A DEM-FREE APPROACH TO PERSISTENT POINT SCATTERER INTERFEROMETRY [1]

Mr. Mark Warren, Dr. Andrew Sowter, and Dr. Richard Bingley
University of Nottingham, University Park, Nottingham NG7 2RD, United Kingdom

Abstract: Current methods using Persistent Point Scatterers (PPS) for the measurement of land deformation require the use of a digital elevation model (DEM) to act as a reference surface for the deformation. DEMs contain errors that are spatially independent and must be removed before any small change in land motion can be identified. Using an ambiguity search process, it is possible to ignore the effect of the DEM, instead replacing it with a reference interferogram that contains the spatially correlated errors of atmospheric and baseline effects. In this paper, we outline this approach with some initial PPS results over the London area. Although the benefits of a DEM-free PPS method are not yet clear, it is anticipated that the replacement of spatially independent noise with correlated noise will allow a more detailed analysis of neighbouring scatterers.

1. Introduction

Subsidence is a major problem encountered globally. Although the causes are many and widespread, the outcome is usually the same: the collapsing of the ground surface. Subsidence rates can vary from extreme cases of many tens of centimetres per year for seismic events to less than a millimetre per year in areas of water abstraction and settlement. Traditional techniques for subsidence measurement (GPS, levelling, photogrammetry) can be expensive and often lack the spatial density required for some applications.

Differential interferometry (DInSAR) was first demonstrated in 1989 by Gabriel et al [1], and has been successfully used to study land deformation (Zebker et al [2]), earthquakes (Massonnet et al [3]), volcanoes (Briole et al [4]), glacier motion (Goldstein et al [5]), landslides (Fruneau et al [6]) and subsidence (Massonnet et al [7]). The two main problems with DInSAR are that low coherence of the interferogram phase data gives poor results, and the atmospheric effects often swamp the deformation that is sought after.

In 1999 Ferretti et al [8] demonstrated a different process by examining a stack of differential interferograms and looking at the temporal evolution of phase-stable pixels. This technique was called the Permanent Scatterer Technique. Because this technique needs phase-stable (persistent) pixels it is especially good for use over urban areas, where temporal decorrelation

[1] This work has been supported by EPSRC and Infoterra Ltd. Data supplied as part of ESA CAT-1 project 3108.

effects are minimised due to the high number of stable reflective structures (buildings, bridges, etc). Since 1999 other techniques have been suggested following similar processing lines, and have been reported to measure deformation to accuracies of millimetres per year (see Crosetto et al, [9]). The term "Persistent Scatterers" is used to describe them all within this paper.

This paper describes a DEM-free method of Persistent Scatterer Interferometry (PSInSAR), where the need of a DEM for 2-pass DInSAR has been replaced with 3-pass DInSAR. The following chapters show the proposed DEM-free approach together with some initial results from data of the London, UK region. Some conclusions are drawn and further work proposed.

2. DEM-Free PSInSAR Approach

In a traditional PSInSAR approach the 2-pass method is used to generate the differential results. As previously stated this requires the use of a DEM. No DEM is 100% perfect – there will always be an error associated with it. DEM errors are not, in general, spatially correlated but are more likely to contain a random element, with SRTM DEMs having a random error with magnitude $\pm$ 2-5m [13]. This means that the 2-pass results will contain errors due to this DEM error term. In the PS techniques this is taken into account and the error term is attempted to be modelled out [11]. However, a 3-pass approach will not have any DEM errors whatsoever. Below there follows a review of the 2-pass PSInSAR approach as proposed by Ferretti et al 2001, and thereafter a description of the DEM-Free 3-pass PSInSAR approach.

