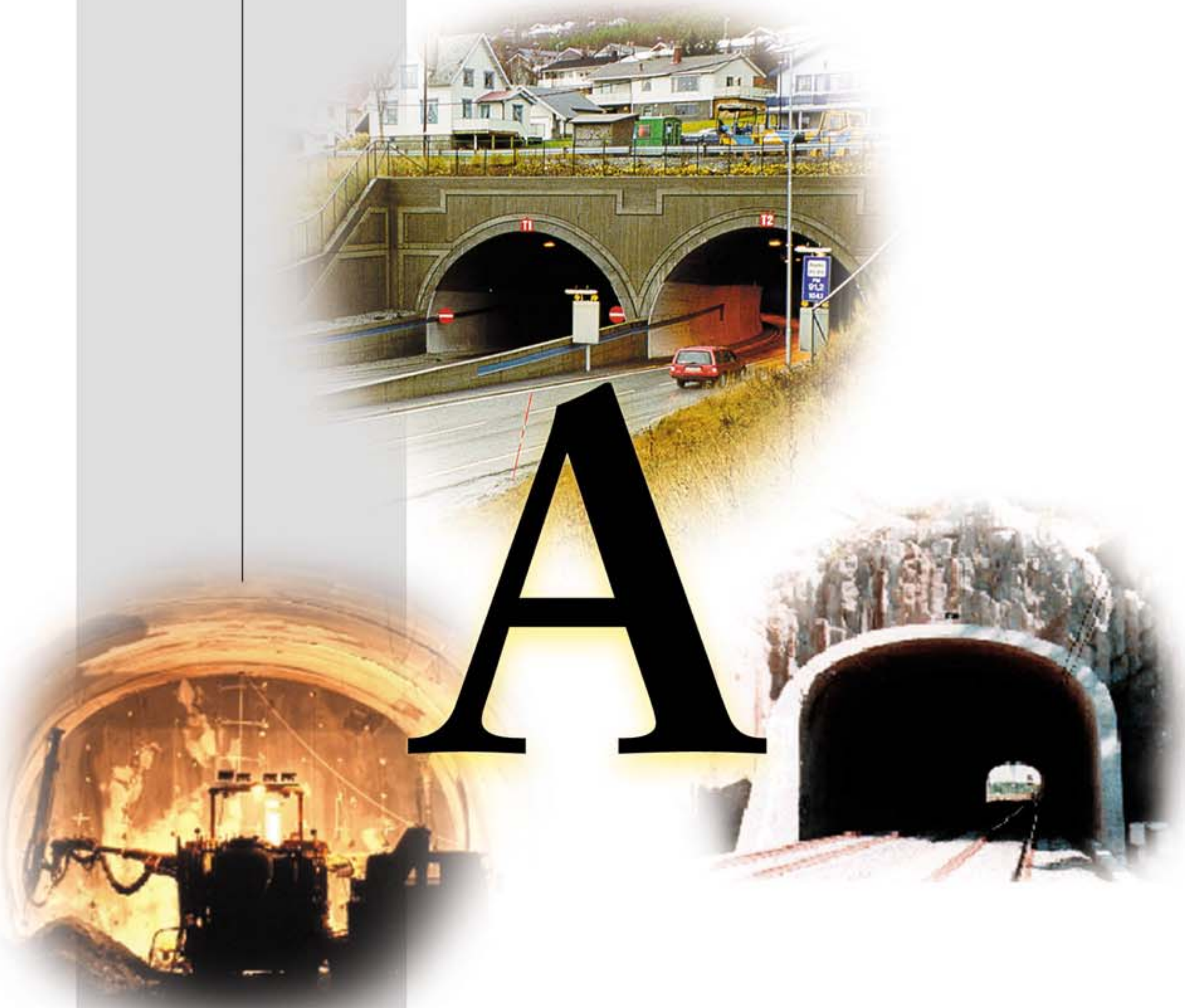
Miljø- og samfunnstjenlige
TUNNELER

Rapport nr: 37

Analysis of InSAR data over Romeriksporten.



Intern rapport nr. 2346

Statens vegvesen

NGU
Norges geologiske undersøkelse

Geological Survey of Norway
N-7441 Trondheim, Norway

REPORT

Report no.: 2003.076

ISSN 0800-3416

Grading: Open

Title:

Analysis of InSAR data over Romeriksporten

Authors:

Dehls, J. F., Nordgulen, Ø.

Client:

Miljø- og samfunnstjenlige tunneler

County:

Oslo, Akershus

Municipality:

Oslo, Lørenskog

Map-sheet name (M=1:250.000):

Oslo

Map-sheet no. and -name (M=1:50.000)

1914 IV Oslo

Deposit name and grid-reference:

Number of pages: 18

Price (NOK): 150

Map enclosures:

Fieldwork carried out:

Date of report:

06.02.2004

Project no.:

2827.02

Person responsible:

Summary:

Timely identification of subsidence is important in order to ensure that remediation efforts are successful. Even if subsidence cannot be prevented or stopped, it must be accounted for in new construction planning. Identification and monitoring of ground deformation can be accomplished using a number of surveying techniques. Levelling and GPS are both expensive and the number of benchmarks that can be controlled is limited.

Since the early 1990's satellite-based radar interferometry has been used to identify large ground movements due to earthquakes and volcanic activity. Data stacking methods that take advantage of a growing archive of radar images, as well as increasing computing power, have led to a large increase in the precision of the technique. Both linear trends and seasonal fluctuations can be identified using the Permanent Scatterers technique.

The Geological Survey of Norway has tested the ability of the Permanent Scatterers technique to detect and measure the subsidence due to tunnel construction at Romeriksporten. By using the archive of ERS scenes available from 1992 to 2001, we have been able to compare and contrast the results with those obtained by other techniques. We were able to detect subsidence and construct displacement-time series for numerous buildings that experienced up to 2 cm displacement over the period of tunnel construction. Buildings that experienced higher rates of subsidence were not detected due to unwrapping errors.

Although we were not able to detect and measure subsidence in all buildings, where measurements were obtained, they are in close agreement with those obtained from optical levelling. Both timing and magnitude of subsidence was confirmed. More importantly, perhaps, we were able to identify and measure displacement in a number of buildings that had not been monitored by other techniques.

Keywords:

subsidence

interferometry

urban geology

CONTENTS

FIGURES

1. INTRODUCTION

Timely identification of subsidence is important in order to ensure that remediation efforts are successful. Even if subsidence cannot be prevented or stopped, it must be accounted for in new construction planning. Identification and monitoring of ground deformation can be accomplished using a number of surveying techniques. Levelling and GPS are the most common. Both are expensive and the number of benchmarks that can be controlled is limited.

