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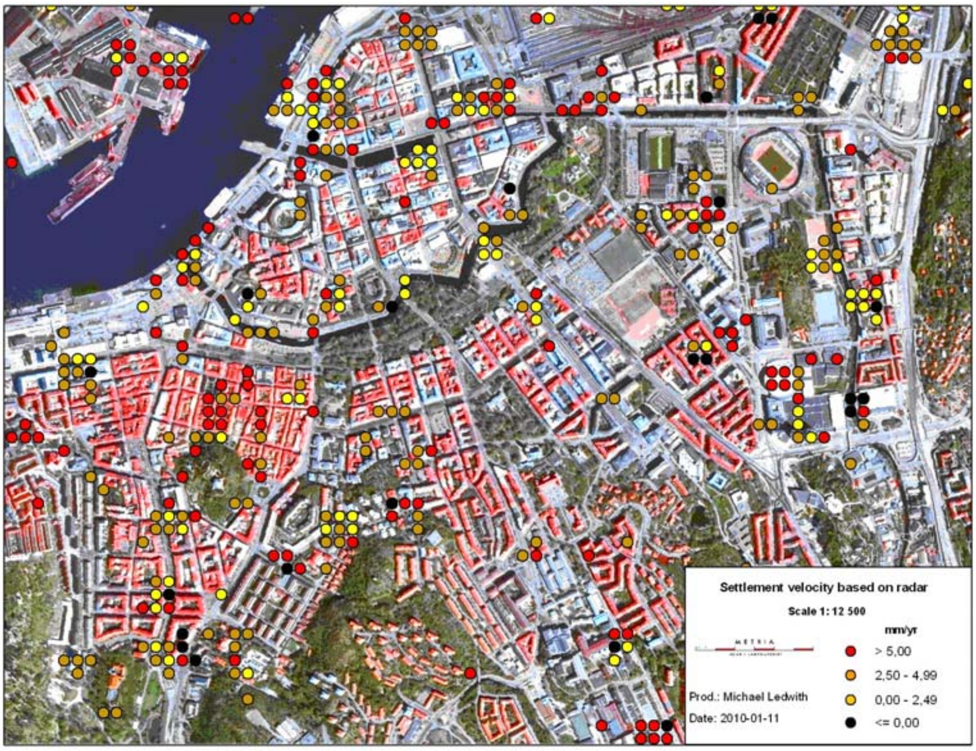

Mapping subsidence in an urban area with Differential InSAR and comparing with traditional methods – test area Gothenburg

Hjördis Löfroth
Michael Ledwith

Varia 610

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PREFACE

In this project, interferometry techniques were tested to see if they can be applied to urban settings with ongoing land subsidence, for geotechnical conditions as those in Sweden. This report describes the results of a comparison between settlements measured with traditional precision leveling in the central parts of Gothenburg and settlements registered with DInSAR and PSInSAR from ERS satellites. The project has been funded by the Swedish National Space Board and the Swedish Geotechnical Institute (SGI) and the City of Gothenburg, Office of City Planning, has provided data from the precision leveling within Gothenburg.

The interferometric analyses have been performed by Metria and the analysis of the precision leveling data by the SGI. The authors would like to express their gratitude to those who have provided data to the project, those who have worked on the project and those who have given their views on the report.

Linköping and Stockholm, March 2010

The authors

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1 SUMMARY

The main idea of this project is to investigate whether interferometry technique – more specifically Differential SAR Interferometry (DInSAR) - can be applied to urban settings where human activities such as deep excavations due to building works or mining causes land subsidence, for geotechnical conditions as those in Sweden, and to compare the result with results from traditional methods for settlement measurement.

Gothenburg was chosen as the testing ground as measurements of ongoing settlements in the central parts of Gothenburg has been carried out for a long time and vertical as well as horizontal movements has been measured at the start (before, during and after) construction of the Göta Tunnel. Metal pegs are installed in several places around buildings and precision leveling of the pegs are today carried out every fifth to seventh year by the City of Gothenburg using precision leveling instrument. The results of the measurements are noted in Excel sheets, one for each quarter. In this project, diagrams of the measured settlements have been drawn for chosen quarters, and the results have been visualized on an areal photography of the central parts of Gothenburg.

Initially, only the DInSAR technique would be tested and used for comparison. However, early on it became evident that due to the overwhelming presence of forests and urban green areas, simple DInSAR would not be able to provide adequate results for ground movement in the vicinity of Gothenburg. Therefore, the focus of the analysis was switched from DInSAR to PSInSAR. Initially, very conservative parameters were chosen with respect to minimum coherence between image pairs and the threshold for matching pixels in the image stack. Further refinement and an expansion to less restrictive input parameters increased the amount of measured points and in the central portion of the city the number of measurements increased from 36 to 774. In addition, the time span of images was reduced from 16 years to eight years. The natural land rise in Scandinavia was taken into account during the intermediate stages of the analysis – after the points with high coherence values were identified.

Comparisons between the precision leveling and the PSInSAR analysis from the ERS satellites were carried out in two steps. First a comparison was carried out for the PSInSAR analysis with coherence threshold of 0.75. It was clear that with this high threshold, and with no correction for land rise not all the ongoing settlements were registered. It was also noted that several points from the PSInSAR analysis registered heave. Thus, the threshold was lowered to 0.5 and a correction for land rise was carried out. Also the time span was reduced from 16 years (1992 – 2008) to eight years (1992 – 2000) as mentioned above.

The result from this PSInSAR analysis shows that the number of measuring points within the area of interest is more than the double and the points are mainly located in areas where ongoing settlements have been measured by the traditional leveling. But still, many of the quarters with ongoing settlements were not registered by the satellite analyses. In addition, the size of the ongoing subsidence registered by the PSInSAR analysis is now generally larger than the ongoing settlements measured by leveling. The results from the comparison can be summarized as follows:

- with PSInSAR analysis from ERS satellites it is not possible detect all quarters with ongoing subsidence.

- PSInSAR analysis from ERS satellites does not give the right picture in which quarters the largest settlements are occurring.
- in some quarters with no clear trend of ongoing settlements during the measurement period of the leveling, the PSInSAR analyses have actually registered subsidence.
- the size of the measured settlements from the nPSInSAR analysis are not in agreement with the size of the settlements measured with leveling.

Currently, satellite analyses as DInSAR and PSInSAR from ERS satellites are not accurate and reliable enough for use as follow-up on settlements of buildings. However, a new class of radar satellites as the TerraSAR-X, along with its sister satellite TanDEM-X, will provide high quality radar images for DInSAR and PSInSAR analyses, which will enhance the possibilities for use of this technique as follow up of settlements.

2 INTRODUCTION

Interferometry has successfully been utilized internationally for a wide variety of satellite-based analyses such as: detecting slow landslides, change detection and land subsidence due to groundwater extraction. Innumerable methods and algorithms have been developed in the field of interferometry (e.g. Permanent Scatters (Colesanti, 2002), DEMs (Sowter, 2003) (Kim, 2005). Established techniques generally follow a pattern that includes the import of the radar data utilizing a DEM, to help eliminate elevation effects, resulting in a radar interferogram – additional processing results in differential interferograms and eventually land movement maps. The cutting-edge approach will include an analysis that attempts to determine and remove any effect of clouds on the interferograms (Yonezawa and Takeuchi 2003).

However, the technique has so far been used in countries outside Sweden, where the geotechnical/geological conditions are different. In the PREVIEW project the use of DInSAR to monitor Swedish (quick) landslides in soft clay revealed difficulties to register the small movements that may indicate a coming landslide and such quick movements as during the slide (e.g. Löfroth et. al 2009).

The main idea of this project is to investigate whether interferometry technique – more specifically Differential SAR Interferometry (DInSAR) - can be applied to urban settings where human activities such as deep excavations due to building works or mining causes land subsidence, for geotechnical conditions as those in Sweden, and to compare the result with results from traditional methods for settlement measurement.

3 BACKGROUND AND PURPOSE

The movement of ground can be attributed to natural processes or to human activity – and such movements can often be sufficient to cause damage to buildings and infrastructure. Therefore, deep excavations for construction or underground work require vertical and horizontal monitoring of the ground both on the surface and at depth. These ground movements are traditionally monitored on-site with measuring instruments.

The use of DInSAR to detect vertical movements due to excavations or underground work covers a wider area than the traditional methods and would provide additional information of the magnitude and distribution of the movements at the time of construction. It will also be possible to ascertain eventual ongoing settlements before an excavation, so as to determine the actual cause of damage on surrounding buildings.

Historically, the use of satellite radar data has been limited for many reasons, among them the prevalence of very high resolution optical imagery, unfamiliarity with radar analysis techniques and the significant pre-processing of the radar images required prior to use.

The purpose of the project is

- To test the feasibility of measuring small-scale – i.e. centimeters - vertical land movements within an urban environment using interferometric techniques,
- Provide SGI and the end-users with products that identify the sections of urban areas that have experienced (and are experiencing) vertical land movement (in the form of A0-sized maps, image files, GIS vector files and/or script files),
- Provide SGI and the end-users with products that give information of the size of the measured movements (e.g. mm/month) and the trend of the movements (increasing/decreasing),
- To compare the result with measurements of settlements with traditional methods, and to restrain the need for traditional measurements for monitoring purposes in urban areas in connection with building works, mining or other human activities.