2.1. Permanent Scatterers Approach

The Ferretti method [11] is summarised as follows:

- An analysis of the amplitude dispersion of the SAR images is undertaken to identify possible Permanent Scatterers. A simple thresholding process is used where pixels with dispersion below a certain value are selected as possible PS candidates.
- Interferograms are formed using a common master image, which has been selected due to its temporal and geometrical position, i.e. such that it lies in the middle of the data set to minimise the temporal and geometrical decorrelation.
- Differential interferograms are then formed using the 2-pass method and an appropriate DEM.
- The analysis then examines the data both up the stack (temporally) and at each interferogram level (spatially). This is performed using an iterative method, where the atmospheric phase screen at each level is modelled using a linear phase model and a linear velocity and DEM error are modelled temporally for each PS; this can be difficult due to the nature of the phase (it being wrapped). A periodogram technique is implemented.
- These estimates are then removed from the data and the process repeats until the modelled velocity and DEM errors converge. The phase residue that is left over is assumed to be due to atmosphere that doesn't relate to the linear model and phase noise.

- This is then filtered and interpolated (using a kriging interpolator [17]) to the full processed scene before being removed from the original phases. The result is "atmospheric-free" phase.
- Linear velocity and DEM error estimation process is repeated, albeit selecting the PS points using phase dispersion instead of amplitudes.

Due to the inaccurate atmospheric model (i.e. considering it as linear), this method can only be used over regions of approx. 5km*5km. Other methods can get round this problem, for example see Ferretti et al [14].

2.2. 3-pass PSInSAR Approach

Replacing the 2-pass differential framework with a 3-pass method in the PSInSAR technique, could allow improvements to be made to the method. With no DEM there would be no DEM error, maybe allowing an easier approach to the mitigation of the atmospheric phase screens (APS). But the DEM has been replaced by a second interferogram, therefore replacing the DEM errors with interferogram errors (typically atmospheric and decorrelation noise) which can be much larger in magnitude than a DEM error. The errors may also behave differently. The main constituent of the interferogram error is the APS, which is spatially correlated over short distances of approx. 1km [12]. This could allow an easier removal of the 3-pass interferogram errors than the 2-pass DEM errors.

The proposed DEM-free algorithm follows closely to that described above in 2.1 but with a few slight alterations:

- A DEM can be used to unwrap the topographic component of the interferometric phase without the error term affecting the final result. This can be viewed as performing the Integer Ambiguity Search process [10] at each pixel using the DEM as ground control [15].
- Use of a 3-pass differential technique to create the differential interferograms. For this end an interferogram should be selected as the "topographic" one, i.e. the interferogram that is to be used in all of the 3-pass differentials as the topographic pair. The 3-pass differential interferograms are produced using the formula [16]:

$$\phi_{diff} = \phi_i - \frac{B_i \perp}{B_{ref} \perp} \phi_{ref} \qquad (1)$$

  where ϕ_{diff} is differential phase, ϕ_i is the phase of the i[th] interferogram, ϕ_{ref} is the topographic phase and $B_i \perp / B_{ref} \perp$ is the ratio of the perpendicular baselines.

- Calculating the differential phase as in (1) without wrapping it allows an estimate of errors in ϕ_{ref}. This is achieved by means of a linear model using the phase data of the time series of the point, albeit referenced to the baseline ratio magnitude instead of time.

After this step the processing follows a similar path to that in described in 2.1, implementing periodograms to estimate the linear velocity, updates to the ϕ_{ref} error and atmospheric phase screens. The process is shown in Fig. 1.

3. Thames Region

The algorithm has been tested using data from the River Thames region in London, UK. London is a large urban area and so should have many persistent scatterers.

