SCEC Community Geodetic Model: Report on workshop held March 12 – 13, 2018, Scripps Institute of Oceanography

Jessica Murray, David Sandwell, Gareth Funning, Rowena Lohman, Michael Floyd

Introduction

The Community Geodetic Model (CGM) will consist of crustal motion time series and derived products with high spatial and temporal resolution for use in a variety of SCEC research on interseismic strain rates, postseismic processes, environmental (e.g., hydrological) contributions to deformation, spontaneous slow fault slip, and other transient phenomena. The CGM is designed to leverage the complementary spatio-temporal characteristics of Global Positioning System (GPS) and Interferometric Synthetic Aperture Radar (InSAR) data. A major component of the project is the evaluation of existing approaches and development of new methods to incorporate multiple data sets and data types into self-consistent geodetic data products.

We held an in-person workshop March 12 – 13, 2018 at the Scripps Institute of Oceanography where participants who are focused on GPS and InSAR components of the CGM came together to discuss the results of test exercises designed to help further define CGM methodologies, approaches toward development of joint GPS-InSAR CGM data products, and next steps for the collaboration. The workshop agenda is included in Appendix A, and the list of participants in Appendix B. In preparation for the in-person workshop, the GPS group and the InSAR group each held virtual workshops (via videoconference) during which they framed the test exercises and reviewed progress. The goal of this approach was to ensure that participants would have sufficient results in-hand at the in-person meeting to enable substantial interaction and discussion, as opposed to holding passive, presentation-based workshop sessions. The following sections summarize the outcomes of the GPS and InSAR sessions, the group's discussion of joint GPS-InSAR products, and a session focused on SCEC IT resources needed to support the CGM.

GPS component of the CGM

Through prior workshops and group collaboration, we have produced consensus time series for southern California continuous GPS (cGPS) stations. This involved merging daily position estimates for each station component (where components are east, north, and vertical) by scaling position errors, transforming daily positions into a North America fixed reference frame, and taking the weighted average of each day's positions. We have also reprocessed campaign GPS data collected between 1986 and 2014, generating time series which will be incorporated into the CGM GPS products.

These cGPS position time series, which cover the 1996 – 2018 timespan, provide the input for estimating three-dimensional station velocities, offsets, seasonal, postseismic, and other derived quantities. The focus of this workshop's GPS activities was to evaluate velocity fields estimated from the cGPS data via different time series analysis approaches with the goal of developing a consensus approach for producing a CGM GPS velocity field. This velocity field will be a key input to an integrated GPS-InSAR characterization of time-varying crustal motion.

Prior to the workshop, the GPS group had two telecons, on Monday 8 January and Monday 5 February. During the first telecon, each participant reviewed the status of their contributions to-date or presented geophysical analyses of time series as examples of the kind of analysis that would utilize a community geodetic product. At this stage, we designed and carried out a time series analysis test exercise. This exercise was discussed in a poster presented at the 2018 UNAVCO science workshop (see Appendix C) and is summarized here. Using the consensus cGPS time series described above and an amalgamated list of dates at which discontinuities may appear in each stations' time series, participants applied six different time series analysis methods and reported the estimated velocities and velocity uncertainties: MIDAS (Blewitt et al., 2016), tsfit (e.g. Herring, 2003), Hector (Bos et al., 2013), est_noise (Langbein, 2004), analyze_tseri (e.g. Dong et al., 2002), and a bespoke method employed by A. Borsa (UC San Diego). These methods take different approaches to handling time-varying signals and temporally-correlated noise, which leads to variation in both the velocities and uncertainties produced by each analysis. Four of the methods parameterize the observations as a combination of constant velocity, offsets, logarithmic and/or exponential decay, and sinusoidal terms and take various approaches to estimating parameters that describe these terms. The other two methods take an iterative approach in which the time series are detrended by estimation and removal of a velocity, and then other terms (e.g., offsets) are estimated using least squares methods. We thus hope to assess some epistemic uncertainty by comparing the range of estimates yielded from multiple techniques.

