RADAR INTERFEROMETRY TECHNIQUES BY SPACEBORNE AND GROUND-BASED SAR SENSORS: PERSPECTIVES FOR THE MONITORING OF ARCH AND EARTH DAMS

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ABSTRACT

The basic principles of Synthetic Aperture radar (SAR) interferometry are introduced. The results of two measurement campaign aiming to measure dam surface displacements on an arch and an earth dam by means of Ground-Based SAR (GBSAR) interferometry are presented and commented.

1. Introduction

The basic space-borne Synthetic Aperture Radar (SAR) interferometry and more advanced processing techniques of time series of interferometric SAR images have applied to the monitoring of many geological phenomena. Many of these applications have been developed using spaceborne C-band SAR data. However, the spatial resolution of C-band SAR images, about 20-30 m, is in many cases too low to adequately image dams. Furthermore, the accuracy of interferometric measurements is a fraction a fraction of a centimetre being the wavelength of about five centimetres. The currently operating X-band TerraSAR-X and Cosmo-Sky-Med spaceborne sensors of the German and Italian Space Agencies, respectively, promise an increase in both the spatial resolution (up to 1 metre in the case of spotlight radar acquisitions) and in the precision of displacement measurements due to the smaller wavelength, of about 3 centimetre. The displacement obtained by processing spaceborne SAR data is mainly related to a possible vertical movement of the dam. Besides spaceborne SAR missions, ground-based SAR systems have been developed. In the last few years these systems have been applied to solve the problem of continuous monitoring of small scenes, such as dams, landslides, buildings, bridges, or to extract information on terrain morphology [2],[3]. A ground-based SAR system is a stepped-frequency radar. A couple of TX/RX antennas are mounted on a computer-controlled positioner that synthesizes a linear aperture along the so called azimuth direction. A microwave source illuminates he observed scene at different discrete frequencies within the frequency band 16.70–16.78 GHz. The length of the synthetic aperture is 2.0 m. The sampling rates in frequency and space are set in order to satisfy the Nyquist criterion. The working range distance to the study area ranges from about less than 100 m up to more than 2000 m. The spatial resolution in range is 0.75 m while that in azimuth depends on the distance between the radar and the observed scene but is always at maximum of a few meters. The research project "Slope stability of earth dams: pilot project for the merging of high-resolution X-band TerraSAR-X and ground-based Ku-band SAR images has been approved by the German Space Agency for the joint use of spaceborne and ground-based SAR sensors in dam monitoring. The aim of the project is to carry out experiments for a joint monitoring of dam displacements by both ground-based and space-borne SAR systems. The advantage of using the two kinds of SAR system would be to measure the same displacement from two different positions, so extracting a deeper information on the structural behaviour of dam. The SAR interferometry technology will be used to monitor both small arch dams in mountain regions and large earth dams in hilly areas. The structure of the paper is the following. The basic principles of SAR interferometry and the properties of space-borne and ground-based SAR sensors are presented in section 2. The characteristics of dams used in this paper are summarized in section 3. The first results obtained by ground-based SAR interferometry are presented in section 4. Finally, a few conclusions are drawn in section 5.

2. SAR interferometry

A Synthetic Aperture Radar (SAR) is an active microwave sensor used to produce 2D microwave images of the observed scene [1]. The main advantage of microwave images is their capability to observe a scene without the need of solar illumination and in any weather condition. For these reason this kind of sensor has been used in spaceborne missions to observe the earth surface. The SAR interferometry (InSAR) technique relies on the processing of two SAR images of the same scene obtained by either from two slightly displaced positions (spatial-baseline interferometry) or from the same position (zero-baseline interferometry). The acquisition geometry is typical of repeat-pass space SAR interferometry, while the second geometry is common in ground-based SAR interferometry. Each pixel on a

SAR image corresponds on the monitored object to a surface area whose dimensions are very large compared to the radar wavelength. This surface contains a large number of elemental scatterers. The returned echo is the result of the coherent summation of all the returns due to the single scatterers. The echo power depends on the dielectric properties of scatterers, their spatial distribution and their orientation with respect to the SAR sensor. If the same surface is observed from two slightly different positions of the SAR sensor, the returned echo differs. Furthermore, the returned echo also changes over time due to modifications in the landscape. Differencing the phase of two coherent complex-valued SAR images identify the phase contribution due to the scene morphology or caused by its displacements. In other words, the phase difference φ between the corresponding pixels of the two SAR images results in a fringe pattern also called interferogram. It contains information about the scene morphology and eventually its temporal variations. In this last case the phase difference is proportional to the displacement normalized to the radar wavelength.

