NEW GROUND TRUTH CAPABILITY FROM INSAR TIME SERIES ANALYSIS

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ABSTRACT

We demonstrate that next-generation interferometric synthetic aperture radar (InSAR) processing techniques applied to existing data provide rich InSAR ground truth content for exploitation in seismic source identification. InSAR time series analyses utilize tens of interferograms and can be implemented in different ways. In one such approach, conventional InSAR displacement maps are inverted in a final post-processing step. Alternatively, computationally intensive data reduction can be performed with specialized InSAR processing algorithms. The typical final result of these approaches is a synthesized set of cumulative displacement maps.

Examples from our recent work demonstrate that these InSAR processing techniques can provide appealing new ground truth capabilities. We construct movies showing the areal and temporal evolution of deformation associated with previous nuclear tests. In other analyses, we extract time histories of centimeter-scale surface displacement associated with tunneling. The potential exists to identify millimeter per year surface movements when sufficient data exists for InSAR techniques to isolate and remove phase signatures associated with digital elevation model errors and the atmosphere.

OBJECTIVES

The goal of this study is to assess new satellite SAR data and InSAR processing techniques for improvements to current remotely-sensed ground truth collection capability for determining seismic source location, depth and characterization. Specifically, we are

- applying InSAR time series analysis to sets of European Remote Sensing Satellite (ERS) and Envisat radar interferograms and
- using InSAR results to constrain geophysical source modeling to improve determinations of seismic source location, depth, and mechanism.

RESEARCH ACCOMPLISHED

This paper presents results from the application of an InSAR time series technique in which a linear inversion is applied to a database of interferograms to produce a sequence of interferograms which show cumulative deformation relative to a reference start date. We present results for two sites of interest: Lop Nor, China, nuclear test site and London, UK, underground tunnels. In both cases, we detect a time evolution of displacement signals that would not be possible using standard processing techniques. The new time series allow for more detailed analyses of the location and time history of subtle deformation signals and provide more accurate ground truth information from the same InSAR dataset.

Methodology

The goal is to obtain deformation measurements at each of the SAR acquisition dates for a set of interferograms overlapping in time and exhibiting generally good coherence. The result is a history of cumulative deformation relative to a user-selected SAR reference date.

This InSAR time series problem can be formulated as a linear system of equations (Usai, 2001; Schmidt and Bürgmann, 2003):

$$Ax = b \,, \qquad (1)$$

where b is an array of input interferogram displacements, x is the estimated cumulative deformation at each of the SAR acquisition dates, and A is a matrix relating the measurements to the parameters to be estimated. A single output date is associated with a column in A. The rows correspond to the input interferograms with the measured displacement assumed to be the difference between the estimated cumulative subsidence values between two image dates. Specifically, each row of A contains the following integer values: +1 at the interferogram reference date, –1 at the interferogram secondary date, and zeros for all other dates.

We find the solution x to the linear system through singular value decomposition. To address error propagation, error estimates associated with each of the input interferograms can be computed by summing the phase noise and Digital elevation model (DEM) error variances. Errors of the estimated displacements x are then computed as the square root of the main diagonal elements of the output covariance matrix:

$$\operatorname{cov} x = \left(V\Lambda^{-1}U^{T}\right)\operatorname{cov} b\left(V\Lambda^{-1}U^{T}\right)^{T} \qquad (2)$$

where $A = U\Lambda V$ is the singular value decomposition. The decomposition is readily obtained from any number of computational software packages.

The InSAR time series analysis examples presented in the next two sections were performed as an InSAR post-processing procedure. In other words, conventional differential InSAR processing was followed by an inversion of the geocoded displacement maps. Some other approaches, e.g., permanent scatterer analysis, require specialized intermediate processing steps to generate the final time series. Our post-processing strategy is motivated by a desire to make best use of any number of conventional InSAR software packages and provide a means to easily extend the analysis of a study site when additional data is obtained.

Lop Nor, China Nuclear Test Site

InSAR data processing began with image formation for 15 SAR data acquisitions spanning 1996-1999 (Table 1). One hundred and five initial interferograms were created from the possible image-pair combinations. The maximum spatial and temporal baselines were 327 meters and 1191 days. The initial interferograms were evaluated and several discarded due to decorrelation. A mosaic of Shuttle Radar Topography Mission (SRTM) 3-arcsecond digital elevation model data was used to remove the topographic phase variations from the remaining interferograms.