The main goals for the GPS group at the workshop were to discuss the status of generated products for the CGM in detail while ensuring that these were ultimately being pursued with the grand vision of the CGM being the driving motivation. These fell under two categories: (1) How to combine, average or otherwise incorporate results of each method into the SCEC CGM, and (2) what types of products should ultimately be available to the community and how these would be disseminated through the SCEC web site.

The GPS group had a break-out session on the first morning where we discussed several metrics and plots that would be useful to begin assessing answers to the question of reproducibility between the various time series analysis algorithms. During this productive hour, the time series fits produced during the pre-workshop preparations were shared, formatting errors relative to the standard identified, and a series of plots produced. The plots presented comparisons of the velocities between methods in both map and graph form, which immediately identified sites or regions with the largest discrepancies. These figures were ultimately compiled into the poster that was presented at the UNAVCO Science Workshop two weeks after the SCEC CGM workshop. The initial comparisons discussed indicate that the largest sources of discrepancies are short time series, unaccounted-for offsets in the time series, postseismic deformation, and significant time-varying excursions that are not accounted for in the parameterizations used by the time series analyses. The first action item resulting from this exercise is to refine the agreed-upon list of offset dates to address missing dates while at the same time minimizing extraneous dates. An example of the latter might be the inclusion of the date of an earthquake for stations that are outside the source-station distance likely to have experienced resolvable displacements for that event. A concurrent action item is for participants to review their time series analysis results to identify the source of significant discrepancies among the velocity estimates produced by different methods and make adjustments to their methodologies as needed. Consideration should be given to whether the methods applied in the test exercise are sufficiently diverse or whether additional approaches should be included.

Once the time series analysis methods have been fine-tuned, the velocity fields and associated uncertainties resulting from these analyses must be combined in some way to produce the CGM GPS velocity field. Possible approaches discussed by the group include computing the median velocity for each station-component, using the individual station-component probability density functions to calculate a combined probability density function for each station-component velocity, and exploring Bayesian approaches for combining time series parameters.

InSAR component of the CGM

Most published InSAR products are average velocity models based on stacking of interferograms or SBAS analysis. The techniques are well developed but until the last few years the InSAR community lacked a data set having the regular acquisition cadence and baseline control to generate time series that are sufficiently accurate for interseismic studies and strain rate mapping. Moreover, only two look directions, i.e. two components of motion, are available so comparison and combination with GPS is challenging. Over the past 4 years, the 12-day regular TOPS (also known as interferometric wide-swath, or IW) SAR acquisitions from the Sentinel-1A and B spacecraft have provided a unique data set for time series analysis. The workshop participants decided to analyze Sentinel-1 data along two tracks (ascending and descending) over a large area of Southern California centered on the Cajon Pass section of the San Andreas Fault. The objectives of this exercise were to: compare TOPS-mode interferograms from different InSAR processing packages (ISCE and GMTSAR), compare InSAR time series generated by different groups and different software, and identify best practices in forming InSAR time series. The ultimate objective is to refine methods for merging GPS and InSAR time series to provide high spatio-temporal resolution and accuracy for earthquake hazard analysis.

The participants involved in the InSAR exercises were Gareth Funning, Wesley Neely, Zhen Liu, Katia Tymofyeyeva, Xiaohua Xu, Manoochehr Shirzaei, Chandra Ojha, Kang Wang, Heresh Fattahi, Piyush Agram, Yuri Fialko, and David Sandwell. There were three pre-workshop meetings prior to the face-to-face meeting at SIO on March 12 and 13. Several participants joined the workshop virtually. During the first pre-workshop meeting on February 12, the participants set the guidelines for the exercises so everyone was working with the same data sets. The basic parameters were:

- Sentinel-1 SAR data using the interferometric wide-swath (IW) mode and SLC products for the time period - June 1, 2015 to December 31, 2017.
- The area covered was 33.6–35.2°N and -118.7–-116.5°E.
- The data were from path 64 (ascending viewing geometry) and path 71 (descending).
- The SRTM1 data would be used for topographic correction.
- The products to be compared in radar coordinates were wrapped phase, coherence, and unwrapped phase for a connected circuit of interferometric pairs for each viewing geometry, including at least one short time span and one long timespan pair.

