A Community Workbench for the Integrated Modeling and Analysis of Geodetic Observations

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GEODESY: OBSERVING THE PHYSICAL EARTH SYSTEM

The changes in Earth's geometry, gravity field, and rotation (the "three pillars of geodesy") are observed with a portfolio of geodetic techniques spanning from point-geodetic methods, surface imaging techniques for land, ice and ocean surfaces, and emerging reflectometry, to in situ and space-borne gravity sensors. These techniques capture signals of many physical processes in the Earth system acting on a wide range of spatial and temporal scales. In order to study any of these processes based on geodetic observations, it is often necessary to account for many other processes. In particular, tectonic processes often have similar spatial and temporal scales as signals resulting from mass transport in the fluid envelope of the solid Earth (Fig. 1).

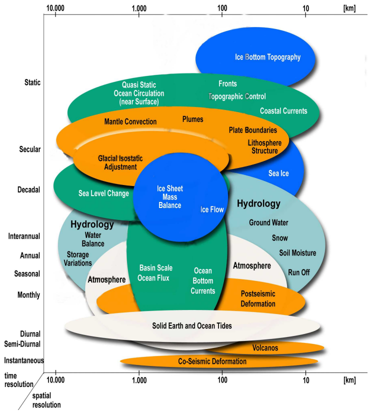

Figure 1: Physical Earth system processes and geodesy and their spatial and temporal scales. The geodetic observation techniques capture signals of many processes overlapping in spatial and temporal scales. Modified from Ilk et al. (2005).

THE "CURSE" OF INCREASING ACCURACY: EVERYTHING MATTERS

The rapidly improving accuracy of the geodetic observations increasingly requires an interdisciplinary Earth system approach to the analysis of the observations. This poses a challenge to small research groups, who often do not have the expertise to model all processes that contribute signals to the observations. Although the time-variability of Earth's geometry, gravity field, and rotation are caused by the same Earth system processes, this fundamental link between the different observations is not yet widely explored in geodesy for the analysis and interpretation of the geodetic observations. Even within one of the pillars, focus is often on one aspect of the Earth system, e.g., either tectonic process, or loading due to land water storage, or loading due to the atmosphere.

Are we as a community exploiting the full potential of the rich, accurate, comprehensive, and complementary geodetic observations in the three pillars?

THE (SLOW) PROGRESS TOWARDS INTEGRATION OF THE THREE PILLARS

The Global Geodetic Observing System (GGOS) and other services of the International Association of Geodesy (IAG) have emphasized the importance of integrating the three pillars of Geodesy (Plag and Pearlman, 2009), however, little progress has been made towards this goal. A number of initiatives within the EarthScope community have improved data sharing, interoperability, and research coordination. UNAVCO has contributed significantly to cyber infrastructure that facilitates multi-technique integration across discipline. The emerging Earthcube can be expected to add new capabilities (Gurnis et al., 2011). However, a community-validated integrated expandable modeling framework supporting specialized studies in a comprehensive model environment is not available.

A CASE STUDY: SIERRA NEVADA UPLIFT

A. Determining the uplift

Using the Global Positioning System (GPS), Interferometric Synthetic Aperture Radar (InSAR), and models, we have determined a high-accuracy picture of the vertical motion of the Sierra Nevada and adjacent areas in the Southwestern USA (Figure 2, Hammond et al., 2012). The horizontal strain map, derived from horizontal GPS measurements, was used to separate the signals attributable to horizontal deformation from the InSAR measurements. This high-resolution solution for 3d surface motion estimated from InSAR and GPS is an example of data assimilation and integration by using a kinematic model within one pillar. Taking into account all error sources, the uplift of the Sierra Nevada with respect to the center of mass of the Earth system (CM) is between 1 and 2 mm/yr (Hammond et al., 2012).

