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The Scientific Value of High-Rate, Low-Latency GPS Data

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Recent and ongoing technical advances in uses of the Global Positioning System (GPS), combined with decreasing equipment and data acquisition costs, portend rapid increases in accessibility of data from expanding global geodetic networks. 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 its ability to make measurements of displacement that are local to global in scale. Scientists and the public will soon have access to high-rate, continuous data streams and event-specific information within seconds to minutes rather than days or months. The availability of these data present opportunities to observe Earth system processes with greater accuracy and detail. Recently, members of the EarthScope Plate Boundary Observatory Advisory Committee authored a white paper [*Hammond et al*., 2010] that discusses the expected future scientific value of real-time GNSS information.

What is "Real-Time" GPS?

GPS is a satellite system which broadcasts signals toward the Earth, allowing a receiver to solve for its position when four 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 1980's and 1990's improved the accuracy of positioning from meters to cm, but such precision usually required continuous data collection for 24 hours or longer periods; solutions estimated more frequently were considered high-rate. More recently, position solution accuracy and speed have advanced to the point where cm-precision coordinates are available within seconds, and mm-precision is available for daily solutions, even for stations 1000s of km apart. For some applications position solution sample rates of 100 Hz have been demonstrated. We refer to "real-time" GPS (RTGPS) as GNSS positions that arrive with high-rate (e.g., at 1 Hz or higher) and low-latency (e.g., seconds or less).

The principal scientific benefit of RTGPS data are when high-rate information provides improved 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, structure and dynamics of the atmosphere, movements of ice, and landslides. In many cases the availability of low-latency data will substantially enhance the processes and outcomes of the research itself. For example, low-latency assures 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 data bearing on the largest displacements or atmospheric effects. Use of low-latency data will enhance rapid scientific response by improving targeting, activation of new data streams, or in changing instrument settings based on early results.

The availability of RTGPS information will also have important impacts on how we prepare for and cope with natural disasters. As a rule of history, mitigating the effect of natural disasters such as earthquakes, tsunami, volcanic eruption, and landslides requires knowledge of the underlying Earth science coupled with information about specific events delivered and updated as quickly as possible.

The ability to detect and characterize events quickly can make a crucial difference during the minutes to hours that follow. This point was clearly made following mega-disasters that occurred during the last decade (e.g. the 2004 Sumatra earthquake and tsunami in which nearly 230,000 people lost their lives).

Presently ~240 GPS stations of the EarthScope Plate Boundary Observatory (PBO) in the vicinity of the Cascadia subduction zone are being upgraded to provide 1-Hz GPS observations at better than 0.3 second latency. The NASA Jet Propulsion Laboratory provides streams of positions at 1 Hz for over 120 globally distributed stations with ~5 seconds or better latency via its GDGPS system. The California Real Time Network (CRTN) at Scripps distributes data and positions from over 150 stations in California. Other sites and networks are also being upgraded through various initiatives (Figure 1). In light of these and other developments we take this opportunity to describe the broad new realm of processes that will be studied with RTGPS.

