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EXECUTIVE SUMMARY

This deliverable addresses two separate topics. The first one describes some technical issues related to the PanGeo PSI products specification, while the second one collects the available information related to the PSI Validation results. The first part of this document describes some important technical issues related to the PanGeo PSI products specification, which were identified during the Terrafirma Validation Project (described in the second part of the document), as “PSI open problems”. The most important outcomes are summarized below:

• The minimum number of SAR images needed to derive reliable PSI products.
In the PanGeo project it is **encouraged the use of at least 25 SAR images** to derive new PSI products. If the number is less than 25 it is fundamental to **properly document this fact** in the corresponding PSI Processing Report.
• The spatial coverage of the PSI products.
It is recommended to get a **spatial coverage between a minimum of 100 km^2 and a maximum of 600 km^2** for the new PanGeo PSI processings.
• The tilts/trends that might affect the PSI products.
The tilts/trends are removed in all the PanGeo PSI products.
• The indices used to describe the quality of the PSI results.
In the PanGeo project **the quality index to be attached to each generated PS** (Persistent Scatterer) **is the so-called temporal coherence**.
• The spatial density of PS, and its relation to the PSI quality indices.
In the PanGeo project the **decision of fixing the quality thresholds** depends on the specific processing chain at hand and it **is responsibility of each PSIP**.

The above open problems were discussed in the PanGeo consortium, involving, in particular the four PSIPs (TRE, Altamira Information, Gamma Remote Sensing and Fugro-NPA) and the Institute of Geomatics.

The second part of the document describes some important PSI validation results carried out in the last years, including the Terrafirma Validation Project and other validation activities undertaken by the PanGeo PSI Service Providers (PSIPs). The main objective of this section is to provide the Geological Survey with a concise and complete summary of PSI validation results.

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1 INTRODUCTION

This deliverable contains two separate sections. The first one describes some technical issues related to the PanGeo PSI products specification, while the second one collects the available information related to the PSI Validation results.

The first part of this document is related to the Service Design and Product Specification of PanGeo, which includes: (i) the product specification for the PSI products, including both the existing PSI datasets generated during the Terrafirma project and the new products to be produced in PanGeo; and (ii) the product specification for the Geohazard Layer, which is the PanGeo final product. In particular, this deliverable describes some important technical issues related to the PanGeo PSI products specification, which were identified during the Terrafirma Validation Project (described in the second part of the document), as "PSI open problems".

The second part of the document describes some important PSI validation results carried out in the last years, including the Terrafirma Validation Project and other validation activities undertaken by the PanGeo PSI Service Providers (PSIPs). The main objective of this section is to provide the Geological Survey with a concise and complete summary of PSI validation results.

2 PSI OPEN PROBLEMS

This section discusses some technical issues related to the PanGeo PSI products. The so-called "PSI open problems", which were identified during the Terrafirma Validation Project, and are reported in the PanGeo Description of Work (page 15), include:

- *Different providers utilise different coherence quality indices. This can result in different distributions of scatterers of different quality*. This is addressed below at the point 4 (Section 2.4).
- *Phase trend ambiguities can exist due to imprecise satellite orbit knowledge, meaning that low-frequency trends can occur across PSI results that could be mistaken for, e.g. crustal deformation*. This is addressed below at the point 3 (Section 2.3).
- *Time series data can be inaccurate due to a number of variables, leading to false estimates of terrain motion at a particular time and place*. The time series will be provided, together with the average annual displacement rates, to the Geological Survey (GS). However, in the PanGeo D3.4 "Production Manual" the limitations of the PS time series are appropriately described.
- *Non-specialists cannot easily interpret PSI results*. The PanGeo D3.4 "Production Manual" provides a step by step guide to interpret and exploit the PSI results.
- *Motion-vector ambiguity caused by processing only single line-of-sight descending-mode radar data. This means, for example, that horizontal motion could be confused with vertical subsidence*. This issue is treated in the PanGeo D3.4 "Production Manual". In addition, one has to consider that 12 cities will receive both ascending and descending PSI data.

The following issues are treated in the following sections:

1. The minimum number of SAR images needed to derive reliable PSI products.
2. The spatial coverage of the PSI products.
3. The tilts/trends that might affect the PSI products.
4. The indices used to describe the quality of the PSI results.
5. The spatial density of PS, and its relation to the PSI quality indices.

The above open problems were discussed in the PanGeo consortium, involving, in particular the four PSIPs (TRE, Altamira Information, Gamma Remote Sensing and Fugro-NPA) and the Institute of Geomatics. Each topic is discussed below.

2.1 NUMBER OF SAR IMAGES

The number of SAR images used in the PSI processing influences the quality of the PSI results. In fact, the number of images is related to the number of observations used to estimate these products. During the Terrafirma Stage 2 project, it was observed that the number of SAR images used to derive the so-called H products varies considerably, e.g. from only 13 images in the Envisat analysis of Rome up to 111 images used to study the Bernina area. Considering that this issue clearly impacts the quality of the derived products, it was recommended to carefully inform the recipients of a given product, especially in the case it was derived using a low number SAR images.

