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URBAN LAND SUBSIDENCE STUDIES IN FINLAND USING SYNTHETIC APERTURE RADAR IMAGES AND COHERENT TARGETS

Kirsi Karila[1,2], Mika Karjalainen[1], Juha Hyyppä[1]
[1]Finnish Geodetic Institute, Department of Remote Sensing and Photogrammetry
P.O. Box 15, FI-02431 Masala, Finland
Kirsi.Karila@fgi.fi, Mika.Karjalainen@fgi.fi, Juha.Hyyppa@fgi.fi
[2]Helsinki University of Technology, Institute of Photogrammetry and Remote Sensing

ABSTRACT

Ground subsidence is a known problem in several cities in the Europe causing difficulties for urban planning, and occasionally, severe damages for existing buildings. In Finland, even though subsidence problems have been detected in the city of Turku and Helsinki, however, extensive information about phenomena does not exist. Synthetic aperture radar (SAR) interferometry enables the observation of large areas and it has been successfully applied to measure ground deformations in various parts of the world. Heavy vegetation in Finland complicates the use of the INSAR technique. This study, however, showed that advanced interferometric techniques could also be applied in northern vegetated city areas. The subsidence areas were clearly visible in the deformation map, which was formed using a long time series of SAR data and an advanced INSAR algorithm. The INSAR deformation rates agreed well with the levelling measurements that have been carried out in the area and as well as with the soil data.

1. INTRODUCTION

A SAR image contains information on both the amplitude and phase of the backscattered signal received by the radar. The pixel intensity is related to the backscattering properties of the target, including surface and volume scattering, and the signal phase is related to the satellite to ground path length of the signal. In SAR interferometry (INSAR), two SAR images are combined to form an interferogram. In the interferogram calculation, the amplitudes of the two images are multiplied and phases differenced for every resolution element. The phase of a SAR interferogram includes contributions from the elevation differences, deformation, atmosphere, and noise. Furthermore, differential SAR interferometry (DINSAR) is an extension to the INSAR, where the topographic part of the interferogram is eliminated by using another interferogram. Therefore, in DINSAR the remaining fringes present the movement of the target area. Principles of INSAR have been described, for example, by Massonnet and Feigl (1998).

Originally, DINSAR was applied to study ground deformations caused by irrigation (Gabriel et al., 1989). The technique is typically applied to study natural phenomena such as earthquakes (e.g. Zebker et al., 1994; Massonnet et al., 1993), volcanoes (e.g. Briole et al., 1997), and also glacier and ice sheet movement (e.g. Goldstein et al., 1993), where deformations can be very rapid and large. The deformations that are related to human activities, such as construction, are usually smaller than deformations caused by natural phenomena. These kinds of phenomena studied by DINSAR are, for example, urban subsidence, mining, soil, and tunnel construction.

The traditional DINSAR exploits only 2-4 SAR images, therefore, it is a fast and simple method to measure deformation. However, it can only be applied to a limited number of deformation cases. For example, atmospheric disturbances may be interpreted as deformation, but also temporal correlation due to vegetation and other changes in the target complicate deformation detection from a single interferogram, and in some cases interferogram generation does not produce any fringes. Techniques based on the phase information of the time series of interferograms and stable targets have been developed to overcome these problems. The original idea of so-called permanent scatterer (PS) technique was presented by Ferretti et al. (2000). Basic assumption in PS technique is that temporal decorrelation does not affect stable targets, which are called persistent scatterers, permanent scatterers, or coherent targets depending on the algorithm. PSs are usually buildings, structures or rocks that dominate the scattering of a single pixel.

In city areas the ground subsidence is often a severe problem. The subsidence might cause damages to buildings and, thus, expensive renovations are needed. For instance, in Turku the estimated cost of the pilework renewal was 90 million euros (Helsingin sanomat, 2004). Figure 1 shows the reparation work at Turku main library. At the moment, selected known urban subsiding areas are monitored by levelling, which on the one hand provides detailed information about the phenomena, but on the other hand is time-consuming and requires a great deal of labour. The major advantage of the INSAR techniques over the levelling measurements would be the more extensive and frequent monitoring of the subsiding areas.

