GMES

TERRAFIRMA
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TERRAFIRMA USER GUIDE

A guide to the use and understanding of Persistent Scatterer Interferometry in the detection and monitoring of terrain-motion

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ACRONYMS

DEM: Digital Elevation Model. A geocoded grid of height values that represents the earth‟s surface (not terrain, which accounts for buildings, plants, etc – this would be a DTM).

DTM: Digital Terrain Model – accounts for objects on the ground (buildings, trees, etc.).

ERS: European Remote Sensing Satellite. ESA-built and operated radar satellite. ERS-1 was launched in 1991 providing data until 2000. ERS-2 was launched in 1995 and is still in service.

ESA: European Space Agency.

GIS: Geographic Information System.

GPS: Global Positioning System

LOS: Line-Of-Sight. PS motions are measured in the satellite Line-Of-Sight. The satellite LOS depends on the incident angel of the radar.

OSP: Operational Service Provider, companies who specialise in PSI processing.

PSs: Persistent Scatterer(s), a point on the terrain for which a motion history is derived.

PSI: Persistent Scatterer Interferometry. Radar processing technique with the ability to derive precise motion histories for points on the earths surface. Terrafirma is based upon the technology of PSI.

SAR: Synthetic Aperture Radar, a side looking radar system.

SRTM: Shuttle Radar Topography Mission. A DEM derived by radar interferometry conducted on data gathered by a Space Shuttle orbiting the Earth.

UTM: Universal Transverse Mercator, a map projection system.

WGS84: World Geodetic system established in 1984, a reference frame for spatial data.

1: PURPOSE OF MANUAL

This manual is intended as a guide to new and potential users of the Terrafirma service and its products. The goal is to stimulate the interest of end users, assure them of the accuracy and quality of the technique, steer them towards its optimal use whilst helping avoid known pitfalls and maximise the return on investment of both time and money in applying Persistent Scatterer Interferometry.

The following items are covered:

- A description of the Terrafirma service and products.
- The uses and benefits of using such a service, highlighting the key users of the service.
- The theory of the Persistent Scatterer Interferometry processing chain.
- Summaries of validation activities and statements on the accuracy of the products.
- The practicalities of the Terrafirma service are discussed; ensuring the user is informed about important considerations and required inputs.
- Using the data.
- Limitations of the technique and their solutions.
- Case-studies illustrating a range of appropriate and successful applications.

2: WHAT IS TERRAFIRMA?

- *Terrafirma* is a GMES project designed to deliver services to public users concerned with geo-hazard risk assessment. *Terrafirma* is an open service partnership where competitor service providers work together to produce a standardised and validated service.
- *Terrafirma* services combine qualified InSAR service products with expert interpretation and ground data to provide a series of services for specific themes. The generic (non-interpreted) services provided in the previous stages can also be provided.
- *Terrafirma* services are designed for use in natural hazard assessment for the good of the citizen. This does not mean they are not useful for commercial exploitation (e.g. for the oil and gas industry) but the user base is focused on entities that work for the "good of the citizen".
- *Terrafirma* brings together a network of users that have expressed interest and have in many cases gained exposure and experience in using InSAR-derived motion services. Potential new users are encouraged to contact *Terrafirma* to enquire about particular areas of interest.
- *Terrafirma* Stage 3 is designing a wide-area service ideal for regional assessment and overview or as input to a wide area version of the services.

The Terrafirma project operates in three discrete stages. Stage 1 ran from years 0 to 2 and was concerned with consolidation of both service providers and users. The second three-year stage, Stage 2, ran from years 2 – 5and was concerned with rolling-out the service across all 25 Member States of the EC. In Stages 1 & 2 the services delivered were generic in nature however the user evaluations allowed the logical grouping shown in Table 1 to be made.

In the current third stage (years 5 to 8) the primary focus is to achieve the sustainability of the service into the longer term. Building on the geohazard groupings made in the first two stages and in order to facilitate the integrated use of the TF services in the user‟s working practices it was decided to focus the activities into **three principle themes**, thus allowing more detailed and specific products to be delivered.

The **thematic service groups** for *Stage 3 are:*

1. Hydrogeology (groundwater, abandoned mines, landslides).
2. Tectonics
3. Flood

2.1: SAR interferometry

Terrafirma is based upon the application of InSAR technologies: mainly Persistent Scatterer Interferometry (PSI), but sometimes conventional 2-pass differential InSAR, and Site-Specific InSAR (corner reflectors or transponders). These technologies can be applied to detect and monitor terrain-motions such as subsidence, uplift, building stability, landslides, flood risk and seismicity. In fact the word „terrain‟ is purposefully used as it is often not the ground *per se* that „scatters‟ back to the satellite, but buildings and other man-made features on the ground.

PSI is a non-invasive surveying technique able to measure millimetric motions of individual terrain features over wide-areas in both urban and semi-urban environments. PSI exploits the fact that a substantial global archive exists of radar data acquired by a number of different satellites. This means that over all areas of Europe for example, many tens if not hundreds of radar scenes have been acquired over the same places, providing large „multi-temporal" data-sets covering periods from 1991 to the present. InSAR, in general, compares the *phase* information in each radar scene to derive terrain-motion measurements.

Using these multi-temporal radar data-sets, the PSI algorithm specifically identifies common geographical locations in each scene that reliably and *persistently* reflect the radar signal back to the satellite. These locations, or „persistent scatterers" (PSs) are generally parts of man-made structures such as buildings, bridges, pylons, etc., though they can also include bare rocks and outcrops. They act as persistent scatterers because of their serendipitous geometry, surface-roughness and electrical conductivity. The exact location of PSs, therefore, cannot be predicted in advance of processing, but over urban areas their densities are usually measured in the hundreds per square kilometre.

After identification of the PSs in a data-set, the algorithm compares the inherent phase data between all common scatterers across all scenes. If the phase data for a particular scatterer are the same across all scenes, then the scatterer is deemed not to have changed its relative location. Conversely, any difference in phase equates to motion. This does not of course account for a number of variables, one of which is atmospheric refraction which, in effect, can change the signal path length and hence the phase data, giving false information. The statistical computation of an „atmospheric phase *screen'* to correct for this effect is consequently a vital part of the process.

A unique benefit of PSI is its ability to provide both average annual motion rates as well as multi-year motion histories for individual scatterers. The PSI technique takes conventional InSAR a step further by correcting for atmospheric, orbital and Digital Elevation Model (DEM) errors to derive relatively-precise displacement and velocity measurements at specific points on the terrain.

2.2: Integration with other information

Terrafirma involves the integration of InSAR measurements with conventional ground-based *in situ* measurements within a GIS environment, where data are merged and interpreted by geologists and geophysical experts to produce value-added, higher-level products. The InSAR measurements which feed into this process are (currently) supplied by four Operational Service Providers (OSPs) in Europe, who co-operate in providing a standardised service through an Open Service Partnership Protocol.

Value is added to these measurements by geoscience organisations (normally national geological surveys) who work in partnership with the OSPs under the terms of a Service Level Agreement. Such organisations are key to Terrafirma as they represent the normal institutional repositories of geohazard information within a country and hence, routes to users. The engineering sector is also key to Terrafirma as a user of terrain-stability measuring and monitoring products and also works in partnership with OSPs to compile higher-level products.

2.3: Terrafirma product suite

Terrafirma offers two types of product **ATM-Mapping** and **ATM-Modelling**. Both products start with the generation of the quality-controlled, geo-referenced Persistent Scatterer SAR interferometry (PSI) output from the *Terrafirma* PSI-Value Adding Companies (PSI-VACs). PSI data are then integrated with external data and value is added by the value adding Terrafirma partners.

1. Advanced Terrain Motion Mapping (**ATM-Mapping**) involves analysis by a geophysical expert and integration with other geospatial data to provide an initial interpretation of the cause of any motion observed.

2. Advanced Terrain Motion Modelling (**ATM-Modelling**) products involve geophysical modelling to provide a risk assessment or some forecast as to future events.

These two basic products are inputs for the following services of the application themes:

- **Hydrogeology theme**
    - Groundwater management services
    - Mining Inventory services (MNI)
    - Mining Monitoring services (MNM)
    - Landslide Inventory services (LSI)
    - Landslide Monitoring services (LSM)
- **Tectonic theme**
    - Major and local fault investigation
    - Earthquake cycle investigation
    - Vertical deformation sources in urban areas
    - Vulnerability maps
- **Flood theme**
    - Basic PSI-Wide Area Service

  - Subsidence Hazard mapping service for flood prone areas
  - Flood defence monitoring service
  - Advanced subsidence modelling service for flood prone areas

Furthermore a **Wide-Area PSI product** is being developed which could input into any of the previous themes. This service takes the form of a basic PSI-service in that it will deliver PSI-derived GIS-layer and database for a larger area than pervious Terrafirma products.

3: WHY USE TERRAFIRMA?

The key strengths of the Terrafirma service are:

- **Qualification of Terrafirma OSPs:** The four OSPs are the only InSAR providers in the world to have undergone a stringent qualification and certification procedure, ensuring quality and consistency of product.
- **The capability to measure historical deformation:** Suitable radar data exists from 1992 onwards. This gives the ability to investigate past motions for which other monitoring data do not exist.
- **Wide area coverage:** Results can be obtained for several thousand square kilometres, resulting in hundreds of thousands of points with a motion history.
- **Average motion rates:** The average motion of a point can be derived for the whole study period, giving a good overview of motions in the study area.
- **Detailed motion evolution:** A history of how each PS point has moved during the study period is derived therefore allowing detailed investigations.
- **Sensitivity to small motions:** The resulting motion history data has a millimetric level of precision.
- **Interpretation of the motion signal:** The unique association of OSP"s and geological surveys means that, if required, deformation can be interpreted by a person with knowledge of both the local geology and the processing technique.
- **Data continuity**: Terrafirma mainly exploits the „C-band" satellite data archives of ERS-1/2 and Envisat. ERS-1 is out of commission and both ERS-2 and Envisat are beyond their design lives. Continuity of the data-types provided by these satellites is consequently assured by the forthcoming Sentinel 1a and b, to be launched in 2012.

3.1: Who uses Terrafirma

The Terrafirma service is applied to detect millimetric terrain-motion. The causes of terrain-motion are many and can include anthropogenic or natural factors, and since they are related to the nature of the terrain (its geology or the buildings thereon) the effects can occur in both urban and rural environments. In many cases the motions detected by this technique would have remained undiscovered until they perhaps manifested in some form of catastrophic failure. It can be important to monitor these small motions as they often precede larger, more damaging, motions. Consequently, if the smaller motions can be detected in advance, the effects of the motion can be avoided or mitigated. Terrafirma offers *pro-active* monitoring.

Many of the processes that cause terrain-motions can extend over large areas that might affect tens or even hundreds of properties. Monitoring changes in the terrain enables damaging motions to be anticipated. However, ground-based surveys are time-consuming, very expensive and practicably not always possible if, for example, whole conurbations are to be monitored. An air or space-borne monitoring system, capable of resolutions of a few centimetres or better, has great potential to assist in the minimisation and mitigation of damage caused by both natural and anthropogenic processes.

Information on ground motion is therefore a valuable asset. The following list gives an idea of potential users of Terrafirma products; however this list is by no means exhaustive:

- Public Sector:
  - Regulators, government ministries and public authorities
  - Planners
- Extraction Industry:
  - Mineral, oil, gas, water, coal, salt, etc.
- Structural Engineering:
  - Builders and constructors including engineering consultants
  - Utility operators
  - Transport providers
- Risk Assessment:
  - Development initiators and property owners
  - Information providers
  - Insurers
- Researchers:
  - Universities
  - National geological surveys
  - Geoscience institutes

3.2: What are the applications of Terrafirma?

Although Terrafirma has many application areas the geohazard groupings made in the first two stages (**Table 1**) have been analysed and in order to facilitate the integrated use of the TF services in the user"s working practices it was decided to focus the activities into **three principle themes**, thus allowing more detailed and specific products to be delivered.

The **thematic service groups** for *Stage 3 are:*

- **Hydrogeology including the detection of landslide areas and unstable slopes:** The input, movement and abstraction of water from the ground can all cause associated terrain-motions that can be detected using Terrafirma. Terrafirma can provide quantitative information often lacking in the analysis of active slopes
- **Tectonics and crustal deformation:** The measurement time-scale and ability of historical measurements means Terrafirma is suitable for studies of neo-tectonics and crustal deformation. This information is valuable as input to the management of seismic and volcanic risks.
- **Flood risk:** Motions in areas prone to flooding can be realised leading to future flooding models.

Terrafirma is also applicable to:

- **Detection of areas subject to subsidence or uplift**: These terrain-motions may have many possible sources such as pumping of water, gas or hydrocarbons, mining activity, tectonic motion, differential settling of sediments and dissolution. More examples are given in Table 1 below.
- **Engineering and site investigations:** Terrafirma studies can be conducted to ascertain the stability of a site prior to the commencement of work.
- **Planning of new roads and infrastructures:** Terrafirma data can be used when taking strategic decisions on the planning of new roads and infrastructures.
- **Insurance industry:** Stability check of private and public buildings and architectural heritages.
- **Damages caused by major works:** Such as the construction of subway lines and tunnels: The historic archive of radar data allows retrospective analysis of the cause-effect links between construction works and damages sustained by buildings.
- **Waste Disposal** and associated monitoring of sites.

More detailed case-studies, which illustrate how PSI has been applied to specific problems, are given in section 9.

