Scientific Value of Real-Time Global Positioning System Data

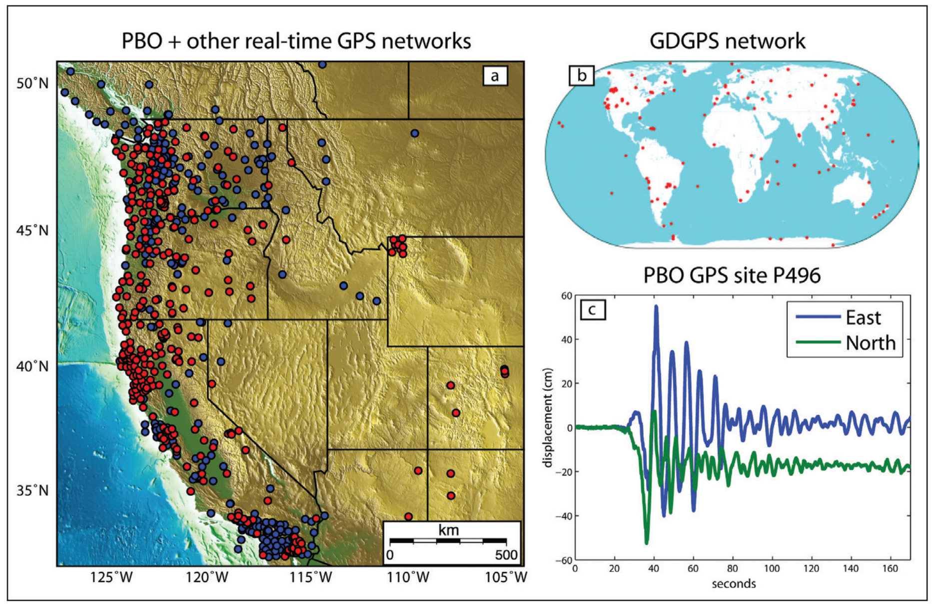

Fig. 1. (a) EarthScope Plate Boundary Observatory (PBO) sites (red dots) plus other Global Positioning System (GPS) sites (blue dots) in the western United States that have been or soon will be, upgraded to real-time streaming capabilities. (b) Global distribution of real-time GPS sites of the Global Differential GPS (GDGPS) network (from http://www.gdgps.net/, courtesy of Y. Bar-Sever). (c) Time series of 5-hertz displacement, collected 70 kilometers from the 4 April 2010 El Mayor-Cucapah M 7.2 earthquake epicenter in Baja California (courtesy of K. Larson). Coseismic offset of approximately 20 centimeters is clearly resolved in the north component 40 seconds after shaking begins.

The Global Positioning System (GPS) is an example of a Global Navigation Satellite System (GNSS) that provides an essential complement to other geophysical networks because of its high precision, sensitivity to the longest-period bands, ease of deployment, and ability to measure displacement and atmospheric properties over local to global scales. Recent and ongoing technical advances, combined with decreasing equipment and data acquisition costs, portend rapid increases in accessibility of data from expanding global geodetic networks. Scientists and the public are beginning to have access to these high-rate, continuous data streams and event-specific information within seconds to minutes rather than days to months. These data provide the opportunity to observe Earth system processes with greater accuracy and detail, as they occur.

What Is "Real-Time" GPS?

GPS is a satellite system that broadcasts signals toward the Earth, allowing a receiver to solve for its position when three or more spacecraft are in view. It was originally designed to provide accurate positioning, navigation, and time anywhere on Earth within seconds. Systems and analysis improvements in the 1980s and 1990s increased the accuracy of positioning from meters to centimeters, but such precision usually required continuous data collection for 24-hour or longer periods before measurements were produced. Solutions estimated more frequently than daily were considered high rate.

More recently, position solution accuracy and speed have advanced to the point where centimeter-precision coordinates are available within seconds, and millimeter precision is available for daily solutions. Relative motions between stations thousands of kilometers apart can be resolved. For some applications, position solution rates of 100 samples per second have been demonstrated. With the evolution of observation technologies in mind, members of the EarthScope Plate Boundary Observatory advisory committee recently authored a white paper (see http://unavco.org/research_science/science_highlights/2010/RealTimeGPSWhitePaper2010.pdf) that discusses the expected future scientific value of real-time GNSS information, particularly with regard to GNSS positions that arrive with high rate (e.g., 1 hertz or higher) and low latency (e.g., seconds or less). Such measurements are termed real-time GPS (RTGPS).