The purpose of this research is to study possibilities to use advanced DINSAR techniques in Finland, which is heavily vegetated and sparsely inhabited and urban areas are small. Goal is to assess how the information about the spatial extent of the subsidence could be provided to the cities of Turku and Helsinki.

Figure 1 The pilework reparation work of Turku main library

2. DATASETS AND STUDY AREAS

2.1 Study areas

Ground deformation has been studied using DINSAR in two Finnish cities where subsidence has been reported: (1) Turku, which is located on southwest coast of Finland, and (2) in the Helsinki metropolitan area. Typically, the densely built urban areas in Finland are rather small and have a great deal of vegetation. The study areas can be seen in Figure 2, where two SAR mean amplitude images are represented.

Turku has partly been built on tens of metres thick layer of clay. Subsidence is known to take place in the city centre of Turku. The city centre is situated by the River Aurajoki. Clay and bedrock areas occur alternately in the area. As the ground water level lowers in the clay areas, the old wooden pile work decomposes, and the buildings subside and suffer damages. The Real Estate Department of Turku has been observing single damaged buildings by levelling measurements, but spatially extensive data about the subsidence is not available. There are many historically valuable buildings in the city, and subsidence of many of these buildings has been reported. The renovation of the pile work is expensive. However, spatially extensive measurements have not been carried out.

Some local subsidence areas have been detected in Helsinki, but the problems are not as comprehensive as in Turku. The subsidence is usually due to inferior soil. For example the Helsinki main railway station has been built on former seabed and the Malmi airport has been built on top of a swamp and a new residential area has been planned for this area. New residential areas such as Arabianranta and Pikku-Huopalahti have been built using expensive modern techniques, since the soil quality for construction work is bad due to soft clay and mire layers. Still some subsidence occurs in these areas.

