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Validation of existing processing chains in Terrafirma stage 2

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1. INTRODUCTION

During Terrafirma (TF) Stage 1 it was identified that for operational acceptance of Persistent Scatterer Interferometry (PSI) by targeted Terrafirma users, the quality of the PSI techniques needs to be demonstrated. Initial work during Stage 1 resulted in an outline comparison based on published ground truth data for the Jubilee Underground Line in London, see [JLE]. In parallel with the Terrafirma activities, ESA ran a PSI validation project named PSIC4 (Persistent Scatterer Interferometry PSI -Processing Over a Validation Test Site), which involved PSI service providers and academic institutions, see [PSIC4]. The "Validation of existing processing chains in Terrafirma Stage 2", or shortly the "TF Validation Project", represents a PSI validation exercise within Terrafirma Stage 2, focused on the current four TF Operational Service Providers (OSPs), i.e. Telerilevamento Europa [TRE], Altamira Information [ALT], Gamma Remote Sensing [GAM] and Fugro NPA Ltd [NPA].

The main objectives of the TF Validation project include (i) the comparison of the outputs from the different PSI processing chains to certify that all OSPs produce consistent results; (ii) providing independently verified evidence of the quality of the PSI results; (iii) characterising the Terrafirma H-1 products; (iv) clarifying the product limitations; and (v) making recommendations for product improvement.

The project includes two main parts. The first one is labelled process analysis, which involves the inter-comparison of processed slant-range outputs of the different OSPs, and the analysis of their intermediate results. The goal of the process analysis is to test the "equivalence" of the OSP chains, detecting the cause of differences in their results, if any. The second one is product validation, where the geocoded PSI products are validated against ground truth.

The TF Validation Project includes two test sites, which have complementary characteristics: Alkmaar and Amsterdam. The Alkmaar area is a rural area which includes spatially correlated deformation fields due to gas extraction. Over this site ground truth data from levelling campaigns are available. In the project this site is studied using two datasets, i.e. ERS-1/2 (from April 1992 to September 2000), and ASAR-Envisat (from March 2003 to March 2007). The Amsterdam area includes autonomous and mainly spatially uncorrelated movements. For a part of this area, which corresponds to the trajectory of the future N-S metro line, ground truth data from different geodetic tools are available. Over this site only the ASAR-Envisat data were used (from March 2003 to March 2007).

The OSPs had no access to the ground truth data. However, some basic information was provided as to the nature of the ground motion and ground truth involved. The results of the project have an anonymous character. Besides the OSPs mentioned above, the project includes the following participants: Institute of Geomatics (IG), project lead and inter-comparison; DLR, process analysis; TNO, ground truth support and product validation; TU Delft (TUD), product validation; BGS, supervisor and link to the Terrafirma Product Validation Workgroup (PVW); Fugro NPA Ltd, overall project management.

The project involved three main steps. The first one included the test site selection and the definition of the key rules to run the project, see Section 2. The second step, which involved the OSP processing and the screening of these results, is described in Section 3. The last step involved the process analysis made by DLR (Section 4); the inter-comparison performed by IG (Section 5); the validation over Amsterdam made by TNO (Section 6); and the validation over Alkmaar made by TUD (Section 7). Conclusions of this project are discussed in Section 8 and the recommendations in Section 9.

2. TEST SITE SELECTION AND VALIDATION RULES

The test site selection and the definition of the rules to run the TF Validation Project were part of the workpackage WP VAL.01 "Review methodology and validation site". The main goal of this workpackage was that all project partners discuss and agree on the proposed methodology of both the process analysis and product validation. Furthermore, this workpackage involved the selection of the project test areas.

This work package defined the foundations of the project. The first source of information was given by previous PSI validation activities, like the Jubilee Line study [JLE] and the PSIC4 project [PSIC4]. The lessons learnt from these activities suggested to avoid future disappointment and to run the Validation Project on a "typical TF site" (Jubilee Line and PSIC4 concerned non standard PSI applications). Another valuable input source was given by the lessons learnt in the Provence inter-comparison, which are collected in the conclusions of [PROV], e.g. concerning the co-registration of the OSP datasets in the radar coordinate system, the filtering of outliers in the time series, etc. Finally, useful site selection criteria were provided by the Terrafirma PVW. All project participants were involved in the main decisions associated with this workpackage.

