Swedish Geotechnical Institute

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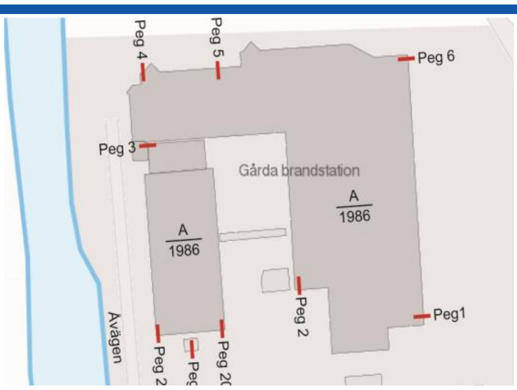

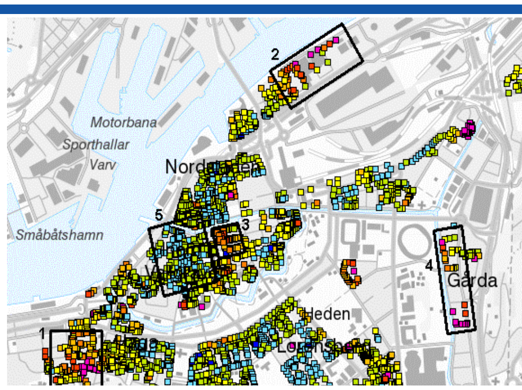

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Mapping subsidence with very high resolution (TerraSAR-X) radar images and comparing with traditional measurements – Test area Gothenburg

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Preface

Construction and maintenance of buildings and infrastructure is a major societal commitment. In most cases, ground movements are sufficient to cause damage to buildings and infrastructure. For a safe, efficient and sustainable ground construction, site conditions and geotechnical properties of soil must be taken into account already in the planning phase. Poor knowledge of ground conditions may cause high costs for society.

The Swedish Geotechnical Institute (SGI) is an expert agency that promote safe, economic and environmentally sustainable development in the geotechnical field. SGI provide research, advisory services and convey knowledge in order to streamline ground construction.

In 2008 SGI and Metria carried out a project using interferometry based on ERS 1/2 satellite radar images to assess the magnitude of ongoing subsidence and compare with traditional methods. A main conclusion was that the resolution of the radar images hindered the specification of objects that were measured.

The objective of this project was to investigate whether interferometry using very high resolution radar images can improve the previous results and provide detailed enough subsidence measurements to serve as a basis for a commercial service.

The report describes the results of a comparison between settlements measured with traditional precision leveling in the central part of Gothenburg and settlements measured with DInSAR and time-series DInSAR analysis from TerraSAR-X satellite images.

The project has been funded by the Swedish National Space Board and SGI. The City of Gothenburg, Office of City Planning, Anna-Maria Edvardsson and Malin Klarqvist, has provided data from the precision leveling within Gothenburg and the Swedish Transport Administration, Anders Hansson, has provided data from the West Link. The interferometric analyses have been performed by Michael Ledwith, Metria and the analysis of the precision leveling data by Hjördis Löfroth SGI. Jim Hedfors, SGI, has developed the GIS-portal used in the analysis and Hanna Tobiasson-Blomén, SGI, has carried out the study on settlement and foundation. The report has been reviewed by Bo Lind, SGI.

The authors, Hjördis Löfroth (SGI), Michael Ledwith (Metria) and Jim Hedfors (SGI) 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.

Approval for publication was given by the undersigned

Linköping, November 2015

David Bendz
Research Director

Content

Sammanfattning

Markrörelser, vare sig de beror på naturliga processer eller mänsklig aktivitet, kan ofta vara tillräckliga för att orsaka skador på byggnader och infrastruktur. Sättningsmätningar i de centrala delarna av Göteborg har utförts under lång tid. I flera områden har metalldubbar installerats på byggnader och infrastruktur. För närvarande utför Göteborgs stad precisionsavvägning av dessa dubbar vart femte till sjunde år, vilket innebär en relativt stor arbetsinsats.

Satellitbilder täcker ett större område och kan bidra med ytterligare information såsom storlek och utbredning av sättningsrörelser inom ett område. Inom vissa områden behövs dock särskilt noggrann bestämning av pågående rörelser, vilket kräver precisa metoder såsom precisionsavvägning. I dessa fall kan dock satellitbilder bidra med insikt om inom vilka områden mer noggranna mätningar behövs. Utifrån satellitbilder är det också möjligt att fastställa pågående rörelser inom ett område före utförandet av en schakt eller andra konstruktionsarbeten.

Syftet med detta projekt är att undersöka om interferometri med användning av mycket höguppflösta radarsatellit TerraSAR-X-bilder, kan förbättra resultaten från en tidigare studie och generera tillräckligt detaljerade sättningsmätningar i ett urbant område, för att de ska kunna användas som bas i en kommersiell tjänst.

Differentiell interferometri, eller DInSAR, bygger på en metod att extrahera ytliga höjdvärden från ett radarbildpar (interferometri). Genom att använda denna metod kan små ytrörelser – mindre än en centimeter – mätas noggrant. I denna studie gjordes DInSAR-bearbetning med användning av den kommersiellt tillgängliga mjukvaran Erdas Imagine tillsammans med Radar Suite-modulen.

Permanenta spridare (PS) eller tidserier DInSAR bygger på DInSAR-funktioner och teknik där en stack av differentiella interferogram införlivas (relativt en enstaka huvudbild). Hänsyn tas endast till de tidskoherenta pixlar som är närvarande i alla bildpar (det vill säga permanenta spridare). I denna studien genomfördes tidsserieproceduren efter att DInSAR-analysen färdigställts. Genom att använda mellanliggande resultat identifierades potentiella permanenta spridare baserat på ett högt koherensvärde genom samtliga bildpar.

En jämförelse mellan resultaten från tidserier DInSAR och precisionsavvägning indikerar att, generellt, är sättningshastigheten som erhålls från tidserier DInSAR-analysen något högre än sättningshastigheten mätt med precisionsavvägning. Man ska då komma ihåg att mätperioden för de två mätmetoderna skiljer sig åt. Det kan också noteras att de områden där pågående sättningar observeras är ungefär desamma med båda metoderna, men baserat på tidserier DInSAR-analysen är dessa områden större.

För att få en överblick av pågående sättningar och sättningshastighet inom ett område kan tidserier DInSAR förväntas bli ett användbart komplement till traditionella metoder för sättningsmätning. Detta har också noterats av Trafikverket som kommer att använda tidserier DInSAR som ett komplement till precisionsavvägning och bälgslangsmätningar för att följa upp sättningar i samband med byggandet av Västlänken i Göteborg.

1. Summary

Ground movements, whether they are attributed to natural processes or to human activity, are often sufficient to cause damage to buildings and infrastructure. Subsidence measurements in the central parts of Gothenburg have been carried out for a long time. Metal pegs have been installed in several places around buildings and infrastructure. Currently, precision leveling of the pegs is carried out every fifth to seventh year by the City of Gothenburg, which requires a great deal of work.

Satellite images cover a wide area and can provide additional information such as the magnitude and distribution of movements in an area. In certain areas, the requirements demand very precise movement measurements through methods such as precision leveling. However in these cases, the satellite images can provide insight as to which areas need the more detailed precision leveling. It is also possible to ascertain ongoing movements in an area before an excavation or similar construction.

The objective of the project is to investigate whether interferometry using very high resolution satellite radar TerraSAR-X images, can improve the results from a previous study and provide detailed enough subsidence measurements in an urban area, to serve as the basis for a commercial service.

Differential interferometry, or DInSAR, builds upon a method of extracting surface elevation values from a pair of radar image (interferometry). Using this technique, small surface displacements – less than one centimeter can be precisely measured. DInSAR processing was carried out using the commercially available Erdas Imagine software, along with the Radar Suite module.

Permanent scatter (PS) or time-series DInSAR builds upon DInSAR functions and techniques by incorporating a stack of differential interferograms (relative to a single master image). However, only the time-coherent pixels that are present in all image pairs (i.e. permanent scatterers) are considered. The time-series procedure was carried out after the completion of the DInSAR analyses. Using the intermediary results, potential permanent scatterers were identified based on a high coherence value throughout all of the image pairs.

A comparison between the results from time-series DInSAR analysis and precision leveling indicates that, in general, the settlement rates obtained by time-series DInSAR are slightly higher than the settlement rates measured by precision leveling. It should then be remembered that the measurement period for the two measurement methods differ. It can also be seen that the areas where ongoing settlements are observed are about the same by both methods, but based on the time-series DInSAR analysis these areas are larger.

To get an overview of settlement rates in an urban area, time-series DInSAR is expected to be useful as a complement to traditional settlement methods. This has also been noticed by the Swedish Transport Administration that will use time-series DInSAR as a complement to precision leveling and bellow-hose settlement gauges to follow-up on settlements for construction of the West Link in Gothenburg.

2. Introduction

2.1 Background

Gothenburg is Sweden's second largest city situated on the west coast in an area, to a great extent, covered with deposits of high compressible soft clays and thus prone to landslides. Vertical movements caused by applied loads from buildings and infrastructure built on the soft and compressible clays occur continuously, but with varying rate. Vertical movements can also be attributed to natural processes such as ground water fluctuations.

Ground movements, whether they are attributed to natural processes or to human activity, are often sufficient to cause damage to buildings and infrastructure. It is important to distinguish between slow movements related to load of structures, which will cause long term damage, and rapid movements related to low stability, which involve acute safety risks. For municipalities and builders, getting geotechnical information concerning on-going movements in an area is also crucial prior to the start of construction building.

Subsidence measurements in the central parts of Gothenburg have been carried out for a long time. Metal pegs have been installed in several places around buildings and infrastructure. Currently, precision leveling of the pegs is carried out every fifth to seventh year by the City of Gothenburg. This requires a great deal of work and the measurements have to be carried out in a rotating basis with portions of the total monitored area measured each year.

Satellite images cover a wide area and can provide additional information such as the magnitude and distribution of movements in an area or region. In certain areas, the requirements demand very precise movement measurements through methods such as precision leveling. However in these cases, the satellite images can provide insight as to which areas need the more detailed precision leveling. It is also possible to ascertain ongoing movements in an area before an excavation or similar construction. By combining information of the movements of structures/buildings, related to their foundation, and eventual general movements of a larger area, it will be possible to distinguish between natural and anthropogenic movements. In addition, anomalies and disturbances in the ground movement pattern that may lead to acute risks can be detected. It will also be possible to identify areas where further investigation related to low stability/landslides or foundation of structures is needed.

Figure 1 Approximate area (blue rectangle) covered by TerraSAR-X Stripmap images centered over central Gothenburg.

In Sweden the use of interferometry has been limited. In 2008, SGI and Metria, carried out a project to compare the vertical land movement measurements obtained using satellite radar images to those using traditional methods (RyS dnr 171/07, Löfroth and Ledwith, 2010). The focus in this project was subsidence of buildings and infrastructure.

A main conclusion of the project is that the resolution of the radar images (12.5m pixels from the ERS-1/2 satellites, which were further degraded during the analysis) hindered the specification of objects that were measured. In addition, the accuracy of the vertical movements was not sufficient. The main idea of this project is to build upon those results by utilizing very high resolution, TerraSAR-X images, which are available in resolutions of one to five meters, as the input into the differential interferometry analysis (Figure 2). As the wavelength of the TerraSAR-X radar is smaller than ERS1/2 (31 mm instead of 56 mm) the accuracy of the subsidence measurements will increase, with approximately 50%, making it possible to measure movements smaller than one centimeter. Thus, as demonstrated in the previous study, DInSAR/PInSAR can be used to detect vertical movements, although the accuracy needs to be enhanced.

Figure 2 Comparison of the raw pixel sizes of an ERS SAR image and a TSX image (three red boxes). The three yellow boxes represent the corresponding resolution after the image processing has been conducted. The differences in the area of analysis highlight the difficulty in resolving a specific radar reflector (e.g. automobile, statue, roof top.) within an analysis cell and the relationship between image resolution and the eventual results.