2.1 Spaceborne SAR sensor

Spaceborne SAR sensors observe the earth surface with a revisiting time ranging from a few days to a few weeks depending on the satellite carrier. The data they acquire can be processed using SAR interferometry techniques to provide information on displacement phenomena of terrain or structures. Using data of both current and passed spaceborne SAR mission it is possible to monitor current displacement and to study displacement phenomena occurred or started in the recent past (starting from nineties when the first spaceborne interferoemtric SAR data became available for commercial and scientific use. Among the past missions we mention the European ERS-1/2 and Envisat C-band SAR sensors, the Canadian C-band Radarsar-1 sensor and the Japanese L-band ALOS sensor. Currently are operating the C-band Radarsat-2 and the X-band TerraSAR-X and Cosmo-Sky-Med sensor. In a few months the European Space Agency will launch the C-band Sentinel SAR sensor which will provide free data to the SAR community. The SAR interferometry provides only the Line-of-Sight component of the real displacement, i.e. the component along the radar line of sight. For this reason, the displacements measured by spaceborne SAR sensors are mainly related to a vertical movement of the observed scene being the sensors looking downward with a look angle variable depending on the acquisition configuration.

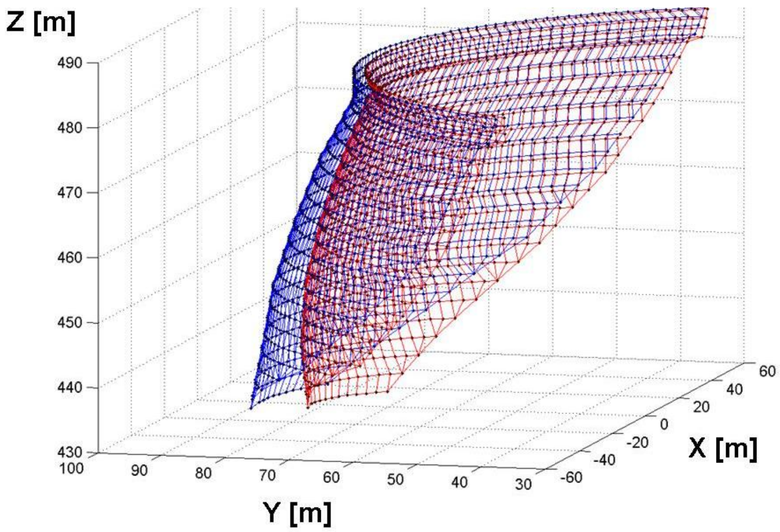
2.2 Ground-based SAR sensor

In the last decade, Ground-Based Synthetic Aperture Radar systems have gained an increasing interest in different applications ranging from terrain mapping and deformation measurements, to structural analysis of man-made constructions [2]-[3]. These systems have been developed to solve the problem of continuous monitoring of small scenes, such as dams, landslides, 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 GB-SAR effectiveness for remote monitoring of terrain slopes and as an early warning system to assess the risk of rapid landslides [3]. This non-destructive radar technique can provide displacements measurements of structures and natural scenes with a sub-millimetre precision. A GBSAR system is installed at a distance from the observed object ranging from less than one hundred metres up to a four kilometres. The interferometric processing of two coherent SAR images results in a map of displacements occurred between the acquisitions 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. In this paper we describe the technique, providing details on how SAR images are properly focused and used to generate displacement maps. GB-SAR systems provide some advantages with respect to spaceborne SAR sensors such as higher image resolution and shorter revisiting time. A single image is acquired in few minutes, while the working range distance to the study area ranges from about less than 100 m up to about 4000 m. Furthermore, the capability of GB-SAR interferometers to measure deformations with a sub-millimeter precision together with their flexibility makes them a useful tool for monitoring landslides and other geological phenomena in emergency cases [3].