In the following we briefly summarize the main outcomes of the review methodology and validation site activities.

1) "Specification of validation approach – Part 1: Process Validation". This document describes the process analysis of the different PSI systems involved in the project, which is based on intermediate processing outputs. The document specifies the key features of the intermediate products to be delivered by the OSPs, the planned process analyses and their outcomes.
2) "Specification of validation approach – Part 2: Product Analysis Tasks". This document describes the analysis tasks to be performed within the product validation, identifying the input information, the validation procedure and the expected easy-to-understand validation outputs.
3) "Specification of validation approach – Part 3: General rules to run the project". This note describes the main aspects of the project, like the input data to be provided to the OSPs, the information on the ground motion, the goals of PSI analysis, the input SAR images and auxiliary data, and other relevant inputs for the PSI processing.
4) "List of OSP deliverables– extended". This document specifies the main inputs to be provided to the OSPs for their PSI processing and the rules to be followed during the processing. The OSPs were requested to follow these rules, which concern, e.g., the selection of the common ERS and ASAR-Envisat datasets to be processed, the chosen master scene, the DEM to be used, etc. Furthermore, the document provides a list of intermediate products, including detailed formatting specifications.
5) "Technical note on the test site selection". This note collects the key information needed to perform the site selection. It was prepared considering two contrasting objectives, i.e. providing the fundamental information to judge the suitability of the candidate sites of Alkmaar and Amsterdam and, at the same time, not disclosing too much information on the available ground truth. The complementary characteristics of Alkmaar and Amsterdam (spatially correlated deformation field vs. autonomous and mainly spatially uncorrelated movements) were identified as a positive aspect, which is useful for both the process and product validation. Furthermore, the different types of deformation phenomena that occur in the same site are important to highlight the PSI deformation measurement and

monitoring capabilities. For each of the two areas the pros and cons were assessed. Among the pros the availability of good reference data, the high chance of success of the PSI measurements and the high societal relevance of the deformation phenomena at hand were highlighted. A disadvantage of Alkmaar was the relatively small magnitude of the deformation over the site, with deformation rates up to 3-4 mm/yr. However, the moderate rates reduce the unwrapping-related problems that were experienced in PSIC4, and validating PSI with moderate rates is useful to highlight the PSI capability in detecting and measuring small deformations. A disadvantage of Amsterdam is that the tunnel boring did not commence during the period under evaluation. Consequently, potential observed deformation is due to other, perhaps more localized, effects. All project partners, including the OSP representatives, were involved in the final site selection. The key features of the chosen test site are described in the document "Ground truth dossier: Alkmaar-Amsterdam", which was not distributed to the OSPs during the project.

In this project the main goals of the PSI analysis by the OSPs were clearly indicated before starting the PSI processing. This fact clearly distinguishes this project from PSIC4, where, for the sake of setting up a completely blind validation test, the nature of the deformation phenomena and the purpose of the deformation analysis were only explained *a posteriori*. This was later identified as a limiting factor that does not reflect the typical conditions of PSI deformation analyses, where the nature of the deformation signal of interest is usually known *a priori*. The main goals of the analysis were: i) detecting and measuring any significant deformation phenomena that occur in the covered areas; ii) measuring the land deformation of Alkmaar; and iii) measuring the deformation phenomena in the area of the N-S line in Amsterdam. The OSPs were expected to use their standard PSI processing, corresponding to the TF H-1 standard products. Taking into account the above goals, they were invited to properly tune their processing, in particular the thresholds relating to PS selection, to get a good balance between PS coverage and PS measurement quality.

3. OSP PROCESSING, SCREENING AND PRE-PROCESSING ISSUES

The OSPs processed three datasets: ERS-1/2 (from April 1992 to September 2000) and ASAR-Envisat (from March 2003 to March 2007) over Alkmaar, and ASAR-Envisat (from March 2003 to March 2007) over Amsterdam. The results of the project have an anonymous character. The identity of the four OSPs involved in the project is kept anonymous by labelling, in an arbitrary way, the results as TA, TB, TC and TD. Note that some of the deliverables make use of slightly different names, e.g. OSP A or Team A instead of TA, referring however to the same OSP in a consistent way.

