used to produce 2D microwave images of the observed scene. The main advantage of microwave images is their capability to observe a scene without the need of solar illumination and in any weather condition. In the last few year, ground-based SAR systems have been developed to solve the problem of continuous monitoring of small scenes, such as dams, land-slides, buildings, bridges, or to extract information on terrain morphology. The Ground-Based Synthetic Aperture Radar (GB-SAR) interferometry is a relatively new technique that, in the last ten years, has gained an increasing interest for deformation measurements due to the continuous monitoring capabilities of medium-scale sites. A number of experimental results demonstrated the GBSAR effectiveness for remote monitoring of terrain slopes and as an early warning system to assess the risk of rapid landslides [5].

Ground-Based Synthetic Aperture Radar (SAR) interferometry is a non-destructive radar technique to measure displacements of structures and natural scenes with a sub-millimeter accuracy.

The interferometric processing of two coherent SAR images results in a map of displacements occurred between the acquisition of the two SAR images. Radar measurements give the projection along the radar line-of-sight of the 3D displacement vector. The main advantage of GBSAR interferometry with respect to many traditional techniques is its capability to provide 2D information on the displacement field rather than measurements of displacements in only a few points.

2 GBSAR TECHNIQUE

2.1 Introduction

SAR is an abbreviation for Synthetic Aperture Radar. While in Real Aperture Radar (RAR), image resolution is limited by the physical dimension of the antenna, in SAR the antenna is synthetically elongated by moving the sensor perpendicular to the look direction. Radar stands for RAdio Detection And Ranging. An imaging radar system emits and receives electromagnetic waves in the radio spectrum to obtain information about distant objects. Typical frequency bands used for SAR are between L and Ku-band

Band name	Wavelenght (cm)	Frequency (GHz)
P-band	30-75	1-0.4
L-band	15-30	2-1
S-band	7.5-15	4-2
C-band	3.75-7.5	8-4
X-band	2.5-3.75	12-8
Ku-band	1.67-2.5	18-12
K-band	1.11-1.67	27-18
Ka-band	0.75-1.11	40-27

As it is an active remote sensing system, it provides its own illumination and can therefore operate day and night and penetrate clouds.

Furthermore, it is a coherent imaging technology which gathers amplitude and phase information of the reflected signal.

The result of one SAR acquisition is a two dimensional image with range and cross-range resolution. Each resolution cell contains amplitude and phase information. The amplitude determines the reflectivity of a target and the phase depends on distance between object and instrument and atmospheric properties. Only the wrapped phase (between $-\pi$ and $+\pi$) is observed and thus, the absolute distance between instrument and object cannot be retrieved. By computing the difference between two phase images, an interferogram is formed.

The phase φ is a function of distance r between sensor and target:

$$2r = -\frac{\lambda}{2\pi}\varphi \qquad \varphi = -\frac{4\pi}{\lambda}r$$

The observed phase φ^{w} (i.e. wrapped phase) is a relative phase, as it is always wrapped into the interval $[-\pi,\pi)$. The relation between absolute phase φ (i.e. unwrapped phase) and observed phase φ^{w} is

$$\varphi^{w} = W\{\varphi\} = \mathrm{mod}\{\varphi+\pi,2\pi\} - \pi = \varphi - 2\pi n$$

given by

with W{.} being the wrapping operator. The phase ambiguity n (i.e. integer number of full phase cycles) is unknown. Thus the absolute distance r cannot be determined.

Comparing two SAR images of the same area, either collected at different time periods and/or from different sensor positions, the phase difference Φ^{w}, i.e. interferometric phase, is related to the changes in

$$\Phi^{w} = W\{\varphi_1^{w} - \varphi_2^{w}\} = W\left(-\frac{4\pi}{\lambda}(r_1 - r_2)\right) = W\left(\frac{4\pi}{\lambda}\Delta r\right)$$

distance between sensor and target $\Delta r = r_2 - r_1$ by:

The maximum unambiguous change of distance

$$\Delta r_{\max} = \pm\frac{\lambda}{4}$$

Δr_{max} is restricted by the wavelength λ:

If amplitude a and phase φ are represented as

$$z = ae^{i\varphi} = a\cos(\varphi + i\sin\varphi)$$

complex value z with:

an interferogram is formed by:

$$z_1 z_2^{*} = a_1 a_2 e^{i(\varphi_1 - \varphi_2)}$$

whereas z* is the complex conjugated of z.

