Slow Motion Deformations: Potential and Quality Assessment of Ground-Based Radar Systems

Niemeier, W. and Lehmann, M.

Technische Universität Braunschweig, Institute for Geodesy and Photogrammetry,
Pockelsstraße 3 (Okerhochhaus), 38106 Braunschweig, Germany,
E-mail: w.niemeier@tu-bs.de

Abstract

This paper presents the possibilities and limitations of ground-based synthetic aperture radar interferometry (GBSAR) for slow motion deformation monitoring. The technology has several advantages compared to classical monitoring concepts or space-based radar interferometry.

Main focus here are theoretical considerations and experimental studies to validate the potential of this new technique. These studies cover field tests to verify the resolution of displacements in range direction and the stability of the frequencies of the radar head. Additionally first results for the correction of the dominant atmospheric influences on the detection of displacements are presented.

Finally a preliminary, generalized estimate of the potential and achievable quality of GBSAR for slow motion deformation processes is given.

Key words: ground-based radar interferometry, slow deformations, resolution of displacements, atmospheric effects, quality assessment

1 INTRODUCTION

One of the main tasks in Engineering Geodesy (Kuhlmann et al. 2013) is monitoring of geo-objects (landslide effected areas, rock slopes, subsidence areas, etc.) and large scale structures (dams, bridges, towers, etc). For these tasks the new methodology of ground-based radar interferometry can be used since several years. This paper is oriented to the applicability of GBSAR for monitoring of slow motion displacements, while in some of the next papers in this session monitoring of the dynamic behaviour of structures with radar interferometry systems is discussed.

Compared to space-based sensors, the advantages of ground-based systems (see e.g. Bernardini et al. 2007, Pieraccini et al. 2006, Niemeier et al. 2010, Rödelsberger et al. 2010) are depicted in Figure 1. The primary sensitivity of radar sensors to detect displacements is given in line-of-sight (LOS), i.e. for many applications a ground based system is advantageous, as here the radar head can be oriented directly towards the critical deformations.

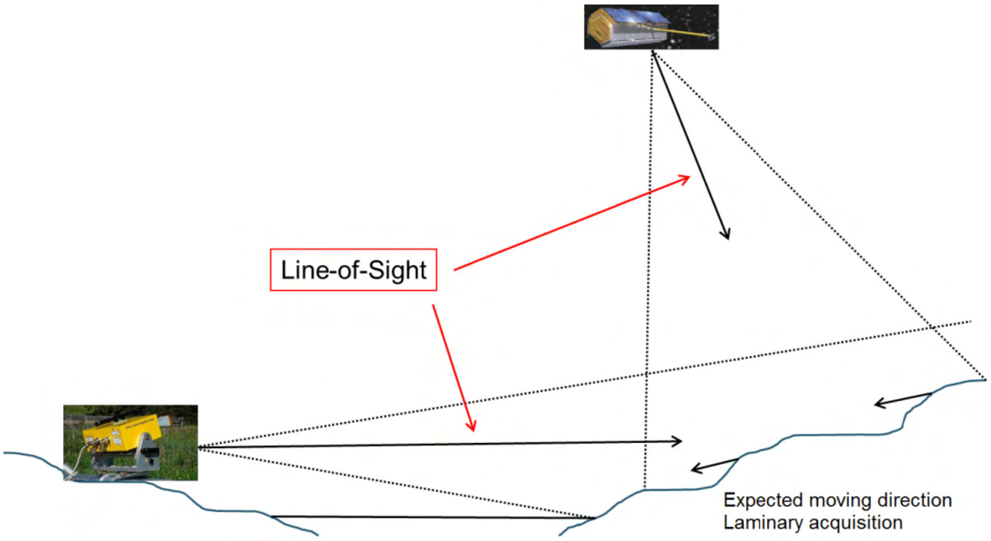

Figure 1 Sensitivity of ground based radar interferometry for slope movements, compared to space based systems

Aside, the repeat time e.g. of TerraSAR-X is 11 days, while ground-based systems can be used almost continuously, what allows a much better potential to study the deformation processes in detail.

2 GROUND BASED RADAR INTERFEROMETRY

At present, a few ground-based systems for radar interferometry are available, most popular is the IBIS-L, developed and produced by the Italian company Ingegneria dei Sistemi (IDS). This system is presented in Figure 2. The radar head is oriented directly towards the monitoring objects. By a flexible selection of the location of the instrument set-up, the observation interval and the type of antenna the system can be adapted to specific requirements of the monitoring task. The system is designed for continuous operation for weeks or months; the processing starts immediately after the first acquisitions are performed.