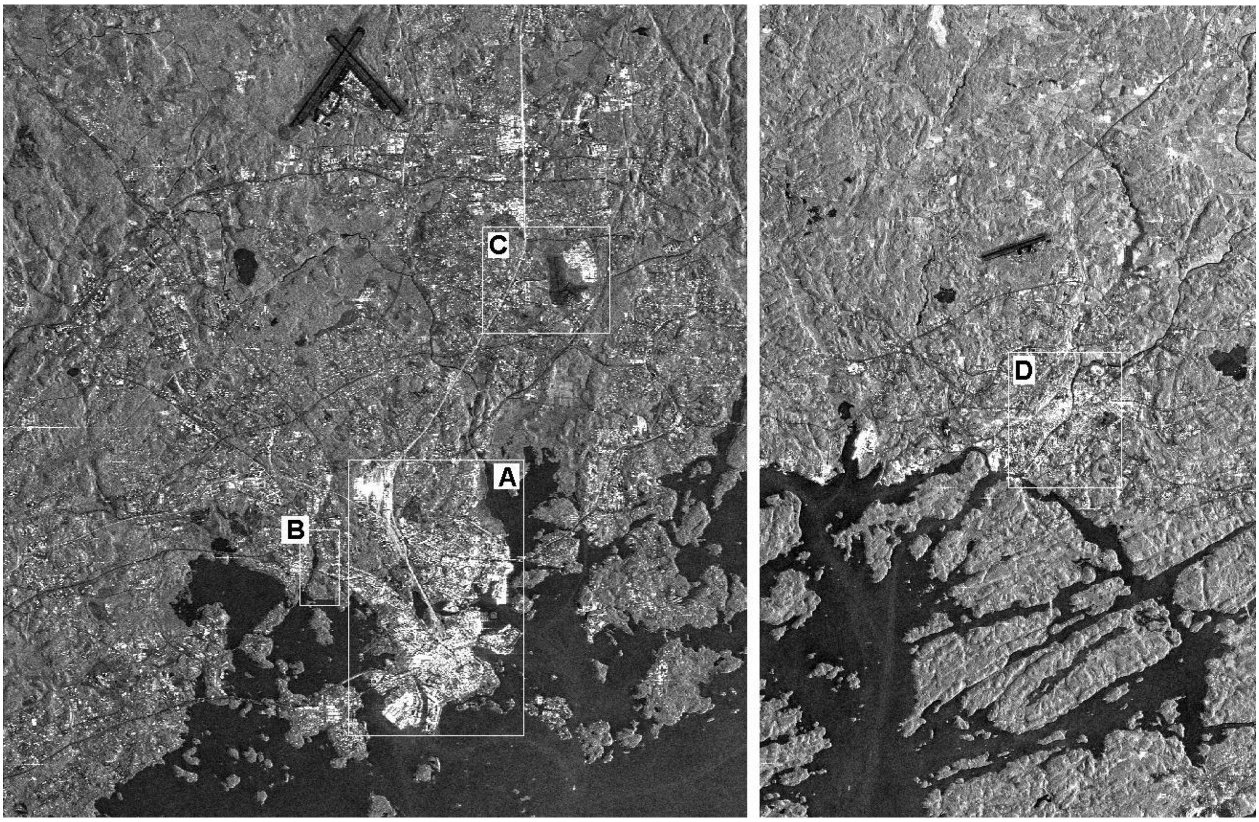

Figure 2 Helsinki (left) and Turku (right) study areas as SAR mean amplitude images and some areas of interest: Helsinki city centre and Pasila (A), Pikku-Huopalahti (B), Malmi (C) and Turku city centre (D). (Original data (c) ESA, processed by FGI)

2.2 Satellite data

A total of 40 ERS-1/2 SAR images from 1992-2002 were acquired from both study areas. Weather data, including information on temperature, precipitation, snow depth etc., was used to assist the selection. In winter time the coherent targets may be covered with snow and are unusable in the time series analysis. Melting snow causes severe loss of coherence and heavy rain may also change the signals path and cause measurement errors (Ge et al., 2002). Therefore snowy and rainy images were avoided.

2.3 Reference and other data

Building data was extracted from the base map of city of Turku. The building data was used to study spatial distribution of the permanent scatterers. By using this data it was possible to determine which coherent targets correspond to which building. A set of aerial images from the city area was used for visual inspection.

Soil data for Turku was available from Geological Survey of Finland. Unfortunately, the very centre areas had not been mapped, but the Turku base map contained some information about bare cliffs. For Helsinki area the soil map of the Geotechnical division of Helsinki was available. Soil map included e.g. classes for clay and bare cliff areas and also information about the thickness of clay layers.

Levelling measurements have been carried out in the area by The Real Estate Department of Turku. The levelling measurements have been carried out for single buildings where damages have been observed. The data set comprises levelling data for 10 different buildings that are located in the city centre area including, for example, the Main library, the Brewery restaurant Koulu, and City Hall. Time span of levelling measurements for different buildings varies. The accuracy of the measurements is not known.

3. METHODS

The satellite data was processed using the Coherent Target Monitoring (CTM) module of the EV-InSAR software published by Vexcel Canada (formerly Atlantis Scientific). The automatic coregistration of several SAR scenes using a single master image, formation of interferograms and analysis of the interferogram time series of 33 interferograms were performed. An image acquired on August 27th 1995 was selected as the master image. The full resolution of ERS SLC images, 4 m in azimuth and 20 m in range direction, was used in the analysis.

The CTM module allows processing of the data with different parameters for the deformation model and with different iteration schemes. A stable area close to the deformation area is needed for the initial atmospheric estimation. The selection of the atmospheric correction area is essential for a successful completion. Linear deformation model was used in calculations. During deformation modelling estimate for DEM error was also obtained. The objective was to maximize temporal coherence, which is a measure of phase stability. The coherent targets were chosen based on their temporal coherence value. Temporal coherence threshold of 0.7 was used in the processing. Two iteration rounds were performed. For the first iteration round a constant atmospheric phase model was used. For the second iteration round the atmospheric phase was estimated as phase average.

