Monitoring of Deformations of Infrastructure Objects by Radar-Interferometry - Prerequisites, Potential and Limitations

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Abstract. Synthetic Aperture Radar (SAR) Interferometric techniques are well suited for deformation studies. Limitations of the conventional SAR Interferometry (InSAR), are partially overcome by advanced techniques and especially by multi-temporal InSAR, which time series provide temporal and spatial information of the phenomena under discussion. Depending on the number of SAR images, the nature of the event under study, decorrelation problems and other factors that can affect the quality of results, an accuracy comparable to terrestrial methods (e.g., levelling, GPS) can be achieved.

Relative rapid assessment of civil infrastructure at risk of failure and valuable data for decision making is possible by the exploitation of this technique. Particularly, through the inspection of the anomalies observed in the history of displacement, complex processes acting can be identified and modelled. This way, forecasting and mapping of hazardous zones negatively influencing construction and upcoming small and large scale engineering projects can be performed.

Here, examples of radar-monitoring for important local structures in Mexico City and Duesseldorf are presented by means of InSAR, addressing as well constraints and imperative conditions of this satellite-based procedure to obtained high-quality displacement rates.

Keywords. Radar interferometry, geodetic monitoring, infrastructure, non-linear subsidence, Mexico-City, Duesseldorf.

1 Problems to be addressed

One of the main problems in our urbanised world is the stability / safety issue of existing infrastructure. Due to more and more extreme structures (bridges, sky-scrapers, towers, tunnels, etc.), a heavy increase of the traffic loads (individual weights and traffic frequency) and extreme environmental effects (heavy rainfall, flooding, storms, rapid changing weather conditions, etc.) we can no longer expect that all these influences are fully covered by the design parameters of the structures. Aside, several buildings are coming to age, the loading conditions since their construction have changed dramatically and the knowledge on safety of structures has increased (hopefully).

Therefore nowadays there exists a worldwide demand for adequate monitoring solutions. The development and proper application of monitoring systems for infrastructure is an interdisciplinary challenge, where experts from different engineering disciplines play the most prominent role, but legal-, economic-, environmental- and social aspects have to be included, too, to come up this an acceptable solution.

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2 Requirements for Infrastructure Monitoring

2.1 Types of monitoring

In principle two different types of monitoring for infrastructure are of interest, which can be differentiated by their time scale:

Long-term monitoring: Here the displacement / stability of the structure over years is of main interest, where effects of consolidation, changes in (traffic)-loads and of environmental parameters could be studied. This is an adequate objective for InSAR techniques, see section 3.

Aside, changes of modal parameters are hints for damages, too. This problem is under discussion using Ground Based SAR (GBSAR) (e.g. Neitzel et al., 2012), but is not the topic of this paper.

Monitoring during construction phase: Here the actual displacements during the construction process itself are of main interest. The challenge is to gain displacement information almost continuously and online, which can be used for guidance of construction machines. At present possible InSAR solutions with a repeat time of satellites of 11 days, or even more, do not serve this requirement.

But it is possible to get overall information on displacement rates, as shown in section 4, what might be of interest for an evaluation of the damages caused by the construction process.

2.2 Precision of displacements

One main advantage of radar-interferometry is its high spatial resolution of displacement rates in the range of mm to cm. This high resolution often is taken as precision or even uncertainty estimate, what disregards the disturbing effects of orbital parameters, atmospheric turbulence, limited knowledge of topography and with geo-referencing.

2.3 Point-related information

According to the different processing methodologies, see section 3, the assignment of the displacement information to a well-defined point or part of the structure is difficult. In differential InSAR just rough sections can be identified, which show some displacement pattern. Even with persistent scatterer interferometry (PSI, s. 3.2) the pointwise assignment is difficult, i.e. to identify that part of the structure, which serves as PS.

In Fig. 2 an ideal situation is depicted, where several PS are located at the façade and on the roof of a building; in general the exact position of a PS is hard to identify at the structure. In Fig. 2 the so-called radar shadow is given, too, i.e. those parts of a structure, where due to the direction of the line-of-sight (LOS) no information can be achieved.

3 Radar-Interferometry

3.1 Basic Principles

To derive ground surface displacements from Radar-satellites is a technique, which goes back more than 20 years (Ulaby et al., 1986). First applications were made to study large area subsidence rates using phase differences of ERS, JERS and Radarsat.

A differential radar interferogram (s. Fig. 1) is pronouncedly affected by displacements as well as topographic and atmospheric influences. Large alterations on the earth's surface, e.g. in vegetated areas, cause decorrelations in phase values making reliable calculations almost impossible.