3. Monitored dams

3.1 Arch dam

The arch dam of Ambiesta used in this work is managed by Edipower SpA. This dam has an altitude of 58m and a length of 11m. It is equipped with three topographic marks located at the top of the structure crown and a set of 13 thermometers (7 on the down-stream surface, 3 on the up-stream surface and 3 installed inside the dam structure, in correspondence of the centreline). Five thermometers are installed close to the dam crown, five at the mid height and three at the foot. This dam has been chosen in common agreement between Edipower and the Italy's National Directorate General for Dams and Hydroelectric Infrastructures, Ministry of Infrastructure and Transport (former Italy's National Dams Authority) o study surface displacements of the dam due to daily changes in water level and seasonal temperature variations.



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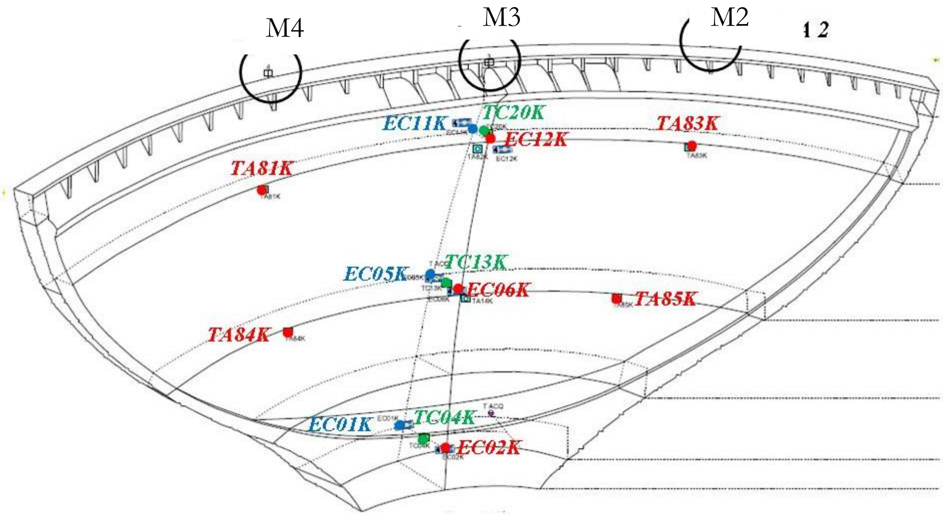
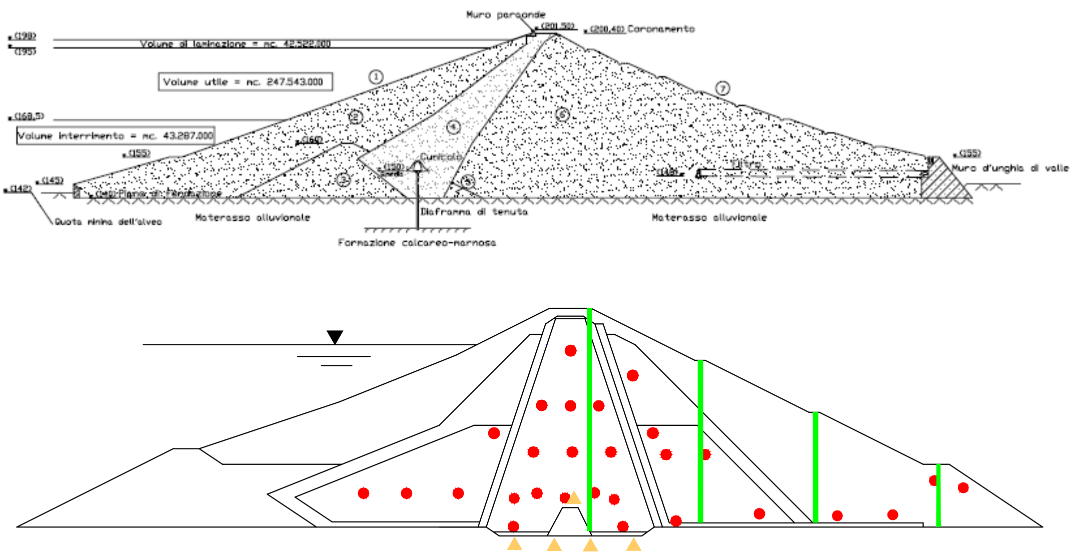


Picture 1: Ambiesta's arch dam: (top) Geometric scheme; (bottom) Localization of topographic marks (big open circles) and thermometers (small filled circles).