4 ACCOMPLISHMENT OF THE PROJECT

4.1 Choice of test area

Initially, two potential testing grounds were identified where traditional measurements of settlements (subsidence) had been carried out. One of them was Gothenburg, where measurements of ongoing settlements in the central parts of Gothenburg has been carried out for a long time and where vertical (and horizontal) movements has been measured at the start (before, during and after) construction of the Göta Tunnel. Another possible testing ground was Kiruna, where mining is ongoing near the surface and relatively large movements have been recorded. Measurement of both vertical and horizontal movements have been carried out with traditional methods for a long time. The intention was to compare the measured subsidence with DInSAR over a certain period with the corresponding measured subsidence using traditional methods.

Contacts were taken with representatives for both Kiruna municipality and LKAB on one hand and the municipality of Gothenburg on the other. The Office for City Planning of Gothenburg were interested in the project and could present results from, in several cases, measurements every seventh year since the 1970^{th}, in addition to more frequent measurements along the stretch of the Göta Tunnel during its building phase. LKAB were interested in the subject, but had already started some research in the area themselves and preferred to continue this work. Therefore, Gothenburg was chosen as a testing ground in this project.

4.2 Description of Gothenburg testing ground

Gothenburg is located on the west coast, in south-western Sweden, at the mouth of the river Göta älv, which feeds into Kattegatt, an arm of the North Sea. The archipelago of

Gothenburg consists of rough, barren rocks and cliffs, which also is typical for the coast of Bohuslän. The Geography of the whole area around Gothenburg is dominated by high mountain ridges with clay plains in the valleys, a so-called rift-valley landscape. The mountains are bare or with only a thin layer of soil. In the valleys, rivers from the inland are flowing. Skansberget and Ramberget are two central hills/mountains in the city. The highest point in Gothenburg, 161.2 m above sea level, lies about 20 km from Gothenburg city center. The surrounding terrain is dominated by the seven valleys that come together in Gothenburg: Säveåns and Göta älv valleys, Gothenburg-Kungsbacka valley, the valley east of Mölndal, Lärjeån valley, Slottsskogen-Askim valley and Kvillebäcken valley.

These, in western Sweden very characteristic rift-valleys are filled with very thick fine-grained sediments. Glacial clay deposited in a marine environment, superposed by post glacial sediments, clay, silt and sand.

The clay in the Gothenburg area is soft and compressible. In areas where no erosion has taken place the clay is so called normally consolidated or only slightly overconsolidated. This imply that every additional load placed on the soil, e.g. fill or buildings, causes the clay to compress and, consequently, settlements occur. To prevent settlements, the foundation of the buildings is normally done so that no additional load is applied on the soil. This can be done in several ways e.g. the buildings may be founded on piles, either floating piles or piles to solid rock, or compensation founding may be used, which means that the weight of a building is equal or less than the weight of removed soil (e.g. for basement plans).

During the last ice age, most of Scandinavia was covered with a thick ice cap – up to three kilometers thick in some areas, which pushed the land mass underneath farther down towards the asthenosphere. As the ice melted, the land mass started to rebound in a process called isostasy. An analogy can be made with an ice cube in a glass of water. If one pushes the top of the ice cube, it moves downward into the water. When the pressure is removed, the ice moves back up towards the surface where it will return to an equilibrium state. In Sweden, the isostacy is still ongoing at a different rate in different parts of the country. In the Gothenburg area the land lift is between one and two millimeter per year (se further Section 5.2.2.2).

4.3 Traditional measurement of settlements

Measurements of settlements (subsidence) of buildings in the central part of Gothenburg have been carried out for a long time, in some cases since the 1940th, under the responsibility of the City of Gothenburg, Office of City Planning. Metal pegs are installed in several places around the building at the base of each building and their location are shown on a map of the actual quarter (see Figure 1). Precision leveling of the pegs are today carried out every fifth to seventh year by the City of Gothenburg using precision leveling instrument. The accuracy of the measurements are one tenth of a millimeter. The results of the measurements are noted in Excel sheets, one for each quarter. In this project, diagrams of the measured settlements have been drawn for chosen quarters.

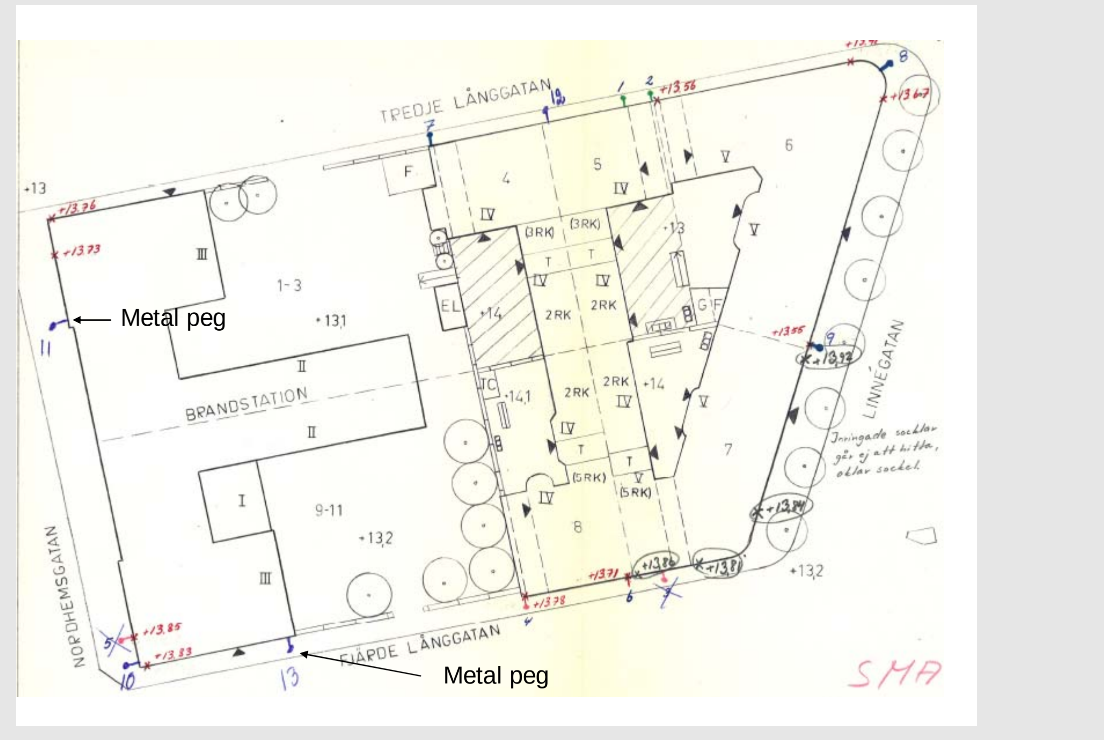

Figure 1: Map of a quarter with location of metal pegs (numbered)

During the construction of the Göta tunnel additional metal pegs were installed in some buildings close to the construction site. Together with the original pegs in buildings close to the construction site, these pegs were leveled more frequently immediately before, under and after the construction of the tunnel. All these measurements have been stored in an Access data base together with additional information about the actual quarters. Also these measurements are carried out by the City of Gothenburg but administration of the database is done by the company Gatubolaget, engaged by the Swedish Road Administration.

4.4 Satellite analyses for measurement of subsidence (settlements)

4.4.1 Radar remote sensing

Airborne imaging radar was first developed in the 1950s and used primarily for military purposes. With the development of SAR (synthetic aperture radar) towards the end of the decade, the resolution of the image improved enough for commercial (i.e. civilian applications. The primary advantage of radar is the all-weather capacity – i.e. its ability to “see through” clouds.

A radar sensor is “active”, meaning that it sends out its own energy. A radar image is essentially a representation of the energy that is reflected back at the sensor (backscatter). Bright pixels in a radar image are areas that are strong reflectors (e.g. buildings, rock outcrops) and dark pixels are surfaces that reflect very little energy (e.g. water bodies, oil slicks). The amount of backscatter is a function of incidence angle, surface roughness and soil moisture.

4.4.2 The DInSAR method

Differential SAR interferometry (DInSAR) is a technique that allows the measurement of terrain displacements that have occurred between different satellite image acquisitions times. Radar interferometry (InSAR) requires at least two complex radar images to create an interferogram, which represents the phase interference between the two images. This process requires the precise coregistration of the satellite images to each other and allows the visualization of the phase differential between the radar images. One way to look at an interferogram is to essentially interpret the results as a digital elevation model (or a series of elevation contours depending on the perspective).

DInSAR is based on the fact that the phase difference between two SAR complex images over the same area, acquired at different times from slightly different positions, is based on topography conditions and any terrain displacement (along the line of sight) that may have occurred between the two acquisitions. The "difference" between two interferograms over the same area (or alternatively one interferogram and an independent digital elevation model (DEM)), represents displacement along the satellite line of sight. ERS satellites are capable of detecting displacements of up to ±2.8 cm (or one-half of a wavelength). The absolute vertical accuracy of a DInSAR analysis, that is the precise elevation of a specific point on the Earth, is said to be on the order of several meters (Hanssen & Ferretti, 2002; Hanssen, 2005).

The goal of DInSAR is thus to separate phase contributions due to topography and displacement in order to get the terrain deformation. Displacement measurement accuracy depends on many factors and in particular on the coherence of the backscattered signals at the various acquisitions. The signal coherence depends on how much the imaged scene has changed in the time between the various acquisition, either because the scene backscattering properties really changes during this time (temporal decorrelation), or because the scene is viewed from a different position (spatial decorrelation).