- Higher level products to be compared included ascending and descending LOS velocity (with and without GPS constraints). LOS time series at a few key locations to be selected by Funning based on a diverse parameter range.

During the second pre-workshop meeting, Xu presented a comparison of data products (interferograms and correlation) submitted by several participants (https://www.dropbox.com/s/cycvdl5ucowqsa4/Time_Series_Comparison_Xu.pptx?dl=0) . Results obtained using ISCE (Liu) and GMTSAR (Xu) are internally consistent - closed circuits sum up to zero, with some differences which are likely due to different filter wavelengths. There was a systematic difference between ISCE and GMTSAR interferograms in a form of a ramp in range. Later it was determined that this ramp was due to an imprecise geometric approximation in the GMTSAR code. After correction the results were in near perfect agreement. These was also a difference due to various alignment choices (geometric vs orbit adjustment to minimize burst discontinuities); geometric alignment resulted in greater burst discontinuities. ISCE results submitted by Funning showed a larger difference and circuit residuals, possibly due to the pair-wise alignment of the SAR images rather than the alignment to a single master. Funning used SLCs provided by Tymofyeyeva in which only the SAR bursts required to cover the area of interest were included. Liu tried to use similar data provided by Xu, but encountered problems, and ended up using a different tool for concatenating the data and selecting the appropriate bursts. Liu will try to use data provided by Tymofyeyeva to check results of Funning. Shirzaei used some combination of GMTSAR and ESA software to produce interferograms. Results were also different for some of the interferograms. The discussion then moved to planning a time series analysis comparison. Funning selected coordinates of pixels at which InSAR time series would be generated - 6 at cGPS sites (one defined as a reference point), and 5 'random' locations where different styles of deformation were expected. Participants could use any choice of interferograms and their preferred analysis approach to produce the time series.

During the third pre-workshop meeting on March 8, the participants began the comparison of time series at the 11 locations provided by Funning. The methods used to construct the time series were all similar. For example, Zhen Liu had the following parameters for track 071: ISCE processing of 129 interferograms; used the ISCE stack processor to align all slaves to one master; unwrap with minimum cost flow; filter strength 0.5; time series SBAS with DEM error correction and spatial and temporal filtering; time series performed in geo-coordinates; spatial filtering 0.001 deg (~100 m) in geocoded interferograms. Wesley Neely used the following parameters: GMTSAR processing of 129 interferograms; used ESD, filter wavelength of 300 m and sampling of 90 m, perpendicular baseline of <250 m, and temporal baseline of <50 days; used Snaphu to unwrap with a 0.05 threshold and used a modified SBAS in radar coordinates for the time series. Xiaohua Xu used a similar set of parameters and posted his results at: https://www.dropbox.com/s/cycvdl5ucowqsa4/Time_Series_Comparison_Xu.pptx?dl=0 . Kang Wang used similar parameters. Gareth Funning recommended that for the workshop all the time series be plotted together for a more direct comparison.

The time series comparison was continued during the first ½ day of the workshop. Piyush Agram and Heresh Fattahi joined this session remotely. Their participation was helpful for better understanding the details of the ISCE processing flow. Just prior to the workshop, Agram, Xu, and Sandwell, worked to determine that the source of the ramp phase difference between GMTSAR and ISCE was due to an approximation to the ellipsoidal shape of the Earth used in GMTSAR. The problem was easily corrected and the two codes agree to the level of the phase noise in the interferograms which is remarkable considering the codes were developed independently using different geometric models. Manoo Shirzaei showed results using a third software package (GAMMA) but there was not sufficient lead time to perform quantitative differences. Xiaohua Xu showed comparison of time series at the 11 locations from the three groups who completed the exercise (see Figure 1 for example). Both Xu and Neeley used GPS time series as constraints essentially constraining the InSAR measurements to match the GPS data. Liu did not use GPS as a constraint, yet showed remarkably good agreement with the GPS. This comparison was a good start but there is a lot more quantitative work to be done. Katia Tymofyeyeva presented time series results with a discussion of circuit misclosure when the circuits are very long as well as common point stacking for atmospheric correction. In addition, she discussed using the horizontal velocity azimuth derived from smooth GPS models to help constrain the third unmeasured component of the InSAR velocity vector. Kang Wang used common point stacking to isolate atmospheric phase screens in the SAR image and then compared with atmospheric phase screens from models. In some cases, there is good agreement while in other cases there is poor agreement. All of these results where summarized to the full group in the afternoon plenary session.

