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Improving the Tectonic SNR in Geodetic Data: Loading Corrections and Seasonal Adjustment

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Abstract

This grant supported the analysis of GPS and other data to develop and utilize tools for removing nontectonic motions related to redistributions of mass from motions of fluids (air, water, oil and gas) from continuous GPS data. Tools were developed for seasonal correction of the data, comparison of loading models with observations, and (unexpectedly) inverting a large signal in the GPS verticals caused by the ongoing drought in the Western US. Particular accomplishments include:

1. Routine processing of continuous GPS data to remove seasonal variations, allowing both for the non-harmonic and time-varying nature of these variations.
2. Discovery of an un-noticed vertical change in the GPS data from the Plate Boundary Observatory (PBO) timeseries, starting in 2013, and determination of which analysis center results were more reliable.
3. Association of this signal with the ongoing drought, and showing that it could be used to determine the temporal and spatial changes of anomalous water storage throughput the western US.
4. Computation of the stress associated with these chnages, both on faults throughout California and on the rupture zone of the 2014 Napa earthquake, showing that the stress changes were much smaller than those usually associated with triggering.

1 Introduction

Thanks to considerable effort on the part of the geophysical community, the decade from 1997 through 2007 saw an order of magnitude increase (to more than 800 sites) in the number of continuous GPS stations installed to measure crustal motion in California. Efforts in processing, archiving, and data dissemination mean that daily time series of position are now routinely produced, and readily available, for all sites.

But this technical advance has not been matched in the amount of geophysically useful information obtained from all this data. It has been straightforward to obtain information about the lowest frequencies (long-term rates) and highest frequencies (coseismic offsets). For larger earthquakes, the data have also been used to study the coherent, and sometimes large, signals from postseismic deformation (e.g., Freed (2007), Freed *et al.* (2007), Barbot *et al.* (2009)).

But it has proved difficult to identify other signals. How much this is caused by the Earth producing only few, and small, aseismic transients remains uncertain; and part of this uncertainty arises from the noise present in the GPS data, which masks all but relatively large signals.

This uncertainty has led to ideas for algorithms that would systematically process GPS data from many stations to identify, and perhaps locate the source of, strain transients. The geodesy group of the Southern California Earthquake Center (SCEC) decided to encourage the development of such methods by supporting systematic comparisons between them. Initial comparisons were done on synthetic data sets made to be as similar as possible to real data, and provided as a blind test. I received SCEC funding to provide these synthetic datasets, which was done by developing software (`FAKENET`: Agnew (2013)) for simulating the random behavior of geodetic data and combining this behavior with the motions expected from different sources. An early version of this package was used to produce datasets used in the Phase I tests in early 2009; a later version produced data for the Phase II tests, starting in summer 2009. These tests (Murray-Moraleda and Lohman, 2010) showed that there was a fairly definite threshold (in terms of source size and duration), above which the source was obvious and below which it was not seen at all.

This result suggested that further progress will be aided most by reductions in the noise of the GPS data. Here "noise" means anything nontectonic that affects the GPS estimated position. Given that the number of GPS series is now such that it is very difficult to just "look at the data" to identify noise sources, noise reduction, like transient identification, will require automated procedures. But to develop these requires that we understand the sources of nontectonic variations in the GPS timeseries. These sources of variation come in two types:

- **Exogenous noise sources:** These sources of noise are intrinsic to the GPS system, and would appear even if the stations never moved; they include receiver noise, orbit error, multipath, time-variable masking of the satellite signal, and unmodeled atmospheric and ionospheric delays. From the GPS analysis point of view they might be termed endogenous, but from the standpoint of geophysics they are "outside".

- **Endogenous noise sources:** These are noise sources that actually cause the stations (specifically the antenna reference point) to move; they would be observed even if the measurements were perfect. These include monument motion relative to the average of the surrounding material; and motions of that material caused by weathering, soil compaction, poroelastic effects, and elastic loading.

Note that some exogenous and endogenous noises may have the same driver, appearing in different ways: atmospheric changes alter the signal delay and also move the station.

This work aimed to investigate, identify, and reduce endogenous sources of noise. This is certainly not a new subject; space geodesy has for some time included investigations into reducing the variability of time series by modeling nontectonic variations. Many of these studies have however focused on global GPS data, particularly on the stations that define the International Terrestrial Reference Frame. The aim was to narrow the focus to GPS stations relevant to NEHRP concerns, with an initial focus on California and the New Madrid region: given the low strain rates in the latter region, any noise reduction to the time series collected will be vital to getting meaningful results.