Mechanisms																																											
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Creep																			🟧									🟥								🟧							
Tectonics				🟥															🟧			🟧			🟧			🟥	🟥		🟧					🟥							🟧
Seismic					🟧															🟧	🟧							🟥		🟧											🟧		🟧
Volcanic																				🟥																							🟧
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Coastal sediment settling									🟧																																		
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Quaternary sediment heterogeneity								🟧																																			
Shrink - swell in clay formations					🟧			🟧														🟧			🟧														🟧			🟧	
Failure of constructed slopes																												🟥															
Waste disposal												🟥		🟥			🟧																										🟧
Reclaimed land														🟧				🟥																									
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Dissolution		🟧											🟥	🟥				🟥		🟥																		🟧					🟥
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Groundwater abstraction			🟥	🟥		🟧			🟧		🟧				🟥	🟥			🟥	🟥		🟧	🟥								🟧					🟥	🟥		🟧		🟧		🟧
Anthropogenic cavities											🟥																																
Oil and Gas extraction															🟥												🟧																
Salt extraction															🟥																							🟧					
Mining		🟥	🟧	🟥					🟧				🟥		🟥													🟥														🟧	🟥
Mineral works				🟥																																					🟧		🟥
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EU27 sites (and Switzerland, Israel, Russia, Turkey)	*Austria*	Belgium - Liege	Belgium - Brussels *	Bulgaria - Sofia *	*Cyprus*	Czech Rep	*Denmark*	*Estonia*	Finland	*France - Toulouse*	France - Lyon *	Germany - Berlin *	Germany - Stass	Germany - Hamb	Greece - Athens *	Greece - Larissa	Hungary	Ireland	*Israel - Haifa **	Italy - Rome	*Italy - Palermo **	*Latvia*	Lithuania	*Luxembourg*	*Malta*	*Netherlands - Alkmaar*	Netherlands - Amsterdam *	Poland - RybnikOstrava	Poland - Sosnowiec *	Portugal - Lisbon *	Portugal - Greater Lisbon	Romania	Russia - Moscow *	Russia - St Petersburg *	Slovakia	Slovenia	Spain - Murcia	*Spain - Zaragoza*	*Sweden*	Switzerland	*Turkey - Istanbul **	*UK - Bristol-Bath*	UK - Stoke *

Table 1. Geohazard mechanisms established as present at Terrafirma Stage 1 & Stage 2 sites. Red boxes indicate that the mechanism has been confirmed by the recipient, while orange boxes show that the mechanism is strongly suspected.

4: THE PSI PROCESS EXPLAINED

4.1: Orbit geometry, LOS and vertical and horizontal motions.

The satellites currently used for acquiring SAR images follow a fixed trajectory around the Earth (inclined by a few degrees off the N-S axis), and circumnavigate the globe at an altitude of approximately 800 km. As the satellite moves along its orbit the Earth is also spinning on its axis, so that at each orbit of the satellite scans a different portion of the Earth"s surface.

A distinctive feature of radar systems, compared to optical sensors, is that they have a side-looking geometry. The look angle varies depending on the satellite but generally ranges from 20˚-50˚ off the nadir (straight down). This fact makes it possible to view the same area from two different geometries. When the satellite travels in the descending part of its orbit, meaning that it is travelling from N to S, it views a target area looking westward, while during the ascending part of its orbit, that is, when it moves from S back to the N, it views the same target area looking eastward (**Figure 1**).

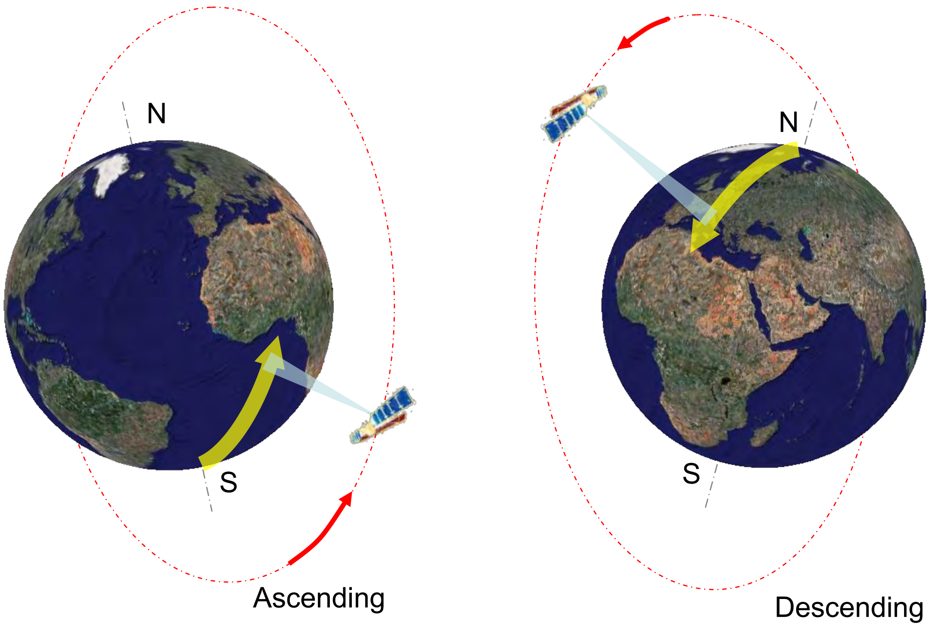

Figure 1: Illustration of ascending and descending satellite orbits.

Radar satellites can only measure motion along their Line-of-Site (LOS). This is defined as the line along which the sensor views the Earth surface target and, due to the side-viewing geometry, it is not vertical but inclined. In other words, what is actually measured by the sensor is the projection of a target"s motion onto the LOS. If the motion direction is close to the angle of the LOS then the measured and actual motions will be similar. However, the LOS motion can often differ noticeably from the real value of motion, especially in cases where the ground motion is not vertical (Figur**e 2**).

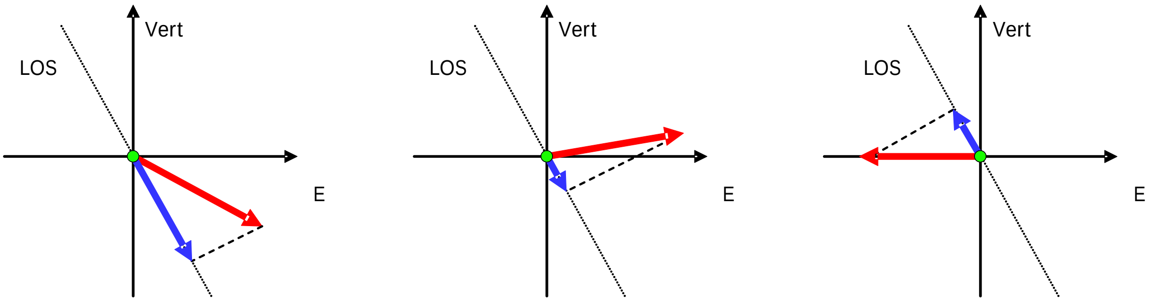

Figure 2: Motion measured by the sensor for different directions of terrain-motion. Red arrows represent the vector of terrain motion while blue arrows represent the LOS motion measured by the radar system.

With this configuration it is possible to view the terrain in both ascending and descending geometry (though not simultaneously with the same sensor). It is therefore possible to combine the measured motion information to obtain an accurate estimate of the actual vertical motion and of the East-West component of the motion (**Figure 3**).

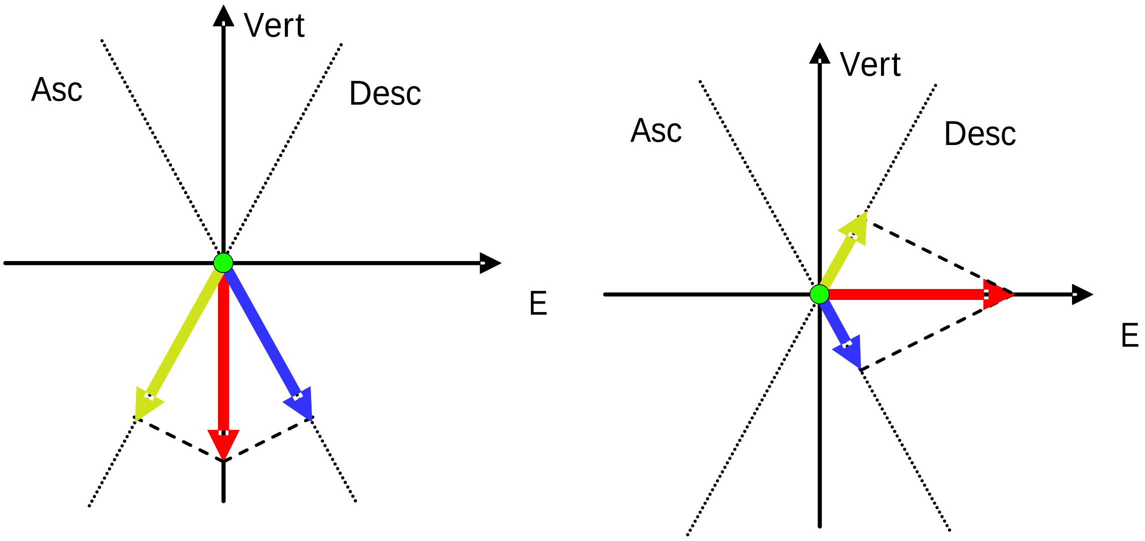

Figure 3: Illustration of the method for obtaining actual motion by combing ascending and descending orbit information. a) In the case of vertical ground displacements the motion components on the ascending and descending directions are both negative (moving away from the sensor) b) while in the case of a horizontal (E-W) motion one vector is positive (moving toward the sensor) while the other is negative.

4.2: PS velocity

One of the key outputs of a PSI analysis is the average velocity of each persistent scatterer (PS) over the entire time period encompassed by the SAR data used, e.g. 1991 to 2009, expressed as an average annual velocity (in mm/yr). Given the large number of PSs and their often high spatial density, the PSs are commonly colour-coded for visualisation purposes (**Figure 4**).

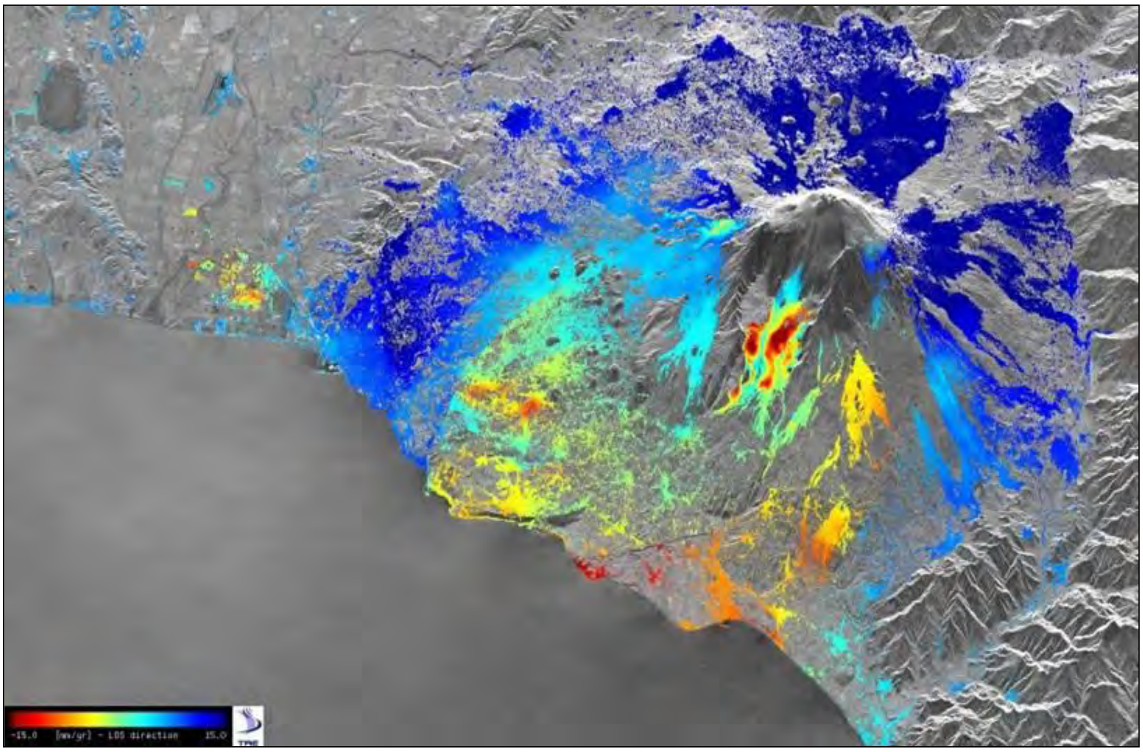

Figure 4: A radar image of Mt. Etna, in Italy, overlaid with color-coded PSs. The colors indicate the average annual velocity of each PS. Note that the extensive blue area indicates that most of the volcano is moving towards the sensor (expanding).

The colours gradually vary from red, which indicates motions away from the sensor, through orange, green, and finally to blue (motions towards the sensor). The velocity classes are uniform in size while the maximum and minimum values depend on the range of velocities actually measured (**Figure 5**).

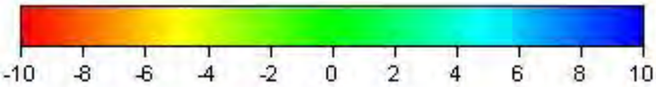

Figure 5. An example of the colour coding legend used for representing PS velocities.

The maximum velocity that can be measured by PSI depends on several factors, including:

- The satellite repeat cycle (time in days for the satellite to retrace the exact same path over the Earth).
- The radar wavelength.
- The direction of the actual motion compared to the sensor LOS.

Using the current satellites, velocities in the order of 20 cm/yr are considered an upper limit.

4.3: Time series of motions

Perhaps the most important distinction between conventional InSAR and PSI is the ability of the latter to create time-series of motion for individual PSs. These comprise a detailed graphical representation of the displacement, usually in mm, of the PS along the LOS as a function of the time between the first and last acquisition.

