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Refinement of geodetic velocities in the Los Angeles basin using improved GPS troposphere delay estimates

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Introduction

A central aim of tectonic geodesy (InSAR and GPS) is to develop the ability to identify anomalous surface deformation signals as they occur. In this way, potential precursory motions, be they accelerations of slow-moving landslides, or some as-yet unknown pre-seismic fault slip or strain transient, could perhaps be recognized in advance of a major disaster. Given that the amplitudes of such signals are typically low – recent creep events on faults on the Hayward and Superstition Hills faults have involved movements of only a few centimeters over the course of several weeks – our ability to detect them can often be hampered by noise. Thus a key challenge in our treatment of geodetic measurements is the implementation of strategies to mitigate the principal noise sources in our data. In the cases of GPS and InSAR, this means estimating the effects of tropospheric water vapor.

Both GPS and SAR satellites sample the troposphere using transmitted microwave signals of different frequencies (L1 GPS at 1.5 GHz, C-band SAR at ~5.3 GHz). Where present, water vapor refracts these signals, creating a phase delay that can bias GPS coordinates or InSAR-derived displacements. The troposphere is not dispersive with respect to microwaves however, and so the delay that is measured with one technique can be used to estimate the delay measured by the other (e.g. Onn and Zebker, 2006; Li et al., 2006). Continuously recording GPS stations track up to 12 satellites as they move across the sky at any given time, which allow them to sample the troposphere within a ~15 km radius. Within a dense network of continuous sites, it is possible to use this information to recover a 1D estimate of tropospheric delay above each site, in addition to site coordinates (e.g. Bevis et al., 1992). If appropriately interpolated, and scaled for the viewing geometry, these estimates could be used as a first order correction for tropospheric effects in InSAR data. Such a reduction in noise could not only aid the detection of transient strain phenomena, but also lead to more robust estimation of other parameters observed with InSAR, such as fault slip rates and anthropogenic deformation, which is common in southern California (Argus et al., 2005).

There are several objectives to this project. First, we aim to investigate temporal changes in tropospheric delay in southern California, by generating time series of delay at a subset of SCIGN and PBO continuous GPS network sites. Second, we further develop the methodology by using surface meteorological data as additional physical constraints on the troposphere delay model. Third, we investigate the spatial structure of water vapor in southern California by comparing SAR interferograms from different satellites and different satellite tracks. Finally, we attempt to develop methods for using the troposphere delay estimated from GPS to remove troposphere effects from interferograms, and to judge the effectiveness of the technique.

Time series of troposphere delay

We process the data recorded from 2004 to 2007 at 46 SCIGN continuous GPS stations in southern California using the GAMIT 10.2 processing software (King & Bock, 2006). We have chosen to estimate up to 14 troposphere delays per day using the atmospheric model of (Saastamoinen, 1972), corresponding to a regular estimate of troposphere state every two hours, plus additional estimates at the times of flyover of the Envisat satellite for ascending track image acquisitions (at approximately 05:30 UT) and descending image acquisitions (at approximately 18:00 UT). We have used a minimum elevation angle for station-satellite pairs of 15º above the horizon. This means, assuming that the tropospheric delay is dominantly from water vapour below 4 km elevation (Baby et al., 1988), every GPS antenna is affected by the troposphere state within a ~30 km radius. As the average station separation of the network is ~5–10 km, the overlap in coverage is sufficient to permit a robust estimate of the first-order spatial variation in tropospheric delay in the LA area, although other areas, such as Orange County and the Inland Empire have much more sparse coverage and poorer constraints on the troposphere delay.

Sample data for the site LONG, in the San Gabriel Valley, for the year 2005 are shown in Figure 2. Values of troposphere delay show a lot of scatter, with a variation of up to 10 cm and a mean of ~2.4 m; this degree of scatter is typical for most sites, although the absolute value varies with elevation, with sites in the High Desert tending to smaller values (1.8–2 m), as expected, given the thinner troposphere layer above those stations. The highest values of delay correspond to the months of July and August (Julian days 180-240), when surface temperatures are typically at their highest, although even then, rapid drops in the troposphere delay do occur.