3.2 Earth dam

The Consorzio di Bonifica di Capitanata (CBC) manages four dams in the Capitanata province, located in the northern part of the Apulia Regions (southern Italy). The CBC manages the Occhito dam, a 432m-long and 60m-high earth dam, one of the biggest ones in Europe. Currently the dam is monitored with an array of piezometers, inclinometers and sensors of pressure. Furthermore, he position of a set of marks is measured by topographic techniques.

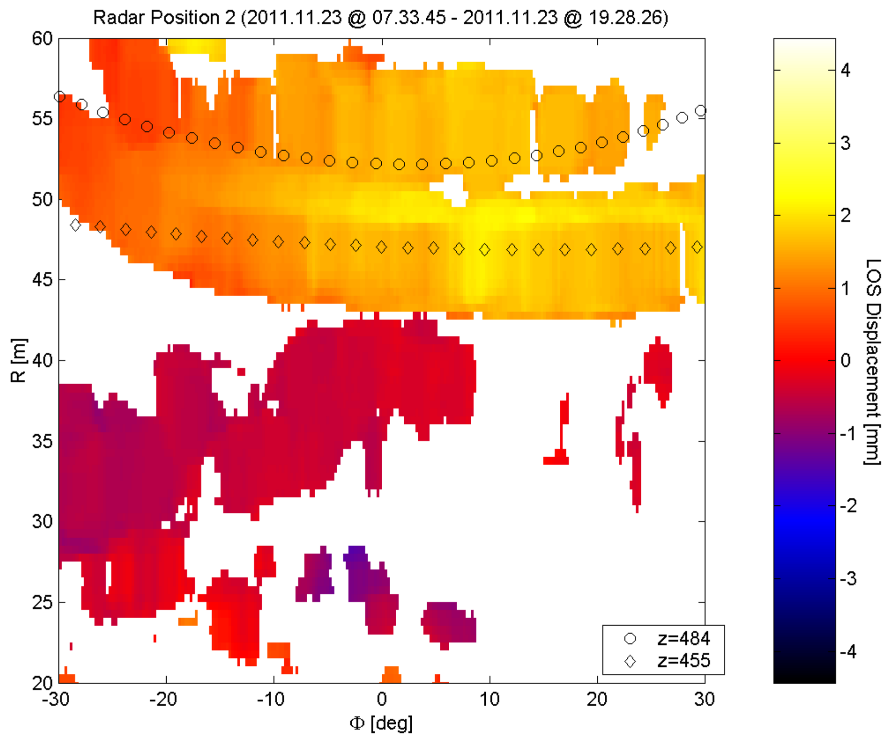


Picture 2: Occhito's earth dam: (top) Geometric scheme; (bottom) Localization of sensors: piezometric cells (circles), pressure cells (triangles), inclinometers/assestimeters (vertical columns).

