# Multi-station Ground-based Real-aperture Radar for Quasi-static Deformation Measurement

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**Key words**: *Deformation Measurement; Ground-based Real-aperture Radar; Interferometry; Monitoring*

**ABSTRACT**

Ground-based Real-aperture Radar (GBRAR) has been applied in recent years for the dynamic analysis of civil constructions. The same technology could be also exploited for the high-precision quasi-static deformation measurement. Unfortunately, in this modality GBRAR still suffers from important drawbacks (accurate repositioning for long-term monitoring, target ambiguity, mitigation of atmospheric effects) which make its application less competitive w.r.t. other techniques. After reviewing a set of experiments to evaluate the instrumental performances of IBIS-S sensor by former IDS Sistemi Italian company, a solution based on the use of multiple stations ('stereo-radar') is discussed. This approach may help discriminate target ambiguity and improve the geometric definition of spatial displacements. 'Stereo-radar' is based on the use of at least two GBRAR sensors to work concurrently to monitor quasi-static observations. Here a preliminary test to demonstrate the feasibility of this technique is reported.

## I. INTRODUCTION

*Ground-Based Real-Aperture Radar* (GBRAR) technology has been designed to provide high-precision measurements in both the dynamic (Luzi *et al.*, 2017b) and static range (even better than 0.1 mm), see Pieraccini (2013). Applications developed up until today concerned the monitoring of civil structures and infrastructures, including the historical heritage and the assessment of post-earthquake damage (Luzi *et al.*, 2018). GBRAR sensors are able to measure relative displacements along the Line-of-Sight (LoS), unlike *Ground-Based Synthetic Aperture Radar* (GBSAR) that may also provide cross-range resolution (Rödelsperger *et al.*, 2010; Monserrat *et al.*, 2014). On the other hand, GBRAR do not incorporate moving parts and may grant a faster acquisition rate.

The majority of GBRAR applications that can be found in the literature concern the 'dynamic' deformation measurement mode, especially for the modal analysis of civil constructions (see Gentile & Bernardini, 2008; 2010; Gikas. 2012; Stabile *et al.*, 2013; Luzi *et al.*, 2014; 2017; 2017b; Saisi *et al.*, 2016; Livitsanos *et al.*, 2019).

The other operating mode ('quasi-static' deformation measurement) has resulted to be poorly investigated and applied, though potentially promising. This is mainly due to the spatial ambiguities of GBRAR measurements. Due to the mono-dimensional measurement along the range direction, the instrument is not able to distinguish multiple targets that may be located at approximately the same distance from the sensor. For this reason, other techniques with similar performances but fewer limitations are preferred in applications for monitoring quasi-static deformations, such as robotic total stations (Scaioni *et al.*, 2010), laser trackers (Barazzetti *et al.*, 2015), and terrestrial laser scanners (Lindenbergh & Pietrzyk, 2015).

This paper discusses the concept and some first experiments of a new GBRAR-based solution for quasi-static deformation monitoring of civil structures and infrastructures. Instead of using a single radar station, two or more are setup so that the object to monitor is illuminated by multiple radar sources. This solution has been addressed to as 'stereo-GBRAR' in Scaioni *et al.* (2017), since it requires at least to measurement stations. The presentation of this solution within the IBIS-S radar sensors produced by the Italian company IDS Sistemi will be the object of Section III. In Section II, a review of a series of experiments carried out to access the basic metrological properties of IBIS-S is reported. In the end, some conclusions about future experiments and some suggestions for technological development of GBRAR sensors, which are necessary to foster and spread out thier application for deformation monitoring of civil constructions (see Marsella and Scaioni, 2018) will be drawn.

## II. TESTING IBIS-S SENSOR

### A. *IBIS-S GBRAR sensor*

The GBRAR IBIS-S sensor was developed in cooperation by IDS Sistemi Company (Pisa, Italy) and the the University of Florence, Italy (Luzi *et al.*, 2010; Montuori *et al.*, 2016). Currently, the sector of this company dealing with microwave and georadar sensors is part of Hexagon Geosystems group under the name of IDS GeoRadar (www.idsgeoradar.com). IBIS-S was launched in 2007, and now is continued by IBIS-FS and IBIS-FS Plus, the latter equipped with a compensation system able to mitigate the effects of vibrations when working in construction areas. The radar sensors adopted in IBIS-FS can be expanded into the GBSAR system (IBIS-FL).