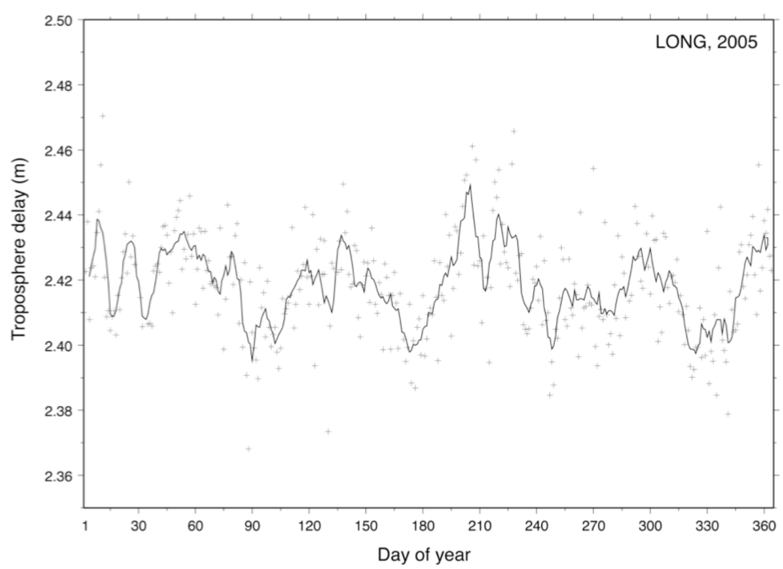

Figure 1: Time series of troposphere delay for 2005 for site LONG in the San Gabriel Valley (location in Figure 4). Crosses show the daily values of troposphere delay at the time of overpass of the Envisat satellite on its ascending orbit. The solid line is a seven-day moving average.

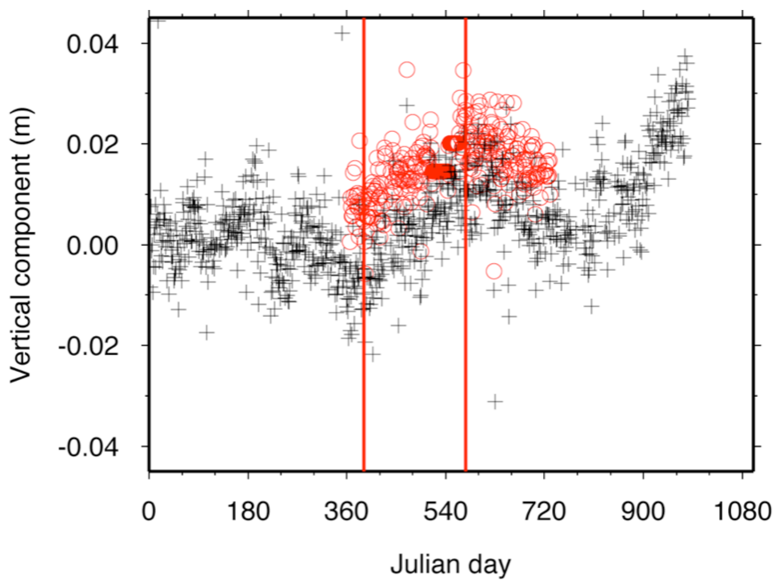

Figure 2: Vertical coordinate time series for 2004–2006 for site CVHS in the San Gabriel Valley. Here, black crosses show the daily solutions for vertical position without using additional constraints from meteorological data; red circles show the same quantities where the constraints were applied. The net effect of the constraint is to add a static shift to the vertical coordinates, and to reduce the scatter. The change in vertical coordinates between Julian days 360 and 720 is a result of aquifer inflation; the red bars correspond to acquisitions of SAR data spanning the inflation episode (see below).

We combine these data with surface observations by constraining the troposphere delay model for the GPS site JPLM to agree with meteorological data from its collocated weather station. The effect on the time series on other nearby sites (e.g. Figure 2) is to shift the vertical coordinates, suggesting that a bias has been corrected. In addition, the scatter in the coordinates is reduced. The horizontal coordinates are not significantly changed, implying that it is only the vertical coordinates that trade off against troposphere delay. Utilizing additional surface meteorological data from across the region may likewise improve repeatability in vertical coordinates, and thus vertical velocities, across a wider area.

InSAR observations of troposphere delay

A single SAR image contains phase information that is effectively a snapshot of the distance from the satellite to the ground, overprinted by the phase delay due to water vapor in the troposphere. In order to isolate the signal due to the troposphere in an interferogram, it is necessary to minimize or cancel any signal due to changes in satellite-ground distance. We can attempt this in two ways – construct interferograms spanning the shortest possible time periods, or find intervals where it is possible to construct both Envisat-Envisat and ERS2-ERS2 interferograms, and difference them. The first approach is hampered by the often very rapid movements of the surface in the Los Angeles basin due to aquifer recharge/discharge and oil extraction (e.g. Argus et al., 2005). The result of such movements is that interferograms formed from two images with the minimum repeat time (35 days for ERS2 or Envisat) can still contain significant deformation signal (although this is typically located in the same place in every interferogram).