The InSAR processing resulted in 101 geocoded maps consisting of radar line-of-sight displacements at 3-arcsecond horizontal postings. Errors corresponding to each output product pixel were assumed to come from two sources: phase noise associated with interferogram decorrelation and DEM errors. Phase standard deviations were calculated from the correlation coefficient, and a 10-meter SRTM one-standard deviation height error was used for time series error analysis. Atmospheric phase variations are also superimposed on the displacement measurements.

The 101 geocoded displacement and corresponding error maps were inverted to arrive at a time series of 14 synthetic displacement maps, one at each of the radar acquisition dates (Table 1, Figure 1). The 19960730 and 19980804 images are noticeably afflicted with atmospheric artifacts. Time series plots of several features of interest were extracted (Figure 2) and show ground motion both toward and away from the radar.

Figure 1 shows a time series of cumulative deformation observed of the Lop Nor, China, nuclear test site relative to a start date of January 1, 1996. Each frame represents cumulative deformation from the reference date (1/1/96) to the date labeled in the frame (e.g., the first frame labeled 960416 represents the cumulative deformation between Jan. 1, 1996 and April 16, 1996). The top row of frames shows no significant deformation occurring between 1/1/96 and 5/21/96. A deformation signal is suspected in the first frame of the second row (960730), but this frame is also contaminated with significant atmospheric noise. In the second frame of the second row, there is much less atmospheric noise, and the suspected deformation signal remains. This demonstrates how the time series helps identify and confirm suspect deformation signals. We know from published literature that there was an underground nuclear test conducted in the vicinity of the InSAR signal on 96/06/08 (Waldhauser et al., 2004). We are comparing these signals with those from the Nevada Test Site (Vincent et al., 2003) to learn more about the effect of rock type, etc. on the surface deformation signals from underground nuclear tests to be in a better position to use InSAR to help identify potentially clandestine nuclear test activities.

London, UK Underground Tunnels

We began our analysis of London with 31 SAR acquisitions distributed over the period 1992-2001 (Table 1). Due to the carefully controlled nature of the ERS-1 and ERS-2 orbits over Europe, we found all 465 potential SAR data pairs to have spatial baselines suitable for interferometry. We were able to visually inspect and remove initial interferograms with significant atmospheric variability associated with the 19960816, 19970801, 19971219, and 19990319 SAR acquisitions. SRTM DEM data was used to remove the topographic phase signature from interferograms with spatial baselines less than 200 meters. After performing consistency checks between combinations of interferograms, 211 3-arcsecond radar line-of-sight displacement maps were inverted using the InSAR time series approach previously discussed.

Figure 3 shows our time series results for London, UK, where a subsidence signal increases linearly with time over an underground utility tunnel owned by London Electric Company. Figure 4 shows a plot of the deformation time series associated with a single pixel in the deformation maps. A linear trend of indicates ongoing subsidence from 1993 through 2001. This tunnel is known to be 60 feet underground in a thick clay layer, which suggests that a soil creep dynamic may be responsible for the observed linear subsidence with time. We are currently working on a soil creep finite element model to simulate this creep process. The ability to identify the rate of subsidence with time is critical for accurate simulations of the subsurface processes causing the observed signals. We are also working on modeling similar tunnels in solid and fractured rock that have nonlinear deformation with time, as well as damage zones above past underground nuclear tests, e.g., Vincent et al. (2003).

CONCLUSIONS

InSAR time series approaches provide an organizational framework for the use and interpretation of InSAR deformation products resulting from anything more than a handful of SAR images. We have applied one such approach to two sites of interest: Lop Nor, China, and London, UK. Our results show detailed temporal and spatial information not easily obtained from the tens of displacements maps generated with conventional InSAR processing. The Lop Nor time series shows surface deformation appearing at the time of a known underground nuclear test as well as other interesting features that are under further investigation. The London time series shows the appearance and steady increase of subsidence with time associated with a known underground tunnel. The new observations afforded by InSAR time series analysis provide more detailed ground truth information which can be used to produce more accurate, time-dependent deformation models and better constrain seismic and aseismic subsurface sources of deformation. This information can ultimately help location and identification studies if a sufficient number (>10) of SAR image acquisitions are available.

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Table 1. Dates of SAR acquisitions used in Lop Nor and London InSAR time series analysis. Four London SAR acquisitions were discarded because they contained noticeable atmospheric artifacts.

