MAJOR URBAN SUBSIDENCE MAPPED BY DIFFERENTIAL SAR INTERFEROMETRY

Mark Haynes, Ren Capes — Nigel Press Associates, Crockham Park, Edenbridge, Kent TN8 6SR, UK

Phone: + 44 1732 865023, Fax: + 44 1732 866521

info npagroup.co.uk

Geoff Lawrence — TREIC° L, 46 Pondcroft Road, Knebworth, Hertfordshire SG3 6DB, UK

Phone: + 44 1438 813681, Fax: + 44 1438 816513

geoff treicol.demon.co.uk

Andy Smith — Phoenix Systems, 60 St. Albans Road, Kingston-upon-Thames, Surrey KT2 5HH, UK

Phone: + 44 181 5498878, Fax: + 44 181 5498878

David Shilston, Geoff Nicholls — WS Atkins Consultants Ltd, Woodcote Grove, Ashley Road, Epsom, Surrey KT18 5BW, UK

Phone: + 44 1372 726140, Fax: + 44 1372 740055

Abstract

At NPA we have investigated a variety of ground displacement phenomena using our *CivInSAR* differential interferometric system, as part of our BNSC ADP2 programme. We report here a spectacular case of major urban subsidence, over a 100km^2 area, amounting to 78mm over almost 3 years. This has been validated by a GPS ground survey for which both the calculated displacements rates and overall trend are in close agreement with our interferometric results.

Keywords: Differential SAR Interferometry, Subsidence Mapping

1. Introduction

The capability of differential SAR interferometry to map catastrophic ground movements such as earthquakes is now well established, having been demonstrated several times recently. Examples have included the events at Landers (California) in 1992, Kobe (Japan), as well as the 1995 Grevena (Greece) earthquake which the authors investigated [1]. Very often for these single, sudden events the temporal bracketing with a suitable interferometric pair of SAR images (given acceptable orbital criteria) can be optimised to a minimum since the time and date of occurrence are unique. However more subtle, long-term ground displacement events, such as subsidence and volcanic deformation present more of a challenge to this technique since the timeframes (on the scale of years for subsidence) often result in low coherence conditions which in turn degrade any interferometric results.

As part of our *Application Demonstrations Programme 2* with the British National Space Centre, we have investigated a variety of ground displacement phenomena world-wide, using our proprietary *CivInSAR* differential interferometric processing system at NPA. Most recently, and in spite of the above-mentioned obstacle, we succeeded in detecting and clearly mapping a major and ongoing urban subsidence event, stretching over a period of several years. However, due to the sensitive nature of these results at the time of writing, we have been bound to keep location details confidential, which means that some of the specifics in our data description and geology discussion have been withheld. Nevertheless this paper provides an otherwise detailed account of our investigation and results of this major ground displacement phenomenon.

2. SAR and Ancillary Data

Raw SAR scenes from the ERS-1 and ERS-2 platforms (descending orbits) were used in our interferometric processing, together with a 50m DEM of the area. The time span of the pairs ranges from almost 3 years down to a 25-hour, tandem pair. The pairs were selected with low perpendicular baseline (B_{perp}) values. Parameters are summarised in Table 1 below.

Image Pair	B_{perp} (metres)	Temporal Separation
α	20.7	2 years 11 months
β	6.7	2 years 4 months
γ	41.8	7 months
δ	27.9	25 hours

Table 1. Temporal and perpendicular baseline parameters of 4 interferometric pairs.

After preliminary full-scene (100km × 100km) SAR processing, the region of interest was limited to approximately 16km × 12km. This area is mostly urban and completely encompasses a major city.

3. Interferometric Processing

The raw SAR format scenes were first processed to ground-range single-look-complex using a commercial SAR processing package (*PulSAR*), with pixel dimensions of 12.5m in range and 3.125m in azimuth (4:1 ratio). In doing so, the nominal orbit state vectors of each scene header were enhanced (and the orbits propagated) using the ESA/DLR precise state vector (PRC) data.

Due to the variation in coherence with time, degrees of pixel averaging were necessary during the interferogram generation process. The amount of averaging was raised for pairs with increasing temporal separations, and using a 1:4 averaging ratio, square cell interferograms were generated, ranging from 12.5m for the tandem pair (δ) to approximately 60m for the 2 year 11 months pair (α).

