PERSISTENT SCATTERER INTERFEROMETRY: POTENTIAL AND LIMITS

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ABSTRACT:

This paper is focused on Persistent Scatterer Interferometry (PSI), the most advanced class of differential interferometric Synthetic Aperture Radar techniques (DInSAR). The paper only refers to the PSI techniques that exploit data acquired by spaceborne SAR sensors. PSI is a powerful remote sensing technique used to measure and monitor the temporal evolution of surface deformation phenomena. In this work we consider the C-band applications based on the ERS and Envisat SAR data. It starts with a concise description of the main characteristics of PSI deformation monitoring, and an outline of the main PSI products. An important part of the paper includes the discussion of the major advantages and the key open technical issues of the technique. The open technical issues include the limitations of PSI to spatially and temporally sample the deformation phenomena, the critical limitation related to the deformation rates that can be observed, etc. The last part of the paper discusses some relevant PSI validation results, which represent a key aspect that drives the applicability and acceptability of this relatively new technique. In the last fifteen years the DInSAR techniques have demonstrated their potential as land deformation measurement tools, while in the last few years their capability has been considerably improved by using the PSI techniques. The paper describes the main outcomes of a major PSI validation project funded by the European Space Agency, which was run within the GMES Terrafirma project. The key findings of this validation exercise are summarized in this paper. The project generated rich PSI data sets and interesting global statistics, which concern large sets of measurements and provide information on the global behaviour of the key PSI products: mean deformation velocities, deformation time series, density of the PSI measurement, topographic corrections and geocoding of each measured point, etc.

1. INTRODUCTION

This paper focuses on Persistent Scatterer Interferometry (PSI), a radar-based remote-sensing technique to measure and monitor land deformation. PSI is the most advanced class of differential interferometric Synthetic Aperture Radar techniques (DInSAR) based on data acquired by spaceborne SAR sensors. The PSI techniques can in principle be used with data coming from terrestrial (Crosetto et al., 2009) or airborne SAR sensors; however, the spaceborne SAR sensors are by far the most important PSI data source. For a general review of SAR interferometry and DInSAR, see Rosen et al. (2000) and Crosetto et al. (2005).

As mentioned above, PSI represents the most advanced class of DInSAR techniques, which started with the so-called Permanent Scatterers technique proposed by Ferretti et al. (2000). Following this approach different other techniques have been proposed in the following years, see e.g. Ferretti et al. (2001), Berardino et al. (2002); Colesanti et al. (2003), Mora et al. (2003), Lanari et al. (2004); Hooper et al. (2004), Crosetto et al. (2005), Pepe et al. (2005), Crosetto et al. (2008). Even though these techniques were initially named “Permanent Scatterers techniques”, now all of them, including the original Permanent Scatterers technique, are called “PSI techniques”. It is worth mentioning that the term “Permanent Scatterers” is directly associated with the original technique patented by Ferretti et al.

There are two main differences between DInSAR and PSI techniques: the first one is the number of processed SAR images (PSI uses large series of SAR images, typically more than 20), and the other one is the implementation of suitable data modelling and analysis procedures that allow one to get the following key products: (i) the time series of the deformation; (ii) the average displacement rates over the observed period; (iii) the atmospheric phase component of each SAR image; (iv) the so-called residual topographic error (difference between the true height of the scattering phase centre and the height given by the used DEM). This parameter is important for modelling purposes (i.e. to separate the residual topographic component from the deformation one), and for geocoding purposes. The main products of any PSI analysis are given by the map of the average displacement rates, and the deformation time series of each measured Persistent Scatterer (PS).

2. ADVANTAGES AND LIMITS OF PSI

In this section we concisely discuss some the major advantages and limits of PSI.

Some of the key advantages of PSI are well-known. Firstly, PSI offers wide-area coverage (ERS and Envisat standard imagery, for instance, cover 100 by 100 km) typically associated with a relatively high spatial resolution. This allows us to get a global outlook of the deformation phenomena occurring in a wide area, keeping at the same time the capability to measure individual features, like structures and buildings. A second important advantage of PSI is its sensitivity to small deformations, which in terms of deformation velocity are in the region of 1 mm/yr. A third advantage is related to the periodic data acquisitions provided by the space-borne SAR sensors. A fourth unmatched advantage is the availability of huge historical SAR archives, which in the case of ERS start in 1991. This confers to PSI the ability to measure and monitor "past deformation phenomena". For instance, it is possible to study ground motion that occurred in the past and for which no other survey data are available.