Lop Nor

Date	Days Since Reference Date
19960101	0000
19960102	0001
19960205	0035
19960416	0106
19960520	0140
19960521	0141
19960730	0211
19970401	0456
19970819	0596
19971202	0701
19980106	0736
19980421	0841
19980804	0946
19980908	0981
19990406	1191

London

Date	Days Since Reference Date
19920505	0000
19920609	0035
19920818	0105
19920922	0140
19930209	0280
19930803	0455
19950413	1073
19950727	1178
19950831	1213
19950901	1214
19960816	Not used
19960920	1599
19970103	1704
19970314	1774
19970523	1844
19970627	1879
19970801	Not used
19971009	1983
19971114	2019
19971219	Not used
19980123	2089
19980403	2159
19990319	Not used
19990702	2614
19991015	2719
19991224	2789
20000127	2823
20000128	2824
20000407	2894
20001103	3104
20010112	3174

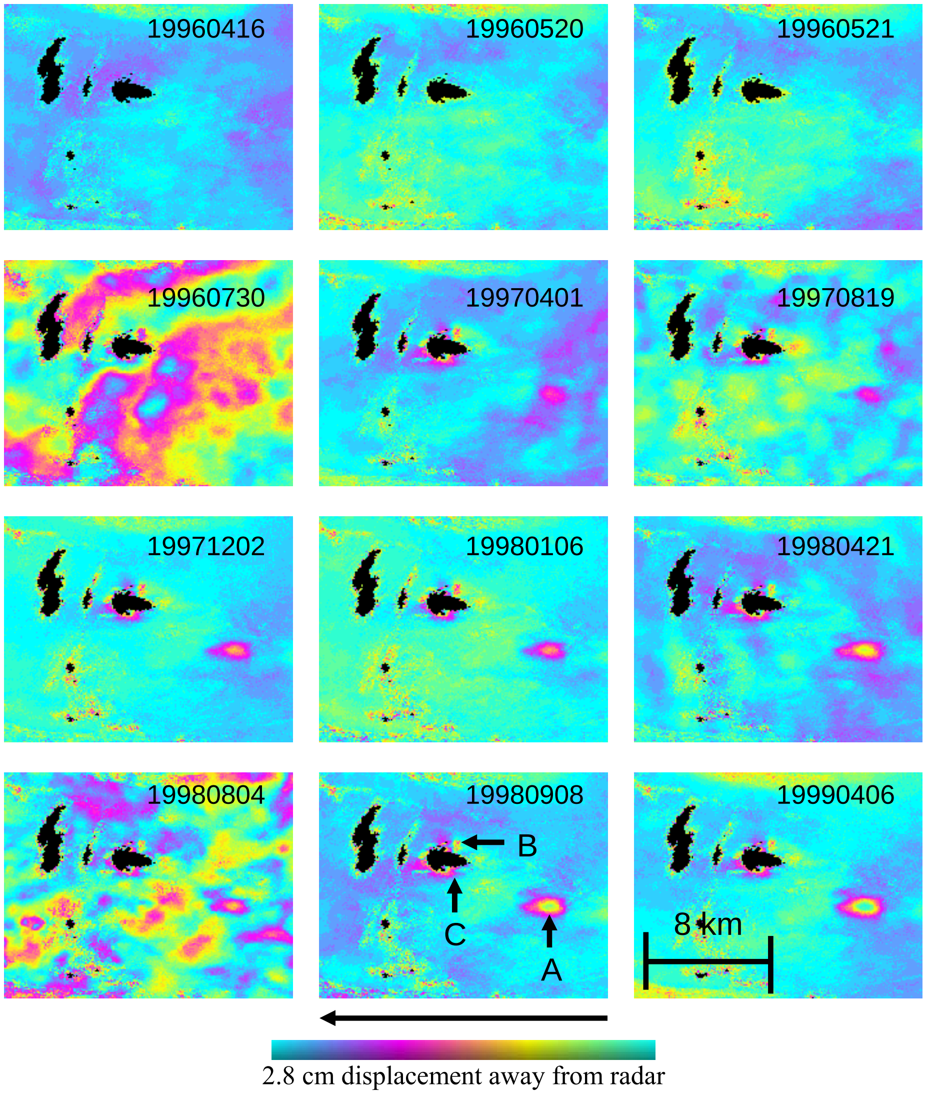

Figure 1. Maps of cumulative displacement since January 1, 1996 for Lop Nor. One cycle through color wheel represents 2.8 cm of radar line-of-sight displacement. The 19960730 and 19980804 images are noticeably afflicted with atmospheric artifacts.