The main input data of the inter-comparison and the product validation are the original PS tables generated by the four OSPs, see Table 1. In this table one may notice remarkable differences in the number of PS delivered by the different OSPs, e.g. in the ASAR Amsterdam case it ranges from about 22000 up to 104000. These differences clearly indicate that the teams used different criteria during the processing, and in particular during the PS selection. Before starting the inter-comparison and validation analyses, a few pre-processing steps were performed, which are briefly summarized below.

1) A general screening of the OSP results was performed in order to check the global consistency of the datasets, the co-registration in the radar coordinate space and geocoding. All errors but one were detected by the validation team during this early stage and subsequently corrected by the OSPs. Later, during the validation, an additional error (a factor -1 in the non-linear values of the time series) was detected and corrected in the ASAR Alkmaar dataset of team TD.

2) In order to get homogeneous and directly comparable datasets, the origin of the PS time series was set to the first date of each time series. For the teams that used over-sampled SAR data we performed an averaging of the PS located in the same pixel at the original 1x1 SLC resolution, rounding the PS coordinates to the nearest integer. However, some validation activities were performed using the original data, i.e. without averaging the PS.

3) For each test site, the datasets were referenced to the same point using these formulae: deformation velocity: $V_{new} = V_{old} - V_{ref}$; topographic correction: $H_{new} = H_{old} - H_{ref}$, and deformation time series: $d_{new} = d_{old} - d_{ref}$; where “old” and “new” are the original and new data, and “ref” indicates the value of the PS chosen as reference.

4) During the Validation Project Meeting 2, held in Frascati on the 24-25 October 2007, it was realised that the OSPs adopted different processing strategies with respect to the residual orbital trends or tilts that can affect the PS datasets. Some of the OSPs, considering the specific goals of the deformation analysis at hand, removed the above tilts, while others did not remove them. It is worth underlining that this issue has not been explicitly addressed within the Terrafirma project, i.e. there is not a common strategy with respect to the above tilts. During the Validation Project Meeting 2 it was decided to remove the potential tilts in the PS datasets by de-trending all of them. All the inter-comparison and validation results refer to globally de-trended data.

5) During the Validation Project Meeting 2 it was decided to allow teams TC and TD to reprocess the ASAR Amsterdam dataset, hence delivering a second PS dataset. In fact, in the first delivery these two teams selected much less PS than the other two teams (see Table 1), a fact that would have limited some inter-comparison tasks and the validation over the N/S metro line made by TNO. Table 2 shows the available PS after the second delivery of teams TC and TD: the differences are remarkably reduced, even though the number of PS still varies from about 75000 to 104000.

# PS	ASAR Alkmaar	ERS Alkmaar	ASAR Amsterdam
TA – 1st delivery	59283	17115	104185
TB – 1st delivery	90209	121269	91038
TC – 1st delivery	54520	34103	33606
TD – 1st delivery	28363	25617	21906

Table 1. Number of PS of the twelve analysed datasets. This table refers to the number of PS after removing "double points" due to over-sampling.

# PS	ASAR Amsterdam
TA – 1st delivery	104185
TB – 1st delivery	91038
TC – 2nd delivery	87911
TD – 2nd delivery	74993

Table 2. Number of PS over the ASAR Amsterdam site, after the 2nd delivery of TC and TD.

After performing the above screening and pre-processing steps, during the process analysis some atypical effects were detected in some of the project datasets, see page 20 of [PROC-DLR]. We briefly mention below the most important of those effects.

a) Some atypical effects, including an overestimation of the deformation velocities by a factor two, affect the 1st delivery of TC over Amsterdam. Their impact is visible in some of the inter-comparison statistics, those of the de-trended velocity differences, see Table 5 in [PROC-IG] and the statistics for the "topographic correction" differences, Table 14 of the same document. It is worth mentioning that these atypical effects are no longer present in the dataset of the 2nd delivery of team TC.

b) A similar atypical effect affects the ASAR Alkmaar dataset of TD. In this case there is an underestimation by a factor two of the deformation velocities. It is difficult to clearly appreciate the effects of this in the global inter-comparison statistics and in the validation results, mainly because of the very small deformation signal (i.e. the low signal-to-noise ratio) of the Alkmaar dataset.

c) Finally the process analysis identified integration errors due to phase unwrapping in the two Alkmaar datasets of TA. Like in the previous case, this effect does not clearly show in the inter-comparison and validation results. This is probably due to the limited extension of the area affected by this type of error.