4.4.3 The PSInSAR method

About ten years ago, the DInSAR method was modified to include only specific highly coherent pixels – called permanent scatterers. This method, called Permanent Scatterer Interferometry (PSInSAR), is patented and is based on a time series, or stack, of images to eliminate the effects of atmospheric inhomogeneities (Ferretti, et al., 1999). The primary advantage of PSInSAR is that it measures small movements but does not require a continuous spatial area of high coherence in order to complete the phase unwrapping. The method takes advantage of the time series to identify small differences at specific locations throughout the radar image (Woodhouse, 2006). A notable limitation is that the phase difference (i.e. movement) between scene acquisition times must be less than 2π otherwise there will be phase ambiguity.

Generally, good quality measurements can be obtained with relatively few points in urban areas, arid terrain and on man-made infrastructures. Depending on the availability of SAR data, these coherent points can be identified by considering spatial and/or temporal signal statistics. However, the use of a time series of acquisitions is essential to reduce the impact of atmospheric artifacts, i.e. the uncertainty of the measurements caused by effects on signal propagation by different atmospheric conditions at the various acquisitions dates. With ERS and ENVISAT data, the potential accuracy of the measured displacement ranges from one centimeter up to a few millimeters – at least in theory.

5 ANALYSIS OF SUBSIDENCE MEASUREMENTS

5.1 Traditional measurements

There is a vast amount of leveling data in the Excel sheets and the data base. Therefore, within this project, it has not been possible to analyze the measurements of all the quarters where measurements of settlements have been carried out. To focus on the areas within central Gothenburg with ongoing settlements, the satellite analyses were carried out first. Based on the results of the initial satellite analyses, areas where these analyses showed ongoing subsidence were chosen for analysis. It shall be noted that, in some areas leveling has been carried out on buildings in all quarters and in other areas only buildings in some quarters are leveled.

The time of construction of the respective buildings, as well as the type of foundation of each building within a quarter may vary. Also the soil conditions, e.g. the depth of the soft clay may vary both between buildings and within one building. Therefore, the settlements of the different buildings within a quarter may vary, and also the settlements between different parts of a building.

In this project, only a general picture of the settlements for various quarters is given. The foundation of each building has not been mapped out, and the difference in settlements between the various buildings within a quarter or within specific buildings has not been studied. The reason for this, apart from the restricted funds of the project, is that the accuracy of the satellite analyses horizontally (in plane) is not good enough to separate parts of a building or even different buildings within a quarter (see further Section 6.3 below).

As the acquired radar images are from 1992, also leveling data from 1992 has been used. In most of the studied quarters leveling has been conducted every fifth to seventh year, and different year in different quarters. Therefore, to obtain a trend, in some cases measurements from the years immediately before 1992 have been included. In most quarters where leveling is still carried out, the latest measurements were carried out some time between the year 2000 and 2005.

The analysis of the leveling data has been done in two steps. First a diagram of the total settlements of the pegs in a quarter during the actual period has been drawn, e.g. see Figure 2. Then, in most cases, a diagram of the settlement velocity of these pegs during the period has been drawn. In the cases when the pegs have only been leveled two times during the period, the settlement velocity has been evaluated without drawing a diagram. In all quarters, the settlements, as well as the settlement velocity, differ within the quarter. For the evaluation, the lowest and the highest settlement velocity in each quarter have been used. In cases where the settlement velocity varies during the period, a mean velocity is used. A table with total settlements as well as estimated settlement velocity for the analyzed quarters are shown in Annex A.

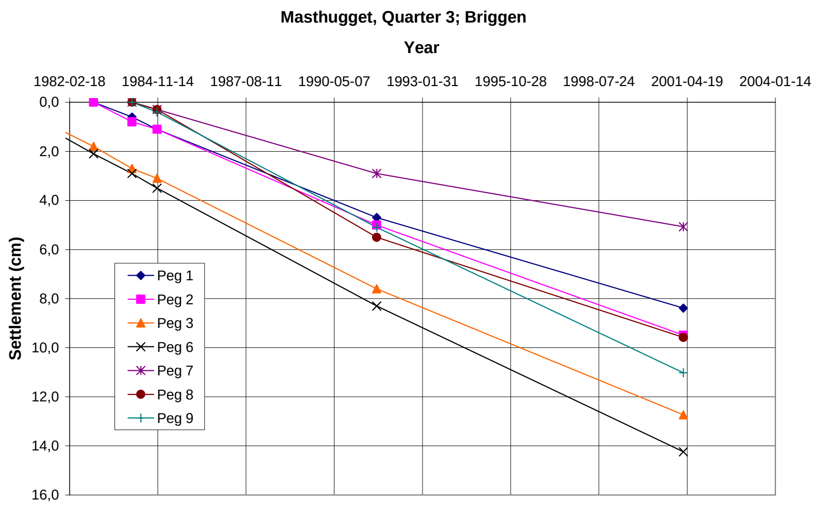

Figure 2: *Measured settlements in one of the quarters.*

5.2 Analyses based on EO-data

5.2.1 DInSAR processing procedure

Thirty ERS single look complex radar images were used for the DInSAR analysis. The first image, also called the master, was acquired on November 29, 1992. The other images were acquired between March 14, 1993 and October 2, 2002.

The radar images were processed using Erdas Imagine. As a first step, the master and slave images are declared, along with a digital elevation model encompassing at least the area defined by the union of the two radar images. The need for an independent DEM is so that a synthetic interferogram can be produced and used in the later stages to eliminate topographic effects within the interferogram.

The two radar images are then co-registered to each other. This is the most important step in the entire process since a poor co-registration will have repercussions throughout the entire process and result in a low quality interferogram.

After co-registration, an interferogram, a differential interferogram and a coherence image is created. An automatic adaptive filter was applied during this stage to compensate for low coherent interferogram regions.

Since the interferogram is expressed in values from $-\pi$ to $+\pi$, unwrapping of the interferogram is required to reconstruct the absolute interferometric phase. It is this absolute interferometric phase that represents the surface motion (in the line-of-sight direction).

The final step in the process – which is actually optional – is the creation of a georeferenced DEM. Theoretically, any height differences between the reference DEM and the constructed DEMs represents ground movement.

The two radar images are then co-registered to each other. This is the most important step in the entire process since a poor co-registration will have repercussions throughout the entire process and result in a low quality interferogram. The RMS (root-mean-square) for the co-registrations was less than one pixel for all of the image pairs.

The final step in the process – which is actually optional – is the creation of a georeferenced DEM. A DEM created with ERS images are given a default pixel resolution of approximately 45 meters. It is possible to increase the pixel spacing during the creation of the DEM and during this analysis a pixel size of 15 m was used, which roughly corresponds to the resolution of an ERS image. Theoretically, any height differences between the reference DEM and the constructed DEMs represent ground movement.

5.2.2 PSInSAR processing procedure

5.2.2.1 General procedure

The PSInSAR analysis is similar to the DInSAR process with the addition that only specific, highly coherent image pixels are chosen for the final measurement of movement. This allows for the measurement of ground displacements to a high degree of accuracy that is not achievable with DInSAR.

The images are co-registered as in the process described in Section 5.2.1. The master image was the same as that used for the DInSAR analyses (1992-11-29) and the results of interest for the PSInSAR analyses are the differential interferograms. In general, the interferograms with a long baseline were noisy and did not maintain a high level of coherence. Interferograms could be successfully created for 18 master-slave image pairs. That is, the coregistration of the two images could be made with a minimum correlation and with a sufficient number of tie points within each image quadrant.

A coherence threshold of 0.78 was used in the initial analyses. This value proved too high as few coherent points could be discerned for many of the interferograms. Additionally, these coherent points tended to be on the rocky islands off the coast that are free from vegetation. In later analyses, this threshold was reduced to 0.75 and then 0.50 based on similar analyses (Ostir and Komac, 2007. A lower threshold means that more points will be included in the analysis. The major drawback to lowering the threshold is that potentially invalid points (false positives) will be included and thus provide erroneous information. This reduction in the threshold was necessary primarily due to the amount of vegetation and woodlands in and around the vicinity of Gothenburg.

In the final analysis, a total of 11 893 scatterer points were extracted for the area of interest. The values ascertained were then converted into average movement per year for each point (mm/year). The measured movements ranged between +10 mm/year to -9.8 mm/year.

However, these measurements were not adjusted in any way for the natural land lift that has been occurring since the last ice age (~20 000 year ago). The rate of natural rise in the Gothenburg area has been estimated 1.17 mm/year according to Lantmäteriet. Recently, adjustments made to the intermediate results to take into account for this affect reduced the final movement range of the points to +1.6 mm/year to -17.8 mm/year – with 95.4% of the measurements indicating subsidence.

5.2.2.2 Correction for natural land lift

Natural land lift (see Section 4.2) will have an affect on any land subsidence measurements produced using interferometric methods. Since actual data relating to natural land rise at the permanent scattering points used in the PSInSAR analyses do not exist, it was necessary to use a general value for the entire Gothenburg area. 1.17 mm/year was the value used, although the land lift model produced by the Nordic Commission for Geodesy (NKG) suggests a value between 1.5 and 1.75 mm/year.