To analyse their characteristics the coherent targets were overlaid on the base map of Turku. In that way the INSAR measurements for individual buildings could be compared with the levelling data. The points in slant range coordinates were first transformed to the WGS84-coordinate system and then projected to the Finnish national grid coordinate system. The estimated DEM error of the scatterer was used in the geocoding process.

4. RESULTS

First, some coherence maps and differential interferograms from study areas were formed and studied. Temporal decorrelation was very strong in both study areas and interferograms with long temporal baselines did not have any clear fringes. The areas where coherence was maintained were very small. Differential tandem interferograms also showed atmospheric effects in the study area. Therefore, traditional DINSAR was not feasible and advanced DINSAR algorithm was needed to get information about the subsidence.

Output product of the CTM software was a subsidence map with the subsidence rates of the coherent targets and displacement time series for each coherent target. In Figure 3 shows coherent targets in Turku. The points were imported to GIS software for more detailed analysis.

Figure 3 Coherent targets in Turku with some base map data. The vertical motion rates are in millimetres per year.

For coherent targets in Turku overlay analysis with building data showed that coherent targets were mainly located in buildings. Direction, shape, height and material of the roof or building were the main parameters to affect the backscattering. Chimney-stacks and other structures on roofs were often the coherent targets since they dominate the scattering. The effect of the side looking radar configuration was noticeable. Some of these effects can be seen in figure 4.

Figure 4 The coherent targets and their vertical motion rates (mm/year) on an aerial image (©Turku City). Turku main library and other buildings.

For Turku study area the levelling measurements for single buildings were compared with the INSAR results. Levelling data was available for 10 buildings or parts of larger building. Coherent targets in these buildings or in corresponding building parts were identified. The subsidence rate of the building was calculated from both observations and the results were compared. Subsidence rates for buildings are presented in Table 1. R-squared value for the average subsidence rate of building was 0.89. On the average INSAR measurements resulted in 0.6 mm/year lower subsidence rates than the levelling measurements. The RMSE of the INSAR measurements was 0.75 mm/year.

Table 1 Vertical motion rates per year for 10 different buildings from INSAR and levelling measurements.

Building	**INSAR mean deformation**	INSAR maximum deform. Rate	INSAR minimum deform. rate	Number of INSAR targets	**Mean deformation rate from levelling**	Maximum deform. rate from levelling	Minimum deform. rate from levelling	Levelling bench-marks
Linnakatu 39	**-5.2**	-6.1	-4.5	11	**-5.8**	-6.6	-5.1	8
Koulu Brewery	**-5.3**	-6	-4.5	4	**-6.6**	-8.1	-5.2	6
City Hall	**-3.6**	-3.8	-3	8	**-4.4**	-4.8	-4	8
Orth. church	**0**	0	0	3	**-1**	-1.5	-0.3	4
Art hall	**-3.8**	-3.8	-3.8	5	**-4**	-4	-4	4
Music library	**-2.9**	-3.8	-2.3	7	**-2.8**	-3.7	-1.8	8
Library	**-1.7**	-2.3	-0.8	19	**-2.2**	-2.6	-1.4	9
Katedralskolan	**-3.6**	-3.8	-3	8	**-3.3**	-4	-2.2	3
Hjelt	**-2.5**	-3	-2.3	3	**-3.5**	-5	-3	8
Brinkkala	**-1.7**	-6	1.5	17	**-3**	-6	-1	23

The time series from the levelling measurements and the subsidence time series from INSAR measurement were compared. Time series for two points in two different buildings are shown in Figure 5. No deformation was expected to take place between master image and the image from August 28th 1995. As it can be seen, the time scale for measurements varies and the observations are not evenly distributed temporally. The overall deformation rates were almost the same for the INSAR and the levelling measurements, but single observations may vary several millimetres. It can also be stated that there were some divergent observations in the INSAR data.