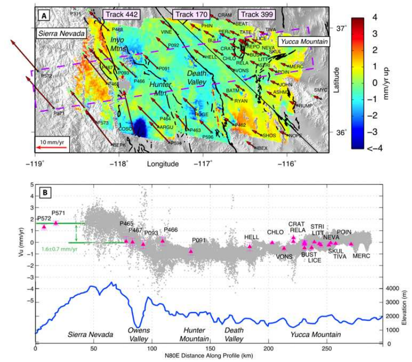

Figure 2. Vertical velocity from InSAR. A: Red vectors with site names show horizontal GPS velocity with respect to North America (with 95% confidence ellipses). Black lines are major faults. Dashed box indicates location of profile. B: Profile of vertical rate derived from InSAR and vertical velocity from GPS (magenta). Uncertainty bars are 2σ. Blue line indicates topography across profile. Green bars highlight mean uplift rate from InSAR.

B. Attributing the Causes

Potential causes for the uplift:

- tectonic uplift: 3 km over 3 to 60 Million years;
- postglacial rebound due the last ice age (far-field): on the order of 1 mm/yr but with large spatial scales;
- postglacial rebound after increased glaciation during the Little Ice Age, possibly on the order of 0.3 mm/yr; with North to South increase;
- elastic response to present-day changes in land water storage; could be on the order of 1 mm/yr if large groundwater changes;
- elastic response to changes in atmospheric and ocean loading.

C. Modeling the Uplift

Modeling the contributions to the observed uplift requires:

- tectonic model, including crustal structure and visco-elastic crustal properties;
- postglacial rebound models, far-field contributions;
- ice history for the last 500 years;
- visco-elastic model for recent ice load changes (transient rheology);
- land water storage changes over the observation period; elastic model to predict the signals;
- atmosphere and ocean loading predictions;

Results of joint analyses, joint inversions, and model studies indicate that there is a considerable potential of geodetic observations to constrain Earth system models.

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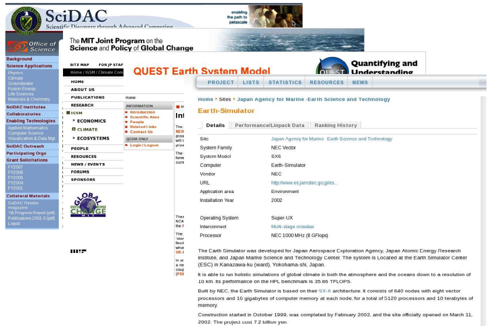

Figure 3. The solid Earth in Earth System models. There are many Earth system models, but in all of them, the solid Earth serves as a rigid lower boundary. It is a challenge to integrate a dynamic solid Earth into these models. Geodesy might have to consider an alternative approach based on physical Earth system models.

Should we create a community modeling framework that would facilitate the joint analysis and interpretation of geodetic observations?

TOWARDS A WORKBENCH FOR GEODESY

Already in 2010, the Third Annual Workshop of the IGCP Project 565 "Developing the Global Geodetic Observing System into a Monitoring System of the Global Water Cycle" recommended that a community-based hydrogeodetic modeling framework be developed to facilitate the use of geodetic observations for hydrological applications. We used the example of the Sierra Nevada to demonstrate the importance of considering tectonic, hydrological, and atmospheric processes in the interpretation of accurate geodetic observations of vertical displacements. This example illustrates the challenges of an interdisciplinary approach and highlight the current obstacles hampering the analysis in a comprehensive system framework. We conclude that a more comprehensive geodesy workbench would serve the broad geodetic community and support the integration of the three pillars of geodesy. The workbench could be developed following the example of other community-based modeling frameworks, such as the Community Surface Dynamics Modeling System (CSDMS), the Global Earthquake Model (GEM), and the emerging community ice model systems (Lipscomb et al., 2009). The EarthCube cyberinfrastructure could be the place to host the workbench, with UNVACO coordinating the community in building the tools, ensuring appropriate standardization and interoperability.

Components and Benefits of a community-built, web-based (virtual) workbench for geodesy include:

Components:

- data archive(s) for observations in the three pillars;
- data analysis tools (software);
- data analysis results (time series, grids, ...);
- integrated modeling software;
- model predictions.

Benefits:

- standardization, interoperability, data assimilation;
- joint analyses in an interdisciplinary context;
- support local and regional studies, access to expertise;
- framework for community products; global availability (capacity building);
- significant impact on education.

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