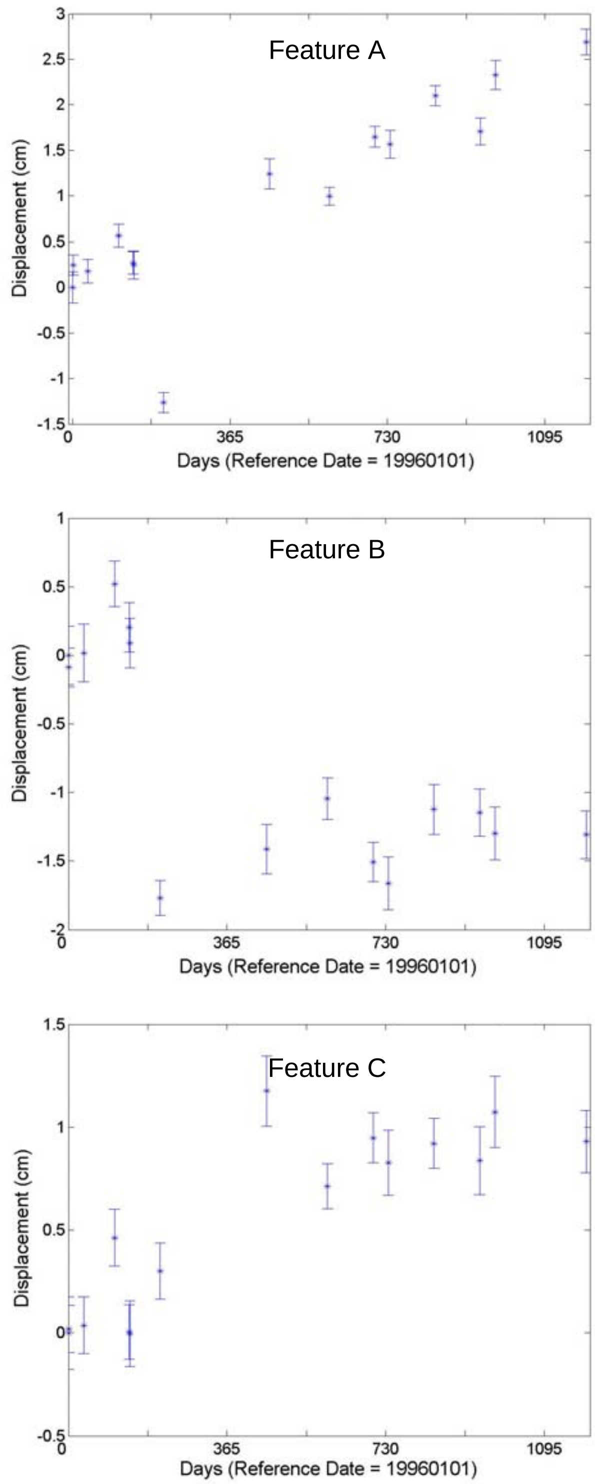

Figure 2. Cumulative displacement along radar line-of-sight since January 1, 1996 for features identified in previous figure. Positive (negative) displacement represents movement toward (away from) radar. Error bars correspond to one standard deviation for interferogram phase noise and SRTM DEM error variances propagated through inversion.

