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Settlement monitoring using space-borne radar interferometry, in the context of large infrastructure projects

Surveillance de la déformation du terrain par interférométrie radar, dans le cadre de grands projets d'infrastructure

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ABSTRACT: Geodetic data acquisition in urban areas and along linear infrastructure are major cost drivers in big infrastructure projects. Modern remote sensing methods help us to manage data acquisitions with high effectiveness during the different phases of such projects. Here, we show how we apply space-borne radar interferometry to monitor settlements. We showcase two examples: a) the new E18-highway development project in Bærum, Norway; and b) the Follo Line railway project between Ski and Oslo. Monitoring is done by exploiting very high resolution TerraSAR-X data (ca. 1.5 x 1.5 m spatial ground resolution) in the E18 case, and high resolution Radarsat-2 data (ca. 7 x 7 m spatial ground resolution) in the Follo Line case. In both cases, the interferometry results are communicated to the end users through a web-based map- and time-series portal.

RÉSUMÉ: L'acquisition de données géodésiques en zones urbaines et le long des infrastructures linéaires représente un coût majeur dans la réalisation de grandes infrastructures. Les méthodes modernes de télédétection spatiale peuvent aider à gérer efficacement ce type d'acquisitions. Nous montrons comment l'interférométrie radar par satellite peut être utilisée pour le monitoring des tassements différentiels. Nous présentons deux exemples : a) le nouveau projet d'extension de l'autoroute E18 à Bærum, en Norvège; et b) le projet de voie ferrée Follo entre Ski et Oslo. Nous exploitons les données TerraSAR-X de très haute résolution (résolution spatiale au sol d'environ 1,5 x 1,5 m) dans le cas de la E18 et les données Radarsat-2 de haute résolution (résolution spatiale au sol d'environ 7 x 7 m) dans le cas de la voix ferrées de Follo. Dans les deux cas, les déplacements observés sont communiqués aux clients via un portail cartographique Web.

Keywords: Infrastructure, development, settlements, radar interferometry

1 INTRODUCTION

Ground settlement and associated deformation of existing infrastructure is a major risk in urban development projects. Project owners in such areas have a responsibility to document and manage settlement records before, during and after construction works. Traditionally, land surveying has been the state-of-practice tool to provide settlement monitoring data. Modern radar interferometry provides the opportunity to drastically increase the number of monitored locations, while at the same time reducing expenses for traditional geodetic survey work. We illustrate this technology for two large urban road and railway development projects in the wider Oslo area in Norway.

2 METHODS AND DATA

Radar interferometry is a technique which uses two or more radar images, acquired at different times, to generate surface deformation maps with millimetre per year accuracy (cf. Berardino et al., 2002; Ferretti et al., 2001; Cespa et al., 2016). Man-made infrastructure is usually a perfect target for this type of deformation monitoring, since buildings and other infrastructure (such as crash barriers, lamp posts, railway tracks) have a high reflectivity as well as a good coherence and thus provide good data quality. Radar interferometry enables contact-less measurement and monitoring of parameters that are crucial in both the planning and development stage of large infrastructure projects; and this with a measurement density of several thousand points per square kilometre. Thereby, it is possible to considerably reduce costs by targeting the traditional in-situ measurements to areas of special interest.

Prime opportunities, as well as limitations, are determined whether terrestrial or satellite based platforms are used. Satellite systems, usually applying synthetic aperture concepts, can cover large areas and are mainly sensitive to slow, sub-vertical movements. Terrestrial radars can be used for discrete sites and are capable of sensing horizontal movements, both rapid in real time and slow via multi-year monitoring. Both solutions offer millimeter deformation accuracy with varying degrees of spatial resolution from 10s of centimeters to 10s of meters.

All results presented here are based on data processing with a Permanent Scatterer workflow (Ferretti et al., 2001) implemented in the *SARscape* software package (sarmap SA, Switzerland).

2.1 Case 1: Highway development project, E18 West corridor

In the west of Oslo, the existing highway E18 (linking the city of Kristiansand in the south with the capital of Oslo) shall be considerably improved over the course of the coming years (https://www.vegvesen.no/Europaveg/e18lysakerasker). Among other things, there will be built 17 km new highway lanes, of which 8.5 km will be laid in tunnels. There will also be built a 2 km long tunnel for one of the local roads, 17 km of bus routes and 17 km bicycle paths and local roads.