Figure 2 The IBIS-L ground based radar system in front of an open-pit mining area. The radar head moves on a 2m long rail and is oriented towards the critical slope (IDS)

Some specifications of the IBIS-L system are given in Table 1. The used wavelength characterize the emitted signals as microwaves, which are heavily influenced by the atmosphere, see section 3.3.

Table 1 Characteristic parameters of IBIS-L

IBIS-L

Antenna type
- Synthetic Apertur

Area of Application
- Area-related capture of deformations of distinct objects

Parameters
- Frequency band: Ku-Band (17.1 – 17.3 GHz)
- In range resolution: 0.75 m
- Resolution in cross range direction (Azimuth): 4,4 mrad
- Precision of displacements: 0.1 – 1 mm (LOS, dependent on distances)
- Maximum range: up to 4000 m
- Time for one acquisition (Image): 5 min (dependent on distances)

The IBIS-L system uses the Ku-band (17.1 – 17.3 GHz). This results in a wavelength of 17.8 mm. To increase the accuracy of the range measurement the IBIS-L is using a special technique called Continuous Wave – Stepped Frequency (CW-SF). This means the radar unit is sending a continuous wave and during the measurement the frequency is changing stepwise; technical details are described e.g. in Rödelsperger et al. (2010).

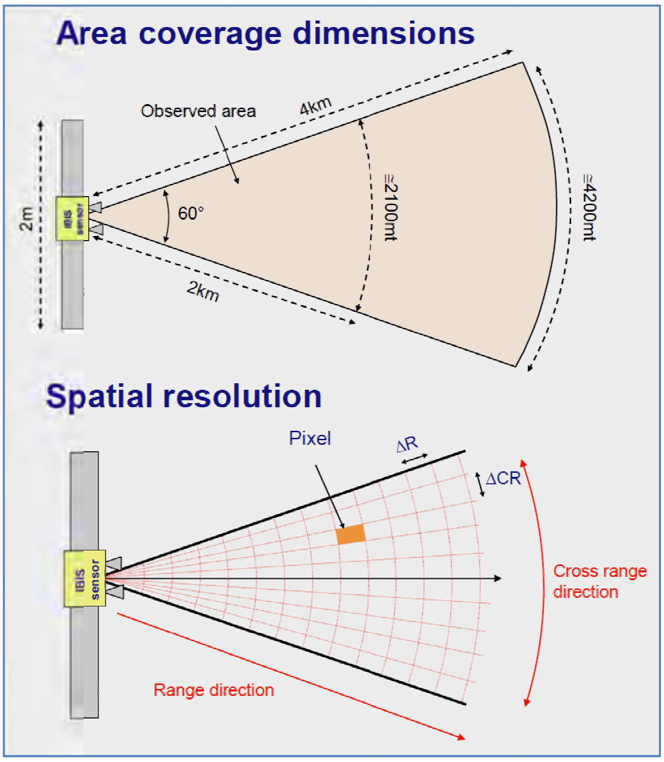

Figure 3 Area coverage and resolution in range and cross-range direction for IBIS-L

Caused by the CW-SF technique the measured distance is divided in so-called range-bins. Due to the principles of technique the detected signal of one range-bin is the sum of all signals that are reflected in this spatial area. The length of a range-bin can be adjusted, but the standard length is 0.75 m. The number of the steps is also adjustable in the IBIS-L system, so the system is able to detect signals up to a distance of 4000m.

By taking the geometry of the acquisition into account, it is possible to calculate also the displacement component of the geo-object which is of interest. In the most cases this will be the horizontal component.

By moving the radar sensor on a special rail (see Figure 2) the measurements are done repeated and the single measurements can be summarized by the synthetic aperture radar (SAR) technique to one radar image providing a resolution in range and azimuth (see Figure 3). A resolution in cross direction of 4.4 mrad can be achieved.

Main advantage of this system is its characteristics to be continuous in time and space, what was considered to be an important issue for future monitoring systems e.g. by Heunecke/Niemeier (2004). Shortage is the low spatial resolution of 4.4 mrad in cross range direction, what equals a pixel width of 4.4 m for objects 1 km apart (Bernardini et al. 2007).