Since the early 1990’s satellite-based radar interferometry has been used to identify large ground movements due to earthquakes and volcanic activity. Data stacking methods that take advantage of a growing archive of radar images, as well as increasing computing power, have led to a large increase in the precision of the technique. Numerous studies of urban subsidence using radar interferometry have been published (Amelung et al., 1999; Fruneau and Sarti, 2000; Galloway et al., 1998). Both linear trends and seasonal fluctuations can be identified (Colesanti et al., 2003a; Colesanti et al., 2003b).

NGU has been experimenting with the use of radar interferometry to detect fault movements and landslides (Dehls et al., 2002). Involvement in the project “Miljø- og samfunnstjenlige tunneler” led us to speculate that perhaps this technique could be useful in identifying and quantifying short-term subsidence due to underground construction. The well-known subsidence caused by groundwater drainage during the construction of the Romeriksporten tunnel presents a perfect test case. Levelling had been done on a number of buildings before, during and after construction.

2. DIFFERENTIAL SAR INTERFEROMETRY (DINSAR)

Differential SAR Interferometry (DInSAR) is a technique that compares the phases of multiple radar images of an area to measure surface change. It first became well known after an image of the Landers Earthquake deformation field was published in the journal Nature in 1993 (Massonnett et al., 1993). The method has the potential to detect millimetric surface deformation along the sensor – target line-of-sight.

A radar satellite emits pulses of radar energy, which are scattered by the Earth's surface. When such a pulse of radar energy is reflected back to the satellite, two types of information are recorded. The first information recorded is the amplitude of the signal. This is the information displayed in typical SAR images (Figure 1). The amplitude is influenced by factors such as the surface material, the slope of the surface and surface moisture content.

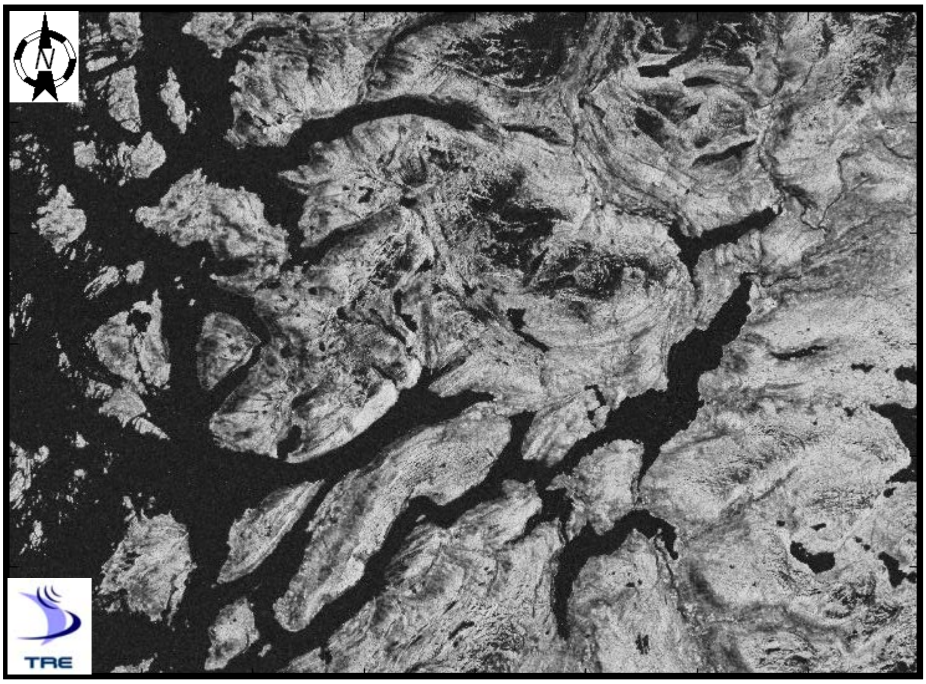


Figure 1. SAR image showing Ranafjorden and Svartisen glacier, July, 1995.

The second information recorded is the phase of the wave. ERS satellites have a radar wavelength of 5.66 cm. The phase of the wave upon return depends primarily on the distance between the satellite and the surface. It is also affected by changes in the atmosphere, but this is a very small effect. If two images are acquired of the same area from the exact same position, any difference in phase is due to movements of the ground surface toward or away from the satellite during the time between the two images. If two images are acquired from different positions within a small period of time, the difference in phase can be used to determine the surface topography (Figure 2). Differences in phase between two images are easily viewed by combining, or interfering, the two phase-images. In the resulting image, the waves will either reinforce or cancel one another, depending upon the relative phases. The resulting image is called an interferogram and contains concentric bands of colour, or fringes, that are related to topography and/or surface deformation.

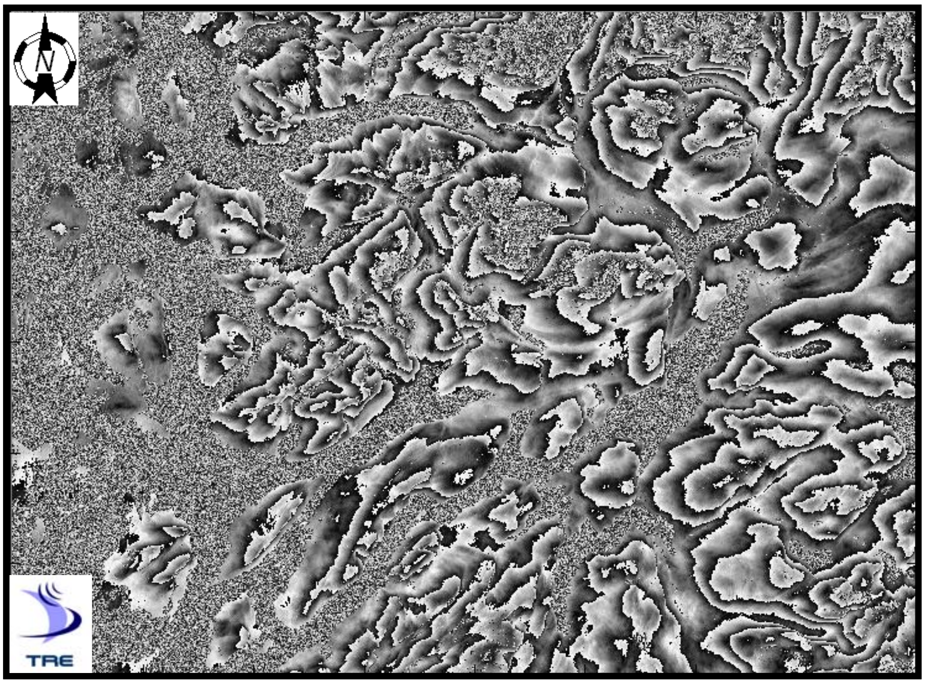


Figure 2. SAR interferograms obtained from a pair of images acquired July 15 and 16, 1995, by the ERS-1 and ERS-2 satellites. The area is the same as Figure 1. Fringes are related to topography.