The second approach uses the fact that Envisat and ERS2 are in the same orbit, separated by only 28 minutes, thus any differential deformation signal between two interferograms formed in this way is minimal, and will cancel when the interferograms are differenced. The level of remaining signal depends strongly on how static the troposphere is on the two acquisition dates – if there is no change in the position of bodies of water vapor in the troposphere on either of the two acquisition dates, there should be zero signal in the differenced interferogram. If, on the other hand, there is a significant change on one or other acquisition date, due to wind, for example, a signal should be seen; the movement of a water vapor body should be manifest as a paired set of positive and negative signals, offset parallel to the local wind direction. Such paired signals can be seen in several of our differenced interferograms (e.g. Figure 3), suggesting that troposphere models need to be able to account for such rapid variability.

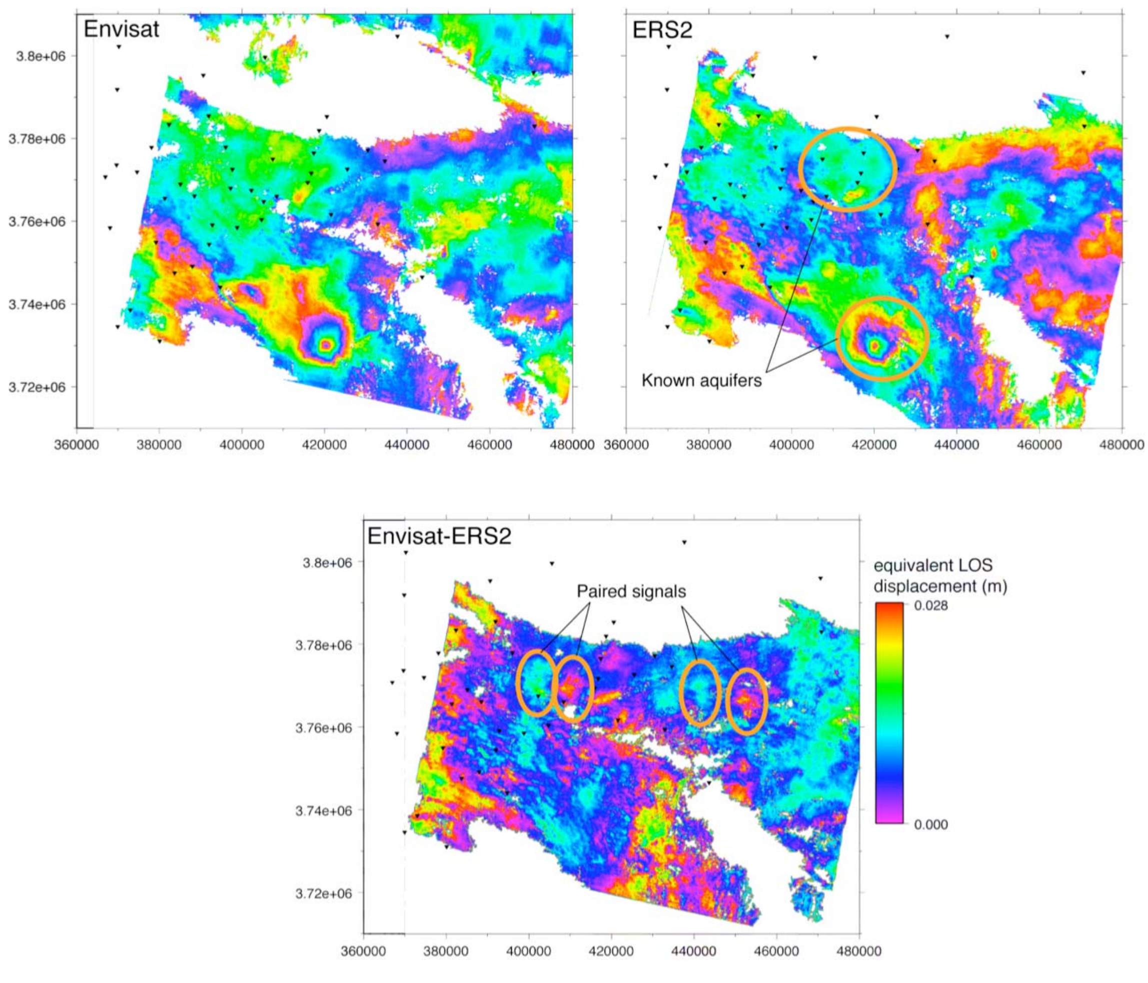

Figure 3: Example of a differenced pair of Envisat and ERS-2 interferograms with identical acquisition dates (interferograms span the 70 day interval 04/14/2007–06/23/2007). In the individual interferograms, the largest signals visible are collocated with known aquifers, and are likely to be deformation due to aquifer discharge. These deformation signals disappear in the differenced interferogram, which instead shows paired positive and negative tropospheric signals reflecting a change in troposphere state in the 28 minutes between satellite passes.