Within each resolution cell the measured phase response is the integrated reflected signal and this information is used to determine the displacements between two or more acquisitions. In Figure 4 the situation for this interferometric principle is depicted: For an identical position and orientation of the instrument the observed phase difference $\Delta\varphi = \varphi_2 - \varphi_1$ can be converted directly into linear displacements d of the corresponding pixel.

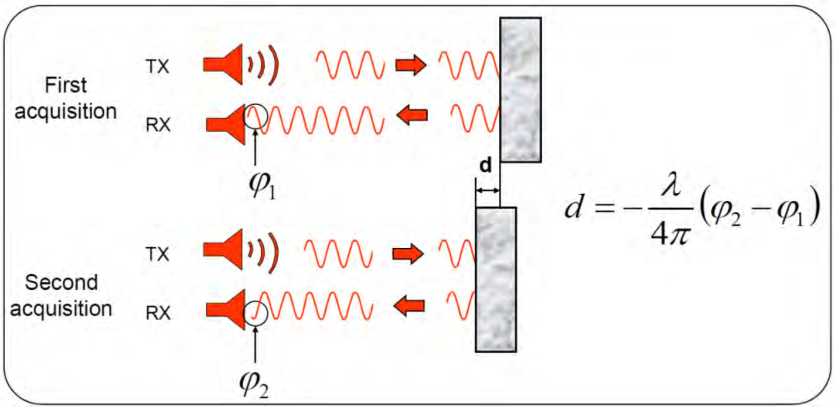

Figure 4 Determination of displacements using the difference between phase observations (IDS 2009)

3 VALIDATION OF THE POTENTIAL OF IBIS-L

Considering a ground-based radar interferometry system as a geodetic instrument, makes it necessary to evaluate the measuring quantities in terms of precision and reliability and to analyse internal and external effects on the complete measuring process. As first step into this direction the following aspects were analysed here:

- Resolution for displacements in range and cross range direction
- Stability of used frequencies
- Atmospheric effects on phase observations

For these aspects theoretical considerations and experimental studies were carried out in 2013 in the vicinity of Braunschweig, Germany.

The results give a first impression on the quality of the achievable results with the system IBIS-L, but just the above given parameters could be considered and more research is needed. Anyway, a general idea on the potential of this new technology can be given and this might help practitioners to make an estimate on the usefulness of this methodology.

3.1 RESOLUTION FOR DETECTION OF DISPLACEMENTS

In Table 1 for the precision of displacements the following values are given: 0.1 – 1 mm. These are extremely good values and it has to be proven whether or not these quantities are realistic. A maximum range of up to 4000 is given in Table 1, too, and the applicability of an IBIS-L for such long distances has to be checked.

The basic principle to validate these values and the experimental setup are given in Figure 5: Within the visible field corner reflectors are positions, which are located on a movable support on a tripod. The instrument itself was positioned on top of our institute building, approximately 2000 m apart. A more detailed description can be found in Lehmann et al., 2013.