Since it is nearly impossible to obtain two images of the same area from exactly the same point at two different times, three images are typically used to analyse surface change. First, an image pair taken during a short interval is used to determine the topography. Second, an interferogram is created using two images with a longer time interval. The effects of topography are removed using the results of the first interferogram, and the resulting image contains fringes due to surface deformation. Each fringe represents one-half wavelength of surface movement. In the case of the ERS satellites, this is less than 3 cm.

Radar interferometry has one stringent condition that must be met in order for it to work. The many small reflective objects contributing to each pixel must remain unchanged, or *coherent*, between images. Decorrelation may occur due to variations in the complex reflectivity of individual sampling cells as a function of the acquisition geometry (geometric decorrelation) and/or time (temporal decorrelation). In addition, atmospheric phase screen, mainly due to the effect of the local water vapour content, can be difficult to discriminate from ground deformation.

2.1 Permanent Scatterers Technique (PSInSAR)

The SAR processing group at Politecnico di Milano has developed a new method based upon the identification of stable natural reflectors (called permanent scatterers) that are coherent over a long period of time (Ferretti et al., 2001). These permanent scatters (PS) can be identified and used in many images over a long period of time.

The PS approach is a two-step processing technique aimed at isolating the different phase terms (atmospheric phase screen, deformation and residual topography) on a sparse grid of phase stable, point-wise radar targets. The PS approach is based on the exploitation of long time-series of interferometric SAR data (at least 25-30 images). The technique is able to overcome both main limiting factors: PS are only slightly affected by decorrelation and can be used to estimate and remove the atmospheric phase screen.

The sparse PS grid can be thought of as a high spatial density (up to 400 PS/km2, in highly urbanized areas) geodetic network allowing ground deformation measurements (along the line-of-sight direction) with millimetric accuracy (0.1-1 mm/yr on the average line-of-sight deformation rate and 1-3.5 mm on single measures).

Since Permanent Scatterers mainly correspond to portions of man-made structures, and a minimum PS density is required to guarantee the measurements reliability, most significant PS results have been obtained analyzing urban areas and their immediate neighbourhood. The PS approach allows the identification of isolated phase-stable targets in low coherence areas. These provide precise surface deformation data in areas where a conventional DInSAR approach fails due to decorrelation noise.

2.1.1 Standard Processing vs. Advanced Processing

Standard PS processing is fully automatic, with quality checks performed only on the final results. A linear rate of movement is assumed and search parameters are optimized to process areas up to several thousand square kilometres. Advanced processing can be performed on smaller areas once ground motion is identified. The main differences with advanced processing are:

- finer sampling grid of the focused and fitted data.
- lower thresholds for atmospheric phase screen estimation and removal to obtain a higher PS density.
- ad hoc procedures are carried out for a better detection of seasonal motion or abrupt steps in rate of movement. No "a priori" models on the PS behaviour are imposed.
- manual control by the operator for a better refining and calibration of the processing parameters.

2.1.2 Notes about velocity values

Several points must be kept in mind when interpreting the velocity values obtained by this method.

- All values are relative to an arbitrarily chosen reference point that is assumed to be stable.
- The standard deviation of velocity errors increases with distance from the reference point. For this reason, the reference point is chosen as close as possible to the centre of the area of interest.
- As stated earlier, the velocity given is the velocity along the line-of-sight to the satellite, which is on average 23º from the vertical. If the true movement direction is vertical, the line-of-sight velocity is an underestimate of the true velocity.

- No images are available for 1994 and early 1995. During that year, the European Space Agency used the ERS-1 satellite for several different missions that had a different orbital geometry.

- One of the gyroscopes onboard the ERS-2 satellite failed on January 7, 2001, and very few images acquired since then have been of sufficient quality to use for interferometry.

3. RESULTS

Advanced processing was carried out using 48 images from track 337, covering the time period 1992 to 2002. The area processed covers the western part of Romeriksporten tunnel, as well as the Alnabru area to the north. The area processed includes the areas most affected by the groundwater withdrawal associated with tunnel construction. The results from this area are presented in Figure 4. The most striking feature is the subsidence in the Alnabru area, probably due to compaction of surficial deposits. Within the Godlia and Hellerud areas, there is no obvious pattern of subsidence revealed by the average displacement rate.

In order to identify subsidence related to the tunnelling activity, displacement-time series were generated for all points, including those with low coherence. These charts were then examined to identify non-linear displacement. Numerous houses show accelerated subsidence during the time of tunnelling. Indeed, subsidence in Godlia clearly began before subsidence in Hellerud (Figure 3). In other cases, ongoing subsidence shows no acceleration during the time of tunnelling. These results are discussed in more detail in section 3.1.

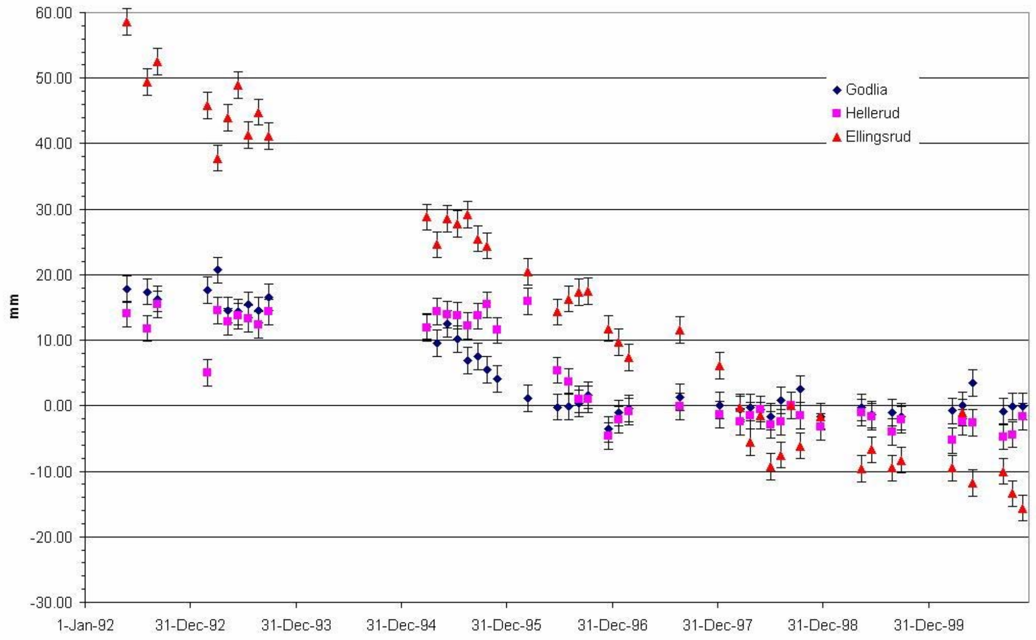


Figure 3. Displacement-time series for selected houses along the trace of the Romeriksporten tunnel. Accelerated subsidence in Hellerud and Godlia coincides with the time of tunnel construction in those areas. The subsidence in Ellingsrud shows no acceleration.