In the PanGeo project it is **encouraged the use of at least 25 SAR images** to derive new PSI products. However, on a case by case basis and in case of limited available SAR datasets, the PSIPs can decide to perform a PSI analysis with less than 25 images. In addition, it is worth recalling that the above mentioned minimum may not be accomplished for some of the products already generated during the Terrafirma project. If in both cases, for the new PanGeo products and those coming from Terrafirma, the number of SAR images is less than 25 it is fundamental to **properly document this fact** in the corresponding PSI Processing Report, indicating:

- The number of scenes used;
- Is the number of scenes used very limited or the temporal distribution challenging? If yes, specify potential impacts on PSI results quality.

2.2 SPATIAL COVERAGE OF THE PSI PRODUCTS

The spatial coverage of the PSI products is not, per se, an open problem. It is rather a technical and management issue important to ensure a minimum degree of uniformity between the 52 PanGeo products. In fact, there are major differences in the spatial extent of the 52 cities covered by this project: some cities have just more than 100000 inhabitants, while others are big metropolis with several millions of people.

In order to guarantee some uniformity, it is recommended to get a **spatial coverage between a minimum of 100 km^2 and a maximum of 600 km^2** for the new PanGeo PSI processings. It is worth emphasising that these numbers are indicative and that, in principle, some flexibility is expected from the PSIPs. This flexibility will be of particular help during the early interaction between the PSIPs and the Geological Surveys (GSs), which will be essential to collect key information prior to the PSI processing, including the exact definition of the area to be covered, the priority areas including existing deformation phenomena, etc.

2.3 TILTS AND TRENDS IN THE PSI PRODUCTS

The existence of tilts or trends in the derived deformation maps represents an insidious type of error in the PSI products. These tilts can be a result of uncompensated orbital errors or low frequency atmospheric effects. Note that both effects are associated with single SAR images. The impact of these effects is usually reduced during PSI processing, using appropriate estimation and filtering procedures. However, some residual effects can remain in the form of tilts or trends in the deformation maps. It is worth noting that the same effect, even though less visible, also affects the deformation time series.

In the Terrafirma project it was found that tilt effects were present in some deformation maps, e.g. Moscow and Sofia. It is worth underlining that in both cases the tilt in the deformation velocity map could be due to residual processing errors or to a real geophysical signal. The key question is the following one: is it possible, in a standard PSI processing, to estimate low-frequency geophysical deformation signals? If this is the case, we could say that a tilt in the deformation product indicates the presence of a large-scale geophysical phenomenon. By contrast, if a deformation map shows no tilt then we would know that no noticeable large scale geophysical signal is observed. On the other hand, if this is not the case, two opposite situations may happen. Firstly, we may get tilts in the products that are interpreted as geophysical signals while, in fact, they are simple residual processing errors. Secondly, we may get products without any tilt, which is interpreted by a geophysicist as no signal, e.g. quiescence of a given phenomenon, while in fact the site may have undergone significant geophysical low-frequency deformations that have been removed during processing.

In order to eliminate the above potential confusion, **the tilts/trends are removed in all the PanGeo PSI products**. That is to say, these deformation products do not include the deformations characterized by low-spatial frequencies, i.e. if there are deformations characterized by low-spatial frequencies they are not measured or seen by the PanGeo products.

The tilts and trends are supposed to be removed by the PSIP before delivering the PSI dataset of a given PanGeo town to the GS. At the beginning of the procedure to generate the Geohazard Layer, the GS has to check if residual tilts or trends are visible in the deformation velocity map. If this is the case, it is invited to contact the PSIP to remove the tilt, getting a new version, tilt-free, of the PS dataset.

2.4 PSI QUALITY INDICES

Attaching quality indices to the PSI results is key for a correct exploitation of these results. In fact, the quality indices are fundamental to understand the quality of PSI results, and then to fully take advantage of them. During the Terrafirma project this issue was analysed in detail, with the main goal of proposing indices as homogeneous as possible between the products generated by different Terrafirma PSIPs.

In the PanGeo project **the quality index to be attached to each generated PS** (Persistent Scatterer) **is the so-called temporal coherence**. The PSIPs have to use the same definition and way to compute it, to ease the direct inter-comparison of PSI results coming from different PSIPs. The need of homogenizing the temporal coherence was identified in the Provence inter-comparison report (www.terrafirma.eu.com/Provence_intercomparison.htm). The same recommendation was later given in the final report of the Terrafirma Validation Project (www.terrafirma.eu.com/Terrafirma_validation.htm).

Temporal coherence from time series describes how well the interferometric phase observations fit the used temporal displacement model. If the used model is linear, the quality index should be called “degree-of-fit to the linear model” (goodness-of-fit). This term should be more informative than “temporal coherence”. The degree-of-fit to the linear model can be directly obtained from the PS time series, i.e. from the output of the PSIPs. The procedure works PS wise and involves three steps:

- Transforming the N sample of the time series from deformations [mm] to phases [rad].

- Computing the mean velocity from the time series by least-squares (linear fit). No weight is applied in this estimation.
- Computing the degree-of-fit to the linear model using this formula:

$$Fit\_lin = \frac{1}{N} \cdot \sum_{i=1}^{N} e^{j(\varphi_{tseries\_i} - \varphi_{lin\_i})}$$

2.5 PSI DENSITY AND QUALITY

In the Terrafirma project some concern was expressed on the idea of delivering dense PSI results by using lower thresholds on the temporal coherence, leaving the choice between PS quality and density to the end users.