2.2 Objective

The objective of the project is to investigate whether interferometry using very high resolution satellite radar images, can improve the previous results and provide detailed enough subsidence measurements in an urban area, to serve as the basis for a commercial service.
The project goals are:

- To enhance the accuracy of measurements of vertical land movements in the Gothenburg area, using the most appropriate interferometric technique (DInSAR/PInSAR) on very high resolution satellite radar images (TerraSAR-X);
- To deliver a product that identifies the sections of urban areas that are experiencing vertical land movement;
- To develop a product that gives reliable information of the size of the measured movements (e.g. mm/month) and the trend of the movements (increasing/decreasing);
- To compare the results with measurements of subsidence using traditional methods, and to restrain the need for traditional measurements for monitoring purposes in urban areas;

3. Methods and area for validation

3.1 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 finegrained 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 implies 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).

In Sweden, the isostatic rebound 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. The earth tide-effect generates fluctuations of the earth crust with about 25 cm in central Sweden. However, by using a local or regional fix-point as reference (that is lifted in the same way as the studied object) the effect of the moon gravity may be disregarded. In addition, as the satellite image is acquired at the same time of the day the influence should be negligible.

3.2 Radar remote sensing – Satellite analyses for measurement of subsidence

3.2.1 The DInSAR method

Differential interferometry, or DInSAR, builds upon a method of extracting surface elevation values from a pair of radar image (interferometry). Using this technique, small surface displacements – less than one centimeter – can be precisely measured.

The DInSAR method utilized in this study requires two radar satellite images in side-look complex format, as well as an existing digital elevation model over the study area. In this case, two digital elevation models were tested. The standard GGD elevation model (with a 50m cell resolution and a +/- 2.5m elevation accuracy) and the newer Swedish national elevation model (NH 2+), which was degraded to a 5m model. The major advantage of the two-image plus elevation model technique is that it doesn’t introduce any additional atmospheric error into the calculation of the interferograms.

An important factor in the processing of the radar images is the distance between the two perpendicular baselines of the two images. Generally, a perpendicular baseline of less than 200m – the so-called Short Baseline – is recommended for differential analyses, which was achieved in this study.

A second critical factor in DInSAR analyses pertains to the coherence, or measure of intra-scene stability at the wavelength scale, between the two input images. This must be as high as possible for a successful result. Previous research (Crosetto et al, 2005) indicates that an interferogram with coherence >0.5 is acceptable, in general, while urban areas might have a lower value (>0.35).

3.2.2 The Time-series DInSAR method

Permanent scatter (PS) interferometry was developed in the late 90's in an attempt to compensate for some of the limitations of "normal", or repeat pass, interferometry (i.e. temporal decorrelation). The method builds upon DInSAR functions and techniques by incorporating a stack of differential interferograms (relative to a single master image). However, only the time-coherent pixels that are present in all image pairs (i.e. permanent scatterers) are considered.

Permanent scatterer candidate pixels are identified, the atmospheric phase is accounted for via a filtering algorithm and – during the final estimation – points with a low estimated coherence are discarded. Typically there will be several hundred usable points per km^2 in an urban setting.

The methodology does not take horizontal movements into account. Thus, any horizontal movement will have an effect on the result, although the way of correcting this is to use a time series of measurements to get a trend of the movement.

3.2.3 Methods for correction of land lift

Post-glacial rebound, or isostatic adjustment, affects northern land masses that were pressed downward from the weight of the ice sheets during the last glacial period. Two methods were used separately during the analyses to account for this natural land lift in the Gothenburg region.

The simplest means to correct for natural land lift is to calculate the expected rise, using published data from the Geological Survey of Sweden, for the time elapsed between the registrations of the images. The average land lift here is between 1 and 1.25 mm/year, according to a published map from the National Land Survey. A disadvantage with this technique is that land lift is not typically continuous, occurring at a single fixed rate. Additionally, the value has been extrapolated from a generalized map and the actual rate might be very different from the published figure.

A different, more robust, method is to establish a fixed point, where it is assumed that no differential vertical movement has occurred, and calculate all land movements relative to this point. The disadvantage with this method is that there are no real fixed reference points. Any fixed point on the surface of the earth is very likely going to experience some sort of movement. However, this addition source of uncertainty can be minimized by choosing a good reference point.

3.3 Traditional measurement of settlements

3.3.1 Precision leveling by the City of Gothenburg

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 beginning of the 20th century, 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, their location is defined by coordinates and the location is shown on a map of the actual quarter (see Figure 4 below). Precision leveling of the pegs are today carried out every fifth to seventh year by the City of Gothenburg using precision leveling instrument. A time-scheme of the measurements is included in Annex 1. The accuracy of the measurements is one tenth of a millimeter. The results of the measurements are noted in Excel sheets.

3.3.2 Precision leveling for the West Link

For the construction of the commuter train tunnel under the central part of Gothenburg, The West Link, a program for measurements of ongoing settlements has been established. In several areas (see Annex 2), metal pegs on buildings, bridges and on the ground have been installed. Their location is defined by coordinates and the location is shown on maps (see Annex 2). These metal pegs are measured by precision leveling. The results of the measurements are noted in Excel sheets, one for each area.

In addition, bellow-hose settlement gauges have been installed vertically in the ground, which will enable measurements at different levels in the ground enabling determination of in which layers settlements occur.

4. Analysis of subsidence measurements

4.1 Analyses based on EO-data

To carry out the analyses based on EO-data a “stack” of radar satellite images, i.e. five satellite images over the same area (Gothenburg), and one archive satellite image was acquired from EADS-Astrium. Information of the sensors and date of registration of the satellite image is shown in Table 1.

Table 1 Radar satellite images used in the study.

Sensor	Source	Date
TerraSAR-X	Archive	2009-05-11
TerraSAR-X	New registration	2012-05-26
TerraSAR-X	New registration	2012-11-07
TerraSAR-X	New registration	2013-04-10
TanDEM-X	New registration	2013-10-25
TanDEM-X	New registration	2014-03-28

4.1.1 DInSAR processing procedure

General procedure

The DInSAR processing was carried out using the commercially available Erdas Imagine software, along with the Radar Suite module. The technique involves a number of pre-processing and processing steps. The table below provides details concerning the orbital relationship of the image pairs:

Table 2 Details concerning the orbital relationship of the image pairs for the DInSAR processing.

Image Pairs	Baseline (m)	Parallel Baseline (m)	Perpendicular Baseline (m)	Height of Ambigui-ty (m)
2012-05-26 and 2012-11-07	77.75	32.3	70.72	102.25
2012-05-26 and 2013-04-10	203.9	-54.59	-196.46	36.79
2012-05-26 and 2013-10-25	298.27	-229.27	190.79	37.9
2012-05-26 and 2014-03-28	425.38	-423.97	34.64	-

Single Look Complex (or SLC) images are required for the analysis because only SLC images contain the required phase information. However, these images are considered “raw” and need to be imported into the software program, along with elevation data. The two radar images (master and slave) are then co-registered to each other manually.

A spectral shift filter is then established in order to maximize the coherence for each of the pixels of the interferogram, followed by the creation of the interferogram and differential interferogram. Unwrapping of the result, which involves reconstructing the absolute interferometric phase representing line-of-sight surface motion, comes next. Finally, baseline refinement, if necessary and generating a geo-referenced output is performed. Total processing time for a single image pair was on the order of a day.

Correction for natural land lift

As detailed previously, natural land lift was taken into account via two separate methods resulting in two slightly different DInSAR results. During the first analysis, the average movement (+1.25) was subtracted from the resultant displacement raster, after adjusting for the appropriate time period. For example, the radar image pairs from 2012-05-26 and 2012-11-07 are 165 days apart. So 0.565 mm/year ((165d/365d) * 1.25mm/year) was subtracted from the displacement raster.

During the second analysis, a fixed point – located on the small rocky isle of Skifteskär, west of the city, in Kattegat (57.65 N, 11.82 E) – was used. It was assumed that no differential movement occurred at this place and all other measurements are relative to this fixed reference point.

4.1.2 Time-series DInSAR processing procedure

General procedure

In 1999, the Permanent Scatterer Interferometry (PSI) technique was developed by researchers at the Polytechnic University of Milan, Italy, (Ferretti et.al., 1999, 2001). The PSI algorithm was patented, although the term PSI has come to mean any type of interferometric stacking approach. In other words, an advanced time-series approach to DInSAR. Such an approach was utilized during this project and will be herewith referred to as time-series DInSAR.

The time-series procedure was carried out after the completion of the DInSAR analyses, using the intermediary results. Potential permanent scatterers – both point scatterers within the urban environment and distributed scatterers distributed throughout the study area – were identified based on a high coherence value throughout all of the image pairs.

Based on the land cover classification of the Swedish Real Estate maps, approximately 52% of the radar images are covered by forest. An additional 13% is covered by water. These areas were excluded from further analysis due to inherent incoherence of these land cover types over time. The resultant focus area (consisting of urban areas, agricultural fields and open land) was approximately 713 km2. About 126,500 potential permanent scatterers were identified in these areas.

Weighted least-squares integration was used to obtain the unwrapped residual phase in the inteferograms. Atmospheric contribution to phase was then removed via a high-pass filter. Finally, any points that had an estimated coherence below a threshold of 0.4 were removed. The final result contained over 115,000 points with information pertaining to vertical movement.

Correction for natural land lift

For the DInSAR analyses, natural land lift was accounted for via the fixed reference point method. The movement rates associated with the permanent scatterer points were adjusted so that all movement rates are relative to the fixed point at Skifteskär. The table below (Table 3) shows the actual adjustments applied to the time-series DInSAR image pair results (cm/year), due to the reason that the level of the fixed point in relation to the master image differs between the DInSAR image pairs:

Table 3 Adjustments applied to the time-series DInSAR image pair results (cm/year).

	2012-11-07	2013-04-10	2013-10-25	2014-03-28
2012-05-26	-6.12			
2012-11-07		9.89		
2013-04-10			-3.63	
2013-10-25				1.46

4.2 Analysis of traditional measurements

4.2.1 Analysis of settlement measurements on metal pegs

The aim has been to compare the measured subsidence from satellite data with precision leveling from the same period of time.

However, the precision leveling by The City of Gothenburg is carried out every fifth to seventh year in a rotating scheme covering some quarters every year. To cover all measured quarters within the central part of Gothenburg, measurements from year 2000 to 2014 have been analyzed. During this period, precision leveling of the metal pegs have been conducted at least two times in each quarter. The satellite radar images, on the other hand, have been obtained covering the year 2009 (one image) and 2012 - 2014 (5 images) but only the ones between 2012 and 2014 have been possible to use in the DInSAR analyses.

Also, the precision leveling on metal pegs for the West Link do not cover the same period as the DInSAR analyses. They were installed, and zero measurements were carried out during the period May to August 2013. A second measurement has been carried out during the period April to June 2014, indicating a measuring period of nearly one year. The total number of point measurements is 476 pegs.

The results of this precision leveling are visualized in two GIS layers as a settlement in mm/year. In total 3411 point locations (2935 from The City of Gothenburg and 476 from the West Link) were used to compare with 17187 points (in the same sub-area) from the DInSAR dataset. Although the results are presented as a 2D point location map with classified settlement rates, each individual metal peg can be visualized in terms of settlement over time. Figure 3 shows an example of settlement for 4 metal pegs in the Gårda area between 1987 and 2012.

