DAM DEFORMATION MEASUREMENTS USING TERRESTRIAL INTERFEROMETRIC TECHNIQUES

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***Abstract**: In recent years were developed various sensors that can be used to determine the precise deformations of massive construction and beyond. The determination of deformations for the large concrete dams often requires new researches for an easy and reliable monitoring and also for the safety of these structures.*

Using terrestrial radar interferometer, as non-contact sensors, called Ground-Based SAR interferometry (GBInSAR) for common dam deformations monitoring and measuring is easy for specialists, the obtained results having a very high resolution for any point of the monitored surface.

The main advantages of microwave interferometry are: measuring distance (up to 4000 m) without requiring any other sensors or targets on the monitored object, operating in any weather conditions, day and night.

***Keywords:** deformations, sensors, terrestrial interferometry, microwave.*

1. Introduction

A Ground-Based Synthetic Aperture Radar (GB-SAR) is an active microwave acquisition sensor that provides its own illumination and measures the reflected signal. This makes data acquisition possible day and night independently of natural light. Synthetic Aperture Radar (SAR) is today a relatively mature technique implemented on numerous satellites and aircrafts. In recent years the SAR technique have been implemented on ground-based platforms with the advantages of being able to illuminate an area of interest from an optimal angle and the possibility to acquire images at any time in comparison to available satellite systems. In case of fast deformations this is a decisive factor.

Furthermore in contrast to other terrestrial deformation measurement instruments the GB-SAR covers a continuous surface up to approximately 1 km^2 from a single measurement position. GB-SAR has been used for landslide monitoring, glacier monitoring, avalanche prediction, volcano front monitoring, dams monitoring and subsidence monitoring (Noferini, 2004).

The general concepts of Ground-Based Synthetic Aperture Radar valid for the GB-SAR are fundamentally based on three different techniques:

- Stepped Frequency Continuous Wave (SF-CW), a frequency modulation technique that makes it possible to resolve resolution in range.

- Synthetic Aperture Radar technique (SAR), which makes it possible to resolve the cross-range resolution.
- Interferometric Technique (InSAR), exploits the coherent phase of the received echoes.

Radar is an acronym for Range Detection and Ranging and refers both to a technique and an instrument. A radar works by transmitting short pulses of electro-magnetic energy, which are propagated at speed of light and reflected by the terrain surface creating return echoes that are collected by the receiving antenna. Measuring the time delay of the two-way propagation of the echo determines the range *R* by the equation:

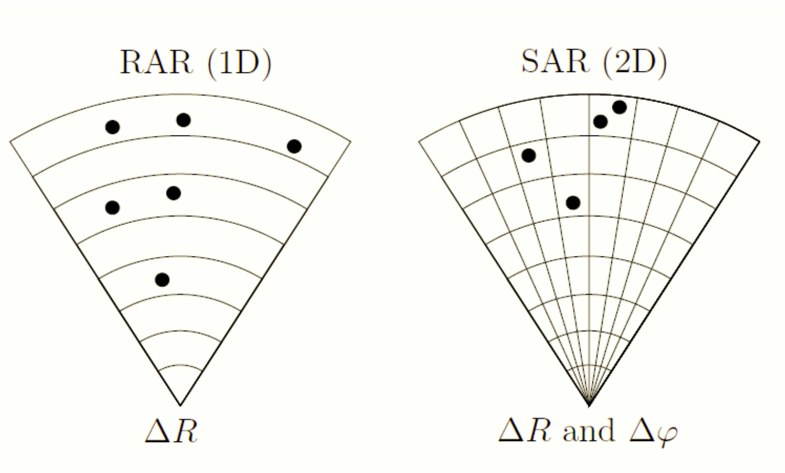
$$t = \frac{2 \cdot R}{c}$$

where *c* is the speed of light. The ability to determine range by measuring the time for the radar signal to propagate to the target and back is probably the distinguishing and most characteristic of conventional radar (Skolnik, 1990).