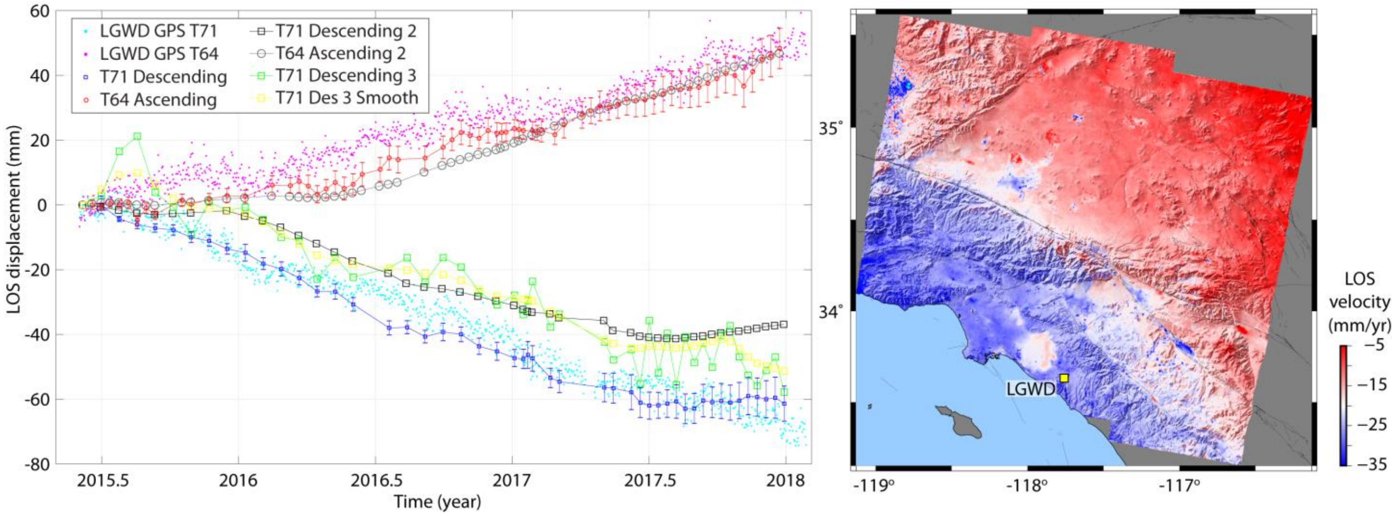

Figure 1: Left – Comparison between GPS daily solutions provided by UNAVCO for station LGWD and InSAR time series derived using different software packages and algorithms for the location of LGWD. Cyan and magenta dots are GPS daily solutions in ITRF08 projected into satellite LOS directions. Blue and red curves, respectively, represent the descending and ascending solutions (Xu, 2017) using GMTSAR. Black and grey curves show the descending and ascending solutions by Zhen Liu using ISCE and framework developed by H. Fattahi. Green and yellow curves show descending solutions (Neely et al., 2017) using GMTSAR, with different degrees of smoothing applied. All curves are referenced to zero displacement at the start of time series. Right – LOS velocity map produced from descending track T71 with constraints from GPS ITRF08 velocity field (Xu, 2017). Location of GPS station LGWD marked by yellow square. Figure courtesy of Xiaohua Xu.

Cyberinfrastructure issues for the CGM

During the afternoon of the first day, we heard details of the setup and process for web support at SCEC from Philip Maechling. The main point of discussion was how to move from exercises and preliminary products to community dissemination and, ultimately, feedback with which to improve and develop the products. Although a web page for the CGM already exists (http://topex.ucsd.edu/CGM/CGM_html/), it requires updating and linking to products, such as the consensus time series, which may already be made operationally available easily, and ultimately porting across to be hosted by SCEC (e.g. http://www.scec.org/research/cxm/). During this session, we discussed the pros and cons of how to update the web pages frequently while under SCEC's purview, as well as possible models of web pages that already exist whose user interface we would prefer to emulate.