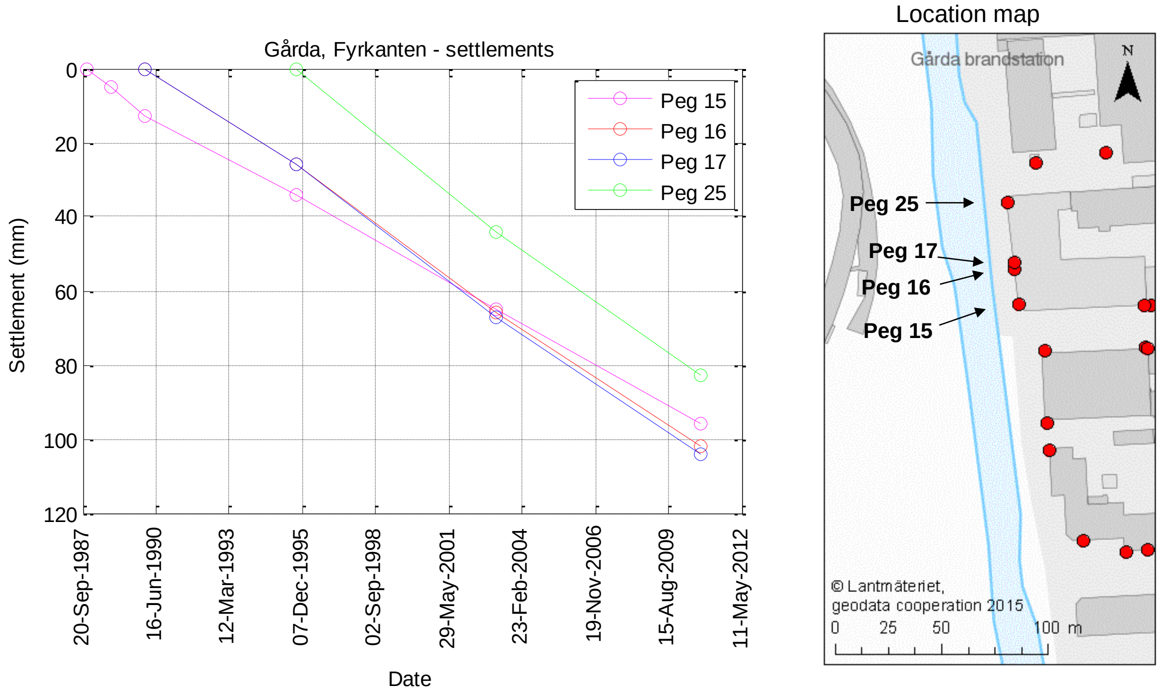

Figure 3 Time-series of settlements in quarter Fyrkanten, Gårda, between 1987-2012. Colored circles connected with lines represent the measurements for individual metal pegs, 15, 16, 17 and 25. The map to the right shows their locations.

4.2.2 Comparison of settlement with foundation method – examples

To be able to compare settlements of pegs on specific buildings with the foundation of the buildings for some quarters, the settlements also have been visualized as diagrams in Excel. As a basis for this analysis, measurements during the whole measuring period have been used.

Within the project an attempt has been made to link a high settlement rate of a building with type and year of foundation and the depth of soft clay for some chosen quarters. Three quarters with high settlement rate were chosen for this study; Quarter 15 Fyrkanten in the Gårda area; Quarter 21 Smaragden in the Heden area and Quarter 10 Kryssaren in the Masthugget area. Information about year of building permit and type of foundation for each building has been obtained from the City of Gothenburg, Office of City Planning.

In quarter Fyrkanten measurement of settlements has been carried out on 5 buildings. The buildings and the position of the metal pegs are shown in Figure 4 and foundation data in Table 4. As can be seen in Table 4 the buildings on four of the city plots are from the early 1900 and founded on wooden cohesion piles. On one of the city plots the building (Fire station) is from 1986 and founded on wooden and concrete creep piles. Limited information about clay depth on the quarter maps, indicate depths of more than 50 m. Thus, the age of the buildings differ, but the foundations of the buildings are quite similar and the depth of the clay as well.

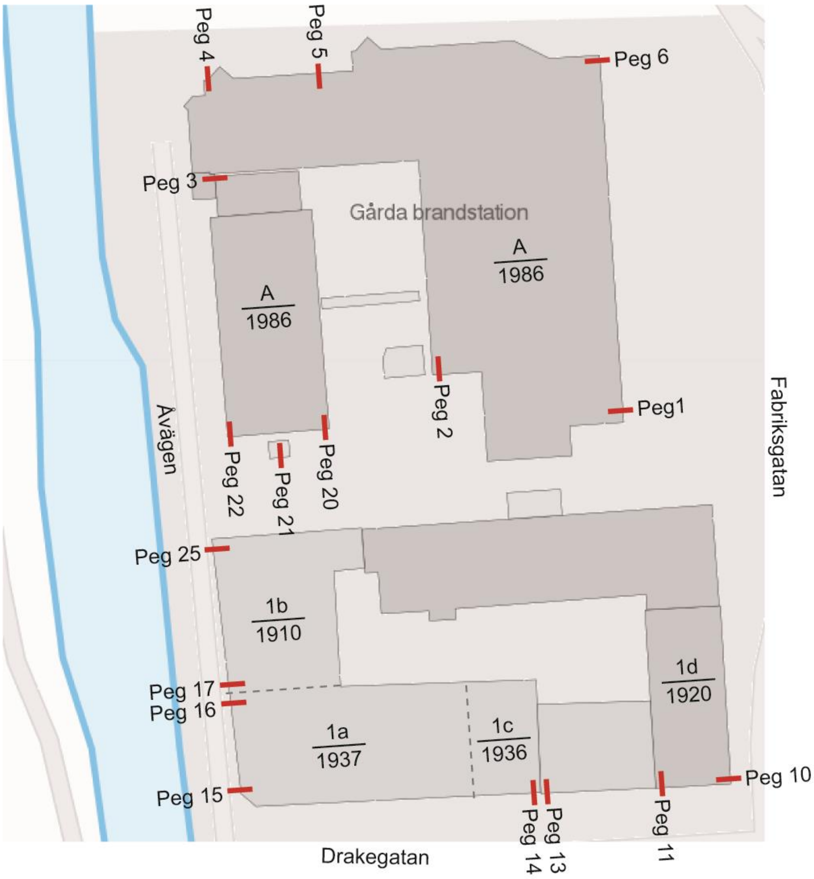

Figure 4 Quarter Fyrkanten, Gårda, location of buildings and metal pegs.

Table 4 Quarter Fyrkanten, Gårda, data of buildings.

City plot	Building permit (yr)	Type of foundation	Specifications of foundation	Remarks
A	1986	Interaction foundation, Creep piles	Wooden and concrete piles (total length 9 - 31 m)	
1a	1937	Cohesion piles	Wooden piles (total length ca 30 m)	Connected to 1b and 1c
1b	1910	Cohesion piles	-	Connected to 1a
1c	1936	Cohesion piles	Wooden piles (total length ca 30 m)	Connected to 1a
1d	1920	Cohesion piles	Wooden piles (total length 13 and 15 m)	Additional floor 1931

The measured rate of settlements, i.e. the inclination of the curves in Figure 5, is highest on the metal pegs 15, 16, 17 and 25. These pegs are located on building 1a and 1b along the street Åvägen. The rate of settlements on the metal pegs 10, 11, 13 and 14 on building 1c and 1d along Drakegatan are not that high despite the age and the foundation of these buildings are about the same. The settlement rate is about the same as the settlement rate for pegs 1 - 4 which is placed on the newest building.

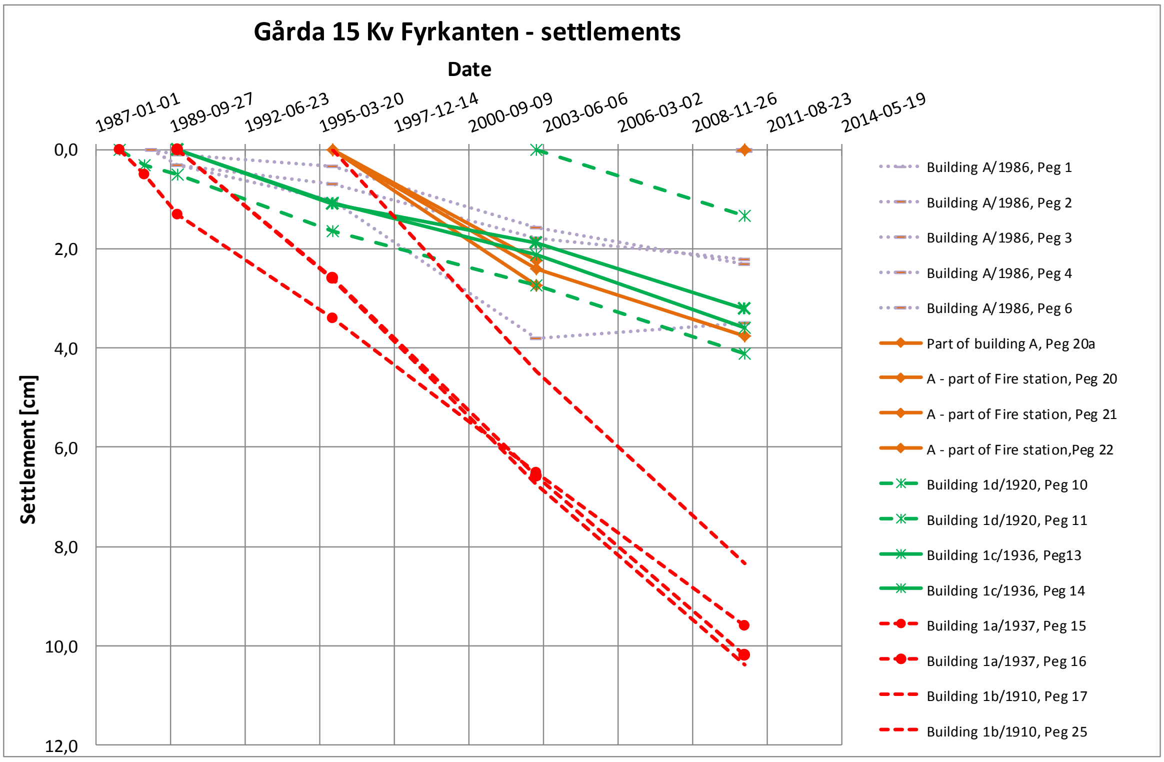

Figure 5 Settlements in quarter Fyrkanten, Gårda.

In quarter Kryssaren measurements of settlements have been carried out on 8 buildings. The buildings and the metal pegs are shown in Figure 6 and foundation data in Table 5. As can be seen in the table four buildings are from the late 1800's and founded on wooden rust bed and foundation walls. One building from 1985 has an interaction foundation with creep piles and the remaining buildings are from the mid-1900's and founded on cohesion piles. Point information about clay depth on the quarter maps indicate depths of more than 30 - 40 m within the quarter. So, the buildings are of varying age, the foundations are mainly of two types (wooden piles and rust bed) and the clay depth is about the same.

Figure 6 Quarter Kryssaren, Masthugget, location of buildings and metal pegs.

Table 5 Quarter Kryssaren, Masthugget, data of buildings.

City plot	Building permit (yr)	Type of foundation	Specifications of foundation	Remarks
16	1960	Cohesion piles	Wooden piles (total length 20 or 30 m)	Watertight cellar
3	1959	Cohesion piles	Wooden piles (total length 30 m)	
4	1985	Interaction foundation, Creep piles	Wooden and concrete piles (18 m and 3 - 12 m respectively)	Watertight cellar
15a	1906	Cohesion piles	-	
15b	1955	Cohesion piles	Wooden piles (total length 36 m)	Watertight cellar
15c	1953	Cohesion piles	Wooden piles (total length 36 m)	Watertight cellar
15d	1955	Cohesion piles	Wooden piles (total length 36 m)	Watertight cellar
15e	1950	Cohesion piles	Wooden piles (total length 36 m)	Watertight cellar
10	1874	Rust bed, foundation wall	-	
17	1873	Rust bed, foundation wall	-	
18	1868	Foundation wall	-	
19	1871	Rust bed, foundation wall	-	

The measured rate of settlements, i.e. the inclination of the curves in Figure 7 is highest on the metal pegs 14, 16, 19-25 and 28. That is the pegs located on the oldest buildings founded on rust bed and foundation wall. Thus, in this quarter there is a clear link between type of foundation and settlement.