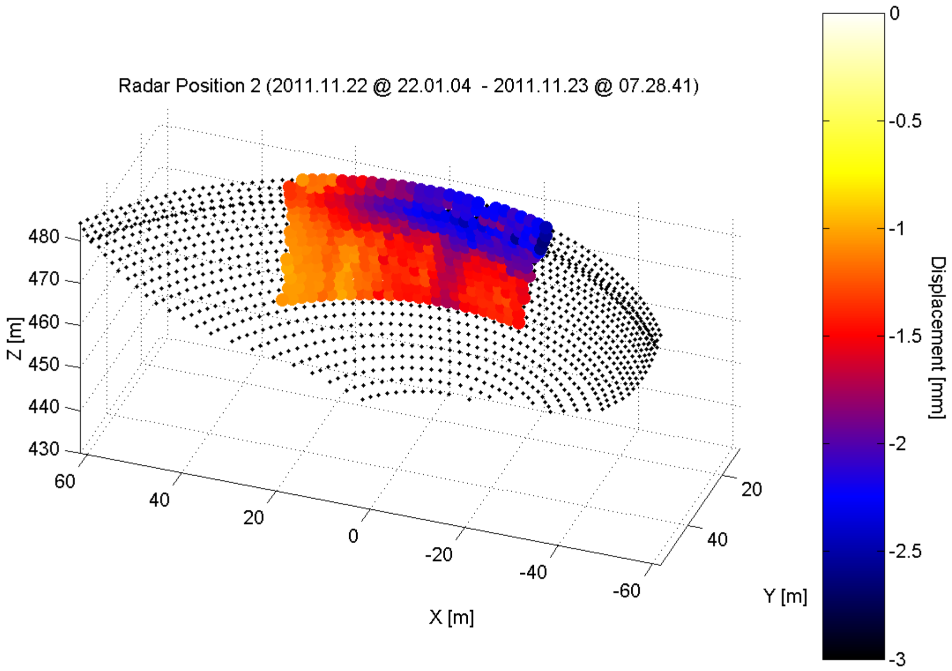
4. Results

In this section we present the results provided by the GBSAR technique in two measuring campaigns carried out on the Ambiesta's arch dam and the Occhito's earth dam. The aim of this section is make the reader familiar with displacement maps provided by a GBSAR system and their information content. Details on the measurement accuracy and precision, as well as on the comparison with traditional measuring techniques or numerical modelling have presented in previous works [3][4].

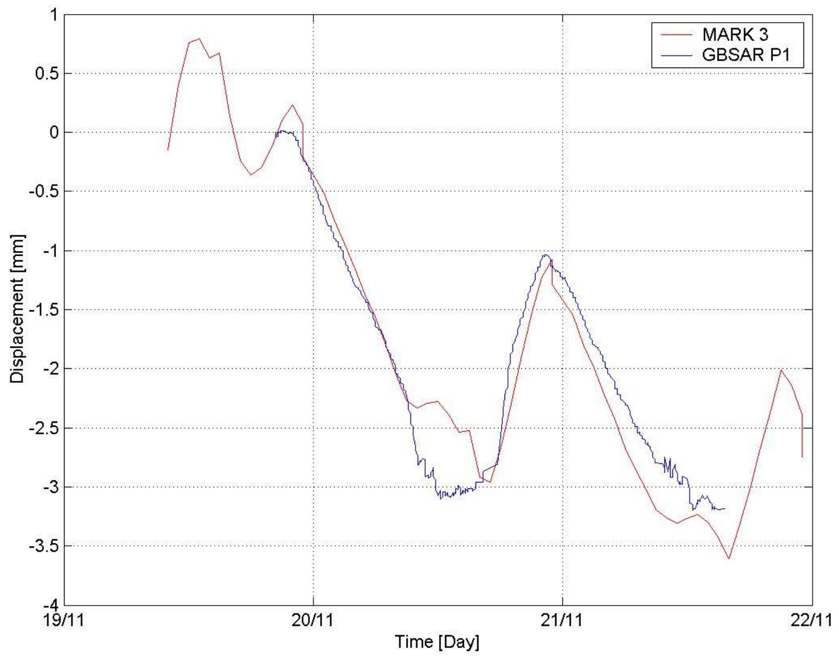
First, we present the results obtained at the Ambiesta's dam. Figure 3 displays an example of displacement map measured by the GBSAR sensor in a 13-hour time interval. The map is the typical GBSAR coordinates, i.e. range distance from the centre of the rail and angular position measured with respect an axis perpendicular to the rail. White areas correspond to the patches on the dam surface having a low signal-to-noise ratio. It is worth noting that the radar measurement provide only the Line-of-Sight component of the true surface displacement. In order to facilitate the recognition on the map of the different dam structural elements, we reported the dam arches at altitudes z= 455m y z=484m. A similar map obtained by the GBSAR system on the same dam but at different time is shown in figure 4. In this case, the map is rendered on the dam mesh. As can be observed, this kind of processing including a geocoding step makes the GBSAR measurement more familiar and useful to identify the displacement of each structural element. The comparison with topographic measurements, shown in figure 5, emphasizes how the radar and topographic measurement are in good agreement even if having different characteristic. In fact, topographic measurement provides a point-like displacement while GBSAR measure the mean displacement of the dam surface corresponding to a pixel on the radar image.



Picture 3: Ambiesta's arch dam: Line-of-sight (LOS) displacement map in radar coordinate of the dam surface. Displacements refer to November, 23rd, between 7:00 am till 8:00 pm.



Picture 4: Ambiesta's arch dam: Line-of-sight (LOS) displacement map of the dam surface render on the dam mesh. Displacements refer to the interval between November, 22nd at 10:00 pm and November 23rd at 7:28 am.