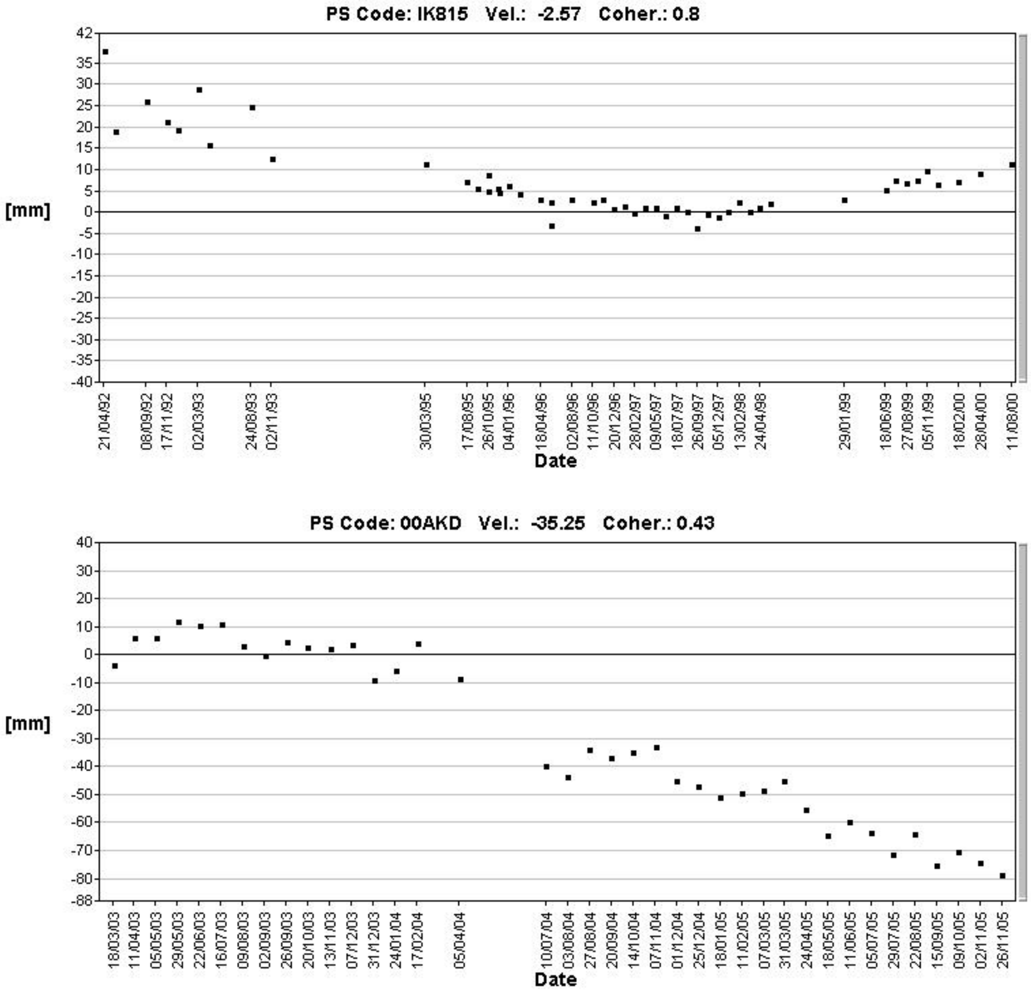

Figure 6: Examples of PS time-series. The upper plot shows a non-linear motion while the lower plot shows an accelerating motion. The dates along the bottom of each plot represent the individual radar scenes used in that particular process.

The gaps that are often visible in time-series plots are due to missing radar scenes. This occurs for a variety of reasons such as non-acquisition of images, data quality issues or adverse terrain conditions (e.g. snow cover).

Time-series data provide valuable information concerning individual PS behaviour that cannot be discerned by simply observing the mean annual velocity. It is possible to identify non-linear motions, seasonal trends, accelerations, and the times when changes in motion behaviour took place. Time-series represent a powerful tool in the analysis of terrain-motions.

When a time-series shows relatively rapid motion and there are gaps in the monitored period, it is important to consider the possibility of phase unwrapping errors (also known as phase ambiguity). In such situations there can be several possible solutions regarding the actual motion of the PS (**Figure 7**), each of which differs by a multiple of the radar wavelength. This can be expressed as *n*L + ΔR, where *n* is the number of cycles, L is the wavelength and ΔR is the terrain displacement between image acquisitions.

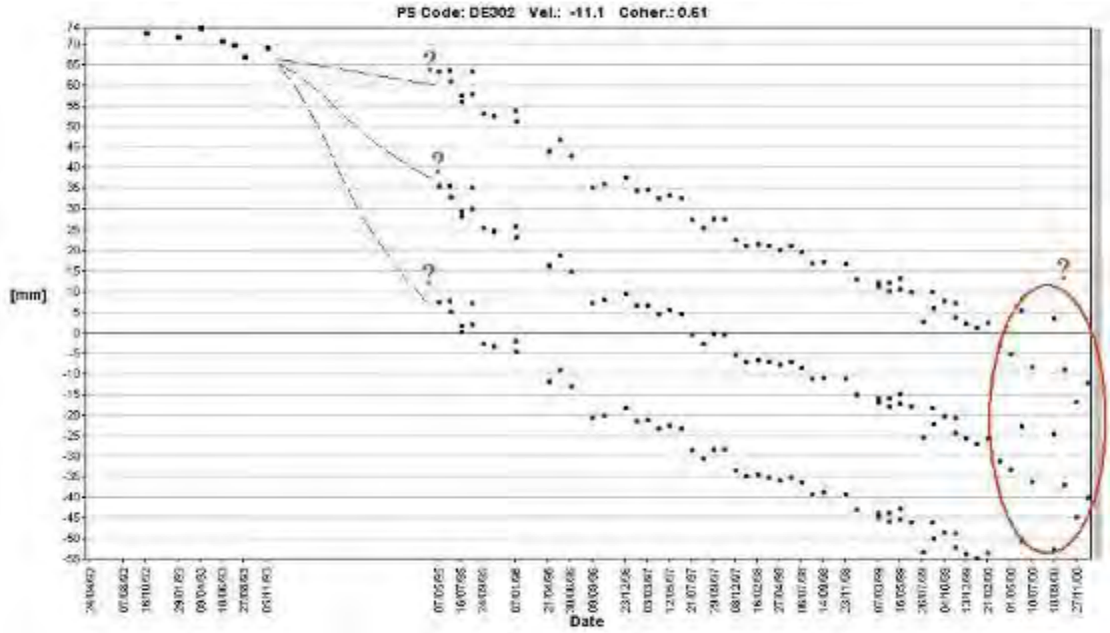

Figure 7: Example of a time-series with three different possible motion solutions, all of which are plausible.

In cases with multiple plausible solutions, and if no other independent motion measurements exist, it is left to the experience of the operator to determine which is the most likely to be correct.

4.4: Coherence

Synthetic Aperture Radar (SAR) works by illuminating the Earth with a beam of coherent radiation, where the term coherence describes systems that preserve and compare the phase of both the transmitted and received signal. This information is essential for SAR data processing. The comparison of the phase of the transmitted signal with that of the signal that is backscattered from the ground surface allows the detection of objects on the ground and also to determine if, and by how much, a target has moved between image acquisitions.

In interferometry, coherence is also a measure of correlation. Values near 0 indicate that there is little useful information in the interferogram while values close to 1 denote a high level of correlation between the backscattered signal received from date1 and date2.

The coherence of an interferogram is affected by several factors, including:

- Topographic slope angle and orientation (steep slopes lead to low coherence)
- Terrain properties (presence of vegetation, agricultural fields, rock outcrops, buildings)
- Time between image acquisitions (longer time leads to lower coherence)
- The distance between satellite tracks within an orbit (baseline): larger baselines lead to lower coherence.

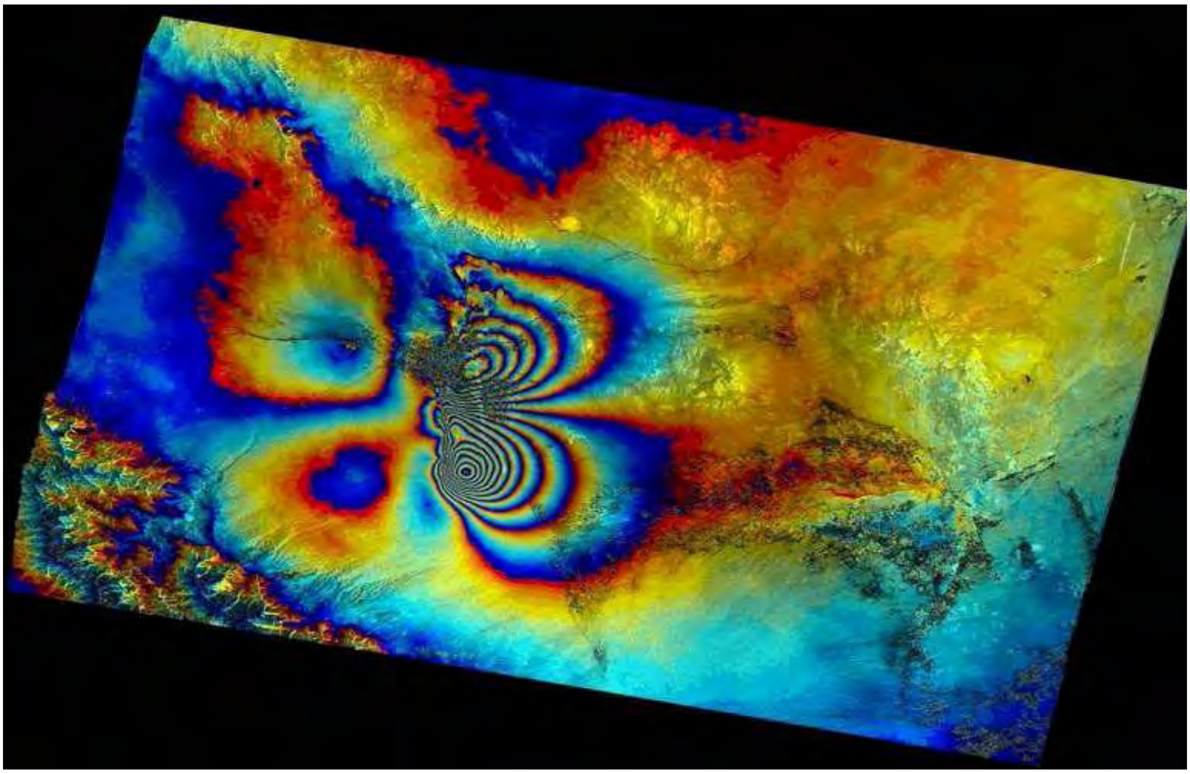

Figure 8: Interferogram showing the deformation associated with the Bam earthquake (Iran) of December 2003. Each complete fringe represents a LOS deformation of 28 mm. Coherence in this case is quite high.

To add to the confusion, coherence is also used as a quality indicator of the goodness-of-fit of the model (height correction, displacement rate, atmospheric compensation factors) to the observations (interferogram phase values). The index is based on the maximisation of a function that takes into consideration the number of scenes used in the analysis and the coherence of the stable reflectors identified as possible PS. By applying appropriate thresholds to the values obtained from the function it is possible to determine which reflectors become PSs.

4.5: Radar coordinates and geocoded PS

A digital SAR image can be thought of as a mosaic (*i.e.* a two-dimensional array comprising columns and rows) of picture elements (pixels). Each pixel is associated with a small area of the Earth"s surface, usually referred to as a resolution cell. Each pixel is defined by a complex number that carries amplitude *and* phase information integrated from any or all of the smaller scatterers within the cell. While amplitude values depend on the amount of energy that is backscattered by a certain radar target, phase information is related to the sensor-to-target distance and plays a key role in PSI.

As the satellite travels on its orbit and occupies different *azimuth* locations, radar signals are emitted in a perpendicular direction to form a strip map (**Figure 9**). The strip map is composed of multiple rows of pixels, each row having a unique *azimuth* location. At the same time, the radar sensor is „measuring" the distance to each pixel within the row, creating a slant *range* location. The dimensions of the resolution cell in azimuth and slant-range coordinates (referred to as "*radar coordinates*") depend on the SAR system characteristics and they typically measure a few meters in both range and azimuth. It should be noted that the actual terrain area imaged in each SAR resolution cell is affected by the local topography.

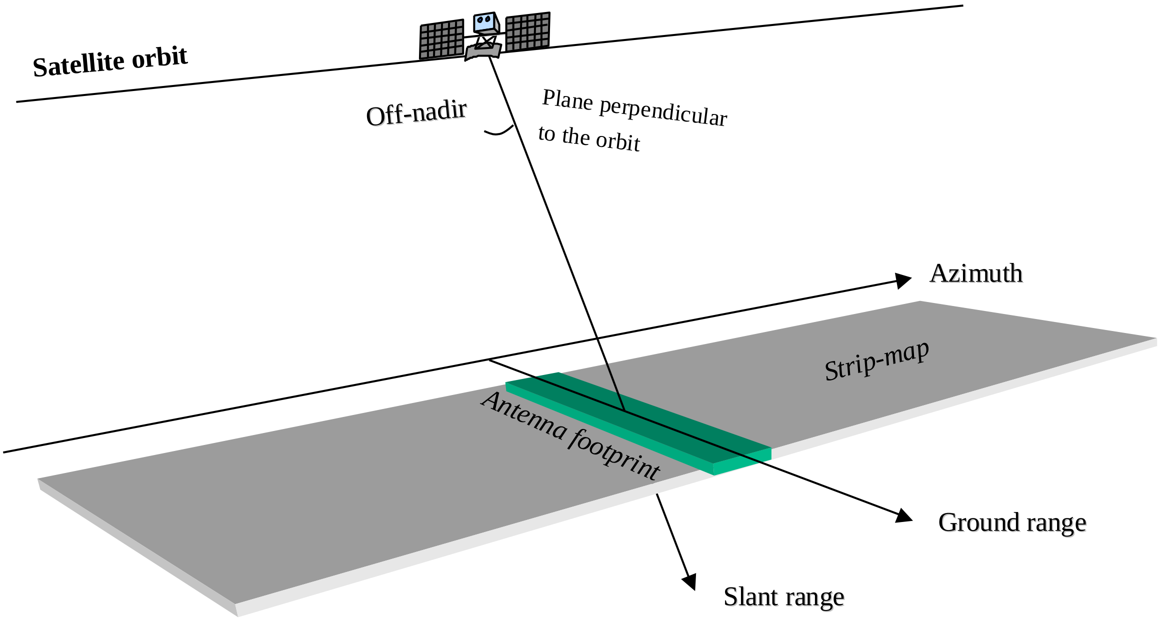

Figure 9: Schematic layout of SAR acquisition geometry

PSs correspond to objects that exhibit a stable radar return in time and, typically, have a dimension much smaller than the resolution cell. Each PS can be identified by a specific pair of radar coordinates, corresponding to a certain image pixel.

Once the elevation of the PS has been estimated (and this is possible when using a multi-temporal dataset of radar images acquired over the same area of interest with slightly different look angles), the position of the measurement point with respect to an Earth-fixed coordinate system can be easily computed. From radar coordinates (range, azimuth) we can then pass to a “standard positioning” of the PS, using - for instance - the same coordinates used by GPS stations (i.e. latitude, longitude, ellipsoidal height). To this end, it is essential to know very accurately the acquisition geometry and the “state vectors” of the satellite platform (i.e. satellite position and velocity at any time. As a rule of thumb, apart from possible systematic errors, geo-coding accuracy of a PS identified in ERS data-stacks can be better than 5m [R3]. Of course, better figures can be achieved with the new generation of SAR sensors providing data at a much higher spatial resolution then the ERS missions (e.g. RADARSAT-2, TerraSAR-X and Cosmo SkyMed).