Towards combination of GPS and InSAR time series

On the second day, instead of separating into GPS and InSAR groups to discuss relevant issues internally, we broke into small groups of four or five, with at least one representative of the InSAR, GPS and potential user communities in each group, to facilitate cross-expertise understanding. These groups were tasked with discussing the preferences, desires and limitations of their current contributions and ultimate expectations for the CGM in a “big picture” sense, considering what we had heard about the status of the CGM products and the possible implementations of a web interface on day 1. Each group reported back with a brief description of discussions and one or two key points for the CGM Working Group as a whole to consider as it continues to move towards a product release. Some of these suggestions anticipated potential uses and posed issues for another group to solve, such as the desire for consistent horizontal and vertical velocities in a stable reference frame. Others put clear goals, particularly for the GPS side, for products needed to move forwards with integration of GPS and InSAR, such as the assessment and removal of all non-tectonic signals in GPS time series and sheer density of sites being identified as highly important. These necessitate the consistent application of time series fits between the survey and continuous time series components, and a close interaction between these two groups within the GPS component of the CGM. Lastly there were product format suggestions to facilitate the accessibility of information that is likely to be sought by more advanced users, such as value ranges and scatter (e.g. WRMS) where multiple algorithms are used to estimate the final community product. Such information will also encourage any users to understand more about the quality of the data they use from any product. Other “meta-products” such as a consensus ranking of GNSS sites was suggested, to inform users of the likely quality (accuracy) of data and derived quantities for specific sites.

Ultimately, discussion both within the GPS group and involving both GPS and InSAR workshop participants throughout the workshop helped to define what the CGM GPS products should consist of. These comprise consensus cGPS time series, including versions with and without the removal of outliers and/or instrumental offsets; a list of offset dates/times categorized as earthquake-related or other; the consensus 3D velocity field discussed above; and offset estimates associated with changes in station instrumentation derived using methodology similar to that for combining the velocity estimates from different time series analyses. Additional CGM GPS products such as interpolated velocity fields or time-dependent velocity maps might be useful for InSAR or combined GPS-InSAR analyses and will be explored in the future.

The InSAR time series will be based on Sentinel-1 data; they will begin in mid-2014, have a 12-day cadence, and be updated every 6 months or more often in case of an event. The spatial sampling will be 500 m. Higher resolution will be needed near creeping faults. Two components of line-of-sight data, based on ascending and descending acquisitions, will be produced as well as a 3-component product using average velocity azimuth from gridded horizontal GPS velocities. The correction for atmospheric delay is still an area of research where some groups will use tropospheric models while other groups will use common point stacking.

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Appendix A: Workshop agenda

SCEC Community Geodetic Model
Agenda for In-person Workshop
March 12-13, 2018, SIO
Martin Johnson House

Session 1 – March 12, 9:00 – 12:30

GPS Group Review Exercises in Martin Johnson House

Review exercise results
Develop consensus approach for CGM v.2 velocity field estimation
Discuss broader topics raised during the March 5th telecon
Identify follow-on exercises that may be needed e.g., for interpolating velocity field on a grid; coordinate with needs of InSAR group
Map out action items (current and future)

InSAR Group Review Exercises in Spiess Hall 303

Review differences in interferograms and coherence maps
Review InSAR time series
Discuss atmospheric mitigation approaches
Identify best practices for InSAR time series
Map out action items (current and future)

Lunch 12:30 – 1:30

Session 2 – March 12, 1:30 – 3:30

Joint GPS and InSAR

GPS group reports on exercises and plans
InSAR group reports on exercises and plans
Discussion of GPS/InSAR Integration

Session 3 – March 12, 3:30 – 6:00

Subgroups work on matters arising from discussions in Sessions 1&2

Dinner 6:30 – 7:30

Session 4 – March 13, 8:30 – 11:30

Joint GPS and InSAR

Report back on any additional outcomes of subgroup activities from Session 3
Proposals for GPS InSAR integration
Discuss web site and data products
Planning of follow-up work