In the PanGeo project the **decision of fixing the quality thresholds** depends on the specific processing chain at hand and it **is responsibility of each PSIP**.

It is worth noting that through the above mentioned interaction PSIP-GS it is sometimes possible to identify, in the area at hand, areas known to be subjected to non-linear or fast deformation, where typically the coherence can be low and the PS density low or even nought. If this information is available, it has to be clearly reported in the PSI Processing Report.

3 PSI VALIDATION RESULTS

There has been an important effort to validate the PSI deformation monitoring technique in the last decade. This is an aspect of paramount importance for the acceptability of any new technique. In the context of the PanGeo project this is an important issue, especially for the GSs that are required to fully take advantage of the PSI data to derive the PanGeo Geohazard Layers: they need to be properly informed about the accuracy, potentials and limitations of this technique. For this reason this section summarizes the main PSI validation projects performed in the past. In addition, it is worth emphasising that **the four PanGeo PSIPs**, i.e. Telerilevamento Europa (TRE), Altamira Information, Gamma Remote Sensing and Fugro NPA, **have undergone a "certification process" during the Terrafirma project**, which is also valid for PanGeo.

3.1 SUMMARY OF VALIDATION PROJECTS

The main PSI validation activities have been performed within the Terrafirma (TF) project. During TF it was found that the TF products offer a new and unique way to monitor and detect terrain motion; however, the process itself is complex and subject to several variables that can impact the quality of the results. A number of activities have therefore been carried out (some outside TF) to "validate" the reliability and accuracy of PSI [Terrafirma Validation Project].

The main Terrafirma validation activity was:

- **The TF Alkmaar/Amsterdam Validation Project** [Terrafirma Validation Project]: This major 9-month activity was conducted as part of TF. Two contiguous areas in the Netherlands, one of gas production and the other of a new metro tunnelling, were analysed in order to perform a detailed comparison of (i) the PSI processing output from the TF PSIPs, and (ii) the PSI output against ground truth. Thus validating both the "process" and "product" stages of TF outputs. Section 3.2 is devoted to this project due to its relevance.

Other significant TF validation activities are:

- **Jubilee Line Extension inter-comparison** [JLE Intercomparison]: This project focused on the relatively small area of the Treasury Building in London. The PSI processing carried out by NPA, TRE, Altamira and Gamma was compared against high quality ground truth collected during tunnelling for a new extension to the London metro system. The conclusions of this project are:
    1. The TF H-1 product, when presented as "deformation map", appears to have the potential to identify areas of "higher ground motion rate" (such as tunnelling) in urban areas. This has potential application at the site selection stage and in providing a synoptic view for activities such as urban tunnelling.
    2. At the moment deformation maps are best used to assist in the identification of potential areas of ground hazard rather than as a tool to derive quantitative measurement data. Further work should be undertaken to evaluate the accuracy and precision of the movement data presented in "deformation maps".
    3. It is not clear at this time why there is such a significant difference between the PSI-calculated displacements and the research-quality ground truth data for the JLE project. Furthermore, work should be undertaken to evaluate the accuracy and precision of the vertical movement

data in terms of "deformation maps" and "time-series". The accuracy and precision of georeferencing of PS points also needs to be evaluated.

4. Ground motion due to tunnelling is by definition a non-linear ground motion. Guidance on the selection of "linear" or "non-linear" displacement models is needed.

- **Persistent Scatterer Interferometry Codes Cross-Comparison and Certification Project** [PSIC4; Raucoules et al. 2009]: The PSIC4 project was conceived as an exercise of inter-comparison and validation of PSI data computed by eight different teams. The aim of this exercise was to evaluate performances of the eight different PSI methodologies by comparing the results with ground based observations and by inter-comparing the results from the eight processing chains. The results of this study provide an assessment of the absolute (validation) and relative (inter-comparison) accuracy of the PSI techniques. The PSIC4 exercise is a blind test carried on the mining area of Gardanne, which is characterised by different magnitudes and evolutions of deformation and variable land cover. It is worth emphasising that the PSIC4 represents a unique experiment for the number of PSI teams involved and the quality of the available ground truth, which involves more than 1000 levelling benchmarks measured once or twice per year. The work was divided into two phases. The first one concerned parallel processing of identical stacks of data by the participating earth observation PSIPs contractors. The second is an independent validation of the results carried out by a separate consortium of survey experts. The main conclusions of this project are:

1. One of the most important conclusions of the project is related to the characteristics of the mining test site selected for PSIC4, which include abrupt non-linear movements with magnitudes that range from few centimetres up to some decimetres. These are harsh characteristics from the viewpoint of C-band PSI with the temporal acquisition capabilities of ERS and Envisat. The characteristics of the deformation are very important because, in principle, PSI can measure surface displacements with millimetric precision, but this can only be achieved under the following conditions:
   - If the right model to describe the deformation is adopted. This is difficult to accomplish with abrupt nonlinear movements.
   - If the aliasing due to low PS density and/or low temporal sampling with respect to deformation, which may cause phase unwrapping errors, is controlled. This is difficult or impossible to achieve with strong deformation magnitudes.
   - If the assumptions to separate the atmospheric contribution from deformation are correct. This typically fails in presence of non-linear motion.
2. The PSIC4 project was conceived in a specific framework, where the teams worked under "blind conditions", so no *a priori* information on deformation type, driving mechanism, deformation magnitude, etc. was provided. Furthermore, the teams did not have information on the exact deformation signal of interest, i.e. the goal of the PSI analysis. By contrast, the validation focused on a specific deformation phenomenon, i.e. the deformation associated with the mining area of Gardanne. This point is important because it plays a key role in the PSI processing. In fact, instead of tailoring the processing to a specific objective of the analysis, the teams used a standard approach and a processing which was feasible with reasonable