4.6: Atmospheric disturbance on radar images

As already mentioned phase information is related to the delay of the return echo and is a proxy of the sensor-to-target distance. Phase information is then the key-factor in detecting possible range displacements of a radar target on the terrain (this is the basic idea of any interferometric approach). In multi-temporal data-sets, the radiation travel path can be severely affected by different atmospheric conditions at the time of the radar acquisitions (refraction). In particular, atmospheric humidity, temperature and pressure values have an impact on any procedure aimed at detecting and monitoring possible surface deformation phenomena. This impact is usually confined to within a +/-3cm range variation of the estimated values of the sensor-to-target distance and, typically, exhibits a smooth spatial variability, since its "correlation length" *L* ranges from a few hundred meters to a few kilometres [R[3]]. A precise definition of correlation length is beyond the scope of this manual; it should suffice to say here that two radar targets separated by less than *L* are affected by "similar" atmospheric effects, hardly impacting the estimation of their *relative* positioning.

As an example, the atmospheric phase contribution to an ERS interferogram generated on the Pianura Padana (Northern Italy) is shown in
Figure *10*. Since this interferogram shows the phase variation between two radar images acquired along two almost identical satellite tracks, a constant phase contribution was expected in the central (flat) area, corresponding to no anticipated ground deformation. Contrary to expectations, a phase modulation is clearly visible in the interferogram and is actually due to the differential atmospheric contribution generated by different tropospheric conditions at the time of the two radar acquisitions.

It should be noted that, since the time lapse between two consecutive radar acquisitions from the same nominal orbit always exceeds 1-2 weeks, tropospheric and ionospheric conditions can be very different from one acquisition to the next (cloud and water vapour distribution can change in minutes). Therefore, atmospheric disturbances can usually be considered uncorrelated (or even independent) in time: this is a key-element for designing advanced InSAR strategies, and indeed is a strong hypothesis exploited in PSI algorithms, where atmospheric components are estimated and removed from the available dataset, based on the statistical behaviour of the "atmospheric phase screen" [R[1]][R[2]][R[3]]. Displacement time-series are usually correlated in *time*, while atmospheric disturbances are *spatially* correlated: this different behaviour allows the SAR practitioner to develop *ad hoc* filtering procedures to enhance data usability.

A PS can exhibit an extremely good "radar signature" (i.e. the PS is a very good "radar target", with a high signal-to-noise ratio), yet displays a "poor" time-series, severely affected by atmospheric effects due, for example, to microclimatic influences, such as local topography, vegetation, average humidity, etc. In other words, a PS can be "coherent", but not suitable for surface deformation monitoring, because of the challenges, under certain conditions, in detecting and removing the atmospheric components superimposed on the signal of interest (i.e. displacement time series). An example can perhaps illustrate this point: installing a few artificial reflectors (having, by definition, a good and stable radar return) over a certain site to create "good" measurement points can be rendered useless if the typical correlation length of the atmospheric components affecting the radar data is larger than the average distance between the reflectors, making it impossible to exploit the statistical behaviour of the atmospheric disturbance.

The effectiveness of the filtering procedure depends on many factors, such as the local PS density i.e. the average distance between two nearby measurement points, the temporal distribution of the acquisitions (any significant time gap in data continuity can compromise the filtering), the radar cross section of the PS (the lower the RCS, the higher the noise level), and the presence of abrupt changes in the displacement time-series (the signal of interest is often considered as varying slowly in time). A

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[1] A. Ferretti, C. Prati, F. Rocca, "Permanent Scatterers in SAR Interferometry" - IEEE Trans. on Geoscience and Remote Sensing, Vol. 39, no. 1, January 2001.

[2] C. Colesanti, A. Ferretti, C. Prati, F. Rocca, "Monitoring Landslides and Tectonic Motion with the Permanent Scatterers Technique", Engineering Geology, Vol. 68/1-2, February 2003.

[3] R. Hanssen, *Radar Interferometry – Data Interpretation and Error Analysis*, Kluwer Academic Publishers, Dordrecht, The Netherlands, 2001.

detailed description of the algorithms in use is beyond the scope of this manual and the reader should refer to [R1][R2][R4].

Finally, the separation of motion and atmospheric effects within phase data is still an active research area. In the future, better algorithms, exploiting the always increasing computational power of computing hardware, as well as the new features of the most recent satellite sensors, will allow an increasingly effective extraction of the signal of interest, although the number of radar images available and the average PS density within an area of interest will remain the two key factors for the success of any filtering procedure.

Figure 10: An example of atmospheric phase contribution to the ERS interferogram generated on the Pianura Padana. The imaged area is about 100x100 km. Every pixel exhibits a certain phase variation. Data are in radians, ranging from 0 to 2pi. One phase cycle corresponds to about 3cm of travel path variation.

4.7: Systematic errors and "low frequency" components

In the previous section we mentioned how the estimation and removal of atmospheric components is a key issue in PSI, since these disturbances can compromise the measurements of the displacement values of the PS identified in a certain area of interest. Rather than entering the technicalities of the filtering procedures, it is important to recall here that - no matter the complexity and the quality of the filtering procedure – the displacement information obtained from PS data will always be affected by an "atmospheric leakage" exhibiting statistical features (such as the correlation length) similar to the original atmospheric components affecting the dataset.

A golden rule to bear in mind while working on PS datasets is that *the smaller the distance between two measurement points, the better is the accuracy of their relative motion*. This is somewhat similar to what happens in conventional geodetic networks as well as in differential GPS surveys, although in PSI this feature can often become the most significant factor in any error budget. Low frequency components, characterising the result at low scales, can hardly be very accurate, also because, apart from atmospheric and ionospheric components, any uncertainty in the description of the acquisition

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[4] B. Kampes, *Radar Interferometry – Persistent Scatterer Technique*, Kluwer Academic Publishers, Dordrecht,The Netherlands, 2006.

geometry (e.g. errors in the satellite state vectors) can create spurious low frequency components on the PS displacement fields.

It should be noted, however, that PS data can be “calibrated” using possible prior information, using, for instance, 3-4 permanent GPS stations, available within the area of interest, to remove spurious trends in PS regional analyses over thousands of square kilometres [R[3] - page 22], [R[4] - page 23]. Moreover, while this kind of error does have an impact in tectonics studies, it has hardly any impact in other applications such as the spotting of unstable areas or the stability assessment of individual structures.

4.8: Data Sources

The data required for the Terrafirma service are available from a variety of satellite SAR sensors. In the past the sensors (ERS-1, ERS2, JERS-1) were operated exclusively or at least for the majority of the time in a single mode, which was suited to interferometry. As a result significant archives of repeat observations that are essential for interferometry were acquired. More recent sensors on the other hand can be operated in many different modes. The existence of a significant time-series of repeat observations therefore depends on the mission strategy and other factors such as spatial resolution. In the case of highly flexible sensors with high spatial resolution modes such as TerraSAR-X, Cosmo-SkyMed and Radarsat-2 the building of a systematic archive with many repeat observations is not easily possible and at present not foreseen. Programming of acquisitions over an area of interest is therefore necessary to ensure adequate data exists over a given site. Acknowledging this problem for interferometry, the operation strategy of ENVISAT ASAR and ALOS PALSAR was adapted such that a few main operation modes were selected to build up more consistent archives for these main modes. In the case of ENVISAT ASAR the main mode used is IS2 VV-polarization, which corresponds closely to the mode of ERS-1/2. Sentinel-1, due to be launched in 2012, will focus again on building up consistent archives with many repeat observations.

Apart from building archives, the revisit time (temporal resolution) is relevant. Short revisit times permit monitoring of faster deformation. While most of the work done in Terrafirma so far has employed C-band data with 35 days revisit time, significantly shorter intervals are possible with some of the newer sensors. TerraSAR-X is operated in an 11-day repeat orbit, and since Cosmo-SkyMed uses multiple satellites even shorter intervals are possible. Nevertheless, good temporal coverage is only achieved for a very small fraction of the total area, namely if acquisitions were programmed. Sentinel-1 the future C-Band radar mission planned by ESA for launch in 2012 will provide more complete acquisitions with 12 day intervals.

4.9: Comparison with existing survey techniques

The monitoring of ground deformation and the motion of buildings thereon, can be accomplished by several types of technique, including geodetic methods, such as leveling, theodolite and total station surveying, GPS-based systems, photogrammetric methods, as well as a plethora of specific tools, like inclinometers, extensometers and creep-meter. These techniques have different characteristics in terms of precision, reliability, cost, automation and real-time capability. In general, the most precise techniques require expensive instruments or time consuming and labour-intensive procedures. Furthermore, even if some techniques offer highly automated solutions, e.g. the continuous GPS-based deformation monitoring of structures, they can usually only be used to measure a limited number of points or cover relatively small areas. PSI represents a particular type of monitoring tool, which can be competitive in different ground deformation applications. In fact, PSI offers the typical advantages of all remote sensing techniques, such as data acquisition over inaccessible areas, wide area coverage, periodic and low-cost data acquisition, while, at the same time, it can potentially monitor deformations at millimeter level of the Earth's surface, buildings and structures. The potential reduction in the amount of ground-based observation by using PSI has several beneficial consequences: targeted and simplified logistics operations, reduced network maintenance costs, personnel time and cost savings, the ability to work in insecure, hostile, remote or inaccessible environments.

4.9.1: <u>What is the difference between PSI and GPS?</u>

PSI measures terrain-motion along the Line-Of-Sight (LOS) of the satellite and is more sensitive to vertical motions than to motions in the horizontal direction. The sensitivity is further reduced for horizontal motions in the north to south (azimuth) direction due to the satellite orbit geometry. By contrast, GPS has less sensitivity to vertical motions than horizontal, and can measure horizontal displacements which are hardly detectable by radar. In general, it is difficult to compare the precision of PSI and GPS, especially because there are different types of GPS techniques, with horizontal precision that ranges from millimetres to meters. Concerning measurement density, a PSI analysis allows surveying at a much higher density. GPS has higher costs because it requires an operator at the area of interest and can not provide historical measurements, unless they are available from previous surveys.

Drawbacks of PSI as compared with GPS measurements are the fact that the current SAR systems provide a limited sampling frequency (temporal resolution), related to orbital periodicity, while GPS networks have continuous observation capabilities. On the other hand, classical GPS networks are usually surveyed with a time frequency that is lower than one campaign per month. A disadvantage to PSI is that scatterers (measurement points) are distributed spatially in an opportunistic manner depending on the characteristics of the terrain. By contrast, GPS and all other *in situ* measurement techniques provide measurements over strategically located, well identified points. It is possible to remove the opportunistic element of PSI measurements if corner reflectors are used, a corner reflector being a metal trihedral structure installed and aligned in a location where the PSI point is required. Obviously there can be no historical time-series data generated before the reflector was installed.

4.9.2: <u>What is the difference between PSI and optical levelling?</u>

Optical levelling data can be extremely accurate in the vertical direction (up to a fraction of millimetre), but errors are integrated while more and more measurements are carried out. Thus the final accuracy strongly depends on the number of benchmarks, their reciprocal distances, and often on the logistical conditions of the surveying campaign. Moreover 3-4 people are necessary for accurate optical levelling surveys.

Optical levelling data are much more precise in vertical direction with respect to GPS surveys, but small horizontal displacements of the benchmarks are usually not measured. In any case, it is easy to compare PSI and optical surveying in a GIS environment, possibly supposing that target motion is merely vertical. On the other hand, whenever deformation data are not full 3D, it will not be possible to complete a quantitative and rigorous analysis.

4.9.3: PSI integration with GPS

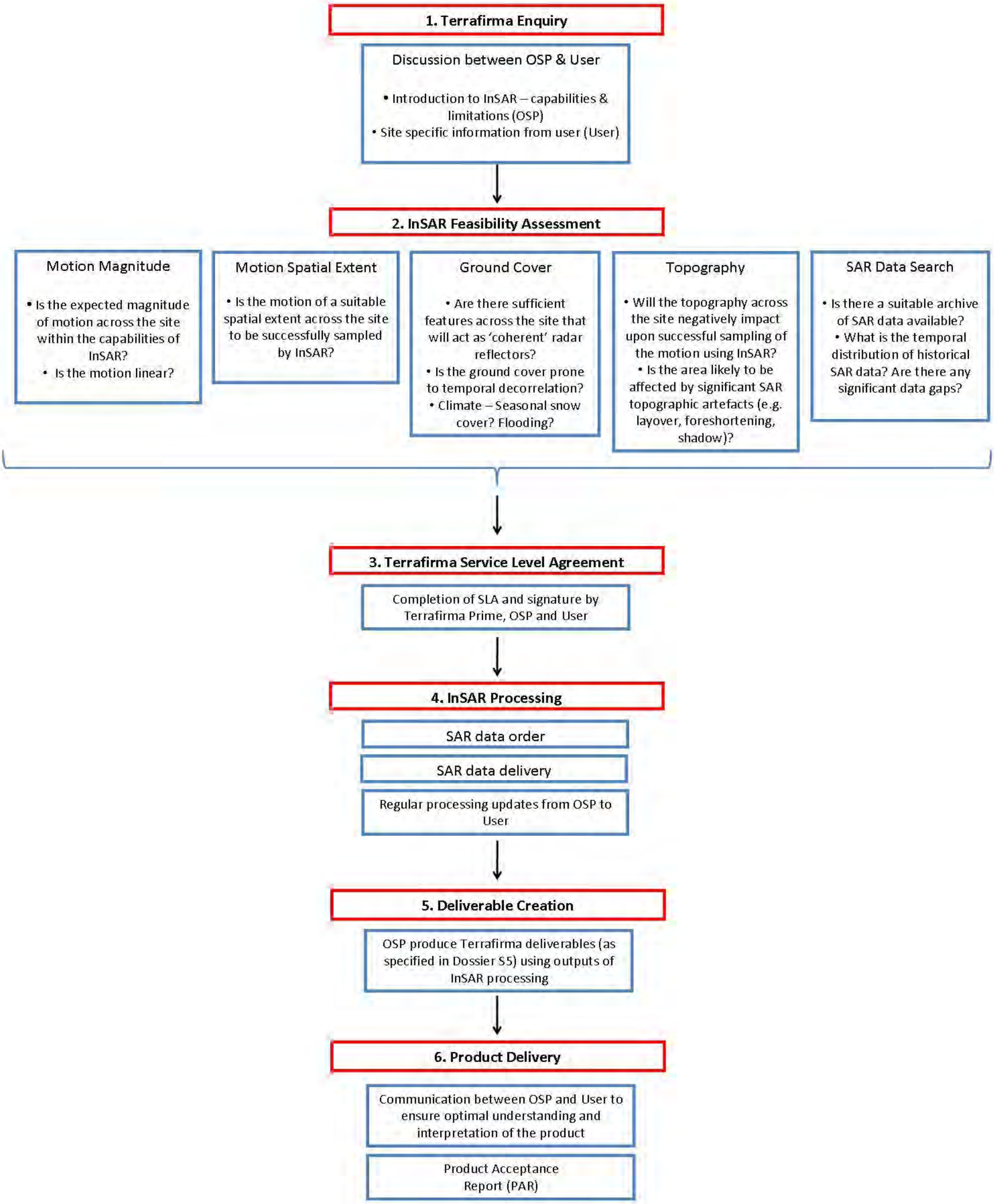
The integration of PSI and GPS measurements creates a dataset which overcomes the disadvantages of a sole GPS or PSI survey. PSI measurements provide a means of validating the GPS station network. Individual GPS stations maybe affected by local motions, such as those brought about by water abstraction. Motions such as these could falsely bias the GPS network interpretations. PSI would fill in the gaps between the GPS network, which correspondingly does not need to be dense.