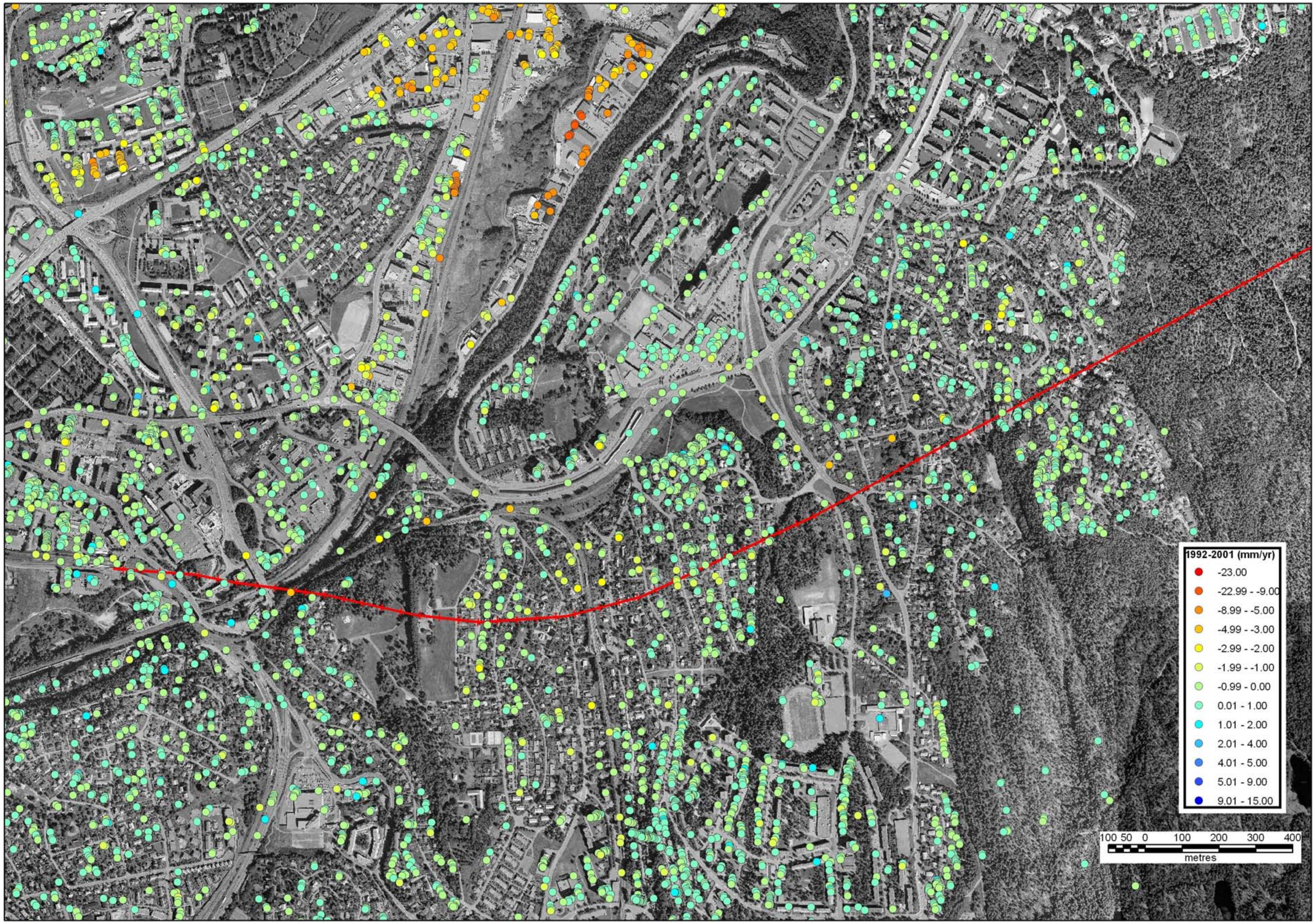


Figure 4. Average relative velociy, 1992-2001, for the area around the western end of Romeriksporten tunnel. The trace of the tunnel is shown in red. Scale is approximately 1:10,000.

Figure 5 shows the location of houses in Hellerud where an independent study (Faggruppen for setningsskader, 2002) has confirmed subsidence and damage due to the tunnelling activities. There is a clear reduction in PS density in the area most affected. There are several possible explanations for this.

- The rate of subsidence was great enough to lead to phase unwrapping error. In other words, displacement of more than one half wavelength took place between successive image acquisitions.
- The deformation led to a change in orientation of the scattering objects, leading to decorrelation. This could be the case where houses experienced significant tilting (Figure 6).
- Reconstruction or significant repairs during the period of analysis led to a change in the surface of the building. In other words, there were no *permanent* scatterers.