It is worth emphasising that the above atypical effects are mainly due to operator-related errors, i.e. they are not caused systematically by errors in a given processing chain. This is confirmed by the fact that these effects do not occur in the three processed datasets of any OSP. Despite their small impact on the inter-comparison and validation results, these effects show the importance of strengthening the quality control procedures implemented by each OSP. Considering the above effects, DLR proposed a new version of the quality control procedure to be adopted for the TF products, and the OSPs strengthened their quality control steps, responding in light of the weaknesses exposed.

4. PROCESS ANALYSIS: KEY RESULTS

The process analysis was based on intermediate and final processing outputs in the original radar slant range geometry. This analysis offers several advantages, like the possibility of detecting at early stages the deviations in the OSP outputs, avoiding the error-prone interpolations in time and space that usually are needed by product validation, etc. This analysis was aimed at detecting differences between the OSP outputs due to different implementations of the PSI technique, for instance co-registration with varying robustness and accuracy, etc. The process analysis was designed and performed by DLR, which has developed its own independent scientific PSI processing chain. This chain, named PSI GENESIS, was used as a reference in the process analysis. That is, the intermediate and final results generated by PSI GENESIS were used as reference to assess the OSP results. It is worth noting that the interpretation of these results requires a special attention. In fact, the OSPs make use of different PSI philosophies, and their inter-comparison with the DLR results (which are based on a given chain that adopts a specific PSI philosophy) could be misleading. For this reason the process analysis was mainly used for internal TF Validation Project purposes, e.g. for the qualification of the OSPs. For this reason, the process analysis results are kept separated from the results coming from inter-comparison and validation activities. The distribution of the deliverable [PROC-DLR], which describes the process analysis, is restricted to the TF Validation Project and ESA. Some of the main results of the process analysis are described in [ADAM-07].

Taking into account this restriction, we briefly mention below the key results of the process analysis. The standard deviation of the velocity differences (OSP vs. PSI GENESIS) varies spatially depending on the signal-to-clutter ratio of each scatterer. The standard deviation of velocity differences was predicted for an optimal scatterer[1], giving values that are in good agreement with the theory. The deformation estimation is limited by an inherent noise floor in the interferometric phase caused for example by the radar thermal noise, focussing and co-registration. This limit, always in terms of velocity differences using GENESIS as reference, is about 0.2 mm/yr for a typical Envisat ASAR or ERS test site with an observation time span of about four years.

In the course of this analysis, an enhanced understanding of random and systematic errors was achieved. The chosen approach proved to be effective in isolating atypical effects in some of the OSP results. In principle, no bias or other systematic effects should be found in an error free PSI processing. However, atypical effects were detected, which concern heterogeneous quality of the estimates, systematic effects, etc. Some of these effects are described in the previous section. These effects were reported in detail to the respective OSPs. The above results confirm that the three datasets used in this project are suitable for the validation and qualification of PSI chains.

[1] The optimal scatterers are described by a temporal coherence of 1.0. These scatters need to have an infinite signal to clutter ratio and at the same time a linear displacement history over the full observation time span.

5. INTER-COMPARISON: KEY RESULTS

The IG inter-comparison involved the direct comparison of the slant-range outputs of the different OSPs. This mainly concerned deformation velocities, deformation time series, PS density and topographic corrections. The most relevant results are summarized below.

1) Velocity inter-comparison: global statistics. The average standard deviation of the velocity differences is 0.56-0.75 mm/yr. Assuming the same precision for the compared teams and uncorrelated results between teams[2], the estimated standard deviation of the deformation velocity of each team ranges from:

   $\sigma_{VELO} = 0.4 – 0.5$ mm/yr

   These values, which come from large sets of 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 the TF end users. It is worth noting that the above statistics are largely dominated by PS with zero or very moderate deformations. The above values are representative of all PSI studies that concern areas with similar characteristics to those of the three test sites of this project.