Lunch 11:30 – 12:30

Appendix B: Workshop participants

Piyush Agram (Jet Propulsion Observatory) [remote participation on day 1 only]

Adrian Borsa (UC San Diego)

Eileen Evans (CSU Northridge)

Heresh Fattahi (Jet Propulsion Laboratory) [remote participation on day 1 only]

Yuri Fialko (UC San Diego)

Mike Floyd (MIT)

Gareth Funning (UC Riverside)

John Galetzka (UNAVCO)

Alejandro González Ortega (CICESE)

Bill Hammond (University of Nevada, Reno)

Thomas Herring (MIT) [remote participation on day 1 only]

Emilie Klein (UC San Diego)

Zhen Liu (JPL)

Philip Maechling (SCEC)

Jessica Murray (USGS)

Mark Murray (New Mexico Tech.)

Wesley Neeley (UC San Diego)

Katia Tymofyeyeva (UC San Diego)

David Sandwell (UC San Diego)

Zheng-Kang Shen (UC Los Angeles)

Manoochehr Shirzaei (Arizona State University)

Kang Wang (UC Berkeley)

Xiaohua Xu (UC San Diego)

Yuehua Zeng (USGS)

Appendix C: Poster on CGM GPS test exercise, presented at UNAVCO Science Workshop , March 2018

The SCEC Community Geodetic Model:
Development of a consensus Global Positioning System time series data set and velocity field

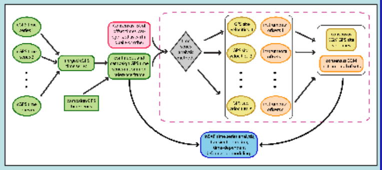
Jessica R. Murray[1], Michael Floyd[2], Thomas Herring[2], Adrian Borsa[3], William Hammond[4], Zhen Liu[5], and Zheng-Kang Shen[6]

[1]U.S. Geological Survey, Menlo Park, CA, [2]Massachusetts Institute of Technology, [3]Scripps Institution of Oceanography, [4]Univ. of Nevada at Reno, [5]NASA Jet Propulsion Laboratory, [6]Univ. of California Los Angeles

Abstract

The Community Geodetic Model (CGM) is a project sponsored by the Southern California Earthquake Center (SCEC) to produce crustal motion time series and derived products with high spatial and temporal resolution for use in a variety of SCEC research on interseismic strain rates, postseismic processes, environmental (e.g., hydrological) contributions to deformation, and other transient phenomena. The CGM is designed to leverage the complementary spatio-temporal characteristics of Global Positioning System (GPS) and Interferometric Synthetic Aperture Radar (InSAR) data, and a major component is the evaluation of existing approaches and development of new methods to incorporate multiple data sets and data types into self-consistent geodetic data products. This poster presents recent work focused on producing consensus time series and a velocity field from southern California GPS data. These will be key inputs to an integrated GPS-InSAR characterization of time-varying crustal motion. The accompanying flowchart depicts the development of the GPS component of the CGM.

Figure 1: Framework for developing the GPS component of the CGM. Portion outlined in dashed purple box is the subject of the time series analysis comparison exercise. cGPS: continuous GPS. *M* investigators (1…m) provide cGPS time series from their processing of raw data. *N* investigators (1…n) use the merged consensus time series to estimate velocities, instrumental offsets, and other parameters at individual sites using their preferred approaches.



GPS time series analysis comparison exercise

The GPS velocity field will provide input for the InSAR line-of-sight velocity field and InSAR time series analysis that are also part of the CGM. Multiple approaches exist for deriving a constant velocity field from GPS time series, but the way in which time-varying signals, especially postseismic motion, and temporally-correlated noise are accounted for can strongly influence the resulting estimates of velocities and uncertainties. Here we present preliminary results from a comparison exercise in which several CGM participants applied different methods in order to calculate velocities and other quantities such as offsets, postseismic decay, and seasonal signals from the merged cGPS time series data set spanning 1996 - 2018.