If an interferogram is formed using two SAR images collected at different time periods but from the same

sensor position, the resulting phase difference is related to temporal changes of the distance between sensor and target (e.g. displacements). The difference between the two time periods is referred to as the temporal baseline B_t.

If the two SAR images are collected at the same time period but from different sensor positions, the resulting phase difference depends on the topography of the illuminated area. The effective distance between the two sensors is referred to as spatial baseline B_s. In conventional spaceborne SAR, a temporal and spatial baseline are present whereas in GB-SAR the spatial baseline is usually zero, if it is not introduced intentionally.

Depending on the type of baseline, the interferometric phase Φ^w is the sum of several effects:

$$\Phi^{w} = \Phi^{topo} + \Phi^{disp} + \Phi^{atm} + \Phi^{noise} - 2\pi n$$

Φ_{topo} is the phase difference due the topography in case of a spatial baseline, Φ_{disp} and Φ_{atm} are temporal phase changes due to displacement and atmospheric effects, Φ_{noise} is noise and n is the integer phase ambiguity.

For displacement monitoring applications, Φ_{disp} can be determined by

$$\Phi^{disp} = \Phi^{w} - \Phi^{atm} - \Phi^{noise} + 2\pi n$$

whereas it is assumed that the spatial baseline is zero.

The measurements were performed using a FastGBSAR (owned by MetaSennsing) to monitor an arch dam displacements. The radar is a Ku-band (17.2 GHz operating frequency) ground based interferometric radar system designed for deformation monitoring, vibration measurement and stability assessment of natural slope and man-made structures. The system can operate in two different operational modes:

- Real Aperture Radar (RAR);
- Synthetic Aperture Radar (SAR)

In RAR mode the FastGBSAR is particularly suitable for statistic and dynamic structural monitoring of structures, the radar unit is mounted on a tripod without moving the sensor, therefore only range resolution can be obtained. In SAR mode the sensor is moved along a linear rail to obtain the synthetic aperture, producing two-dimensional (range and azimuth) images. It is suitable for deformation monitoring of aerial structures and natural hazards such us mines, dams, dikes, landslide, slopes, etc.

The FastGBSAR can be also used in two different hardware version: standard with two antennas and polarimetric equipped of four antennas.

In particular the polarimetric version, used in this campaign, is equipped with two transmitting and two receiving antennas, this allow acquisitions of full polarimetric data for retrieving additional information about the monitored area.

3 A dam monitoring experiment and preliminary results

An arch-dam was investigated by using FastGBSAR system in order to measure displacements due to the reservoir water and temperature variation. The dam is currently controlled by traditional topographic techniques that consist of high precision leveling lines and optical collimators to detect horizontal displacements. In addition, a high-resolution 3D model of the structure itself was obtained using the TLS. The TLS survey was carried out by combining different scans acquired from three scanpositions in order to obtain a complete numerical model of the structure.

Raw point clouds was filtered to remove errors and vegetation and then combined in a single discrete model, made by about 2.700.000 points.

Total station and GNSS measurements were performed to georeferencing the model and the GBSAR targets (Fig.2).