A simple linear adjustment was made to the intermediary results prior to determining the average movement for each identified permanent scatterer. These data were adjusted by reducing the result by 1.17 mm for every 365 days between the two images used for the interferogram or portion thereof.

6 RESULTS

6.1 Results of the traditional measurements

The results of the traditional measurements of settlements have been visualized on an areal photography of the central parts of Gothenburg as shown in Figure 3. All quarters where an analysis of settlements have been carried out are marked with a circle. However, the quarters where measurements have stopped before the year 2000 are not included, as the period is judged to be too short. If the total settlement during the measurement period is less than one centimeter, the circle has been colored white. In these cases there may have been hardly any settlements or alternating heave and settlement within the quarter. For these quarters, measurements may have stopped before the year 2000, but with no clear trend that settlements is ongoing.

Figure 3: Settlements within different quarters measured by leveling and visualized on a map of central Gothenburg

If settlements larger than one centimeter has been measured within a quarter, the minimum and the maximum velocity are indicated with different colors in the two halves of the circle (minimum to the left and maximum to the right). The colors used for different settlement velocity are yellow for settlements 0 – 2.4 mm/year, orange for settlements 2.5 – 4.9 mm/year and red for settlements larger than 5.0 mm/year. Quarters with no circles have either not been analyzed or no measurements of settlements have been carried out. Generally, measurements have been carried out for the quarters within the moat (the channel around the central parts of Gothenburg in the northern part in Figure

3). For most of the quarters at some distance from the town centre, no measurements have been carried out (most quarters to the south and east in Figure 3).

6.2 Results of the satellite analyses

6.2.1 DInSAR analysis

Initially, only the DInSAR technique would be tested and used for comparison. However, early on it became evident that due to the overwhelming presence of forests and urban green areas, simple DInSAR would not be able to provide adequate results for ground movement in the vicinity of Gothenburg. Figure 4 shows an interferogram constructed from two ERS images taken one day apart in December 1995. This interferogram shows strong coherence between the two images with the notable exception of the forested areas to the right of the image (grey areas indicate low coherence). The city of Gothenburg can be seen in bright magenta in the middle of the image. In this figure, one fringe represents approximately 8.5 meters of elevation.

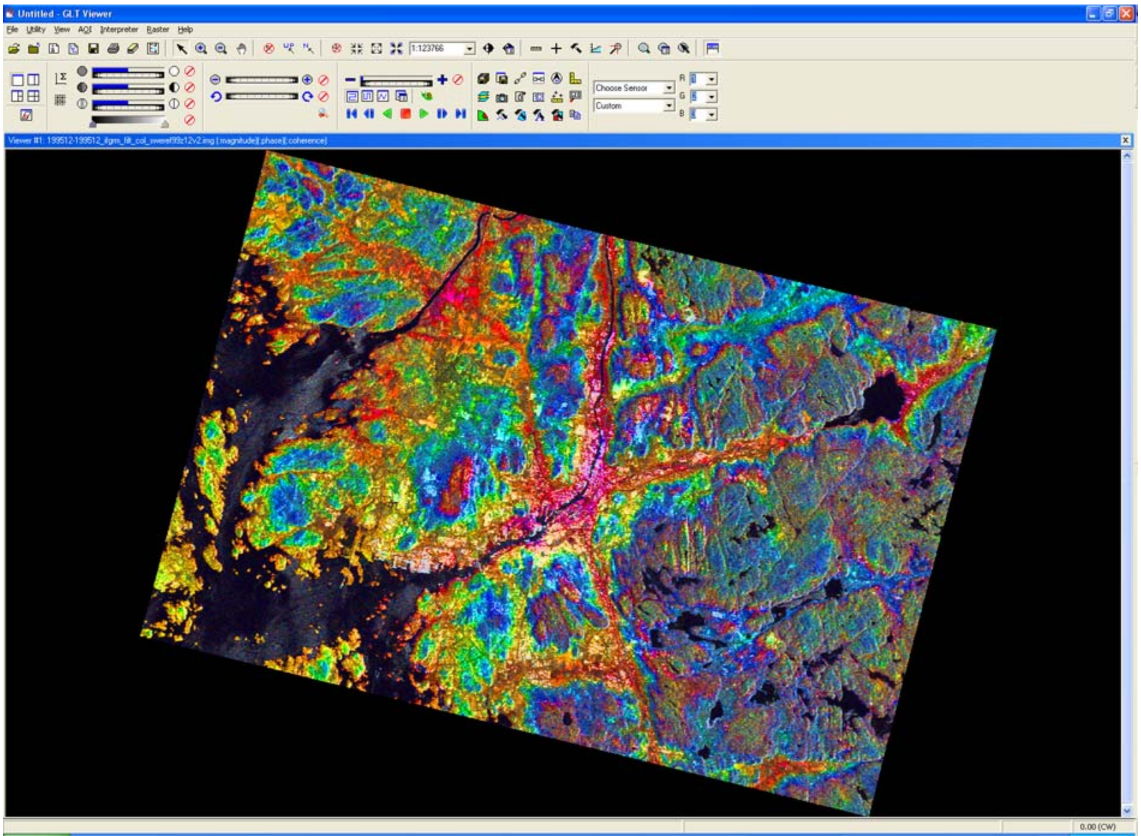

Figure 4: An interferogram based on ERS images taken on December 12 and 13, 1995.

A second interferogram, shown in Figure 5, demonstrates the difficulty associated with DInSAR analyses in heavily vegetated areas. These images were acquired 105 days (about three months) apart in mid to late 1995. Already the vast majority of coherence has been lost between the two images. Only the built up areas in the central part of the city and the sparsely vegetated islands near and off the coast provide any valid information.

A third interferogram (Figure 6) indicates almost complete incoherence between two images acquired only 175 days (less than six months) apart. Only small isolated areas show any significant coherence.

An additional problem associated with DInSAR is the degree of precision for any vertical movements. Theoretically, two interferograms based on the same master image could be compared. Any differences between the two would represent vertical movement. Theoretically, movements within one half of a wavelength (2.8 cm for ERS) can be detected. However, the absolute vertical precision of such measurements is on the order of several meters. The required precision, in order to be able to compare earth observation methods with traditional techniques for geotechnical measurements, is on a centimeter scale or better.

In an effort to account for low coherence between the images and to achieve a higher degree of precision for the vertical measurements the focus of the analysis was switched from DInSAR to PSInSAR.

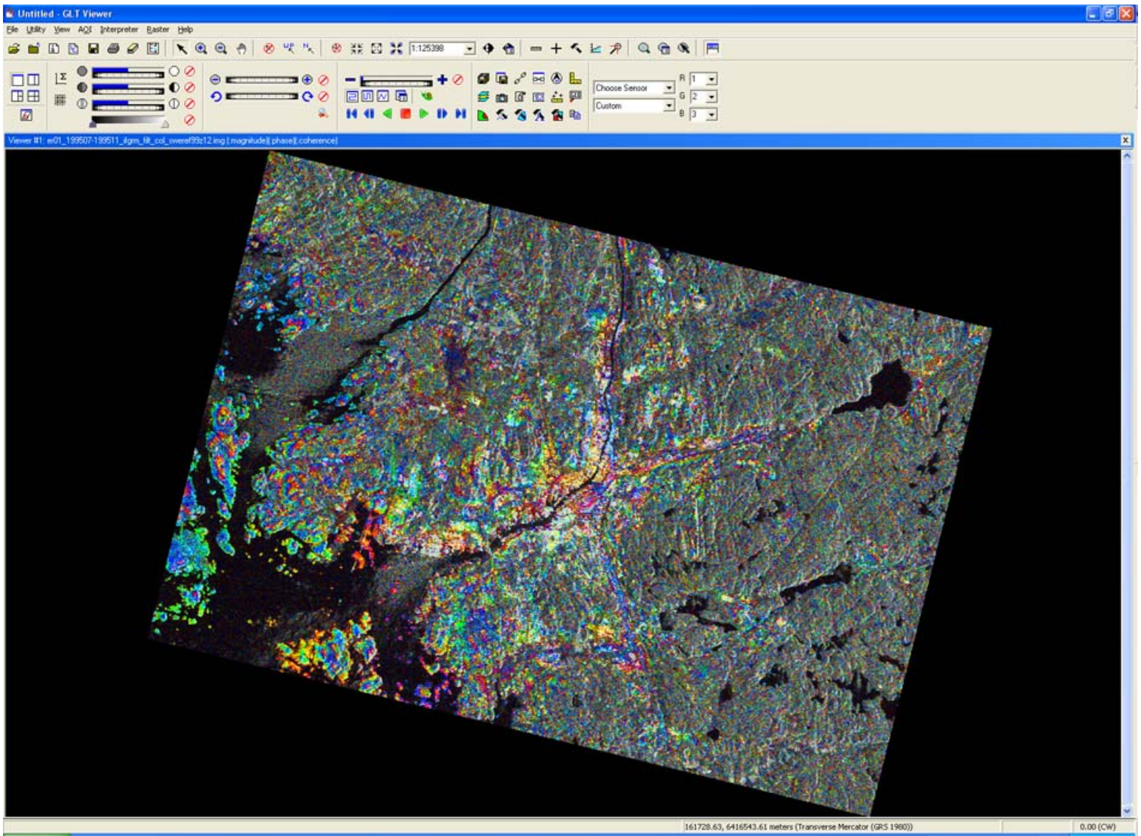

Figure 5: An interferogram based on ERS images taken on July 25 and November 11, 1995.