PSI measurements are relative, integration with GPS measurements makes all the PSI measurements absolute. PSI data can then be used to make true geodetic measurements. Through the integration GPS measurements, which are largely only accurate in the horizontal domain, can be used to de-correlate the line-of-sight measurements of the PSI to provide virtual 3D components.

In summary, the advantages of integrating PSI with GPS are as follows:

- The integrity of the GPS-station network can be validated, e.g. there might be local motions affecting individual stations because of, say, water abstraction, which could falsely bias the GPS network interpretations.
- Many of the gaps can be filled in between the GPS network, which correspondingly does not need to be dense.
- The GPS measurements can be used to make the PSI measurements absolute for true geodetic measurements.
- GPS measurements, which are largely only accurate in the *xy* domain, can be used to de-correlate the line-of-site measurements of PSI to provide virtual 3D components.

5: THE TERRAFRIMA ORDERING PROCESS



1. Terrafirma Enquiry

Discussion between OSP & User

- Introduction to InSAR – capabilities & limitations (OSP)
- Site specific information from user (User)

2. InSAR Feasibility Assessment

Motion Magnitude

- Is the expected magnitude of motion across the site within the capabilities of InSAR?
- Is the motion linear?

Motion Spatial Extent

- Is the motion of a suitable spatial extent across the site to be successfully sampled by InSAR?

Ground Cover

- Are there sufficient features across the site that will act as 'coherent' radar reflectors?
- Is the ground cover prone to temporal decorrelation?
- Climate – Seasonal snow cover? Flooding?

Topography

- Will the topography across the site negatively impact upon successful sampling of the motion using InSAR?
- Is the area likely to be affected by significant SAR topographic artefacts (e.g. layover, foreshortening, shadow)?

SAR Data Search

- Is there a suitable archive of SAR data available?
- What is the temporal distribution of historical SAR data? Are there any significant data gaps?

3. Terrafirma Service Level Agreement

Completion of SLA and signature by Terrafirma Prime, OSP and User

4. InSAR Processing

SAR data order

SAR data delivery

Regular processing updates from OSP to User

5. Deliverable Creation

OSP produce Terrafirma deliverables (as specified in Dossier S5) using outputs of InSAR processing

6. Product Delivery

Communication between OSP and User to ensure optimal understanding and interpretation of the product

Product Acceptance Report (PAR)

5.2: Topography

It is difficult to apply PSI in mountainous areas due to the effects of foreshortening, layover and shadowing, these being inherent limitations of side-looking radar systems. These limitations are discussed more in section 8.5:

5.3: Landcover

The service provider can broadly advise a customer if PSI processing is likely to result in a satisfactory number of PS points. This takes into account the land cover, slope inclination and the orientation of the study area in relation to the satellite orbit.

5.4: Motion characteristics

Prior to processing there is a need to understand the probable mechanisms and characteristics of the ground deformation in the proposed study area. Information is needed on the linearity and the likely speed of the expected motion. Advice may be required from an expert such as a geologist who understands the area.

During PSI processing a linear model is used, however if motion is significantly non-linear there is a danger of loosing some motion signals during processing (**Figure 12**). Prior information on the expected type of motion enables the OSP to apply the most suitable model for the area in question.

Large motions between subsequent image dates can cause problems for PSI, more information can be found in section 8.3: It is only possible to resolve certain amounts in the change of position of a PS point between subsequent images, the amount relates to both the operating frequency of the radar system and temporal resolution of the radar dataset used. Knowledge of the likely motion rates therefore allows the service provider to select the most suitable radar system.

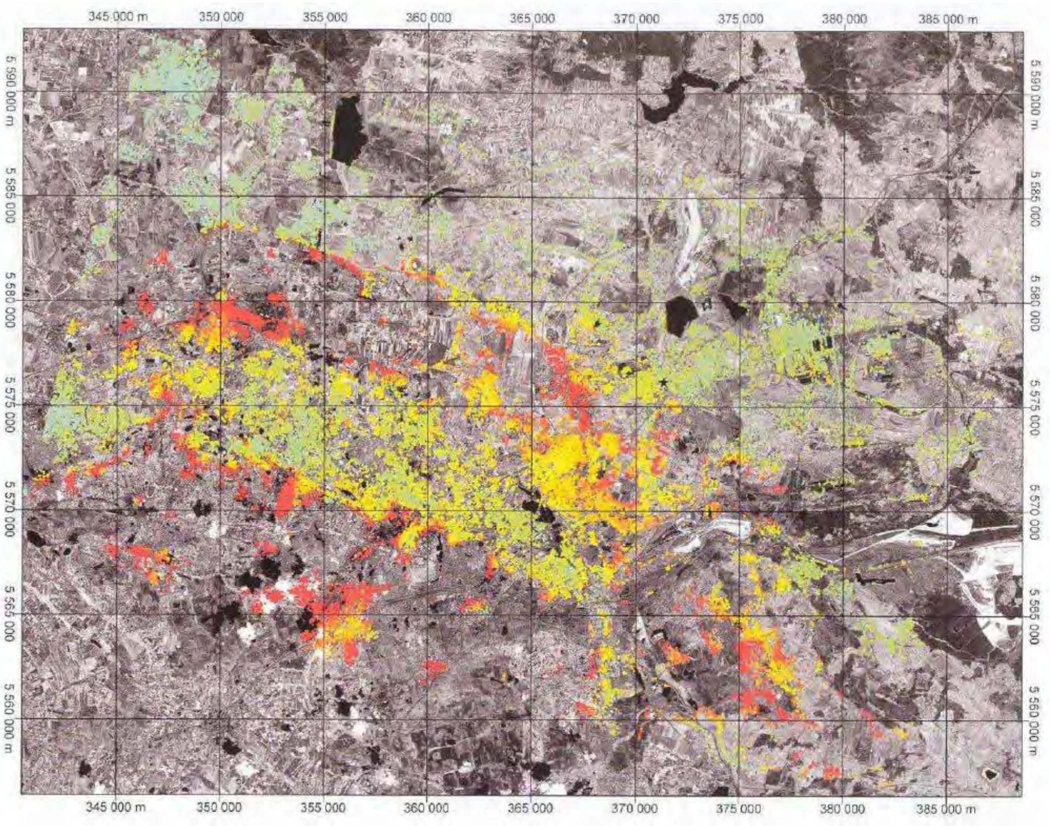


Figure 12: Example of a Terrafirma product over Sosnowiec, Poland. This area was processed with a linear model; however the deformation in the area is governed by non-linear rapid undermining-related motions. This has led to holes in the PS coverage.

5.5: Data Processing

5.5.1: Inputs to the Terrafirma product

The following datasets are generally used as inputs for the manufacture of PSI products. Note, the quality of the available groundtruth can affect the quality of the end result.

Dataset	Notes
ERS SAR / ENVISAT ASAR data	Descending or ascending data modes
Topographic map / Digital Elevation Model	A DEM is not obligatory for PS techniques. However use of a 3 arc second or better resolution DEM is encouraged.
Satellite state vectors	Either from Delft University or from DLR
Reference map or high resolution optical satellite data (for georeference purposes).	Output product georeference dependent on quality of reference data. The end-user should supply high-resolution reference data. If none is available then Landsat ETM/TM or Google Earth data will be used by default.
Ground-truth information regarding stable regions for reference point location.	Aids the calibration of the PSI measurements.

5.5.1.1: Master image

Analyses can use a single or multiple master images against which all displacement measurements are relative. In the case of a single master image, it should be chosen to be as temporally central as possible within the spread of all the image dates within the dataset defining the epoch of interest, and also spatially central so that the spread of satellite baselines is minimised. In addition, master images should only be used if the prevailing weather conditions at the time of acquisition were good, as severe weather, (e.g. snow or storms) can not only affect the refractive properties of the atmosphere through which the satellite signal travels giving rise to possible phase ambiguity, but can also obliterate scatterers that might otherwise „persist" throughout the rest of the dataset.

5.5.1.2: Reference point

The reference point is the point within the study area against which all ground velocity and height measurements are relative. As such, it is desirable that the reference point is itself not moving over time. Verification and validation of the stability of the reference point should always be sought and considered during the feasibility assessment before processing begins, and any issues relating to it should be detailed in the corresponding Processing Report. Following processing it might be found that a reference point is not stable, in that the rest of data is <u>all</u> showing an apparent motion. In this case a simple „shift" factor should be introduced into the data to account for the offset introduced by the moving reference point.

5.5.1.3: Coherence

PS points are identified by an analysis of each pixel"s response in every scene throughout the entire dataset. The velocity measurements are retrieved starting from the initial interferometric observations and separating the deformation component from the atmospheric, orbital, residual topographic and noise-phase components. Not all PSs and their measured displacements are of the same quality. A <u>key</u> quality indicator of the velocity measurements is the PSs" *coherence*. This quality index indicates the "degree-of-fit to the linear model" of the initial interferometric observations. Points with high coherence will show good correlation to the linear motion rate. Points with low coherence will exhibit greater deviation from a linear motion rate – this can be due to higher noise levels or due to some degree of non-linear behaviour, such as the more sudden motions associated with mining collapse. It is worth emphasising that this index does not inform on the quality of the deformation time series. Using appropriate quality indices is fundamental to properly exploit the full potential of the PS measurements. In order to improve the PS measurement exploitation in Terrafirma, new quality indices are currently under development.

5.5.2: <u>The number of PSs and their quality</u>

During processing, criteria have to be applied in order to select the PS points. Decisions made at this stage can influence the number and distribution of PSs found. PSs are selected based on their persistence throughout all the data used and their coherence value i.e. how stable the backscattered signal is from a feature for all scenes (se above). PSs are discarded if their value is below a certain threshold coherence value. The choice of threshold value will therefore affect the number of PS points found by the algorithm. The OSP will make a decision at what value to reject points, and this has implications not only for the density and distribution of PSs, but also for their quality (reliability). Preferably such decisions on thresh-holding should be made in consultation with the end-user and their aims: does the user want more but lower quality PSs or less PSs but of higher quality? There is no right answer – it is application-dependent.

It may be possible to increase the number of PS points found by processing only a subset of all available images belonging to a certain time period. A drawback is that working over a shorter time period decreases the precision with which PS displacements are measured and of course limits the measurements to the time period analysed.

5.6: Terrafirma outputs

Currently there are seven outputs that the user will receive when a PSI study is commissioned:

1. Database of PSI average annual displacement rates.
2. Image of PSI average annual displacement rates.
3. Database of PSI time-series.
4. Reference point location.
5. Processing report (metadata).
6. Background reference image.
7. Quality control sign-off.

All products are received in a UTM, WGS84 projection with the relevant UTM zone as standard; a local projection system can be specified.

The seven outputs are further detailed in the following sections:

5.6.1: Database of PSI average annual displacement rates

A database that provides an average displacement rate in millimetres per year for each PS point in the study area; these data can be displayed to allow a quick assessment of which areas are undergoing motion (**Figure 13**).

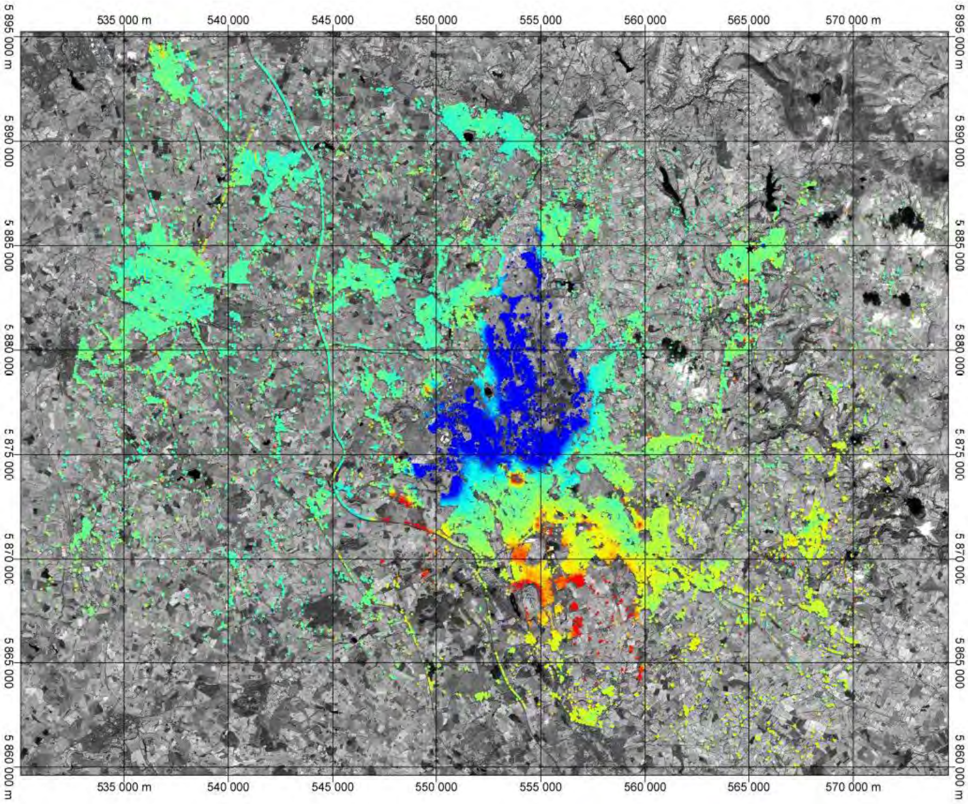


Figure 13: Average annual displacement rates colour coded and displayed on a Landsat backdrop for the Stoke-on-Trent region in the UK. Blue areas indicate motion towards the satellite and red indicates motion away from the satellite.

