MEASUREMENT OF DAM DEFORMATIONS BY TERRESTRIAL INTERFEROMETRIC TECHNIQUES

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ABSTRACT:

In this paper the application of a novel non-contact GBInSAR sensor to the measurement of daily deformations of an arch-gravity dam is described. The sensor, named *IBIS*, is a Ku-band interferometric radar sensor apt to simultaneously monitor the displacement response of several points belonging to a large structure. Moreover, the possibility of scanning the monitored object with the radar sensor moving along a stable track enables to implement the interferometric SAR technique to improve the cross-range resolution in the direction parallel to the baseline. The presented application addresses the monitoring of the displacement of the dam due to an increasing load of the water basin during two days and to temperature change. The displacement results have been compared with the measurements obtained by a coordinatometer installed on the central section of the dam for validation purpose; a good agreement between innovative radar methods and well assessed monitoring sensors has been achieved.

1. INTRODUCTION

In the recent years the need of information about deformations of large concrete dams has been highly demanded by researchers and operators involved in maintenance and safety of these structures. Indeed, nowadays the development of innovative techniques for the static and dynamic structural modelling would allow to sharply improve the capability of predicting collapses, reducing so that the risk of disasters. A fundamental prerequisite that all mathematical models should have to adhere to reality is the availability of precise and dense observations, either from a geometric point of view and about boundary conditions. Several monitoring techniques could give their contribute to this aim, accounting for geodetic measurements and for sensors capable of measuring local deformations, rotations, and displacements.

Broadly speaking, current techniques allow one to monitor a set of specific control points on a dam, without covering every portion of the structure itself. This lack of information is an important drawback for structural modelling, especially when comparing previsions of theoretical analysis with true deformations under external conditions is needed.

In order to provide deformation measurement on large portions of a structure's surface, experimentation of two different kinds of sensors have been carried out in the latest years: *Terrestrial Laser Scanning* (TLS) and *Ground-Based Interferometric SAR* (GBInSAR).

1.1 Terrestrial laser scanning

Different authors reported about applications of *Terrestrial Laser Scanning*, which allows to capture dense point clouds made up of 3-D unspecific points with a high degree of automation, but with a poor accuracy for deformation measurement. This result could be improved by exploiting the data redundancy when the surveyed object features a regular geometry (see e.g. the application to tunnel deformation measurements - Van Gosliga *et al.*, 2006 – or to a television tower - Schneider, 2006), or when it can be decomposed in many small planar patches (Lindembergh & Pfeifer, 2005). In both cases, equations of regular surfaces can be estimated based on a redundant dataset of observed points, and accuracy higher than that of the original 3-D observations can be achieved (see Monserrat & Crosetto, 2008). Unfortunately, errors due to sensor georeferencing at different epochs usually worsen the quality of results (Alba *et al.*, 2006). By considering results achieved so far, TLS can be used to evaluate seasonal deformations of structures with points featuring a few cm displacements, but not for the continous monitoring.

1.2 Ground-Based interferometric SAR

In the last decade some terrestrial sensors have been developed to perform *Ground-Based Interferometric SAR* (GBInSAR) measurement of deformations (Rudolf *et al.*, 1999; Harries *et al.*, 2006; Bernardini *et al.*, 2007c). Even though the density of tracked points is lower w.r.t. TLS, the intrinsic achievable accuracy enables its use for continuous monitoring of large structures as well. Nevertheless, in case of constructions like dams, featuring large regular surfaces, a huge point density is

not a key issue, like the accuracy is.

