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REPORT

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Title:

Subsidence in Trondheim, 1992-2003: Results of PSInSAR analysis

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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.

In a previous project, standard processing was performed on two independent series of radar images covering the Trondheim region. By processing two sets of images, we obtained two independent datasets that could be compared at a regional and local scale. The pattern of subsidence was identical where the datasets overlap. In this study, advance techniques were used to study in more detail the city area. More scenes were used, and the subsidence data were updated to include 2003.

Several significant areas of subsidence are found, including the harbour area, City Lade, part of Loholt and Eberg. These are described in more detail.

A new project has been started at NGU to enable future updates to this dataset on a regular basis.

Keywords:	Subsidence	Interferometry
Urban geology	Fjernanalyse	Fagrapport

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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 successfully used radar interferometry to detect fault movements, landslides and subsidence (Dehls et al., 2002; Dehls and Nordgulen, 2003a, b). In this report, we present results from the Trondheim region.

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.

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.

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). 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.

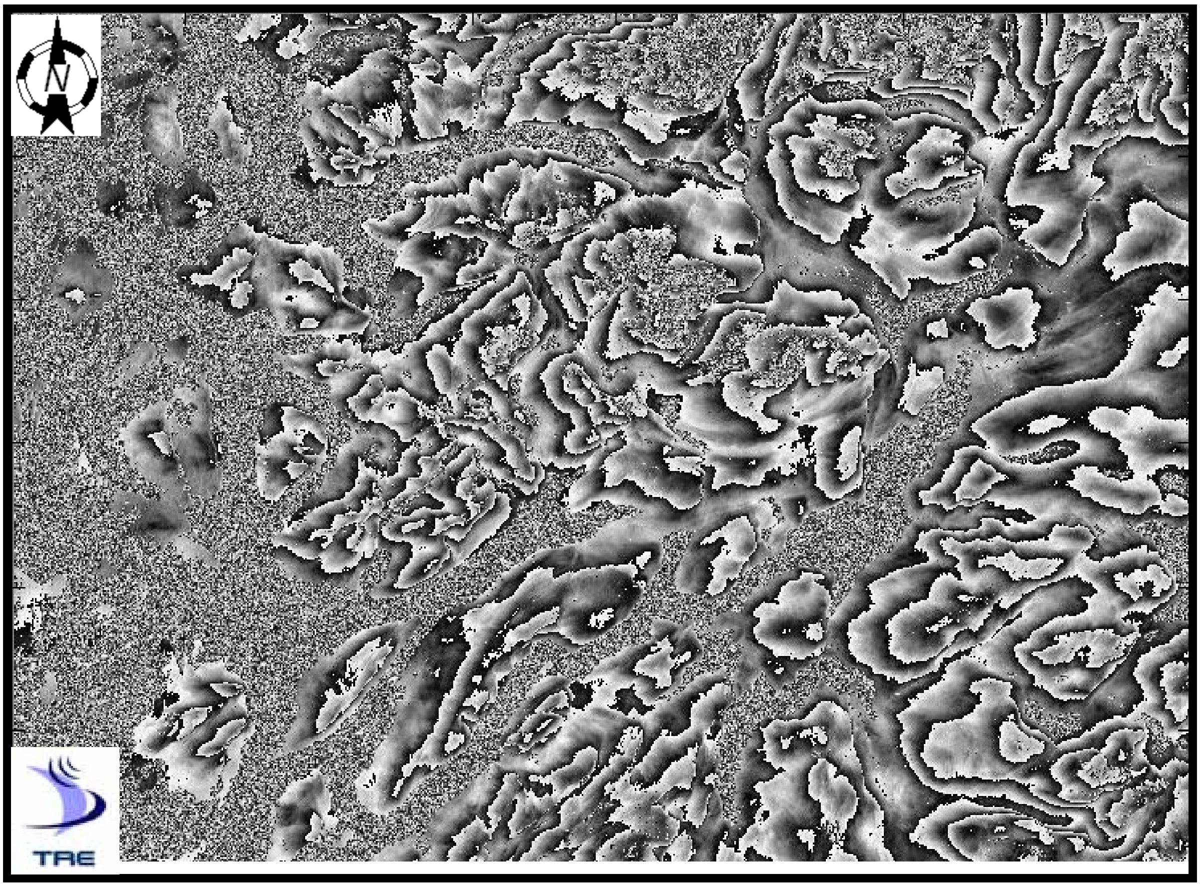


Figure 2. SAR interferograms obtained from a pair of images acquired July 15 and 16, 1995, by the ERS-1 and ERS-2 satellites. The area is the same as Figure 1. Fringes are related to topography.