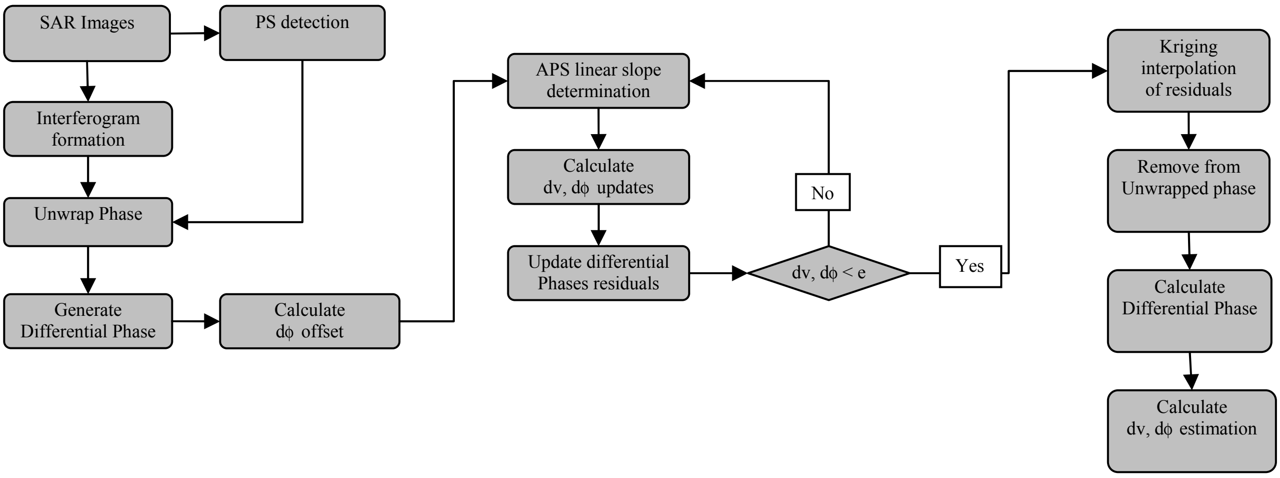

Figure 1: Flow diagram of the DEM Free PSInSAR method. δφ and δv are the topographic phase error and velocity estimate respectively, e is some suitable threshold level.

There is also a GPS network set up along the Thames, which has been used since 1996 primarily for the monitoring of land motions with respect to tide levels [18]. Figure 2 shows the extent of the GPS network.

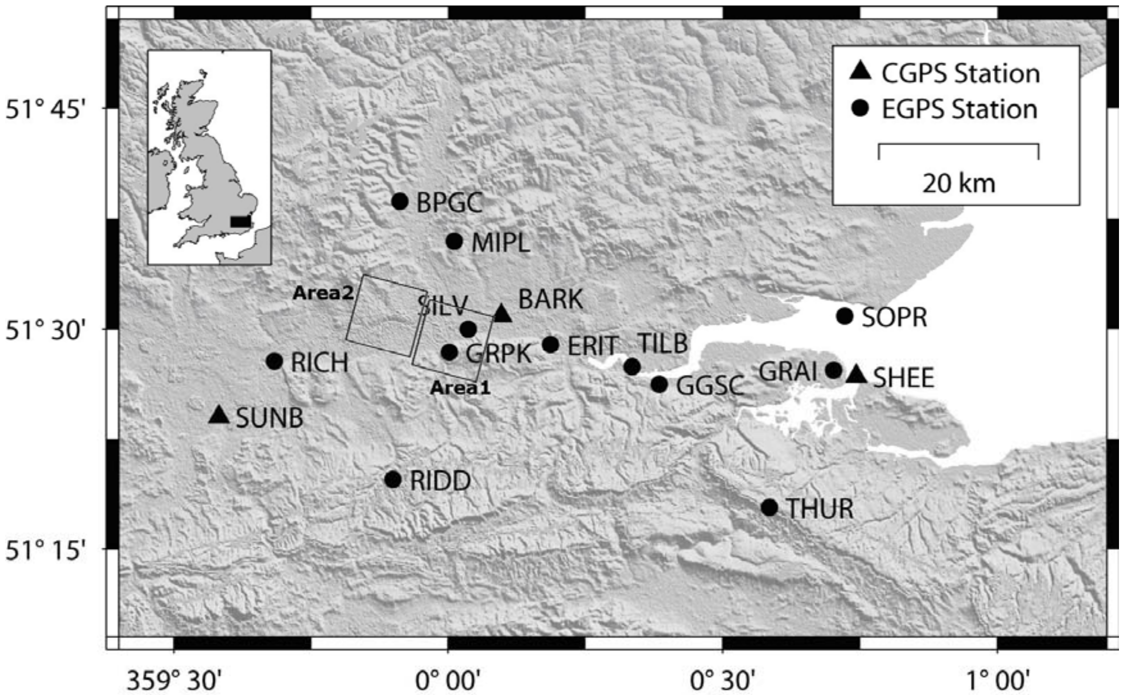

Figure 2: Thames Region GPS Network with study areas highlighted.