   In all datasets, the smallest standard deviations correspond to the velocities around zero, e.g. between ±1 mm/yr. In this range the standard deviations are concentrated around 0.5 mm/yr. When the velocity module increases, for both negative and positive values, the standard deviations in general slowly increase.

2) Time series inter-comparison: global statistics. The mean standard deviations of the time series differences range from 1.56 to 5.57 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:

   $\sigma_{TSeries} = 1.1 – 4.0$ mm

   These values can be used to derive error bars to indicate the quality of the PSI time series. 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. The ERS dataset has worse estimated standard deviations than the two ASAR datasets: ERS values roughly double the ASAR ones. This indicates that the ERS time series are noisier than the ASAR ones.

3) Time series pairwise correlation. The correlation coefficient between pairs of time series estimated over the same PS measures the degree of similarity of the deformation patterns of these time series. The percentage of PS with correlation coefficient above 0.7 in ASAR Amsterdam varies from 24.3 to 74.0%. The impact of the choice of reference point was found to be relatively small, provided that this point is characterized by high coherence for all teams. Comparing the correlation coefficients computed over the original vs. de-trended time series, a global decrease of correlation was observed, which is particularly severe in some cases. Possible explanations could be that some PS really do not have non-linear deformation, or that this is mainly “masked” by the PS measurement noise. In addition, the type of processing strategy has an influence on the above results: this should be further studied.

[2] Note however that two OSPs used identical processing software. Consequently, it is likely that these results are not uncorrelated, which could result in an underestimation of the standard deviation.

4) PS density. In the three datasets there is a remarkable difference in the number of PS delivered by the OSPs. This indicates that the teams effectively used different criteria during the processing and in particular during the PS selection.

5) Topographic correction inter-comparison: global statistics. 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, from these values we derive an estimation of the standard deviation of the "topographic correction" of each team:

   $\sigma_{TOPO} = 0.9 – 2.0$ 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:

   $\sigma_{GEOCODING} = 2.1 – 4.7$ 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 shifts (biases) that might affect all PS of a given dataset. The above geocoding precision affects roughly 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. This is key information for the end users of the Terrafirma products. To the above geocoding error one has to add the error due to the uncertainty in the position of the PS inside the resolution cell, which affects both the north to south and the west to east directions.

6. VALIDATION - AMSTERDAM: KEY RESULTS

The validation over Amsterdam concerns the N/S-line, a 9.5 km long metro line which is currently being built and runs 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. Along the 3.8 km an extensive monitoring system has been set up and installed in 2001, which includes robotic tachymeters (total stations), precise levelling, and sub-surface monitoring by inclinometers, extensometers, etc. The system and data are owned by the North/South-line project office of the city of Amsterdam.

The key results of the Amsterdam validation, which was performed by TNO, are summarized below. More details can be found in [VAL]. For Amsterdam, due to geocoding errors it is not possible to make a perfect one-to-one comparison between PS and buildings. Therefore, in evaluating the results, intrinsic uncertainties due to geocoding errors should be considered.

1) <u>Velocity validation.</u> 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 show a declination from the x=y axis, suggesting 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.

2) <u>Time series validation.</u> 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. However, all trend lines show a declination from the x=y axis, indicating a tendency for all teams to underestimate the deformation velocity with respect to data obtained by tachymetry in the higher velocity ranges. Furthermore, there is no significant difference in validation results between the four teams: all teams show similar results.

A suggestion for future work is to repeat the validation procedure when the construction of the N/S metro line will be finished. It is expected that due to tunnel boring, which will commence in 2008, more buildings will be affected by deformation and also the amount of deformation will probably increase. This would result in a more evenly distributed velocity spectrum and a better comparison of velocities in the higher velocity range. A second suggestion for future work is to evaluate the PSI algorithms and estimate the contribution of the various components such as atmospheric phase screen, height-estimate and noise-component to the total error-budget.