resources. It is worth emphasising that the area covered by most of the teams was considerably larger than the 100 km^2 area used for validation. None of the PSI teams performed an advanced or refined PSI analysis, because neither the area of interest nor the goal of the refinement was defined. This explains the fact that most of the PSIC4 results lacked PSs in the mining area of interest.

3. It is worth analysing a specific consequence of the above point that explains the different densities achieved by the teams. PS densities are different because there is no “definition” of what exactly a PS is. The teams used their standard PSI approach (instead of an advanced or tailored one) and delivered the PSs only where both velocity and time series could be extracted with reasonable reliability. Unfortunately, the validation area represents a difficult area where phase unwrapping errors represent the main problem. Due to the high probability of this type of error many teams did not deliver unreliable information. Note that this did not occur outside the mining area.
4. Considering the above points and the results achieved in the Gardanne mining area it can be said that PSIC4 has clearly demonstrated that the PSI limitations are real, i.e. that PSI is not applicable everywhere. Though this was already clear to many PSI specialists, now this evidence has been widely documented. The PSIC4 results only concerned the “difficult” mining area of Gardanne, while most of the PSI teams covered considerable larger areas, which include gentle deformation and stable areas. For this reason, it was decided to run an additional inter-comparison study over the same dataset of PSIC4 within the ESA-founded project TF. This work, named 'Provence Intercomparison' was restricted to four of the eight teams of PSIC4.
5. Finally, the limitations of PSI over deformation areas with similar characteristics to Gardanne open some new important issues for the future. We briefly mention two of them. The first one is the importance of a feasibility study before running a PSI analysis. This may help to avoid false expectations and disappointing results. Note that a feasibility study is now implemented within the TF project. A second issue concerns the appropriate ways to inform the PSI users of the limitations of the technique, especially in those cases where PSI is employed under non-ideal conditions.

- **Provence inter-comparison** [Provence Intercomparison]: The “Provence Inter-comparison”, an activity of the TF Stage 2 project, involved the inter-comparison of the products of four PSI teams involved in the PSIC4 project; Altamira Information, DLR, Gamma Remote Sensing and TRE [Crosetto et al. 2007]. The site was located around the mining area of Gardanne, in Provence (France). The main motivation for starting this complementary study was to take advantage of the full PSIC4 dataset by extending the analysis beyond the Gardanne mining area, thus getting new insights into this unique set of PS data. An additional motivation to perform this study was to collect inputs for the preparation of a new validation experiment, to be carried out as part of the TF project. The results discussed should not be confused with those obtained from validation experiments, where the PSI products are compared against ground truth. The key results of this project are:

1. The global statistics of the velocity inter-comparison showed a standard deviation of the velocity differences, which ranges between 0.45 and 0.66 mm/yr (TF Validation Project), and 0.58 and 0.80 mm/yr (Provence dataset). These values, obtained from very large datasets, are useful to derive an indication of the global quality of the PSI velocity products.
2. The statistics for the velocity differences, computed for different classes of velocity, showed that the best PS differences correspond to velocity around zero, while the dispersion of the differences increases when the module of the velocity increases. This interesting result needs to be further analysed in the frame of the TF Validation Project.
3. The global statistics of the "topographic correction" inter-comparison showed that the standard deviation ranges between 1.29 and 2.68 m. These values, obtained from very large datasets, are useful to derive an indication of the global geocoding quality of the PSI products. The above values result in a geocoding standard deviation (in the east to west direction) between 3.03 and 6.30 m.
4. Finally, the inter-comparison study addressed the issue of the information contained in the deformation time series. The correlation coefficients, computed over pairs of time series, are rather low. For the ASAR datasets only 30% of pairs have a correlation coefficient higher than 0.7. This percentage ranges between 14% and 18% for the ERS datasets. All the above values decrease if the same analysis is repeated over detrended time series. In the case of ERS datasets, the percentages range between 1.3% and 5%. These low percentages indicate that, apart from the linear component, there is little in common between the time series. The explanation of these results is not straightforward. Some PSs could have a purely linear deformation (e.g. this is the case of all perfectly static points). The errors generated during the PSI processing can, in some case, be dominant and hide the common pattern of time series. Note that a portion of the non-linear deformation of the PSs can be lost during the PSI processing. Additional effects, e.g. coregistration errors between the inter-compared PS datasets and the type of reference points used by the different teams, can contribute to lower the correlation coefficients. These results call for further investigations.
5. The results of the Provence inter-comparison show better performance than those obtained at the PSIC4 project for both the deformation velocity maps and the time series. It is worth underlining that the results of the two projects are not contradictory. In some cases they simply show different complementary aspects. For instance, the Provence inter-comparison is largely based on data outside the Gardanne mining area, which were simply not analysed in PSIC4. In other cases the results are rather similar.