2. GB-SAR concepts

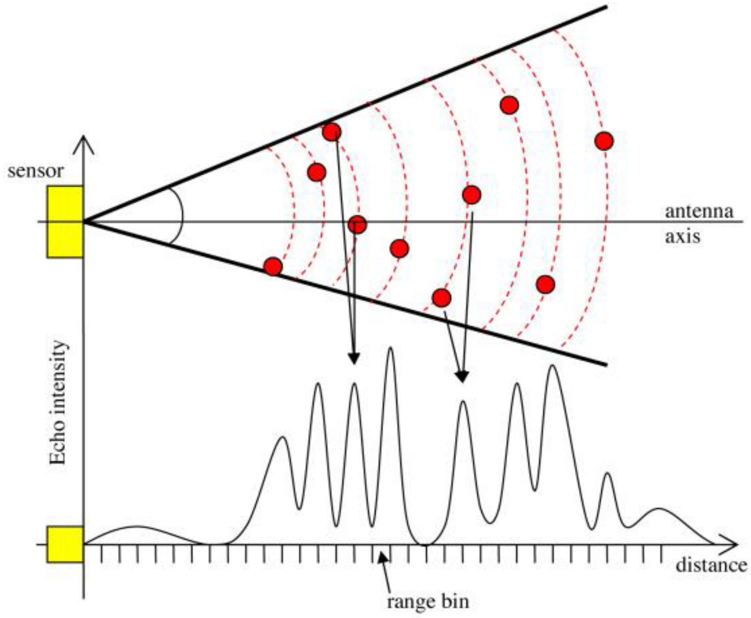
A Real Aperture Radar (RAR) instrument measures distances and is not able to distinguish between different objects located at the same distance. Objects in the same range bin return a cumulative response. This means RAR data are measurements in range and hence is one dimensional.

The Synthetic Aperture Radar (SAR) setup on the other hand acquires hundreds of RAR acquisitions observing the same scene while moving along a rail perpendicular to the illuminated area. This makes it possible to focus the acquisitions into two dimensional data using Fourier transformations.



Resolution is defined as the minimal distance at which two distinct scatters of the same brightness can be uniquely discerned as a separate signal (Hanssen, 2001). To distinguish between objects at different distances a short pulse is used. A shorter pulse means a better resolution (Skolnik, 1990).

This is referred to as pulse compression and defines range resolution ΔR as a function of bandwidth by where c is the speed of light, τ is compressed pulse duration and B is bandwidth. Each discrete distance defined by ΔR is referred to as a range bin. See Figure below. The range measurements are one dimensional which makes it impossible to distinguish between objects located in the same range bin. Multiple targets in the same range bin return a cumulative response.



Stepped Frequency Continuous Wave (SF-CW) is commonly used in close range applications since it permits modulated pulse duration to be longer than the two-way propagation delay of the signal. Frequency is increased in discrete steps through instrument bandwidth dwelling on each frequency step long enough for the transmitted signal to return. The SF-CW technique consists of synthesis and transmission of a burst of N monochromatic pulses equally and incrementally spaced in frequency (with fixed frequency step of Δf) within a bandwidth B (Bernardini et al., 2007a,b), where

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

For each frequency step both the orthogonal In-phase (I) and Quadrature (Q) complex components of the returned echo are stored representing the frequency response of the N pulses. The data is then reconstructed in time domain using an Inverse Discrete Fourier Transform (IDFT). From the time domain quadrature components the amplitude and phase is obtained by means of the magnitude and the argument of the complex parts, respectively:

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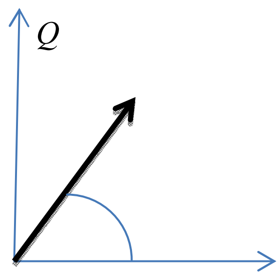
$$A = \sqrt{I^2 + Q^2}$$

$$\varphi = tan\left(\frac{Q}{I}\right)$$



where A is the amplitude and φ is the phase.

Using only one range measurement it is not possible to distinguish between different objects located at the same distance, but combining all coherent range acquisitions acquired, observing the same scene slightly offset and creating a synthetic long antenna makes it possible to focus the acquisitions into two dimensional images exploiting the Synthetic Aperture Radar technique.

This is accomplished by displacing the sensor along a rail parallel to the illuminated scene observing the same scene from slightly different angles. All offset range measurements acquired are focused into a single image with origin at the centre of the baseline.