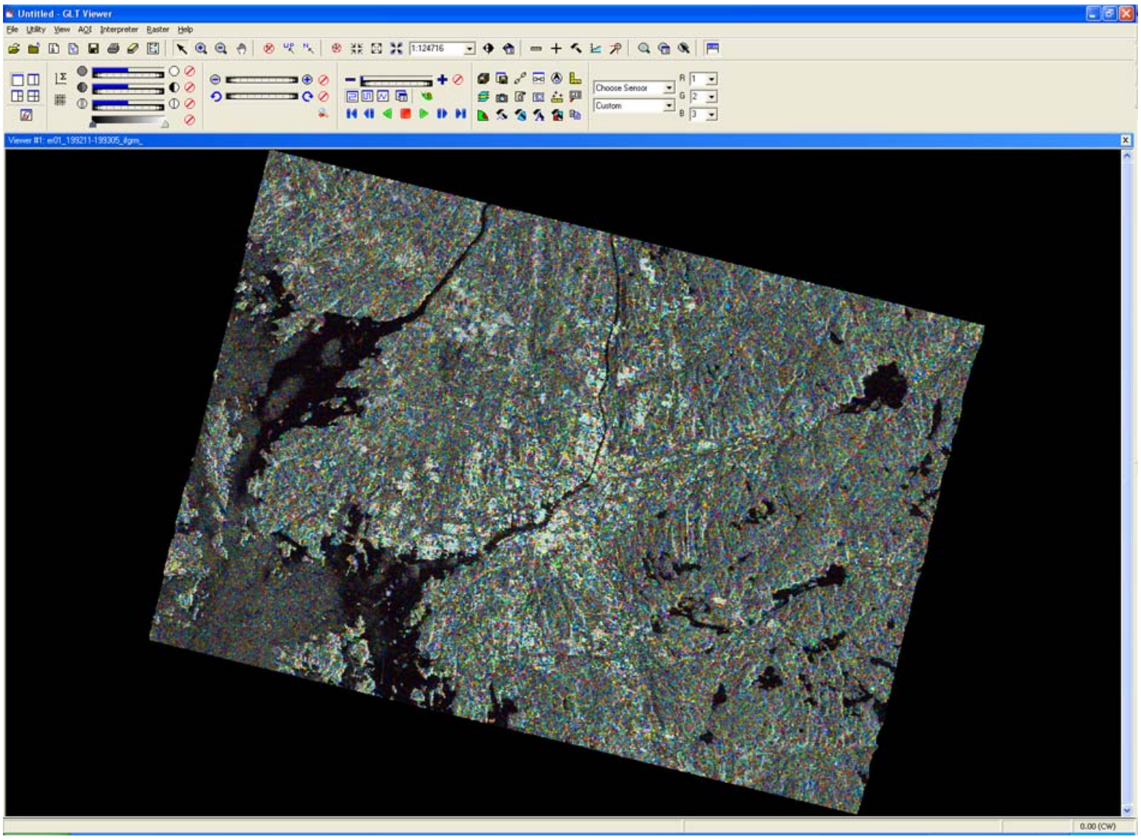

Figure 6: *An interferogram based on ERS images taken November 29, 1992 and May 23, 1993.*

6.2.2 PSInSAR analysis

Initially, very conservative parameters were chosen with respect to minimum coherence between image pairs and the threshold for matching pixels in the image stack. The result was that very few points – only 197 in total – were found within the area of interest. Figure 7 shows the initial results, centered around the inner city. Only an industrial area on the northern side of the canal showed indications of subsidence. Other measurements indicated small amounts of land rise. However, these measurements do not take into account the natural land rise occurring throughout Scandinavia.

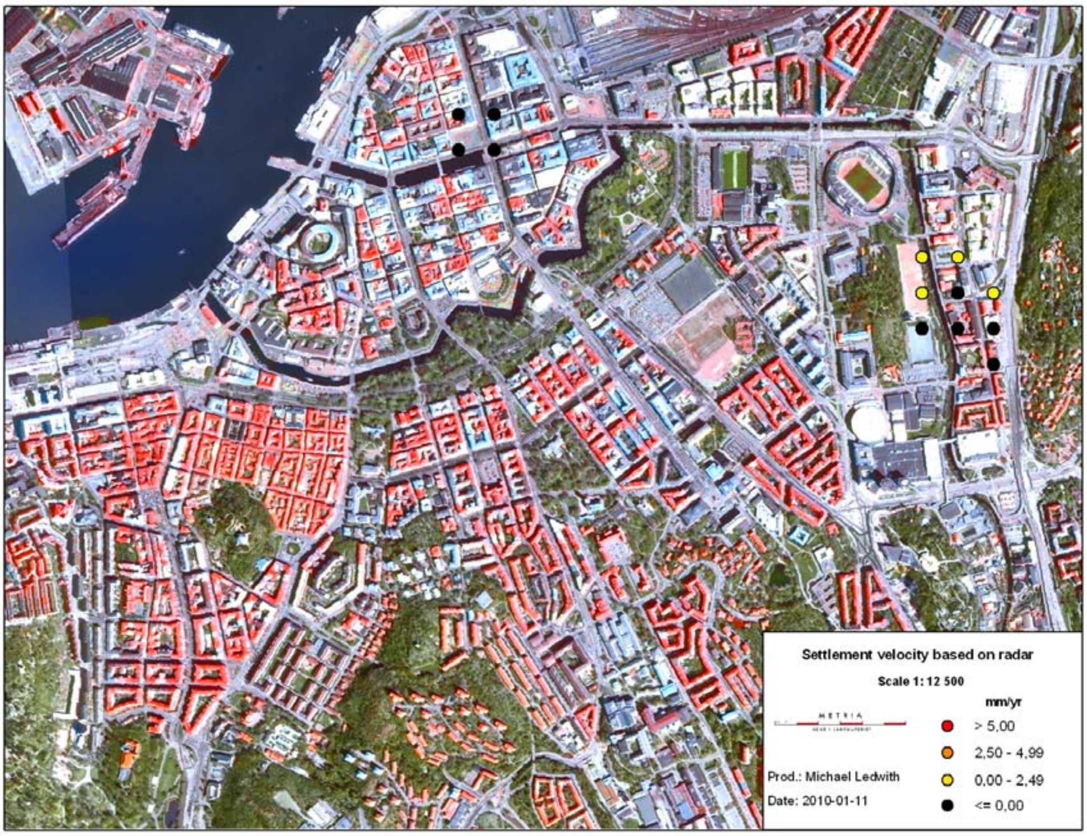

Figure 7: Initial PSInSAR measurements near the center of Gothenburg. Orange points indicate subsidence and green indicate land rise.

Further refinement and an expansion to less restrictive input parameters increased the amount of measured points by a factor of almost 100. The number of measurements in the central portion of the city increased from 36 to 774. In addition, the time span of images was reduced from 16 years (1992 – 2008) to eight years (1992 – 2000). This was done in an effort to increase the accuracy of the measurements (by removing the likeliest sources of erroneous points) and to reduce the amount of data (since coherent points in many image pairs were very difficult to find).

As visible in Figure 8, the majority of the points in central Gothenburg are colored yellow, suggesting little movement (± 1 cm / year). Orange and red points indicate more significant subsidence. Green points show land rise. As pointed out previously, these data points have not been adjusted for the natural land rising in Scandinavia. According to Lantmäteriet, the average rate of rise in Gothenburg is 1.17 mm/year. Therefore, the total potential land rise for the area, simply due to isostasy since the last ice age, during the time frame of this analysis is about 11.5 mm.

This natural land rise was taken into account during the intermediate stages of the analysis – after the points with high coherence values were identified. A new set of point measurements is presented in Figure 9. As is evident, most of the values are now indicative of subsidence. In fact, over 95% of the measurements show at least some subsidence.