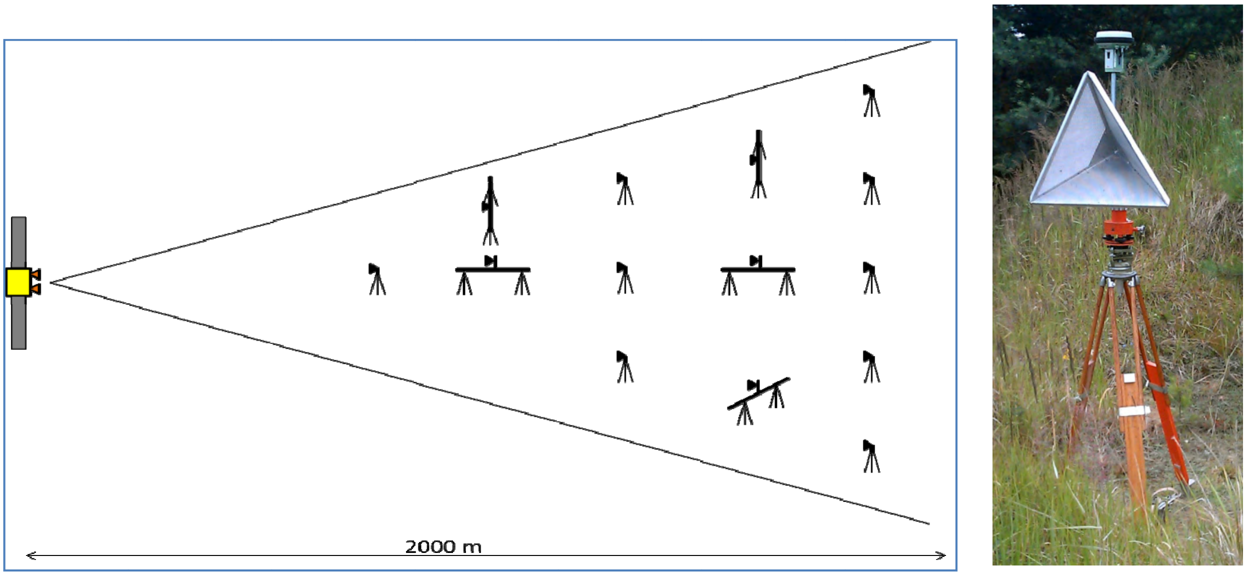

Figure 5 Principle and experimental setup to evaluate the resolution of the IBIS-L

The corner reflector, oriented precisely towards the instrument, was moved in predefined steps of 2 mm up to a total displacement of 30 mm. The results from IBIS-L observations, processed with the software IBIS-DV are depicted as blue line in Figure 6. In direct vicinity to this variable target an old and stable building ("bunker") was observed; the results are given as red line in Figure 6.

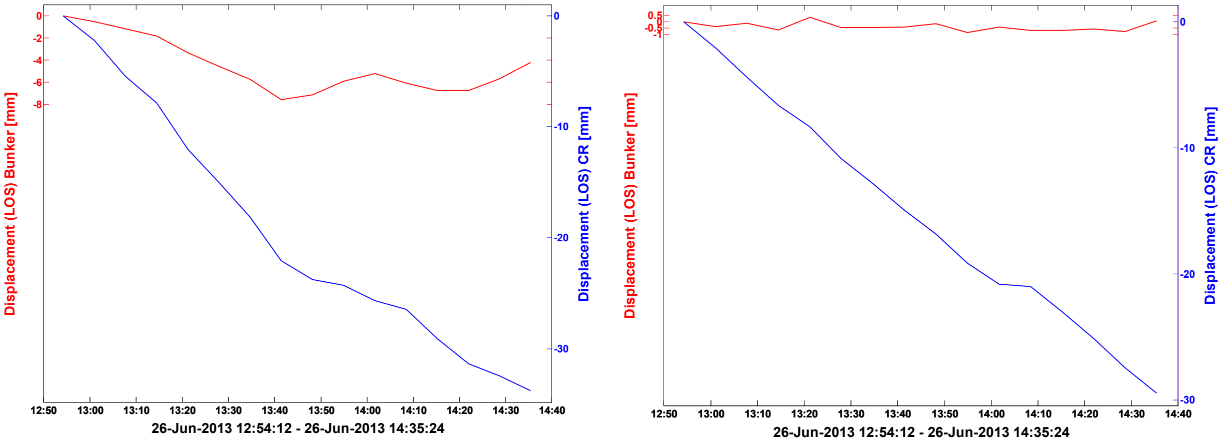

Figure 6 Results for displacements of movable target and for reference point (bunker).
LEFT: Original values. RIGHT: With assumption on stability of bunker

The bunker can be assumed to be stable, what means that the variation of about 6 mm in Figure 6 “left” can be explained as atmospheric effect, see section 3.3. In Figure 6 “right” the displacements for the movable target are corrected by the model “bunker is stable ground control point”; now the remaining discrepancies between the pre-set values and the observed displacements are all below 0.5 mm.

These results are in very good coincidence with the claimed precision. One has to state that these experiments were conducted within one resolution cell. More critical are targets that are located at the edge of one cell or between two cells; here detailed studies have to be performed, both in range and cross range direction.

3.2 STABILITY OF USED FREQUENCIES

For IBIS-L a basic frequency of 17.1 GHz is given in Table 1 and the bandwidth for a sweep of the SF-CW measurements is 200 MHz. To analyse the real frequencies, a Spectrum Analyzer, provided by PTB (Physikalisch-Technische Bundesanstalt, Braunschweig), could be used. The experimental set-up is depicted in Figure 7.

Figure 7 Frequency check for IBIS-L: The antenna of a spectral analyzer is positioned outside the radar head.

Without going into detail it had been proven that the instrument is working with 17.1050 GHz, was is very close to the claimed 17.1 GHz; the bandwidth of 200 MHz is reached and the frequency steps do have the proposed equal distances.