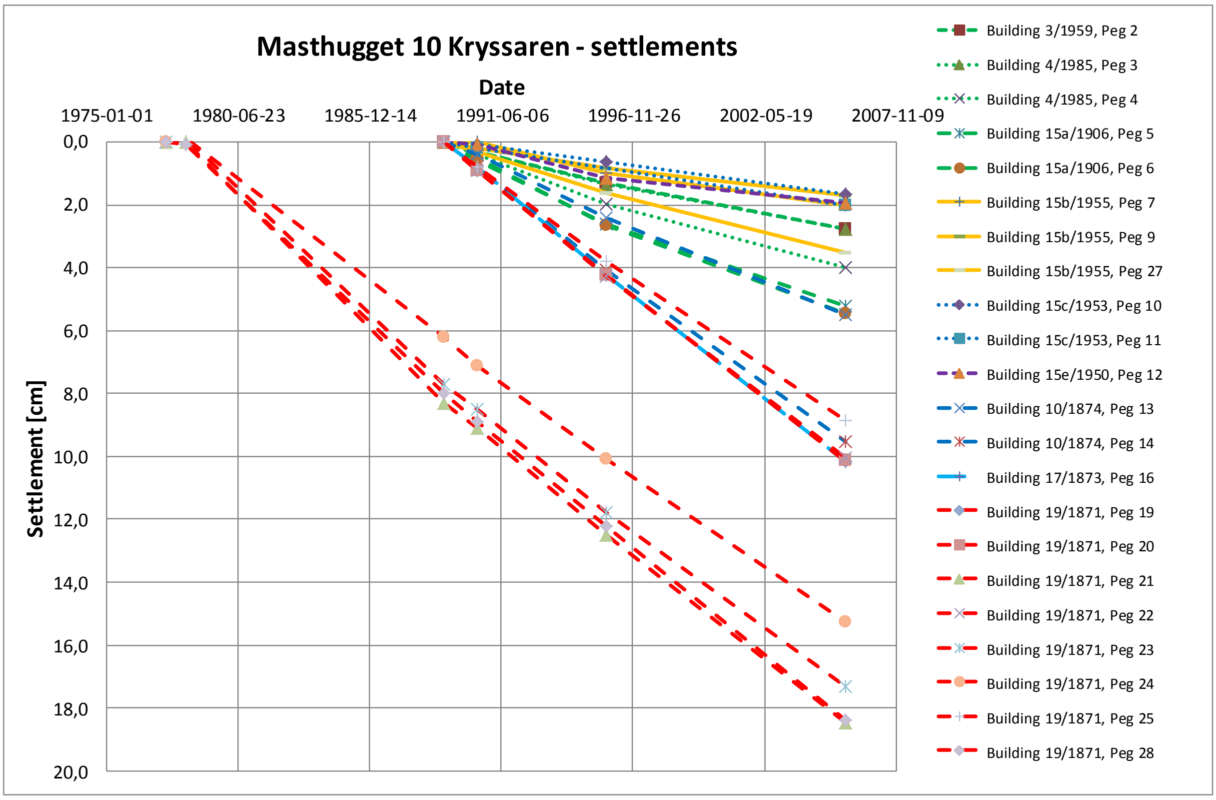

Figure 7 Settlements in quarter Kryssaren, Masthugget

In the third quarter Smaragden the foundations are rust bed with either wooden cohesion piles or foundation wall. All buildings are from the late 1800's. Limited information on the quarter maps indicate clay thicknesses of at least 15 to 20 m. In this quarter the highest settlement rate is concentrated to the metal pegs on one large building founded on rust bed and wooden cohesion piles.

One could expect buildings with older foundations to have higher settlement rate than newer and buildings with foundation walls to have higher settlement rate than buildings on cohesion piles. However, from this very limited study it is not possible to draw any general conclusions about settlement rate and type of foundation. For very old buildings probably the condition of the foundation is as important as the type of foundation.

5. Results and comparison of the subsidence measurements

5.1 Results of the satellite analyses

5.1.1 DInSAR analysis

DInSAR analyses were conducted on all radar image pairs resulting in fifteen interferometric analyses over the area. Unfortunately, five of the DInSAR results, those that include the 2009 image, turned out to be unusable. Over time, the DLR (Deutsche Luft Raum) have adjusted the parameters of the satellite so the quality of the images have improved. A list of all the combinations is given in Table 6 below.

Each result was analyzed visually. This is one of the strengths of the DInSAR analysis in that the result provides a continuous surface of measurements over the study area. Areas that show indications of significant change compared with the surrounding area can then be isolated and investigated in more detail. An example of one of the DInSAR analyses is detailed below, Table 6 and Figure 8.

Table 6 A cross-diagram showing the image pairs used for DInSAR analysis. In total, 15 pairs were constructed, although the results that include the 2009 image were not usable.

Image registration date	2009-05-11	2012-05-26	2012-11-07	2013-04-10	2013-10-25	2014-03-28
2009-05-11		X	X	X	X	X
2012-05-26			X	X	X	X
2012-11-07				X	X	X
2013-04-10					X	X
2013-10-25						X

Figure 8 shows the result of the DInSAR analysis between the images acquired in October 2013 and March 2014. Red-orange colors indicate subsidence (negative values) and green-blue colors indicate lift (positive values). It should be noted that the image in this figure has not been edited to take into account forested areas, which become incoherent fairly rapidly and thus the values over these areas cannot be considered trustworthy. Although the scale of the data shown in the figure extends from about -15 cm/year (subsidence) to almost 18 cm/year (uplift), the vast majority of the area is shaded yellow indicating insignificant movement. In any case, certain trends are evident, in particular when focusing on the central area of Gothenburg, surrounded by a black square and detailed further below and in Figure 9.

The area around the central portion of Gothenburg has four to five areas indicating greater than background subsidence between October 2013 and March 2014. In addition, three areas show a slight uplift during the same period. It should be pointed out that the measured uplift in question is, at most, two centimeters in this area and that the measurement precision for a DInSAR analysis with x-band radar images is one-half of a wavelength, or 1.9 cm.

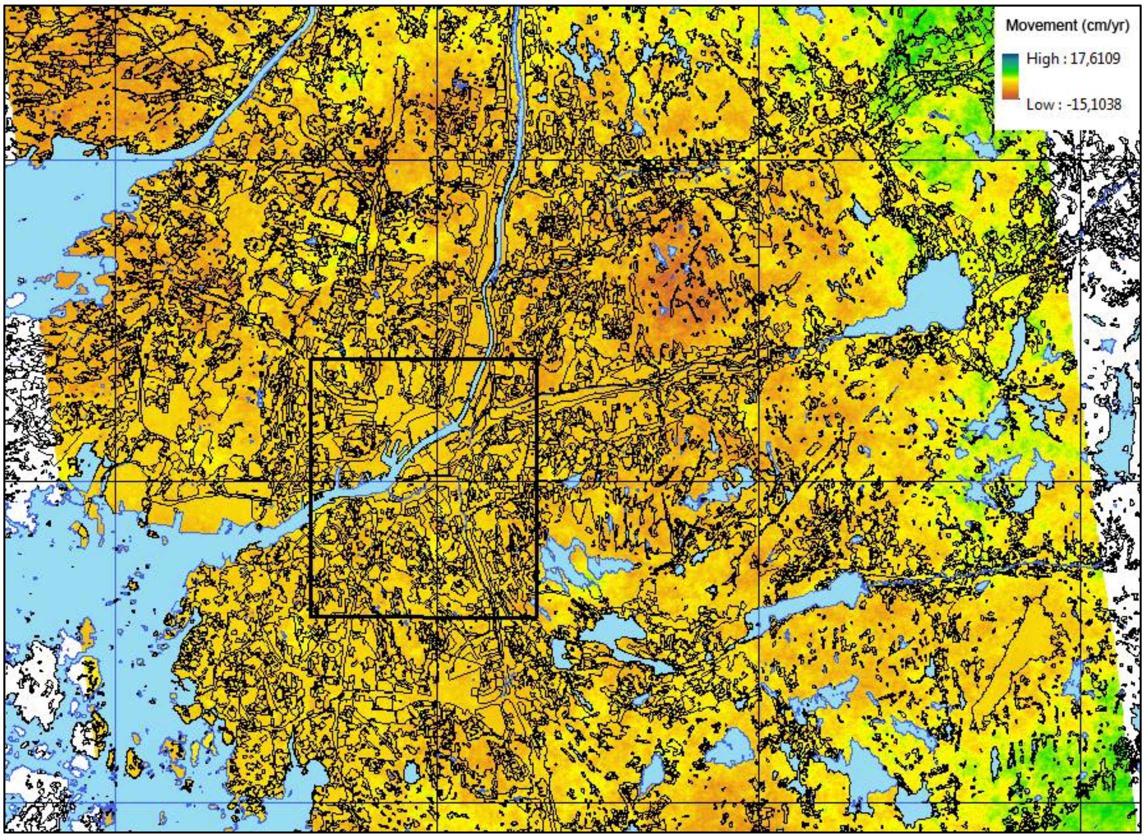

Figure 8 A close-up image showing the result of the DInSAR analysis for the images from October 2013 and March 2014. The results shown have not been corrected to take into account forested areas.

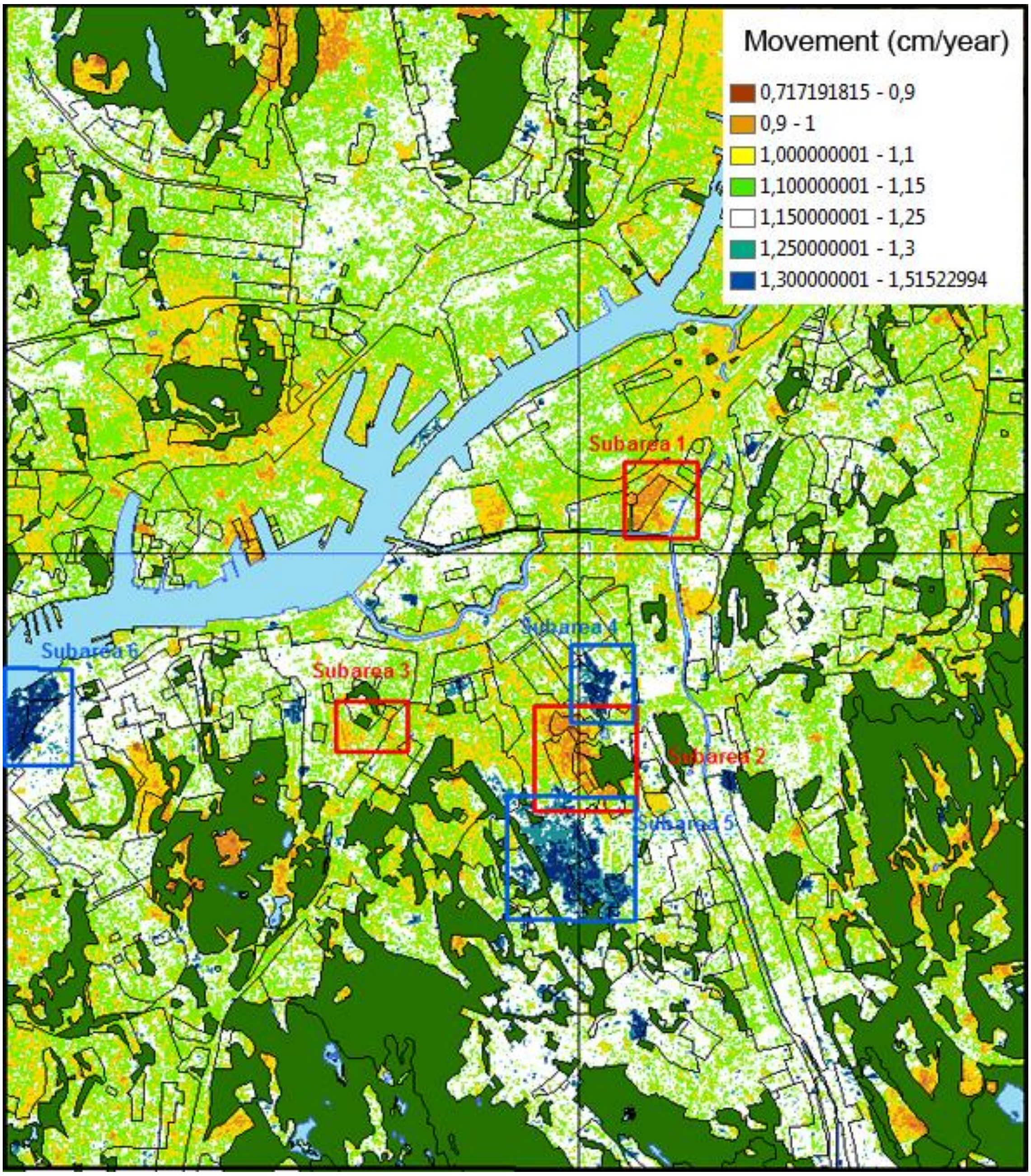

Figure 9 A closer view of the center of Gothenburg. The dark green polygons are forested areas and the light blue polygons are water bodies according to the National Land Survey's Real Estate maps. The majority of the area shows no significant sign of movement (within the error of margin considering the wavelength of the x-band radar signal), although a few areas do stand out (dark orange suggest subsidence, dark blue lift). The red (subsidence) and blue (lift) rectangles mark areas that are discussed further in the text.