The largest and most easily modeled signal come from elastic loading of the Earth. Because the Earth is not rigid, varying loads on its surface induce instantaneous vertical and horizontal displacements due to elastic yielding of the crust (Farrell, 1972), which can be measured at the submillimeter level using GPS. The largest loads come from the ocean, and GPS has been used to observe displacements from both tidal (Baker *et al.*, 1995; Vergnolle *et al.*, 2008; Penna *et al.*, 2015; Bos *et al.*, 2015). and nontidal (Williams and Penna, 2011) variations in sea level. Improved methods, and longer time series, have also enabled GPS-based detection of displacements caused by seasonal changes in hydrologic systems, whether in lakes (Elósegui *et al.*, 2003) or in river basins (Bevis *et al.*, 2005; Bettinelli *et al.*, 2008). Measurements of vertical or horizontal motion caused by changing loads integrate the effects of the loads around them, which is both an advantage, in providing data from areas otherwise not measured, and a problem, since the actual spatial distribution can only be estimated through an inversion of the data.

In the event the timing of the work presented the opportunity to study a very large endogenous signal caused by the drought in California: (ongoing as of the date of writing). While this was a change from the work originally envisaged, it provided both a GPS signal that might be mistaken for tectonics (as had happened on an earlier occasion (King *et al.*, 2007)),

and a chance to investigate the ability of GPS position timeseries to examine changes in water storage – a subject of considerable interest to some parts of the USGS. This grew from an examination of GPS time series by Dr. Adrian Borsa, a member of the Research series at Scripps/UCSD, and some portion of salary was provided to him to enable the investigations described in the next section.

2 Work Plan and Results

This section describes our investigations. The initial step was the development of the software needed for initial data cleanup and examination of a large number of stations. The procedure was to detrend each time series to remove secular tectonic motion, and remove seasonal displacements using the STL (Seasonal-Trend-Loess) procedure (Cleveland *et al.*, 1990), smoothing the result by loess filtering with an L_1 misfit criterion. Seasonal signals from water loading (Steckler *et al.*, 2010; Argus *et al.*, 2014) are traditionally modeled by annual and semiannual sinusoids, but additional harmonics and the modulation of harmonic amplitude and phase often appear in GPS time series (Bennett, 2008; Davis *et al.*, 2012), requiring this more general form of seasonal adjustment.

Figure 1 shows an example of this process. Applying it to the data produced by the Plate Boundary Observatory one feature that became immediately apparent was uplift at the beginning of 2013. Further examination showed that these feature was extremely widespread, extending across the entire United States – something more consistent with a reference-frame shift than some endogenous signal. However, when the analysis procedure was done on the separate series (NMT and CWU) produced by the PBO analysis centers, it could be seen that this continent-wide uplift was seen only in one series (CWU), suggesting that the reference-frame shift was present only in that series, from which it had appeared in attentuated form in the PBO combined series. Further analysis thus focused on the time series from the NMT center, produced using the GAMIT/GLOBK software.

To study recent vertical motion in the WUSA, we analyzed the last 11 years of daily vertical positions estimated for continuous GPS stations in the Plate Boundary Observatory (PBO) and in several smaller networks. We included only stations whose data span at least the period 2010-2013, are at least 75% complete, and have no gap longer than 91 days. Removing the seasonal signal and smoothing day-to-day changes allows us to detect transients more reliably. Transient displacements can be driven by volcanic or tectonic sources (Dzurisin, 2007), poroelastic effects created by local and regional groundwater extraction and recharge (King *et al.*, 2007; Galloway and Burbey, 2011), and the response to varying loads, such as changes in surface water storage (Elósegui *et al.*, 2003; Wahr *et al.*, 2013). Based on data from the 2003-2012 period, these effects contribute no more than about ± 10 mm of cumulative vertical displacement for any given station Figure 2. While fictitious ver-