GBInSAR systems are capable to make measurement of deformation along the *Line-of-Sight* (LoS) from the sensor head to the surface to be monitored. Thus only variations in range can be evaluated, which however could be decomposed along other lines if the local geometry is known (see Sub-sec. 3.3). The spatial resolution of measurements is defined in both range and cross-range directions. The target surface is divided in pixels, as can be seen in figure 3, and the pixel is tracked along different epochs. The surface geometry and position plays a fundamental role in the localization of measured points. On the other hand, also TLS can be used to detect deformations occurring in range directions, because in the other it cannot operate if there are not discontinuities (like e.g. on a concrete dam face). An advantage of TLS is the better point localization, thank to the recording of horizontal and vertical angles as well.
In literature an experience of deformation monitoring using a GBInSAR sensor is reported by Tarchi *et al.* (1999). A large double curvature dam was observed at 5 epochs during a period of about 2 months. The radar system was periodically repositioned in the same position, and the data reconstruction into the same reference system was supported by the availability of a DSM of the dam itself. Deformations of the whole downstream face has been measured and validated in comparison to readings of a coordinatometer internal to the dam. Even though this check concerned only a few points in the main vertical section, it resulted in an accuracy under ±1 mm.

Recently a novel radar system, named IBIS, was developed: this system is able to measure the dynamic and the static response of many points of a structure with up to 10÷20 μm displacement sensitivity (Bernardini *et al.*, 2007a). The sensor was studied and setup by IDS company in collaboration with the Dept. of Electronics and Telecommunication of the Florence University (Pieraccini *et al.*, 2004, 2005).

Currently IBIS is a commercial GBInSAR system that has been conceived to be used independently by end-users, without specific knowledge of radar theory. It is based on two equipment configurations aimed to different applications:

- IBIS-S: it's a 1-D radar sensor that can be used for static and dynamic response measurement; it features high range resolution and short range from sensor to target (up to 1,000 m);
- IBIS-L: it's a GBInSAR sensor based on the IBIS-S radar; it is devoted to static response measurement and features both range and angle (cross-range) resolution, and medium range (up to 4,000 m).

Both configurations exploit Interferometric technique, derived by satellite earth monitoring application, in order to detect sub-lambda displacement of the structure induced by environmental or human stresses.

The assessment of the IBIS in the -S configuration was performed by IDS and the Dept. of Structural Eng. of Politecnico di Milano, within an ongoing research programme aimed to the validation of IBIS-S performance in dynamic testing of full-scale structures. The radar system was used in ambient vibration testing (*AVT*) of several different R.C. bridges. Results of these tests are available in Bernardini *et al.* (2007b).

The Surveying Dept. of Politecnico di Milano gave to IDS the opportunity to perform a real-scale test with IBIS-L system on an arch gravity dam in Alta Valtellina, and to compare the radar measurements with those obtained by a coordinatometer. The dam was loaded by the water of the basin whose level was increasing during the two days survey. On the same dam an experimental application on the use of TLS for deformation measurement is ongoing since 2005 (Alba *et al.*, 2006). In addition, the availability of a 3-D model of the whole construction has resulted in the knowledge of local geometry, which is almost important to augment the information achievable from radar measurements. Currently IBIS is an operational commercial system that has been conceived to be used. Results of these tests are summarised in section 4.

Hereinafter the paper continues with the description of IBIS-L radar sensor (Sec. 3) and with the presentation of the radar techniques and principles adopted (Sec. 4).

2. IBIS-L DESCRIPTION

The IBIS-L microwave interferometer (Fig. 1) is a Ku-band (16.6-16.9 GHz) radar sensor designed for the simultaneous monitoring of the response of several points belonging to a large structure, providing for each point the displacement between two different epochs.

With respect to conventional contact sensors, like strain-gauges, the use of a non-contact radar-based techniques overcomes some limitations and drawbacks. First of all, the number of control points is strongly increased, so that IBIS-L supplies a continuous displacement map of the entire observed area which can reach up to hundreds of thousands of square metres. The radar system simultaneously measures the displacements of all points in the area illuminated by the antenna beam with accuracy up to 0.1 mm. On the opposite, the precise localization of control points is more difficult. The access to the structure is not needed, because remote structural monitoring can be performed without installing sensors or optical targets on the surface to measure.

IBIS-L provides also detailed information on the movement of specific points belonging to the scenario, because for each control point the position along range is archived in a DB. The sampling rate might be up to an interval of 5 minutes. This capability allows the continous deformation monitoring of structures with fast displacements. In addition, the IBIS-L system can be accurately repositioned at different epochs, in case a periodic control in a long-period is needed. In this case, an uncertainty limited to about ±0.2 mm is to added up to the deformation measurements.