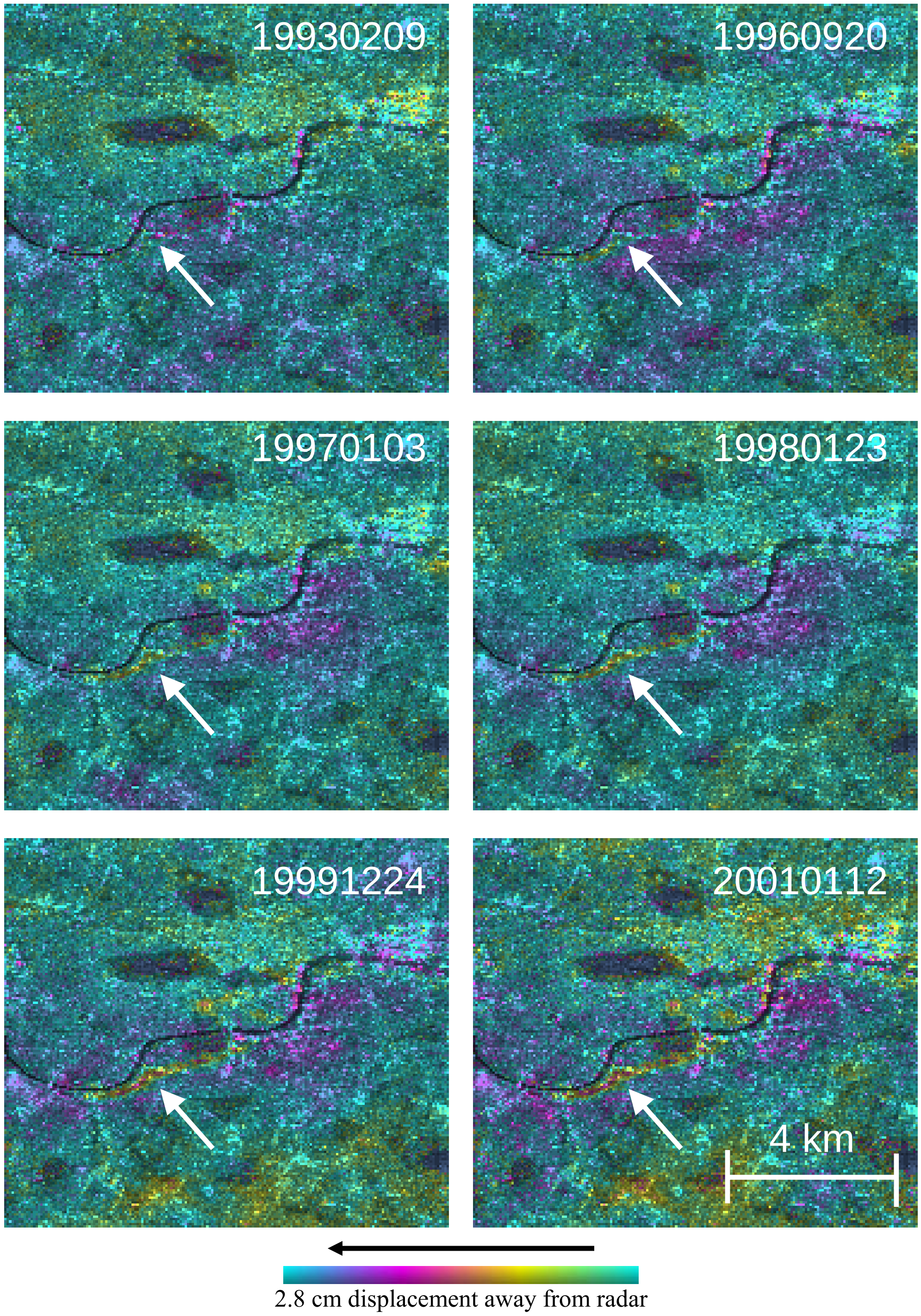

Figure 3. Maps of cumulative displacement since May 5, 1992 for London tunneling area. One cycle through color wheel represents 2.8 cm of radar line-of-sight displacement.

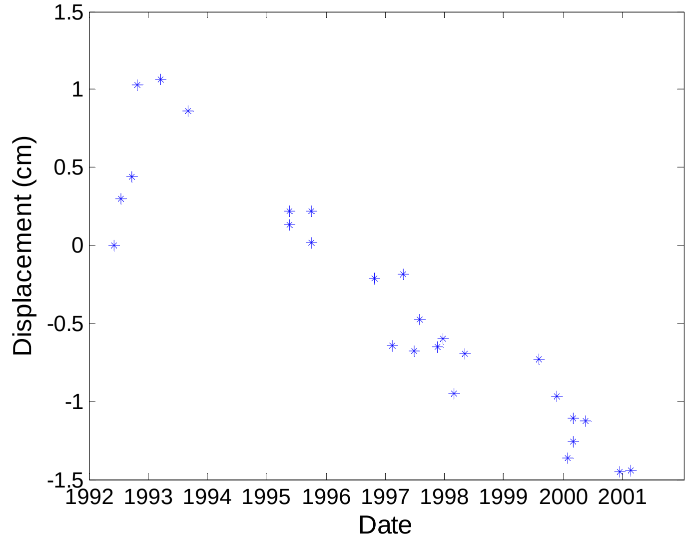

Figure 4. Cumulative displacement along radar line-of-sight since May 5, 1992 for London tunneling area identified by arrow in previous figure. Positive (negative) displacement represents movement toward (away from) radar.