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.

3. DATA PROCESSING

In 2004, standard processing was performed on two independent series of radar images (Dehls, 2004). This was possible due to the large overlap between images from neighbouring orbits at this high latitude. 40 images from track 423 and 38 images from track 151 were processed, covering the time period 1992 to 2001. The areas covered were large (2800 km^2 and 1500 km^2), with an overlapping area covering the city (400 km^2). A number of areas undergoing movement were discovered. They will be discussed in detail below. In order to extract more information about these areas, it was decided to reprocess one of the sets of images using a more advanced processing algorithm and a smaller area of interest, approximately 500 km^2.

3.1 Standard processing

By processing two sets of images, we obtained two independent datasets that could be compared at a regional and local scale. In addition, since the acquisition geometry was slightly different, only a subset of the PS in the two dataset corresponds to the same objects. Thus we obtained a higher total density of measurements.

Figures 3 and 4 show the two velocity fields. The PS density is clearly related to the density of man-made structures. The highest density, in the city center, is over 600 PS/km^2 in track 423 and over 800 PS/km^2 in track 151.

Since the two datasets were processed independently, each has its own arbitrarily chosen reference point, which is considered stable. For this reason, the velocity values vary slightly from one dataset to the other. Nonetheless, the pattern of subsidence is identical where the datasets overlap.

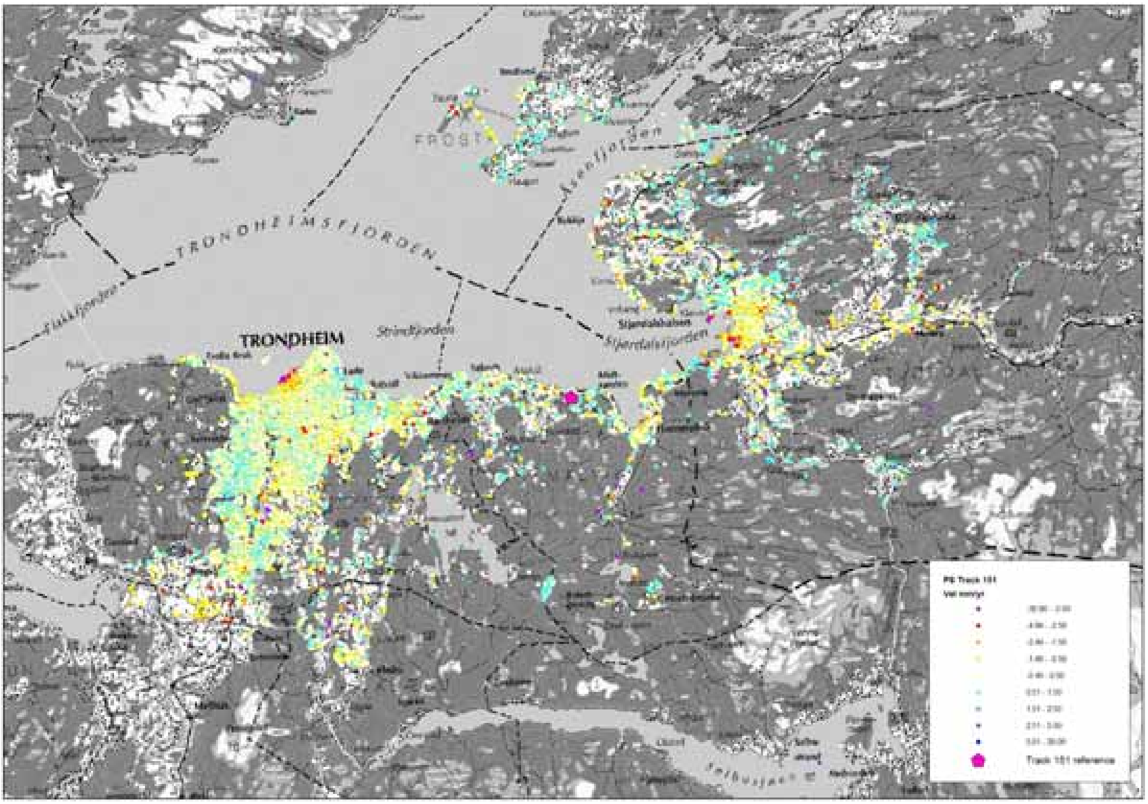


Figure 3. Average line-of-sight velocity field over the Trondheim – Stjordal region determined from SAR images along track 151. All velocities are relative to the purple reference point, which is assumed to be stable.