Microwave interferometer can be used both day and night and in all weather conditions.

Furthermore, the possibility of operating even at a significant distance and without the need of installing and wiring sensors permits the investigation during emergency situations when monitoring activity can be required to ensure the safety of people.

The main operational characteristics of IBIS-L system are summarized in table 2.

As figure 1 shows, the IBIS-L system consists of the following

modules:

1. *the radar module*: this unit generates, transmits and receives the electromagnetic signals which will be processed in order to measure the displacement of the investigated structure;
2. *the linear scanner* consisting of a 2.5 metre long aluminium track, along which the sensor is moved under the control of a step-by-step motor;
3. *the control PC*, installed with the system management software. It is used to configure the acquisition parameters, to manage and to store measurements and to display first results just after ground data acquisition;
4. *the power supply unit*, providing power to the system through a pack of two 12V batteries or connection to a external energy supplier (electricity main network or photovoltaic panels).

Fig. 1. IBIS-L system installed on a concrete foundation

Parameter	Value
Maximum operational distance	4,000 m
Spatial resolution @ 1Km	0.5 x 4.5m
Acquisition rate	5 min
Displacement sensitivity (accuracy)	0.1 mm
Power consumption	100 Watt
Weight of the whole system	130 kg

Table 2. IBIS-L operational characteristics

3. PRINCIPLES OF THE ADOPTED RADAR TECHNOLOGY

The *IBIS-L* sensor is based on three well-known radar techniques: (i) the *Stepped-Frequency Continuous Wave* (SF-CW), providing the system with range resolution capability; (ii) the *Synthetic Aperture Radar* (SAR) technique that, combined to the SF-CW technique, allows the system to retrieve a two-dimensional image of the scenario, resolving it into several pixels of limited area; (iii) the *interferometric* technique that allows the system to measure at the same time the displacements of the monitored area, thanks to the comparison of the phase information of the backscattered electromagnetic waves collected at different times. In the following these techniques will be briefly reviewed.

3.1 SF-CW technique

The *Stepped-Frequency Continuous Wave* (SF-CW) technique provides the system with range resolution capability, up to 0.5m

exploiting the duality between time and frequency domains: instead of transmitting a short pulse of duration τ in time with a large bandwidth in the frequency domain as pulse radars do, IBIS-L radar module transmits a burst of *N* monochromatic pulses equally and incrementally spaced in frequency (with fixed frequency step of *Δf*) within a bandwidth *B*:

$$B = (N-1)\Delta f \qquad (1)$$

For a pulse radar, the range resolution *Δr* is related to the pulse duration *τ* by the following elementary relation *Δr=cτ/2*, where *c* is the speed of light in free space. Since the pulse duration is equal to the reciprocal of the frequency bandwidth *B* of the pulse (*τ=1/B*), the range resolution may be expressed as:

$$\Delta r = \frac{c}{2B} \qquad (2)$$

Eq. (2) highlights that the range resolution of the system is inversely proportional to the swept bandwidth of the E.M. wave transmitted by the radar.

By taking the Inverse Discrete Fourier Transform (*IDFT*) of the samples acquired in the frequency domain, the response is reconstructed in the time domain of the radar. The amplitude range profile of the radar echoes is then obtained by calculating the amplitude of each sample of the *IDFT* of the acquired vector samples. This range profile gives a one dimensional map of scattering objects in the viewable space in function of their relative distance from the equipment.

