Community Geodetic Model Workshop: January 28-29, 2016

Report for SCEC Award #15152
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I. Project Overview

A. Abstract

In the box below, describe the project objectives, methodology, and results obtained and their significance. If this work is a continuation of a multi-year SCEC-funded project, please include major research findings for all previous years in the abstract. (Maximum 250 words.)

The goal of the CGM project is to develop spatially and temporally dense time series of ongoing deformation that provide unique input for addressing the fundamental problems of earthquake physics targeted by the SCEC community. The CGM draws upon expanded Global Positioning System (GPS) coverage, new SAR missions, and maturing data analysis techniques that leverage the complimentary features of both data types. By adopting a community-driven approach, we bring together the kind of broad expertise and diverse perspectives needed to explore the effect of modeling choices and provide a window into the scope of epistemic uncertainty.

B. SCEC Annual Science Highlights

Each year, the Science Planning Committee reviews and summarizes SCEC research accomplishments, and presents the results to the SCEC community and funding agencies. Rank (in order of preference) the sections in which you would like your project results to appear. Choose up to 3 working groups from below and re-order them according to your preference ranking.

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

C. Exemplary Figure

Select one figure from your project report that best exemplifies the significance of the results. The figure may be used in the SCEC Annual Science Highlights and chosen for the cover of the Annual Meeting Proceedings Volume. In the box below, enter the figure number from the project report, figure caption and figure credits.

D. SCEC Science Priorities

In the box below, please list (in rank order) the SCEC priorities this project has achieved. See *https://www.scec.org/research/priorities* for list of SCEC research priorities. *For example: 6a, 6b, 6c*

1d, 1e, 5b

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?*

The CGM effort is leading to more rigorous joint use of GPS and InSAR data for a variety of applications that are central to SCEC's mission including the quantification of crustal strain rates, interseismic fault locking, and fault-related transient deformation. The project has spurred efforts within the geodetic community to work together in developing best practices for fully utilizing the wealth of existing and newly available geodetic data.

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?*

The further development of analysis techniques and evaluation of geodetic data products being carried out by the CGM group not only are providing more robust and precise geodetic data sets and models for southern California but are more generally applicable to the combined use of GPS and InSAR data internationally. This is especially important given the new SAR satellites that several countries have recently launched and/or are planning.

G. Project Publications

All publications and presentations of the work funded must be entered in the SCEC Publications database. Log in at *http://www.scec.org/user/login* and select the Publications button to enter the SCEC Pubications System. Please either (a) update a publication record you previously submitted or (b) add new publication record(s) as needed. If you have any problems, please email *web@scec.org* for assistance.

II. Technical Report

The technical report should describe the project objectives, methodology, and results obtained and their significance. If this work is a continuation of a multi-year SCEC-funded project, please include major research findings for all previous years in the report. (Maximum 5 pages, 1-3 figures with captions, references and publications do not count against limit.)

See attached document.

Report on the Community Geodetic Model Workshop, January 28 – 29, 2016, Pomona, CA

Workshop Leaders: Jessica Murray, David Sandwell, and Rowena Lohman

Introduction

On January 28 – 29, 2016, 32 members of the SCEC Community Geodetic Model (CGM) working group participated in a 1.5 day workshop. The meeting took place at the Kellogg West conference center in Pomona, CA; five attendees took part remotely. The main workshop was followed by an optional half-day meeting concerning Interferometric Synthetic Aperture Radar (InSAR) processing methods for the new wide-swath data streams from the Sentinel-1A and ALOS-2 satellites.

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In earlier stages of CGM development, two working groups were formed – one focused on the contribution of GPS data to the CGM and the other on InSAR. In this latest workshop the GPS and InSAR practitioners met together to focus on integration of GPS and InSAR results into a combined CGM product. Additional workshop objectives were to identify action items for the last year of SCEC4 research and outline next steps that will carry the CGM into a hoped-for SCEC5 collaboration.