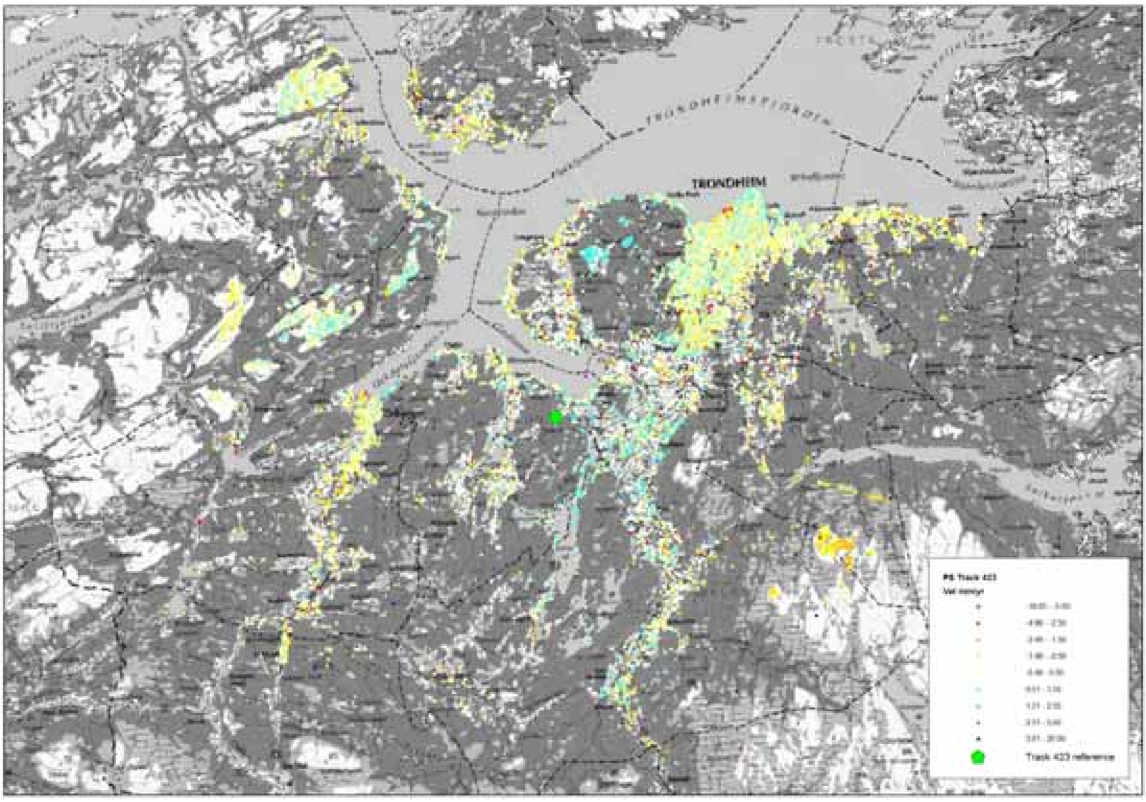


Figure 4. Average line-of-sight velocity field over the Trondheim – Orkanger region determined from SAR images along track 423. All velocities are relative to the green reference point, which is assumed to be stable.

3.2 Advanced processing

Advanced processing was performed using scenes from track 423. This track was chosen because it covered all of Trondheim kommune. Initially, we intended to include all available ERS and Envisat scenes. However, there were insufficient Envisat scenes available to integrate with the ERS scenes. Nonetheless, several new ERS scenes were available, and the new data now covers the period up to 2003.

77 ERS scenes were purchased. During the previous standard processing, all winter scenes were excluded, leaving 40 scenes in the analysis. In the current processing, enhanced selection techniques, using amplitude and phase analysis, allowed some of the winter scenes to be used. The result is that 59 scenes were included in the final processing.