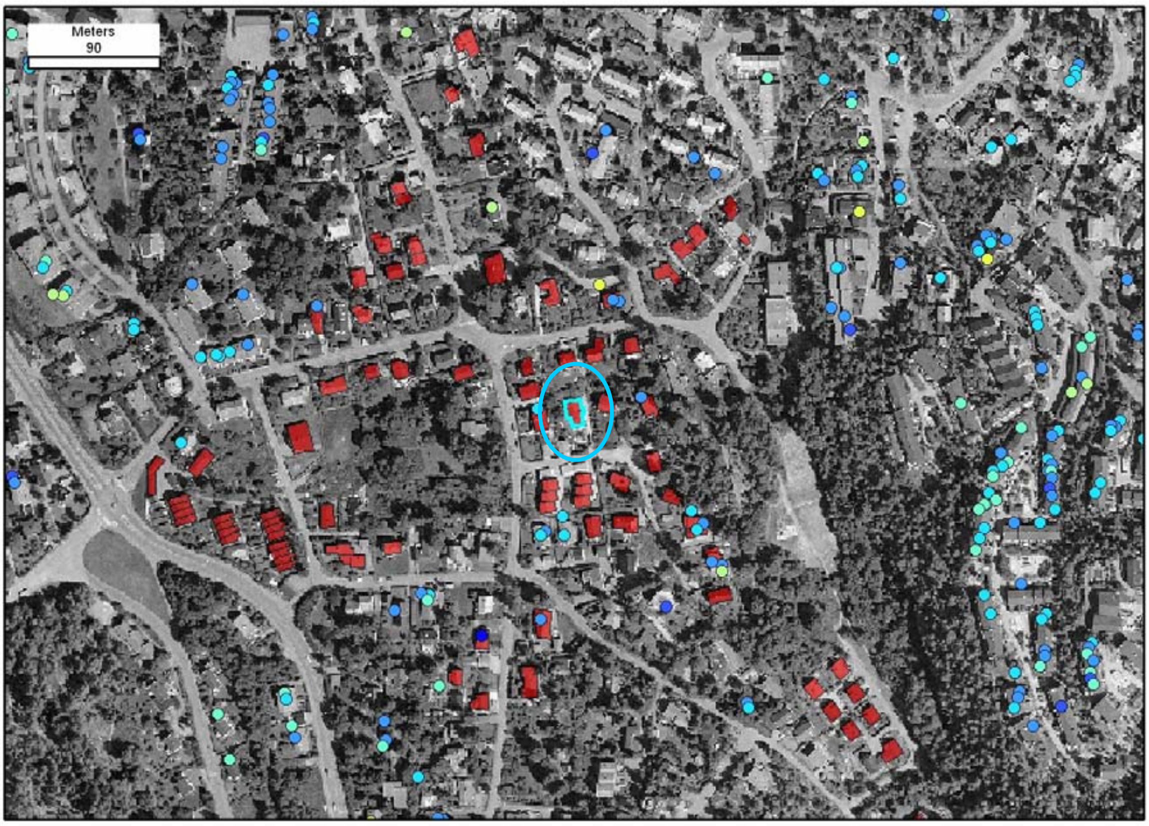


Figure 5. There is a very low density of PS (circles) in the region with the highest number of affected buildings (in red). In many cases, such as Hellerudveien 42B (circled in blue, see Figure 6) the rate of subsidence was too great for the method to work.

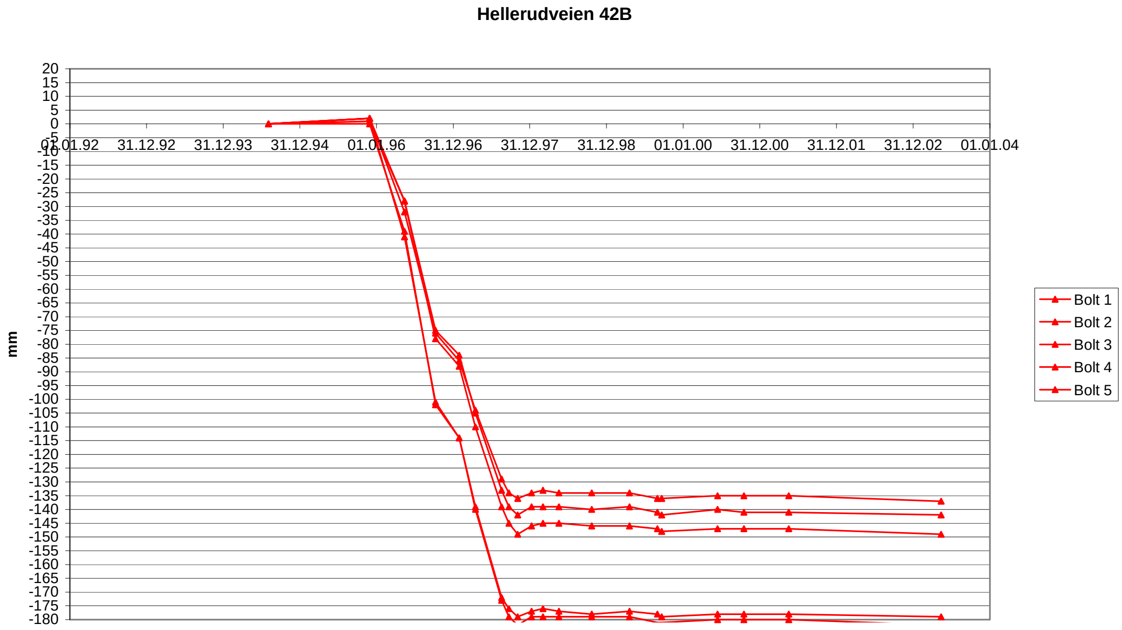


Figure 6. Measurements of subsidence in Hellerudveien 42B (circled in blue in Figure 5) obtained by levelling. The high rate of subsidence, combined with the tilting (bolts are on various corners of the building) made it impossible to identify any PS.

3.1 Comparison with levelling

Jernbaneverket had, and still has, a program for monitoring subsidence related to the construction of Romeriksporten tunnel. Many buildings were levelled before, during and after tunnel construction. Others were levelled only after subsidence was detected. We were supplied with the levelling data from a number of houses in Hellerud, Godlia and Ellingsrud in order to evaluate the results of the PS technique.

Based upon data obtained from advanced PS analysis, displacement-time series can be shown for individual PS. This has been done for selected buildings where significant subsidence is evident. It should be noted that there is a varying signal-to-noise ratio throughout the dataset. This ratio is quantified by a value called the *coherence*. Although the maps and figures in this report show the velocity values for all points with coherence better than 0.65, reliable displacement-time series should only be extracted for points with coherence better than about 0.80. This threshold value is dependant upon the number of scenes processed for an area. Of the more than 10000 PS in the Romeriksporten area dataset, more than 3800 PS meet this criterion.

In the following figures, displacement-time series from permanent scatterers have been shown, even if they have low coherence. Since the signal-to-noise ratio for these points is quite low, individual displacements between successive images cannot be measured accurately. Nonetheless, the general trends show clear offsets that compare well with independent observations.