3.2 THE TERRAFIRMA VALIDATION PROJECT

The TF Validation Project [Terrafirma Validation Project] was a major PSI validation exercise run as an integral part of TF Stage 2, focused on the four PSIPs: TRE, Altamira Information, Gamma Remote Sensing and Fugro NPA. The project was designed (i) to compare the outputs from different PSI processing chains to certify that the four TF PSIPs produced consistent results, (ii) to provide independently verified evidence of the quality of the PSI results, (iii) to characterise the TF products, (iv) to clarify the product limitations and (v) to make recommendations for product improvement. It consisted of two main parts: the **Process**

analysis [Crosetto et al. 2008a], which involved the inter-comparison of processed slant-range outputs of the different PSIPs and the analysis of their intermediate results; and the **Product validation** [Hanssen et al. 2008], where the geocoded PSI products were validated against ground truth. For the first time, accuracy of PSI processing over typical PSI test sites was obtained. This inter-comparison resulted in strengthened quality control in the processing chains and represents the standard of qualification procedures to be followed within TF to qualify existing PSIPs and future PSIP candidates.

Two test sites, Alkmaar and Amsterdam, were selected by consensus amongst all project partners, including the PSIPs. Alkmaar is a rural area which includes spatially correlated deformation fields due to gas extraction. The sparse levelling data available were complemented by modelling of the expected subsidence bowl. This site was studied using ERS (1992-2000) and Envisat (2003–2007). Amsterdam is a typical urban area which includes autonomous and spatially uncorrelated ground motion over the 9.5km long N-S metro line route. Surveying, levelling, inclinometer and extensometer data are available since 2001. Amsterdam was studied using Envisat (2003 - 2007).

The nature of the deformation and the main targets of the PSI analysis were shared with the PSIPs. The main goals of the PSI analysis were to detect and measure any significant deformation in the study areas. Specifically to measure land deformation in Alkmaar and measure deformation above the N-S line in Amsterdam. The standard PSI processing (H-1 TF standard processing) was used, although the PSIPs were invited to adjust their processing, especially the thresholds on PS selection, to get a good balance between PS coverage and measurement quality. The datasets delivered by the PSIPs were anonymous.

The process analysis was based on intermediate and final processing outputs in the original radar slant range geometry. This analysis was aimed at detecting differences between the PSIP outputs due to different implementations of the PSI technique. DLR used results from its own independent, scientific PSI processing chain as a reference to assess the OPS results. The next step was direct inter-comparison of the PSIPs results as deformation velocities, deformation time series, topographic corrections and PS density. The results indicated large differences in the number of PS and the coherence values among the outputs delivered by the PSIPs, which are used as quality indicators within TF. In this sense, it was recommended to standardise the procedure used to estimate the temporal coherence, in order to generate a quality index usable to inter-compare the PSI results of different teams over different test sites. Finally, the last stage consisted of comparing the PSI results of each PSIP to the ground truth available at each site.

A highlight of the Alkmaar validation was the innovative analysis approach using validation in the parameter space. This overcomes an important limitation of classical validation: the often unsupported assumption that both PSI and ground truth measure the same parameter at the same location and the same time. It also highlighted a key PSI capability: the high number of available samples. Even though the deformation signal is weak, the PSI vs. levelling comparison provided good results. All PSIPs' PSI data enabled estimation of the signal of interest, despite the difference in PS density. In Amsterdam it was found that geocoding uncertainty limited the comparison of PS points with individual buildings. This is a necessary comparison where spatially variable ground displacements exist and represents an intrinsic problem for the study of small objects. The PSI data of all PSIPs show a reasonably good correlation with the tachymetry data and there are no significant differences in their validation results.

The time series validation results did not provide much useful information, due to the inherent limitation of the comparison and the limited temporal samples of the ground truth data. It was recommended to further study the deformation time series, which represent a key PSI product. Users interested in mining subsidence and landslides need to know the expected PSI performance when displacement rates are larger, e.g. up to 2 cm/year. An experiment in this direction would be welcome.

The success of this PSI inter-comparison and validation has allowed this approach to be adopted as the standard qualification procedure to be followed within TF. A key component of this success was the careful selection of the test sites, which are representative of typical sites analysed in TF, and the communication of the main targets of the PSI processing to the PSIPs prior to processing, which reflects the working relationship that is built between user and provider within TF. It was recommended to continue this approach to support ongoing PSI validation activities within TF. This is a fundamental requirement 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 TF. For detailed information on this project see Raucoules et al. 2009, Crosetto et al. 2007 and Crosetto et al. 2008b.

3.3 VALIDATION ACTIVITIES UNDERTAKEN BY THE PSIPs

A summary of validation activities in which the PSIPs have been involved is provided in this section.

