GPS constraints on InSAR-based velocity models

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I. Project Overview

A. Abstract

In recent years, the steadily increasing volume of GPS observations and freely-available SAR imagery has prompted calls from the community for a model of ground deformation that is consistent with both of these data types. Such products have been produced in the past, such as the Crustal Motion Map, which included contributions from campaign and continuous GPS data, as well as models of coseismic offsets. A growing number of research groups have versions of a secular model of motion at existing sites, as well as models of hydrologic loading/seasonal cycles. In Southern California, the density of GPS stations is high enough relative to the size of individual SAR frames to motivate consideration of how consistent secular models are between the two observation types.

The SCEC community, therefore, proposed the creation of a Community Geodetic Model (CGM), with the goal of developing a consensus model characterizing deformation in Southern California. Such a model could be used as input to efforts such as the Crustal Stress Model, aseismic transient detection, block modeling and characterization of long term slip rates along faults, the integration of geodesy into hazard maps, and an important record of interseismic deformation rates in the event of a large earthquake in Southern California, facilitating later studies of the observed postseismic deformation and/or interactions with other faults. Here, we propose to explore a problem identified during the latest CGM workshop – the appropriate choice of metrics to use when comparing InSAR and GPS-based models of deformation. We ended up focusing further on atmospheric models used in correcting InSAR, and on ways to present 3D deformation fields generated from GPS and InSAR.

B. SCEC Annual Science Highlights

Tectonic Geodesy
Stress and Deformation Through Time (SDOT)
Aseismic Transient Detection

C. Exemplary Figure

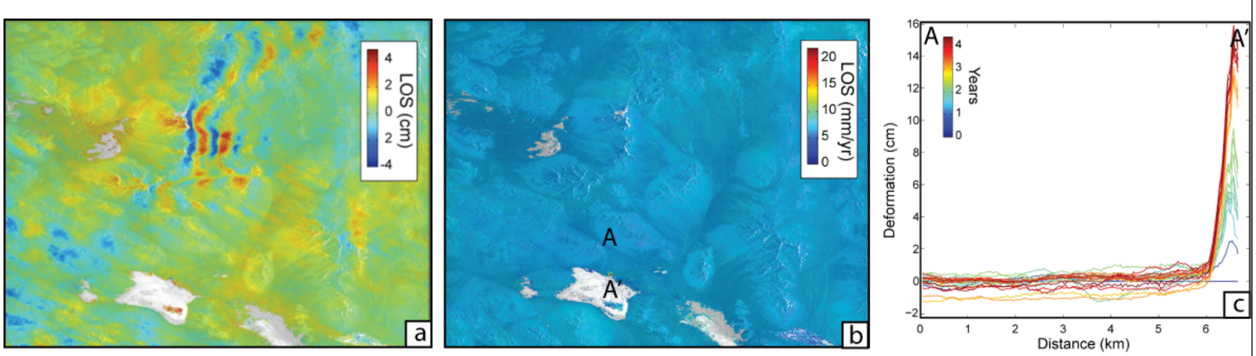


Figure 1: InSAR time series analysis - Mojave desert example. a) Single interferogram with significant atmospheric perturbations - image is in radar coordinates, image is approximately 100 km in width. Gray area to lower left is a salt flat that decorrelates in most interferograms. b) Average secular rate for interferogram stack – color scale is large to highlight the small region with very high rates of subsidence to the north of the salt flat. c) Profile from A-A' in (b), actual line not shown in (b) to avoid obscuring signal, showing cumulative displacement colored by date. Note that rate is approximately constant during this time period.

D. SCEC Science Priorities

Has made progress towards:

1d: Development of Community Geodetic Model
1e: Combined modeling of GPS/InSAR for fault parameters
5b: Applications of geodetic transient detectors

E. Intellectual Merit

How does the project contribute to the overall intellectual merit of SCEC? *For example: How does the research contribute to advancing knowledge and understanding in the field and, more specifically, SCEC research objectives? To what extent has the activity developed creative and original concepts?*

This research contributes to our understanding of crustal motions over time, in particular within the vertical direction.