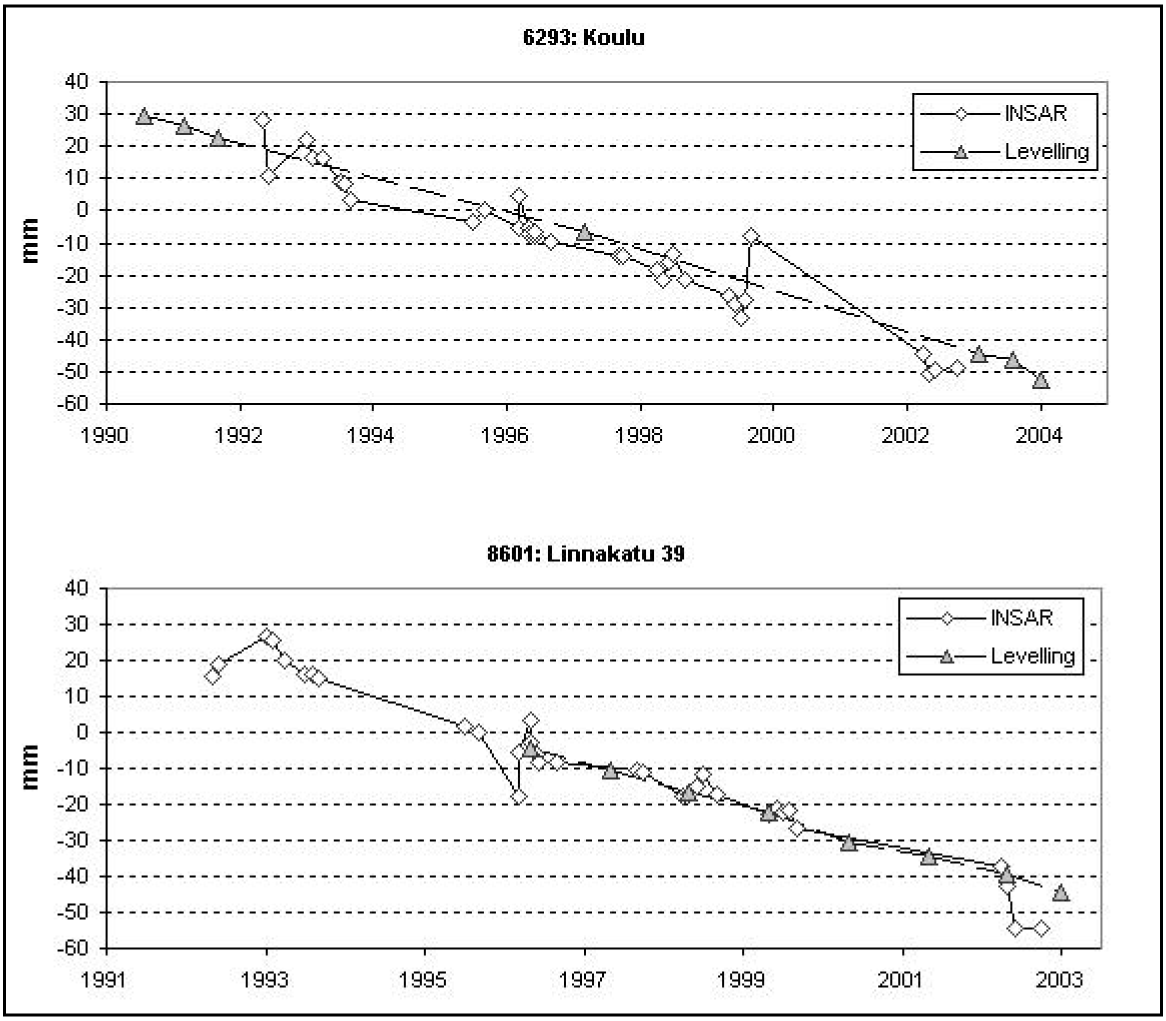

Figure 5 The subsidence rates of two buildings in Turku from INSAR measurements. Levelling time series and INSAR coherent target velocities. Deformation is in millimetres.