As mentioned above, the most important advantages of PSI are rather well understood and documented in the PSI literature. By contrast, we believe that this is not the case for some of the main limits of PSI, which are sometimes not clearly documented. Some of them are briefly discussed below. Note that the aspects related to the quality and validation of PSI products are discussed in the following section.

The first key limit of PSI is related to the capability of temporally sampling the deformation phenomena, which basically depends on the revisiting time capabilities of the SAR satellites (e.g. 35 days for ERS and Envisat, 11 days for TerrSAR-X) and their data acquisition policies. The temporal SAR sampling directly impacts the temporal resolution of PSI, which can typically monitor slow deformation phenomena which evolve over several months or years. The actual spatial sampling of PSI represents a second important limit. PSI is an "opportunistic deformation measurement method", which is able to measure deformation only over the available PSs, that is the points where PSI phases are good enough to get reliable deformation estimates. PS density is relatively high in urban areas (for instance densities up to 1000 PS/km^2 can be achieved with ERS and Envisat data), while it is usually low in vegetated and forested areas, over low-reflectivity areas (very smooth surfaces), and steep terrain. It is worth underlining that the location of the PSs cannot be known prior to the PSI processing. The spatial density limitation is particularly evident for the ERS, Envisat and Radarsat sensors, while for the high-resolution ones, like TerraSAR-X, PS density should considerably improve. A third limit of PSI is the line-of-sight (LOS) measurements capability. The deformation measurements coming from PSI and all DInSAR techniques are made in the LOS of the used SAR sensor. Therefore, given a generic 3D deformation, PSI provides the estimate of the LOS component of this deformation (i.e. the projection of the 3D deformation in the LOS direction). By using ascending and descending SAR data one can retrieve the vertical and approximately the east-to-west horizontal components of deformation.

A fourth limitation of PSI is related to the deformation rates that it can observe. Due to the ambiguous nature of the PSI observations, which are 2π-wrapped, PSI suffers limitations in the capability to measure "fast" deformation phenomena. This limitation depends on the spatial pattern of the deformation phenomenon at hand. As a rule of thumb, with the current revisiting times of the available C-band satellites, PSI has usually difficulties to measure deformation rates above 4-5 cm/year. A fifth limitation is due to the fact that most of PSI approaches make use of a linear deformation model in their estimation procedures, e.g., this occurs in all products of the Terrafirma project (www.terrafirma.eu.com). The linear model assumption, can have a negative impact on the PSI deformation estimates for all phenomena characterized by non-linear deformation behaviour, i.e. where the assumption is not valid. In areas where the deformation shows "significantly non-linear motion" and/or high motion rates the PSI products lack PSs.

In the following we mention two further limitations, which play an important role in the exploitation of the PSI products. The first one is the achievable geocoding precision. The standard geocoding methods employ the DEM used in the DInSAR processing to geocode the DInSAR products, i.e. they use an approximate value of the true height of the scattering phase centre of a given pixel, which results in a location error in the geocoding. By using the so-called residual topographic error this kind of error can be largely reduced, thus achieving a more precise geocoding. According to the results of the Terrafirma Validation project, which are discussed more in detail in the next section, the east-to-west PS positioning precision (1 σ) is in the region of 2-4 m. Even though these values are certainly good for satellite-based imagery, they limit the interpretation and exploitation possibilities of PSI results. A second important aspect that affects the PSI product exploitation is related to the deformation time series. They provide a deformation estimate to each of the acquisition dates of the used SAR images. However, they are particularly sensitive to phase noise. In addition, their interpretation should take into account that, as mentioned above, the linear deformation model assumption is often made. To the authors' experience the real information content of the PSI deformation time series has not been fully understood so far. Even if excellent time series examples have been published in the literature, their limitations have been not clarified.

3. PSI VALIDATION

Over the past few years PSI techniques have remarkably increased their capability as a deformation measurement and monitoring tools. In parallel to this, different efforts have been made to validate the PSI techniques by assessing the performances of their products. In the following we mainly refer to the validation activities of the Terrafirma project, a project of the GMES (Global Monitoring for Environment and Security) Service Element Programme aiming to establish a long-term market for PSI products, see www.terrafirma.eu.com. A key step to increase the acceptability of PSI and establish a long-term PSI market is to prove the quality of PSI measurements. For this purpose, Terrafirma has run a PSI validation exercise that addressed the following key issues: quality assessment, assessment of performances, estimation of precision and accuracy, and evaluation of the consistency of PSI results coming from different service providers. The key findings of the above validation exercise, which is referred to hereafter as the Validation Project, are briefly summarized below.