IBIS-S (and now IBIS-FS/IBIS-FS Pro) is probably the only operational, commercial GBRAR instrument which his available today, though other non-commercial solution exist. As recalled in the Introduction (Sect. I), IBIS-S offers two operational measurement modes to observe *quasi-static* and *dynamic* displacements, which are documented in the technical literature.

An IBIS-S sensor is composed of:

- a Sensing Unit that can generate, broadcast and record of a coherent radar bandwidth;
- a Control Unit installed on an industrial laptop;
- a Support System that may be a photographic/topographic tripod, or a plate for precise centering and repositioning; and
- an Energy Supply Unit.

Table 1 reports some technical features of IBIS-S, while Figure 1 depicts an instrument unit during operations.

Table 1. Main technical properties of IBIS-S GBRAR sensor by IDS Sistemi company.

| | |
|---|---|
| *Radar technology* | SFCW, interferometric |
| *Operating frequency bandwidth* | Band Ku (12-18 GHz) |
| *Operating range* | 20 - 1000 m |
| *Range resolution* | 0.5 m in radial direction |
| *Precision of relative displacement measurement* | 0.01-0.1 mm |
| *Sampling frequency* | up to 100 Hz (in 'dynamic' mode) |
| *Size of Sensing Unit* | 40 x 40 x 15 cm (L x P x H) |
| *Weight of Sensing Unit* | 12 Kg |

IBS-S sensor can locate and simultaneously track a set of targets in the portion of space illuminated by the radar signal. However, only one target can be detected inside each 'range bin,' which is the volume of the radar wavefront included between distances *R* and *R+ΔR* from the sensor (see Fig. 2), with *ΔR* the range resolution that is independent from range *R*. This involves that, if a highly-reflecting element is predominant inside a single range bin, this feature will be effectively tracked within time. But in the case two or more reflectors are inside the same range bin, they cannot be discriminated.

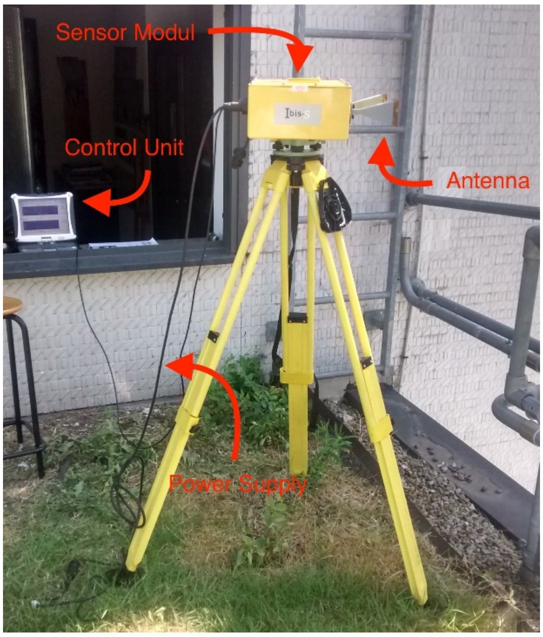

Figure 1. IBIS-S measurement unit installed on a topographic tripod.

In general, civil structures presents several elements that may play as reflectors. Is it is also possible to include "artificial" *corner reflectors* (CR) as in the case of spaceborne InSAR.

## B. *Measurement technology*

The measurement process is based on *Continuous Wave Step Frequency* (CWSF) and *Differential Interferometry* techniques, see Pieraccini *et al.* (2004).

The adopted bandwidth of the radar signal results in a *range ambiguity* ($\lambda_{amb}$) depending on the central wavelength ($\lambda$=17.6 mm) according to the formula:

$$\lambda_{amb} = 0.25\lambda = 4.4 \text{ mm} \quad (1)$$

The *spatial resolution* is constrained to the range bins, each of them featuring a typical depth *ΔR*= 0.5 m. The recorded signal consists of a 'range profile,' showing the amplitude of the reflected radar signal in each range bin. In the upper part of Figure 2, each sector defined by radii *R* and *R+ΔR* corresponds to a *range bin*, where only one target (red circles) can be solved for. In the lower part, the resulting range profile showing the amplitude of tracked targets is shown. In some cases, a peak in this profile may correspond to multiple targets located in the same range bin.

The other information recorded per each range bin is the phase of the radar signal, which is used within the differential interferometry technique to determine the relative displacement of the potential target between consecutive observation epochs.