The principal scientific benefit of RTGPS data is realized when high-rate information improves temporal resolution in observations of natural processes. RTGPS likely will demonstrate an impact similar to that of other high-rate geophysical observations (e.g., from seismological and meteorological networks) for monitoring and understanding earthquakes, seismic wave propagation, volcanic eruptions, magmatic intrusions, movements of ice, landslides, and structure and dynamics of the atmosphere. In many cases the availability of low-latency data will substantially enhance the processes and outcomes of the research itself. For example, low latency ensures that high-rate data are reliably transmitted to laboratories until the moment catastrophic events destroy instruments or disable transmission lines. Immediate delivery can save precious near-field measurements of the largest displacements or atmospheric effects. Use of low-latency data will enhance rapid scientific response by improving targeting, by activation of new data streams, or by changing instrument settings based on early results.

The availability of RTGPS information will also have important impacts on how scientists and societies prepare for and cope with natural disasters. As a rule of history, mitigating the effects of natural disasters such as earthquakes, tsunamis, volcanic eruptions, and landslides requires knowledge of the underlying Earth science coupled with information about specific events delivered and updated as quickly as possible. Rapid detection and accurate characterization of events can make a crucial difference during the minutes to hours that follow. This point was clearly made following disasters that occurred during the past decade, including the catastrophic 2004 Sumatra and 11 March 2011 Tohoku-oki earthquakes and tsunamis. In both of these events, the initial seismic notification of earthquake magnitude was available in minutes but was more than an order of magnitude smaller than the true event size. GPS systems can address this uncertainty in the rapid estimation of large earthquake magnitudes.

Presently, about 240 GPS stations of the EarthScope Plate Boundary Observatory in the vicinity of the Cascadia subduction zone are being upgraded to provide GPS observations at 1 hertz and faster than 0.3-second latency. The NASA Jet Propulsion Laboratory provides streams of positions at 1 hertz for more than 120 globally distributed stations with 5-second or faster latency via its Global Differential GPS system. The California Real Time Network (CRTN) at the Scripps Institution of Oceanography distributes data and positions from more than 150 stations in California. Other sites and networks are also being upgraded through various initiatives (Figure 1). In light of these and other developments, broad new realms of processes can be studied with RTGPS.

Seismic Source, Event Characterization, and Warning

Integration of RTGPS with seismic time series will push forward the science of broadest-band seismology, meaning that studies of "seismic" sources can be increasingly viewed as studies of Earth deformation events that occur over a very wide range of time scales, some of which may not necessarily generate seismic waves. The inclusion of RTGPS to extend measurements beyond typical seismic frequencies is essential to understanding the complete spectrum of fault slip behaviors associated with the earthquake cycle. For instance, GPS-measured static displacements and waveforms (Figure 1c) can produce improved and rapidly available models of earthquake slip, surface deformation, and strong ground motion [e.g., *Rolandone et al.*, 2006]. Such data are invaluable for first-response efforts that require knowledge of the areas of strongest ground motion and surface rupture.

To supplement current seismic early warning systems, RTGPS data will play a vital role in early warning for large events with long ruptures [*Böse and Heaton*, 2010]. For these events, an integrated RTGPS could provide information about an ongoing earthquake quickly enough to make a prediction of shaking before it occurs. This type of notification could give people a few seconds to minutes to prepare themselves, machinery, and infrastructure for shaking.

Tsunami Event Characterization and Warning

Tsunami warning has particular requirements for calculating accurate earthquake magnitude, propagation direction, and vertical and horizontal motion of the seafloor. The goal is to rapidly recognize that a tsunami event is occurring and improve predictions of where the wave will rise on near and distant coasts. Displacements at GPS sites are used to constrain a fault slip model, which predicts motion of the seafloor. An adequate near-field network is preferred to constrain the slip distribution. Had a GPS-based warning system been in place for the 2004 Sumatra earthquake, a more accurate magnitude could have been estimated within 15 minutes [*Vigny et al.*, 2005; *Blewitt et al.*, 2006].