The interpolated subsidence map for Turku study area is presented in Figure 6. The faster the subsidence rate the bluer the colour. Yellow areas are stable. The two main subsidence areas, one around River Aurajoki and the other by the main railway station, were clearly distinguishable.

Examination of the subsidence areas with soil data showed that bedrock areas are very stable and no subsidence is expected to take place in these areas. Of course, some deformations of the buildings smaller structures are possible. The buildings on clay area have been subject to subsidence and the subsidence can be seen in INSAR results. The clay and bedrock areas were clearly distinguishable in the INSAR deformation map.

Figure 6 An interpolated subsidence map of Turku. The blue areas subside.

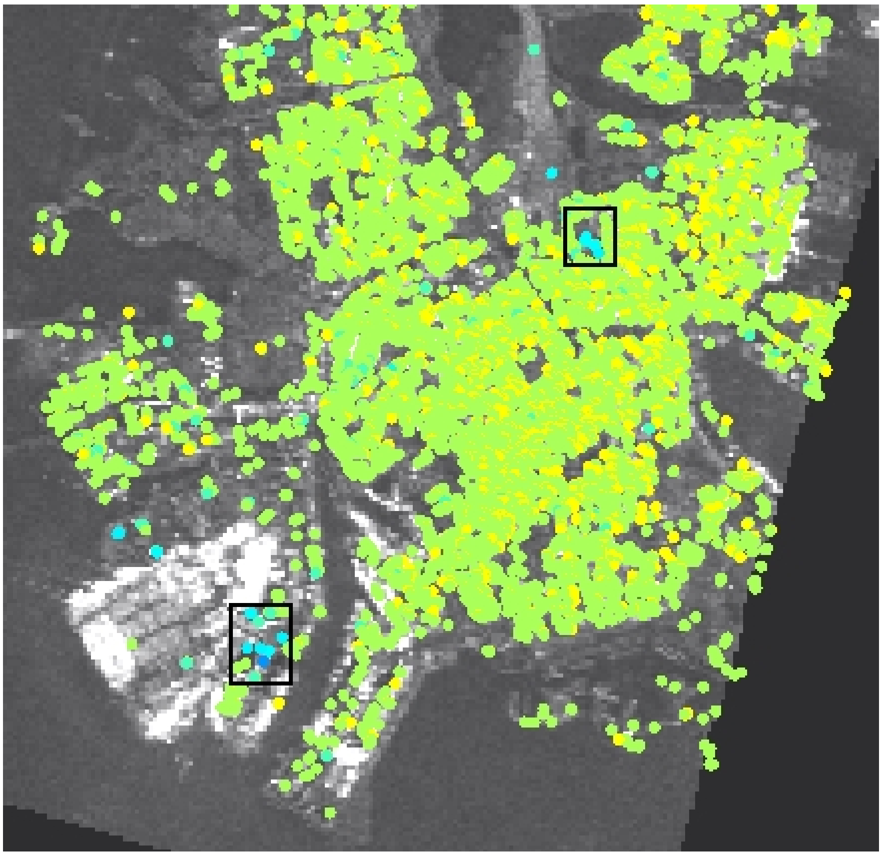

Figure 7 An INSAR deformation map of Helsinki, in which two subsidence areas are highlighted: Rautatientori and Jätkäsaari.

The INSAR subsidence map of Helsinki (Figure 7) showed small local subsidence areas in different parts of the city at the rate of a few millimetres per year. For example Rautatientori square by the railway station (3 mm/yr), Jätkäsaari harbour area (4-7 mm/yr), new residential area in Pikku-Huopalahti (2-5 mm/yr), and Malmi airport area (2-5 mm/yr) were subsiding according to the INSAR measurements. For INSAR results no usable reference measurements were available. However, by analysing the soil map and by examining newspaper articles it is clear that subsidence is likely to occur in these areas. Both the subsidence area in Jätkäsaari and at Rautatientori have been build on artificial fill area overlying clay more than 3 m. Malmi airport has been build on thick clay area. The residential area in Pikku-Huopalahti has been built on clay and some artificial fill areas.