The concept of range profile is better illustrated in figure 3, showing an ideal range profile obtained when the radar transmitting beam illuminates a series of targets at different distances and different angles from the sensor. As previously stated, the range profile refers to *N* target points, being 0.50 m apart. This means that two or more different objects with similar scatter properties lying into the same *range bin* (in this case with a depth of 0.50 m) would result in a unique radar echo. In this case, it is impossible to discriminate about displacements of different points, but the echo will give the description of the mean changes of all scatterers.
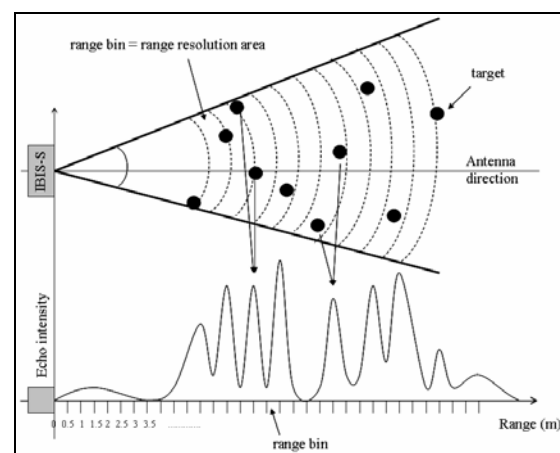

Fig. 3. Range resolution concept

3.2 SAR technique

Synthetic Aperture Radar technique allows radars with wide physical antenna beam width to obtain high angular resolution in azimuth thanks to the acquisition of the scenario from different view angles: the coherent composition of the acquisitions permits to obtain a synthetic antenna whose beam width is inverse proportional to the relative movement between the scenario and the radar (Ferretti *et al.*, 2007).

For strip-map radar as IBIS-L the obtained angular resolution is given by:

$$\Delta \vartheta = \frac{\lambda}{2L} \qquad (3)$$

where λ is the wavelength of the E.M. signal and L is the length of the relative movement of the radar head w.r.t. the target. In case of IBIS-L, the movement of the sensor module on the 2 m linear scanner permits the system to have an angular resolution of 4.5 mrad.

The combination of the SF-CW technique with the SAR technique leads to the radar image being organized into pixels with dimensions of: 0.5 m in range and $4.5 \cdot 10^{-3} r$ m in cross-range, where r is the distance from radar to target.

The following figure 4 shows an example of a resolution grid for a system with a distance resolution of 5 m and angular resolution of 5.2 mrad. A look to this figure enable to quickly understand that the shape of the object under monitoring is fundamental to allow the discrimination between specific observed points. Considering for instance the range and cross-range directions in the horizontal plane, if the object features a vertical surface, the number of observed scatterers will be very small. On the contrary, if the object presents a tilted surface, the number of scatter points would sharply increase.
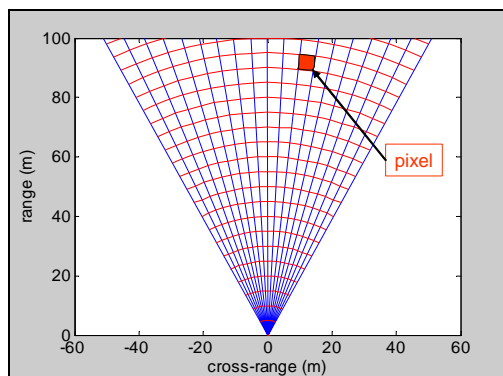

Fig. 4: Example of a spatial resolution grid

3.3 Interferometric technique

Once the 2-D map of a structure has been determined at uniform sampling intervals, the displacement response of each pixel is evaluated by using the Interferometic technique. Interferometry is a powerful technique that allows the displacement of a scattering object to be evaluated by comparing the phase information of the electromagnetic waves reflected by the object in different time instants.

The displacement of the investigated object is determined from the phase shift measured by the radar sensor at the discrete acquisition times. The *Line-of-Sight* (LoS) displacement d_{LOS} (i.e. the displacement along the direction of wave propagation) and the phase shift $\Delta\varphi$ are related by the following:

$$d_{LoS} \propto -\frac{\lambda}{4\pi}\Delta\varphi \qquad (4)$$

The first applications using the interferometric technique were performed by satellite to detect the displacement of large areas of terrain, with a resolution at ground level of a few meters; now the same technique can be used with radars installed on the ground, permitting the illumination of specific areas with a very high range resolution.