Radar interferometry measurements are now performed for the Norwegian Public Roads Administration, in order to map and monitor subsidence of buildings that may be affected by the construction work, as well as to provide an overview of areas where subsidence is ongoing already today, before the construction work has started.

In this project, very-high resolution data from the German TerraSAR-X satellite is exploited. This data has a spatial ground resolution of ca. 1.5 x 1.5 m. A total of 48 data scenes were processed for the first delivery (see below). An average of one data scene per month was used in the period April 2014 to March 2017 and data intervals of 11-days in the period April to June 2017. For the further analyses, one scene per month is acquired, during spring, summer and autumn (March to December), with a pause in winter to avoid processing artefacts due to snow cover.

The first delivery was a "historical" baseline analysis for the period 2014 to 2017. This baseline analysis gives an overall picture of the status-quo in the study area, i.e., a mapping of areas with currently ongoing settlements and of areas that are currently unaffected by settlements. In addition, the baseline analysis reveals buildings that are poorly covered with satellite measurements. This happens, for example, if a building has very poor back-scattering properties (e.g., buildings with grass-covered roofs, where the radar signal is not reflected satisfactorily) or due to unfavorable geometry of a building with respect to the satellite orbit (e.g., buildings that are located in the "shadow" of a much higher building). Such buildings need to be monitored by other methods, e.g., by traditional surveying of bolts.

2.2 Case 2: Follo Line tunnelling project

The Follo Line will form the core part of the InterCity development southwards from Oslo (https://www.banenor.no/en/startpage1/Projects/New-double-track-Oslo-Ski/). The project is currently the largest infrastructure project in Norway and includes a 20 km long tunnel, which will be the country's longest railway tunnel and the first long twin tube rail tunnel ever construced in Norway. Combined with the existing Østfold Line, four tracks towards the capital Oslo will provide more and faster trains, and more trains on schedule.

The Follo Line project is being built with a clear focus to minimise possible damage to the environment. To monitor possible movements in the ground during the advancement of the four tunnel boring machines (TBMs), data from bolts in more than 2,200 buildings along and across the track have been registered. The current system using bolt levelling provides a good level of reliability for the builder and residents. The exact measurements are taken at selected points, but in some cases it can be challenging to identify the best measuring points. Therefore, radar interferometry results are delivered as a supplement to the traditional methods of monitoring ground movements.

Radar interferometry results improve the factual basis for monitoring any changes that might occur during the construction period. Satellite-based radar interferometry monitoring provides a sustained overview of the entire site.

Here we use satellite data from the Radarsat-2 satellite, with a spatial ground resolution of ca. 7 x 7 m. An average of one data scene every 24th day has been acquired since 2014 and ongoing.

3 RESULTS

3.1 E18 West corridor

The first results document the subsidence history from April 2014 to June 2017 (Figure 1, on page 4). The results contain measurement points in the project's area of interest (7.3 km^2). On average, 27,250 measurement points (with coherence values 0.65 or better) were measured per square kilometer. This corresponds to a total of 220,060 measurement points within the area of interest.

The average settlement velocity in the area of interest is between zero and -20 mm/year during the observed period. At most of the measurement locations (210,637 out of 220,060), no settlements are observed. Settlements greater than minus three mm/year are observed for 9,122 (out of 220,060) measurement points. Such results enable the identification of settlements and subsidence phenomena that are already present before the highway construction will start in 2020 (cf. Figure 2).