Summary of results

GPS

The workshop began with a recap of efforts to-date. CGM GPS accomplishments include gathering and processing of survey-mode GPS (SGPS) data collected since 2004 (the end of the data set used in the SCEC Crustal Motion Map v.4), compilation and comparison of continuous GPS (CGPS) time series from multiple data processing centers, generation of merged CGM time series for southern California derived from the individual time series, and comparison of constant velocities estimated from each processing center's CGPS time series using a consistent parameterization and noise model.

The SGPS compilation has resulted in the addition of 130 sites to the CMM4 set, and the updated set includes stations with time series spanning up to 23 years. Ongoing work is focused on validating the processed SGPS positions, identifying outliers, and tracking down the sources of discrepancies such as incorrect RINEX header information. The SGPS time series will then be incorporated with the CGPS merged time series using tie-in CGPS sites that have been included in the SGPS solution.

The CGPS comparisons demonstrated that variation among the time series provided by different processing centers is for the most part small. For comparison purposes, constant velocities were estimated by fitting all time series with a parametric model that also included offsets, seasonal terms, and logarithmic decay following major earthquakes. Velocities estimated in this way also varied little among the processing centers.

More generally, however, significant variation in velocity estimates can arise due to modeling choices. Workshop participants presented alternative methods for constant velocity estimation, one of which uses a median-based trend estimator with no explicit handling of postseismic and another in which velocities are derived from a regional block model with various deformation sources included. The way in which postseismic signals are accommodated has a large impact, and this is particularly true for the many southern California GPS sites that have no data preceding major earthquakes of the last 25 years. It will always be necessary to employ some sort of model-based constraints on postseismic (e.g, fitting logarithmic or exponential terms to each time series, using afterslip or viscoelastic relaxation models that predict time-dependent surface displacements). The uncertainties attributed to velocity estimates should reflect this source of epistemic uncertainty.

In addition to the overall combination and comparison of time series and velocities, additional GPS-related efforts have focused on quantifying the vertical velocities and their time dependence as well as seasonal and longer-term hydrologic loading effects. The time series and velocity comparisons highlighted the potential effect of reference frame realization and removal of common mode signals on analyses of vertical and seasonal movement. For instance, including a scale term in the reference frame alignment can remove vertical signal, and common mode estimates can often absorb seasonal motion that may be of interest for some applications. Taken together, the new methods and findings suggest a path forward for CGM derived products such as seasonal time series and detailed vertical rate analysis.

<u>InSAR</u>

Another major topic covered during the workshop was InSAR time series analysis, both to obtain line-of-sight (LOS) velocities and the underlying time varying deformation. As a first step to identify best practices, CGM participants applied a variety of InSAR time series analysis techniques to a common dataset consisting of 47 Envisat acquisitions, compared the resulting LOS velocities, and discussed the impact of differences in analysis approach. The resulting best practices are summarized in the 2014 workshop report.

Substantial discussion in the 2016 workshop focused on the extent to which GPS is needed to constrain long-wavelength components of the InSAR data and, if so, over what spatial scales. Depending on the location and number of available acquisitions, GPS-free InSAR time series analysis can provide LOS velocity estimates that agree with GPS observations at the few mm/yr level. For C-band data, GPS-independent LOS velocities can often be achieved over length scales < ~100 km; correcting for local oscillator drift (LOD) is required for Envisat. For L-band data, ionospheric effects can have a substantial contribution to the signal, warranting further research on mitigation approaches.

Correction for atmospheric effects can also improve the solution in some cases. Spatial correlation between topography, atmosphere, and tectonic signals of interest can be especially problematic. Furthermore, seasonal atmospheric signals can be aliased in the time series analysis, particularly in cases with sparse temporal coverage. Mitigation of atmospheric effects can be performed in various ways.

For example, MODIS and MERIS data, as well as GPS-derived zenith wet troposphere delay estimates, can provide useful atmospheric corrections in some instances. When many SAR acquisitions are available it is possible to reduce the impact of atmospheric noise through assumptions about the temporal characteristics of the underlying deformation (i.e., that it is smooth or constant). The resulting reduction in time series scatter achieved independently of GPS reveals time varying motion including, in some cases, seasonal signals. Approaches like this that depend on large numbers of interferometric pairs will benefit from the more frequent acquisitions and better baseline control offered by the newest satellite missions.