F. Broader Impacts

How does the project contribute to the broader impacts of SCEC as a whole? *For example: How well has the activity promoted or supported teaching, training, and learning at your institution or across SCEC? If your project included a SCEC intern, what was his/her contribution? How has your project broadened the participation of underrepresented groups? To what extent has the project enhanced the infrastructure for research and education (e.g., facilities, instrumentation, networks, and partnerships)? What are some possible benefits of the activity to society?*

This project has worked towards enhancing the intellectual infrastructure (codes, etc.,) behind the integration of InSAR and other datatypes (e.g., GPS, weather models) in ways that will better enable us to use InSAR to study fault behavior, groundwater withdrawal and geothermal power generation.

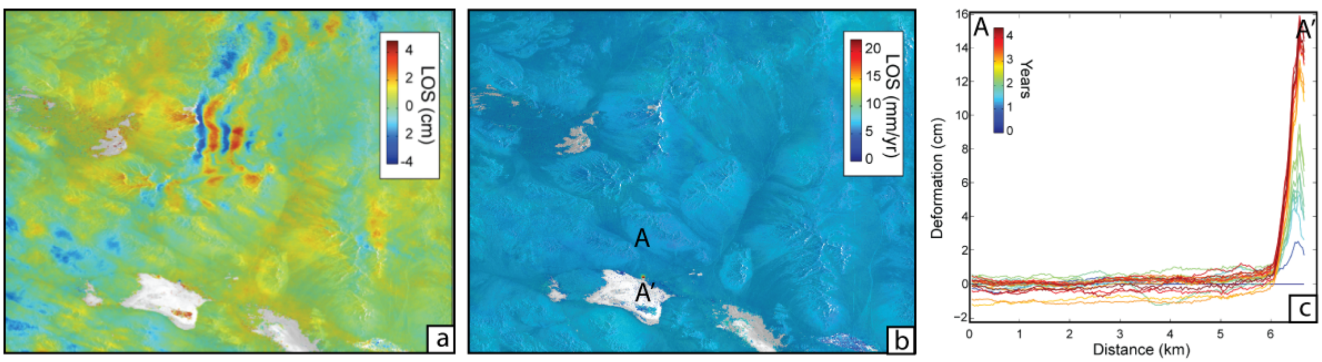
G. Project Publications

Scott C. and Lohman R. B., 2016. Sensitivity of earthquake source inversions to atmospheric noise and corrections of InSAR data, Journal of Geophysical Research, accepted.

II. Technical Report

The proposed work initially was meant to focus on the time series within the frame of the previous InSAR joint comparison exercises, with a time series being generated for that frame using several methods of combining the GPS data. As we entered into this project, it was apparent that much of the difference between the individual InSAR models that were being submitted by different groups came in the form of atmospheric models that were used as corrections (either independent models from atmospheric sciences, or empirical models such as elevation-dependent fits), or of filtering approaches that would necessarily remove (or insert) signals with particular scale ranges.

Figure 1 illustrates one particular example from the Mojave desert, where a single interferogram (left) indicates the presence of a very large, almost 10cm signal that is much smaller inspatial scale (few km) than what could be captured in an atmospheric model. Despite the presence of this sort of noise, time series over this location are quite smooth (no atmospheric corrections used), allowing constraint on a very small scale but large magnitude subsidence signal associated with saline brine generation (A-A') profile.



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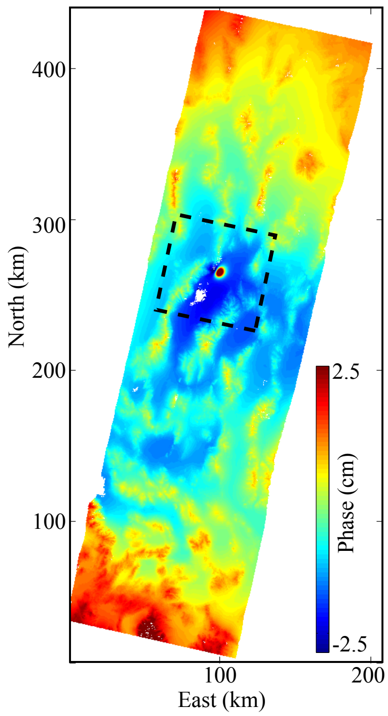
While this case is intriguing from the perspective of the increasing number of anthropogenic deformation signals that are becoming measureable, tectonic signals of interest to the SCEC community tend to be below a much smaller detection threshold. Problematically, these signals also often are correlated with topography, as are variations in tropospheric water vapor. This means that we either need to have very good models of the atmospheric characteristics and their variations over time, or so much data that we can rely on the atmospheric contribution to average out to below our required detection threshold. This problem led to some renewed effort in our group on understanding the impact of atmospheric corrections on SCEC-style research.