5.6.2: <u>Database of PSI time-series</u>

Time-series data give the *xy* position of the PS point in UTM and radar coordinates, the average annual displacement rate and the displacement position of the point (in relation to the master image (section 4:) for each radar date processed. These point positions can be graphed to give a motion history for the point (**Figure 15**).

5.6.3: <u>Reference Point Table</u>

This is the position of the reference point, a point within the processing area, which is presumed to be stable; all PS measurements are relative to this point.

5.6.4: <u>Processing Report (metadata)</u>

The Processing Report provides the user with the statistics relevant to the site processed. The Processing Report gives a number of quantitative and some qualitative information regarding all PSI products delivered. It aims to provide the user with site-specific information, e.g. number of scenes used, date range of analysis, basic ground motion statistics, etc.

Process Date			
Software used			
Version			
Number of scenes used			
Date range of analysis			
Satellite data used			
Master Scene Date			
Georeference (X,Y) accuracy			
Reference data used for georeference			
Projection system used			
Reference point location			
Area of results			
Interferograms used for analysis			
Master Date	Slave Date	Bperp	Temporal Separation
....	....	....	....
Number of PS identified			
PS density (PS/km^2)			
Point motion statistics (mm/year classes)		% of points in each mm/year class	
-max to -3.5			
-3.5 to -1.5			
-1.5 to +1.5			
+1.5 to +3.5			
+3.5 to +max			
Average annual motion rate of the entire processed area			
Standard deviation of average annual motion rate			
Observations			
Uncompensated atmospherics			
Visible tilt or phase trends in motion map			
Are there any regions not covered by InSAR results? If so, where and why?		Lack of scatterers/coherence Suspected significantly non-linear motion Suspected high motion rates (above 4.5 cm/year)	

Table 2. Example of PSI processing report containing metadata.

5.6.5: Background Reference Image

An image generated from the radar data used for the PSI processing can be used as a background image for visualisation. This may be the Landsat ETM+ / TM data used within the geocoding of the PSI data or multi-image reflectivity image (MIR) produced from the individual SAR amplitude images processed as part of the PSI analysis process. The background reference image is provided as a GeoTIFF raster.

5.6.6: Raster of interpolated average annual displacement rates

This data layer is produced using the average annual displacement rate field of the PS table, and is useful for gaining an initial understanding as to the nature of the result. The interpolation method employed minimises the distance to 50m over which the PS results are extrapolated. The PS average annual displacement rate is interpolated using a surface-fitting algorithm to produce a displacement rate map of the study area. The interpolation is carried out using a minimum curvature, surface-fitting algorithm for a distance up to 50m from any one PS point. Null cells are inserted in areas that are further than 50m from a PS point. This image is used primarily for visualisation purposes as the pixel values contain only an RGB colour value. An accompanying legend object is provided for reference. This image is provided as a GeoTIFF – a raster image with internal tags holding information on the geo-location of the image.

5.6.7: Quality Control sign-off

Each service provider is applying their own, acknowledged quality control procedure. Proof of quality control is provided to the Recipient by way of a copy of the corresponding quality control document, fully signed by the OSP, accompanying the finished processing.

6: ACCURACY OF THE TERRAFIRMA PRODUCT

6.1: Terrafirma Validation Project

The Terrafirma Validation Project conducted an inter-comparison of the radar geometry outputs of each OSP and validated the geocoded PSI products against ground truth. These validations were carried out for two areas in the Netherlands: Alkmaar is a rural area which includes spatially correlated deformation fields due to gas extraction where levelling data are available. The Amsterdam area includes autonomous and mainly spatially uncorrelated motions. It covers the area of the future north-south metro line, where ground-truth data coming from different topographic tools are available.

6.1.1: Inter-comparison results

A direct comparison of the radar geometry outputs of the terrain-motion velocities, time-series, PS density and topographic corrections gave the following precisions:

1. Estimated standard deviation of the terrain-motion velocity was 0.40 – 0.53 mm/yr.
2. Estimated standard deviation of the terrain-motion time-series was 1.1 – 4.0 mm.
3. The standard deviation of the “topographic correction” was 2.14 – 4.71m.

6.1.2: Validation results

The validation of velocities by comparison with tachymeters (any of several instruments for rapidly determining distances, directions, and differences of elevation) in Amsterdam shows an absolute standard deviation of the double difference of **1.0 – 1.2 mm/yr**. While the time-series validation for Amsterdam shows that the average RMS errors of single deformation measurements range from **4.2 to 5.5 mm.**

In the spatially correlated deformation seen over the Alkmaar gas fields of the Netherlands, validation against levelling shows the RMS error for velocity measurements range from **1.0 – 1.8 mm/yr**. Time-series have an RMS error based on double differences (differences between PSI and levelling, and between measurement epochs) ranging from **6.2 – 8.7 mm for ERS, and 3.6 – 4.8 mm for Envisat.**

More information on the Terrafirma validation project can be found at:

http://www.terrafirma.eu.com/Terrafirma_validation.htm

7: USING TERRAFIRMA DATA

The raster of interpolated (section 5.6.6) average annual terrain-motion provides a rapid means of understanding the location and magnitude of any terrain-motions. Examination of the image will direct the course of any subsequent analysis. The GeoTifff raster can be viewed in any image viewing software and printed out at various sizes, while the georeferencing allows quick comparison with other spatial data. The image can be displayed over a background reference image to understand the contextual location of any motions (**Figure 14**).

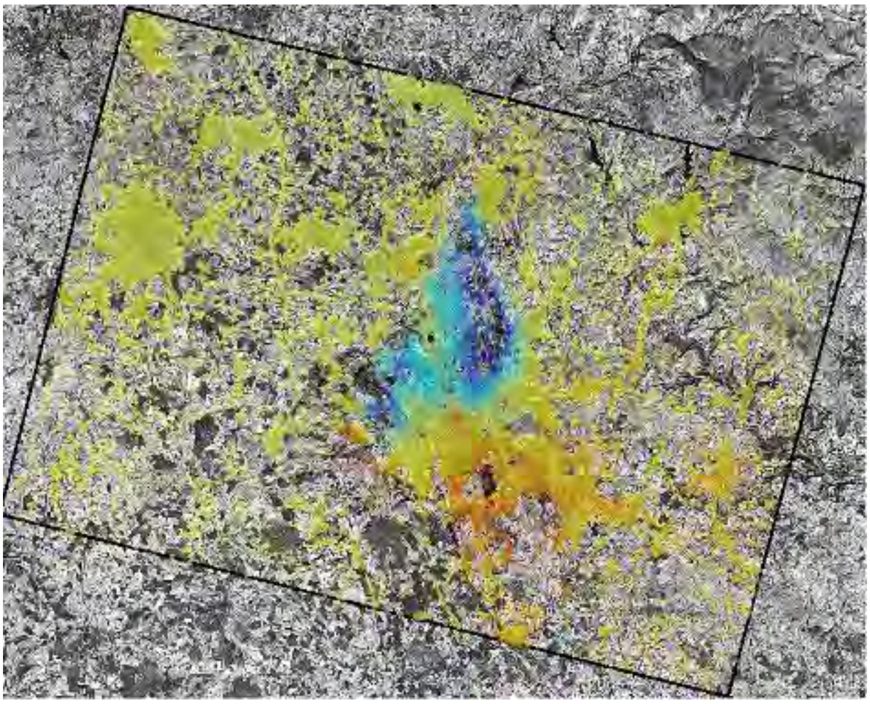


Figure 14: Example of the interpolated average annual motion rate image for Stoke-on-Trent in the UK superimposed over a georeferenced background image (Landsat band 5).

7.1: Geographic Information Systems

Since the raster is a product of interpolation with each PS influencing a 50m area, the raster cannot be used to accurately study the location of a PS point. This can be accomplished by displaying the point data, held in the database file, in a Geographical Information System (GIS). The GIS environment enables PS points to be visualised in relation to other spatially referenced data, for example aerial photography.

The real strength of a GIS is the power to display any spatial data and to interrogate the properties of all the data to start building up relationships between datasets to aid with interpretation. Data which can be displayed along with the PS data can range from simple spatial data such as topographical maps, to data which may provide a reason for the observed motion, examples below:

- Digital Elevation/Terrain Model
- 2D geology
- 3D geology
- Lithology
- Superficial thickness
- Mineralogical properties
- Quarries and underground works
- Geotechnical properties
- Water table
- Borehole data
- Soil moisture deficit/rainfall
- Spring lines
- Extraction records
- Well locations
- Drainage patterns
- Hydrogeological properties
- Demographics
- Mining maps
- Critical infrastructure
- Transportation network
- Land use

If the user wishes to interpret the PS data for the underlying causes of any detected terrain-motions then it is important to have access to digital versions of the types of data as listed above.

7.2: Examining PS histories

Once spatial relationships have been identified, the time-series data can be used to examine the terrain-motion history in more detail. PS points can be identified in the GIS, and the underlying motion history data exported. Graphs of the motion through time can be constructed in a spreadsheet utility such as Microsoft Excel. The graphs of motion and date can be used to relate the timing of the motion to timing of possible causal factors. An example of the relationship between the PSI time-series data and other spatial data as displayed in a GIS is shown by **Figure 15**.

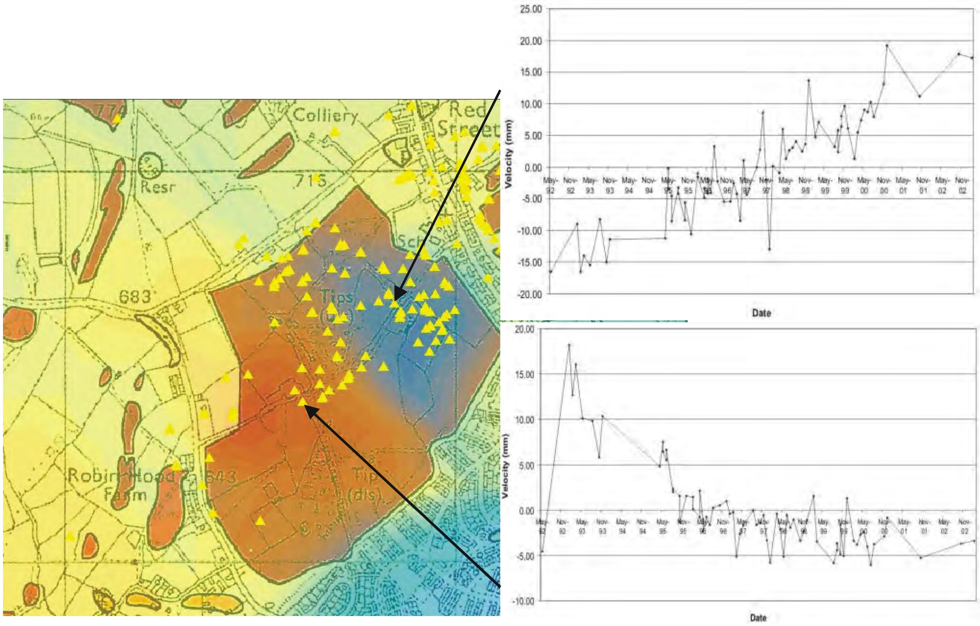


Figure 15. Example of PSI time-series for a landfill site in the Stoke area (UK). This former opencast coal mine was backfilled at two different times. The orange polygon shows the mined area, yellow triangles are PS points with time-series and the blue and red colouring is an interpolated display of the average annual displacement rates. It can be seen that the average annual motion rates show the southwest of the landfill to be subsiding (red) and the northeast to be uplifting (blue). The detail of these motions is seen in the graphs of the time-series.

8: LIMITATIONS OF PSI

8.1: Data quantities and frequencies

PSI relies on a large number of multi-temporal SAR scenes. For some locations, particularly outside Europe, insufficient data may be available to apply the technique. Furthermore, the satellite mission specifications determine its re-visit interval; for ERS and Envisat, the same place on the ground can only be imaged once every 35 days in each of the satellite‟s operating modes (see section 4.1). For some motion types, such as rapid collapse of mine workings, the frequency of revisit may not be sufficient to accurately monitor the phenomena in question. This limitation can be partially mitigated by using both descending and ascending data (section 4.1). New radar satellite systems such as TerraSAR X and the forthcoming ESA Sentinel missions have much better temporal resolution and will therefore open up new types of terrain-motion phenomena for investigation.

8.2: PS locations

A feature of PSI is that the number and location of persistent scatterers cannot be predicted before processing, as a good 'back-scattering' point depends on the geometry and properties of the target in relation to the satellite. It is therefore impossible to guarantee that a feature of interest will have a PS associated with it. It is also important to recognise that most PSs are back-scattering features *on* the ground (buildings, bare rocks, etc), and do not represent the ground itself. Furthermore, measurements may be the result of so-called 'multi-path' reflections (e.g. from satellite to pavement, to building, to another building, then back to satellite). These attributes of the PSI process should be taken in account, especially when considering the nature of individual or 'spurious' points.

Permanent scatterers represent sub-pixel features. This needs to be remembered when comparing the location of points to high resolution imagery and maps. It can also be difficult to tell to what terrain feature a PS point relates. An example of this is seen in **Figure 16**.

Figure 16. Position of PS points from two processing sources displayed on high resolution imagery. Points on the left appear to be in the correct location, points on the right appear shifted, however this shift is less than the pixel size of a SAR image.

