SCEC Community Geodetic Model (CGM) Workshop Report
Palm Springs, California, September 6th, 2014
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Background

The development of a Community Geodetic Model (CGM) is a SCEC4 initiative with the goal of producing a comprehensive geodetic time series data product that leverages the complementary spatial and temporal features of Global Positioning System (GPS) and Interferometric Synthetic Aperture Radar (InSAR) data. The benefits of jointly using these data types have been demonstrated in several studies (e.g., figure 1), and the CGM effort aims to take such work to the next level by promoting methodological advancement and application of vetted techniques. By bringing together experts in the field of geodesy to identify and implement the best strategies for processing, analyzing, and merging the wealth of GPS and InSAR data now available for southern California, the CGM will not only provide input for a variety of SCEC science activities but will be a valuable resource for a broad range of studies both within and beyond the field of earthquake science. Development of the CGM is directly tied to the fundamental problems of earthquake physics that are central to the SCEC science plan.

SCEC initiated the CGM as a 5-year project with the expectation that participants would both independently examine GPS- and InSAR-based geodetic models, as well as develop methods for generating a geodetic time series model that is consistent with both data types. The process of developing such a model necessarily includes characterization of transient deformation due to earthquakes and anthropogenic manipulation of subsurface fluids, as well as both natural and anthropogenic seasonal signals. Previous workshops supporting this effort included discussions aimed at identifying the requirements for data going into such a model, as well as methods for selecting the appropriate spatial and temporal resolution.

Initially, a GPS-focused working group has compiled data and metadata and established a framework for detailed comparisons of position solutions from several groups. The InSAR working group conducted a test exercise aimed at comparing secular rates in the satellite line-of-sight, using a consistent set of input data. Many of the InSAR approaches ingest secular rates based on GPS data as part of their processing, so one of the key goals has been to identify methods for intercomparing InSAR-based solutions in a manner that can focus on identifying the best approach in a way that is not dominated by the GPS portion of the processing flow.

2014 workshop

GPS:

Topics covered by the GPS subgroup included 1) campaign data compilation and reprocessing, 2) comparison of continuous GPS time series solutions from five analysis centers, 3) approaches for combining solutions at the time series level, and 4) next steps.

Campaign GPS data reprocessing is underway with the goal of compiling a comprehensive dataset for southern California that includes data collected in recent years. Reprocessing is necessary to ensure self-consistent solutions; to utilize new satellite and receiver antenna phase center calibrations that are now available; and to employ an improved troposphere delay model, pole tide model, and ambiguity resolution strategy. Reprocessing will involve verifying the metadata accuracy.

In preparation for generating a combined time series solution, Tom Herring led a comparison of continuous GPS time series from several processing centers (Central Washington University, JPL, New Mexico Tech, Scripps, University of Nevada at Reno, and USGS as well as the combined PBO solution). Preliminary comparison of time series for a few stations showed very good agreement among the solutions. Furthermore, the comparison highlighted a problem affecting one solution that arose from a sign error in application of antenna phase center offset corrections for ground receivers.

The group discussed approaches that could be used for combining the processing centers' time series into a single time series solution. One possibility is to use a Kalman filtering approach as implemented in various software packages (e.g., st_filter, QOCA, GLOBK). This has the advantage of propagating the full variance-covariance matrix but is computationally intensive. Another approach would be to put the time series in a common reference frame and average them (for days which have station-positions in multiple solutions) or, alternatively, average and estimate the reference frame simultaneously. Both averaging strategies (and especially the former) would be faster than the Kalman filtering approach, and take advantage of the fact that for time series obtained through precise point positioning the site-to-site correlations would be zero.

Additional discussion addressed strategies for estimating derived quantities such as secular rates, seasonal signals, offsets, and transient deformation in the presence of temporally correlated noise. Providing realistic uncertainty estimates for derived quantities is critically important for their follow-on use, for example as part of the InSAR analysis, slip rate modeling, or strain rate mapping.

The action items for the GPS component are:

- Data compilation and processing
    - Finish compiling and reprocessing campaign GPS data. Migrate data from SCEC archive to UNAVCO archive so that SCEC archive can be phased out.
    - Systematically and quantitatively evaluate where further campaign data would make a significant improvement to our ability to record deformation signals of interest.
- Combine CGPS time series; incorporate campaign time series
    - Extend preliminary continuous GPS time series comparison to obtain statistics using full southern California dataset; assess implications of comparison results for data to be included in combined time series

    - Compare results from different approaches for removing common mode noise.
    - Compare results of time series averaging to those from the Kalman filter approach for combining time series and identify the approach to be used for the CGM.
    - Apply chosen time series combination approach.
- Analyze time series to obtain derived quantities
    - Compare derived quantities (e.g., secular rate, seasonal signals, coseismic and postseismic) and estimated uncertainties using different time series analysis and noise modeling approaches.
    - Choose and apply a time series analysis method and generate CGM GPS derived products.