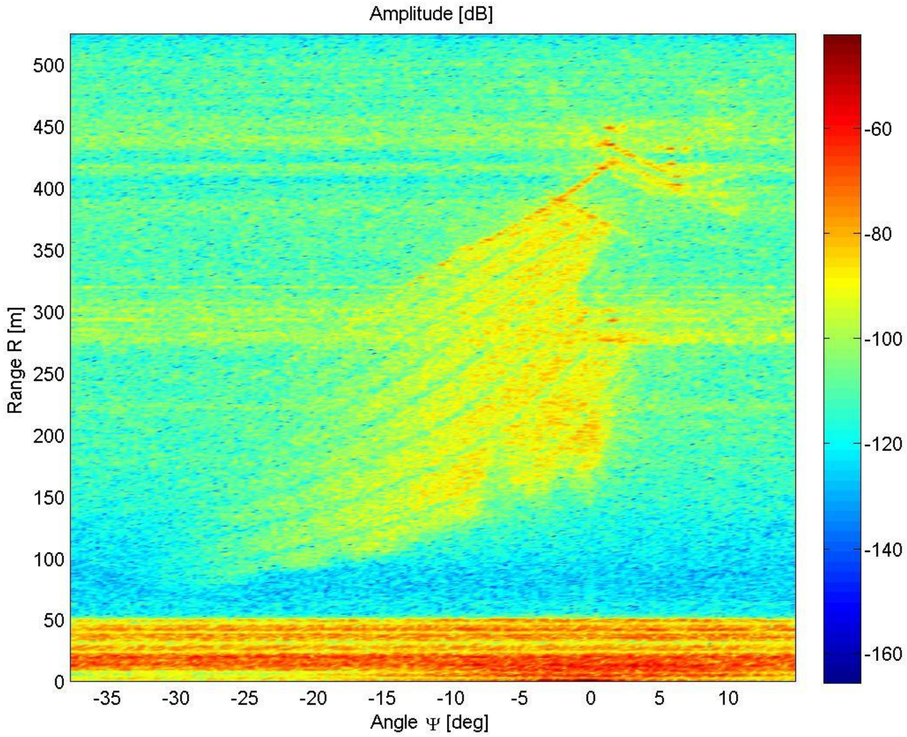
Picture 5: Ambiesta's arch dam: Comparison between displacements measured by GBSAR and topographic techniques at location of marker 3.

Displacements measured at the Ambiesta's dam were related to daily changes in the water level.

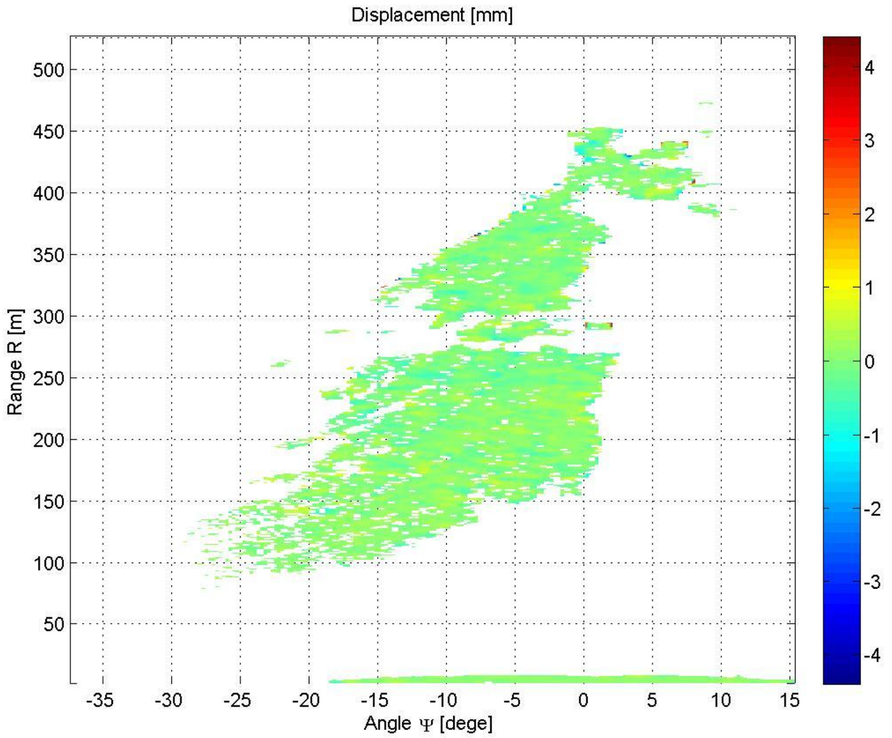
As far the Occhito dam is concerned, a 2-hour measurement campaign has been done. In this case was not any change in the water level. The aim of this campaign has been to set a "zero" measurement with respect to which to compare radar measurements acquired in subsequent campaigns.

