Use of GPS and InSAR technology and its further development in earthquake modeling

Andrea Donnellan, Gregory Lyzenga, Don Argus, Gilles Peltzer, Jay Parker,

Frank Webb, Mike Heflin, and James Zumberge

Satellite Geodesy and Geodynamics Systems Group, Jet Propulsion Laboratory (NASA), Pasadena, California, USA (e-mail: andrea@cobra.jpl.nasa.gov; phone: +1-818-354-4737; fax: +1-818-393-4965).

Abstract

Global Positioning System (GPS) data are useful for understanding both interseismic and postseismic deformation. Models of GPS data suggest that the lower crust, lateral heterogeneity, and fault slip, all provide a role in the earthquake cycle. Future GPS results should also provide insight into fault interactions. Interferometric synthetic aperture radar (InSAR) is also providing valuable crustal deformation data. We are developing analytic and finite element models to be used for the interpretation of geodetic data and earthquake modeling.

Introduction

Global Positioning System (GPS) data, collected since 1986 in southern California, have proved worthwhile in assessing current rates and styles of tectonic deformation. More recently, GPS has been used to measure postseismic deformation following several moderate to large earthquakes. We focus here on GPS results and modeling related to the Ventura and Los Angeles basins, and to the Northridge earthquake. We will also touch on the use of InSAR data and its application to the Northridge earthquake.

GPS data and quality

GPS analysis techniques have now improved to the point that daily absolute horizontal and vertical positions can be determined to 3 and 8 mm respectively (Zumberge et al, 1997[9]). Using continuous data horizontal velocities accurate to 1 mm/yr can be achieved in 5 years (Argus and Heflin, 1995[1]. Campaign style measurements can yield velocities accurate to 3–5 mm/yr over two years (Donnellan and Lyzenga, 1998[5]) and to better than 2 mm/yr over longer time-spans (Shen et al, 1996[8]).

The 1994 Northridge earthquake provided a catalyst for implementing a densely spaced continuously operating GPS network called the Southern California Integrated GPS Network (SCIGN). When complete the network will consist of 250 stations throughout southern California, but concentrated within the LA basin. Before the earthquake four stations, as part of the Permanent GPS Geodetic Array (PGGA), had been operating in southern California since 1992, and prior to that data were collected in individual campaigns approximately yearly.

Interseismic results

Results from both campaign data collected in the Ventura basin, and continuous SCIGN data indicate that a narrow band of shortening runs along the front of the Transverse Ranges through the Ventura and northern Los Angeles basins (Donnellan et al, 1993a,b[3][4]; Argus et al, manuscript in preparation[2]). The shortening rates are 7–10 mm/yr and 5–6 mm/yr for the Ventura and Los Angeles basins respectively. Analysis of the data shows nearly pure shortening indicating thrust faulting environments.

Forward and inverse elastic modeling, when combined with geologic data, proved useful in estimating fault slip rate and geometry for the Ventura basin. The Ventura basin is bounded by thrust faults that dip away from the basin. The Northridge earthquake occurred along the southeastern portion of the basin on a fault similar to that defined by elastic forward models. The models required, however, that the faults bounding the basin be creeping from the lower crust up to a depth of about 5 km and the Northridge earthquake ruptured from a depth of 18 km. This leads to a problem. Can faults both creep and be seismogenic or are they completely locked to their seismogenic depth?

Viscoelastic finite element models in which a ductile lower crust relaxes between earthquakes can partially explain concentrated strain rates and deep seismogenic depths, but still result in a strain pattern broader than the observed. Addition of a compliant basin between the faults produces a more narrow band of deformation (Hager et al, manuscript in preparation[6]). The models are useful in bounding the long-term shortening rate across the basin, because there is a trade-off between shortening rate and lower crustal viscosity. Based on the geology a longer relaxation time (stiffer lower crust) and lower geological rate is favored.

Considerable modeling is still required, however, in order to understand what geodetic data tell us about the earthquake cycle. Are high strain rates the results of postseismic relaxation from past earthquakes or do they indicate some sort of failure beginning on active faults. The role of the lower crust in the earthquake cycle is not yet well determined by geodetic data. Does lower crustal relaxation or lateral heterogeneity dominate the deformation field? Can faults both creep and rupture in large earthquakes? More data in both space and time combined with complex time dependent models will begin to answer these questions.

Postseismic data from the Northridge earthquake

As mentioned above, the Northridge earthquake occurred on the southeast margin of the Ventura basin. The GPS data collected after the earthquake as well as interferometric synthetic aperture radar (InSAR) data have proved useful in understanding the deformation that occurred in the 1–2 years following the earthquake.

Analysis of aftershock data from the earthquake indicates that less than 10% of the postseismic deformation can be attributed to aftershocks. The predicted surface displacements from the aftershocks show generally the same sense of motion as the GPS observations, suggesting that the same stress field is responsible for both seismic and aseismic modes of postseismic deformation.