While LOS and 2D velocity and time series solutions abound, they are generally restricted to certain geographic regions, tracks, satellites, and/or tectonic regimes. Generating a southern-CA wide model is more challenging. Constraints, such as the assumption that horizontal motion is fault parallel or regarding the type of temporal variability that is expected, that are used in some analyses are not always generally applicable.

A variety of software tools and interfaces for discovering, obtaining, processing, comparing, and sharing raw SAR data, interferograms, and time series are under continual development. UNAVCO's web-based SAR archive has several features that could be directly used by the CGM project including the ability to upload/download interferograms and InSAR time series and the option to assign a DOI to these data products to ensure proper attribution. The interface also incorporates useful tools for converting among data formats to facilitate user participation. Tools under development at JPL have the potential to be a valuable resource that promotes full utilization of observations from new missions such as Sentinal-1a, ALOS-2, and eventually NISAR.

During the optional half-day session following the main workshop, InSAR experts compared processing approaches for the new wide swath data from ALOS-2 and Sentinel-1A. During the first 9 months of the ALOS-2 mission the radar bursts were not aligned accurately enough to form interferograms. This was corrected in February of 2015 and now standard InSAR processing methods provide seamless 350 km by 350 km interferograms. Many interferograms have large phase ramps with still unknown origin. The ALOS-2 data appear adequate for providing an additional line-of-sight time series when several years of data become available. Similarly the Sentinel-1A time series is now approaching 1.5 years with frequent repeats (12 and 24 day) and small baselines. The new wide swath mode from Sentinel-1A (TOPS) is a completely new data type requiring image alignment to 1/1000 of a pixel that can only be achieved using accurate software and precise orbits. The participants compared results from three software packages (ISCE, GMTSAR, and SNAP) and agreed on a set of standard data for benchmarking the various codes. This half-day session and the interactions after the meeting have been extremely productive for moving the new TOPS-mode data from software development into full production of time series.

Looking ahead

Much of the CGM-related work done during SCEC4 has been focused on compiling data, comparing methodology, and identifying best practices. At this stage the initial component parts of a CGM exist and can be brought together. Through workshop discussions, a framework for formalizing the CGM emerged which will allow for its continued evolution as new data, techniques, and results become available.

Initial CGM components will include the merged CGPS time series and regional LOS velocity map(s) aligned with GPS at long wavelengths. With existing tools and methods it is possible to use the merged CGPS time series to obtain velocities using (at least) three approaches: parametric time series fitting (including a constant rate, seasonal motion, offsets, and postseismic terms), median-based trend estimation, and as predictions from a time-dependent regional deformation model constrained by geodetic observations. The resulting velocity fields are likely to differ primarily due to postseismic motion and may or may not include vertical components. InSAR time series for specific satellite tracks or regions are another CGM component for which some results can be incorporated now.

Next generation models to be included in the CGM will include seasonal models, vertical velocity fields, and postseismic time series. LOS, 2D, and 3D velocity maps spanning larger areas; InSAR time series including analyses of multi-track and multi-sensor data; and results from new SAR satellites will be added as available.

As the CGM components coalesce, we will need an interface that facilitates its use by participants and the broader scientific community. Such a web interface has been developed for the SCEC Community Stress Model (CSM), allowing researchers to contribute, obtain, and compare models. It includes valuable tools for model visualization and enforces the collection of metadata that document the models. We hope to adapt the CSM interface for use by the CGM, perhaps linking it with the SAR-specific tools available in UNAVCO's archive.

The application of diverse analysis approaches and evaluation of results using different methods have been a central focus of CGM activities. The results of these efforts demonstrate that there is no one-size-fits-all approach to building a CGM. Constraints and assumptions that are valid and useful when analyzing a spatial or temporal subset of the data may not apply in other cases; filtering might remove signals of interest. Since the CGM will provide a suite of models from which people can choose, an awareness and understanding of these factors is critical for correctly integrating datasets and using the CGM for follow-on applications. At the same time, the cutting edge research presented at the workshop points the way toward future CGM iterations of increasing sophistication, spatiotemporal resolution and resolving power for a variety of deformation and other processes.