InSAR:

The CGM workshop held in May 2013 involved the generation of maps of secular deformation rates for a particular track covered by both ERS and ENVISAT data in Southern California, stretching from the Los Angeles Metropolitan area up north to the Mojave Desert. One finding from this workshop was that it was impossible to compare, on a pixel by pixel basis, the rates for approaches that did or did not ingest GPS data as part of their methodology. We also found that the fact that the participants used different temporal ranges of data, which spanned different amounts of postseismic deformation, resulted in large discrepancies.

For the September 2014 workshop, participants used the same set of dates and were asked to submit more details of their approach to enable better comparison between the methods. Instead of comparing the interferograms on a point by point basis, we compared differences in rates across spatial apertures sampled by GPS sites. Not surprisingly, the approaches that used GPS data to constrain the large-scale deformation pattern (primarily due to interseismic motion associated with the San Andreas fault system) matched the GPS observations over long spatial scales better than those that empirically removed a plane or smooth function from the interferograms (an approach known as “flattening”). One important finding, however, was that a correction for a known problem with ENVISAT data (local oscillator drift) resulted in a very good fit of InSAR-only time series to the GPS data. This finding is particularly encouraging given that, in most areas of the world, we are not fortunate enough to have the spatially dense and long-timescale GPS network that is present in Southern California.

InSAR participants also relied heavily on video teleconferencing this year, in preparation for the September workshop. We found that this approach worked very well, with participants sharing slides and discussing aspects of the test that allowed us to use our time in Palm Springs more efficiently. The action items for the InSAR component are:

- Generate GPS-constrained InSAR velocity product which will
    - cover all regions of southern California that are not decorrelated

- involve rates projected into the InSAR Line-of-Sight (LOS)
- include detailed description of the GPS data used in constraining the LOS velocity product (time series, combination of continuous and/or campaign, projection into LOS)

- Evaluate constraints on seasonal terms from the InSAR time series and compare against GPS observations, where available
- Evaluate whether the existing approach constitutes best practices and develop framework for incorporating future observations

Joint InSAR-GPS discussion:

Discussion for the final portion of the workshop included the dissemination of results from the InSAR- and GPS-focused groups and discussion of publications that could result from this effort in the near term. We agreed that a publication based on the combined GPS product would be desirable. Because the InSAR solutions often (although not always) ingest GPS information as part of the processing, it might make sense for a publication based on the InSAR to be a follow-on article to the GPS one. Both groups plan to continue utilizing videoconferencing to coordinate activities in the coming year, culminating in an in-person workshop targeted for fall 2015.

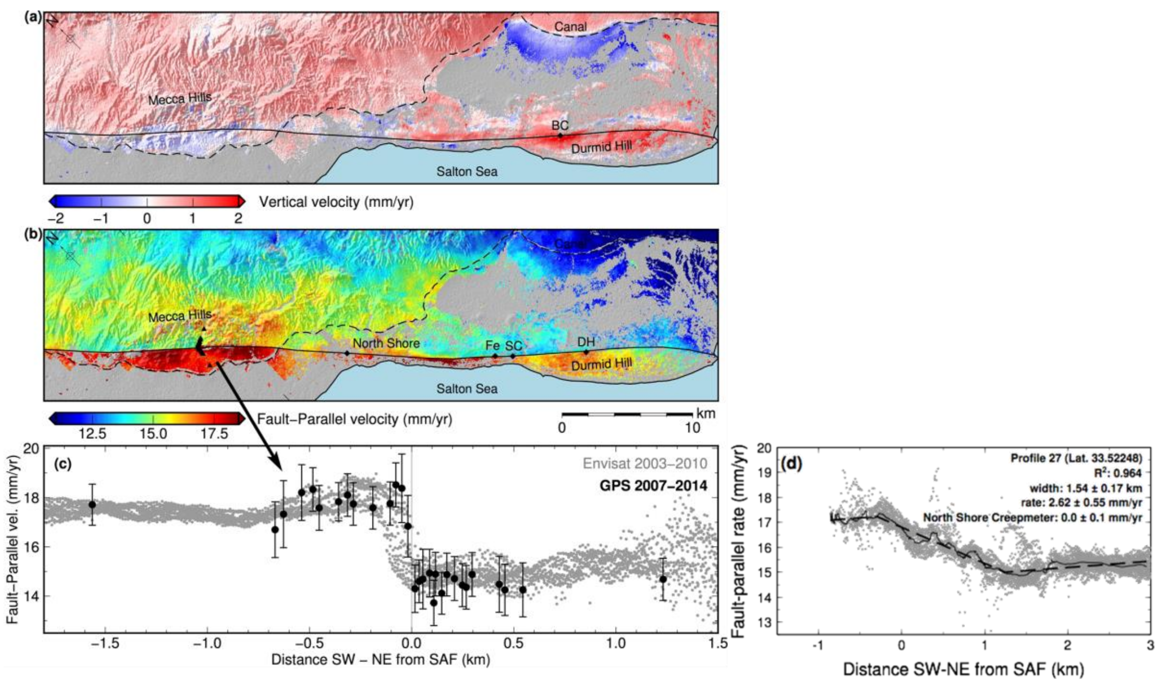

Figure 1: An example of the complementary nature of GPS and InSAR deformation rate estimates. InSAR and GPS data show near-fault creep, uplift, and distributed yielding on the southern San Andreas fault (SAF). Transpressional areas of the SAF show localized creep in a narrow zone while transtensional areas exhibit distributed deformation across a broader zone. From Lindsey et al., JGR in review, 2014.

