Estimating orbital trajectories from fringe gradients in SAR interferograms for measuring crustal strain

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***Abstract*— We develop and assess a new orbital tuning approach by applying differential Synthetic Aperture Radar (SAR) interferometry. We use interferograms of the same site for estimating across-track and radial orbit adjustments from fringe gradients caused by orbit uncertainties. Our approach eliminates these fringes by using the improved short-arc orbit estimates. Taking six estimates from the Delft Institute for Earth-Orientated Space Research (DEOS), the approach yields mean standard deviations of 2.4 cm for the across-track and 4.5 cm for the radial components. The interferograms calculated with our post-fit orbital estimates compare favorably with those corrected with a conventional orbital tuning approach. We can now distinguish between orbital and deformation contributions to interferometric SAR phase gradients and are able to measure surface deformation changes over an interseismic time interval longer than one year. Our new approach is limited, however, to well-correlated interferograms where it is possible to measure the fringe gradient. We have also applied Permanent Scatterers (PS) technique to 42 SAR images acquired by ERS between August 1992 and June 1998. This approach estimates the average range change rate of more than 3 million PS with a formal standard deviation of 0.3 mm/yr along the line of sight. We obtain a phase coherence factor greater than 0.8 and a standard deviation of 3 mm for a single Line Of Sight (LOS) measurement. This velocity field is much easier to interpret than the separate interferometric pairs. Interpreting these interesting features in terms of geophysical models of inter-seismic and post-seismic deformation, however, will require further research effort.**

I. Introduction

Differential Interferometric Synthetic Aperture Radar (InSAR) images still contain contributions from orbit uncertainties as well as atmospheric and topographic artefacts. Consequently, the usefulness of an interferogram is limited by the problem of distinguishing deformation signals from orbital uncertainties [1]. The standard processing scheme assumes that errors in the satellite trajectories create a planar interference pattern with parallel fringes. Sometimes called a "phase ramp", this pattern is indistinguishable from a crustal deformation field with constant fringe gradient.

Currently, the best available trajectory estimates for the European Remote Sensing satellites (ERS)-1 and ERS-2, based on the fully independent Delft Gravity Model (DGM)-E04 and the GeoForschungsZentrum (GFZ) PGM055, show root mean square orbit differences of about 7 cm in the radial, 24 cm in the along-track, and 18 cm in the across-track directions [2]. These values should, in principle, be amenable to improvement by using the interferometric SAR phase change to measure range within a fraction of the ERS SAR wavelength (5.6 cm).

II. Approach and Results

For our approach, we assume that (absolute) orbit or state vector errors can be etimated by counting their artefactual fringe gradients in several interferograms of the same scene calculated with the erroneous orbit estimates and their corresponding SAR acquisitions. We count fringes along Distance and Azimuth to estimate the along-track and radial error component seperately. Errors in radial and across-track components both produce orbital fringes parallel to the track. The fringes perpendicular to the track reveal a variation of the previous ones or, in other terms, a wrong estimate of the radial and across-track velocities. Along-track errors are usually accounted for during the coregistration of the two SAR images [3], making the problem two-dimensional.

We develop equation systems for the differential range change along Distance and Azimuth to estimate the across-track error at two distinct times (beginning and end of acquisition) and the radial error at two different ranges (Near and Far Range), respectively. We thus measure the fringe gradients between the four distinct corner points of the interferogram. We seek to find the best linear unbiased across-track and radial correction parameters by solving the Gauss-Markoff model equation. Since we omit the pair composed of the first and last SAR epochs and have two free parameters for each orbit component, we always have a rank deficiency of two for each equation system. To overcome it, we regularize the solution by constraining the sum of the adjustment components of the i-th orbit to be zero. This constraint generates orbit adjustments with respect to quasi-absolute or virtual reference trajectories.