In the area covered by this dataset, the standard processing found 17000 permanent scatters. The new processing found 42000. Data density is as high as 1300 PS/km^2 in city centre. In addition, there is a higher signal to noise ratio.

4. RESULTS

Mapsheet 1 is an overview map showing the results for the entire city at 1:20000 scale. Mapsheets 2, 3 and 4 show areas with significant subsidence at 1:5000 scale. These areas will be discussed in this section.

Several points must be kept in mind when interpreting the velocity values.

- All values are relative to the arbitrarily chosen reference point that is assumed to be stable.
- The standard deviation of velocity errors increases with distance from the reference point.
- As stated earlier, the velocity given is the velocity along the line-of-sight to the satellite, which is on average 23° from the vertical. If the true movement direction is not along this line-of-sight, the velocity is an underestimate of the true velocity. This is especially true if there is a large horizontal component.
- Individual points on the time-displacements curves should not be over-interpreted. While we believe the accuracy of the velocity rates to be better than 1 mm/yr, the accuracy of each individual point is not better than 3 mm/yr. The signal-to-noise ratio for each curve is indicated by a value called ‘coherence,’ with higher values being better.

4.1 Mapsheet 2, City Centre and harbour area including Nordre avlastningsvei project

In general, the city centre area is quite stable. There are numerous isolated permanent scatterers that indicated significant subsidence. These, however, are mostly associated with buildings that also have several stable points. Most likely those that show movement are related to unstable structures on the roofs of the buildings. One exception, however, seems to a building on the northwest corner of Schultzgate and Munkhaugveita, which has a steady subsidence rate of between 3 and 3.5 mm/yr.

Along the coastline, there is significant subsidence in the areas that have been built out into the fjord. This is the case in both Nedre Ila and Brattøra. In the case of Nedre Ila, the subsidence is approximately 2-4 mm/yr. In Brattøra, however, the subsidence rates are as high as 30 mm/yr. In the Nyhavna area, subsidence is less severe. The most significant subsidence in that area affects Dora. The southwest side of the building is subsiding at a rate of 3-4 mm/yr, while the northeast end is stable.

4.2 Mapsheet 3, Trondheim east, including E6 Øst project

The only significant areas of subsidence in this mapsheet are Dora (described above) and City Lade. The subsidence affecting City Lade is concentrated in the northern section of the building, with velocities as high as 4 mm/year.

4.3 Mapsheet 4, Trondheim southeast

Four significant areas of subsidence are seen in the mapsheet. The first is a section of the E6 south, where Omkjøringsvegen begins, which is subsiding between 1 and 3 mm/yr. The second is SINTEF Petroleumsforskning's building, at S P Andersens v 15 B. This building is subsiding between 2 and 3 mm/yr.

The third area is around Loholt. This is a residential area, and numerous houses are subsiding at rates as high as 12 mm/yr. Figure 5 shows the 1:50000 surficial geology of the area, along with the subsidence data. The affected area is built partially upon marine clays and partially on reclaimed peat bog.

Several houses in the neighbourhood were monitored using optical levelling between 1998 and 1992. Figure 6 shows the average subsidence rates for that period compared with the rates determined in this study.