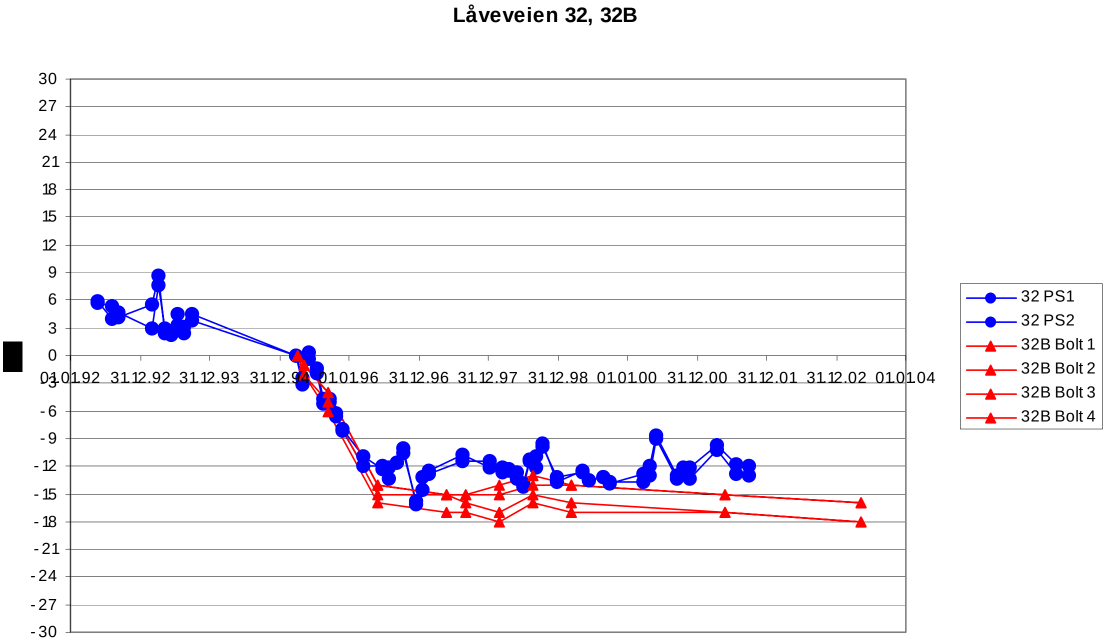
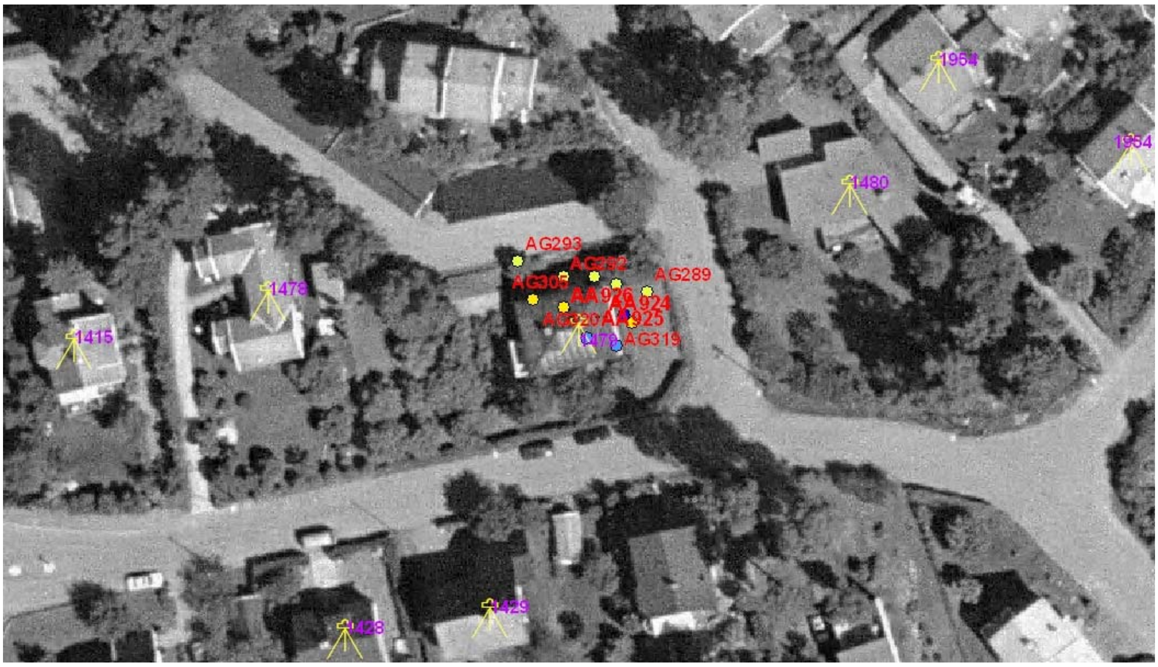


Figure 7. Subsidence measured in Låveveien 32B by levelling compared with PS from Låveveien 32, next door. PS velocity is along the line of sight with the satellite (23° from vertical). Yellow symbols indicated houses that were monitored by levelling.



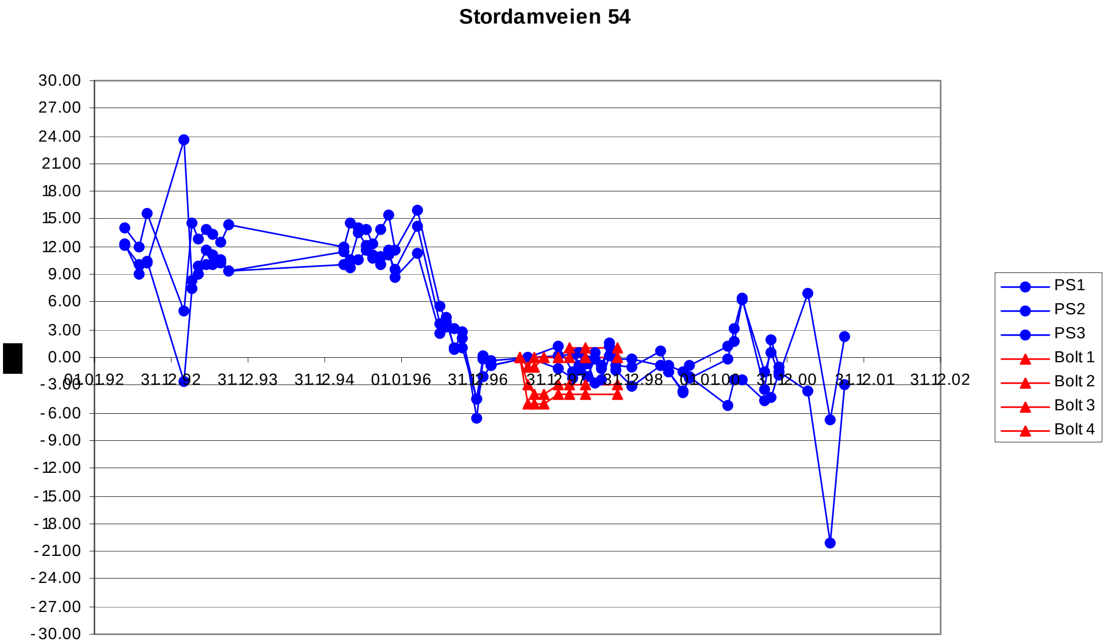


Figure 8. Subsidence measured in Stordamveien 54 by levelling compared with three PS from the same building. PS measurements reveal subsidence not detected by levelling, which began only afterwards.