Information on the long-term stability of these frequencies are not yet available, but they would have influence on the derivation of displacements.

3.3 ATMOSPHERIC EFFECTS ON PHASE OBSERVATIONS

Most ground-based radar interferometers use microwaves that are heavily influenced by meteorological parameters, the air temperature and the air pressure, but the dominant factor is the content of water vapour (humidity). As the estimation of representative values for temperature and water vapour along the signal path is very difficult, one possibility to correct for the integral part of meteorological influences is to use “Ground Control Points (GCP)”, i.e. to include a few points in the observation scheme, which are considered to be stable during the observation time. “Pseudo”-displacements, which are detected at these GCPs are used to correct the displacement rates of other points. This approach was used in section 3.1, the bunker served as GCP.

Due to the variability of the atmosphere, these corrections can only be applied for points in the direct vicinity of the GCPs. This effect was studied in a long-term experiment in spring 2013. In Figure 8 a) the general situation and the setup are presented: The IBIS-L was positioned on top of our institute building and oriented towards the City of Braunschweig.

The reflected signals of all objects were recorded for several weeks, see the intensity map in Figure 8b. For four selected points P1 in 529 m distance, P2 in 517 m, P4 in 970 m and P5 in 1678 m with high reflectivity (landmarks, like mainly towers, high buildings, etc.) the concept of GCPs is applied.

The “Pseudo”-displacements (Figure 8c) range from + 30 mm to – 30 mm, while the “corrected” displacements, using point P1 as stable (see straight line in figure 8D), are much smaller, but still have variations from +3 mm to - 5 mm. Just P2, which is closely related to P1, shows remaining variations of less than 2 mm, what almost coincides with the claimed precision in Table1.

This study indicates very clearly that at present the atmosphere is the limiting factor for terrestrial radar interferometry.