Figure 6 shows a picture taken from the installation position of GBSAR system. From this position the radar observed more than a half of the dam surface and the concrete structural elements at the end of the dam, represented on the right hand side of the picture. The amplitude of one of the SAR images acquired on this dam is represented in figure 7. Pixels with a higher value of dB correspond to patches on the dam surface with a higher scattering capability of radar signal. The comparison with the optical picture in figure 6 helps to easily recognize each part of the earth dam. The map of surface displacements measured by the radar during the 2-hour campaign is displayed in figure 8. In order to better assess the precision and accuracy of the measurement, the histogram in figure 9 reports the frequency distribution of displacement measurements. The mean and standard deviation values are, respectively, 0 and 0.3 mm. Besides the experiment with corner reflectors (see for example [3]) carried out to assess the in-field precision and accuracy of GBSAR measurements, the frequency distribution in figure 9 provides a further statistical assessment of GBSAR capability to provide unbiased sub-millimetre precision measurement of surface displacements.

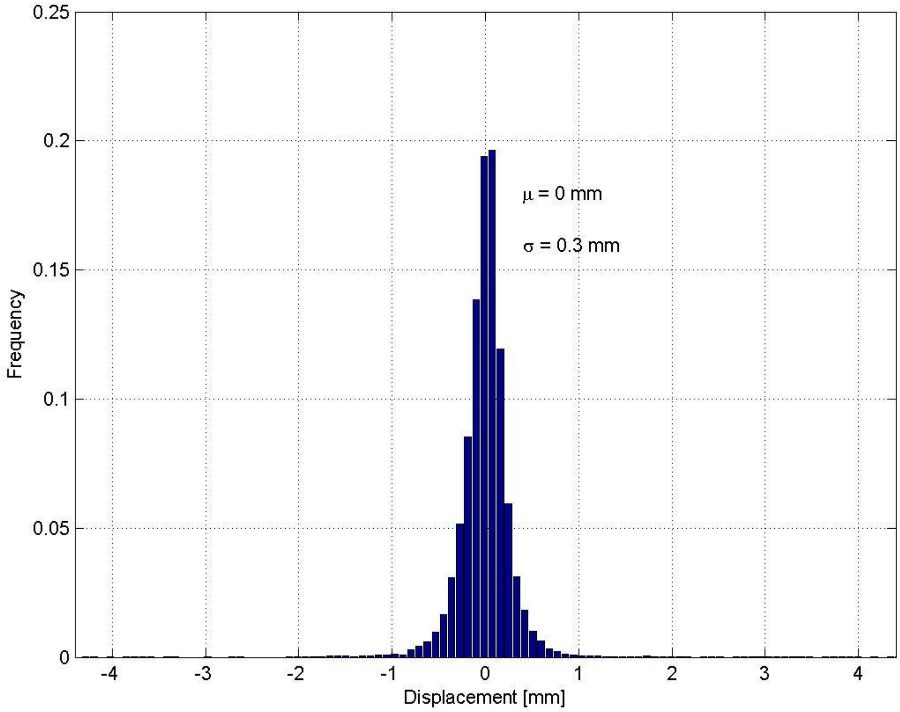
Picture 6: Picture of the Occhito's earth dam as seen by the installation position of the GBSAR sensor



Picture 7: Occhito's earth dam: Amplitude of the radar image acquired by the GBSAR system.



Picture 8: Occhito's earth dam: LOS displacement map in radar coordinates.



Picture 9: Occhito's earth dam: Frequency distribution of dam surface displacement values.

5. Conclusions

The basic principles of Synthetic Aperture Radar (SAR) interferometry have presented with emphasis on the application to the measuring of dam surface displacements using both spaceborne and ground-based SAR sensors. The results obtained by a GBSAR system in two measuring campaigns to measure displacement in an arch and a earth dam have been shown and commented.

6. References

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