Altamira Information

- A multidisciplinary approach, involving radar DInSAR and PSI interferometry, geological field works, geomechanical, and hydrogeological analyses of the Seine river, was developed in Central Paris Grand-Palais and Les Invalides in order to reveal and better understand surface displacements occurred in that area. More than 400 ascending and descending Radar ERS1 and 2 and ENVISAT images from 1992 to 2009 were acquired and processed. A long not linear subsidence thought to be related to the variation of the Seine river level, which affected and deformed buildings on both sides of the Seine river bank, was observed. The results of this study showed the complementarity of these approaches to solve complex geological problems as those present in the study area [Deffontaines et al. 2009].
- A subsidence phenomenon occurred in the metropolitan area of Murcia City (SE Spain) due to groundwater over-exploitation was investigated using an advanced differential SAR interferometry remote sensing technique (A-DInSAR) called Stable Point Network (SPN). The comparison of the temporal evolution of the displacements measured with extensometers and the SPN deformation time series showed an average absolute error of 3.9±3.8 mm. Additionally, results from a finite element model developed to simulate the recorded time history subsidence from known water table height changes compares well with the SPN displacement time series estimations, showing that the average values of the absolute difference between the numerical model and the SPN time series of displacement for all the extensometers locations are 5.5±4.7 mm. This result demonstrates the potential of A-DInSAR techniques to validate subsidence prediction models as an alternative to using instrumental ground based techniques [Herrera et al. 2009a].
- An analysis of the performance of the Stable Point Network (SPN) and the Coherent Pixel Technique (CPT) was carried out in this study. The test site is the metropolitan area of Murcia (SE Spain), which is affected by a moderate slow subsidence induced by the overexploitation of aquifers. SAR data acquired between July 1995 and August 2005 from ERS and ENVISAT sensors

were processed using both techniques and compared with in situ instrumental measurements assumed as reference. The results showed that both SPN and CPT techniques provide estimates of the deformation evolution in time with an absolute difference below 6 mm consistently in all comparisons: SPN vs. extensometer, CPT vs. extensometer and SPN vs CPT. The validation of both A-DInSAR techniques revealed that, even though the SPN technique locates the estimated ground deformation more precisely, the precision of the estimation of the deformation is very similar. The absolute difference between both A-DInSAR techniques with respect to extensometer measurements is almost inexistent (0.5±0.3 mm) [Herrera et al. 2009b].

- Small seasonal-dependant displacements caused by swelling soils in the eastern Paris Basin were monitored by means of DInSAR and PSI methods. The results showed that DInSAR provides poor results and is not very efficient in the study area due to temporal decorrelation. However, the results obtained with the PSI technique reveal the surface displacements and shows high potential to better understand natural hazards produced by swelling soils and the subsequent geological processes [Kaveh et al. 2009].
- The SPN technique was used to monitor the Portalet landslide area (Central Pyrenees, Spain) and the performance of different SAR datasets acquired by ERS-1, ERS-2, ENVISAT and TerraSAR-X satellites was analysed. The main conclusions of this study were: (i) the TerraSAR-X analysis yielded a very dense PS dataset, which allowed obtaining a very good spatial sampling of the area of interest. The density of the TerraSAR-X dataset is remarkably greater than that offered by ERS and Envisat, (ii) the displacement time series of X-band are better than the C-band due to the shorter revisiting time even if some variance errors are still present. This facilitates the detection of the nonlinear trends characteristic of landslide kinematics, e.g. the rainfall influence on the landslide acceleration, (iii) the comparison of the TerraSAR-X results with GB-SAR observations shows rather similar deformation estimates in agreement with the dynamics of the landslide, despite the main limitation of the deformation data referring to non-overlapping period, (iv) in this respect the GB-SAR provides higher spatial density and temporal resolution than satellite-based SAR, allowing the former to detect faster movements and to map active areas in detail [Herrera et al. 2010].
- The subsidence affecting the Vega Media of the Segura River Basin was analysed using SPN. A dataset acquired between January 2004 and December 2008 from ERS-2 and ENVISAT sensors was processed. These results were validated against extensometer measurements, showing good agreement, and compared with subsidence triggering and conditioning factors by means of a Geographical Information System (GIS). The spatial analysis shows a good relationship between subsidence and piezometric level evolution, pumping wells location, river distance, geology, the Arab wall, previously proposed subsidence predictive model and soil thickness [Tomas et al. 2011].

Fugro NPA

- Radar satellite data was used to monitor gas storage in the city of Berlin. 88 ERS SAR images spanning nearly 13 years from May 1992 to October 2005 were used for processing. Levelling data collected at 47 fixed points in the years 2003, 2004 and 2005 was used in combination with PSI data. The PSI data revealed moving ground chiefly for the Berlin Olympia Stadium area (uplift), for numerous land fills (subsidence) and also for the ground along rail tracks (subsidence). The results of this study indicate that combined applications of PSI and levelling is a promising approach in order to improve ground motion monitoring [Kuehn et al. 2009].