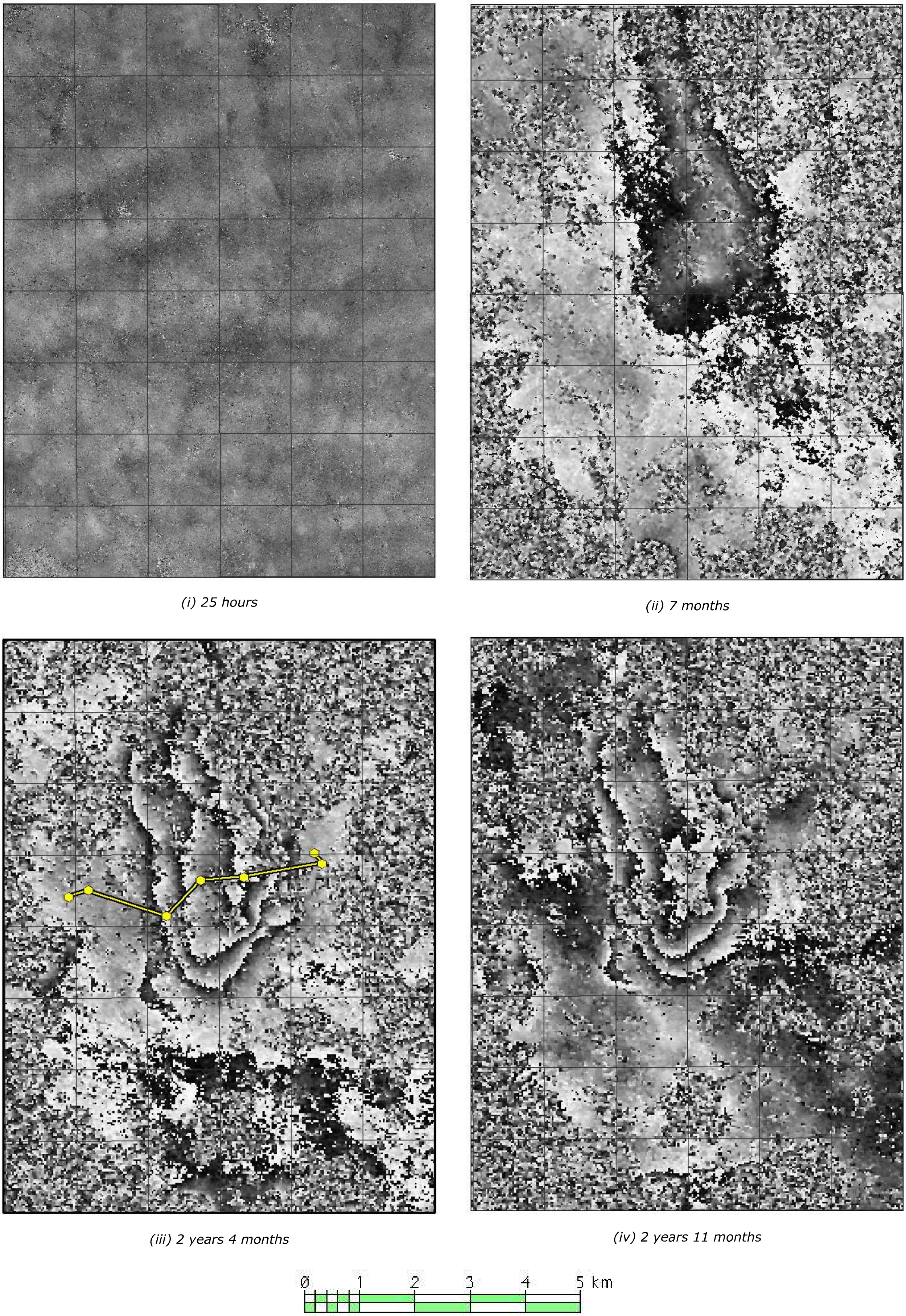
The differential interferometric approach we employed here is the 2-pass-plus-DEM technique, as opposed to the 3-pass approach. Our system imports the elevation and synthesises the phase due to topography to generate the differential phase image from the initial interferogram. Orthorectification and mapping into a suitable projection are in addition applied to this differential result.

The *CivInSAR* processing system also provides residual phase detrending tools which were employed for some pairs - resulting from orbital errors (despite the use of precise state vector data which has a 1m nominal radial accuracy). In addition, and as part of our subsequent analyses and visualisations, coherence maps are also generated with our system, however space does not permit reporting of these additional results and analyses.

Phase unwrapping and deformation map generation complete the process. These and other results and data can then be incorporated into our GIS/value-adding system which was described in our work on the Grevena earthquake [1].