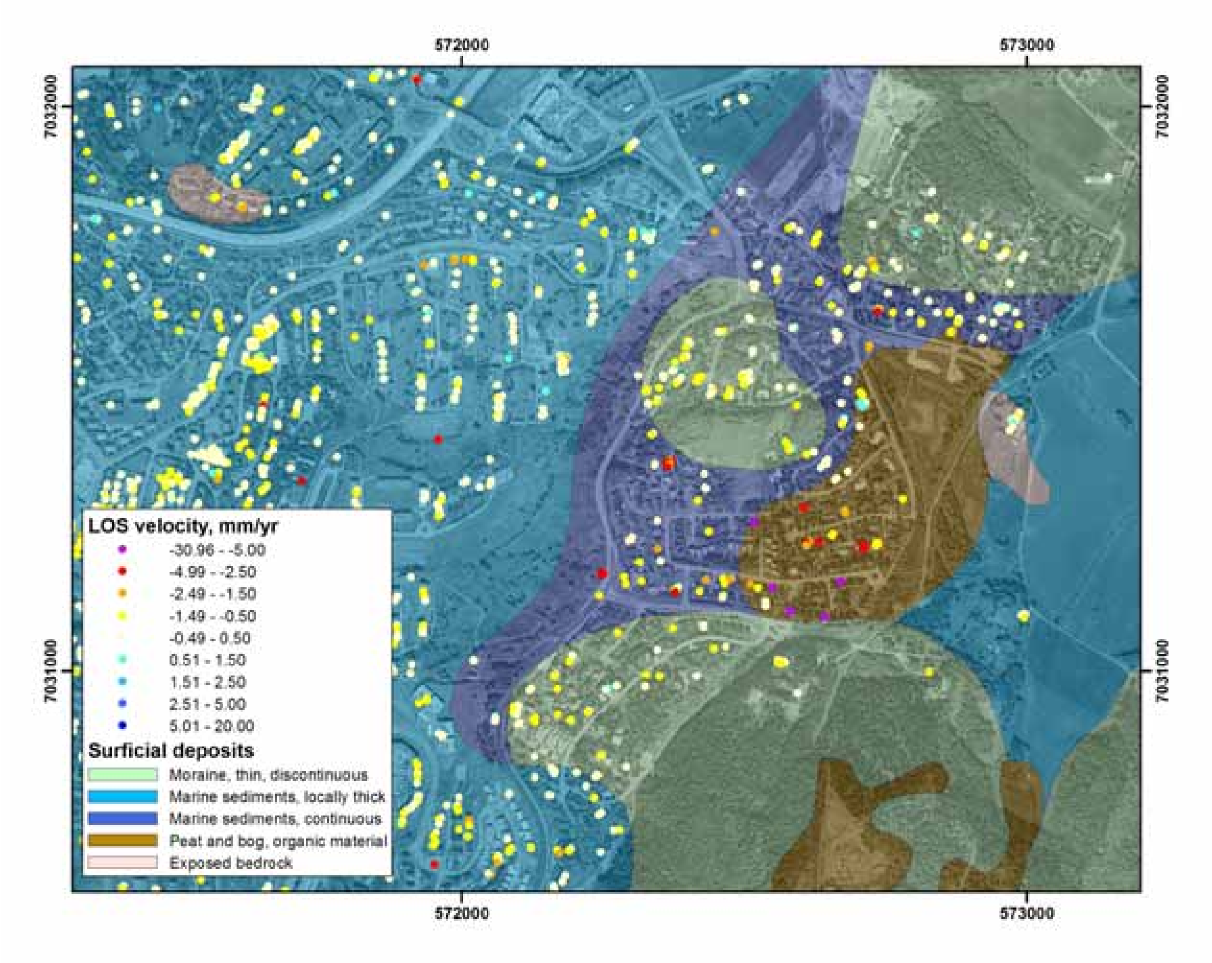


Figure 5. 1:50000 surficial geology in Loholt area. Significant subsidence is taking place in the residential neighbourhood built upon marine clays and peat bogs.