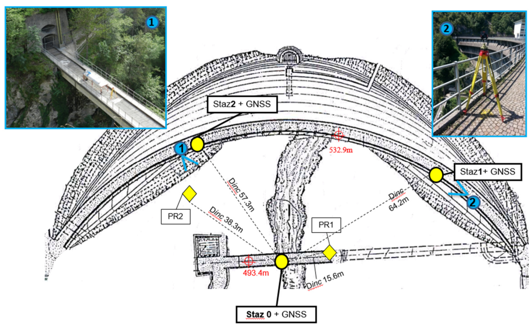

Fig. 1 Measurement network

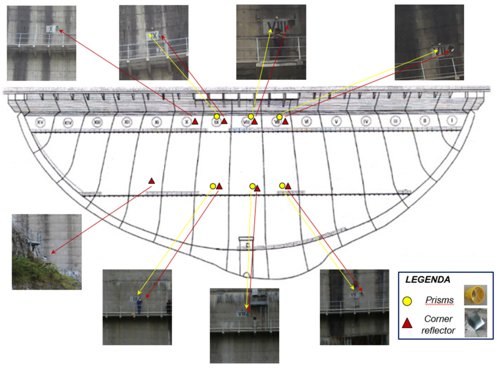

Fig. 2 Location of prisms and corner reflector on the dam

Eight retroreflective prisms were placed to establish a small reference network; two prisms as reference points in the vicinity of the dam, and six prisms on the dam body, near the corner reflectors (Fig.2).

Prisms and target were measured several time in forward and backward mode, in a fully automated way in order to achieve a better precision in the point coordinates establishment.
Local reference system was framed in the RDN-ETRF2000 system by carrying out GNSS measurements.
The campaign was carried out between 18th and 24th of June 2015. The radar was installed in front position at a distance of about 40 m from the illuminated dam surface with an inclination of 40 degree. This positioning has allowed to capture the entire dam displacement along in the range direction during the whole observation time.

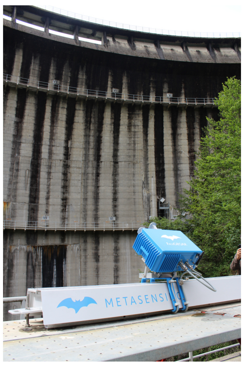

Fig. 3 View of radar during acquisition

The first step in the field measurement should be the identification of backscattering points with known positions and the evaluation of the position in the radar image. Differences in the intensities of the copol and crosspol channels can be noted. The area of interest (the dam) is located between 40m and 60 m in range, therefore the analysis will be focused on this area in the following. Multiple reflections are visible between 100 and 200 m, out the area of interest.
The Figure 4 shows the partially zoom view of the dam and shows the average power intensity over the available 7806 acquisitions. As shown in the Figure 3, the structure of the measured area can be identified very well in the power map. By zooming into the power map the identification of single boxes.

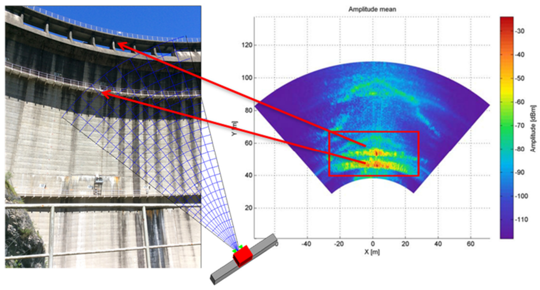

Fig. 4 Mean amplitude obtained by averaging the all 7806 images. The red rectangle identifies the area of interest.

From these two figures we can see that the intensities of the reflected signals from the dam is very high, and the estimated signal to noise ratio (SNR) of the dam area is also high enough to extract the deformation information of the points on the dam by using the resolution cells with high estimated SNR. In Figure 4, we can see the SNR of the most points on the dam are at 30dB, which provide a good foundation for the final accurate results.
Furthermore, the area corresponding to the dam is well identified in the plot of the coherence, which is high in the area of the dam, as showed in the Figure 5.