Gamma Remote Sensing

- A data stack of 16 StripMap TerraSAR-X SAR images covering the period between January and August 2008 was used to monitor surface displacements over an oil field in the Middle East. The results demonstrate that TerraSAR-X interferometry is suited for determination of large scale relatively uniform as well as small-scale highly dynamic surface displacements. The comparison of TerraSAR-X results and high precise GPS measurements showed a good correlation for dynamic movements as well as for the slower, relatively uniform displacements. In the case of large-scale temporally relatively uniform subsidence at relatively low rates displacement maps generated from single interferograms revealed distortions by atmospheric path delay effects. However, this effect can be minimized by temporal filtering thanks to the good temporal sampling achieved with the 11 day repeat cycle of TerraSAR-X. TerraSAR-X interferometry was also efficiently used for the monitoring of stronger and more dynamic movements, thanks to its high spatial and temporal resolution capability [Wegmüller et al. 2009].
- The use of PSI has been primarily feasible in the case of slow (less than a few centimetres per year) uniform movements. This study discusses a case where PSI was successfully applied to monitor relatively fast (including rates up to > 50 cm/year) and non-uniform movements. This was possible due to two relevant factors: (i) high-resolution TerraSAR-X data acquired at relatively short 11-day intervals was used and thus the number of persistent scatterers found was significantly higher than for ERS or ENVISAT data stacks, (ii) the deformation was not estimated in a linear regression to a single reference stack, but considering a multi-reference stack with short intervals. The PSI results achieved were validated using levelling data. The overall good correspondence confirmed the utility of the TerraSAR-X data and the applied PSI methodology [Wegmüller et al. 2010].

Telerilevamento Europa (TRE)

- A comprehensive validation of the PSI approach was performed to assess the limits of its applicability. In this study, two couples of dihedral reflectors were deployed and pointed so that the reflectors were visible along ascending orbits of both Envisat and Radarsat platforms. The aim of the experiment was to move one couple of dihedral reflectors a few millimetres from one acquisition to another, along both vertical and East-West direction, and to compare these displacements with those estimated by means of interferometric measurements applied to ascending and descending data. The experiment was carried out using a series of 25 Radarsat and 8 Envisat acquisitions (considering both ascending and descending data). The comparison of the estimated time series with the imposed motion results in a standard deviation of just 1 mm for both horizontal and vertical components [Savio et al. 2005].
- The results of a blind experiment performed using two pairs of dihedral reflectors was presented in this paper. The aim of the experiment was to demonstrate that InSAR measurements can indeed allow a displacement time series estimation with submillimetre accuracy (both in horizontal and vertical directions), provided that the data are properly processed and the impact of *in situ* as well as atmospheric effects is minimized. One pair of dihedral reflectors was moved a few millimetres between Envisat SAR acquisitions, in the vertical and east–west (EW) directions, and the ground

truth was compared with the InSAR data. Moreover, two pairs of reflectors were used to allow the combination of data gathered along ascending and descending orbits. The standard deviation of the error was 0.75 mm in the vertical direction and 0.58 mm in the horizontal (EW) direction [Ferretti et al. 2007].

- The south-eastern Po Plain, affected by high natural and anthropogenic subsidence, was used to test the application of an observational strategy which combines different techniques to extract information on the spatial and temporal variability of the subsidence. The combination of velocities derived from the GPS and gravity data, further complemented by the results of the PSI technique, allowed monitoring continuously, in space and time, vertical crustal movements. A remarkable consistency was found between the time series derived from the GPS, InSAR, and gravity observations. This study indicates that a systematic and synergetic combination of these technologies appears to be a valuable approach for monitoring and understanding surface deformation [Zerbini et al. 2007].

4 CONCLUSIONS

In this deliverable two technical topics have been addressed: (i) the discussion of some technical issues (open problems) related to the PanGeo PSI products specification, which were identified during the Terrafirma Validation Project; (ii) the description of the available information related to the PSI validation results.

The open problems were discussed within the PanGeo consortium, involving the four PSIPs (TRE, Altamira Information, Gamma Remote Sensing and Fugro-NPA) and the Institute of Geomatics. The outcomes of this discussion, which have a direct impact in the PSI product generation, are collected in this document. They address, in particular, these topics:

- The minimum number of SAR images needed to derive reliable PSI products.
- The spatial coverage of the PSI products.
- The tilts/trends that might affect the PSI products.
- The indices used to describe the quality of the PSI results.
- The spatial density of PS, and its relation to the PSI quality indices.

The second part of this document describes the important effort made in the last years to validate the PSI deformation monitoring technique. This aspect is of paramount importance for the acceptability of PSI, especially by the Geological Surveys that are required to fully take advantage of the PSI data to derive the PanGeo Geohazard Layers. The main PSI validation projects performed in the past have been summarized, providing to the Geological Survey a concise and complete summary of their results. It is worth mentioning that in the frame of the PanGeo project some validation activity will be performed by the Geological Surveys. The validation results are to be included in the Geohazard Reports generated per each site/city and will be available in the PanGeo portal.

5 REFERENCES

Crosetto, M., Agudo, M., Monserrat, O., Pucci, B. (2007). Inter-comparison of persistent scatterer interferometry results. *Proceedings of Fringe 2007*, 26-30 November, Frascati (Italy).

Crosetto, M., Monserrat, O., Agudo, M. (2008a). *Validation of existing processing chains in Terrafirma stage 2. Process analysis report – Part 2: IG inter-comparison*. Terrafirma project report. 27/04/2011. <http://www.terrafirma.eu.com/validation/ValProj/Final%20Reports/IG_Intercomparison_final.pdf>

Crosetto, M., Monserrat, O., Bremmer, C., Hanssen, R., Capes, R., Marsh, S. (2008b). Ground motion monitoring using SAR interferometry: Quality assessment. *European Geologist*, **Vol. 26**, pp. 12-15.