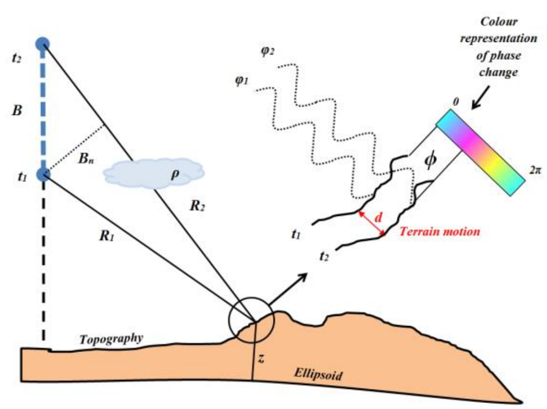

Fig 1 Basic principle of detection of ground displacements by radar-interferometry analysing phase differences (Mark et al., 2012).

The measured differential phase $\varphi_{D\text{-}InSAR}$ is composed of contributions from uncompensated topography φ_{top}, displacement φ_{displ}, atmosphere φ_{atmo}, orbit φ_{orbit} and in intended "noise" φ_{noise} (Adam et al., 2003).

$$\varphi_{D-InSAR} = \varphi_{top} + \varphi_{displ} + \varphi_{atmo} + \varphi_{orbit} + \varphi_{noise}$$

The focus is laid on pixels with a stable backscattering behavior over longer times.

3.2 PSI

In the late 1990s the *Persistent Scatterer Interferometry (PSI)* was developed (Ferretti et al., 2001) to provide a systematic processing strategy of these “stable pixels” by using a large stack of radar acquisitions. The PSI technique is especially useful to measure urban displacements, because many man-made objects have perpendicular edges with metallic patterns which are very well likely to act as stable point-scatterers and backscatter of the radar signal (Fig. 2).

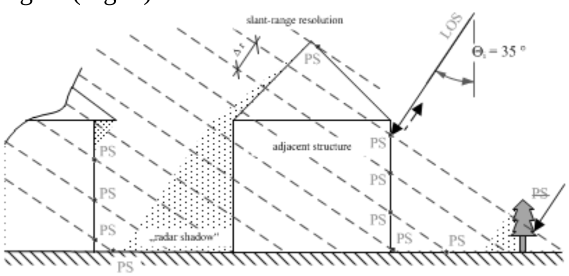

Fig 2 Distribution of Persistent Scatterer in intra-urban areas (simplified)(Krivenko et al., 2012).

Nowadays, PSI is performed with advanced software packages in a computer-aided process. “Pixel by pixel” displacements are derived from a time series of radar images. About 20 images or more are needed to adequately minimize effects of atmospheric delays φ_{atmo}, orbit errors φ_{orbit} and other “noises” φ_{noise}. Then, in ideal cases, the PSI method theoretically supplies sub-millimeter accuracy in the line of sight (LOS). However, in most practical cases a reduced accuracy in the range of millimeters is achieved.

Currently the high-resolution TerraSAR-X satellite is one of the most suitable Synthetic Aperture Radar systems to practice the PSI method for infrastruce surveillance.

3.3 SBAS

A further development is named *small baseline method (SBAS),* where for a series of images D-InSAR analyses are performed with small perpendicular and temporal baselines, this leads to a network of interferogramms (Berardino et al., 2003). Main advantage is a reduction of the effect of decorrelation and by this a more robust determination of the displacements. This approach improves

Finally many processing software for time series of radar images assume a linear, non-linear or arbitrary deformation behaviour for displacement model (Hooper et al., 2004, Wegmueller et al., 2010).

4 Long-term monitoring

In this section typical examples are presented to study slow-motion displacements within a long-term monitoring of structures.

4.1 Mexico-City

It is well-known that the stability of all infrastructure in Mexico-City is affected by an extreme withdrawal of groundwater, due to the dramatic increase of the population and their needs. Aside, the Valley of Mexico is a very active tectonic zone, where regularly heavy earthquakes occur. A general discussion of these problems and a detailed study on the application of radar-interferometry for this region is given in Siles (2015).

Here just one example is presented, the monitoring of the metro line A, which is one of the most important lines within this mega-city. It is parallel to the crowded General Calzada Zaragoza street which connects Mexico City and Puebla. Both infrastructures, very important for connection and transportation reasons, have been seriously affected by subsidence and associated fracturing.