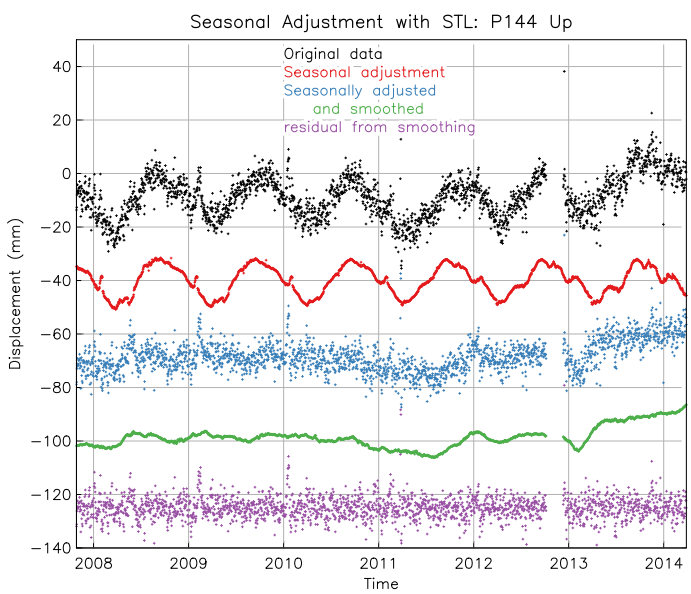

Figure 1: Example of seasonal decomposition of a GPS time series, for the vertical component at PBO station P144, in the Sierra Nevada NNE of Nevada City (39.47°N, 120.89°W, 1440 m elevation). The top trace is the daily data; and below it is the seasonal (red), when this is subtracted it produces a seasonally adjusted series. This in turn is decomposed into a smoothed series, and (green) and a residual (purple); the latter approximates a white noise, with purely random variations. Note the uplift starting in 2013.

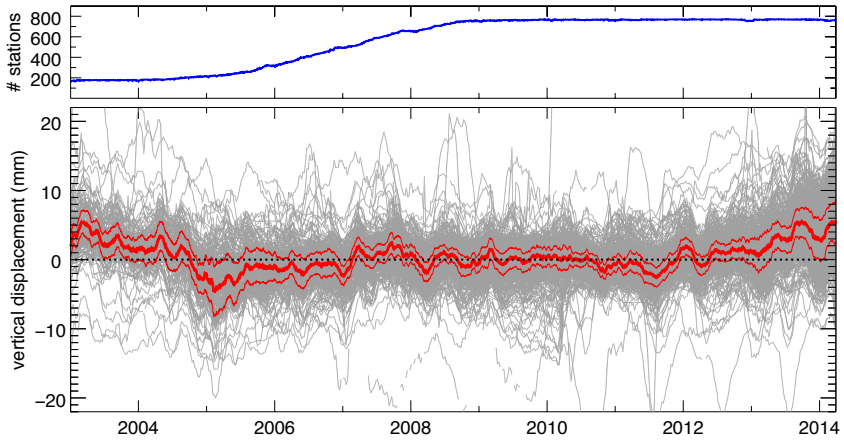

Figure 2: Daily GPS vertical displacements from 771 continuous GPS stations in the western USA. In the lower panel the gray shows all the smoothed, seasonally adjusted station time series (see Figure 1, decimated to weekly intervals after subtracting a trend over the period 2003-2014. The thick red line shows the median value of all data for each day and the light red lines indicate the standard deviation computed from the interquartile range. The uplift that begins in mid-2012 is unprecedented for the period following 2006, when the building of the Plate Boundary Observatory dramatically expanded the number of GPS stations in the region (blue line in top panel shows number of stations used each day).

tical displacements can be caused by variations in the signal-scattering environment close to each station (Elósegui *et al.*, 1995; King *et al.*, 2012), this effect is not spatially correlated and does not affect our results.

Collectively, these adjusted GPS time series reveal regional patterns of crustal deformation not otherwise observable. When averaged over the WUSA, GPS-measured vertical displacements indicate that anomalous uplift definitely began in mid-2012 and has continued through the most recent observations (Figure 2). Although the magnitude of the uplift is only 5 mm relative to the 2003-2012 mean, this represents a significant deviation from the < 2 mm vertical motion present in the median since the start of PBO network construction in mid-2005. (The high variability before 2006 is most likely because there were many fewer stations, most of them in southern California). As of March 2014, the uplift appears across the entire region, with the largest values in central California (Figure 3). A year earlier, the uplift had been limited to central and southern California, while the Pacific Northwest and northern California showed subsidence. In March 2011 the vertical displacement pattern was nearly the opposite of March 2014, with the WUSA exhibiting widespread subsidence, which was also largest in central California.

These results indicate that nonseasonal crustal deformation patterns vary considerably from year to year. Examining the data at weekly intervals shows that these pattern evolve coherently on spatial scales of 100 to 1000 km over the entire period of analysis. This is not the signature of GPS processing error, which would typically cause random noise or network-wide motion, or of groundwater extraction, which primarily affects agricultural or urban areas (Galloway and Burbey, 2011). There is no significant horizontal GPS displacements, which rules out tectonic or volcanic processes (Grapenthin *et al.*, 2010). The only process that can reasonably account for the observed deformation is spatiotemporal variation in crustal loading.