In the following subsections a series of experiments concerning the evaluation of IBIS-S sensor are briefly reported. More details about can be found in Scaioni *et al.* (2017).

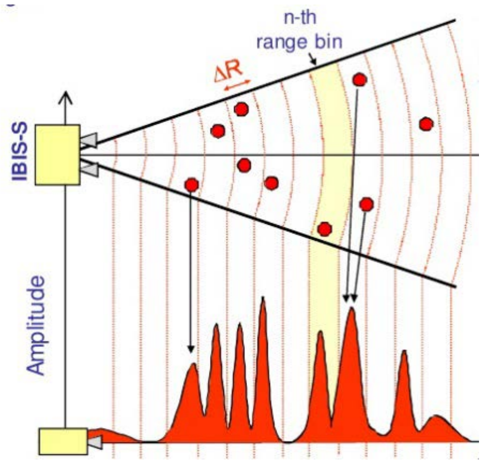

Figure 2. In the upper part a horizontal profile of the radar-illuminated space in front of IBIS-S sensor. In the lower part, the resulting range profile showing the amplitude response per each range bin.

C. *Testing measurement accuracy*

A first group of experiments have concerned the evaluation of IBIS-S instrumental accuracy of relative displacements along the range direction. This task has been carried out by comparing a set of observed displacements against benchmarking values obtained with a micrometric slide (±10 µm accuracy). The experiment has been led in outdoor uncontrolled environment to reproduce real operating conditions. Two artificial corner reflectors (CR) have been positioned to guarantee a proper radar response. One of them has been installed on the micrometric slide to set up a series of known displacements, whose size has ranged from 10 µm to 1 cm. These displacement steps have been operated slowly, so that the instrument could follow the displacements larger than the range ambiguity from Eq. (1).

The RMSE (Root Mean Square Error) of error displacements per each measurement session and the RMS (Root Mean Square) of corresponding standard deviations have resulted 17 µm and 22 µm, respectively. Error distribution has followed the normal distribution centred on the benchmarking values. This result has confirmed the nominal accuracy reported in the technical specifications (see Table 1) as well as the outcomes of a series of experiments operated by IDS Sistemi company.

The same experiments have been also repeated in indoor environment, obtaining much worse results. These are probably due to multi-path effects and interferences due to multiple reflections. Consequently, the application of GBRAR in indoor or narrow spaces has to be carefully considered.

D. *Testing the influence of environmental parameters*

The accuracy of IBIS-S evaluated in controlled conditions (Subsect. C) cannot be achieved in real environments for long measurement sessions. Under such conditions, the variability of local atmospheric temperature and pressure may degrade the quality of the observations. Then, a second group of experiments has been focused on evaluating these effects and trying some methods for their corrections (Monserrat *et al.*, 2014).

The IBIS-S sensor has been fixed on a stable support in a courtyard, while four points to be monitored have been localized in the illuminated scene, according to a distance spanning from 43 m to 125 m. Four CRs have been installed to maximize the amplitude of the reflected signal. One CR has been mounted on a micrometric slide.

Three similar measurement sessions have been repeated in three days from morning to evening. During each session the relative displacements along the range direction have been measured for fixed targets. The sensor has been operated in continuous acquisition mode, recording one observation every minute. In the case of the point installed on the slide, some cycles of given displacements have been repeated. Meteorological data have been recorded at a weather station located at approximately 500 m from the operation area. The high variability of environmental conditions during the experiment has resulted in worsening the accuracy. In some case, errors have reached 3.5 mm. The presence of high-correlation with relative humidity ($\rho$=0.77) has quantitatively proved what was clear from the analysis of radar observation behaviour, i.e., a strong dependence upon environmental parameters.

In order to improve the quality of GBRAR measurements, three methods have been tried to mitigate the effects of environment changes (see Table 2).

Table 2. Methods applied to compensate for the effects of environmental parameter change (P=absolute atmospheric pressure; T=atmospheric temperature; RH=relative humidity; VPP= partial vapour pressure).

| *Method* | *Min. no. (n) of necessary CRs* | *Environmental parameters* |
|---|---|---|
| Corner reflectors (CR) | $n \geq 1$ | none |
| Zebker *et al.* (1997) | none | P, VPP, T |
| Empirical polynomial regression | $n > 1$ | RH, P, T |

Two methods require the use of CRs, which may be presented by already existing or artificial features able to provide a good response to the radar signal. Two methods need the observation of some environmental parameters during the measurement session, as shown in Table 2.