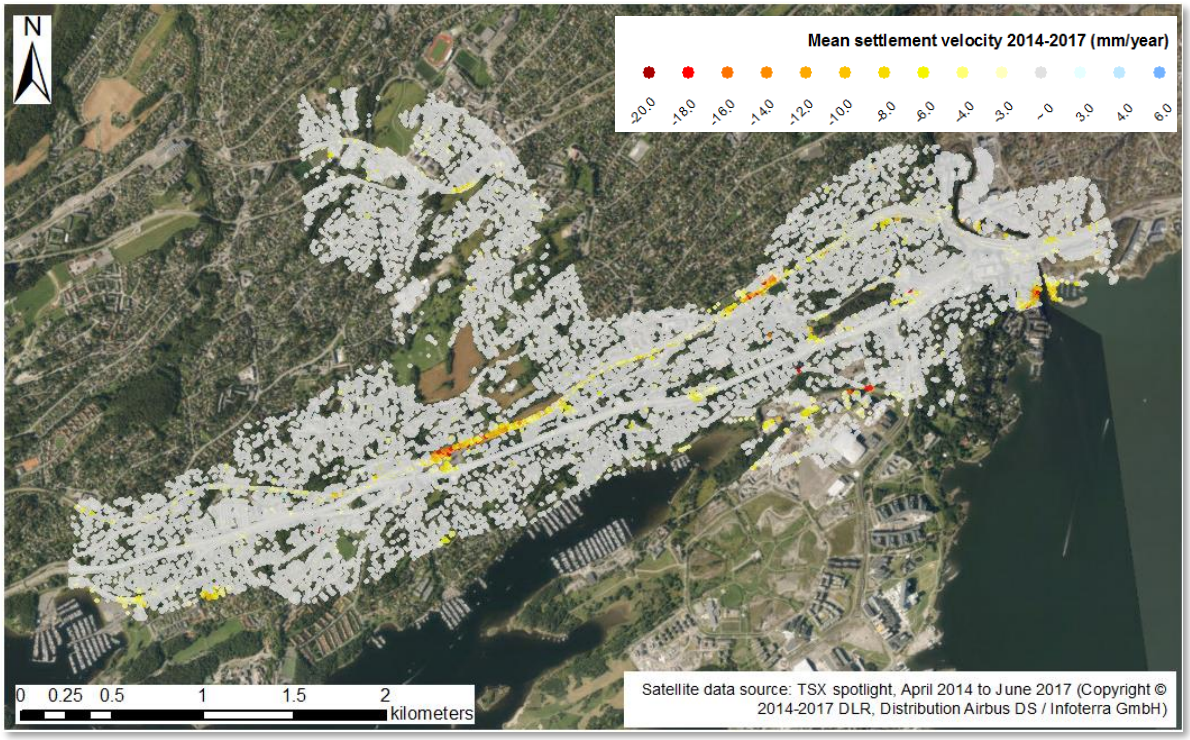

Figure 1. Subsidence in the "E18 west corridor" during the period April 2014 to June 2017, as observed by radar interferometry. Grey markers are locations that are stable, yellow to red markers are locations with settlements during the observation period (with increasing settlement values from yellow to red). The largest observed settlements are in the order of -20 mm/year.

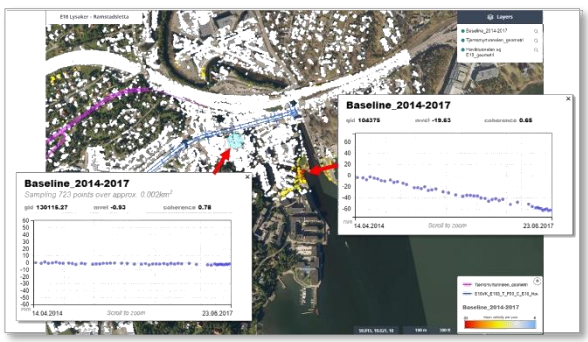

Figure 2. Zoom-in of figure 1, exemplifying an area without subsidence near (left time series) and with existing subsidence record (right time series), as observed by radar interferometry. Grey markers are locations that are stable, yellow to red markers are locations with settlements during the observation period (with increasing settlement values from yellow to red). The largest observed settlements are in the order of -20 mm/year.

3.2 Follo Line

The results document the subsidence history from April 2014 to August 2018 (Figure 3). The results contain 211,888 measurement points in the contracted area of interest, which comprises 104 km^2.

On average, 3,057 measurement points (with coherence values 0.65 or better) were measured per square kilometer, and 6,733 measurement points per square kilometer in built-up areas. The results are updated four times a year and could be updated on-demand any time, if need would arise during the advancement of the TBMs.