The Terrafirma Validation Project was focused on the four Operational Service Providers (OSP's) of this project, i.e. Telerilevamento Europa (www.treuropa.com), Altamira Information (www.altamira-information.com), Gamma Remote Sensing (www.gamma-rs.ch) and Fugro NPA (www.npagroup.com). It included two main parts: process validation and product validation. The process validation involved the inter-comparison of the different OSPs' processed outputs and the analysis of their intermediate results. This analysis was performed in the SAR coordinate system, i.e. the "internal system" of SAR images. This "internal system" is usually not visible to end users, who receive the geocoded PSI products. However, this type of analysis is useful to test the "equivalence" of the OSP chains and to detect the cause of differences in the results, if any. The second part involved product validation, in which the geocoded PSI products were validated against ground truths. The PSI products considered in the Validation Project concerned two test sites, which have complementary characteristics. The first one is the Alkmaar area, with a spatially correlated deformation field due to gas extraction, studied using ERS-1/2 (1992–2000, 83 images) and ASAR-Envisat data (2003–2007, 39 images). Two examples of deformation velocity maps over the two teat sites are shown in Figures 1 and 2.

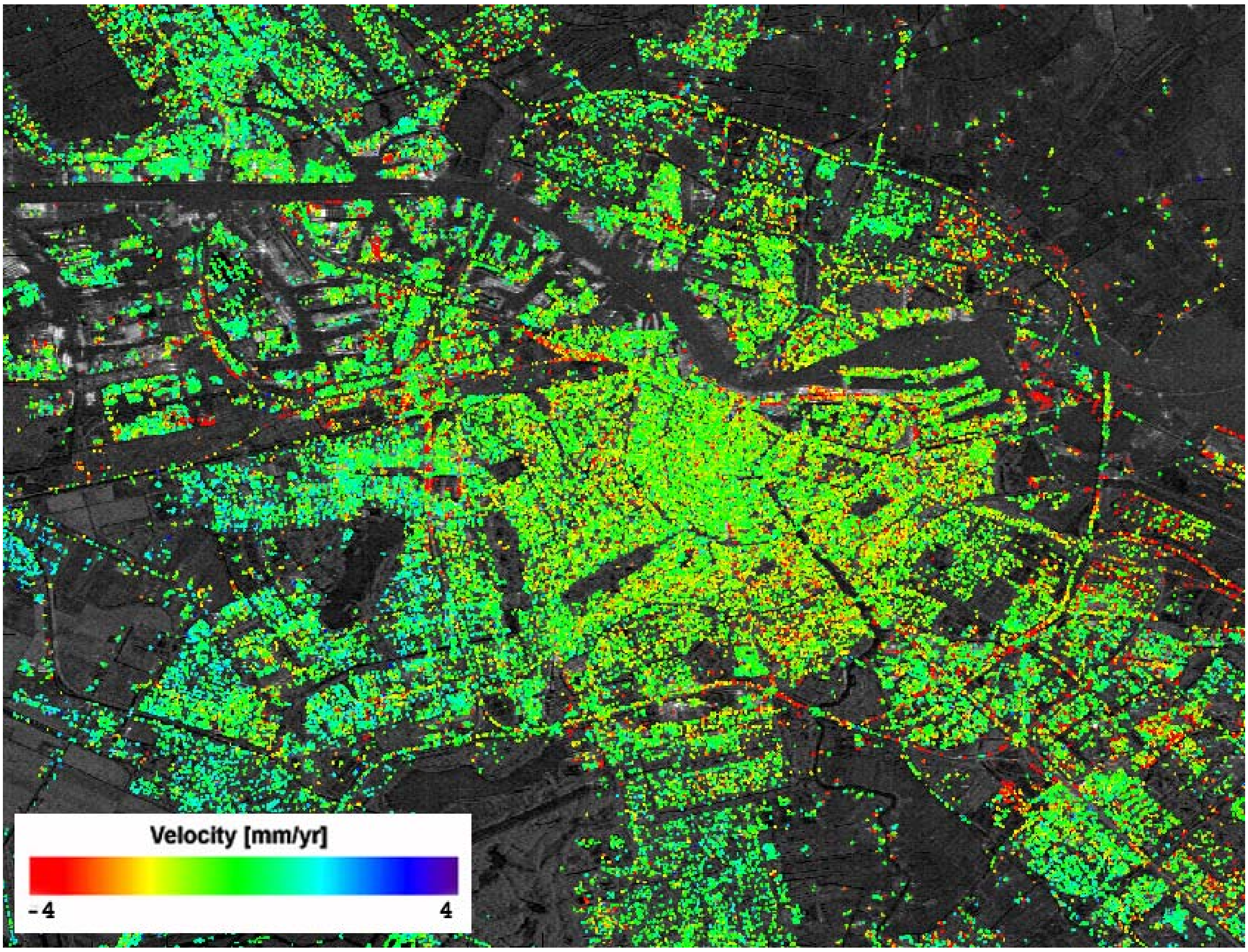

Figure 1: Deformation velocity map over the Amsterdam test site. This map, generated by DLR and used to support the validation activities of the Terrafirma Validation Project, was derived using 39 ASAR-Envisat images covering the period 2003–2007.

Ground truth data on this site are available from levelling campaigns. The second area included the city of Amsterdam, which includes, from a deformation viewpoint, autonomous and mainly spatially uncorrelated movements. Ground truth from different geodetic surveys are available for the area corresponding to the North-South (N-S) metro line. The OSP's had no open access to the ground truth data during the project. The results of the project were anonymous.