The accuracy obtained using the “Corner reflectors” method has resulted the highest (RMSE < 0.1 mm). Other methods have not provided similar good results. One of the grounds of such lower performances is probably the poor determination of local environmental parameters. Indeed, the meteo station was at about 500 m far away from the test field.

### E. *Testing the influence of design parameter*

In this group of tests, the influence of some design parameters that have to be set up when planning a GBRAR monitoring application have been analysed. While the approach used can be retrieved in Scaioni *et al.* (2017), we outline here the final outcomes of these experiments:

- *Size of corner reflectors*: accuracy increases when the size of CRs is larger (CR size tested has been in the range 10-30 cm);
- *Distance between GBRAR-CRs*: accuracy increases when the distance is lower, with the exception of the largest-size targets (30 cm);
- *Angle of the LoS to a CR w.r.t. the radar normal direction*: accuracy is better when the CR is close to the centre of the aperture cone of the antenna; and
- *Maximum acquisition range* (controlling the number of range bins and then the signal gain): accuracy is not affected by this parameter.

## III. 'Stereo-radar' mode

### A. *Concept*

During experiments described in Section II, a wide use of artificial corner reflectors (CR) has been done. In application for monitoring structures and infra-structures, however, the use of CRs is not always possible. Provided that the construction to be monitored might offer natural reflectors, the spatial ambiguity in the recognition of targets may limit the application of the GBRAR technique. The knowledge of the illuminated scenario's geometry may help discriminate targets as well as detect which is the spatial direction of the observed displacements. This is possible thanks to the known positions of potential targets and to the overlap with footprints of the illuminated areas. In the case of objects featuring a prevalent direction (e.g., bridges), the identification of targets is easier. Indeed, if the sensor illuminates the structure from an inclined position, it results that only a small portion of the structure lies in the footprint included between two distances $R$ and $R+\Delta R$ that define a single range bin (see, e.g., Gentile & Bernardini, 2008). In some other cases (for example a dam, see Scaioni *et al.*, 2018) this process may require the acquisition of a 3D model to map the displacement vectors (see, e.g., Anghel *et al.*, 2016) and the determination of GBRAR position and attitude in the same reference system.

To overcome the problem of the geometric ambiguity of target recognition, a new 'stereo-radar' monitoring technique has been firstly proposed in Scaioni *et al.* (2017). This technique is based on the use of the GBRAR sensor from at least two stations located at different spatial positions. Such methodology should help detect the observed targets in individual range bins, since the intersection of the illuminated areas from multiple radar stations could reduce the footprint on the object corresponding to each range bin. Moreover, given that the same natural reflector is recognized in the range profiles from different stations, more displacement vectors could be measured and combined to better define the real 3D displacement vector.

### B. *Experiments*

The experimentation of the 'stereo-radar' technique has been conducted to measure deformations of a seven-floor building of Politecnico Milano, Leonardo Campus (Italy), see Figure 3. Three stations have been set up on the roofs of two other buildings in the nearby. On each station a measurement session of 25 min has been carried out using a 10 s sampling rate. The maximum acquisition distance has been set up to 75 m. Environmental parameters have been also recorded during the measurement sessions using a meteorological station located within 50 m from the area of operations. Since only one IBIS-S instrument was available, the aim of this experiment has not been to accomplish a real 'stereo-radar' measurement. However, since short elapsed times separated the GBRAR measurement sessions and the building deformations were supposed to be slow and small, the aim of this experiment was to detect whether the same natural targets could be tracked from different positions.


Figure 3. The façade of Politecnico di Milano (Leonardo Campus) building selected for preliminary experimentation of 'stereo-radar' monitoring. Red numbers refer to points measured using a total station.

### C. *Results*

A first analysis of range profiles and footprints of projected range bins on the building façade has shown some differences depending on the considered station. A very small number of regions on the building façade corresponded to range bins with high-amplitude peaks in more than one range profile corresponding to different stations. Thus, the analysis could not be limited to those areas corresponding to local maxima of S/N over the threshold in at least two range bins. In fact, other points of the façade have resulted in range bins with local maxima featuring quite high S/N, though below the fixed threshold.

The following approach has then been used:

1. Range bins corresponding to natural features whose 3D coordinates were measured using a total station (see Fig. 3) have been looked for;
2. Foot-prints of these range bins have been projected on the façade (see Fig. 4);
3. A few GCPs have been selected in stable positions to compensate for the effects of environmental parameters' change.