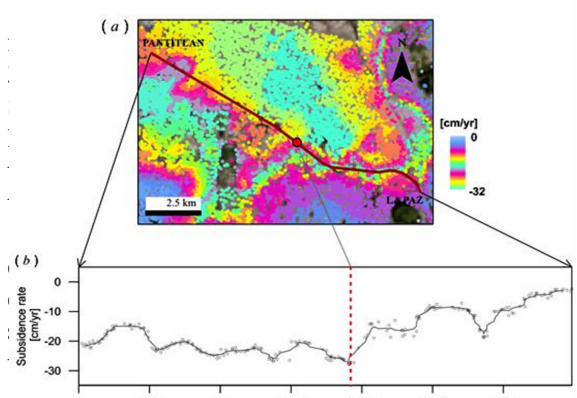

Fig 3 Profile along the metro line A from the Station Pantitlan to La Paz station (dark red line) and the displacement velocities. The dotted red line indicates the area severely affected after the earthquake of 2012 (Siles, 2015).

For this metro line, InSAR results are used to perform a deformation analysis for the period 2002-2010 using ENVISAT data, which are processed by

STaMPS method (Hooper et al., 2004). As given in Fig.3, strong and non-regular displacement velocities can be encountered, leading to serious destructions of this line.

Considering the high traffic on this metro-line, a continuous surveillance of this zone is required. A critical failure in the transportation system due to sudden subsidence or even cracking put into risk thousands of lives.

4.2 Duesseldorf

A data stack of 24 TerraSAR-X radar images from Jan. - Dec. 2011 (strip-map mode, resolution 3mx3m) were processed with PSI techniques and analyzed for different investigations related to surface movements over the city of Duesseldorf.

4.2.1 Singular building complexes

A subset of 8 kmx8 km from the raw data set was processed for getting an overview about surface changes in the city centre of Duesseldorf. Figure 4 shows the PSI results for that area of investigation. Only points with coherence values over 86%, as a parameter for the quality of the determined point velocities.

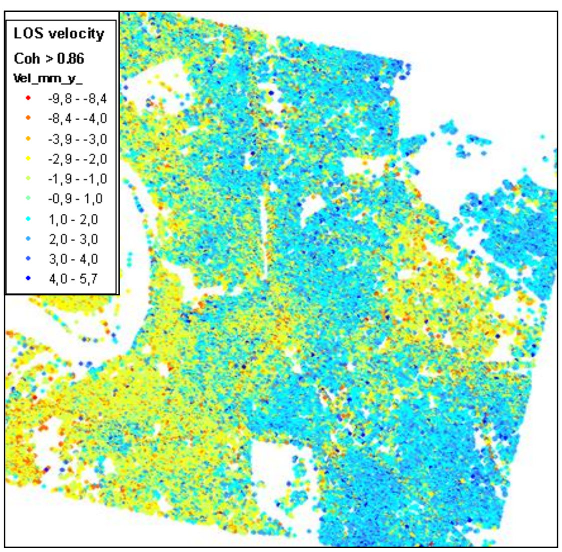

Fig 4 PSI-map for a large area of the city centre of Duesseldorf.

For further consideration we increased the coherence value to 95% to get a very stable solution and tested different spatial and temporal filter lengths.

This data set was reduced additionally by the assumption of a typical processing noise level of ±2 mm/a for PSI processing.

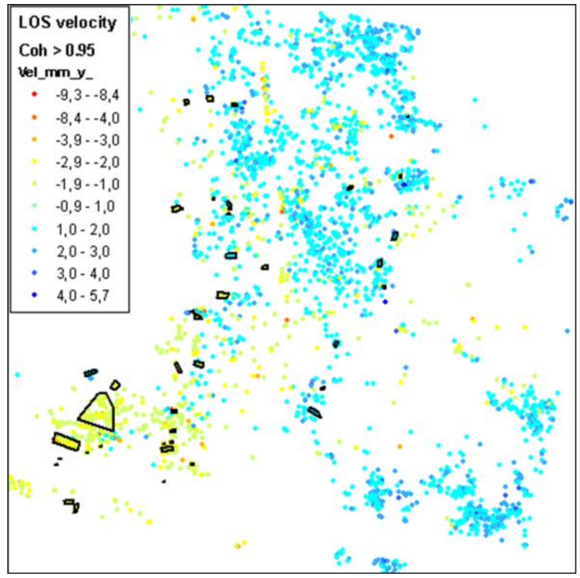

Fig 5 Improved subsidence map with marked polygons (black), that describe surface instabilities and possible subsidences of buildings.

After this data reduction point groups (clusters) were selected and further analyzed on their vertical movement. With this approach one is able to get a reasonable statement on the behaviour of a singular building or a whole complex. The result is mapped in figure 5. The black polygons describe the clusters and finally the building that have significant movement rates.

In this study with short time series of remote sensing data these movement or subsidence rates can give only a first hint on real subsidences and have to be validated by on site observations.

4.2.2 Stability of bridges

With our feasibility study on the stability of bridges we wanted to investigate the limitations in radar data processing related to linear structures in the environment of a big river. One of the observed bridges is in use for railways and the other one will be used by car traffic.