Deffontaines, B., Magalhaes, S., Fruneau, B., Cojean, R., Ledoux, E., Salim, M., Salim, M., Deveughele, M., Goblet, P., Zokimila, P., Prunier-Leparmentier, A.M., Altamira Information (2009). PSI and DInSAR interferometry useful tools for monitoring earth movement: The Grand-Palais-Invalides case example (Paris - France). *EGU General Assembly*, 19-24 April, Vienna, Austria.

Ferretti, A., Savio, G., Barzaghi, R., Borghi, A., Musazzi, S., Novali, F., Prati, C., Rocca, F. (2007). Submillimeter accuracy of InSAR time series: experimental validation. *IEEE Transactions on Geoscience and Remote Sensing*, **Vol. 45** (5), pp. 1142-1153.

Hanssen, R.F., van Leijen, F.J., van Zwieten, G.J., Bremmer, C., Dortland, S., Kleuskens, M. (2008). *Validation of existing processing chains in Terrafirma stage 2. Product validation: validation in the Amsterdam and Alkmaar area*. Terrafirma project report. 27/04/2011. <http://www.terrafirma.eu.com/validation/ValProj/Final%20Reports/ProductValidation_report_TNO-TUD.pdf>

Herrera, G., Fernández, J.A., Tomás, R., Cooksley, G., Mulas, J. (2009a). Advanced interpretation of subsidence in Murcia (SE Spain) using A–DInSAR data – modelling and validation. *Natural Hazards and Earth System Sciences*, **Vol. 9**, pp. 647–661.

Herrera, G., Tomás, R., Lopez–Sanchez, J.M., Delgado, J., Vicente, F., Mulas, J., Cooksley, G., Sánchez, M., Duro, J., Arnaud, A., Blanco, P., Duque, S., Mallorquí, J.J., Vega–Panizo, R., Monserrat, O. (2009b). Validation and comparison of Advanced Differential Interferometry Techniques: Murcia metropolitan area case study. *ISPRS Journal of Photogrammetry and Remote Sensing*, **Vol. 64**, pp. 501–512.

Herrera, G., Notti, D., García-Davalillo, J.C., Mora, O., Cooksley, G., Sánchez, M., Arnaud, A., Crosetto, M. (2010). Analysis with C- and X-band satellite SAR data of the Portalet landslide area. *Landslides*, doi: 10.1007/s10346-010-0239-3.

JLE Intercomparison. 27/04/2011. <http://www.terrafirma.eu.com/JLE_intercomparison.htm>

Kaveh, F., Deffontaines, B., Fruneau, B., Cojean, R., Audiguier, M., Arnaud, A., Duro, J. (2009). Swelling soils monitoring through PSI and DInSAR interferometry : applications on eastern Paris surroundings (France). *EGU General Assembly*, 19-24 April, Vienna, Austria.

Kuehn, F., Hoth, P., Stark, M., Burren, R., Hole, J. (2009). Experience with satellite radar for gas storage monitoring. *Erdöl Erdgas Kohle*, **Vol. 125** (11), pp. 452-460.

Meisina, C., Zucca, F., Fossati, D., Ceriani, M., Allievi, J. (2005). PS InSAR Integrated with Geotechnical GIS: Some Examples from Southern Lombardia. *International Association of Geodesy Symposia*, **Vol. 131**, pp. 65-72, Spain, 17-19 March.

Provence Intercomparison. 27/04/2011. <http://www.terrafirma.eu.com/Provence_intercomparison.htm>

PSIC4. 27/04/2011. <http://earth.esa.int/psic4/>

Raucoules, D., Bourgine, B., De Michele, M., Le Cozannet, G., Closset, L., Bremmer, C., Veldkamp, H., Tragheim, D., Bateson, L., Crosetto, M., Agudo, M., Engdahl, M. (2009). Validation and Intercomparison of Persistent Scatterers Interferometry: PSIC4 project results. *Journal of Applied Geophysics*, **Vol. 68**, pp. 335-347.

Savio, G., Ferretti, A., Novali, F., Prati, C., Rocca, F. (2005). PSInSAR validation by means of a blind experiment using dihedral reflectors. *Proceedings of Fringe 2005*, 28 November – 2 December, Frascati (Italy).

Terrafirma Validation Project. 27/04/2011. <http://www.terrafirma.eu.com/product_validation.htm>

Tomás, R., Herrera, G., Mulas, J., Cooksley, G. (2011). Persistent Scatterer Interferometry subsidence data exploitation using spatial tools: the Vega Media of the Segura River Basin case study. *Journal of Hydrology*, **Vol. 400**, pp. 411-428.

Wegmüller, U., Petrat, L., Zimmermann, K., Al Quseimi, I. (2009). The potential of high resolution satellite interferometry for monitoring enhanced oil recovery. *Procedings of the 5th European Symposium on Improved Oil Recovery*, Paris, France, 27-29 April.

Wegmüller, U., Walter, D., Spreckels, V., Werner, C. (2010). Nonuniform ground motion monitoring with TerraSAR-X persistent scatterer interferometry. *IEEE Transactions on Geoscience and Remote Sensing*, **Vol. 48** (2), pp. 895-904.

Zerbini, S., Richter, B., Rocca, F., van Dam, T., Matonti, F. (2007). A Combination of Space and Terrestrial Geodetic Techniques to Monitor Land Subsidence: Case Study, the Southeastern Po Plain, Italy. *Journal of Gephyscal Research*, **Vol. 112**, doi:10.1029/2006JB004338.