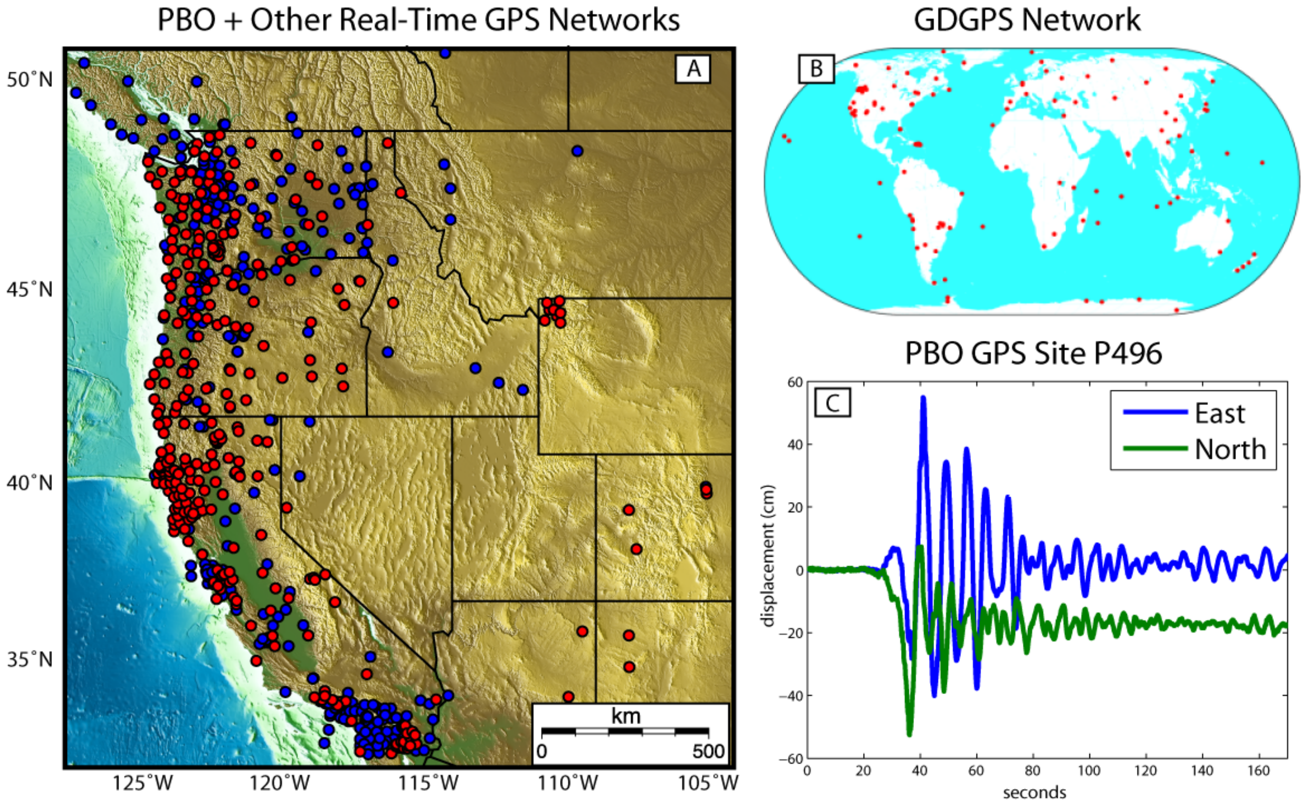

Fig. 1. A) EarthScope PBO (red) plus other (blue) GPS sites in the western U.S. that are presently, or soon will be, upgraded to real-time streaming capabilities. B) Global distribution of real-time GPS sites of the GDGPS Network (from http://www.gdgps.net/ courtesy of Y. Bar-Sever). C) Time series of 5 Hz displacement 70 km from the April 4, 2010 Mayor-Cucapah M 7.2 earthquake epicenter (courtesy of K. Larson).

Seismic Source, Event Characterization and Warning

Integration of RTGPS with seismic time series will push forward the science of very broad band seismology. Studies of "seismic" sources will be increasingly viewed as studies of Earth deformation events that occur over a very wide range of time scales, including sequences that do not 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 system 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, machinery, or critical infrastructure a few seconds to minutes to prepare 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 sea floor. 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 predict motion of the sea floor. An adequate near-field network is essential for constraining the slip distribution. During the 2004 Sumatra event, had GPS data been processed and interpreted in real-time they could have estimated the evolution of slip and true magnitude in less than 15 minutes [*Vigny et al.,* 2005; *Blewitt et al.*, 2006]. Had this been accomplished a tsunami prediction could have been issued hours before the wave devastated coastal regions around the Indian Ocean. RTGPS is currently being evaluated by the Pacific Tsunami Warning Center as an additional 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 Hawaii, the Cascades, Yellowstone, 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 failures. For example, a flank-related slow-slip event at Kilauea was likely triggered ~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 deformations and motions that may precede catastrophic events.

Cryosphere

In just the last few years GPS has had a remarkable impact on ongoing research relating to glacier volume, flow, and history, 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 our 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 minutes (*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 glacial contribution 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]. The 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 antennae [*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 ionosphere research use GPS observations, primarily though 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.

Conclusion

Through rapid and widespread adoption of RTGPS, geodetic information will soon have similar latency, availability and public impact as meteorological and seismic information. This has required overcoming specific technical limitations such as the management of data networks and development of fast algorithms for coping with data streams, but also includes cultural challenges such as exploring the overlap in research activities of geodesists, seismologists, cryospheric and atmospheric scientists. We anticipate that 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. These are essential for improving understanding of high-impact Earth system processes, and for increasing public engagement.

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