An area south of the main train terminal, called Stampen (Subarea 1), contains measurements that suggest slight subsidence, as do a residential areas (Subarea 2) to the northeast of Chalmers University of Technology (bisected by Viktor Rydbergsgatan) and to the southwest of Haga, in an area called Olivedal (Subarea 3). Lindholmspiren, which extends out into the river Göta älv, also shows signs of movement.

The three areas that appear to have experienced uplift during the period between image registrations are a part of Lorensberg by the Museum of Art (Subarea 4), parts of Johanneberg currently occupied by Chalmers University of Technology (Subarea 5) and the Stena Line terminal to Germany) (Subarea 6).

Again, it should be pointed out that the DInSAR analyses – when taken individually – are more suited to being used as a tool to identify potential areas of interest. It is the continuous nature of the results that provides the important input into visual interpretation. However, areas that have low coherence (e.g. forested areas and parks) as well as pixels that have undergone radical change (e.g. movement of a parked automobile) will remain in the final result. This is one reason why advanced methods, such as time-series DInSAR analysis have been developed – to take into account the spurious results from areas that have low coherence and to concentrate solely on the data that can provide dependable information.

5.1.2 Time-series DInSAR analysis

The time-series DInSAR analysis was developed as a way to capture the completeness/thoroughness of the "standard" DInSAR analysis, while at the same time using statistical methods in order to both exclude pixels that don't maintain a consistent level of signal coherence through time and to refine the precision of the measurements down to a millimeter level. This latter capacity is done through the use of a large number of radar images and the establishment of a linear trend for each measurement pixel.

An overview of the settlement rate as a result of the time-series DInSAR analysis is shown in Figure 10. Based on the results from the time-series DInSAR analysis between the year 2012 and 2014 there are ongoing settlements of 4.0 - 5.0 mm/year and > 5.0 mm/year in several areas. Examples of such areas are Masthugget in the west (Subarea 1), north of and immediately south of Stora Hamnkanalen in the central area within Vallgraven (Subarea 2), the area of Gullbergsvass in the north and Stampen, Heden and Gårda in the east (Subarea 3). Areas with no or very little settlements based on the results of the time-series DInSAR analysis are the southern part within Vallgraven, Haga and Vasastaden (Subarea 4).

Comparing the results from the time-series DInSAR with the general results from the less advanced DInSAR (Section 5.1.1) there are similarities but also several differences. The area called Stampen (Subarea 1 in Figure 9, above) appear to have experienced settlements according to both methods. The Subareas 2, 3 and 5 in Figure 9, where the DInSAR indicate signs of settlement, the time-series DInSAR do not indicate more settlements than in adjacent areas. At the Stena Terminal (Subarea 6 in Figure 9) the DInSAR indicate heave whereas the time-series DInSAR indicate more settlement than in other areas.

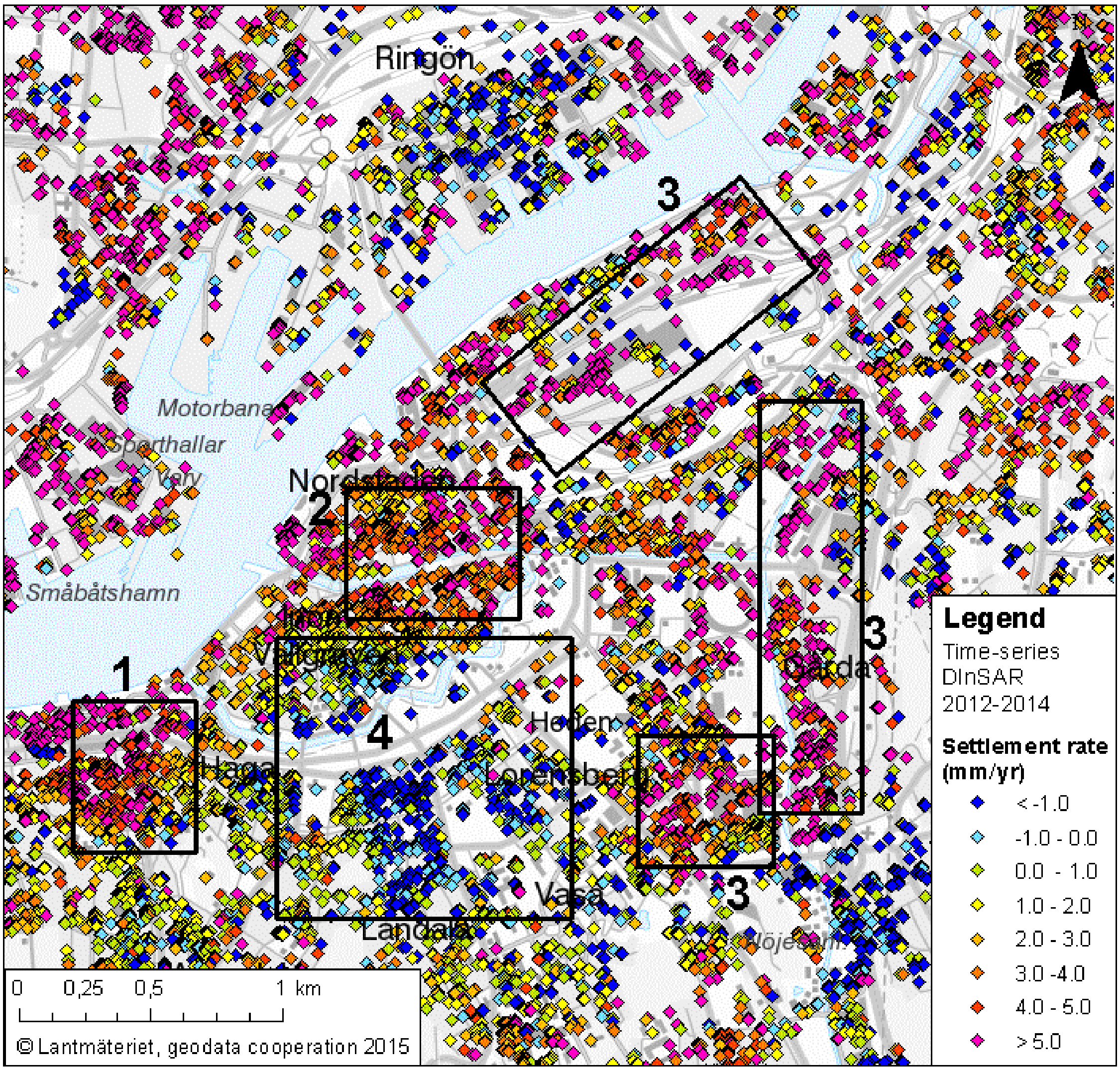

Figure 10 Overview of settlement rate in mm/year during the period 2012 to 2014 by time-series DInSAR analysis. Observe that the numbering of the Subareas is not the same as in Figure 9.

5.2 Results of the traditional measurements

5.2.1 Results of measurements

An overview of the settlement measurements conducted by the City of Gothenburg show that in most areas there are no ongoing settlements, i.e. a settlement rate of -1.0 to +1.0 mm/year during the studied period 2000 to 2014. There are some areas with high settlement rate, i.e. 4.0 - 5.0 or >5.0 mm/year, e.g. Masthugget in the west (Subarea 1 in Figure 11), Gullbergsvass in the north (Subarea 2 in Figure 11), an area close to Stora Hamnkanalen in the center (Subarea 3 in Figure 11), Gårda in the east (Subarea 4 in Figure 11) and some smaller spots. The settlement measurements from the Swedish Transport Administration are shown in Figure 12.

It can be seen that the settlement rates measured by precision leveling are generally lower than the settlement rates resulting from the time-series DInSAR analysis. However the areas where ongoing settlements are observed are about the same, but based on the time-series DInSAR analysis these areas are larger.

Also the central area to the south with small or no settlements, within Vallgraven, Haga and Vasastaden (Subarea 5 and further southeast in Figure 11), coincide, with the result of the time-series DInSAR analysis (Subarea 4 in Figure 10). However, compared to the result of the precision leveling this area with small settlements is extended both to the north and to the east by the time-series DInSAR analysis.

To compare the measurements from the precision leveling with the time-series DInSAR analyses, some areas will be visualized more in detail and described in Chapter 5.3.

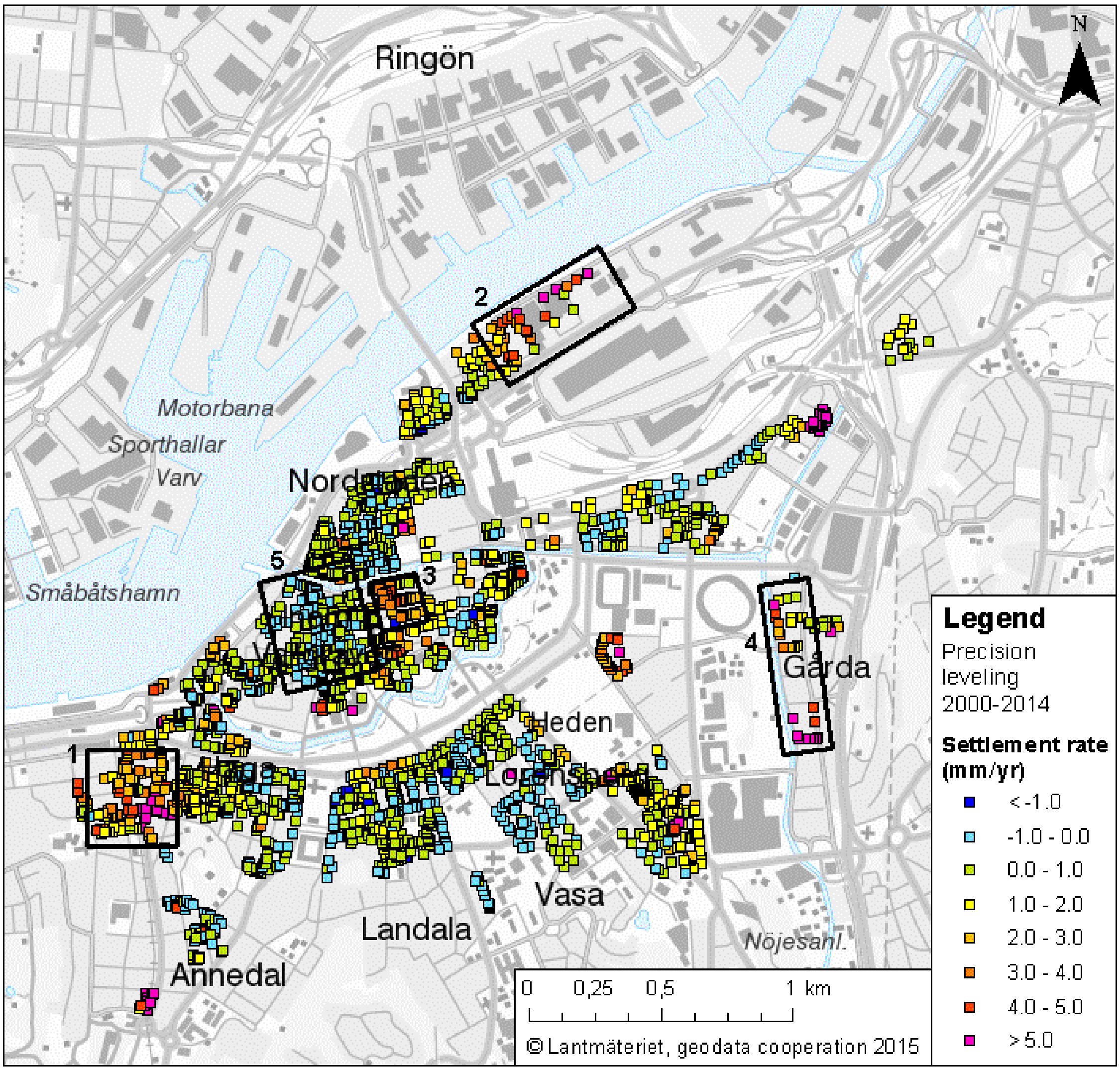

Figure 11 Overview of settlement rate in mm/year during the period 2000 to 2014, measured on metal pegs by precision leveling – central Gothenburg.