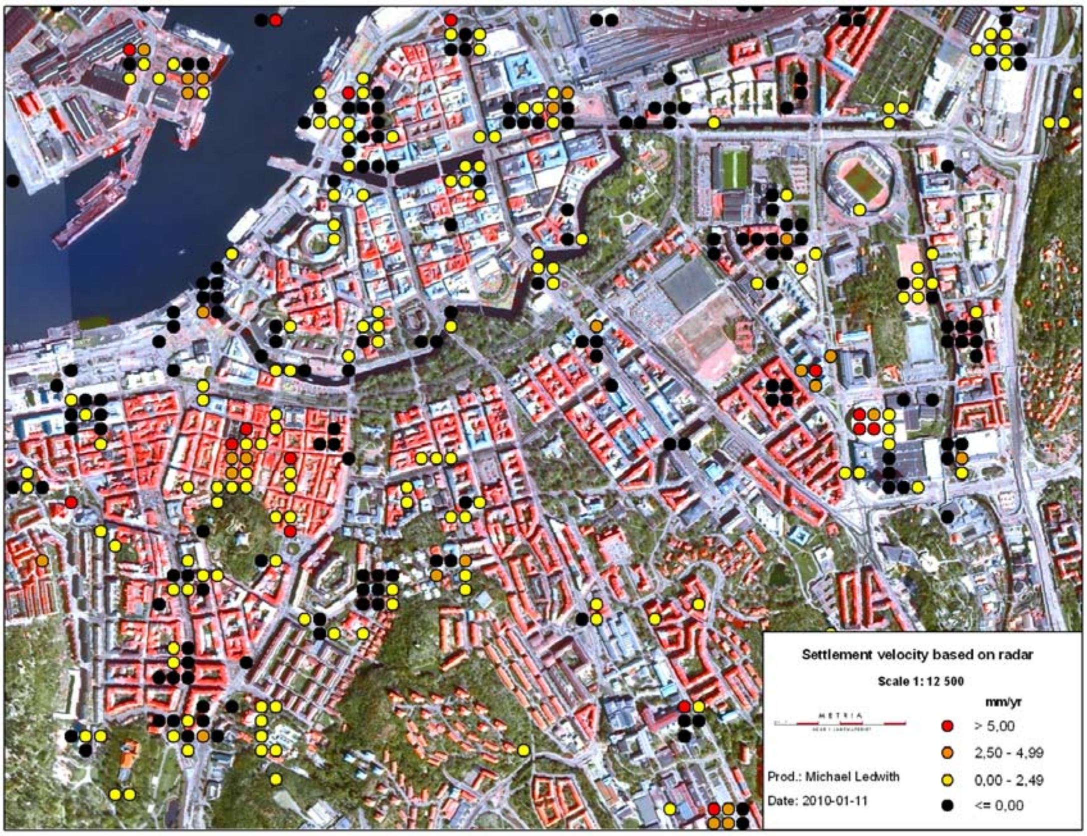

Figure 8: Results of PSInSAR analysis after the coherence threshold was reduced to 0.5.

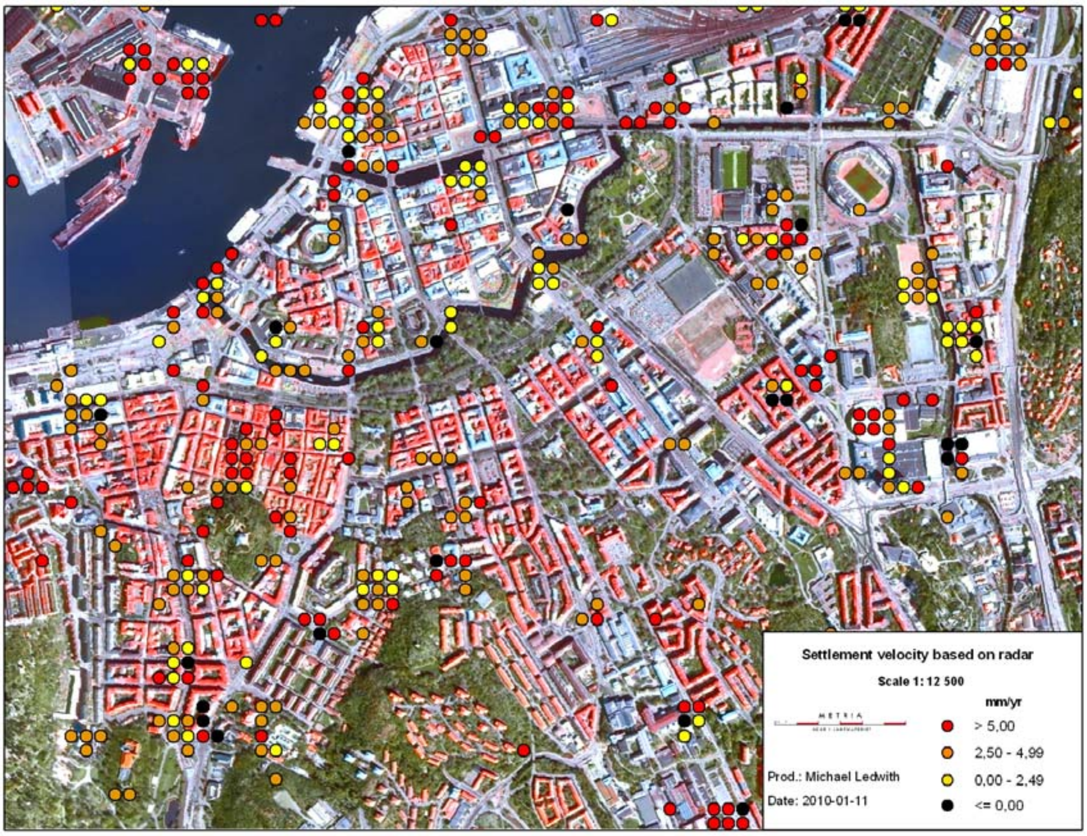

Figure 9: Final results of the PSInSAR analysis taking into account the natural land rise of Scandinavia.

6.3 Comparisons of the results

No comparison was made with the results from the initial PSInSAR analyses (coherence threshold 0.78), as there was hardly any points to compare. In this analysis the natural land rise was not taken into account.

6.3.1 Comparison with PSInSAR analysis with a coherence threshold of 0.75

The first comparison made, was based on the second PSInSAR analysis, the one with coherence threshold 0.75 (see Figure 10). Neither in this analysis the natural land rise of the Gothenburg area was taken into account.

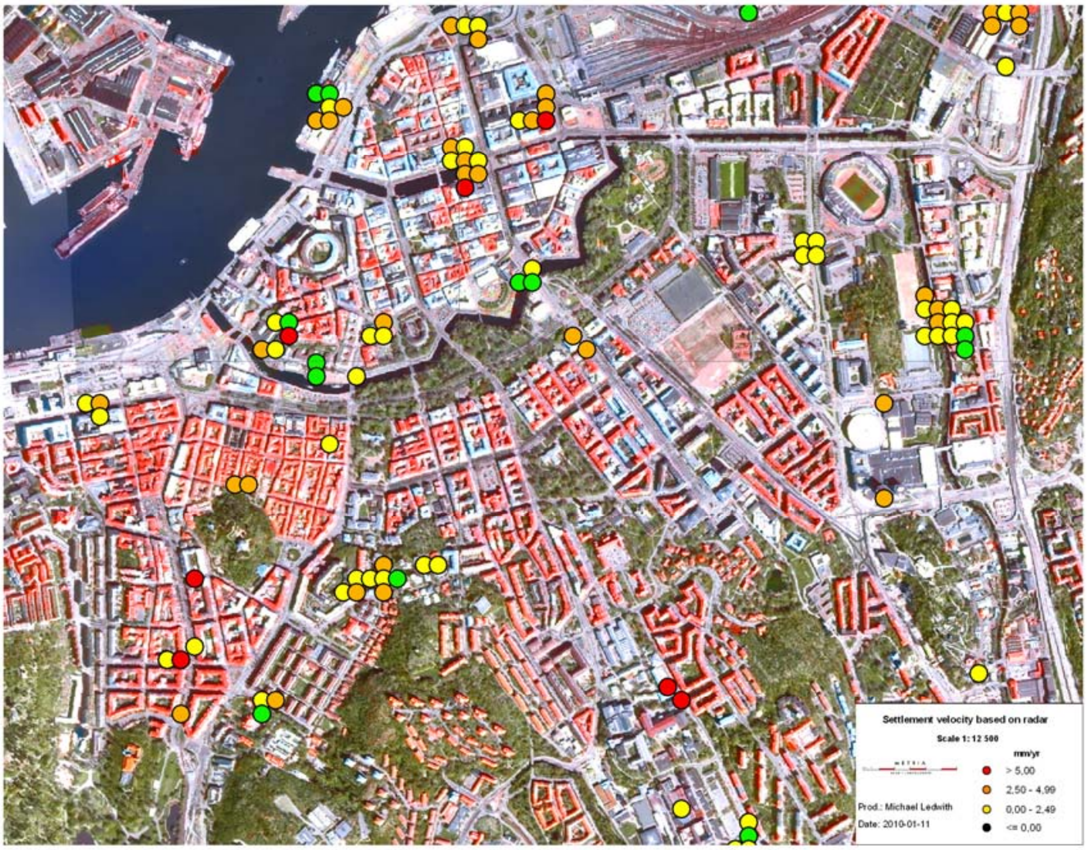

Figure 10: Result of the PSInSAR analysis with a coherence threshold of 0.75 and no correction for land rise.

It is clear that even with this lowered threshold, not all the ongoing settlements are registered. For example, in the areas Masthugget and Haga (in the western part of Figure 11, south of the moat) settlements are registered in a majority of the quarters where settlement measurements have been carried out. It is also in this area the largest settlement velocities have been registered. Altogether, settlements with velocities from zero to more than 5 mm/year have been registered in 23 quarters in this area. Only in 8 quarters, no movements or very small movements have been registered.

Figure 11: Settlements within different quarters measured by leveling. Areas and quarters with large and extensive settlements marked.

From the PSInSAR analyses in the same area, subsidence with a magnitude of 0 – 2.4 mm/year have been registered in two of the quarters (3 measuring points). At the same time, in one of these quarters, heave with the magnitude of 0 – 2.4 mm/year have been registered (2 measuring points). Also in one other place, heave has been registered (1 measuring point). In the rest of this area, no movements at all have been registered by the satellite analyses. All these movements are measured in the line-of-sight of the satellite.

However, there are also correspondences between the two analyses. In the quarter Lammet, in the eastern part (see Figure 11), large settlements have been registered with the traditional settlement measurements (5.8 - 9.4 mm/year). Also with the PSInSAR analyses, several registrations of movements have been made around this quarter (12 measuring points). However, more than half of these are registered as heave. In another quarter, Landeriet, in the southwestern part (see Figure 11), subsidence between 8.7 and 9.8 mm/year have been registered with the traditional measurements. Also the PSInSAR analyses have registered movements but smaller; subsidence of more than 2.5 mm/year (1 measuring point) and heave 0 – 2.5 mm/year (2 measuring points) in the same area, measured in the line-of-sight of the satellite.