The data, particularly near the rupture, show a strong time dependent behavior with a rapid postseismic transient occurring after the earthquake. The decay pattern from the data is consistent with either a logarithmic or exponential function which fit afterslip and relaxation modes of deformation respectively. If the lower crust is stiff in the region as suggested by heat-flow measurements, seismogenic depths, and the modeling then it should relax slowly. Additionally, points above the rupture plane would subside due to relaxation, but are observed to increase in height. Lower crustal relaxation probably does not dominate in the few years following the Northridge earthquake. The models favor afterslip on the rupture plane with additional shallow deformation. The data do not support deep deformation occurring from either relaxation or deep afterslip.

The GPS data do suggest that additional deformation occurs following the Northridge earthquake to the west of the main rupture zone. This is substantiated by InSAR data. When the coseismic rupture model is removed from an interferogram between November 1993 and December 1995 a deformation pattern emerges similar to that observed in the GPS data. There is a strong component of deformation and uplift over the main rupture plane with additional deformation occurring to the west. Additional GPS data that have been collected but not yet analyzed for the Ventura basin may indicate whether the faults bounding the basin have been affected by the Northridge earthquake.

Models in development

We are currently using two classes of models to support our data interpretation effort. We have developed a set of forward and inversion codes based on Okada's methods (1985[7]). These are isotropic elastic models for which 9 fault parameters can be solved (location, depth, dip, length, width, slip). The inversion model uses a residual-minimization procedure based on a downhill simplex simulated annealing algorithm (Donnellan and Lyzenga, 1998[5]).

We are also expanding two-dimensional finite element code to three dimensions. The code includes a sophisticated mesh generator to simplify the complex gridding process. The mesh generator generates a mesh based on specified geometry and rheologies and densifies the mesh where necessary. The code includes viscoelastic linear or nonlinear rheology, and split nodes.

Ongoing development of the finite element code and associated utilities is aimed at a pair of complementary scientific goals. The addition of mature three-dimensional modeling tools will begin to enable, for the first time, realistic simulations of real-world configurations of multiple faults and non-planar fault configurations. This ability will be essential for detailed understanding of complex tectonic environments like the Los Angeles and Ventura basin regions. Secondly, these advanced tools will enable the development of a new level of theoretical intuition and understanding of the evolution and behavior of complex systems of faults and deforming continua. The relative roles of rheology, 3-d geometry, fault mechanics and boundary conditions will become much better understood through the study of these models.

These modeling initiatives have been enabled by the increasing availability of high-performance computing resources, as well as the above-mentioned software innovations borrowed from the engineering disciplines. The future course of their development will initially focus on the achievement of higher performance on 3-d grids. The formidable computing challenge of solving large 3-d systems has long set the limits of finite element applications. We plan to work on applying our methods to conventional high-speed computing workstations, and to leading edge parallel supercomputers and distributed computing systems. In the longer term, our development effort will focus less on this issue of performance, and more on a more integrated approach to the combination of geodetic data and theoretical modeling. We project a data assimilation modeling environment in which eventually, continuously acquired crustal deformation data will interact with a regional grid to obtain optimal descriptive and limited predictive models. We also envisage the further development of transparent and intuitive investigator interfaces with the modeling process.

The models, when combined with geodetic, data should yield more information about interseismic and postseismic processes. They will help elucidate the role of the lower crust and fault slip in the earthquake process. They should also provide insight into fault interactions.

Acknowledgments

This research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Support was also provided by the U.S. Geological Survey, Southern California Earthquake Center, and National Science Foundation.

References

[1] Argus, D.F, and M.B. Heflin, 1995, *Plate motion and crustal deformation estimated with geodetic data from the global positioning system* Geophys. Res. Lett. **22**, 1973–1976.

[2] Argus, D.F., M.B. Heflin, A. Donnellan, F.H. Webb, D. Dong, K.J. Hurst, D.C. Jefferson, G.A. Lyzenga, M.M. Watkins, J.F. Zumberge, *Shortening and thickening of metropolitan Los Angeles measured and inferred using Geodesy, manuscript in preparation.*

[3] Donnellan, A., B.H. Hager, and R.W. King, *Discrepancy between geologic and geodetic deformation rates in the Ventura basin, 1993a,* Nature **366**, 333–336.

[4] Donnellan, A., B.H. Hager, R.W. King, and T.A. Herring, *Geodetic measurement of deformation in the Ventura basin region, southern California, 1993b* J. Geophys. Res. **98**, 21,727–21,739.

[5] Donnellan, A., and G.A. Lyzenga, 1998, *GPS observations of fault afterslip and upper crustal deformation following the Northridge earthquake,* J. Geophys. Res. **103**, 21,285–21,297.

[6] Hager, B.H., G.A. Lyzenga, and A. Donnellan, in preparation, *Reconciling rapid strain accumulation with deep seismogenic fault planes in the Ventura basin, California.*

[7] Okada, Y., 1985, *Surface deformation due to shear and tensile faults in a half-space,* Bull. Seism. Soc. Am. **75**, 1135–1154.

[8] Shen, Z., D.D. Jackson, and B.X. Ge, 1996, *Crustal deformation across and beyond the Los Angeles basin from geodetic measurements,* J. Geophys. Res. **101**, 27,957–27,980.

[9] Zumberge, J.F., M.B. Heflin, D.C. Jefferson, M.M. Watkins, and F.H. Webb, 1997, *Precise point positioning for the efficient and robust analysis of GPS data from large networks,* J. Geophys. Res. **102**, 5005–5017.