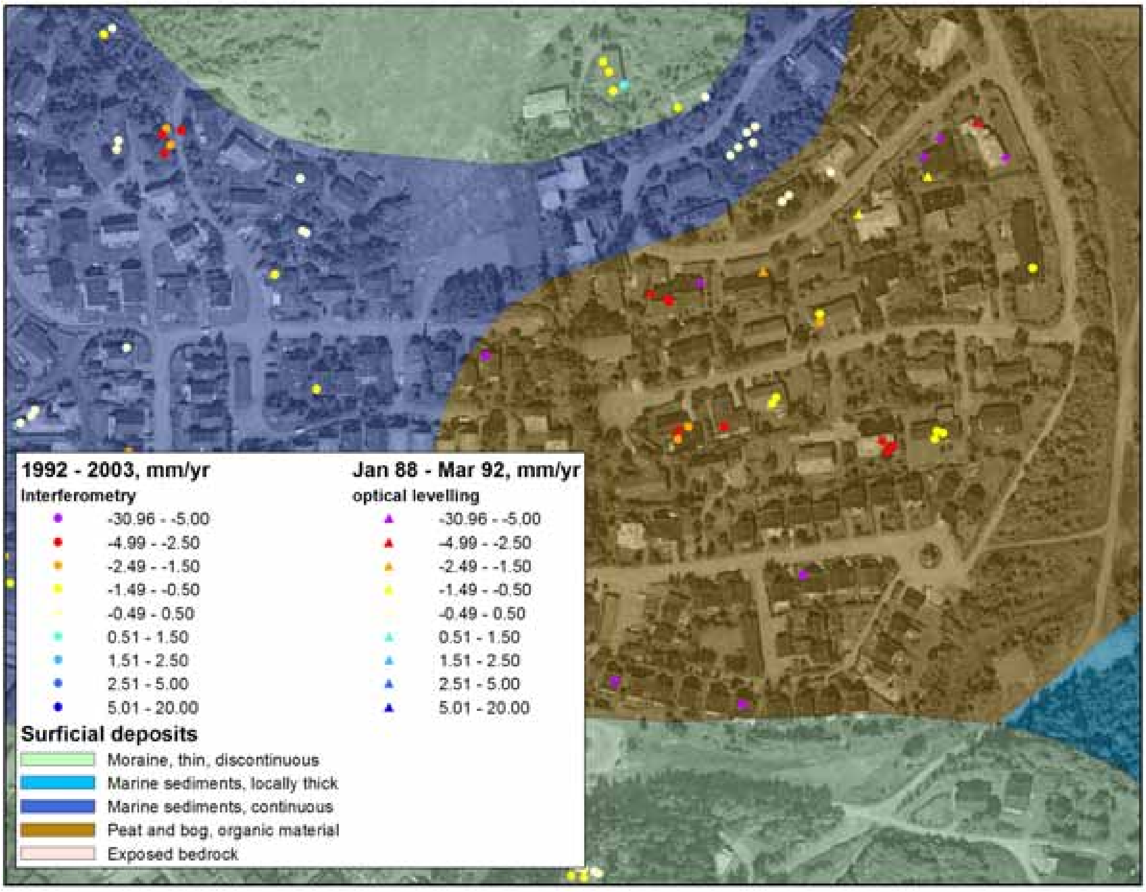
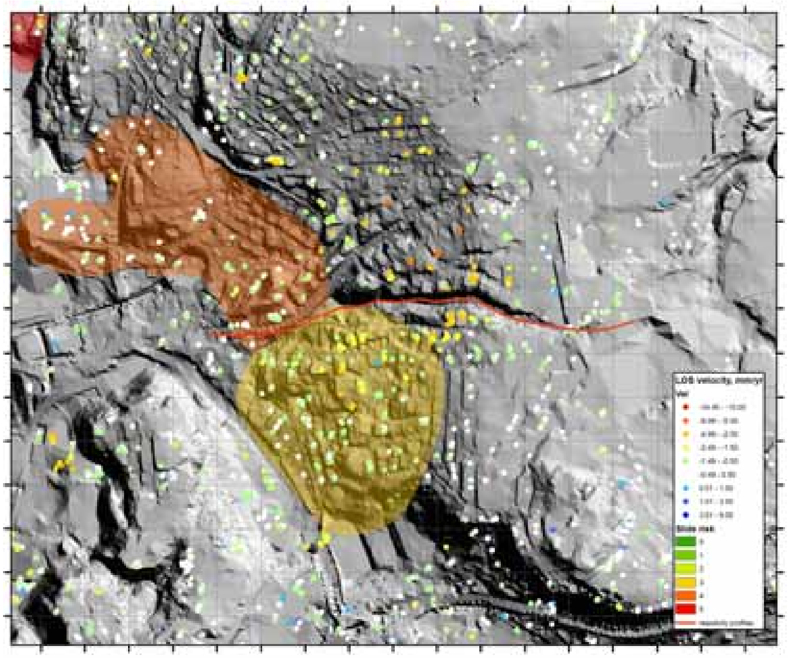


Figure 6. Comparison of subsidence rates determined by optical levelling with those determined by PSInSAR in Loholt area.

The final area of subsidence is in the Eberg/Moholt area. An area approximately 800 metres by 800 metres on the hillside southeast of NTNU is subsiding. The velocity is highest near the centre of the area. The area of movement is well constrained by the top of the slope, along Jonsvannsveien. The area above is stable. Since the technique we are using only measures change in distance between the satellite and the ground, it is theoretically possible that the area in question is moving horizontally (downslope) as well as vertically. This can only be determined using other methods, such as GPS or optical levelling.