Two separate sites have been used to test the PSInSAR algorithm. The first one encompasses Greenwich and is shown as Area 1 in Figure 2. The second test site (Area 2 in Figure 2) is of the Westminster area. Area 2 is expected to give the most "interesting" results of the two sites because at the time the SAR data was acquired (1997-2000), construction work for the Jubilee Line extension of the Underground Train network was taking place. Previous InSAR studies of this area have picked up deformation due to this [21, 22].

4. Data Used

Results have been attained using SAR data acquired between the dates of Jan 1st 1997 and Dec 31st 1999 from the European Space Agency's ERS 1 and 2 satellites. In total 31 SAR images were used. The interferograms have been processed using the Delft Doris processing software [19] and precise orbital data [20]. Other processing has been performed using in-house software. The Digital Elevation Model used in the phase unwrapping process was from the SRTM mission [23].

5. Results

5.1 Area 1: Greenwich

The initial Persistent Scatterer identification has been performed using the amplitude images. The identified candidates are shown in Figure 3 together with the mean amplitude image created from the stack of all the SAR amplitudes. The image at this point is still in radar coordinates and so appears stretched and flipped from left to right. The PS analysis is performed on this selection of points and results in the estimated atmospheric phase maps for each interferogram, an example of which can be seen in Figure 4. These atmospheric phase maps are then removed from the original interferogram phase data before the final stage of the PS analysis. The corrected phase is then used to identify more possible Persistent Scatterers, this time based upon their phase time series, not amplitude.

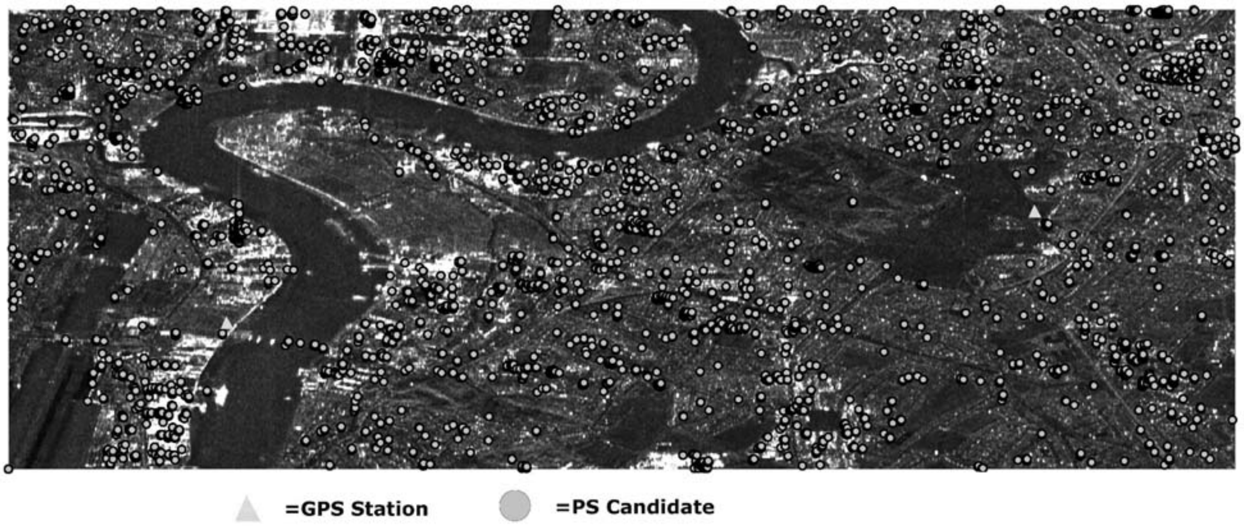

Figure 3: Persistent Scatterer Candidates identified from amplitude statistics shown together with the mean amplitude image. Area corresponds to approximately 5km*5km.