Three main results of the project are described over the following sections. The first part concerns the inter-comparison of the results from the different OSP's. The second discusses the validation results achieved over the Alkmaar test site. Lastly, the third describes the validation results over Amsterdam. More details on the above results can be found at www.terrafirma.eu.com/Terrafirma_validation.htm.

3.1 Inter-comparison results

The inter-comparison of the OSP results was based on intermediate and final PSI outputs in the original radar geometry. The inter-comparison analysis concerned the three main products of PSI: the estimated deformation velocities, the deformation time series, and the so-called topographic corrections. The most relevant results are summarized below.

- Deformation velocity. The average standard deviation of the velocity differences over Alkmaar and Amsterdam is 0.56-0.75 mm/yr. Assuming the same precision for the compared teams and uncorrelated results between teams, the estimated standard deviation of the deformation velocity of each team ranges from:

  $$\sigma_{\mathtt{VELO}} = 0.4 - 0.5 \text{ mm/yr}$$

  These values, which are derived from large sets of measured points (hereafter referred to as PS), provide information on the global inter-comparison behaviour of PSI velocities. They can be used to derive error bars to indicate the quality of the PSI velocity estimates, which is key information for end users. It is worth noting that the above statistics have been derived over two sites largely dominated by zero or very moderate deformation rates. For this reason, the above values are representative of all PSI studies that concern areas with similar characteristics to those of the test sites of this project.

- Deformation time series. The mean standard deviations of the time series differences range from 1.5 to 5.6 mm. Assuming that the teams have the same precision and uncorrelated results, the estimated standard deviation of the deformation time series of each team ranges from:

  $$\sigma_{\text{Tseries}} = 1.1 - 4.0 \text{ mm}$$

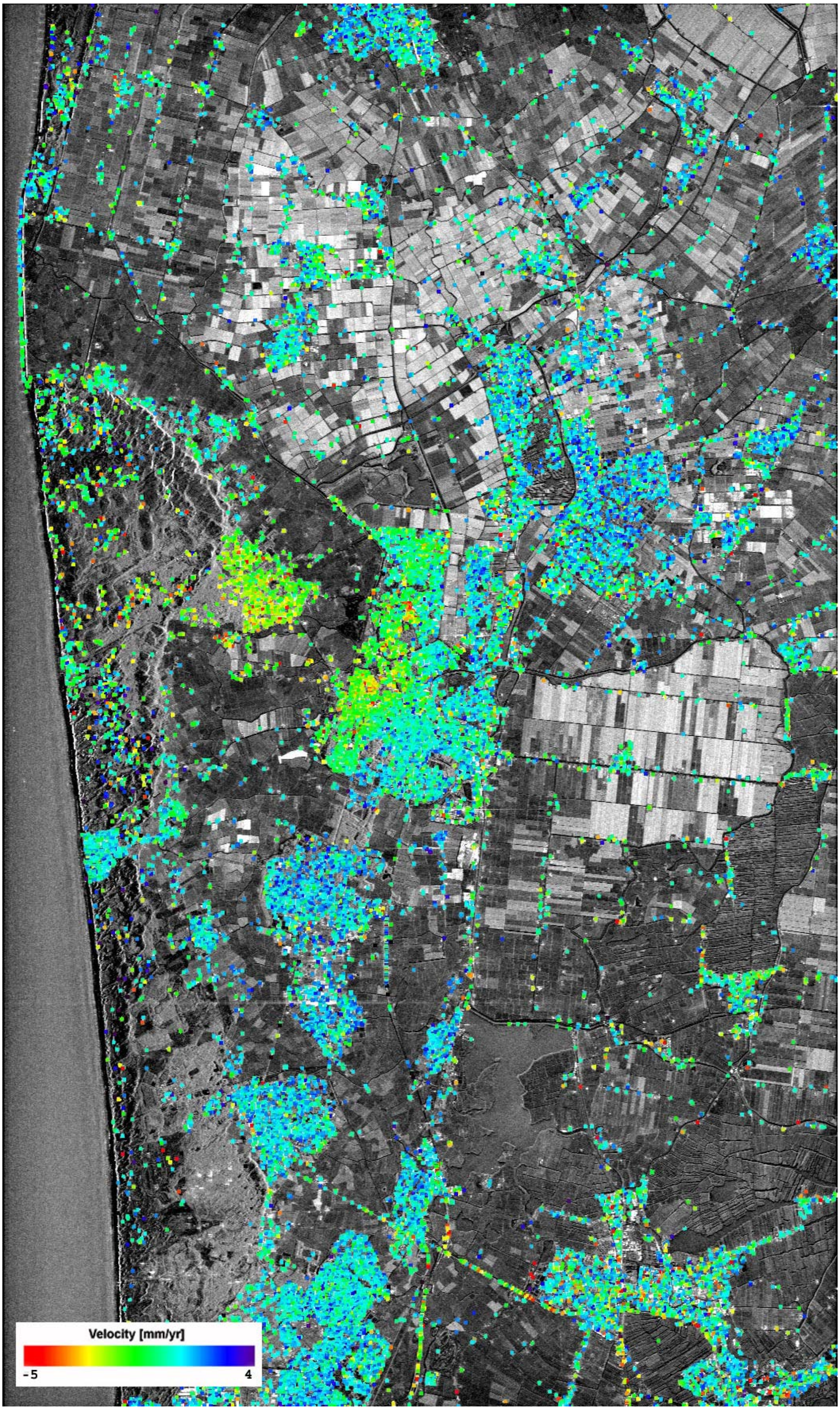

Figure 2: Deformation velocity map over the Alkmaar test site. This map was generated by one of the Terrafirma OSP's (the results of the project are anonymous) using 83 ERS-1/2 images covering the period 1992–2000.

These values can be used to derive error bars to indicate the quality of the PSI time series. As with the velocity values, the above statistics are largely dominated by PS with zero or very moderate deformations. Since the time series performances probably degrade with increasing velocity values, one should be careful in extending these statistics to sites involving stronger deformation rates.

- PS density. There is a remarkable difference among the three datasets in the number of PS delivered by the OSP's. This indicates that the teams effectively used different criteria during the processing and in particular during the PS selection.

- Topographic correction. The standard deviation of the "topographic correction" differences ranges from 1.3 to 2.8 m. Assuming that the compared teams have the same precision and that their results are uncorrelated, we can derive an estimate of the standard deviation of each team's "topographic correction" from these values:

  $\sigma_{\mathtt{TOPO}} = 0.9 – 2.0$ m

  An error in the "topographic correction" has a direct impact on the PS geocoding. Considering the ERS and ASAR geometries, one may expect the following standard deviation in the geocoding:

  $\sigma_{\mathtt{GEOCODING}} = 2.1 – 4.7$ m

  The above values provide information on the PS geocoding precision. Note that these values only include the stochastic geocoding error due to uncertainty in the estimation of the "topographic correction", i.e. they do not include the global geocoding shift biases that might affect all PS of a given dataset. The above geocoding precision roughly affects the east to west direction. In fact, the impact of an error in the "topographic correction" is in the direction perpendicular to the SAR track, which is approximately in the north-south direction.