Since this area is adjacent to a known quick-clay deposit, we have done some geophysical measurements to test for the presence of quick-clay under the slope. Electrical resistivity measurements were carried out along four profiles in the spring of 2005. The measurements indicate the presence of a thick layer of clay, but not quick-clay (Figure 7). Further investigations are ongoing, including geotechnical drilling by NTNU staff and students.



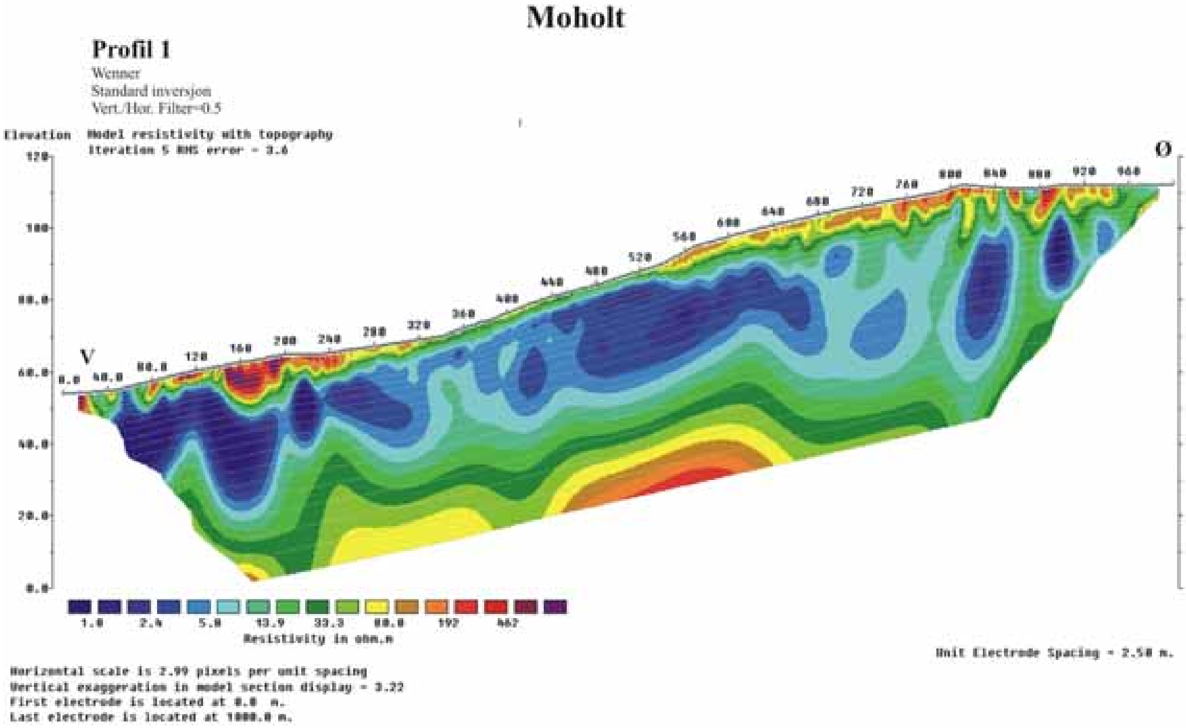


Figure 7. One of four electrical resistivity surveys carried on in Eberg. The blue colour represents clay that is not sensitive (quick).

5. MONITORING POSSIBILITIES

5.1.1 Future monitoring

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. So far there are insufficient images available to integrate with the ERS scenes.

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). In June 2004, Kongsberg Spacetec began to acquire images over Trondhiem and Oslo on the recommendation of NGU. Although the raw satellite scenes will be available for free or a nominal cost, processing costs will have to be borne by the end users.

All the processing for this and previous studies has been carried out by Tele-Rilevamento Europa, in Milano. This company is a spin-off from Politecnico di Milano, and is the world's leading company for this type of processing. Recently, NGU has begun a joint project with Norut-IT to develop InSAR processing capabilities at NGU. Over the next three year, NGU will begin to process all available Radarsat, ERS and Envisat scenes over Trondheim. We plan to eventually be able to offer updates to this dataset on a regular basis.

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