From the results it can be shown that there is very little motion going on. Most PS points have an average velocity of ±2mm per yr, which means we cannot say with any certainty whether they are moving or stationary. This is supported by the GPS results too. Figure 6 (a) below shows a time series of a PS point near to A in Figure 5 together with the GPS time series for the receiver A in Figure 6(b). From these we cannot conclude any definite motion.

Figure 4: An estimated atmospheric phase screen of the interferogram for the area of Figure 3, formed from the 08-April-98 and 07-February-97 images.

Figure 5: The geocoded (to the UTM coordinate system) mean amplitude image. The GPS point is located at point A.

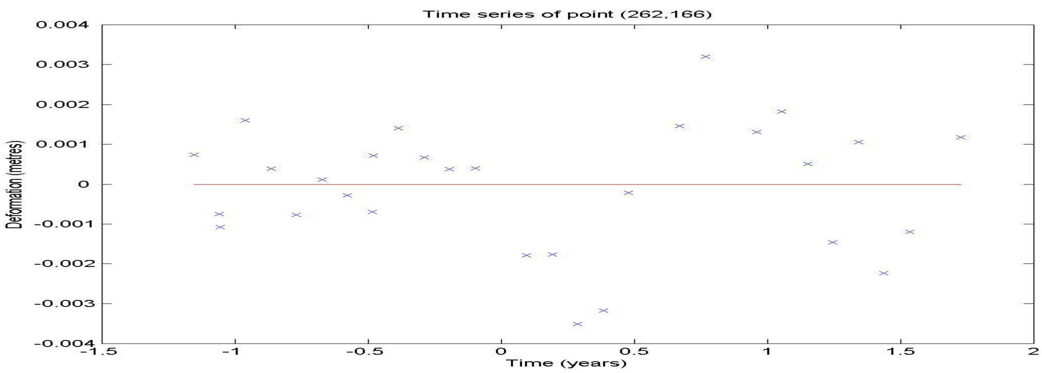

Figure 6(a): Time series of PS point near A, gradient (velocity) of fit = 0. Time is relative to April 1998.

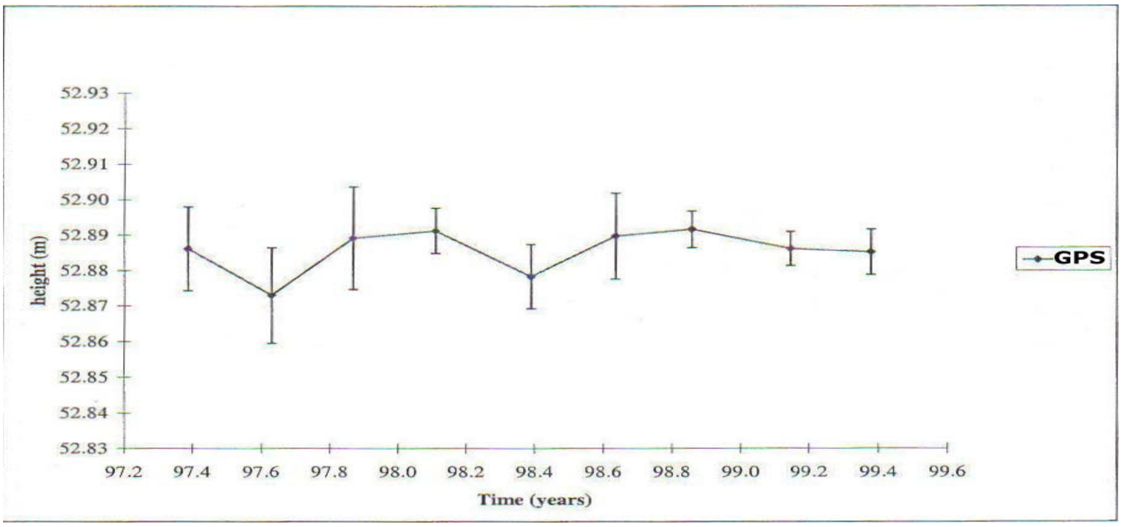

Figure 6(b): Vertical height time series of episodic GPS station A [18].