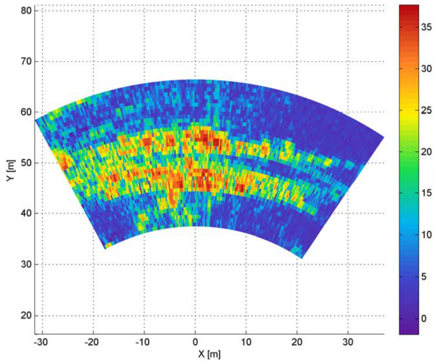

Fig. 5 Estimated Stability Index computed on all the 7806 acquisitions

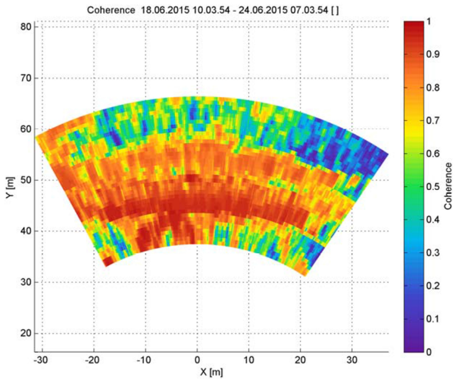

Fig. 6 Coherence computed on 6 acquisitions

The coherence is usually used to determine the stability of the target point, the maximum is 1 and the minimum is 0. The coherence map of the dam is shown in Figure 6, the dam area of the correlation value of each point are close to 1, which is guaranteed to obtain accurate results. Since the long time, real-time monitoring of the entire monitoring process by FastGBSAR system, so the entire monitoring results will be affected by the temperature, humidity and other changes facts because of different environments have different wave propagation speed. Therefore, it is necessary to select a stable point in the stable region in order to obtain the final accurate results, which is the reference point of the dam to calibrate the final results.

By selecting the correction on this reference point for the chosen PS in the analysis, all the displacements will represent movements with respect to the reference point of the dam.

The following plot shows the selection of the reference point.

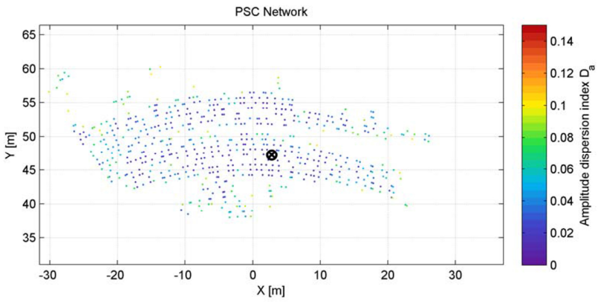

Fig. 6 Selected reference PSC

The Figure 7 below, shows the 2D map of dam displacements measured by the FastGBSAR system, between 18th June at 10.03 a.m. to 24th June at 7.00 a.m. Positive displacements mean that the dam distance from the radar decreased, i.e. up-stream displacement occurred. It can be observed a gradient from the lower to the upper part of the dam which shows displacements in opposite directions. The maximum displacement was observed at the central section at the top of the dam. This displacement is not located at the crest of the dam where a mark of the permanent topographic monitoring system is installed, but few meters below. This is reasonably due to the effect of the water level variation on the reservoir and temperature variation.

4 Conclusion remarks

Results show that FastGBSAR can obtain high accurate and high-resolution deformation of the dam by designing imaging geometry between the radar and dam. The precision of the FastGBSAR deformation estimates ranges from sub millimeters to a few millimeters, and it depends on the characteristics of the target (the stronger its response, the better is the precision), the sensor to target distance, and the distance from the reference point. The whole system deformation monitoring process can be highly automated. It can be used as an operational monitoring tool, even during emergencies.

References

D. Leva,, G. Nico, D.Tarchi, J. Fortuny, A.J. Sieber (2003), "Temporal analysis of a landslide by means of ground-based radar", IEEE Transaction on Geoscience and remote Sensing, 41(4), 745-752.

A. Di Pasquale, M. Corsetti, P. Guccione, A. Lugli, M. Nicoletti, G. Nico, M. Zonno, "Ground-based SAR interferometry as a suporting tool in natural and man-made disasters", 33rd EARSel Symposium, 3-6 June 2013, Matera, Italy. 214.

G. Nico, D. Leva, J. Fortuny-Guasch, G. Antonello, D. Tarchi, "Generation of digital terrain models with a ground-based SAR system", IEEE Transactions on Geoscience and Remote Sensing, 43(1), 45-49, 2005.

G. Nico, M. Corsetti, A. Di Pasquale, D. Donnaruma, L. Doti, L. Fiorentino, M. Nicoletti, "On the monitoring of dams by means of ground-based radar interferometry (GB-SAR)", 9th ICOLD European CLUB Symposium, 10-12 April 2013, Venice, Italy.