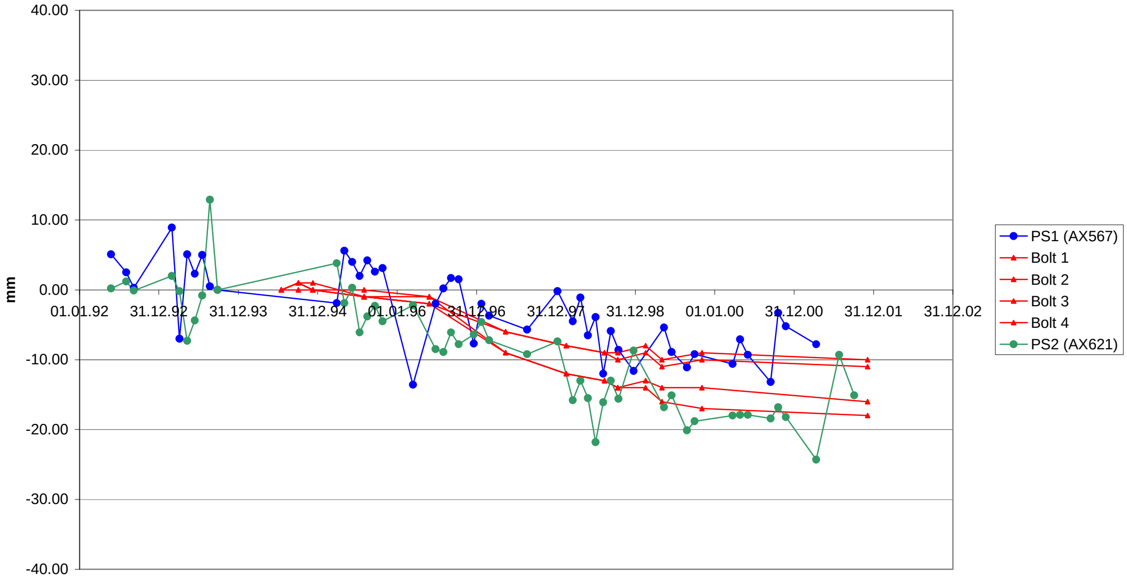
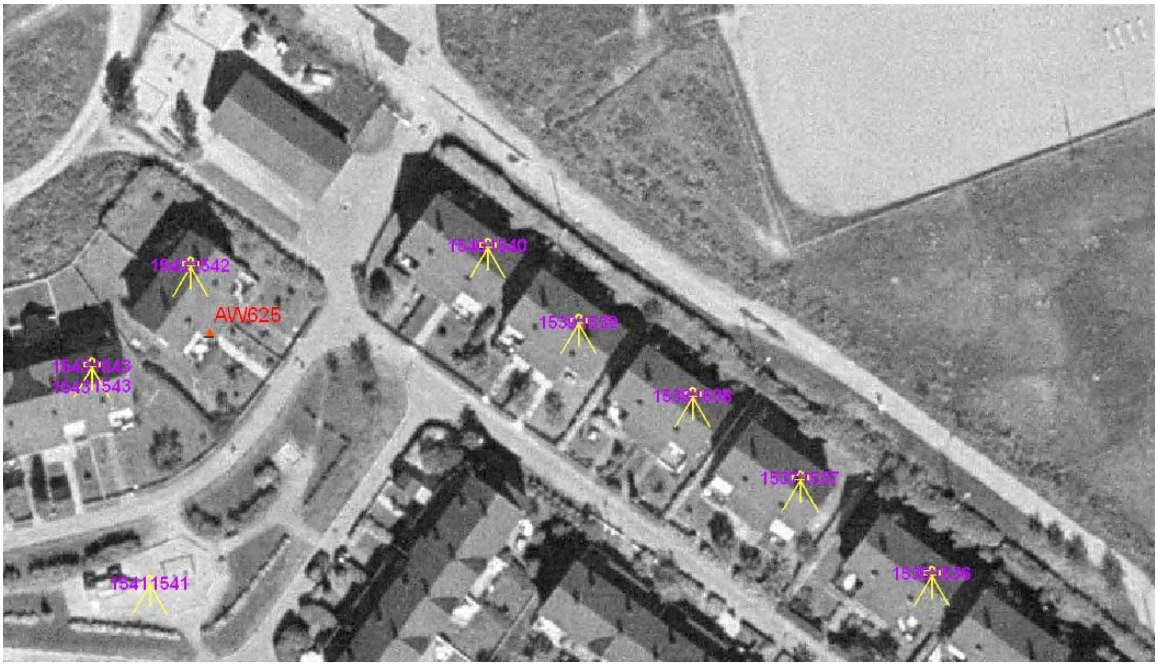

Munkebekken 110, 112

Figure 9. Both levelling and PS reveal between 1 and 2 cm subsidence at Munkebekken 110-112.



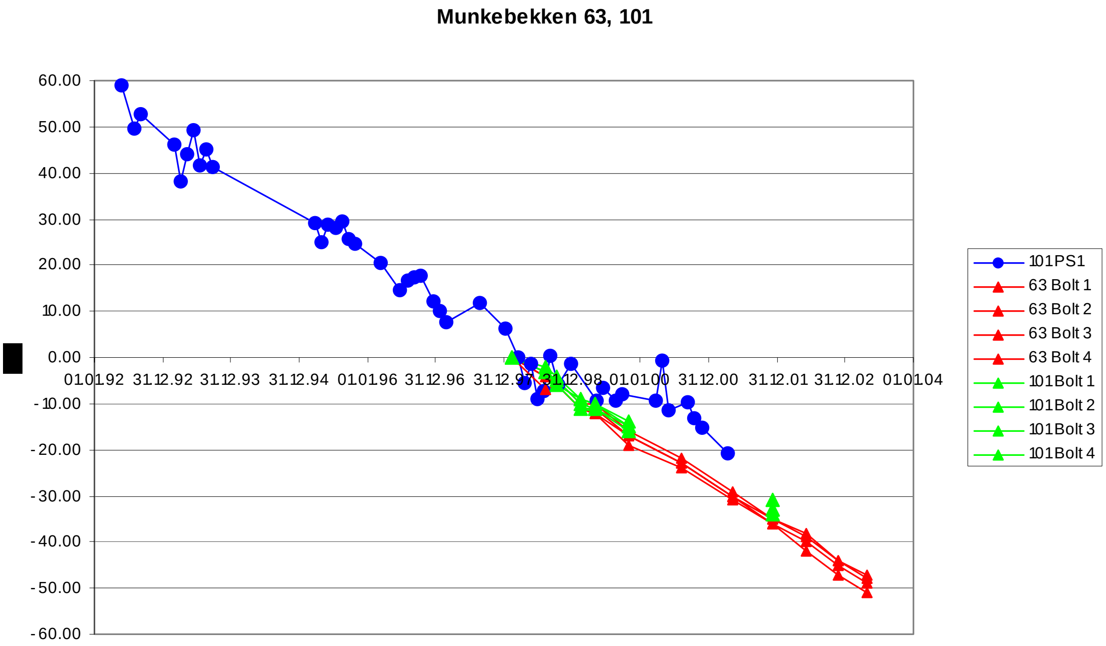


Figure 10. Levelling at both Munkebekken 63 and Munkebekken 101 shows a steady rate of subsidence from 1997. PS analysis (AW625 on Munkebekken 101) shows that this subsidence has had a nearly constant rate since 1992 and cannot be related to the tunnelling activity.