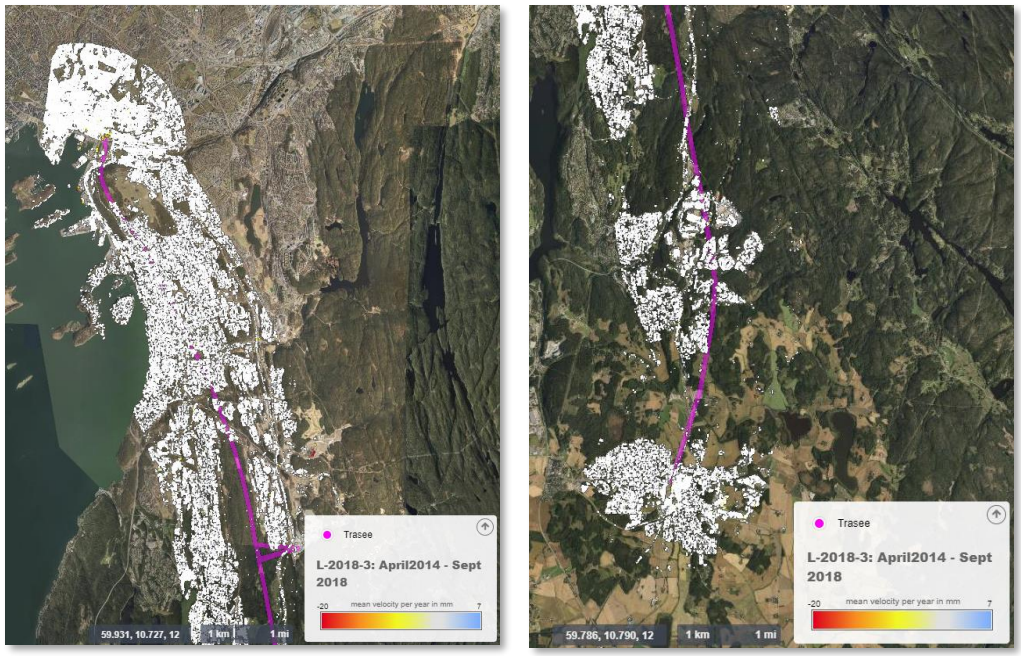

Figure 3. Ground stability situation along the Follo Line project, for the period April 2014 to August 2018, as observed by radar interferometry. Grey markers are locations that are stable, yellow to red markers are locations with settlements during the observation period (with increasing settlement values from yellow to red). The largest observed settlements are in the order of -20 mm/year.

Figure 4. Zoom-in of one region along Follo Line. Colour scale as in Figure 3.

The zoom-in in Figure 4 shows an area where settlements can be observed. The time series show that the settlements started before the onset of the Follo Line construction. It also indicates a acceleration of the settlement velocity between June 2015 and September 2016.

4 DISCUSSION

Interferometric radar is today successfully applied in big infrastructure projects. The method can be applied for historical assessments, in order to measure what has moved when and by how much. Preferably, however, and as shown in the here presented examples, the method should be applied for risk mitigation and asset management during construction (Follo Line example), or for planning and asset management prior to construction (E18 example). Depending on the spatial resolution of the satellite data used, the interferometry results can be used to gain an overview over settlement/subsidence hotspot areas, as is the case for data with resolution in the metres to ten-metres range (Follo Line example). Or the results can be directly tied to pre-existing in-situ measurement records, as is the case for interferometry results based on satellite data with

resolution in the meter to sub-meter range (E18 example).

5 CONCLUSIONS

Remote sensing in general and interferometric radar deformation measurements in particular offer substantial value to geotechnical and civil engineering projects. The key to unlock that value in big infrastructure projects is to integrate these generally very big datasets early-on and in an appropriate way to extract the information that is most relevant to the engineering challenge that needs to be solved. Once such a strategy has been found, the scope of conventional works can be designed at highest effectiveness leading to a thorough understanding of the situation at costs that are comparable or often less than with purely conventional methods.

6 ACKNOWLEDGEMENTS

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