5. DISCUSSION AND CONCLUSIONS

The techniques based on stable targets are needed to measure deformation in areas where traditional DINSAR measurements are not feasible. The plentiful vegetation in southern Finland decreases coherence and makes interferograms very noisy. According to our studies, however, using long time series of data and advanced processing algorithms, deformation can be extracted.

Spatially extensive data about subsidence of buildings in city areas was obtained and even millimetre scale movement can be detected. The rates of subsidence agreed well with the reference data, but since the accuracy of reference measurements was unknown, but believed to be roughly one millimetre, this can be considered as a very good result.

However, there are some limitations to the application of the advanced DINSAR techniques. The size of the area of interest must be small enough. The density of stable targets is also an important parameter. The coherent target approach does not work for sparse network of persistent scatterers. Another algorithm, for example the permanent scatterers algorithm, exploiting different criteria for persistent scatterer selection might be more appropriate for areas having a sparse network of PSs. A high coherence non-subsiding area is needed for the atmospheric phase determination. The selection of atmospheric correction reference area is of high importance and affects the results dramatically.

The comparison of the deformation rates from the two data sources is not straightforward. In our case the levelling points and the INSAR coherent targets were situated in different parts of the building. The levelling benchmarks were in the stone foundations of the buildings. On the other hand, the INSAR coherent targets were more likely in the roof structures and often only on one side of the building. Determining the corresponding measurement points had to be done manually. In addition, the different coordinate systems of the data sets made the overlay process difficult and prone to errors. However, the subsidence rates from the two different sources were consistent.

With advanced INSAR technique first spatially extensive measurements from Turku and Helsinki were obtained. Our results demonstrated that the INSAR measurements can provide a good overall picture of the subsidence in these cities. Anyhow, to obtain more detailed deformation about the building subsidence levelling measurements are still needed, since the coherent targets are not usually evenly distributed in the buildings.

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REFERENCES

Atlantis Scientific Inc, 2004. EV-InSAR User’s Guide, Version 3.1.

Briole, P., Massonnet, D., Delacourt, C., 1997. Post-eruptive deformation associated with the 1986.87 and 1989 lava flows of Etna detected by radar interferometry. Geophysical resesrch letters, vol. 24, no. 1, pp. 37-40..

Ferretti, A., Prati, C., Rocca, F., 2000. Nonlinear subsidence rate estimation using permanent scatterers in differential SAR interferometry. IEEE Transactions on Geoscience and Remote Sensing, Vol. 40, pp. 2202-2212.

Gabriel, A., Goldstein, R., Zebker, H., 1989. Mapping small elevation changes over large areas: differential radar interferometry. Journal of Geophysical Research 94, B7, 9183-9191.

Ge, L., Tsujii, T., Rizos, C., 2002. Tropospheric Heterogeneities Corrections in Differential Radar Interferometry. IGARSS’02, Vol. 3, pp. 1747-1749.

Goldstein, R.M., Engelhardt, H., Kamb, B., Frolich, 1993. Satellite radar interferometry for monitoring ice sheet motion: Application to an Antarctic stream. Science, 262:1525-1350.

Helsingin sanomat, 17.5.2004. Teatteri saa uuden perustuksen Turussa / Turku on savelle rakennettu.

Massonnet, D, & Feigl, K.L, 1998. Radar interferometry and its application to changes in the Earth’s surface. Reviews of Geophysics, 36.

Massonnet, D., Rossi, M., Carmona, C., Adragna, F., Peltzer, G., Feigl, K., Rabaute, T., 1993. The displacement field of the Landers earthquake mapped by radar interferometry. Nature, Vol. 364.

Zebker, H., Rosen, P., Goldstein, R., Gabriel, A., Werner, C., 1994. On the derivation of coseismic displacement fields using differential radar interferometry: The Landers earthquake. Journal of geophysical research 99, B10, 19617-19634.