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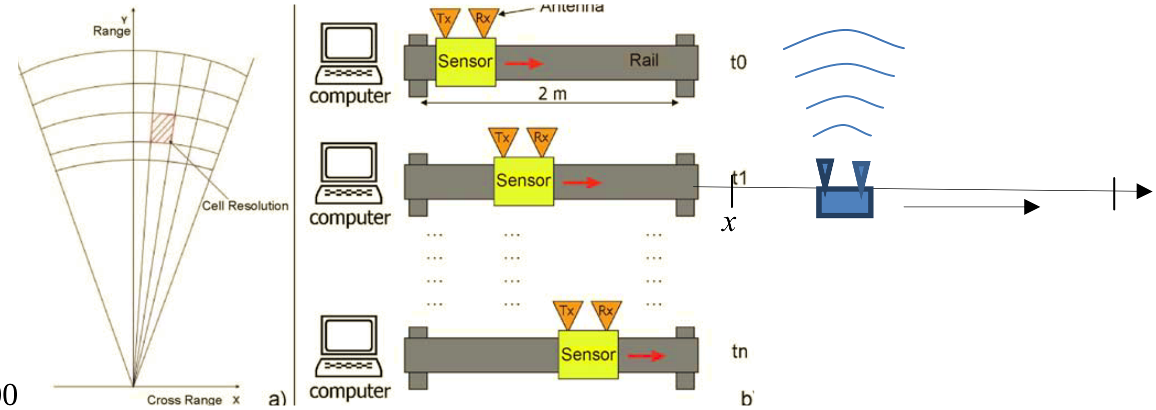

Analogously to pulse compression in range, the resolution in azimuth is obtained by compressing the range measurements in the cross-range direction (Hanssen, 2001). To obtain resolution in range a long pulse is compressed. In the cross-range direction a long acquisition time acquiring multiple range measurements is compressed into a single image considered captured at a same instant of time. Cross-range is defined as an angular resolution

$$\frac{\square}{2 \cdot L})$$

where λ is wavelength and L is synthesized antenna length. Note that the term ½ accounts for the fact that the combined acquisitions were not acquired at the same instant of time. Since cross-range resolution is defined as an angle, the pixel size increases linearly in the cross range direction by distance. Moving objects in the illumined scene may cause focusing distortions since the SAR technique is based on observing the same scene from slightly different angles during a small timespan.

The interferometric technique is based on measuring relative range differences by comparing the phase components of two images, denoted as master and slave. The phase difference of each pixel is calculated by the argument of the point wise multiplicated complex master image M containing the quadrature components I and Q with the corresponding conjugate of the slave image S*. The deformation length d for each pixel is then obtained by

$$\frac{\square}{4 \cdot \pi} \Delta\phi_{M-S})$$

where λ is the wavelength, *arg* represent the argument function of complex numbers and $\Delta\phi_{M\text{-}S}$ is the phase difference of each pixel between the compared image pair, denoted master and slave.

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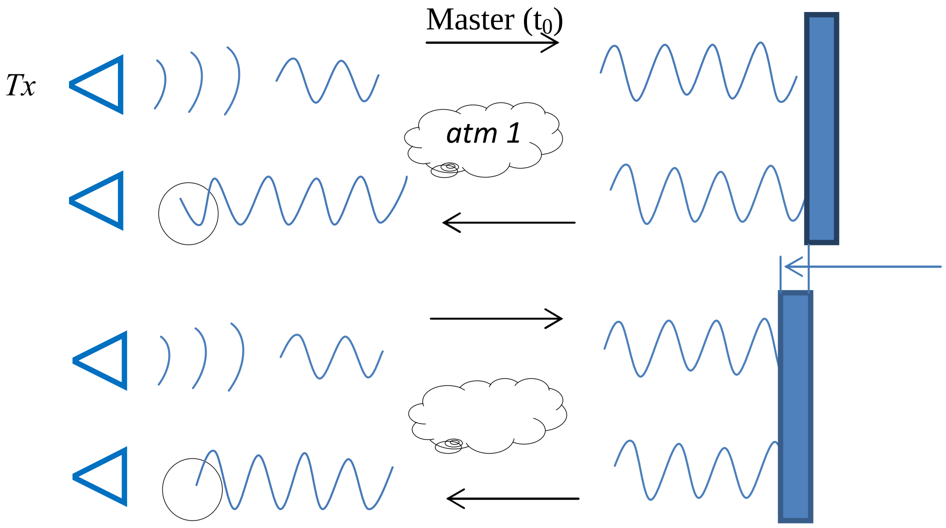

Since the images to be compared are acquired at different instants of time the atmospheric conditions must be considered. The variation of the diffraction index, due to temperature, humidity and pressure, causes a variation of the wavefront propagation velocity which may introduce an error in the range measurements.

Introducing the atmospheric contributions and ambiguity errors, the phase differences are summarized in Equation:

$$\Delta\phi_{M-S} = \Delta\phi(R) + \Delta\phi_{atm} + \Delta\phi_{n} + \Delta\phi_{noise}$$

where $\Delta\phi_{M\text{-}S}$ is the measured phase difference, $\Delta\phi(R)$ is true phase difference, $\Delta\phi_{atm}$ is the atmospheric contribution, $\Delta\phi_n$ is the phase ambiguity and $\Delta\phi_{noise}$ is noise.