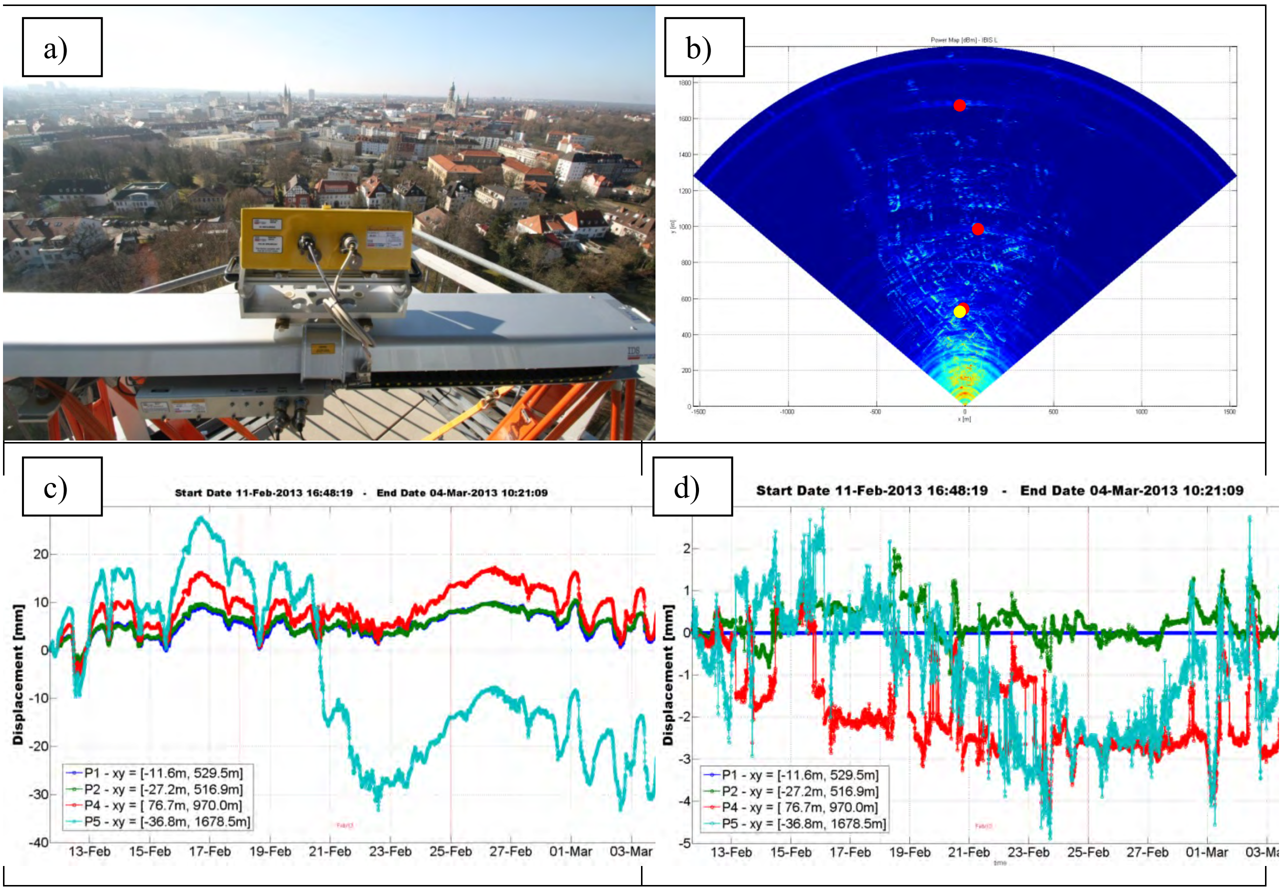

Figure 8 Atmospheric corrections using Ground Control Points:
a) IBIS-L overlooking the city of Braunschweig
b) Intensity map of reflected signals with identified landmarks
c) “Pseudo”-displacements for 4 “stable” landmarks
d) Displacements for the same landmarks after using P1 as GCP

4 CONCLUSION

This short presentation intents to give a first impression on the basic principles as well as the potential and limitations of GBSAR for monitoring slow motion deformation processes. The main advantage is its potential to monitor remote objects continuously in space and time; in ideal situation even without any marked target.

Important is a good and stable reflectivity and a solution to overcome the dominant atmospheric effects. A further shortage for some projects might be the width in cross range direction, which accounts to 4.4 m for objects in 1 km distance.

The internal precision or resolution is extremely high, here the claimed values of about 1 mm could be validated in the experiments.

The outer precision, often called accuracy, mainly is limited by the atmosphere and the surface structure (reflectivity) and here a reliable solution for practical work could not yet be presented.

Very good is the IBIS-L as indicator for instabilities, i.e. for a qualitative analysis e.g. on the stability of slopes and rock faces; to become a real geodetic sensor robust quantitative displacement rates are required and to achieve this, intensive research has to be performed.

ACKNOWLEDGEMENT

This work was partly supported by the GMES4Mining project of EU and North Rhine-Westphalia (Förderkennzeichen: 30 02 531 02 ff).

REFERENCES

BERNARDINI G., RICCI, P., COPPI, F. (2007): *A Ground Based Microwave Interferometer with imaging capabilities for remote measurements of displacements*. GALAHAD workshop within the 7th Geomatic Weekend, Barcelona, Spain

Ingegneria Dei Sistemi (IDS): *www.***ids***corporation.com*

HEUNECKE O., NIEMEIER W. (2004): *Paradigmenwechsel bei der Auswertung ingenieurgeodätischer Messungen.* In: Ingenieurvermessung 2004, ETH Zürich, S. 131-142

Kuhlmann H., Schwieger V., Wieser A., Niemeier W. (2013): *Ingenieurgeodäsie - Definition, Kernkompetenzen und Alleinstellungsmerkmale,* Zeitschrift für Vermessungswesen, vol. 138

LEHMANN M., RIEDEL B., NIEMEIER W. (2013): *A field testing method for GB-SAR instruments - Concept and preliminary Results.* In: Proceedings 2nd Joint International Symposium on Deformation Monitoring (JISDM), Nottingham, UK, Sept. 2013.

NIEMEIER W., RIEDEL B., BAUMBACH H. (2010): *Monitoring von instabilen Hanglagen durch bodengebundenes interferometrisches Radar.* 11. Geokinematischer Tag, TU Freiberg, Germany

PIERACCINI M., FRATINI M., PARRINI F., ATZENI C. (206): *Coherent Radar for Measuring Dynamic and Static Deformations of Architectural Structures.* In: Kahmen/ Chrzanowski/ Retscher (Eds.): 3rd IAG-Symposium Geodesy for Geotechnical and Structural Engineering, Baden b. Wien, Österreich

RÖDELSBERGER S., LÄUFER G., GERSTENÄCKER C., BECKER M. (2010): *Terrestrische Mikrowelleninterferometrie - Prinzip und Anwendungen.* Allgemeine Vermessungsnachrichten, Wichmann-Verlag Karlsruhe, Germany