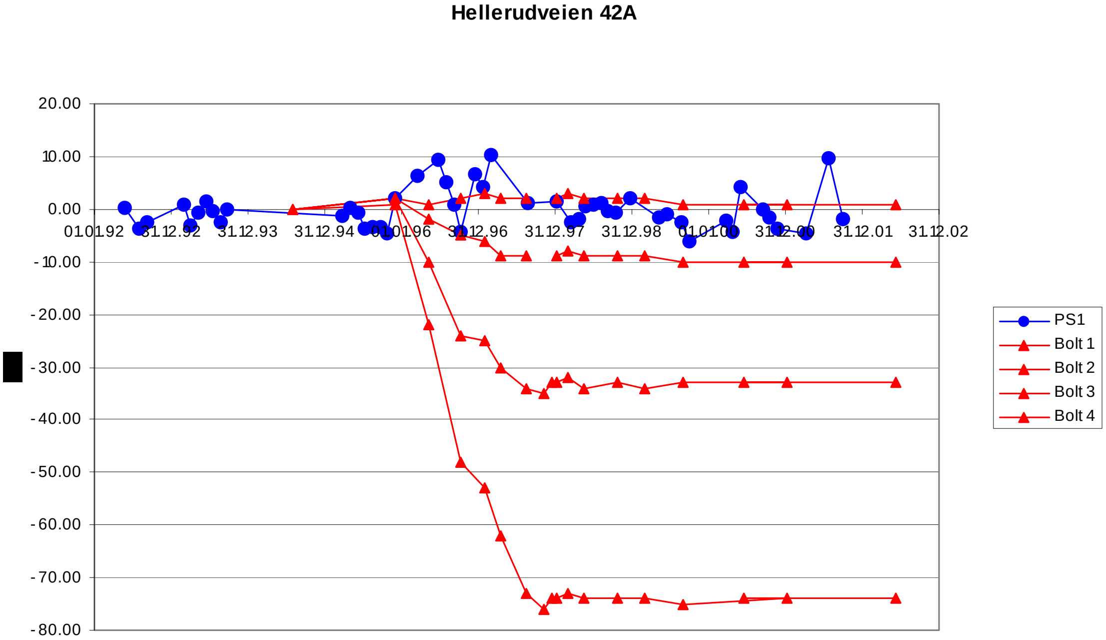


Figure 11. One PS (AG474) at the north end of Hellerudveien 42A, between bolts 1 and 2, is insufficient to reveal almost 8 cm of tilting that occurred from 1996 to 1997.

4. FUTURE MONITORING POSSIBILITIES

The Permanent Scatters technique is based upon the availability of a time-series of SAR images. With the failure of gyroscope 1 onboard ERS-2 on January 7, 2001, very few images have been of sufficient quality to use for interferometry. The ESA satellite ENVISAT, launched in March, 2002, is in the same orbit as ERS-2 and able to obtain very similar images using it's ASAR instrument. It is possible to combine ERS and ASAR images to do PS analysis. Unfortunately, the ASAR instrument currently only acquires images upon request. A 'background mission' has been asked for by a number of groups but it is still unclear how often the database of images will be updated. If we wish to study ongoing deformation, a new and more reliable source of images must be decided upon. The images for a given geographic area must be acquired using the same beam mode and geometry and must be acquired as regularly as possible. The Canadian Radarsat satellites offer the stability and reliability necessary to build up an archive of SAR images over Norway that can be used for current and future ground motion studies. Radarsat-1 was launched in November, 1995. Radarsat-2 is expected to be launched in 2006.

In January, 2003, the Norwegian Space Centre (Norsk Romsenter) signed an agreement with the Canadian Space Agency that assures access to Radarsat data to Norwegian public authorities. The agreement was based primarily on the need for scan-SAR images along the Norwegian coast to support ship detection and oil pollution applications. However, there is provision for the acquisition of a number of scan-SAR and standard mode scenes over the mainland. The main users of these data will be NVE (snow water equivalent determination) and NGU (ground motion detection and monitoring). Over the coming months, NGU will work together with Kongsberg Spacetec to plan image acquisition. It is hoped that we can begin acquiring scenes in early 2004 and have sufficient scenes by mid 2005 to begin monitoring critical areas. In the meantime, we will continue to use the ERS archive to identify areas at risk.

5. CONCLUSIONS

The Permanent Scatters technique has proven to be effective at identifying and quantifying subsidence over large areas with high accuracy and spatial resolution. PSInSAR offers several advantages over traditional techniques. First, it is unique in being able to measure displacements at tens of thousands of points approximately every 35 days. In Hellerud and the surrounding region, over 10,000 were identified. Approximately one third of these have a high enough signal-to-noise ratio to construct displacement-time series. Secondly, it is the only technique available that allows us to identify and measure displacements that took place years ago by taking advantage of the European Space Agency's archive.

By using the archive of ERS scenes available from 1992 to 2001, we have been able to compare and contrast the results with those obtained by other techniques. We were able to detect subsidence and construct displacement-time series for numerous buildings that experienced up to 2 cm displacement over the period of tunnel construction. Buildings that experienced higher rates of subsidence were not detected due to unwrapping errors.

Although we were not able to detect and measure subsidence in all buildings, where measurements were obtained, they are in close agreement with those obtained from optical leveling. More importantly, perhaps, we were able to identify and measure displacement in a number of buildings that had not been monitored by other techniques.

6. REFERENCES

Amelung, F., Galloway, D., Bell, J., Zebker, H., and Laczniak, R., 1999, Sensing the ups and downs of Las Vegas: InSAR reveals structural control of land subsidence and aquifer-system deformation: Geology, v. 27, p. 483-486.

Colesanti, C., Ferretti, A., Novali, F., Prati, C., and Rocca, F., 2003a, SAR monitoring of progressive and seasonal ground deformation using the Permanent Scatterers Technique: IEEE Transactions on Geoscience and Remote Sensing, v. 41, p. 1685-1701.

Colesanti, C., Ferretti, A., Prati, C., and Rocca, F., 2003b, Monitoring landslides and tectonic motions with the Permanent Scatterers Technique: Engineering Geology, v. 68, p. 3-14.

Dehls, J.F., Basilico, M., and Colesanti, C., 2002, Ground deformation monitoring in the Ranafjord area of Norway by means of the Permanent Scatterers technique, Geoscience and Remote Sensing Symposium, 2002. IGARSS '02. 2002 IEEE International, Volume 1: Toronto, p. 203-207.

Faggruppen for setningsskader, 2002, Romeriksporten - setningsskader, Vurdering av skader og tiltak: Oslo, p. 10.

Ferretti, A., Prati, C., and Rocca, F., 2001, Permanent scatterers in SAR interferometry: IEEE Transactions on Geoscience and Remote Sensing, v. 39, p. 8-20.

Fruneau, B., and Sarti, F., 2000, Detection of ground subsidence in the city of Paris using radar interferometry: isolation of deformation from atmospheric artifacts using correlation: Geophysical Research Letters, v. 27, p. 3981-3984.

Galloway, D., Hudnut, K., Ingebritsen, S., Phillips, S., Peltzer, G., Rogez, F., and Rosen, P., 1998, Detection of aquifer system compaction and land subsidence using interferometric synthetic aperture radar, Antelope Valley, Mojave Desert, California: Water Resources Research, v. 34, p. 2573-2585.

Massonnett, D., Rossi, M., Carmona, C., Adragna, F., Peltzer, G., Feigl, K., and Rabaute, T., 1993, The displacement field of the Landers earthquake mapped by radar interferometry: Nature, v. 364, p. 138-142.