In figure 6 it is clear visible, that we get no stable backscattering signal for the main part of the bridges over the river Rhine. On the right side of the river bank the PSI points show a kind of uplifting signal (yellow) that comes from artifacts of the atmosphere, which were not fully eliminated.

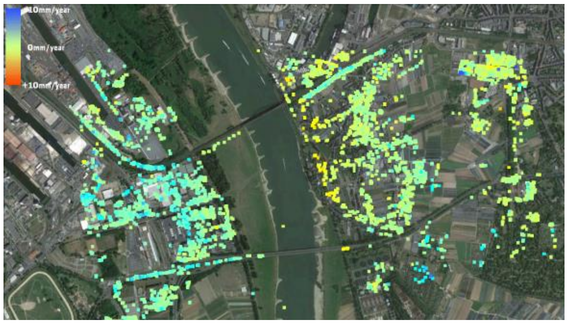

Fig 6 PSI-map for a test area with two bridges over the river Rhine.

Parts of the roads and ramps give us sufficient signal for further analyses, if the time series could be elongated. Finally, we have to state that the reduction of atmospheric influences by short time series and different filter approaches leads to no acceptable results for bridge monitoring purposes.

4.2.3 Monitoring of tunnel construction site Wehrhahn-Linie

It is widely known that tunnelling processes induce ground subsidence which can damage overlying structures, such as buildings. Therefore, it is essential to measure ground deformation for ensuring safety throughout the active phase of the tunnel construction and even after its completion.

In most cases, geodetic measurements (levelling, GPS observations) are carried out to monitor settlements and uplifts due to tunnelling. Providing only pointwise observations, these methods are not able to supply area-wide spatial information about interactions between tunnelling and surface deformation; moreover, terrestrial methods require enormous time and cost efforts.

Fig 7 Location of tunnel construction site “Wehrhahn-Linie” in Duesseldorf, Germany as seen by TerraSAR-X satellite (Krivenko et al., 2012).

In this study (see Krivenko et al, 2012, Mark et al., 2012), the PSI technique was chosen for monitoring the urban surrounding during the tunnel project "Wehrhahnlinie" in Duesseldorf (s. fig. 7).

The hydro-shield tunneling process started in April 2011 and ended at the final railway station about one kilometer ahead in December 2011. The 3 months of observation in advance allowed an estimation of atmospheric effects and adaptive filtering of raw data.

Based on a very precise 3D-city-model of the inner part of the City of Duesseldorf, it then was possible to monitor the effect of the tunneling construction work on the existing infrastructure with new results about every 22 days. This is not frequently enough to be used for steering of the tunneling process, but gave important hints on possible long-term effects.

A special item was the monitoring of one old and valuable building, where the specific technique of compensation grouting (Bolton et al., 1994) was applied to uplift the building before the TBM goes through. It is expected, that after passing the building the original heights are reached again. In Fig. 8 uplift and subsidence rates for this building are depicted, which demonstrate these effects.

Looking at the results of radar-interferometry, levelling and tube water levels (installed in the cellars), one can summarize that comparable results are derived by these completely independent techniques. This indicates that nowadays radar-interferometry is able to monitor infrastructure objects with mm accuracy!

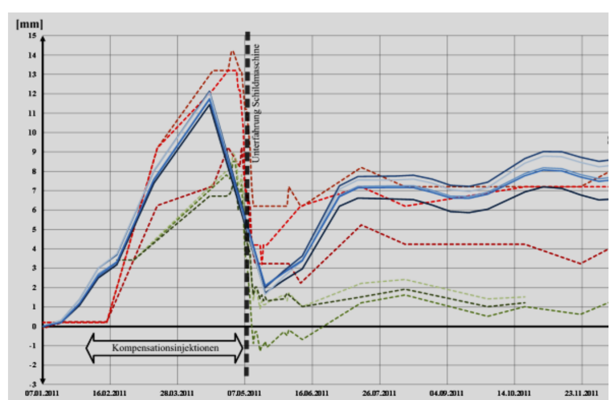

Fig. 8: Comparison of subsidence rates out of 3 different monitoring techniques: **blue** = PSI, **red** = levelling, **green** = tube water levels (Mark et al., 2012)

5 Conclusion

In this paper the potential of the nowadays available radar-interferometry is demonstrated for monitoring of infrastructure objects and by this for urban areas. Due to actual radar sensors and advanced processing techniques detailed information on vertical displacements can be derived with an accuracy of a few mm.

Limitations are low resolution in time, which is given by the repeat rate of the satellites. Further open problem is the reduction of environmental disturbancies, where a restriction to relative information, i.e. spatially limited processing, is a good solution.

Anyway, it can be expected, that radar-interferometry from space will play an important role for monitoring of infrastructure in the future.

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