Using GPS-derived troposphere delay to correct for water vapor in InSAR data

We test our methodology, and its ability to estimate and correct for tropospheric effects, on a known deformation transient. Heavy rainfall in the spring of 2005 was accompanied by an inflation of a shallow aquifer in the San Gabriel Valley, recorded by seven local continuous SCIGN GPS stations as outward radial and vertical displacements (King et al., 2007; Figure 2). A SAR interferogram, constructed from the same data as that shown in Figure 4, and that spanned the inflation episode was also considered to agree with the GPS displacements, and suggested that there may be additional complexity to the deformation pattern, with a concentrated uplift at the center of the aquifer. To test the robustness of this interpretation, we difference and then interpolate our GPS troposphere delay estimates for the two SAR image acquisition times, to create a continuous differential troposphere map to correspond with the interferogram. We use a kriging interpolator, assuming an exponential variogram with e-folding wavelength 15 km, allowing overlap between the responses of different GPS sites. We then difference this map, appropriately scaled for viewing geometry, with the interferogram. Our results suggest that the peak 'signal' over the area in question is significantly mitigated by this differencing (Figure 4) and was at least partially tropospheric. Further details are found in Houlié et al., manuscript submitted to GJI, 2008.

Having qualitatively demonstrated that the application of tropospheric corrections can plausibly change the interpreted deformation field, the next challenge is to find a metric by which the 'improvement' can be quantified. Typically, the troposphere maps have lower effective resolution than interferograms, so that the 'corrected' interferograms may reduce signal power at long wavelengths, but impose errors at short (<5 km) wavelengths. We are currently testing different methods, such as low-pass filtering, and sub-sampling and re-interpolating the InSAR data, in order to find the best means of comparing data and model.

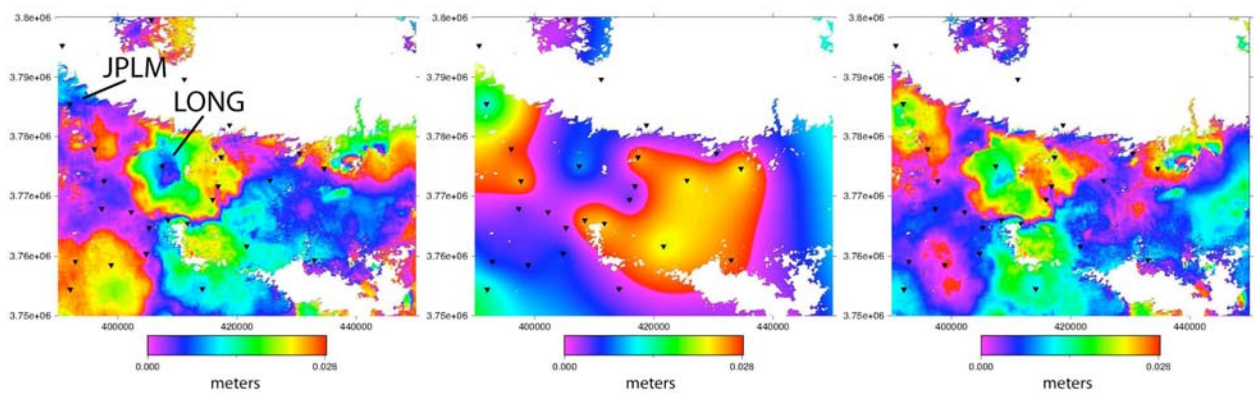

Figure 4: *Left:* Envisat ASAR interferogram of the San Gabriel valley (interval 01/26/2005–07/20/2005, perpendicular baseline 39 m, ascending track 120, frame 675). Displacements are in terms of range change in the line-of-sight of the satellite. Black inverted triangles indicate SCIGN stations used in this preliminary study; key sites LONG and JPLM are indicated. The uplift signal is a hexagonal feature approximately 15 km across, and centered on LONG with an average line-of-sight displacement of ~2 cm, peak deformation is local to LONG and has an amplitude of 1 interference fringe (2.8 cm). *Center:* Interpolated differential troposphere delay map, estimated from GPS and meteorological data and adjusted for SAR geometry. *Right:* Interferogram with estimated troposphere removed. The peak of the signal centered on site LONG, visible in the original interferogram, has mostly been eradicated. [Coordinates given are UTM meters, zone 11.] From Houlié et al. (2008).

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