As the PSInSAR analyses cover a much larger area than the traditional settlement measurements, subsidence have been registered in many other areas. However, as these can not be verified by any traditional measurements, they are not discussed in this report.

It can be noted that rather few measuring points indicating subsidence (or heave) is registered with the PSInSAR analyses during the period 1992 and 2002 and that quite large settlements are registered with the traditional settlement measurements (often larger than one wave-length). It can also be noted that several points from the PSInSAR analyses are registered as heave. A likely reason for this is the ongoing land rice in the Gothenburg region. Thus, a third PSInSAR analysis was then conducted.

6.3.2 Comparison with PSInSAR analysis with a coherence threshold of 0.5

In the third analysis the coherence threshold was lowered to 0.5, and correction for a land rice of 1.17 mm/year was carried out (see Section 6.2.2). In addition, this analysis covered radar images from the period 1992 – 2000 i.e. a shorter time span than the other analyses.

The result from this PSInSAR analysis shows quite a large difference (see Figure 9). The number of measuring points within the area of interest is more than the double. The points are mainly located to areas where ongoing settlements have been measured by the traditional leveling. But still, many of the quarters with ongoing settlements are not registered by the satellite analyses. In addition, the size of the ongoing subsidence registered by the PSInSAR analysis is now generally larger than the ongoing settlements measured by leveling.

Looking again at the quarters Masthugget and Haga, the following can be noted. In Masthugget the PSInSAR analyses have registered subsidence in two of the quarters where traditional leveling has been carried out. The subsidence in these quarters are from 0 – 4.9 mm/year (in the line-of-sight of the satellite). With the traditional leveling settlements have been measured in 9 quarters. The settlements in these quarters are from 0 – 10 mm/year.

In Haga the PSInSAR analyses have registered subsidence in 12 of the quarters indicated by at least one point. The registered subsidence were then from 0 – 17.8 mm/year (in the line-of-sight of the satellite). With the traditional leveling settlements have been measured in 14 quarters. The settlements in these quarters are from 0 – 6.7 mm/year. However, out of the four quarters with the largest settlements according to the leveling measurements (maximum settlements of 5.0 to 6.7 mm/year), only one quarter have clear indications of subsidence according to the PSInSAR analysis (subsidence between 10.0 and 14.9 mm/year (in the line-of-sight of the satellite).

Comparing again two of the quarters that have large ongoing settlements, Lammet (settlements of 5.8 - 9.4 mm/year by leveling) and Landeriet (settlements of 8.7 – 9.8 mm/year by leveling), with the PSInSAR analyses these quarters are not the ones with the largest ongoing subsidence. Within and close to quarter Lammet, 7 measuring points are registered with the PSInSAR analyses. One of them registered heave, 5 registered subsidence of 0 – 2.4 mm/year and one subsidence of 7.5 – 9.9 mm/year (in the line-of-sight of the satellite). Within and close to quarter Landeriet, 5 measuring points are registered with the PSInSAR analyses. One of them registered heave, 2 registered subsidence of 0 – 2.4 mm/year, one registered subsidence of 5.0 – 7.4 mm/year and one subsidence of 7.5 – 9.9 mm/year (in the line-of-sight of the satellite).

From the comparison it can be noted that

- With PSInSAR analysis from ERS satellites it is not possible detect all quarters with ongoing subsidence.
- PSInSAR analysis from ERS satellites does not give the right picture in which quarters the largest settlements are occurring.
- In some quarters with no clear trend of ongoing settlements during the measurement period of the leveling, the PSInSAR analyses have actually registered subsidence.

- The size of the measured settlements from the nPSInSAR analysis are not in agreement with the size of the settlements measured with leveling.

7 EXPERIENCES AND REFLECTIONS

From a geotechnical point of view it is of interest to highlight some findings from this project.

There are a large amount of roads in the Gothenburg area, as highways and motorways. Parts of these roads are founded on clay and most of them settle with time. In the design of these roads some settlements are often accounted for, as it seldom is cost-efficient to design for zero settlement. However, looking at the PSInSAR analyses over the whole area very few points are located on roads. One obstacle could be the lay of new asphalt which is done every now and then when the old asphalt layer is time-worn. But it is hard to believe this is the only reason. As follow-up of settlements on roads is very useful but rarely conducted, it would be an interesting application for methods such as PSInSAR.

A difficulty with the PSInSAR for follow-up of settlements on buildings is that the accuracy in plane (±20 m) is not good enough. Thus, a measuring point located on a roof of a building may as well be located 20 m from this point, which could be on the roof of another building. As it is the settlement of each building, and even the settlement in different parts of a building, that is of most interest, the precise location of the measuring point is important.

To be of use for the follow-up of settlements on individual buildings it is necessary that the satellites are better in registering measurement points on all buildings that settle. Currently, in most areas with ongoing settlements only in some quarters there are also measurement points.

In addition to the above mentioned difficulties, the accuracy of the settlements measured with the PSInSAR method based on data from ERS satellites need to be enhanced.

Since the elevation model is used during the early steps of the interferometric process, an improved DEM would increase the accuracy of the measurements. In addition, it would aid in increasing the geolocational accuracy of the co-registration process and during any latter stage interferogram to interferogram registration.

8 CONCLUSIONS AND EVALUATION INCL. USEFULNESS

Although the PSInSAR method has a potential for measurements of subsidence in urban areas, it can be concluded that using ERS radar images and the SMD elevation model, which currently is the best available DEM over the entire country, do not provide sufficiently accurate results to be effective for the long-term monitoring of subsidence of buildings in an urban environment. However, the SMD will be superseded by an elevation model based on laser scanning (LIDAR) that is currently being constructed.

The following needs to be improved:

- The accuracy in plane (±20 m) need to be enhanced.
- The satellite analyses must be better in registering measurement points on all objects that move, i.e. buildings as well as roads.

- The accuracy of the measured settlements needs to be enhanced.

Currently, satellite analyses as DInSAR and PSInSAR are not accurate and reliable enough for use as follow-up on settlements of buildings.

As regards follow-up of settlements of roads, the measured settlements do not have to be as accurate as for buildings. But to be of use in this respect, the satellites must be better in registering measuring points on objects such as roads.

9 DEVELOPMENT POTENTIAL, DIRECTION OF FURTHER WORK

In 2007 it was decided that Sweden would produce a new national digital elevation model with a 50-centimeter vertical accuracy with a 2.5 meter grid. According to the original plan, the DEM would be produced between 2009 and 2011 using a modern air-borne LIDAR system. There are three areas that have been given the highest priority: Kiruna and its environs, Mälardalen (west of Stockholm) and the region surrounding Vänern (including Göteborg).

TerraSAR-X, along with its sister satellite TanDEM-X, which is scheduled to be launched in early 2010, is a new class of radar satellites providing quality images with very high resolution and unrivaled geometric and radiometric accuracy. In SpotLight mode, 0.5 to 1 meter resolution data can be acquired over an approximately 50 km^2 area (easily covering the central portion of Göteborg). When TanDEM-X is fully functional, the satellite pair will be able to provide unprecedented high quality SLC radar images for use in DInSAR and PInSAR analyses.

It is believed, that with a higher accuracy of the radar images together with a better DEM a much better result of the PSInSAR analyses can be obtained.

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11 ATTACHMENTS

Annex A: Tables with results from analysis of settlements from traditional precision leveling.

The quarters chosen for analysis in this project are primarily the quarters in which settlements have been registered with the PSInSAR analyses.

Approximate movements during the period 1992 – 2007 are estimated from excel-diagrams from the City of Gothenburg, Office of City Planning. The period of measurement is chosen to be about the same as the measurement period with PSInSAR. In some quarters the measurements have been carried out during a shorter period. Then this is mentioned. In most quarters the measurements have started before 1992, but these measurements have not been included as no satellite measurements before 1992 are available.