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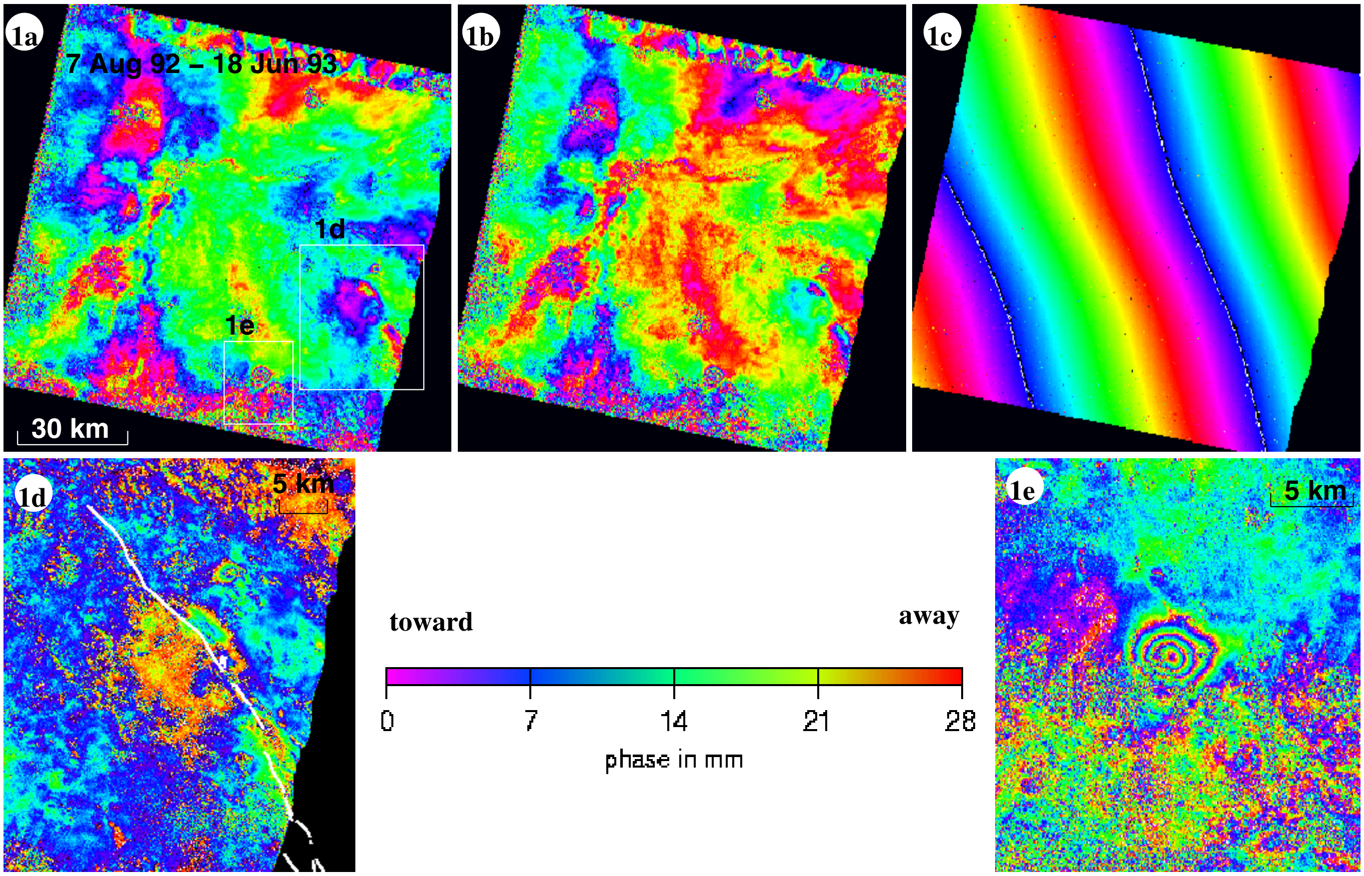

Fig. 1. Post-fit interferograms for the interval of time from 7 August, 1992 and 18 June, 1993 in DEM geometry. One cycle of colour corresponds to one cycle of interferometric phase cycle or 28 of change in the range between the SAR antenna and areflector on the ground. In the upper-left interferogram (Fig. 1a), we see the phase cycles after applying our new orbital tuning approach. In the upper-middle interferogram (Fig. 1b), we see the results after applying a conventional orbital tuning approach [1]. Fig. 1c shows the orbital fringe residual of phase differences from the interferograms calculated with the prior and improved orbital estimates. Figures 1d enlarges the area around the northern end of the co-seismic rupture as mapped in the field (white lines, [5]), that we interpret as post-seismic deformation in the months following the Landers earthquake of June 28, 1992. Figure 1e shows the deformation produced by the Fawnskin aftershock of 4 December, 1992 [10].

Applying our adjustment approach to six prior estimates of trajectory from the Delft Institute for Earth-Orientated Space Research (DEOS), we find a root mean square of 7.3 cm for the across-track correction components and 2.4 cm for the radial ones. Assuming 0.1 fringes for the a priori standard deviation of the measurement, our approach yields mean standard deviations of 2.4 cm for the across-track and 4.5 cm for the radial components. All numerical results and a detailed explanation of the approach are given in [4].

III. Discussion

To study a later post-seismic deformation field, we have re-calculated an interferogram whose SAR images were acquired after the 28 June 1992 Landers, California, earthquake. We have used the corrected, short-arc orbit estimates. We compare our new orbital tuning approach with the old one of a ramp removal [1]. The results are shown in Fig. 1.

This later postseismic interferogram was first calculated by [6]. It was made by differencing two coseismic interferograms, the first composed of images acquired on 24 April 1992 and 7 August 1992 [6]; the second composed of images acquired 24 April 1992 and 18 June 1993 [7]. Fig. 1a shows the immediate interferogram calculated with our improved orbit estimates and the corresponding SAR acquisitions.