5.2 Area 2: Westminster

The same analysis has been performed using Area 2. Figure 7 shows the mean amplitude of the area investigated. It can be seen from Figure 8 that some definite motion has been picked up. The area highlighted by the path from A to B relates to the Jubilee Line. Figure 8 shows a time series of point B together with an average velocity of -7mm per year. This is equivalent to the velocity identified by [21]. There were no GPS points in the subsiding region to use as a comparison.

6 Conclusions

An alternative method of Persistent Scatterer Interferometry has been described, where the 2-pass differential interferometry has been replaced with 3-pass. This means that the DEM error present in other PSInSAR techniques is absent from this one, albeit replaced by interferogram errors due to atmospheric changes and decorrelation noise. At present, the method follows a similar path as to Ferretti's [13] algorithm, giving an alternative method to PSInSAR but without any clear improvements. The results from section 4 are promising, showing that the method is capable of picking up recognised subsidence. Further tests and analyses will have to be undertaken to prove this. The Greenwich area under examination

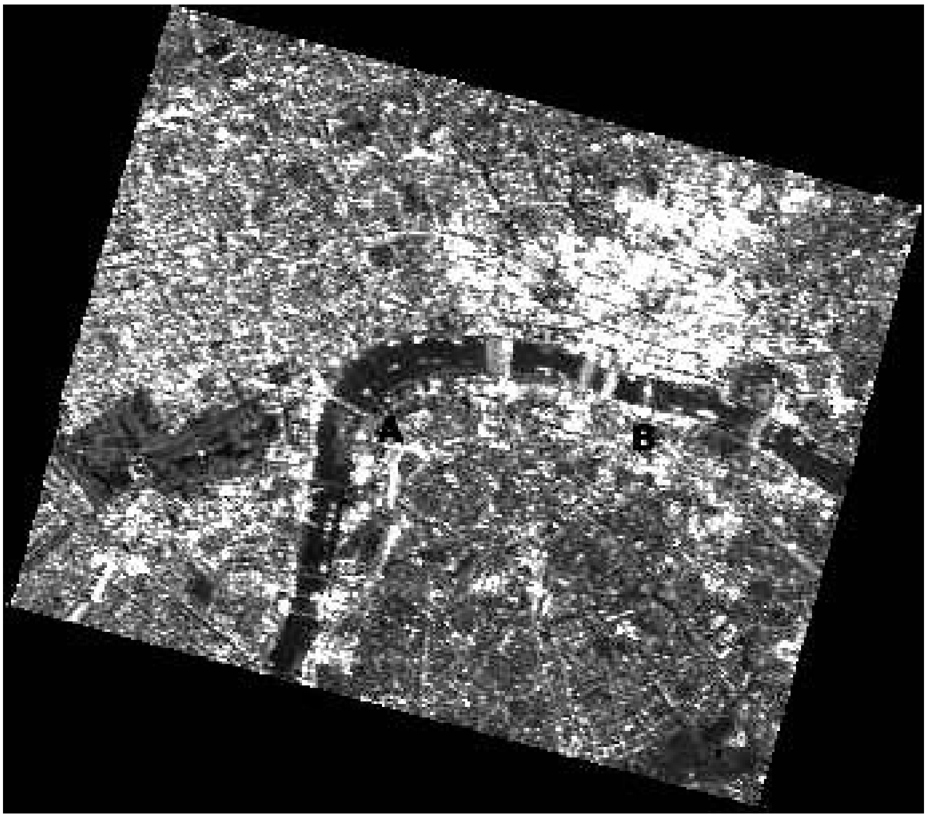

Figure 7: Geocoded mean amplitude image of the Westminster area of London, UK. The path joining points A and B mark where the subsidence has been identified.