8.3: High displacement rates

The capability of PSI to measure linear motions with high displacement rates is fundamentally limited by the SAR data sampling in time and the fact that the phase is wrapped in the range -π to +π. The temporal phase unwrapping employed cannot resolve ambiguities (which occur when the motion is greater than 14mm between two image acquisitions). Therefore in a site with linear motion the maximum detectable motion is 14mm per minimum differential time span (fraction of year). Even in the best cases (where the minimum separation between images in the dataset used is 35 days and the motion linear) motion rates above 14.8 cm/year cannot be resolved.

8.4: Significantly non-linear motion

The standard PSI process assumes terrain-motion that is largely linear in nature, and the standard algorithms employed may therefore average out non-linear motions. Where significant non-linear motion is suspected (e.g. clay shrink-swell), the algorithm employed may be modified, e.g. through application of polynomial models or a reduction in the coherence threshold. Such phenomena should be fully discussed during the feasibility assessment before any processing begins.

8.5: Steep Slopes

Areas of steep slopes can cause problems for the Terrafirma service since these areas are affected by the common radar limitations of layover, foreshortening and radar shadow. If the areas of interest are located on slopes, an assessment of their visibility can be made during the feasibility assessment.

8.5.1: Shadow

Areas of radar shadow will be present when slopes that face away from the satellite look direction have slope angles above 90° – incidence angle. In the case of Envisat and ERS data commonly used in Terrafirma (with incidence angles in the range 19-26°) slopes with angles 64-71° will be in shadow. Such slopes are seen in a very small percentage of the Earth‟s surface and as such radar shadow will rarely be a problem for Terrafirma sites using ERS/Envisat data. Note that such steep slopes will also not be visible if the alternative viewing geometry is used since they will now be subject to layover.

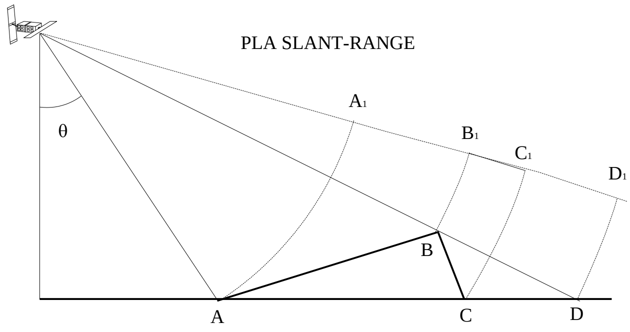


Figure 17: Radar Shadow: The area B-D is in shadow, the region B1-D1 will appear dark in the SAR image. It is not illuminated by the radar since slope B-C is too steep.

8.5.2: Foreshortening

Foreshortening is the narrowing or compression of the slopes facing the radar look direction. The effect of foreshortening intensifies as the slope angle approaches that of the incidence angle. Once the slope angle is greater than the incidence angle the slope produces layover. Typically ERS/Envisat data with incidence angles in the range 19-26° are used for Terrafirma processing. Many slopes will present foreshortening. The effect of foreshortening is to reduce the size of the ground cell as the slope angle increases.

Measurement values are possible but there is an increase in volumetric de-correlation and/or phase aliasing (which is translated into a loss of phase coherence). This is one of the reasons that in hilly areas (in particular for the landslide products) both ascending and descending data are used so that areas which have few usable points due to foreshortening in one geometry can be successfully viewed using the opposing geometry.

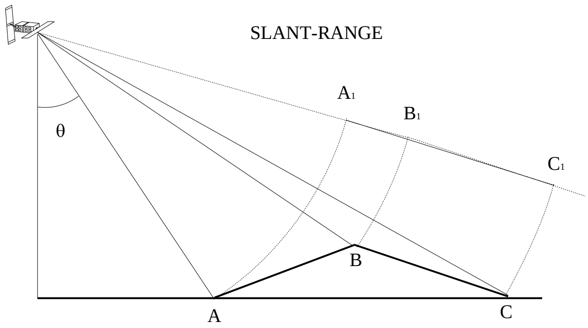


Figure 18: Foreshortening. The slope A-B is compressed into fewer SAR pixels A_1-B_1.

8.5.3: Layover

Layover is the effect of inversion of topography: A mountain peak will be seen inverted onto the foot of the mountain nearer to the satellite. The data from these areas cannot be used for InSAR analysis since a single layover pixel contains a mixture of information from scatterers over a large area. These scatterers are placed at a very different ground position (they have different vertical height, different motion, and different atmospheric condition). The single phase contribution from each of them cannot be recovered since they are placed within the same radar measurement cell. Consequently the phase measured over these pixels does not have any sense. The interferometric coherence is low over these areas. Layover occurs when the slopes facing the satellite present slope angles greater than the incidence angle (i.e. from 19-26° for typical ERS/Envisat datasets). The area affected can be successfully studied using the opposing image geometry (unless it is very steep and produces radar shadowing).

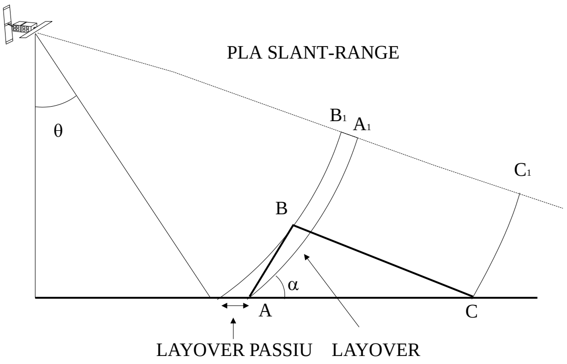


Figure 19: Layover. The slope A-B has slope angle α > incidence angle θ. Therefore the backscatter from B is received before that of the A, resulting in B_1 and A_1 being inverted in the SAR geometry.

8.6: Line of Sight Measurements

Motions can only be measured along the satellite → Earth direction (the satellite line-of-sight, or LOS). This has been discussed in section 4.

8.7: Residual Orbital Trends

Residual orbital trends or „tilts" can be a feature of PSI processing that arises from uncompensated orbital inaccuracies used within the PSI processing chain. They appear as a general tilt from uplift to subsidence across the image of average annual velocities **Figure 20**. These trends can be removed; however, this has implications for any possible low-frequency ground motions (e.g. crustal deformation) which may also be removed. The best course of action is for the user to discuss this with the service provider and make a decision based on the characteristics of the area and the motion type of interest.

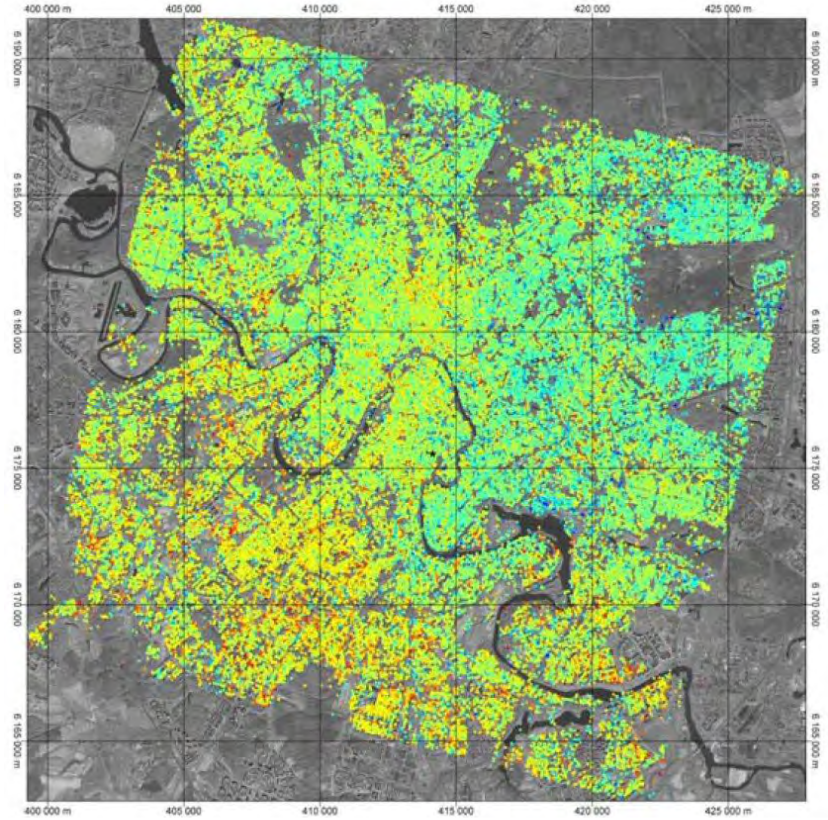


Figure 20. Example of possible tilt effect in a PSI product over Moscow. The tilt can be due to residual processing errors, or to a geophysical signal.

9: CASE STUDIES OF THE APPLICATION OF TERRAFIRMA

9.1: Landslides: Lumnez, Switzerland

9.1.1: Overview

The Lumnez valley, located in the Canton of Grisons, Switzerland (**Figure 21**a), is one of the most active landslide zones in built-up areas of the Swiss territory. The valley has a landslide-affected flank, which is characterised by an active deep-seated roto-translational sliding process. The landslide covers an area of 32 km^2 and affects 8 villages, where more than 2000 people live.

9.1.2: Deformation Analysis

A PSI analysis was performed over the landslide using 68 ascending radar scenes from the ERS and Envisat sensors spanning from 1992 to 2005. In the landslide area, 1,256 PSI points were produced, with higher densities coinciding with the villages. **Figure 21**b shows the results of the analysis, providing the estimated mean velocity of motion along the satellite line-of-sight (LOS). The negative velocities correspond to points moving away from the sensor, approximately from west to east for this study. Positive velocity values, which would correspond to upslope motions, are not present on this slope. Stable areas at the marginal parts of the slope are visible, the middle part of the slope is characterised by a moderate motion, while towards the south there is a zone with high motion.

The estimated velocities represent relative motions with respect to a reference point located outside the sliding area. Considering that the motions of the slope are approximately slope-parallel, the LOS mean motion velocity can be corrected to achieve slope-parallel velocity by multiplying by a conversion factor of about 2.

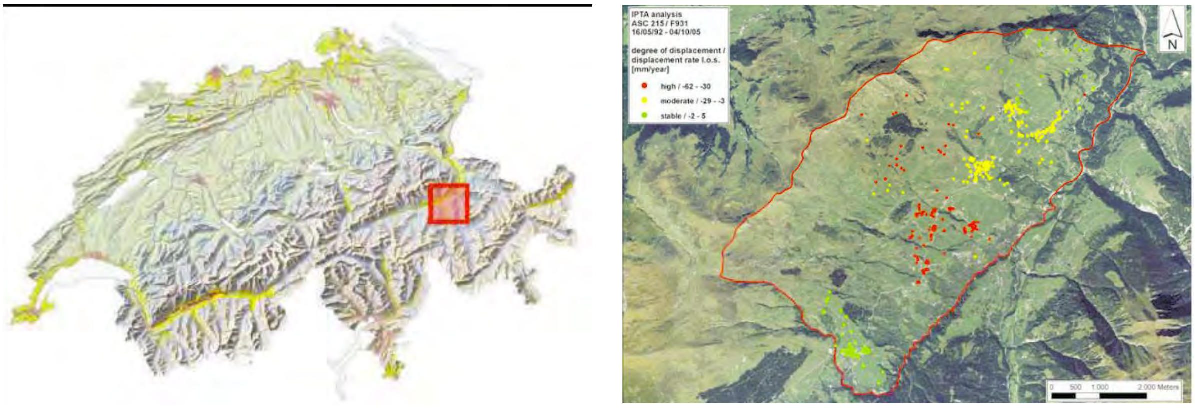


Figure 21: a) The study area. b) Results of the PSI analysis, where the mean velocities of the motion are grouped in three classes: stable, moderate and high deformation areas.

9.1.3: Validation

The PSI results were compared with topographic surveys made in the period 1887-1992 (**Figure 22**). Despite the very short temporal overlap between PSI and topographic data, the agreement between the two datasets is evident. In particular, they show the same spatial pattern of motion. Note that the topographic velocity values refer to the whole period 1887-1992. This explains part of the discrepancies in terms of magnitude of velocities. Besides the comparison, observations carried out in the field showed the effects of the landslide motion on infrastructures and geomorphologic features.

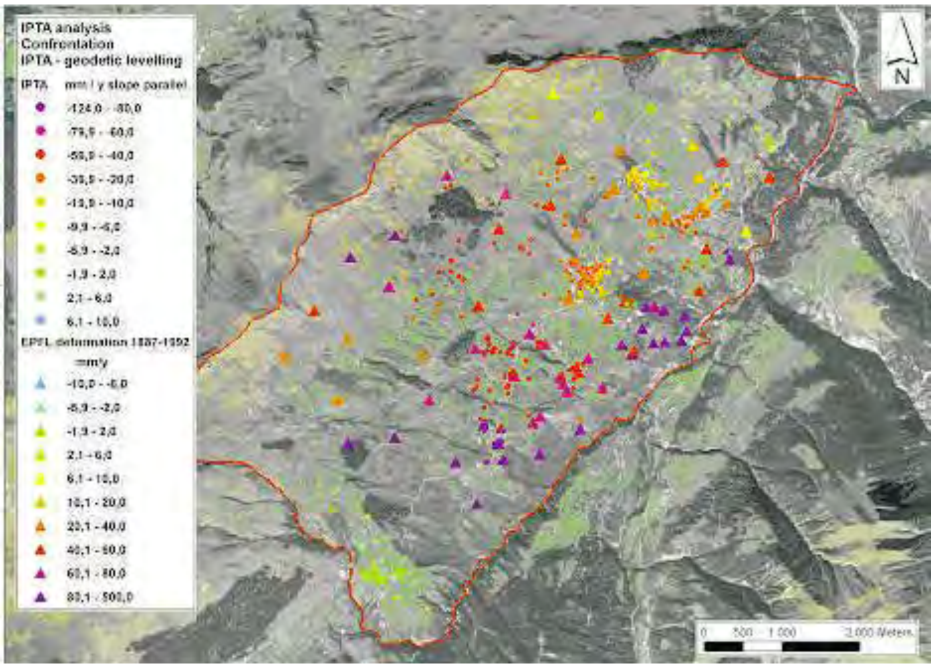


Figure 22: Comparison of the PSI results with those coming from topographic surveys. The legends indicate slope-parallel deformation velocities, and the same colour scale is used for PSI and topographic results.