A. Atmospheric corrections

In brief, our work (just accepted in JGR) involved the generation of synthetic noise on a long InSAR track (5 frames) similar to that being examined across the San Andreas fault and other systems, and then an assessment of the impact of various corrections on the inferred source parameters for a small earthquake if it were to occur within that dataset. We used the North America Regional Reanalysis (NARR) model over our source region, and generated synthetic radar delay maps that followed the actual correlation structure between layers in that model (i.e., we did not impose a particular elevation dependence). An



example of the synthetic noise is shown in Figure 2 – the magnitude and elevation dependence at any one point differs over the area of the interferogram.

Figure 2: An example of a synthetic interferogram containing the topographically correlated component of the atmospheric noise and the coseismic signal. No atmospheric turbulence has been added at this stage. White regions within the interferogram indicate areas with no data in the digital elevation model. After Scott and Lohman, 2016

Not surprisingly, we found in this work that corrections that allowed for spatially variable statistics of the atmospheric noise performed better than ones that assumed these characteristics were uniform across the entire intereferogram. The degree of improvement (i.e., small error bounds when assessed over an ensemble of a few 100 synthetic earthquakes) was different for different source geometries, depths and parameters – stress drop was poorly determined for all cases, but moment and depth improved a great deal in our tests when a more flexible atmospheric correction was used.

B. 3D vectors from 1D data

Our other major area of exploration here has been on the longstanding problem of how to combine GPS and InSAR observations in one or several line-of-sight directions into a 3D deformation field product. These approaches tend to fall into the falling general categories:

1. Give up and just use satellite line-of-sight: This is what we attempted for the group time series comparison exercise. As an initial step, we did not require the participants to move from the "natural" line-of-sight geometry for that track. This meant that comparisons with GPS had to be projected into the line-of-sight, either using the full 3D vector, or the better-constrained 2D vectors in some cases. When the physical model being studied is known (i.e., we know the fault geometry AND we know the correct deformation mechanism, such as that an elastic half space is appropriate) there is no reason to ever move out of this mode and, essentially, downgrade the InSAR data by projecting it into another coordinate system.
2. Add *a priori* information about the 3D deformation field: This allows the researcher to invert for 3D deformation vector fields with a sparse sampling of GPS and one or more satellite line-of-sights. While not perfect, this effort does have the benefit of allowing researchers to qualitatively assess the characteristics of deformation in a more usual coordinate system, AND it allows disparate data types (i.e., leveling and InSAR, InSAR and InSAR from two different tracks with different line-of-sight) to be compared and assessed for changes over time.

The 2nd category is what we discuss here. The key issue is that, for the worst case scenario when only one satellite LOS is available and the GPS data are sparse with respect to actual variations in the deformation field (i.e., they "miss" a subsiding aquifer), there is really no way to uniquely determine how to map variations in the LOS vector onto it's relatively contributions from the E, N, V components, respectively.

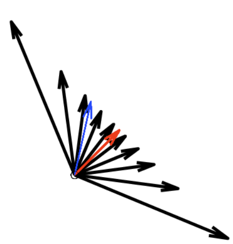


Figure 3: 2D example of LOS nonuniqueness. If the true 2D deformation vector is blue, then a satellite looking along the direction of the red vector will only "see" the projection of the blue vector onto that direction. Any of the black vectors are consistent with a red LOS vector of that length.

For the work pursued here, our questions are the following – what information should we add to the inversion to maximize the likelihood of retrieving the actual deformation fields with the magnitudes and scales likely to exist in Southern California? And, how can we present that information in a way that captures the inherent non-uniqueness in a useful manner?