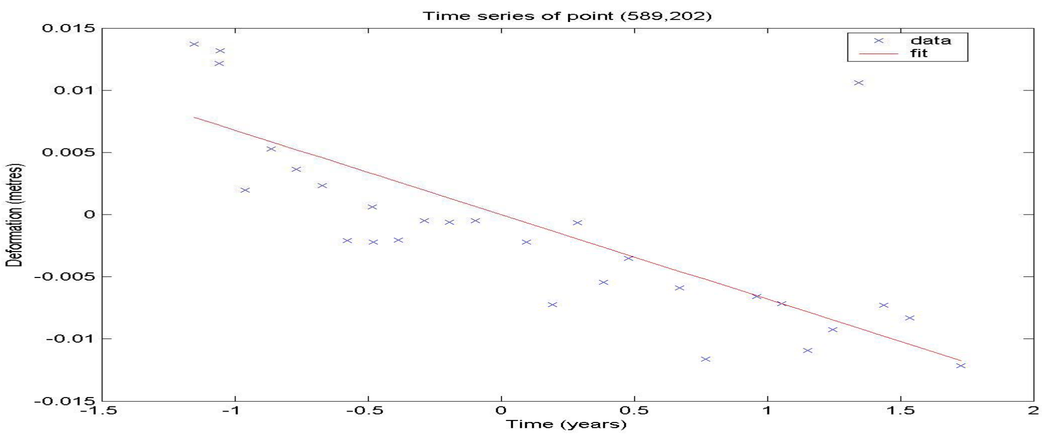

Figure 8: Time series of PS point near B from Fig. 7. Velocity fit =-7mm per year

gave results showing no deformation, which agreed with the GPS results. Most of the PS points are showing velocities within ± 2mm, which is a noise level consistent with other authors [24]. The Westminster area under investigation showed subsidence consistent with previous studies, with some PS points giving velocities of -7mm per year.

In the future the method will be extended so that the assumption of linear atmospheric anomalies is no longer required, following a method more like [14]. This will involve differencing neighbouring pixels to reduce the atmospheric effect and allow easier modelling. It is hoped that because the 3-pass interferometric error is spatially correlated it too will also be greatly reduced – to allow a quick and easy model for the deformation.

References:

[1] Gabriel A. K., Goldstein R. M. and Zebker H. A., Mapping small elevation changes over large areas: differential radar interferometry, Journal of Geophysical Research, Vol. 94 No. B7, pp. 9183-9191, 1989.

[2] Zebker H. A., Werner C. L., Rosen P.A. and Hensley S., Accuracy of topographic maps derived from ERS-1 interferometric radar, IEEE Trans. Geosci. Remote Sensing, Vol. 32 No. 4, pp. 823-836, 1994.

[3] Massonnet D., Rossi M., Carmona C., Adragna F., Peltzer G., Feigl K. and Rabaute T., The displacement of the Landers earthquake mapped by radar interferometry, Nature, Issue 364, pp. 138-142, 1993.

[4] Briole P., Massonnet D.,and Delacourt C., Post-eruptive deformation associated with the 1986-87 and 1989 lava flows of Etna detected by radar interferometry, Geophysical Research Letters, Vol. 24 No. 1, pp. 37-40, 1997.

[5] Goldstein R., Engelhardt H., Kamb B. and Frolich R., Satellite radar interferometry for monitoring ice sheet motion: Application to an Antarctic ice stream, Science, Issue 262, pp. 1525-1530, 1993.

[6] Fruneau, Achache J. and Delacourt C., Observation and modelling of the Saint-Etienne de Tinee landslide using SAR interferometry, Tectonophysics, Vol. 265 Nos. 3-4, pp. 181-190, 1996.

[7] Massonnet D., Holtzer T.and Vadon H., Land subsidence caused by the East Mesa geothermal field, California, observed using SAR interferometry, Geophysical Research Letters, Vol. 24 No. 8, pp. 901-904, 1997.