The geometrical relations between measured displacement and effective point displacement d are obtained with geometrical uniformity,

$$d = d_p \frac{R}{h}$$

where d is effective point displacement, d_p is projected point displacement, R is range and h is height.

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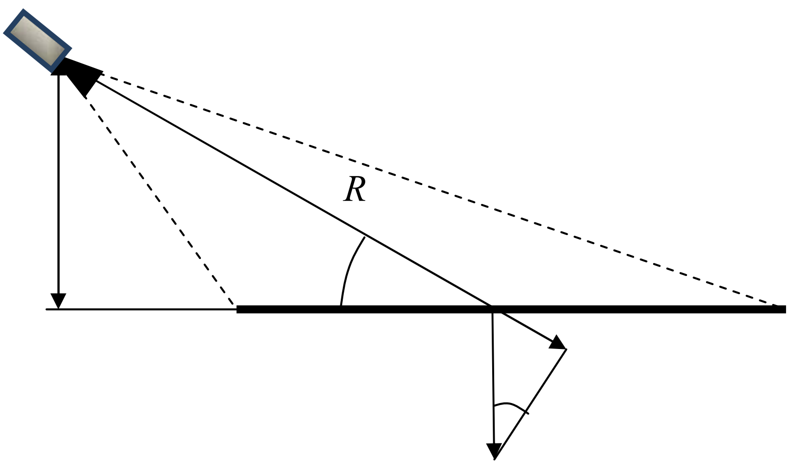
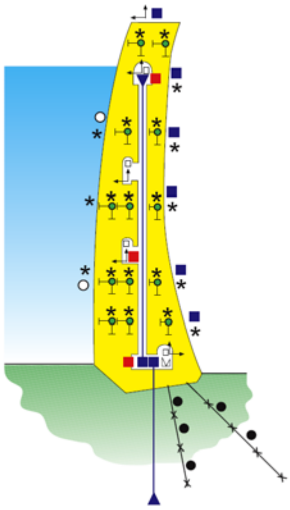


3. GB-In-SAR use for dam

Usually, an arch-gravity dam can be investigated by using GB-In-SAR system to measure deformations due to the filling of the water basin as well as to variation of the structure temperature.

The dam can be currently controlled by topographic techniques, which consist in two high precision levelling 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 (Digital Surface Model) of the structure itself can be achieved by TLS (Terrestrial Laser Scanner). The availability of all these measurements allows performing a GBInSAR data validation.

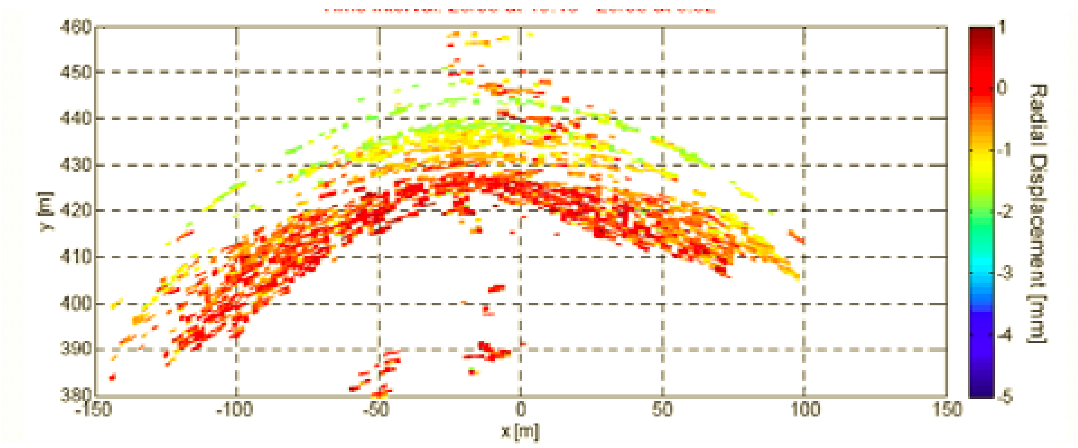


The GB-In-SAR system consists of four main components:

- Sensor module, containing the radar head and antennas.
- Linear scanner, consisting of a 2 - 3 meter long rail and motor used to displace the sensor module parallel to the observed scene to acquire multiple images of the same scene slightly offset exploiting the SAR technique.
- Control unit, PC with software to control the radar system.
- Power supply, containing two serial connected 12 V car batteries, fuses and serves as a hub for PC connections and external power sources.