Appendix

Prior to the workshop we asked the InSAR participants to consider the following 12 questions related to findings and best practices in InSAR processing. The discussion during the workshop touched on each of these topics at some point as we compared the different approaches. A summary of the responses is provided below:

1) Is the LOD correction important? Do other satellites have a similar drift problem?
Yes the local oscillator drift (LOD) in ENVISAT data is an important correction that is easy to apply. Other satellites probably have this type of drift but it has not been characterized yet.

2) What is the maximum baseline for this type of analysis (250 to 400 m)?
For this type of interseismic deformation study having small displacement gradient, the maximum usable baseline is about 300 m. For the older satellites this greatly limits the number of interferograms. However the newer satellites (TeraSAR-X, Sentinel-1a, and ALOS-2) have well controlled baselines so many-more pairs will be available.

3) Does everyone do phase unwrapping prior to time series analysis?
All participants used the Small Baseline Subset (SBAS) method and therefore unwrapped phase prior to the time series analysis.

4) At what point in the processing does one move from radar to geographic coordinates?
Most participants did the SBAS analysis in radar coordinates because the geocoding introduces errors that could smooth sharp signals such as fault creep. It is not difficult to bring the GPS positions and velocities into the radar coordinate system using the geometry of the master of the InSAR set.

5) Do the atmospheric models (e.g. ECMWF) improve the accuracy of the time series? How much? Under what circumstances?
Most of the participants found that the ECMWF models made no improvement in their analysis. Some participants found a marginal improvement but also noted that this particular area does not have large atmospheric signals. The correction may be important in other areas.

6) *Is SBAS the best approach? What about temporal templates?*
All participants used SBAS as the basis for the construction of the time series but there was a wide variation in the methods and extent of spatial and temporal smoothing. Some participants used templates others used wavelets or least-squares smoothing.

7) What is the long-wavelength (i.e. >100km) error in an InSAR only average velocity model?
Many different methods were used to recover the long-wavelength signal. Two participants showed good results for the large-scale velocity across two frames without removing any trends from the data or without any adjustment to the GPS data. This

was a promising development. Others relied on the GPS velocities projected into the line of sight to constrain length scales greater than 20-40 km.

8) *If GPS data (or a GPS-based model) are available, what is the best crossover length scale for combining the two data sets?*
This depends on the ultimate accuracy of the desired time-dependent velocity model. Some participants said GPS should not be used while the majority of participants used the GPS to either constrain a trend in each interferogram or even the smaller-scale components. The optimal combination method continues to be an active area of research.

9) *What is the optimal length scale (~600 m?) for smoothing the InSAR velocity or time series model to compare with GPS point time series?*
The main issue in answering this question is that resolution means different things to different people. The radar community defines a "look" as a boxcar average of a number of pixels to form a single average pixel. Others use Gaussian filters or wavelets to better control the sidelobes of the filter. 4 "looks" with ERS and Envisat data corresponds to ~80 m pixels. The approaches that generated the best fit to GPS data used smoothing over ½ wavelength of ~500 m or more. A lesser amount of smoothing is needed to recover the sharp signals associated with fault creep. Presumably, the "GPS fit" metric is affected by the number of SAR images available, and resulting impact of atmospheric noise, as well as to the seasonal distribution of SAR dates and the amplitude of the actual seasonal signals present in the ground deformation field. A better question may involve the consideration of the "down-stream" users and the appropriate spatial resolution for their use, rather than the somewhat artificial construct of optimizing the fit to GPS.

10) *The InSAR/GPS comparisons are worse when the vertical GPS component is included? Why? Will this improve with refined GPS data?*
Including the vertical GPS component sometimes increases the LOS misfit with the InSAR although it seems to depend on the quality of the GPS and whether the postseismic signals were removed from the GPS. The InSAR researchers don't always understand the "corrections" that go into the large variety of GPS products.

11) *What is the best temporal smoothing to use? Will the temporal smoothing effect the estimate of the secular velocity? Or should it?*
There was no consensus on this issue. It depends on the type of temporal signal under investigation (e.g., secular, annual, atmospheric, or co-seismic).

12) *Given the phase measurements contain three major components: deformation, topographic error, and atmospheric error? Can we quantify the percentage of each component in the phase data in terms of RMS reduction?*
The two participants who answered this question both said that the percentage of each component could be estimated especially when ground-truth GPS data are available.