4. Results

The sequence of 4 differential interferograms is displayed in Figure 1. The rate of ground displacement is well illustrated by this sequence of increasing time separations. This ranges from zero movement in the (δ) tandem pair, to part of one fringe cycle in the (γ) 7-month pair, and strikingly to 3 distinct fringe cycles in the β and α pairs (2 years 4 months and 2 years 11 months respectively). For the β pair we estimated this downward movement at a maximum of 78mm over 2.33 years.



(i) 25 hours

(ii) 7 months

(iii) 2 years 4 months

(iv) 2 years 11 months

Figure 1. Sequence of differential interferograms with increasing temporal baselines over subsidence region. Interferogram (iii) includes GPS ground survey path described in Section 5.

5. Ground Validation

The *CivInSAR* team is grateful to Ws Atkins Consultants Ltd, a major civil engineering company who agreed to undertake a GPS ground survey through the region corresponding to our detected area of subsidence on the interferograms. Heights from benchmarks were surveyed at 7 GPS points along a physical path length of just over 8km in total. The survey points and path overlaid onto the fringe outlines are also illustrated in Figure 1. Recorded height differences were translated to a yearly rate using the number of years back to the previous known benchmark year. These yearly rates (with scaled tolerances) were then projected to the 2.33 years time frame of interferogram pair β for comparison. Table 2 lists these results, and the height profiles of the ground survey results are contrasted with the interferometrically-derived deformation map for pair β at the corresponding GPS stations in Figure 2.

GPS Station Reference Number	GPS Movement since previous recorded benchmark year (mm)	GPS Movement per year (mm)	GPS Movement over 2.33 year interferogram span	Movement at corresponding location in 2.33 year interferogram deformation map (mm)
10	0.0 ± 30	0.0 ± 2.4	0.0 ± 5.6	-4.9
11	+61.0 ± 30	+2.0 ± 1.0	+4.7 ± 2.3	-3.8
12	-62.0 ± 30	-2.0 ± 1.0	-4.7 ± 2.3	-32.6
13	-451.0 ± 30	-15.0 ± 1.0	-35.0 ± 2.3	-72.0
14	-983.0 ± 30	-32.0 ± 1.0	-75.7 ± 2.3	-78.1
15	-100.0 ± 30	-8.0 ± 2.4	-18.7 ± 5.6	-26.3
16	-115.0 ± 30	-9.0 ± 2.4	-21.0 ± 5.6	-26.0

Table 2. Comparison of GPS heights survey (with tolerances) scaled to interferogram time span and interferometrically derived displacements at corresponding locations ('-'sign indicates downward displacement).