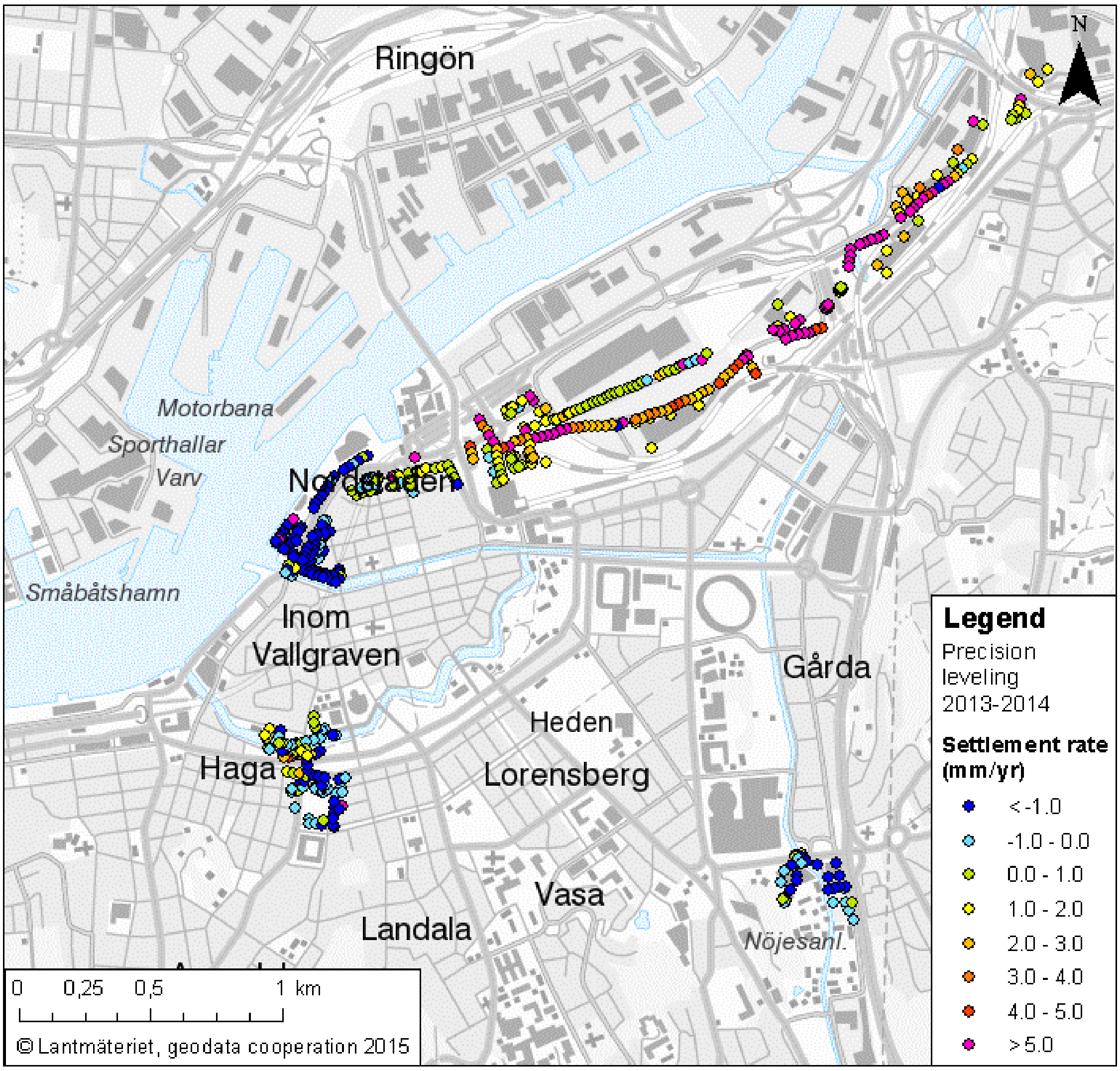

Figure 12 Overview of settlement rate in mm/year measured by the Swedish Transport Administration during the period May 2013 to July 2014.

5.2.2 Settlement linked to foundation method – examples

From the results of the very limited study described in Section 4.2.2 it is not possible to draw any general conclusions about settlement rate and type of foundation of a building. For very old buildings probably the condition of the foundation is as important as the type of foundation.

5.3 Comparisons of the results

5.3.1 Comparison of settlements in the central and western part

The central and western part of the area where precision leveling is carried out is shown in Figure 13 and the same area but with the results from the time-series DInSAR analysis is shown in Figure 14. In Figure 15 all the measured settlement rates are included, both the settlement rate measured on metal pegs by precision leveling by The City of Gothenburg during the period 2000 to 2014 and the precision leveling carried out by the Swedish Transport Administration 2013 to 2014 as well as the settlement rates measured by the time-series DInSAR analysis 2012 to 2014. Observe that the measurement period differ between these three measurements.

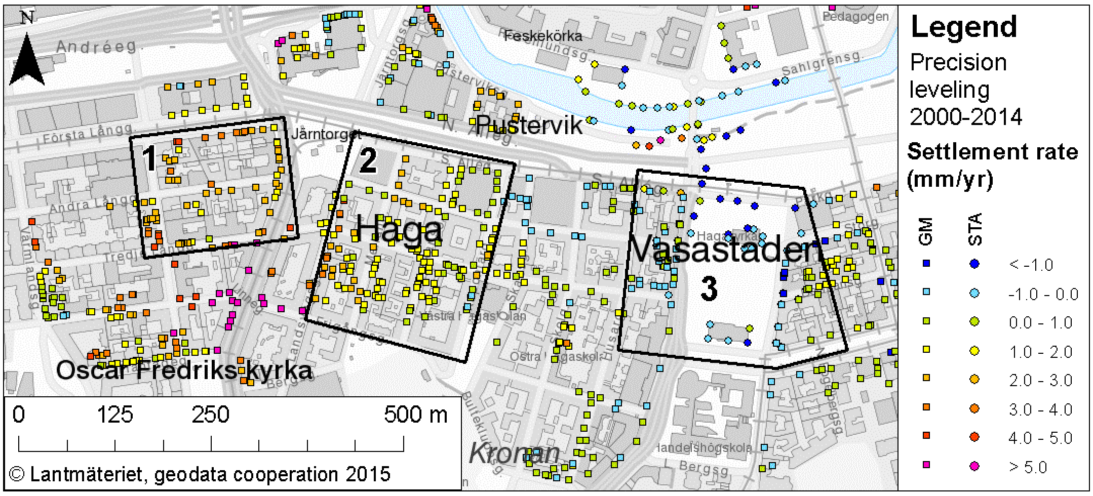

Figure 13 Settlement rate in mm/year during the period 2000 to 2014, measured on metal pegs by precision leveling – the western and central part. In the legend GM stands for the City of Gothenburg (i.e. Gothenburg Municipality) and STA for the Swedish Transport Administration. The measurements by STA do only cover the year 2013 to 2014.

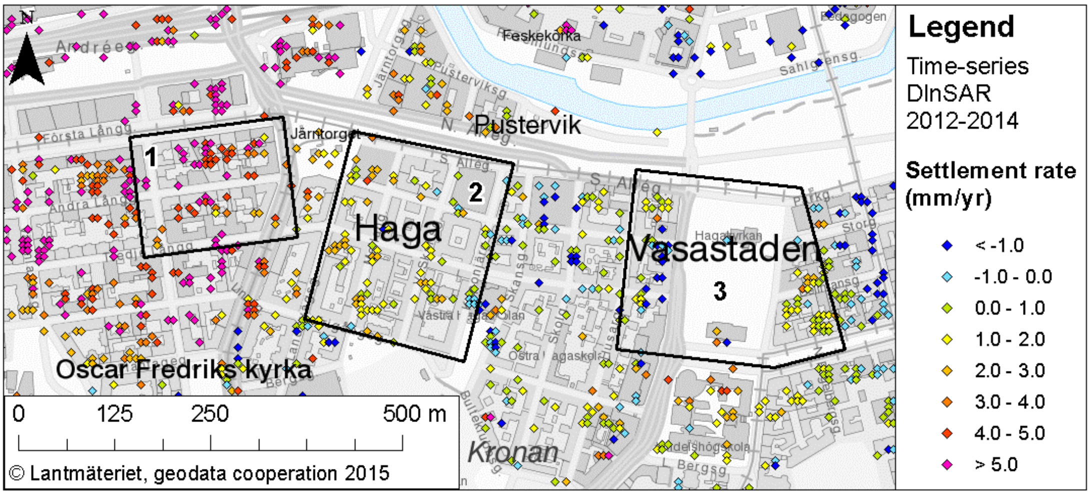

Figure 14 Settlement rate in mm/year during the period 2012 to 2014 by Time-series DInSAR analysis – the western and central part.

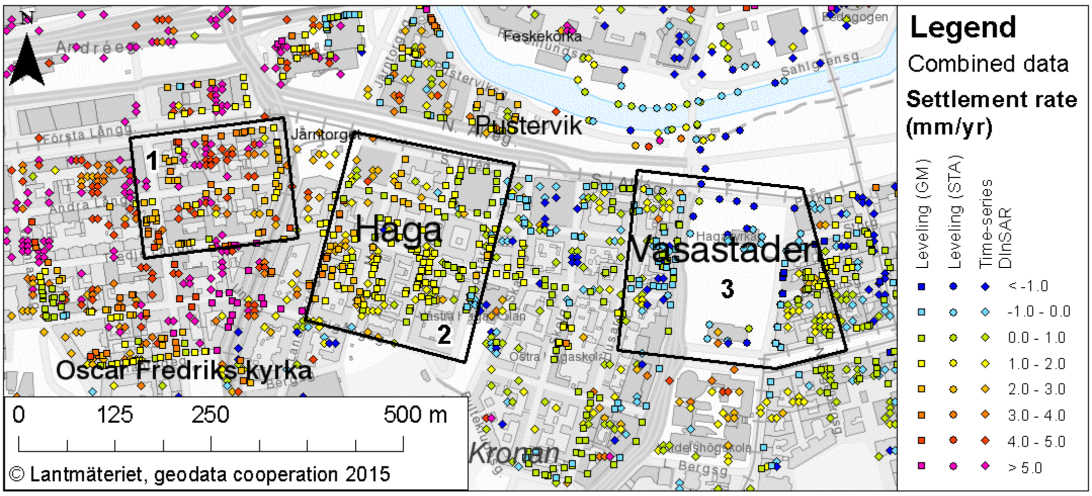

Figure 15 Settlement rate in mm/year in the western and central part, including both the measurements by precision leveling during the period 2000 to 2014 by The City of Gothenburg (GM), the Swedish Transport Administration (STA) and the result of the time-series DInSAR analysis during the period 2012 to 2014.

Comparing the settlement rate in the area of Masthugget in the west, it can be noted that the settlement rate in the two northern quarters (Area 1 in Figure 13 and Figure 14) is mainly between 2.0 and 4.0 mm/year measured by precision leveling. The corresponding settlement rate in these quarters by time-series DInSAR is mainly from 4.0 to larger than 5.0 mm/year. However, in the quarters immediately south of Area 1, both types of measurements show settlement rates of more than 5.0 mm/year.

In the western part of Haga, immediately to the east of Masthugget (Area 2 in in Figure 13 and Figure 14) the settlement rates both from the precision leveling and the time-series DInSAR analysis are between 0 to 3.0 mm/year. Even though the measurement points do not coincide between the two methods, both methods show the highest settlement rates in the western part of the area.