7. VALIDATION - ALKMAAR: KEY RESULTS

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 size. Gas production started in the early 1970's and continued up to date 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 forest, dunes, beach, and small villages, whereas the Amsterdam city area is completely urbanized, leading to different characteristics in their radar reflectivity behaviour. Over this area sparsely distributed, in space and time, levelling data are available. Over the Alkmaar area two types of analysis were performed. In the first one, named 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 are compared, e.g., an estimated subsidence bowl or volume changes of underground reservoirs. This approach overcomes important limitations of the classical validation in the measurement space. The main results for the Alkmaar case are as follows.

1) Velocity validation in measurement space. The maximum settlement rate in the considered period, 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.

2) Time series validation in measurement space. 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.

3) 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 the same point. The analysis highlights a key PSI capability: the high number of available samples. Even though the deformation signal is rather weak, the PSI vs. levelling comparison provides good results. Even teams that have lower spatial point density have 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 matters.

4) The main conclusion is that the results from PSI and levelling are comparable, with an RSME of 1.0 – 1.8 mm/yr for the linear velocity rates. Although the scatter plots of the PSI results versus levelling suggests the absence of a signal when evaluating all observations, the plots of the spatial distribution of the PSI results indicate that the signal-to-noise ratio is sufficient to unambiguously detect the deformation signal of interest. The conclusion is confirmed by the validation in the parameter space. The PSI data of all teams enable the estimation of the signal of interest, despite the difference in PS density.

8. CONCLUSIONS

The TF Validation Project represents a major PSI validation exercise run within Terrafirma Stage 2, which is focused on the PSI results of four TF OSPs, i.e. TRE, Altamira Information, Gamma Remote Sensing and Fugro NPA Ltd. The project included two main parts. Process analysis involved the inter-comparison of processed slant-range outputs of the OSPs, and the analysis of their intermediate results. In the product validation the geocoded PSI products were validated against ground truth. Two test sites, Alkmaar and Amsterdam, which have complementary characteristics, were used. The Alkmaar area is a rural area which includes spatially correlated deformation fields due to gas extraction, where levelling data are available. This site was studied using two datasets, i.e. ERS-1/2 from 1992 to 2000, and ASAR-Envisat from 2003 to 2007. The Amsterdam area includes autonomous and mainly spatially uncorrelated movements. It covers the area of the future N-S metro line, where ground truth data coming from different geodetic tools are available. Amsterdam was measured using ASAR-Envisat data covering the period from 2003 to 2007.

The results of the TF Validation Project represent the standard of qualification procedures to be followed within TF to qualify existing OSPs and future OSP candidates. The key activities were carried out by DLR in the frame of the process analysis. Through the project the existing TF OSPs were qualified. It is worth mentioning that during the project the OSPs had no open access to the ground truth data. However, some base information was provided as to the nature of the ground motion and ground truth involved. The results of the project have an anonymous character. The most important deliverables of the project are available at [VALPR]. The main project conclusions are listed below.

1) The TF Validation Project represents a successful example of PSI inter-comparison and validation. A key component of this success was the careful selection of the test sites, which are feasible from the PSI point of view and are representative cases of the typical sites analysed in Terrafirma. Another fundamental component of the project was the detailed definition of the rules to run the entire project and of the process analysis and product validation methodologies. In this project the main goals of the PSI analysis to be performed by the OSPs were clearly indicated before starting the PSI processing.

2) In general the OSP results show remarkable differences, especially in the datasets of the first delivery, which should be considered as a typical Terrafirma delivery. The most important deviations concern the number of detected PS, see Table 1 in Section 3, and the annotated coherence values, which are used as a quality indicator within Terrafirma.

3) The process analysis was based on intermediate and final OSP outputs in the original radar geometry. The analysis was performed using the DLR PSI chain as a reference to assess the OSP chains. This analysis was effective in detecting deviations in the OSP outputs, and isolating atypical effects in some of the OSP results, e.g. systematic effects, etc. The effects were reported in detail to the respective OSPs, and each concerned OSP in turn formally replied with detail of procedures that have been altered to avoid the above effects. Due to its nature, i.e. the comparison with the results of a specific PSI chain, the interpretation of the process analysis results requires special attention. For this reason the process analysis was mainly used for internal TF purposes, e.g. for the OSP qualification.