It is worth underlining that the interferometric technique provides a measurement of the LoS displacement of all the pixels of the structure illuminated by the antenna beam; once d_{LoS} has been evaluated, the vertical and horizontal displacements (or their projection on another tilted 3-D plane) can be easily found by making some geometric considerations (see the example reported in figure 5).
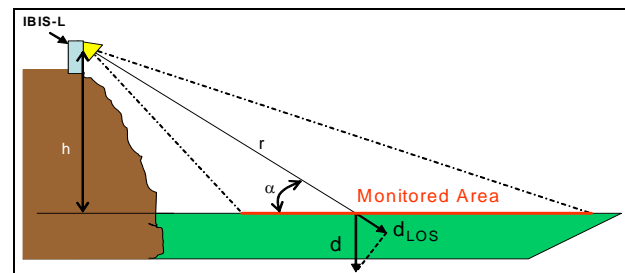

Fig. 5. Line-of-Sight displacement *vs* projected displacement

4. APPLICATION TO A FULL SCALE DAM: SUMMARY OF RESULTS

An arch-gravity dam was investigated by using IBIS-L system to measure deformations due to the filling of the water basin as well as to variation of the structure temperature. The Cancano dam (Alta Valtellina, Italy) features about 90 m height from bottom to top, and 350 m length on the crest, and it is managed by A2A company (see Fig. 6). The dam is currently controlled by topographic techniques, that consist in two high precision leveling lines on the top crest and on the middle height corridor of the structure, in optical collimators to detect horizontal displacements, and in a column of coordinatometers positioned in the middle vertical section. In addition, a precise DSM of the structure itself was achieved by TLS. The availability of all these measurements allows to perform a GBInSAR data validation.

Data acquisition by IBIS-L has been performed at a mean distance of 400 m far from the dam mid-point, during a period lasting 37 hours. The IBIS-L system has been setup on a

temporary stand-points, because the replacement of the instrument hasn't been foreseen for this test. As shown in figure 6, the radar system has been placed just in front of the dam's downstream face. This positioning has allowed to capture the entire dam displacement along in the range direction during the whole observation time. The time needed to scan the whole downstream has been 9 minutes, and each scanning cycle has been repeated without intermediate breaks. It is relevant to notice that the configuration of parameters needed to correctly perform the data acquisition is very easy, because this task can be performed by also non-skilled operators. During the data acquisition, the control software allows one to check the *focalisation map*, which is an information of the reflectivity properties of the object illuminated by the SAR sensor. In addition, a check on intermediate displacements of points tracked on the structure can be seen. This option is very important for continuous monitoring applications.

Fig. 6 – IBIS-L positioned in front of the downstream face of the Cancano dam (Alta Valtellina, Italy)

The results of GBInSAR measurements are 2-D deformation maps of displacements, which reached a maximum value of about 4 mm in the central section. Consider that, in years with the biggest variation of water level in the basin, the full displacement of this point might reach about 80 mm. In figure 7, maps corresponding to three different epochs (after 10, 22 and 37 h) during the test at Cancano dam are shown.

According to an *integer ambiguity* of 4.5 mm ($\Delta\varphi$= 1 rad). such a displacement can be automatically tracked if IBIS-L is continuosly acquiring data, and not more that 1 cycle is increased from an observation epoch and another (in this application these are separated by a 9 minute rate). In case of repositioning of IBIS-L, the processing tool is not able to detect displacements larger than the integer ambiguity. A solution, to this problem could be provided by integrating the GBInSAR system to other ranging sensors featuring lower precision and measurement rate, but that would be able to reconstruct low frequency displacements (e.g. TLS or robotic total stations).