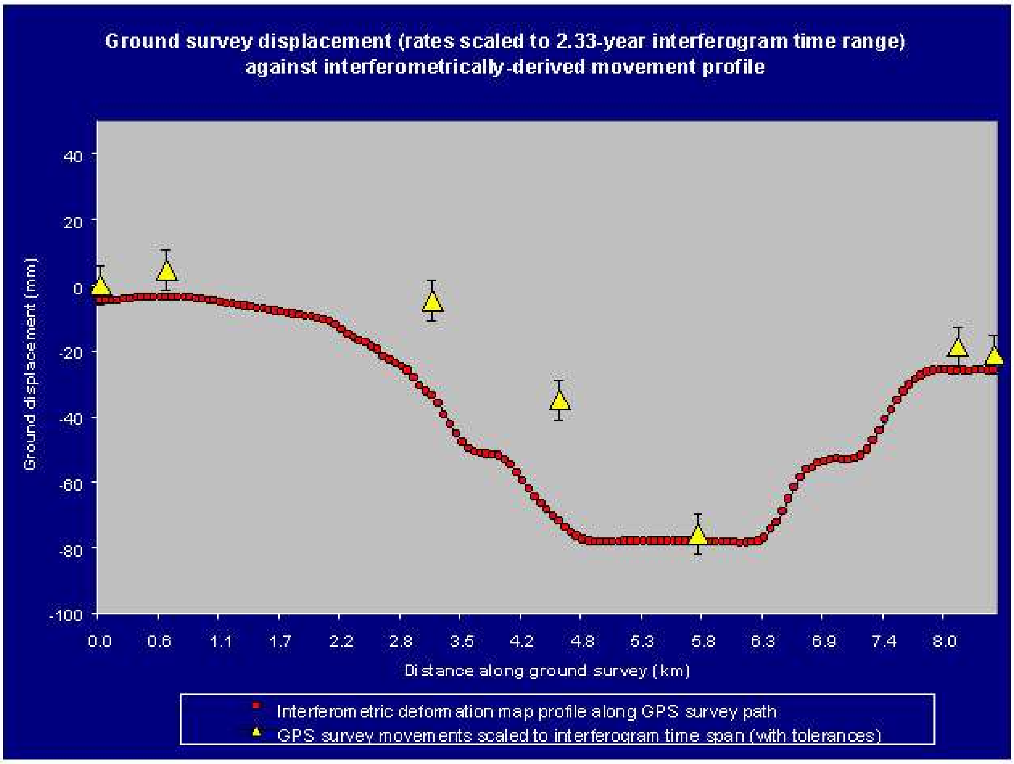


Figure 3. Comparison of subsidence values from GPS survey and interferometric deformation map.

6. Geological Interpretation

Displacements of this magnitude mapped as distinctly as this have been recorded only for earthquake events, for example as we demonstrated over the Grevena earthquake in northern Greece. Slight seismic shocks are not unknown in this area (most associated with collapse of coal workings!) but these are rare slight shallow local events that dislodge chimney pots. Nothing has been recorded that would have produced this amount of displacement.

We do not have to look very far for a reason for this ground displacement. Subsidence over underground coal workings has long caused problems in the conurbation, although there is no complete survey of the hundreds of workings.

There is an unusually thick sequence of Coal Measures in the region, with 52 individual seams from 1cm to 3.5m thick occurring over 1100m of rock succession dipping gently beneath the conurbation in a deep trough. By superimposing the fringe contours over the geology map of the area, we noted that 30 of the 52 coal seams occupy the fringe core. These seams trend north-northwest, exactly parallel to the strike of the core of fringe pattern. This "grain" is shared by the strike of the geological strata, the topography (there is a height range of 80m to 100m across the core of the fringes) and the trend of minor landslips, along steeper slopes where harder sandstone outcrop. These landslips, the largest about 1km long and 150m wide, are nowhere large enough or consistent enough to result in displacement adequate to yield a fringe.

The stacked coal seams reach the surface to the east of, and within, the core of the fringes. They dip westward, mostly consistently, at 10° to 20°, beneath the core of the fringes. The generalised sub-surface distribution of these seams in the geological section shows a coincidence of stacked seams and the fringes that is so strong that this is unambiguous, if circumstantial, evidence for subsidence of the coal workings.

There are an estimated 8000 disused shafts in this conurbation and at least 200 abandoned adits within the area defined by the fringe patterns. There are almost no active coal workings in the area and none whatsoever within the fringe core. There is a very close coincidence of the fringe contours and the outline of the areas of all underground coal workings and, displaced updip (that is to the east), the area of mine workings within 30m of the surface. Many of these workings are ancient and predate systematic survey and recording. As there are only piecemeal survey of these workings, sudden unexpected collapse over mining voids or over areas where the pillars of the old seams, or the mouths of shafts collapse, are a feature of the whole conurbation.

What we have here is subsidence at relatively shallow depths, probably no more than 100m and maybe no more than 30m depth. Extensive underground shafts, "bell-pits", adits and workings, many by pillar and stall (in which pillars of coal are left standing, usually on a rectangular grid to support the workings) underlie the whole conurbation. Mining has been almost totally abandoned, and collapse of roof supports and pillars in particular, and seasonal water logging is causing subsidence.

7. Conclusion

Using our *CivInSAR* interferometric processing system, we have demonstrated our capability to detect, monitor and quantify subtle ground displacement events over a period of years and across a wide physical area. The demonstration reported here was a recent case of major urban subsidence. We were able to both replicate interferometrically this phenomenon and have had our results validated by an independent GPS ground survey team.

8. Acknowledgments

We gratefully acknowledge the technical support of the UK Defence Evaluation and Research Agency (DERA), who are a partner in the CivInSAR programme.

9. References

[1] Capes, R., Haynes, M., Lawrence, G., Smith, A., Muller, J-P., Parsons, B., England, P., Clarke, P. 1996

CivInSAR Quake Assessment: An integration of differential SAR interferometry into a GIS to assist in earthquake risk management, FRINGE 96, ESA Workshop on Applications of ERS SAR Interferometry, Sept/Oct 1996

Keywords: ESA European Space Agency - Agence spatiale europeenne, observation de la terre, earth observation, satellite remote sensing, teledetection, geophysique, altimetrie, radar, chimique atmospherique, geophysics, altimetry, radar, atmospheric chemistry