3.2 Validation results – Alkmaar validation

The Alkmaar area, in the Province of Noord-Holland, is an important on-shore gas-producing area of the Netherlands. The area comprises 16 gas fields of various sizes. Gas production started in the early 1970's and has continued up to the present for most of the fields. The natural gas withdrawal results in spatially correlated deformation fields. The area influenced by subsidence near Alkmaar consists of a mixture of forests, dunes, beaches, and small villages, whereas the Amsterdam city area is completely urbanized, leading to different characteristics in their radar reflectivity behaviour. Levelling data (sparsely distributed, in space and time) are available for this area. Two types of analysis were performed on the Alkmaar area. In the first, called "validation in the measurement space", the PSI results were directly validated against levelling measurements. In the so-called validation in the parameter space, instead of a direct comparison of measurements, derived parameters were compared. The main results for the Alkmaar case are as follows. Further details of this analysis can be found at www.terrafirma.eu.com/Terrafirma_validation.htm.

- Velocity validation. The maximum subsidence rate over the considered period, as measured by levelling, is about 4 mm/yr. After de-trending and removal of the bias between the PSI and the levelling datum, no systematic effects were found. RMS error ranges from 1.0 – 1.5 mm/yr for ERS, and 1.3 – 1.8 mm/yr for Envisat.

- Time series validation. RMS error based on double differences (differences between PSI and levelling and between measurement epochs) ranges from 4.2 – 5.9 mm for ERS, and 4.6 – 6.1 mm for Envisat.

- Validation in the parameter space. The approach overcomes the intrinsic limitation of PSI validation, i.e. the fact that PSI and levelling do not measure exactly the same point. The analysis consisted of comparing the modelling parameters (a subsidence bowl or volume changes of underground reservoirs was modelled) derived using PSI and levelling data. Even though the deformation signal was rather weak, the comparison provided good results. It is worth underscoring that even the teams with lower spatial point density had good results. This stresses the fact that it is not the absolute point density, but rather the sampling locations in relation to the deformation phenomenon that matter.

3.3 Validation results – Amsterdam validation

The validation over Amsterdam concerned the N/S-line, a 9.5 km long metro line which is currently being built through the city of Amsterdam. The sensitive conditions in Amsterdam place high demands on both settlement control and monitoring of structures which could potentially be affected by the works. About 3.8 km of this line will be constructed by a tunnel boring machine. An extensive monitoring system was set up and installed in 2001 along the 3.8 km, including robotic tachymeters, precise levelling, inclinometers, extensometers, etc. The key results of the Amsterdam validation, which was performed by TNO, are summarized below. For more details, see www.terrafirma.eu.com/Terrafirma_validation.htm. In Amsterdam, due to geocoding errors, it was not possible to make a perfect one-to-one comparison between PS and buildings. Therefore, intrinsic uncertainties due to geocoding errors should be considered in evaluating the results.

- Velocity validation. The maximum settlement rate in the considered period, measured by tachymetry, is about 7 mm/yr. The absolute standard deviation of the difference between PS velocity and tachymetry-based velocity ranges from 0.8 to 0.9 mm/yr. The mean and median differences for all teams are close to zero. All trend lines suggest that PSI slightly underestimates deformation velocity with respect to tachymetry. The absolute standard deviation of the double difference in velocity ranges from 1.0 to 1.2 mm/yr.

- Time series validation. The average RMS errors of single deformation measurements range from 4.2 to 5.5 mm. In general the PS data of all teams show a reasonably good correlation with the tachymetry data. Furthermore, there is no significant difference in validation results between the four teams: all teams show similar results.

4. CONCLUSIONS

In this paper the key characteristics of this SAR based technique have been outlined, and the main products of a PSI analysis have been briefly described. The major advantages and the most important open technical issues of PSI deformation monitoring have been discussed. They include the limitations related to spatial and temporal sampling, the problems with fast motion and non-linear deformation, geocoding errors, etc.

In the second part of the paper the issue of PSI validation has been addressed, describing in particular the results of the Terrafirma Validation Project, a major PSI validation exercise funded by the European Space Agency. The key findings of this validation exercise have been summarized. In general, the project generated rich PSI data sets, from which interesting global statistics have been generated, which concern large sets of PS and provide information on the global behaviour of velocities, time series, PS density, topographic corrections and PS geocoding.

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