[8] Ferretti, A, Prati, C, Rocca, F, Permanent Scatterers in SAR interferometry, Proceedings IGARSS 99, Hamburg, Germany, June 28-July 02 1999

[9] Crosetto, M, Crippa, B, Biescas, E, Monserrat, O, and Agudo, M, State of the Art of Land Deformation Monitoring Using Differential SAR Interferometry, ISPRS Hannover Workshop 2005: High Resolution Earth Imaging for Geospatial Information 17-20 May 2005, XXXVI**,** Part 1/w3, 2005

[10] Sowter A., Phase ambiguity determination for the positioning of interferometric SAR, *Photogrammetric Record*, Vol. 18 No. 104, pp. 308-324, 2003.

[11] Ferretti, A, Prati, C, Rocca, F, Permanent Scatterers in SAR Interferometry, IEEE Transactions on Geoscience and Remote Sensing, Vol. 39, No. 1, pp 8-20, 2001

[12] Hanssen R. F., Radar Interferometry. Data Interpretation and Error Analysis, Kluwer Academic Publishers, The Netherlands, 2001. 308 pages.

[13] Falorni, G. et al., Analysis and characterization of the vertical accuracy of digital elevation models from the Shuttle Radar Topography Mission, Journal of Geophysical Research, Vol. 110, F02005, doi:10.1029/2003JF000113, 2005

[14] Ferretti, A, Prati, C, Rocca, F, Nonlinear Subsidence Rate Estimation Using Permanent Scatterers in Differential SAR Interferometry, IEEE Transactions on Geoscience and Remote Sensing, Vol. 38, No. 5, pp2202-2212, 2000.

[15] Warren, M A, Sowter, A, Bingley, R M, An InSAR Persistent Scatterer Approach That Doesn’t Use A DEM: A Paper Study, Proceedings of the Annual Conference of the Remote Sensing and Photogrammetry Society, Portsmouth , CD-ROM, 2005

[16] Zebker H. A., Rosen P. A., Goldstein R. M., Gabriel A. K. and Werner C. L., On the derivation of coseismic displacement fields using differential radar interferometry: The Landers earthquake, J. Geophys. Res., Vol. 99, pp. 19617-19634, 1994.
[17] Cressie, N, Statistics for Spatial Data*,* Revisied Ed., USA, John Wiley and Sons, 1993.
[18] Bingley, RM, Ashkenazi, V, Penna, NT, Booth, SJ, Ellison, RA, Morigi, AN, Monitoring Changes in Regional Ground Level, Using High Precision GPS, Environment Agency R&D Technical Report W210
[19] Kampes B. and Usai S., The Delft Object-oriented Radar Interferometric software, Proc. 2nd Int. Symp. Operational Rem. Sensing, ITC, Enschede, The Netherlands, 16th August 1999. 4 pages (CD-ROM).
[20] Scharroo R., Visser P.N.A.M., and Mets G.J., Precise orbit determination and gravity field improvement for the ERS satellites, J. Geophys. Res., 103, C4, pp. 8113-8127, 1998.
[21] NPA Group, Applications and Case Studies: London, UK. (Website) http://www.npagroup.co.uk/insar/apps/london_psi.htm
[22] Lawrence Livermore National Laboratory, Science and Technology Review, April 2005, Monitoring Earth's Subsurface from Space. (Website) http://www.llnl.gov/str/April05/Vincent.html
[23] Jordan R. L., Caro E. R., Kim Y., Kobrick M., Shen Y., Stuhr F. V. and Werner M. U., Shuttle Radar Topography Mapper (SRTM), in Microwave Sensing and Synthetic Aperture Radar, G. Franceschetti, C. J. Oliver, J. C. Shiue and S. Tajbakhsh, Eds. Bellingham:SPIE, 1996, pp.412-422.
[24] Colesanti, Carlo, Ferretti, Alessandro, Prati, Claudio, Rocca, Fabio, Monitoring landslides and tectonic motions with the Permanent Scatterers Technique, Engineering Geology, Vol 68, 2003. pp3-14.