Accurately modeling the surface loading corresponding to observed vertical displacements requires the removal of GPS time series contaminated by other effects. From the 874 stations examined, we removed 27 stations within a convex hull that bounds California's Central Valley, where significant vertical motion occurs because of groundwater recharge and extraction over a wide range of timescales (Ikehara, 1994; Hanson *et al.*, 2010); extraction has likely increased in the last two years because of dwindling surface water supplies. We also removed 14 stations in the Long Valley caldera, which has been actively deforming over the period we study (Ji *et al.*, 2013), and an additional 55 stations whose seasonal vertical displacements do not exhibit the expected summer peak (Argus *et al.*, 2014), indicating the influence of forces unrelated to loading. From the remaining stations, we removed 13 whose vertical displacements relative to the median in March 2014 were > 3.5 times the interquartile range, leaving 771 stations as the basis of our analysis.

We used the observed displacements to estimate the distribution of loads on a 0.5-degree grid spanning the WUSA, for March 2014. For each GPS site, we calculated the verti-

cal displacement from a unit load at each element of this grid using the Green functions for the response of an elastic Earth to surface loads (Farrell, 1972; Agnew, 2007, 2012). These responses were used to construct the Jacobian matrix for a Gauss-Newton inversion that minimized the root mean square (rms) difference between predicted displacements and their average observed values in March 2014. We stabilized the inversion by applying a minimum-curvature (smoothness) constraint to the gridded loads, and varied the weighting of this constraint relative to misfit to recover loading models of varying smoothness.

For our analysis we chose a model that balanced misfit and smoothness (Figure 4). Predicted displacements from this loading model reduce the rms of the observed vertical GPS displacements by 53% and yield spatially random residuals. Validation testing suggests that, given the 30 km station spacing of the existing GPS network, the inversion is capable of a spatial resolution of 200-300 km, though this is reduced at the northern and eastern edges of the network, where the station spacing is larger.

The result of the inversion is an estimated load that resembles the vertical displacements, though smoother because of the imposed constraints. In March 2014, when most station vertical displacements are farthest from their long-term averages, our results (Figure 4) show crustal unloading over the entire WUSA, with a maximum in the central Sierra Nevada equivalent to 50 cm of water. There appears to be a small amount of real non-tectonic loading in Montana, while the apparent loading just south of the US-Mexico border is probably caused by postseismic effects from the M_W7.2 El Mayor-Cucapah earthquake in 2010 (Pollitz *et al.*, 2012). The arid regions of eastern California, Oregon, Washington and western Nevada show little loading. Estimated loads near the northern and southern boundaries of the grid, and in Arizona, Utah, and Montana, are poorly constrained by the GPS data and are not likely to reflect the actual loading.

We interpret the estimated unloading to represent hydrological variation, specifically changes in water storage in snowpack, near-surface aquifers, and soils. Since seasonal changes have been removed from the GPS time series, the estimated loading represents interannual change in surface water. The widespread negative loading, with its central California maximum, corresponds to observations of the extent and severity of the current WUSA drought. Also, the implied drying relative to the long-term mean appears to be most acute in coastal and mountainous areas and subdued in highly arid regions. This is expected, since in a drought the change in precipitation is proportional to the climatological mean value, so arid regions lose much less water than do wet regions. The area-integrated water deficit over the WUSA in March 2014 is 240 Gt, equivalent to a uniform layer of water 10 cm deep. The total water deficit is relatively insensitive to the choice of model used and does not vary by more than 6% from this value for the range of models investigated.

The temporal and spatial water storage variations implied by the observed displacements is strikingly consistent with observations of precipitation and streamflow in the Western USA. Precipitation (rain and snow) in March of the past four years relative to the long-term