Methods applied

- **MIDAS** (Blewitt et al. [2016])
  - This algorithm obtains the station-component velocity from the distribution of velocities estimated for each pair of positions in the time series that are separated by approximately one year. Subsequently other parameters (intercept, annual and semiannual oscillations, offsets, and postseismic exponential decay if needed) are estimated by least squares from time series detrended with the MIDAS velocities.
- **Least squares time domain fitting**
  - Each station-component velocity is estimated using least-squares to minimize daily position residuals after removal of a seasonal component estimated through least squares fitting of annual and semi-annual sinusoids. After removing the trend and seasonal terms, an iterative algorithm estimates and removes offsets at specified times using the median position in the 90 days before and after each offset date. Postseismic adjustments are not included.

Methods applied (continued)

Several methods fit each station-component time series independently with components of the following function, using various approaches for estimating parameters and quantifying uncertainties.

$$d_i = d_0 - Rt_i + S\,sin(2\pi f t_i) + cos(2\pi f t_i) + O_k(t_i \geq T_k) + A_n\,log\left(1 + \frac{t_i - T_n}{\tau}\right) + A_n(1 - e^{-(t_i - T_n)/\tau})$$

Position at time t_i; Nominal position at $t = 0$; Secular displ.; Seasonal terms; Offset at time T_k; Postseismic decay for earthquake at time T_n

- **Est_noise** (Langbein [2004, 2008, 2012])
  - Offers choice of logarithmic or exponential postseismic decay for each earthquake. Logarithmic decay used for all test exercise time series.
  - Realistic velocity uncertainties are obtained by using a maximum likelihood approach to optimize a temporally correlated noise model consisting of white, flicker, random walk, and, in some cases, band-pass filtered noise contributions while fitting each time series.
- **QOCA *Analyze_tseri* module** (Dong et al. [1998]; Liu et al. [2010])
  - Offers choice of logarithmic or exponential postseismic decay for each earthquake; for test exercise, chose function individually for each time series.
  - Temporally correlated noise is modeled as a flicker noise process with pre-determined, fixed amplitude.
- **HECTOR** (Bos et al., 2013)
  - Uses a spectral analysis approach to estimate time series parameters in the presence of temporally correlated noise. As implemented here, time series are fit with linear velocity, offsets, and annual plus semi-annual pariodic tarms (if tima series spans >2 yaars), and the noise model consists of white plus flicker noise.
- **GLOBK tsfit** (Herring, 2003; Reilinger et al., 2006)
  - Uses weighted least-squares estimation to fit time series with combination of linear velocity, offsets, and annual plus semi-annual periodic terms (if time series spans >2 years). Applies "First-Order Gauss-Markov Extrapolation" to account for effect of temporally correlated noise on the velocity uncertainty.

References

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Consensus time series for continuous GPS sites

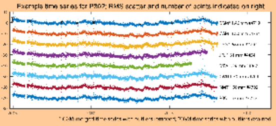
An initial step in the GPS analysis was comparison of southern California continuous GPS (cGPS) time series generated by several participants who use different processing software and settings. A consensus approach was adopted for merging these position solutions in order to leverage the increased robustness offered by incorporating multiple processing strategies.

Steps to merging time series

1) Scale daily position errors of input time series to be self-consistent based on χ²/d.o.f. fits to 500 reference frame stations.
2) Rotate and translate daily positions to align to PBO NAM08 reference frame (Herring et al., 2016).
3) Take weighted average of daily positions; optionally remove outliers using 4-times WRMS scatter

Output:
3-component position time series for 792 cGPS sites within the region bounded by 31N, 38N; -123W, -114W

Example time series for P502; RMS scatter and number of points indicated on right

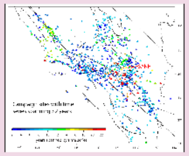


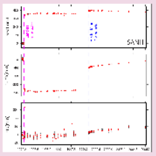
Input time series and scale factors:

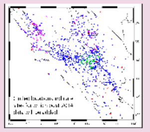
New Mexico Tech (NMT)	1.00 (previously scaled)
Central Washington Univ. (CWU)	1.0 (previously scaled)
PBO combined	1.00 (previously scaled)
USGS Earthquake Science Center (USG)	2.91
NASA Jet Propulsion Lab (JPL) global analysis	2.91
NASA Measures (MEA) combined solutions	1.43