Masthugget (area 12)

Quarter	Measurement period starting 1992	Settlement during this period (cm)	Average settlement (mm/year)	Comment
1 Fregatten	1992 – 2005	1,2 – 4,8	0,9 – 3,7	
2 Skonaren	1992 – 2005	11 - 13	8,5 – 10,0	
3 Briggen	1992 – 2001	2,0 – 6,0	2,2 – 6,7	
4 Barken	1992 – 2005	0 – 3,0	0 – 2,3	
7 Smacken	1992 – 2001	2,5 – 5,0	2,8 – 5,5	
8 Skutan	1992 – 2001	1,6 – 5,0	1,8 – 5,5	
9 Slupen	1993 – 2001	1,7 – 3,2	2,1 – 4,0	
10 Kryssaren	1992 – 2005	1,5 – 8,0	1,1 – 6,1	
30 Snipan	1992 – 2005	3,0 – 4,5	2,3 – 3,5	

Inom Vallgraven (area 1)

(within Vallgraven)

Quarter	Measurement period starting 1992	Settlement during this period (cm)	Average settlement (mm/year)	Comment
South west:				
40 Rosenlund	1998 - 2005	0 – 2,0	0 – 2,8	
69 Boktryckeriet				No measurements
42 Luntanu	1997 - 2007	0		founded on rock
43 Carolus Rex	1997 - 2005	0		founded on rock
45 Hästbacken	1997 - 2007	0		founded on rock
28 Fiskaren	2002 - 2007	0 – 1,5	0 – 3,0	
29 Gamla Latin	-			No measurements after 1993
30 Engelska kyrkan	1992 - 2000	3,0 – 4,7	4,3 - 6,7	
31 Spruthuset	1992 - 2000	< 1,0		

32 Artilleristallet	1992 - 2005	< 1,0		
Rosenlundskanalen (Rosenlund chanel)	1995 - 2007	1,3 – 2,8	1,1 – 2,3	
North east:				
15 Frimuraren	1992 - 2005	1,5 – 4,0	1,0 – 5,0	

Nordstaden (area 2)

Quarter	Measurement period starting 1992	Settlements during this period (cm)	Average settlement (mm/year)	Comment
11 Rådhuset	1992 - 2005	0 (<0,5)		
15 Traktören	1992 - 2005	0 (<0,5)		
16 Högvakten		-		No measurements after 1993
(15 Frimuraren) *see. Inom Vallgraven*				
Gustav Adolfs torg (square)		-		No measurements
17 Borgaren	1992 - 2005 1998 - 2007	0,5 – 4,0 0 – 2,9	2,0 – 3,5	Excel file in data base
8 Köpmannen	1998 - 2005	0		
10 Kronobageriet	1992 – 2005 2000 - 2005	3,0 – 4,0 < 0,5	0 – 1,6	Excel file in data base
Pedestrian tunnel Postgatan Central-station	1992 - 2005	?		Excel file in data base
35 Magasinet	-	-		No data
36 Packhuset		3 – 4 cm settlement 1987 - 1991		No measurements after 1991.
38 Kajskjulet	-			No data

Heden (area 5)

Quarter	Measurement period starting 1992	Settlements during this period (cm)	Average settlement (mm/year)	Comment
21 Smaragden	1992 – 2005/2006	4,4 – 12,2	3,1 – 7,8	
25 Bergkristallen	1992 - 2005	0 – 4 (ca)	0 – 3,3	
26 Ametisten	1992 - 2005	< 1,0		
27 Karneolen	1992 – 2005/2006	1,0 – 3,5	1,2 – 3,5	
28 Agaten	1992 - 2005	0 – 3,0	0 – 2,5	
29 Onyxen	1992 - 2005	1,8 – 4,0	1,5 – 3,2	
30 Granaten	1992 - 2005	0 – 8 (ca)	1,0 – 7,0	
31 Turmalinen	1992 - 2005	0,5 – 2,5	0,5 – 2,5	

Lorensberg (area 6)

Quarter	Measurement period starting 1992	Settlements during this period (cm)	Average settlement (mm/year)	Comment
5 Axevall	1992 -2005	< 1,0		
6 Aranäs	1992 -2005	< 1,0		
7 Torpa	1992 -2005	< 1,0		
23 Drottningholm	1992 -2005	< 1,0		
25 Ulriksdal	1992 -2005	< 1,0		
40 Rydboholm	1992 - 2003	(0 – 3)		Initially heave, then settlement
41 Ulvåsa	1992 - 2003	< 1,0		
42 Fågelvik	1992 - 2003	1,0 – 1,1	0,7 – 0,9	
43 Borganäs	1992 - 2003	1,4 – 2,0	1,5 – 2,5	Irregular settlements ”drops” in the curves
44 Visborg	1992 - 2004	< 1,0		
45 Kastellholm	1992 - 2004	0 – 5,0	0 – 3,0	
46 Kalmarehus	1992 - 2003	< 1,0		
47 Kronoberg	1992 - 2003	1,0 – 1,4	0,5 – 1,4	
48 Vik	1992 - 2003	0 – 1,4	0 – 1,0	
49 Nyköpingshus	1992 - 2003	< 1,0		
50 Örebrohus	1992 -1997	< 1,0		
51 Oppensten	1992 -1997	< 1,0		
52 Borgeby	1992 -1997	< 1,0		

53 Örup	1992 -1995	< 1,0		Short measuring period
54 Svaneholm	1992 -1995	0,7 – 1,1	(2,3 - 3,6)	Short measuring period
55 Glimmingehus	1992 -1995	< 1,0		Short measuring period
57 Örbyhus	1992 -1997	< 1,0		< 1,0 except for one peg
58 Trollenäs	1992 - 2005	< 1,0		

Vasastaden (area 10)

Quarter	Measurement period starting 1992	Settlements during this period (cm)	Average settlement (mm/year)	Comment
1 Alen	1992 – 1997/2004	0 – 2,0	1,1 – 1,5	
2 Almen	1992 - 2004	3,7 – 4,0	2,1 – 3,0	
3 Asken	1992 - 2004	1,2 – 3,0	1,0 – 2,2	
4 Avenboken	1992 - 2004	1,0 – 3,0	0,5 – 1,5	
5 Björken	1992 - 2004	0 – 1,8	0 – 1,2	
6 Masurbjörken	1992 - 2004	< 1,0		
7 Glasbjörken	1992 - 2004	0 – 3,0	0 – 3,0 ca	Varying settlement velocity
8 Boken	1992 - 2004	1,0 – 3,0	1,0 – 4,0	
9 Apeln	1992 - 2004	0 – 2,4	0 – 2,6	
10 Enen	1992 - 2005	< 0 – 1,6	0 – 2,5 ca	Heave approx. 0,5 cm in 2/3 of the pegs
12 Furan		< 1 cm		
15 Granen	1992 – 2004/2005	0 – 3,0	0 – 3,5	Partly varying velocity
16 Sälgen		< 1 cm		
17 Häggen		< 1 cm		
27 Rönnen		< 1 cm		

Haga (area 15)

Quarter	Measurement period starting 1992	Settlements during this period (cm)	Average settlement (mm/year)	Comment
1 Amiralen	-			No measurements
2 Generalen	1994 - 2005	2,2 – 3,5	1,8 – 3,5	
3 Översten	1994 - 2005	0,8 – 2,0	0,5 – 3,0	
4 Majoren	1994 - 2000	< 1,0		
5 Kaptenen	1994 - 2000	1,0 - 2,0	1,7 – 3,3	
6 Löjtnanten	1994 - 2000	ca 1,0	ca 1,7	
7 Fänriken	1994 - 2000	1,0 – 2,5	1,7 – 4,2	
8 Fanjunkaren	1994 - 2000	0 – 3,4	0 – 5,7	
9 Styckjunkaren	1994 - 2000	1,0 – 2,2	1,7 – 3,7	
10 Sergeanten	1994 - 2000	0 – 3,0	0 – 5,0	
11 Kadetten	1994 - 2000	1,2 – 4,0	2,0 – 6,7	
12 Furiren	1994 - 2000	1,0 – 3,0	1,7 – 5,0	
13 Korpralen	1994 - 2000	1,0 – 2,5	1,7 – 4,2	
16 Fanbäraren	1994 - 2000	0 – 1,7	0 – 1,2	
18 Trumslagaren	1994 - 2000	-		Strange curves
20 Grenadieren	1994 - 2000	< 1,0		
21 Sappören	1994 - 2000	0		
23 Dragonen	1994 - 2000	-		Only one peg
24 Infanteristen	1994 - 2000	ca 1,0	ca 1,7	
25 Landsknekten	1994 - 2000	0,5 – 1,0	0,8 – 1,7	
26 Kanonen	1994 - 2000	< 1,0		
27 Geväret	1994 - 2000	< 1,0		
28 Sabeln	1994 - 2000	< 1,0		
29 Bajonetten	1994 - 2000	< 1,0		
30 Laddstaken	1994 - 2000	< 1,0		

Gårda (area 44)

Quarter	Measurement period starting 1992	Settlements during this period (cm)	Average settlement (mm/year)	Comment
15 Fyrkanten	1992 - 2002	1,2 – 6,0	1,0 – 5,2	
18 Svanen	1992 - 2002	1,0 - 3,0	1,0 – 3,5	
19 Bobinen	1992 - 2002	6,5 – 9,0	5,9 - 8,1	
24 Lammet	1992 - 2002	7,0 – 10,0	5,8 – 9,4	

Olivedal, Kommendantsängen, Annedal (area 14, 16, 17)

In these areas, only in some quarters settlement measurements with precision leveling have been carried out.

Quarter	Measurement period starting 1992	Settlements during this period (cm)	Average settlement (mm/year)	Comment
Olivedal:				
11 Bäckebron	1992 - 2002	0 – 14,0	1,0 – 16,0	
12 Landeriet	1992 - 1998	5,0 – 6,0	8,7 – 9,8	
13 Bergfästet				No measurements
Kommendantsängen:				
1 Ryssåsen				No measurements
2 Murbräckan	1992 - 2005	<0,5		Movements of certain pegs
3 Vaktposten	1992 - 2005			Movements of certain pegs
4 Karl XII	1992 - 2005	0 – 8,0	0 – 7,0	
5 Utanverket	1992 - 2005	0 – 4,5	0 – 3,2	
6 Kastellanen	1992 - 2005	1,0 – 6,5	0,2 – 4,0	
7 Batteriet	1992 - 2005	<1,0		
Annedal:				
23 Körsbäret	1992 - 1998	0 – 4,5	0 – 7,5	Only quarter with measurements

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