4) The direct inter-comparison of the OSP results in radar geometry generated a rich set of global statistics, which concern large sets of PS and provide information on the global inter-comparison behaviour of deformation velocities and time series, PS density, topographic corrections and PS geocoding. The most important results are reported in Section 5. These values can be used to derive error bars to indicate the quality of the

estimates derived by PSI, which is key information for the TF end users. The above values are representative of all PSI studies that concern areas with similar characteristics to those of the three datasets of this project (stable area or very moderate deformations). Additional interesting inter-comparison results concern the correlation between pairs of time series, which measures the degree of similarity of the deformation patterns of the time series. Further studies are necessary to assess the actual deformation information contained in the time series.

5) The validation results over Amsterdam concern the displacements in the N/S-metro line area, which are caused by geotechnical instability and localized construction works. These displacements are mainly spatially variable and need a point-wise PS analysis. The one-to-one comparison between PS and buildings was mainly limited by geocoding uncertainty. This represents an intrinsic source of error, which affects in particular the analysis over small objects, e.g. single buildings.

6) The most important results achieved over Amsterdam are reported in Section 6. These values suggest that PSI slightly underestimates deformation velocity with respect to tachymetry. The statistics for velocity and time series are however in the same region found in the inter-comparison. 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.

7) The Alkmaar validation concern a gas extraction area affected by spatially correlated deformation fields, where the PSI results were directly compared against levelling measurements. The key validation results achieved are reported in Section 7. The statistics for velocity and time series are slightly worse than in the Amsterdam case. This is probably due to the characteristics of the area, which is more difficult from the PSI viewpoint, and the types of ground truth, e.g. the lack of levelling epochs in the Envisat time span.

8) The above Alkmaar validation was complemented by an innovative analysis, named validation in the parameter space, which can be applied for the analysis of spatially correlated deformation fields. This approach overcomes the important limitation of the classical validation, i.e. the assumption that both PSI and ground truth measure the same parameter at the same location and the same time. This analysis highlighted a key PSI capability: the high number of available samples. Even though the deformation signal is rather weak, the PSI vs. levelling comparison provided good results. The PSI data of all teams enable the estimation of the signal of interest, despite the difference in PS density.

9. RECOMMENDATIONS

Some recommendations are listed below.

a) The process analysis identified atypical effects in some of the generated PSI datasets, which are mainly due to operator-related errors. During the project the OSPs have strengthened their quality control steps, responding in light of the weaknesses exposed. We recommend continuing within Terrafirma the improvement of the quality control procedures implemented by each OSP, thus improving the reliability of the quality checks to be routinely performed for each PSI product.

b) The four OSPs involved in this project use different definitions of the PS quality index (coherence), which mean the OSPs products are not directly inter-comparable. We recommend homogenizing the way of estimating the temporal coherence, getting a quality index that can be used to inter-compare the PSI results of different teams.

c) Some of the original deformation products generated in this project are affected by trends or tilts, probably due to residual orbital effects. The issue of trends or tilts has not been explicitly addressed so far within Terrafirma. We recommend defining a common strategy to address this issue in the H1 products.

d) For future PSI validation projects the availability of a profound quality description of the ground truth data is desirable. This would enable a more clear separation between the error budgets of PSI and ground truth.

e) The analysis of the pairwise correlation between time series provided interesting results, but did not clarify the actual information contained in the deformation patterns of the time series. The validation results concerning time series did not provide very useful information, due to the inherent limitation of the comparison and the lack of temporal samples of the ground truth data. We recommend devoting further studies to the deformation time series, which represent a key PSI product.

f) The deformation rates in both Alkmaar and Amsterdam sites are moderately low. For some TF users, e.g. those interested in mining and landslide applications, could be of particular interest to know what are the expected PSI performances when the displacement rates are larger, e.g. up to 2 cm/year. An experiment in this direction would be welcome.

g) Finally we recommend continuing the PSI validation activities within Terrafirma. This is fundamental for the PSI products that will be derived from new types of data, e.g. spotlight TerraSAR-X and Cosmo-SkyMed. Furthermore, validation is needed for all new PSI products that could be proposed within Terrafirma. A suggestion for future work could be repeating the validation over Amsterdam when the construction of the N/S metro line will be finished, i.e. when there will be a more evenly distributed velocity spectrum and higher velocity range.

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