During the 11 March Tohoku-oki event in Japan, a prototype GPS-based warning system, the NASA GPS Real-Time Earthquake and Tsunami (GREAT) Alert, was running in test mode. The project team is now evaluating performance of that system, so details are not yet available as this article goes to press. However, once they are operational, systems such as GREAT should help to shave minutes off the time needed to recognize what has occurred, thus supporting quicker warnings that can save lives. The GREAT system is currently being evaluated by the Pacific Tsunami Warning Center as a tool to complement existing tsunami warning systems.

Volcanic and Magmatic Events

Volcanic activities, magma chamber inflation/deflation, dike intrusions, and effusive and/or explosive eruptions often produce measurable surface deformations. These deformations provide information about processes inside magmatic plumbing systems and can vary rapidly in space and time. Because these deformations can precede hazardous eruptions by hours to months, telemetered GPS networks combined with low-latency processing strategies are in operational use in volcano observatories in the United States (Hawaii, the Cascades, and Yellowstone) as well as Japan and Italy.

Additional hazard arises when steep slopes of island volcanoes fail catastrophically and generate a tsunami. Slope failures on some island volcanoes involve poorly understood transitions from slow-slip events to abrupt

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failures. For example, a flank-related slow-slip event at Kilauea was likely triggered roughly 15–20 hours after a dike intrusion in the east rift zone stressed the flank [*Brooks et al.*, 2008]. In these situations, RTGPS networks can monitor motions preceding potentially catastrophic events.

Cryosphere

In just the past few years, GPS has had a remarkable impact on ongoing research relating to glacier volume, flow, and evolution, leading to improvements in measurements of flow velocities, rates of surface snowfall, and isostatic adjustment associated with glacial mass change. High-rate monitoring of the cryosphere has had a transformational effect on scientific understanding of dynamic glaciology. These measurements have shown that glacier flow can change speed and direction on time scales that were once thought impossible: seasonal, fortnightly, daily, and even subhourly [*Nettles et al.*, 2008]. The processes associated with these changes are poorly understood and not included in current models of ice sheet flow, resulting in poor estimates of future glacial contributions to sea level. RTGPS can contribute to a better understanding of sea level by allowing researchers to collect and analyze glacier flow data along with conventional ocean and atmospheric data.

Tropospheric Modeling

RTGPS measurements have the potential to contribute to climate modeling and weather forecasting through integrative measurement of atmospheric water vapor in GPS signal delays and measurements of soil moisture flux. First, microwave frequencies used in GPS are particularly sensitive to the presence of water vapor, and much effort has been devoted to estimation of water vapor along GPS signal propagation paths [e.g., *Braun et al.*, 2001]. GPS water vapor data will become more useful for weather and climate applications as RTGPS networks provide the data with low latency and high reliability. Second, researchers have extracted measurements of snow depth and soil moisture from multipath interference in the environment around GPS antennas [*Larson et al.*, 2008, 2009]. Measurements of local moisture obtained with high-rate sampling could contribute to larger-scale quantification of water fluxes.

Space Weather

Virtually all aspects of ionospheric research use GPS observations, primarily through measurements of total electron content from the differential delays of two signal frequencies. Higher sampling rates of RTGPS will benefit studies of traveling ionospheric disturbances and other wave phenomena, including disturbances from earthquakes and tsunamis, while lower latency will aid in the development of operational forecasting for space weather, with significant implications for global communications systems and satellite maintenance.

Future Directions

Through rapid and widespread adoption of RTGPS, geodetic information will soon have latency, availability, and public impact similar to meteorological and seismic information. This requires overcoming specific technical challenges, such as improving data networks and developing faster algorithms for coping with data streams. It will also be necessary to overcome cultural challenges that inhibit the exploration of the overlap of geodesy, seismology, and cryospheric and atmospheric science. Despite these obstacles, GNSS geodesy will experience a rapid evolution as various communities critically evaluate and use these data for research purposes, leading to the development of accessible and actionable public information products. Ultimately, this evolution is essential for improving understanding of high-impact Earth system processes and for increasing public engagement.

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