Campaign GPS data

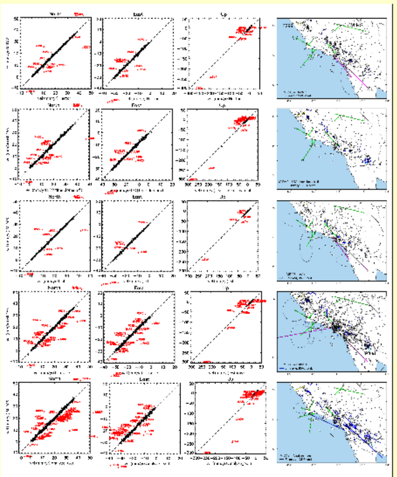
In addition to cGPS data, we have compiled available campaign GPS data collected between 1986 and 2014 for the region, reprocessed these data in a self-consistent manner using the GAMIT software to produce daily position time series, and continue to incorporate observations collected since 2014. Reference frame alignment and time series analysis will be carried out in a manner consistent with that of the cGPS data.







Results of the comparison exercise



Note: Large discrepancies (e.g., WLHG) are not shown on N, E, U component comparisons to save space

Initial velocity comparisons highlight discrepancies, primary sources of which include offsets omitted from the consensus list, postseismic deformation, and time series with substantial temporal variation not captured by the assumed parameterizations.

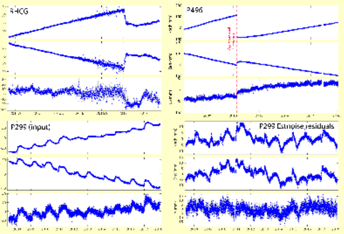
Notes:

1) Analyze_tseri was not applied to stations with time series spanning <1 year, and additional offset times chosen by inspection were included in this analysis.

2) Overall larger error ellipses for Estnoise results reflect temporally correlated noise model that assumes a minimum of 1 mm/sqrt(yr) (horizontal) and 2 mm/sqrt(yr) (vertical) random walk noise.

Left: Comparison of velocities (mm/yr) for indicated method pairs; MIDAS solution chosen at random as reference velocity field. Red dots indicate disagreement >2 mm/yr (horizontal) and >5 mm/yr (vertical). Green vectors: examples with missing offsets; Magenta vectors: examples with time series spanning <1 year. Cyan vector: example with postseismic; yellow vector: example with complex temporal variation. Stations with example time series plotted below are labeled on maps.

Below: Examples of southern California time series for which velocity estimates show large discrepancies. Stations labeled on maps at left. (A) (Gradual) unaccounted for offset. (B) Large coseismic and postseismic signals. (C) Input time series with complex time-varying signals. (D) Residuals for fit to input time series (C) obtained using Estnoise. Seasonal signals of time varying amplitude and multi-year temporal variations are not well-modeled by assumed parameterization.



Outcomes of March 2018 workshop

CGM GPS products should consist of:

1) Consensus cGPS time series obtained by merging daily solutions from multiple processing centers; include versions with no adjustments, outliers removed, instrumental offsets estimated and removed
2) Consensus list of offset times categorized as earthquakes (1992 onward) or other
3) Consensus 3D velocities at GPS sites
4) Consensus instrumental offset estimates
5) Other products of potential use for InSAR or combined GPS-InSAR analyses (e.g., predicted time series, time-dependent velocity maps)

Outstanding issues

1) Effects of reference frame adjustments on common mode and vertical signals
2) Method for producing consensus velocities and instrumental offsets from output of multiple time series analysis methods with error propagation
3) Optimal time series analysis approach for campaign GPS data, considering sparse and uneven temporal sampling

Next steps for CGM-GPS

1) Finalize consensus offset list
2) Make adjustments to time series analysis methods based on exercise results; produce "best" velocity estimates
3) Compare multiple approaches for combining velocity fields and estimating uncertainties; choose method
4) Integrate campaign GPS time series into consensus products