Twelve points have been identified in a couple of range bins out of 14 points measured by using a total station, as shown in Figure 3. The spatial distribution of these points has allowed to reconstruct the deformation trend of this building.

The atmospheric corrections based on the 'GCP Method' (see Subsect. II-D) has provided good results on relative displacements measured from Radar Station 1 (RMSE of residuals of approximately 0.05 mm). Results from other stations have shown larger residuals after correction. By comparing the displacement trends to the recorded environmental temperature, a good correlation has been found. This result confirmed the mere dependency of displacements upon the thermal deformation.

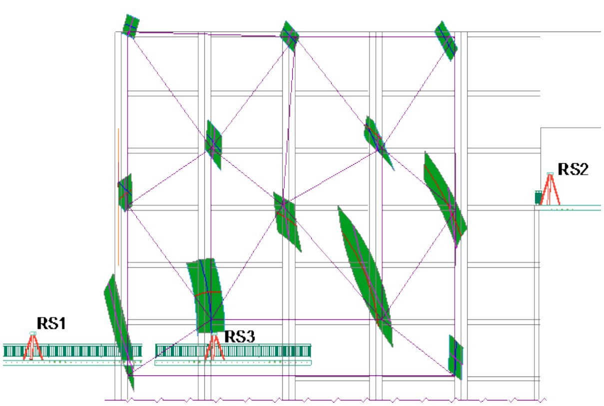


Figure 4. Footprints of intersecting radar signals from multiple stations, considering the façade of Politecnico di Milano displayed in Figure 3. Radar stations are also shown (RS1, RS2, RS3).

This experiment has demonstrated the possibility of tracking the same natural targets on a building façade from different points of view, which represents a prerequisite to operate with a 'stereo-radar' approach. Nevertheless, the initial identification of potential targets on the façade and the measurement of their 3D coordinates by a theodolite has been necessary.

## IV. Conclusions and Future Developments

In the first part of the paper, some experiments carried out to assess the metrological performances of the interferometric real aperture radar (GBRAR) sensor IBIS-S (formerly IDS Company, now IDS GeoRadar, Pisa, Italy) in applications focused on 'quasi-static' deformation monitoring of civil constructions have been reported.

First of all, the obtainable accuracy when using artificial corner reflectors in continuous acquisition mode has been evaluated. The size and shape of corner reflectors and their positions in the radar-illuminated scenario might significantly influence the outcome of monitoring operations. When the instrument is used in uncontrolled environment, the atmospheric conditions may result in degrading the accuracy. Three different methods to compensate for the atmospheric effects have been tested. The 'Ground Control Points (GCP) Method' has provided the best results, although it is the most complex to operate in the real practice because needs fixed reflectors in stable areas. Provided that accurate meteorological data are available during the measurement session, also alternative methods could be used, for example, the one proposed in Zebker *et al.* (1997), which is completely independent from GCPs.

In the second part of this paper, the concept of 'stereo-radar' approach was discussed. Indeed, some factors influencing the effectiveness of this method could be recognized: position and attitude of sensors and the structure to monitor; amplitude of reflected signal; and size of each range bin's footprint on the structure. The preliminary identification of some features that could play as potential natural radar reflectors offered the opportunity to identify corresponding range bins in the range profiles at both adopted radar stations. This has allowed the reconstruction of the deformation trend of the investigated façade. The closer is the time gap between data acquisition from both sensors, the higher is the accuracy obtainable. This solution may be practically obtained by using a couple of radar sensors, which may alternatively record observations to avoid interferences.

The authors envisage a couple of main motivations that could lead to the success 'stereo-radar' in the future. On one side, using fixed multiple radar sensors, which do not entail moving parts, accurate deformations of several points on a civil construction could be monitored. Of course, the technology should develop in the direction to design low-cost GBRAR sensors, that however would benefit from a large-scale production. On the other side, the GBRAR sensors open the chance of operating the contemporary quasi-static and dynamic monitoring, providing this way a multiple output in monitoring civil constructions' health.

## ACKNOWLEDGEMENTS

The authors would like to acknowledge the GICARUS laboratory of Politecnico di Milano, Lecco Campus, for providing the facilities during the experimental phase. In particular we would like to thank Prof. Alberto Giussani, Dr Mario Ivan Alba and Dr Fabio Roncoroni for their contribution to the experimental tests.

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