By thresholding points on the basis of their *coherence* (ρ) and their Signal-to-Noise Ratio (SNR), it is possible to select those which are high accurate control points. The higher are the selected thresholds, the higher is the accuracy in the measurement of the displacement of the selected point. In figure 8, a sub-set $S_{0.99}$ of only points with ρ>0.99 is shown. For each of these the time-series of displacements is fully available. For 5 points on the dam crest, the displacements are shown in the upper part of figure 9, while in the lower part displacements

of points which are vertically widespread are shown. As you can see, the trend of the observed dam displacements agrees to the foreseen static behavior in both cases. Note the magnitude of maxima displacements along the observation period is under 2 mm. Some outliers are present in time-series corresponding to points P34 and P30, which probably are placed on positions disturbed by local turbulence or they might be located on a surface featuring bad reflectivity, despite of the high coherence. On the other hand, these outliers does not result in trend errors, and can be removed by low-pass filtering in the time domain, or by averaging displacements evaluated on close points in the space domain. Indeed, by comparing displacements of points P30 and P29, whose position differ for only 15 m, it is possible to see that only the first of them is affected by anomalous noise (see Fig. 9).
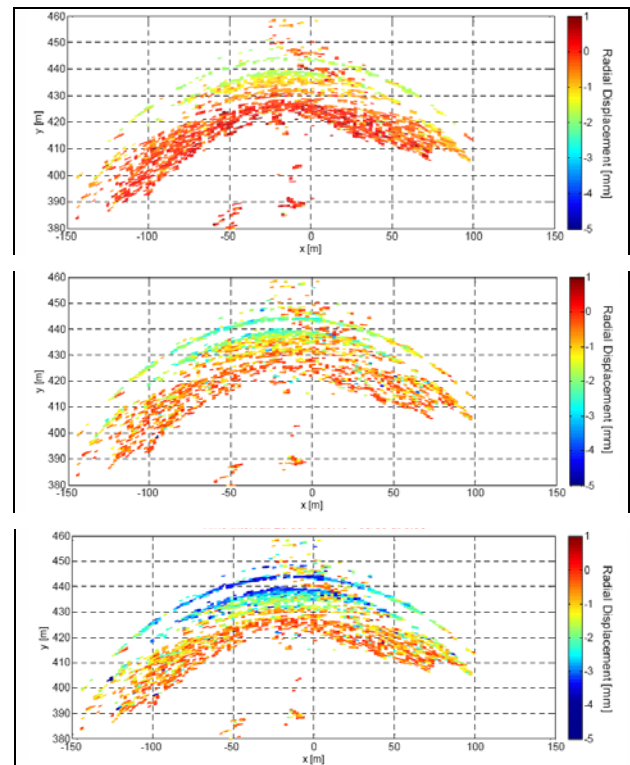

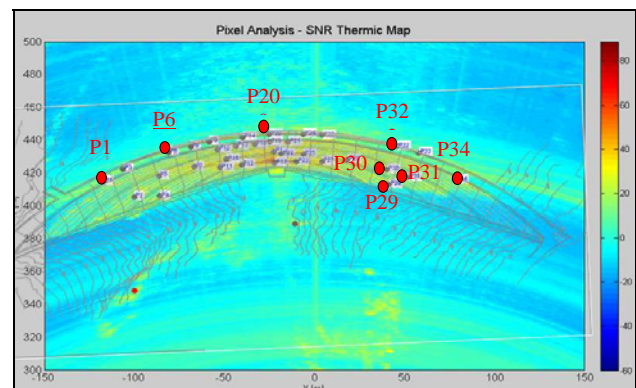Fig. 7 – Complete displacement maps after 10, 22 and 37 hours of observation

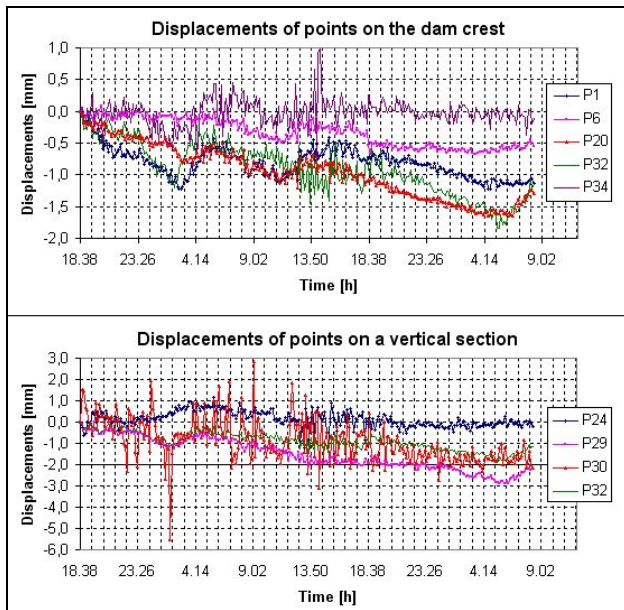Fig. 8 – Location of tracked points on the dam downstream face with a coherence ρ>0.99