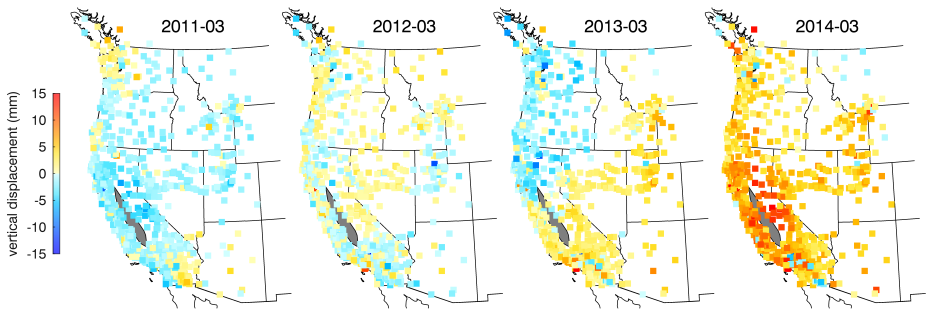

Figure 3: Spatial distribution of the GPS vertical displacements in Figure 2 as of March 1 for the years 2011 through 2014. Yellow-red colors indicate uplift, which first appears in Southern and Central California in 2013, and by 2014 has increased there and spread across the western US. Subsidence, indicated by shades of blue, is visible across the western US in 2011 and in northernmost California and the Pacific Northwest in 2013. Gray region shows the area of excluded stations in the Central Valley of California.

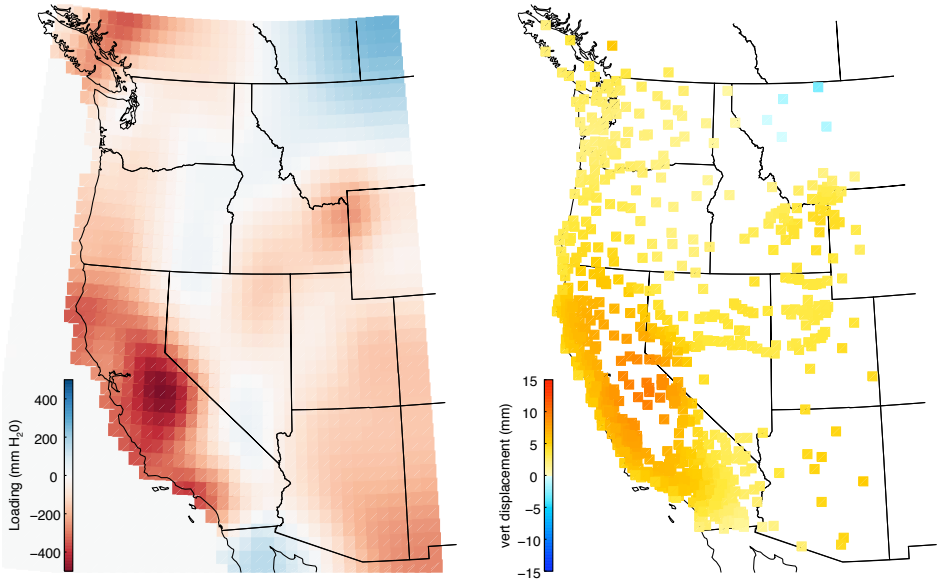

Figure 4: Left: loading estimate for the western USA in March 2014. Redder areas indicate negative loading (a mass deficit relative to the 2002-2012 mean), bluer areas indicate positive loading (mass surplus), and white areas are unchanged. Right: Vertical displacements corresponding to loading model in left panel, at the locations of the GPS stations used in this analysis.

average at 7078 meteorological stations in the National Climatic Data Center's GHCND network highlights the change from the 20111 wet winter throughout most of the WUSA, to the 2013 dry winter in parts of California and the Great Basin, to the 2014 severe drought along the Pacific coast. In particular, the March 2011 and 2014 precipitation patterns match the pattern of vertical displacements for, respectively, excess (wet) and deficit (dry) loading conditions. Daily stream discharge data from the USGS stream gauge network exhibit wet/dry patterns similar to the precipitation data, although it is the years 2013 and 2014 that most closely match the vertical displacements.

It has been suggested (Amos *et al.*, 2014) that seasonal and long-term changes in water load may have had a measurable effect on seismicity rates in along the San Andreas fault. To examine this, we computed the surface strain caused by the load estimate in Figure 4 and converted this to maximum Coulomb stress change (Agnew, 2012; Astiz *et al.*, 2000). Along the San Andreas fault the change in Coulomb stress from the last two years of change in water load is 100-200 Pa, approximately the same as the change caused there by a week of tectonic strain accumulation(Smith-Konter *et al.*, 2011), so stress changes from the drought unloading seem unlikely to affect seismicity. In the particular case of the South Napa earthquake (May ?? 2014) the maximum shear stress from the load was of order 10 Pa or less, far below the level of stress changes associated with the Earth tides.

3 Publications

The only publication from this work to date is Borsa *et al.* (2014); an additional publication on the STL method is in preparation.

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