9.1.4: Interpretation

Following the Swiss landslide classification based on the mass motion velocity, the PSI points were re-classified into three groups: sub-stabilised (slope-parallel velocity < 2 cm/yr), slow (2 – 10 cm/yr) and active (> 10 cm/yr). Such a classification was then employed to estimate the level of landslide intensity for each of the villages affected by the slope motions, which are used for landslide hazard assessment purposes. The PSI measured points were used to derive an improved geomorphologic zonation of the area (**Figure 23**). Besides the information derived from the DEM and aerial images, the PSI results allowed the separation of sectors of the slope characterised by homogeneous morphologic features and state of activity.

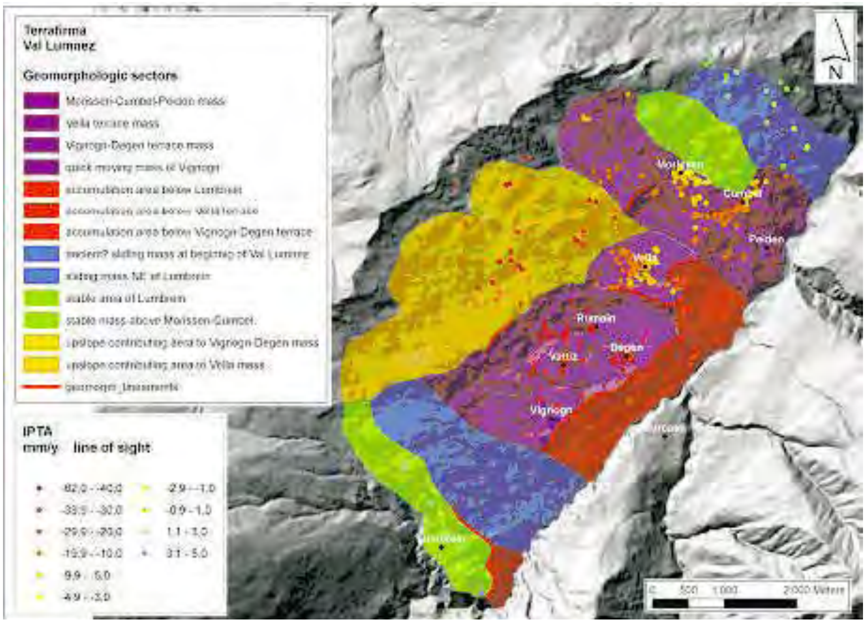


Figure 23: Results of the geomorphologic zonation using the PSI estimates.

9.1.5: Conclusions

The analysis of the landslide provided interesting data related to its activity and the spatial distribution of terrain-motions. The validation of the PSI results against topographic data showed a good agreement between the two datasets. Furthermore, the PSI results are in agreement with the *in situ* observed effects of the landslide motion on infrastructures and geomorphologic features. The motion velocities estimated by PSI were used to estimate the level of slide intensity of the villages included in the landslides, a key input for landslide hazard assessment. Finally, the PSI velocities were used to derive an improved geomorphologic zonation of the area at hand. From this case study, considering the high costs related to landslide activity and the difficulties in the detection of the active, slow and dormant landslides, one may state that the use of PSI can positively impact the current hazard mitigation activities of local authorities.

9.2: MINING CASE STUDY: STOKE-ON-TRENT, UK

9.2.1: Overview

Stoke-on-Trent is part of a large industrial conurbation in the English Midlands (**Figure 24**) that is known for its pottery and china manufacturing. To the NW is the UK's largest halite field where extraction continues today. The area has an extensive history of coal mining, by partial extraction in shallow mines and total extraction in deeper mines as well as opencast workings, and as a result the area has experienced terrain-motion both during the extraction phase and when mine-water levels were allowed to return to normal after abandonment. Even abandoned pits that have been reclaimed and filled by waste material have experienced differential terrain-motion. Industrial heritage combined with ongoing phases of tectonic stressing and de-stressing have resulted in a complex ground motion history for Stoke-on-Trent. As a result, the area is ideal for the application of PSI technology for monitoring terrain-motion.

Figure 24: Stoke-on-Trent study area

9.2.2: Deformation Analysis

PSI data were analysed for a 1,111km^2 area centred on Stoke-on-Trent. 70 radar scenes were used from May 1992 to February 2003. 178,019 points were identified, providing a measure of average terrain-motion velocity over much of the study site (**Figure 25**). Of these points, 68,509 (38.5%) had a full linear velocity history. Negative values of terrain-motion (motion away from the satellite) indicated subsidence, positive values indicated uplift.

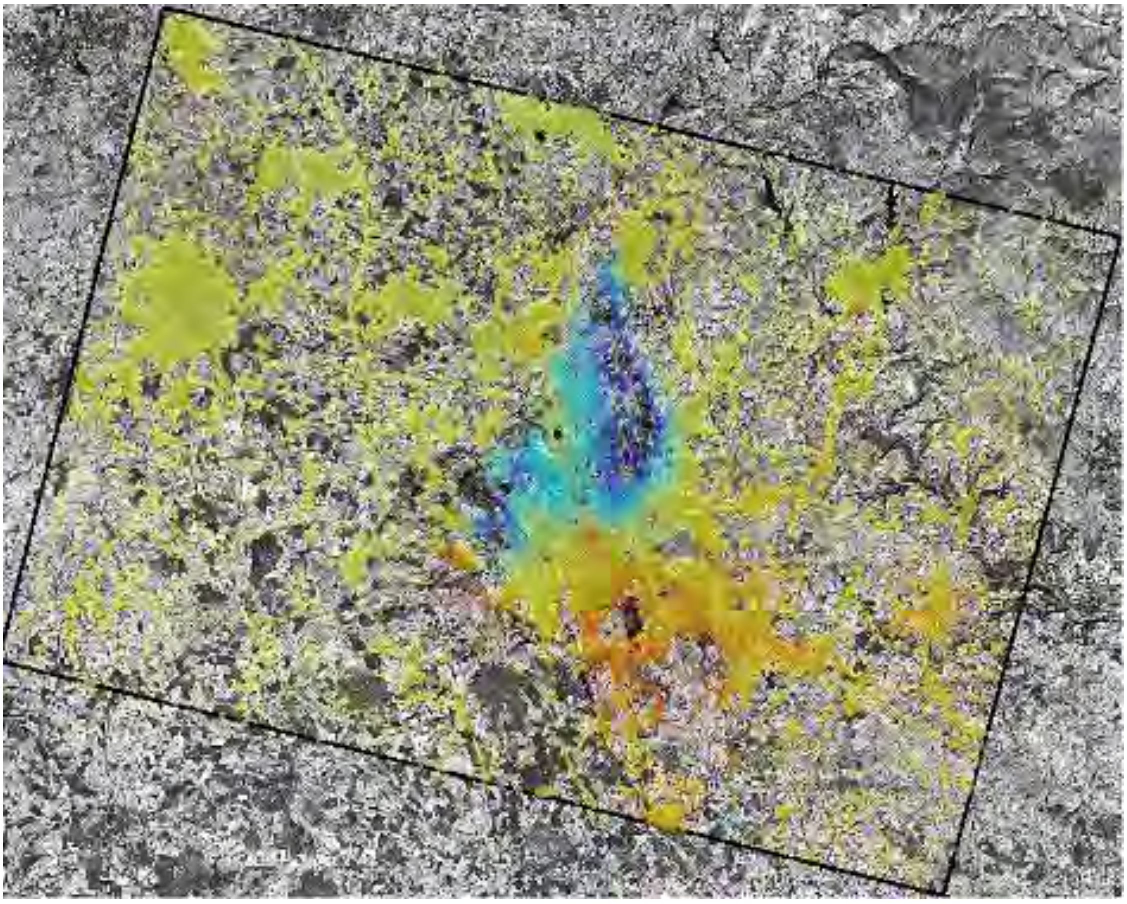


Figure 25: PS average linear velocity (blue is uplift, red is subsidence).

9.2.3: Validation

The average annual velocity was interpolated using an inverted linear distance interpolation algorithm to enhance visualisation. The results show a large area of uplift in the north and areas of subsidence in the south-west and south-east. The average and full history PS values were compared to geo-environmental information from BGS geological maps, OS topographic maps, Intermap's NEXTMap Britain elevation data (**Figure 26**) and BGS-derived geology, geohazard, engineering geology and geophysical data, in order to identify potential causes of the observed ground motion.

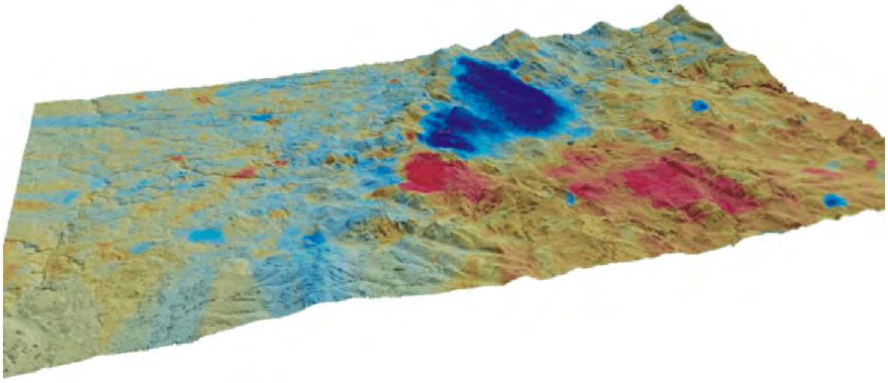


Figure 26: Interpolated points superimposed over NEXTMap elevation data.

9.2.4: Interpretation

Several of the areas that show terrain-motion are fault-bound or heavily fractured. In the north, uplift is observed over older undermined areas suggesting mine closure resulted in ground water recharge and elastic rebound. Uplift also appeared to be associated with in-filled quarries and waste disposal sites, possibly as a result of gas production from the decay of the site materials. In addition, there was good correlation between lower uplift rates and valley alluvium (**Figure 27**). Subsidence in the south showed a strong correlation with an area of recent undermining, although mine collapse and fault reactivation may be an additional cause of subsidence in this area. PSI linear velocity histories extracted at Barlaston suggest PSI data underestimates terrain-motion with 25mm subsidence measured by PSI compared with 130mm measured in the field by Donnelly[1] during the same period. Subsidence also showed a strong correlation with areas associated with salt extraction and dissolution (**Figure 28**, **Figure 28**) and may also be a result of fault reactivation and the self-compaction and artificial loading of compressible valley alluvium [R[5]].

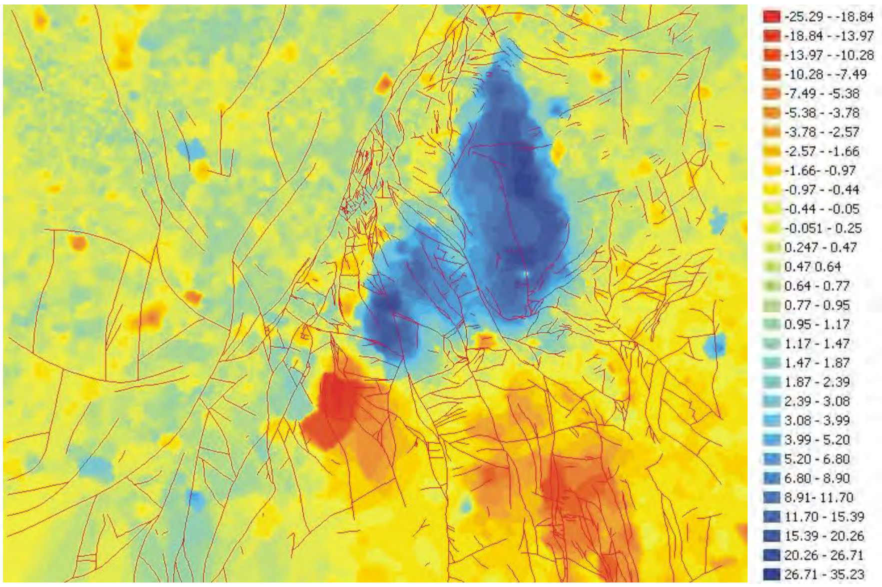


Figure 27. Position of faulting and correlation of valley alluvium and lower PSI uplift rates (cyan).

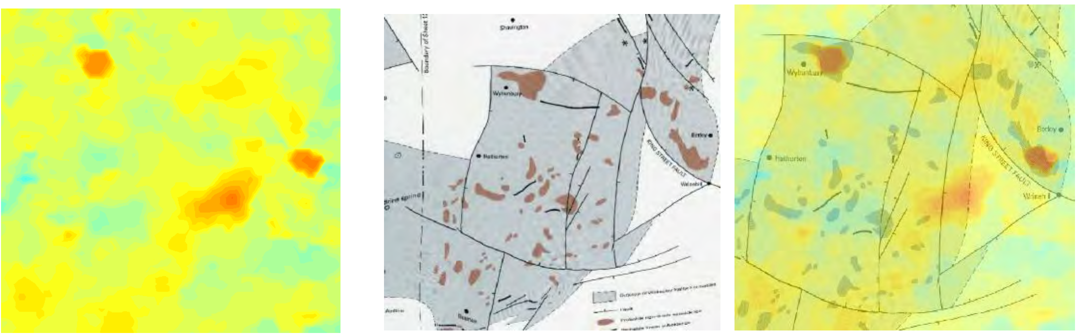


Figure 28: a) PSI subsidence (red). b) Salt dissolution (brown). c) Correlation between PSI and salt dissolution.

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[5] Donnelly, L.J. 1994. *Predicting the reactivation of geological faults and rock mass discontinuities during mineral exploitation, mining subsidence and geotechnical engineering.* PhD thesis (unpublished), University of Nottingham

9.2.5: Conclusions

The Terrafirma product has shown that Stoke-on-Trent has experienced both subsidence and uplift between 1992 and 2004. When compared to geo-environmental information, uplift appeared to be associated with older undermining probably due to elastic rebound from groundwater recharge. Subsidence appeared to be associated with more recent undermining, areas of made ground, compressible alluvial soils and areas underlain by salt. The PSI technique appeared to identify and monitor terrain-motions at local and regional scale. The likely causes of terrain-motion were identified by comparing the data with geo-environmental information. The technique has the potential to provide information useful for environmental management.

END OF MAIN DOCUMENT