Fig. 9 – Time-series of displacements of a sub-set of high-coherence points (ρ>0.99), according to Fig. 8. On the upper graphic, five points belonging to the dam top crest; on the lower, three points that are vertically widespread

4.1 Data validation

At the same time of GBInSAR measurements, the dam was under monitoring by a coordinatometer, whose results were compared to IBIS-L results and exhibited a good agreement, i.e. differences between measurements achieved by different instrumentations during 24 hours have been compared, resulting in discrepancies with a RMSE of ±0.2 mm (see Fig. 10).
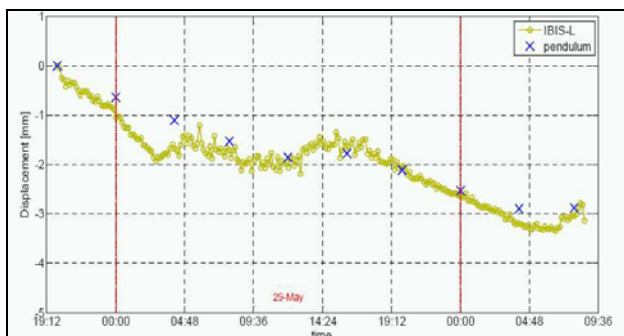

Fig. 10 – IBIS-L single pixel displacement (green circles) on the middle of the dam crest, compared to coordinatometer measurements along the entire period of observation

5.   CONCLUSIONS

The application of an innovative, radar-based measuring system (IBIS-L by IDS, Italy) to static deformation of a large arch-gravity dam has been described in the paper together with the system functioning principles.

The test results highlight very good performance of this sensor coupled with the SAR technique in the measurement of slow movements, if compared with standard monitoring instruments.

Achievements of this experimentation are very promising and open new perspectives for static analysis of large dam behaviour, and of other kinds of large constructions as well. Indeed, instruments and sensors which have been applied so far for measuring dam deformations feature an high accuracy and reliability, even though only a limited number of points could be observed. On the other hand, during this experimentation a very huge number of monitored points has been measured (some thousands) during a period of 37 hours. Also in case of the restricted sub-set $S_{0.99}$ of only points featuring very high coherence, this account for more than 30 points which are widespread on the whole dam downstream face. In addition, no artificial reflectors are needed. The global behaviour of measured displacements and a quality check based on a comparison to readings from a coordinatometer have enhanced an accuracy of this GBInSAR system under ±1 mm. At the current state of the art, this cannot be achieved by other instruments, considering that mountain environments where dams are usually located might requirethe sensor positioning very far from the structure to be monitored (also some hundreds meters); obviously, this fact is a strong drawbacks for remote displacement sensors (e.g. for robotic total stations or automatic collimators), while IBIS-L can operate also from some thouthands meters.

Moreover, the temporal data acquisition rate (9 minutes) and the degree of automation are excellent, if compared to other monitoring sensors. These characteristics make possible to use GBInSAR systems for continuos monitoring purpose, and to integrate them with other monitoring techniques

A second important achievement of this test concerns the possibility by the end-users to adopt a commercial system, like IBIS-L is, for the current practise of dam monitoring activities. The presence of a simple GUI, the low number of parameters to set up and the standardization of SAR processing, allow its use also by non-skilled people in radar techniques.

However, the experimental and theoretical research in this field needs further improvements. In particular, the precize localization of control points is to be developed. Furthermore, the integration between TLS and GBInSAR data is expected to open to further interesting applications, where the former system is able to detect lower frequency deformations with a higher point density, while the latter is capable to monitor higher frequency at a lower spatial resolution.

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