Further to the east, around Vasakyrkan (Area 3 in Figure 13 and Figure 14) both the precision leveling and the time-series DInSAR analysis show from more than 1.0 mm/year heave to 1.0 mm/year settlements.

5.3.2 Comparison of settlements in the northern part, Gullbergsvass

The northern part of the area where precision leveling is carried out is shown in Figure 16 and the same area but with the results from the time-series DInSAR analysis is shown in Figure 17. In Figure 18 all the measured settlement rates are included. Observe that the measurement period differ between these measurements.

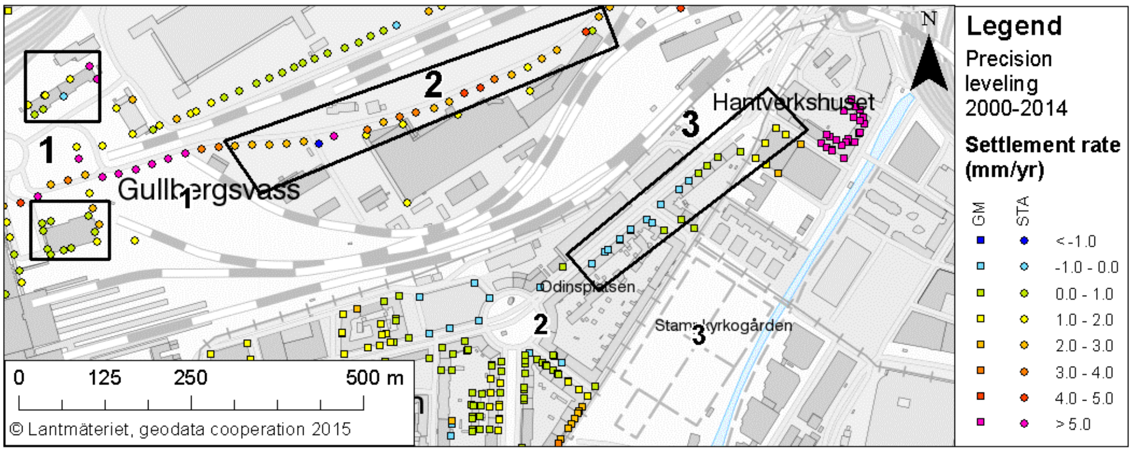

Figure 16 Settlement rate in mm/year measured by precision leveling by The City of Gothenburg (GM) during the period 2000 to 2014 (squared points) and precision leveling by the Swedish Transport Administration (STA) (round points) during the period 2013 to 2014 – the northern area, Gullbergsvass.

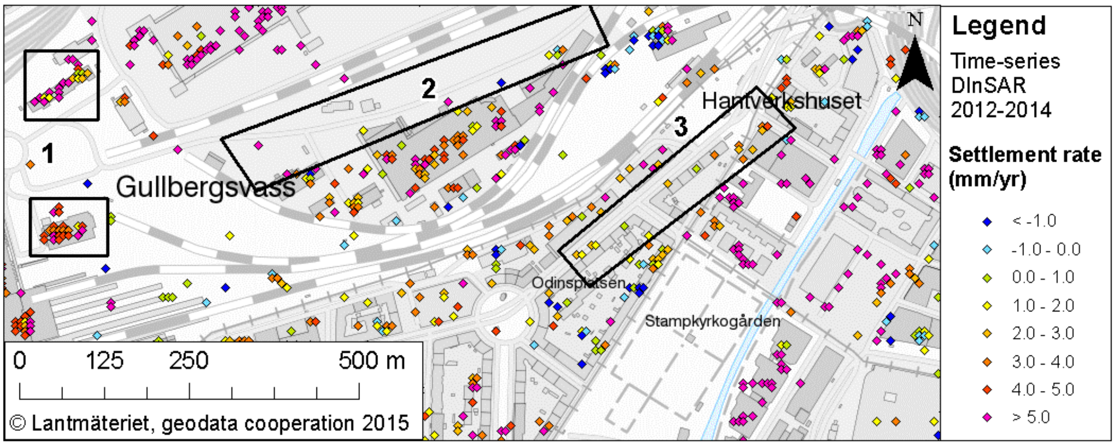

Figure 17 Settlement rate in mm/year during the period 2012 to 2014 by time-series DInSAR analysis – the northern area, Gullbergsvass.

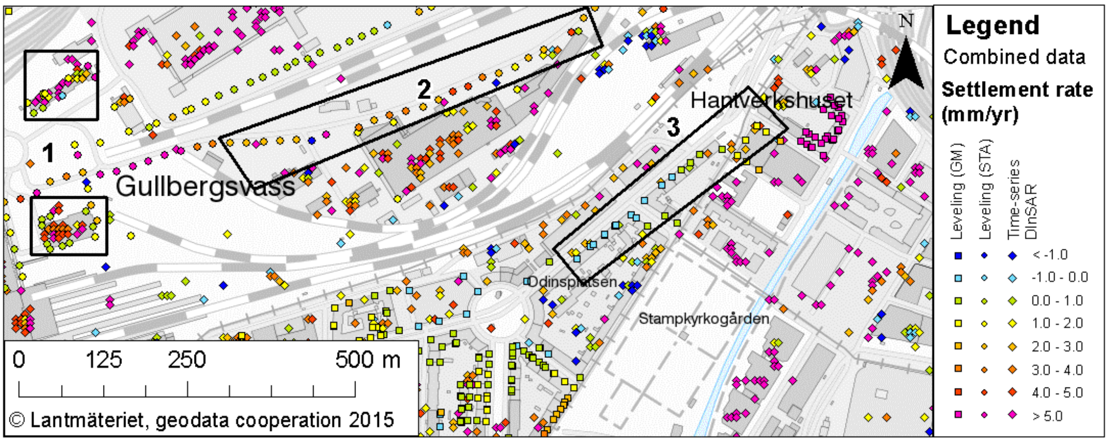

Figure 18 Settlement rate in mm/year in the northern part (Gullbergsvass), including both the measurements by precision leveling by The City of Gothenburg (GM) during the period 2000 to 2014, precision leveling by the Swedish Transport Administration (STA) during the period 2013 to 2014, and the result of the time-series DInSAR analysis during the period 2012 to 2014.

The precision leveling measurements done by the Swedish Transport Administration (STA) on two buildings in the western part (Area 1), compared with the result from the time-series DInSAR analysis, indicate higher settlement rates by time-series DInSAR on both buildings. The settlement measurements by the STA along the streets in the center (Area 2) are difficult to compare as there are hardly any reflection points from the time-series DInSAR analysis. The precision leveling measurements done by The City of Gothenburg on three buildings in the eastern part (Area 3) indicate slightly lower settlement rates (-1.0 to 3.0 mm/year) than the settlement rates by the time-series DInSAR analysis (0 to 4.0 mm/year) in the same area. However, the highest settlement rates are measured on the same buildings by both methods.

5.3.3 Comparison of settlements at the area of Gårda in the east

As the settlements in quarter 44 in Gårda has been studied in detail, see Section 4.2.2, a comparison between settlement rates from the time-series DInSAR and the precision leveling measurements is done in this quarter (Figure 19). It can be noted that a high settlement rate is observed by both precision leveling and time-series DInSAR in the western part of the southern building in Area 1 (4.0 to more than 5.0 mm/year). Low settlement rate is indicated on the northern building (Gårda brandstation) by both methods, but the measured rate is 0 - 2.0 mm/year by precision leveling and 2.0 - 4.0 mm/year by time-series DInSAR. However, there are only two measurement points by time-series DInSAR on this building.

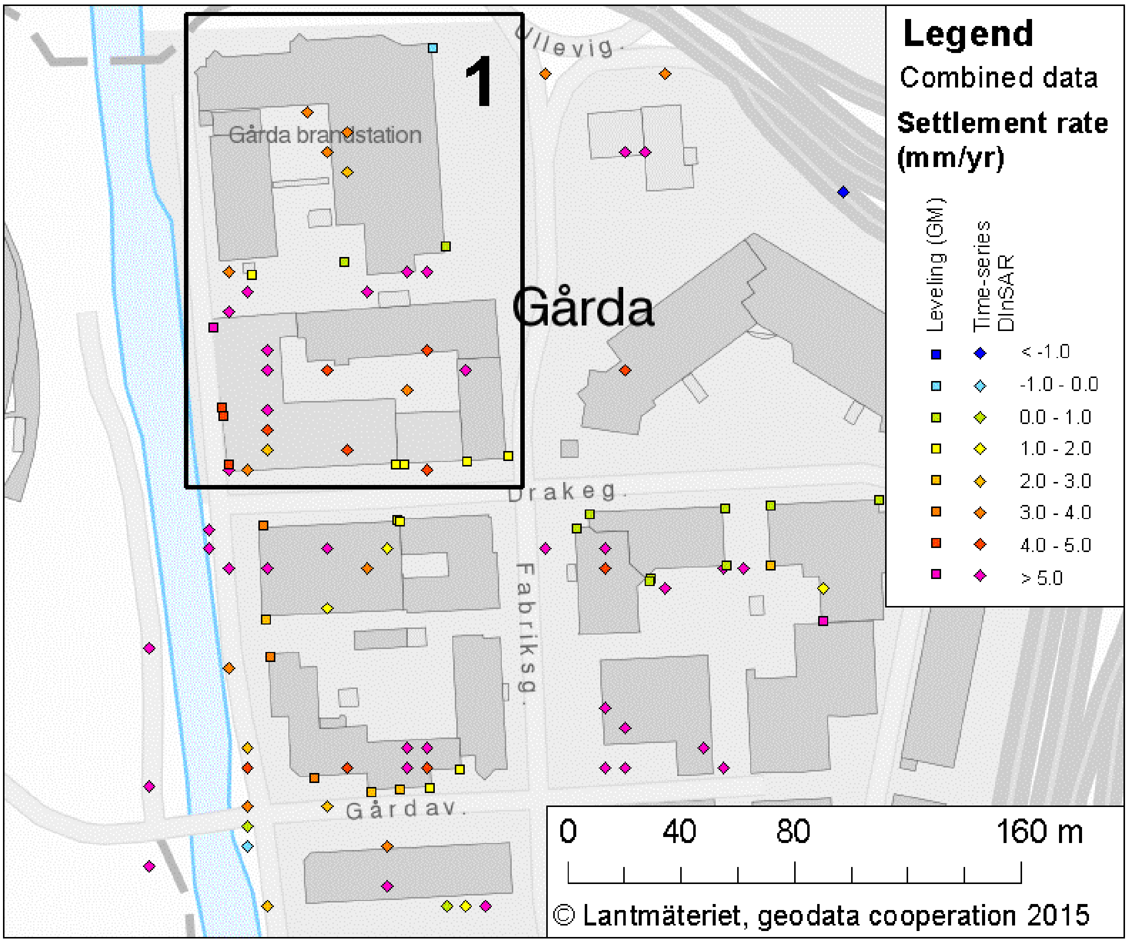

Figure 19 Settlement rate in mm/year in the quarter of Gårda, including both the measurements by precision leveling by The City of Gothenburg (GM) during the period 2000 to 2014 and the result of the time-series DIn-SAR analysis during the period 2012 to 2014.

6. Experiences and reflections

One of the goals of the project was to determine if a limited number of radar images could be used over an extended time period and still produce valid and useable information regarding subsidence. The results of this project suggest that the six month period in between each image registration is probably not a determining factor in calculating measurement points (the so-called permanent scatterers) as long as the study area is in an urban environment. However, the lack of a large stack of movement data for each measurement point was a critical issue and most likely limited the overall validity of the yearly movement rates. In other words, bi-monthly, monthly or, at worst, quarterly registrations are probably needed in order to determine the movement trend and calculate a yearly rate.

A second issue, also critical but perhaps one that does not invalidate the results of this project, concerns the availability of software capable of processing raw SLC radar images and conducting interferometric analyses. Numerous software problems were encountered during the production of the DInSAR movement maps. The most obvious was a “measurement slope” that affected the entire image. This manifested itself as a general decrease in all measurement values from the top of the image to the bottom. Based on numerous discussions with representatives from the software company, it is possible that some type of modification in the baseline adjustment algorithm is warranted. In any event, there are few robust commercial software available today and those are extremely expensive. The S-1 Toolbox, distributed by ESA, looks promising but is currently limited in its analytical capabilities as well as being overly user unfriendly.