For the former, we illustrate with another 2D example – this time using a profile of points where the full 2D vector is constrained at several points (GPS) and a 1D projection onto a satellite line-of-sight is available at all points (InSAR). Note that we have not even added noise at this point – that introduces an entirely different layer of non-uniqueness, but one that can actually be captured in the same way.

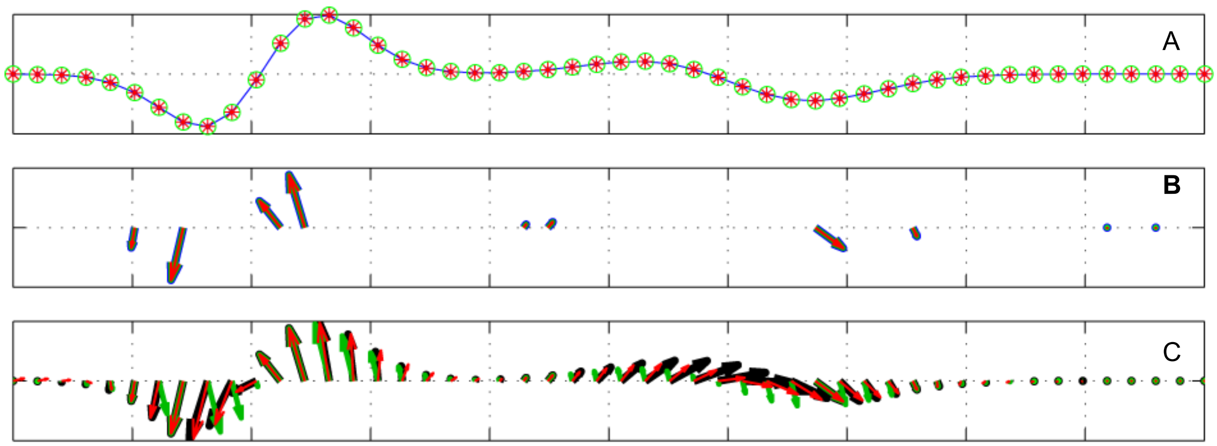


Figure 4: A) "InSAR" data (black dots, magnitude on y axis) vs. distance (x axis) and predictions from models on bottom row (red and green). B) GPS vectors (black) and predictions (red, green). C) Input 2D deformation field (black vectors), "damped" model (green), and "smooth" model (red). Note that both fit the data data in panels A and B exactly.

The point of Figure 4 is that the assumptions made can drastically affect the orientation and magnitude of the output vector field (red and green in 4c) while still fitting the data exactly. A damped least-squares approach will always extract the projection of the input vector onto the satellite line-of-sight, since that is the shortest vector consistent with the SAR data, when no GPS is present. Similar results result when the constraint is that the deformation is primarily vertical – a constraint that is not physical even in the case when primarily vertical hydrologic signals are present. Requirements that the field be smooth (red) work well in this case, when the actual deformation field is smooth, but perform very poorly when there are variations in the input deformation field that are not sampled by GPS.

For a slightly more physical approach, we are now regularizing our inversion using the approach outlined in Holt and Shcherbenko, 2013, where the strain field is minimized. The main difference that this approach introduces is that it ties together the horizontal and vertical components in a way that no longer violates that behavior one expects within an elastic solid (i.e., if there are gradients in the vertical displacements, those must be accompanied by the appropriate ones in the horizontal directions).

At the current time, we feel that the best method for presenting the outcome of an InSAR/GPS joint geodetic model to the community is to develop a suite of models that use a range of the above assumptions, potentially presented as a movie where the vector field is allowed to swing around in ways that are consistent with the raw data types and with a range of additional regularizing assumptions. While this is still a more complicated product than what is desired, it does have the benefit of allowing users to quickly see which characteristics of the model are truly robust (i.e., they do not change w.r.t any of these assumptions) and which are highly dependent on the choice of smoothing, interpolation, etc.

C. References

Holt, W. E. and G. Shcherbenko, 2013. Toward a Continuous Monitoring of the Horizontal Displacement Gradient Tensor Field in Southern California Using cGPS Observations from Plate Boundary Observatory (PBO), Seism. Res. Lett., **84**.

Scott, C. and R. B. Lohman, 2016, Sensitivity of earthquake source inversions to atmospheric noise and corrections to InSAR data, J. Geophys. Res., accepted.