Our improved interferograms show the geophysical deformation more clearly than previous studies. In particular, the postseismic deformation around the northern third of the Landers rupture zone (Fig. 1d) stands out prominently. Although we believe that this signature reflects a poro-elastic effect [8], [9], detailed modeling is beyond the scope of this paper. Similarly, the fringes created by the small thrust aftershock of 4 December 1992 (Fig. 1e), are now distinct from the parallel fringes to the northeast of its epicenter, which presumably recorded (mostly) the coseismic deformation from the Landers main shock combined with (some) orbital effects [10].

For the study of interseismic deformation fields, especially for the observation of slow lithospheric relaxation, long interferometric time intervals are necessary. In long time intervals, however, the physical change of surface scatterers can cause a so-called temporal decorrelation creating a noisy interferograms and making it difficult to observe fringes and then

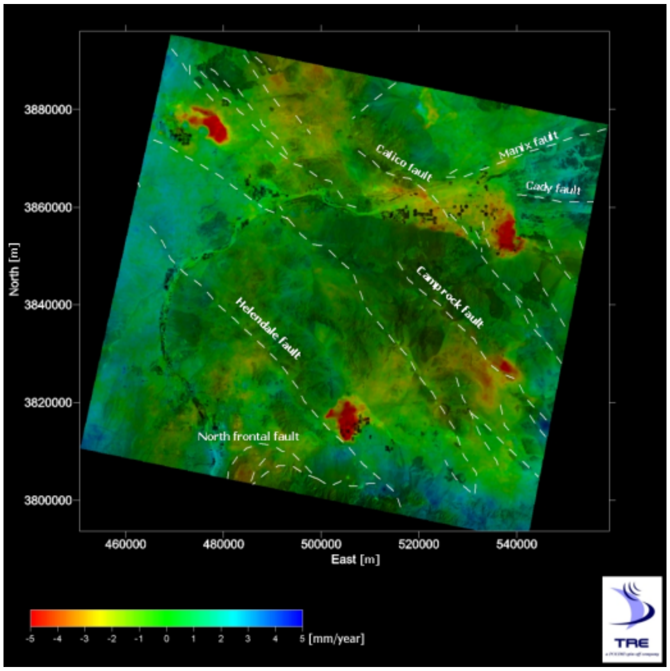

Fig. 2. Range change rate field estimated from PS in SAR images acquired by ERS between August 1992 and June 1998. The red and blue patches represent rapid deformation along the radar LOS that we interpret as post-seismic deformation following the Landers earthquake in June 1992 (lower right quadrant) including the Fawnskin aftershock of 4 December, 1992 [10].

extract useful information. Even in bare regions like the one around the Landers fault zone, this effect becomes significant in time intervals longer than two years [4]. To overcome this problem, we consider the use of the Permanent Scatterers (PS) technique recently developed by Politecnico di Milano [11], [12]. This technique aims at identifying radar reflectors only slightly affected by both temporal and geometrical decorrelation, by exploiting long temporal series of SAR acquisitions. The impact of atmospheric effects and/or orbital fringes can be strongly reduced in the final results, provided that enough data are available (typically > 20). 42 ERS SAR data acquired from August 1992 up to June 1998 have been successfully processed. This has yielded an average range change rate of more than 3 million PS with a formal standard deviation of 0.3 mm/yr along the Line Of Sight (LOS). We obtain a phase coherence factor greater than 0.8 and a standard deviation of 3 mm for a single LOS measurement. The extension of the area of interest is about 8.000 km^2, so the average PS density turned out to be ~ 400 PS/km^2. The final velocity field, reported in Fig. 2, is much easier to interpret with respect to single interferograms and shows interesting features that deserve further research efforts.

IV. Conclusion

Our new orbital filtering approach can significantly improve precise orbit estimates of short arcs of ERS trajectories in an absolute sense by using interferograms as measurements of relative position. It is, however, restricted to those orbital passes in which SAR data were acquired. Our technique is also limited to determining the across-track and radial components of the orbital trajectory. Furthermore, the technique requires additional care for coseismic or coeruptive cases, where the deformation field can cover the entire image. In this case, we must distinguish orbital fringes from deformational fringes, for example by using a separate model to parameterize the latter.

We can nearly eliminate orbital fringes in interferograms of post- and interseismic time intervals spanning more than one year. This permits us to measure interseismic strain fields of about 0.1 mm/km/yr and range change gradients of about 0.3 mm/km. Gradients smaller than this value tend to drown into the noise of topographic contributions or orbital residuals (~ 0.1 fringes).

In interferograms spanning time intervals longer than two years, the effect of temporal decorrelation is a limiting factor for the measurement of fringe gradients. The use of PS networks in bare and non urban areas, however, promises to be a powerful tool for geodetic studies.

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