Despite the software problems described above, it has been possible to obtain useful results from the time-series DInSAR in the central area of Gothenburg. This is likely due to the use of a fixed reference point close to central Gothenburg. Further away from the center the “measurement slope” of the image affects the measured movements.

7. Conclusions

Comparing the results from time-series DInSAR analysis and precision leveling it can be noted that, in general, the settlement rates obtained by time-series DInSAR are slightly higher than the settlement rates measured by precision leveling. It should then be remembered that the measurement period differ. The measurement period for the time-series DInSAR is year 2012 to 2014. For the precision leveling the total measurement period is year 2000 to 2014, with successive measurements every seventh year in each quarter.

The areas where ongoing settlements are observed are about the same by both methods, but based on the time-series DInSAR analysis these areas are larger.

To get an overview of settlement rates in an urban area, time-series DInSAR is expected to be useful as a complement to traditional settlement methods. Although the accuracy is not as good as traditional methods, it gives a better surface coverage. A prerequisite is that there are enough reflecting surfaces.

As the measurement points are not specified in advance, but depends on surfaces reflecting the radar signals, it is difficult to relate each measurement point from the time-series DInSAR to a specific object (building, part of building, street, square, quay etc.). But, as a complement to more accurate measurements on specific objects, time-series DInSAR gives a possibility to relate the settlement rate on these objects to settlement rates in a wider area.

8. Usefulness and development potential

The results of this study show that time-series DInSAR can be a useful complement to traditional settlement measurements to get an overview of settlement rates in an area. This has also been noticed by the Swedish Transport Administration that will use time-series DInSAR as a complement to precision leveling and bellow-hose settlement gauges to follow-up on settlements for construction of the West Link in Gothenburg.

Although the method is useful today to get an overview of ongoing settlements, a better accuracy primarily of the settlement rate, but also of the location of reflection points would widen the use of the time-series DInSAR method.

The availability of software capable of processing raw SLC radar images and conducting interferometric analyses needs to be enhanced, as described in Section 6 above.

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Ferretti, A, Prati, C and Rocca, F (1999) *Multibaseline InSAR DEM reconstruction: The wavelet approach.* IEEE Transactions on Geoscience and Remote Sensing, vol. 37, pp. 705–715.

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Löfroth, H and Ledwith, M (2010). *Mapping subsidence in an urban area with Differential InSAR and comparing with traditional methods – test area Gothenburg.* Swedish Geotechnical Institute, SGI, Varia 610. Linköping.

Annex 1

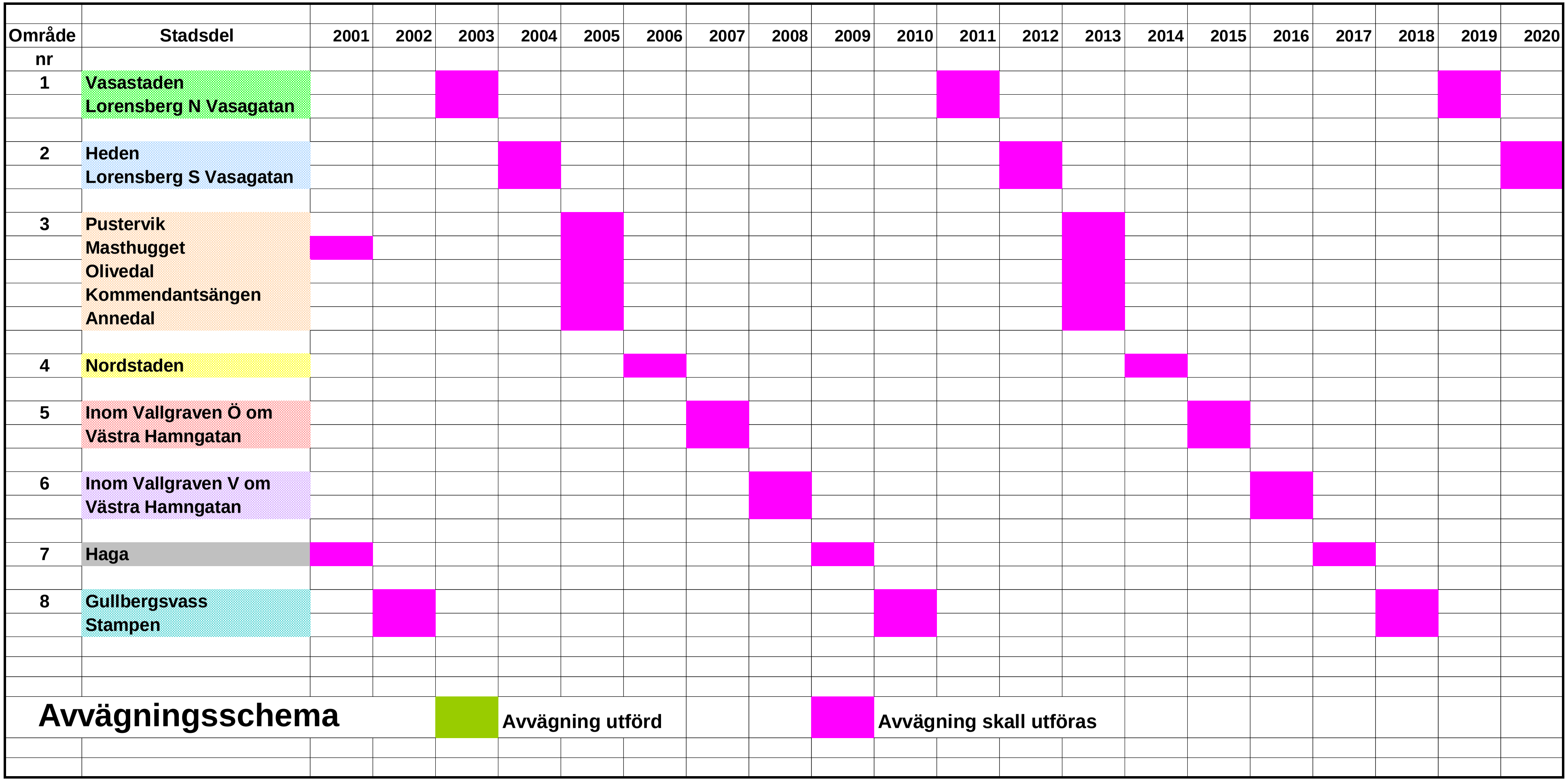
Time-scheme of precision leveling
carried out by The City of Gothenburg

Avvägningsschema

Område nr	Stadsdel	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000
1	Vasastaden	sept	aug	okt							juni							sept			
	Lorensberg N Vasagatan									jan	maj					sept					
2	Heden		okt	dec	okt							sept					aug				
	Lorensberg S Vasagatan			aug	aug	aug								jan					okt		
3	Pustervik									jan	maj					sept					maj
	Masthugget		nov	dec	nov							sept									
	Olivedal			sept	sept	dec							nov							jan	
	Kommendantsängen			aug	sept	okt							nov							feb	
	Annedal			sept	aug	sept							dec							feb	
4	Nordstaden				okt	nov	nov							sept							
5	Inom Vallgraven Ö om					jan	jan	mars						aug							feb
	Västra Hamngatan																				
6	Inom Vallgraven V om					feb	feb	jan						sept							mars
	Västra Hamngatan																				
7	Haga						aug	aug	nov						aug						
8	Gullbergsvass							okt	aug	aug						aug					
	Stampen							okt	sept	okt						aug					

Avvägning utförd

Avvägning skall utföras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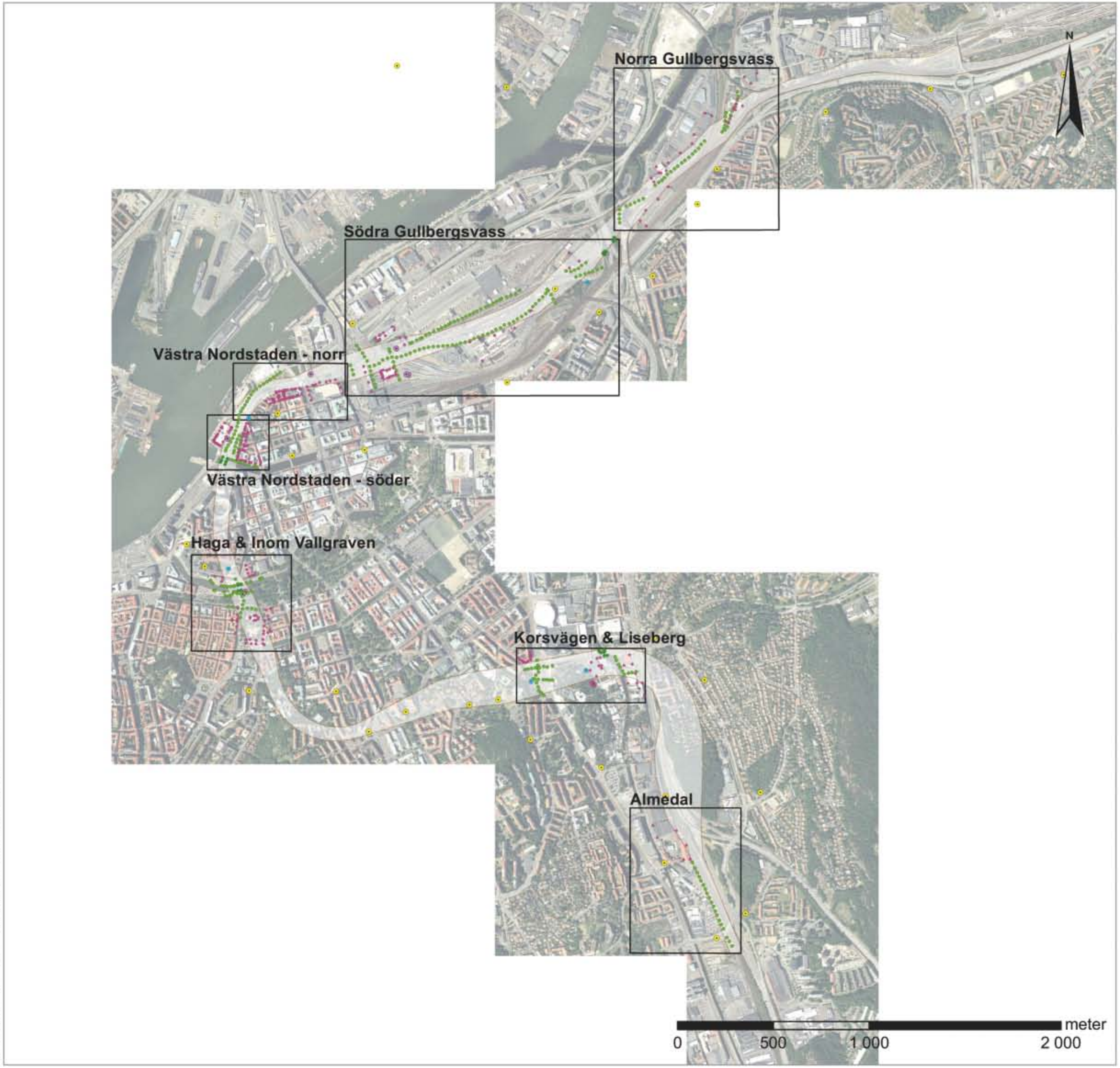
Vasastaden
Lorensberg N Vasagatan
2
Heden
Lorensberg S Vasagatan
3
Pustervik
Masthugget
Olivedal
Kommendantsängen
Annedal
4
Nordstaden
5
Inom Vallgraven Ö om
Västra Hamngatan
6
Inom Vallgraven V om
Västra Hamngatan
7
Haga
8
Gullbergsvass
Stampen
Avvägningsschema
Avvägning utförd
Avvägning skall utföras

Annex 2

Area of installed measurement points for the West Link, Gothenburg

Västlänken
Sättningsavvägningar



Översiktskarta

Teckenförklaring

- Husdubbar
- Bruksfixar
- Fixar
- Brodubbar
- Markspik
- Bälgslangar
- delområden

Skala 1:20 000
Datum: 2013-06-30
Utskriftsformat: A3

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