The radar system has been placed just in front of the dam’s downstream face. This positioning is allows to capture the entire dam displacement along in the range direction during the whole observation time. The time needed to scan the whole downstream can be 5-10 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 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.

The results of GBInSAR measurements can be 2-D deformation maps of displacements.

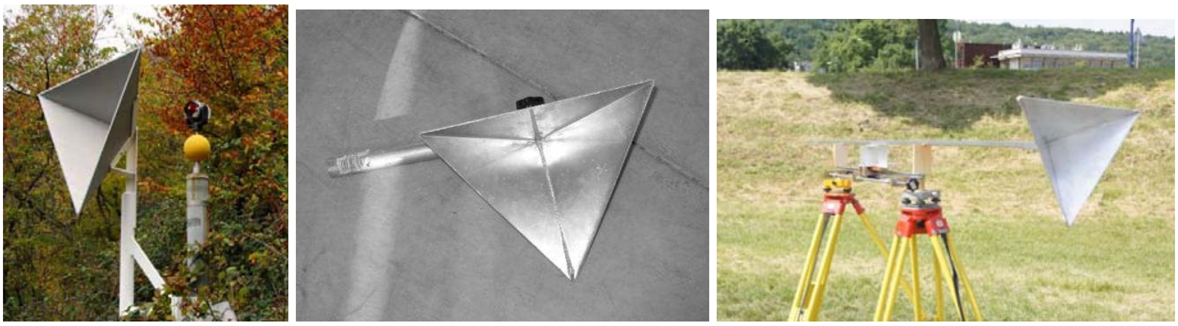


According to an integer ambiguity, such a displacement can be automatically tracked if GBInSAR system is continuously acquiring data, and not more that 1 cycle is increased from an observation epoch and another. In case of repositioning of GBInSAR system, the processing tool is not able to detect displacements 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).

It is possible to predict radar coverage a priori with a surface model. This can also be used to optimize instrument position before the actual GBInSAR acquisition, fact very useful since the instrument is very heavy. GBInSAR provides an image that it is very difficult to interpret so it is necessary the geocoding of this image to relate it with the studied object, for this task is essential to have a digital surface model, in this case obtained by terrestrial laser scanning. Also is necessary to know the coordinates of some identifiable details in the cloud of points (at least 5) to georeference all the data.

Thus, we can install corner cube reflectors (as in figure below) on the known points of the crest of dam and slopes which will clearly reflect waves, allowing for better calibration and georeferenced scenes even when changing the location of GBInSAR system observation.

The fitting mode of these reflectors should allow installation in the same positions of the targets used in TLS, the targets used for total stations or GPS receivers.



It is preferable that these points to be evenly distributed over the dam crest to estimate atmospheric corrections applied correctly to the GBInSAR system records, and thus for a better estimate of the possible deformations that occur. Theoretically, the proper selection of control points should eliminate any influence of the atmosphere, but if there are zones of highly differing weather conditions (e.g. low fog), the final result will be less accurate.

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 require the 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 GBInSAR system can operate also from some thousands meters.

4. Conclusions

According to experiments and achievements of many researchers in this field, such as (Rudolf et al. 1999), (Tarchi et al. 1999), (Leva et al. 2003), (Luzi et al. 2006, 2007, 2010), (Alba et al., 2006, 2007, 2008), (Bernardini et al. 2007), (Ferreti et al. 2007), (Kocierz et al. 2009), and other, can sustain these advantages and disadvantages of the GBInSAR system:

- Determining with under ±1 mm accuracy of the displacement and deformation of the dams in optimal weather conditions and in a convenient position for observation.
- Possibility to precise observing the structure of dam even longer distances of up to 4 km, considering the rugged mountainous terrain of the dam.
- The objective can be monitored continuously at predetermined intervals both day and night; can be included in complex systems for risk warning.
- An important disadvantage is large enough gauge of necessary equipment and high power energy (130 - 150 kg, 100 to 200 Watt).
- Is necessary to achieve a stable platform of concrete fasteners in the same positions at each stage of observations.
- For a better georeferenced of the GBInSAR system records is useful a DSM (Digital Surface Model) made with a TLS (Terrestrial Laser Scanner) at the beginning of the monitoring program that appear common points marked on the dam crest and the slopes.

However, the experimental and theoretical research in this field needs further improvements; in particular, the precise localization of control points is to be developed.

Furthermore, the integration between TLS and GBInSAR data is expected to open to further interesting applications.

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