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

A White Paper

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Introduction

Ongoing upgrades of western U.S. GPS networks to high-rate, low-latency data transmission capabilities has drawn attention to the interest that the scientific community has in these data. GPS provides an essential complement to other geophysical networks (e.g. seismic, strain, gravity) because of its high precision, sensitivity to the longest period bands, its ease of deployment, and its ability to make measurements of displacement that are local to global in scale. New technologies and analysis methods are providing access to GPS data and products with increasing sample rate and decreasing latency, thereby broadening the realm of processes that can be studied with GPS. Recently, scientists involved with the EarthScope project considered their objectives for the coming years and articulated them in the EarthScope Science plan (*Williams et al.*, 2010), which explicitly referred to the need for real-time GPS to investigate EarthScope science questions. These writings, plus the occurrence of several recent sessions at AGU meetings and workshops and results from recent earthquakes (e.g. the April 4, 2010 M7.2 Mayor-Cucapah Earthquake in Baja California - Figure 1) document a rising wave of interest from various quarters of the community.

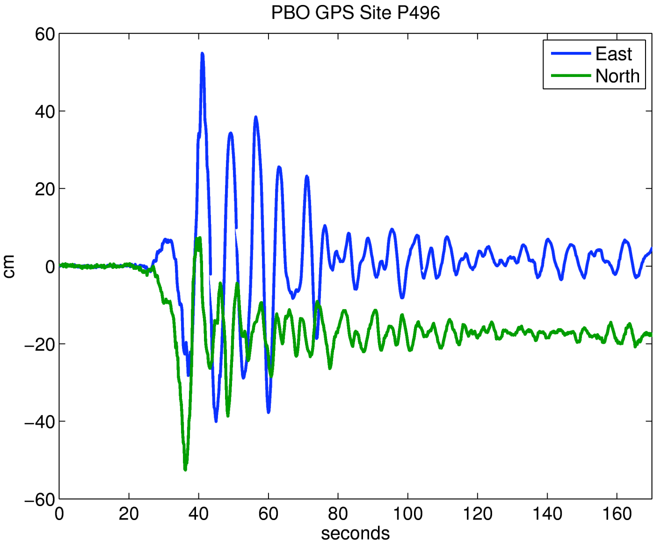

Figure 1 (Left) 5 Hz data plot showing displacement for a GPS site about 70 km from the April 4, 2010 Mayor-Cucapah M 7.2 earthquake epicenter. Data and plot courtesy of K. Larson at the University of Colorado, Boulder. Station information http: //pboweb.unavco.org/shared/scripts/stations/?checkkey=P496.

Presently ~240 GPS stations of the EarthScope Plate Boundary Observatory (PBO) in the vicinity of the Cascadia subduction zone are being upgraded in a three-year ARRA-funded project that will provide 1-Hz data at better than 0.3 second latency. Additionally other PBO GPS sites are being upgraded through various initiatives, including the California Real Time Network (CRTN, http://sopac.ucsd.edu/projects/realtime/), projects with NOAA, and the USGS (Figure 2). Presently UNAVCO provides streams of data for 183 GPS sites in the western United States (available at http://pboweb.unavco.org/?pageid=107), with that number increasing to over 400 in the next two years. The NASA Jet Propulsion Laboratory provides streams of positions at 1 Hz for over 120 globally distributed stations in the ITRF 2005 reference frame via its GDGPS system (http://www.gdgps.net/ - Figure 2). From local and regional networks the CRTN provide data and solutions through the GPS Explorer interface, while the Bay Area Regional Deformation Network (BARD), Pacific Geoscience Centre (PGC), Pacific Northwest Geodetic Array (PANGA), and Scripps Orbit and Permanent Array Center (SOPAC) are all exploring the use of real-time GPS data to rapidly estimate displacements for scientific and natural hazard research.

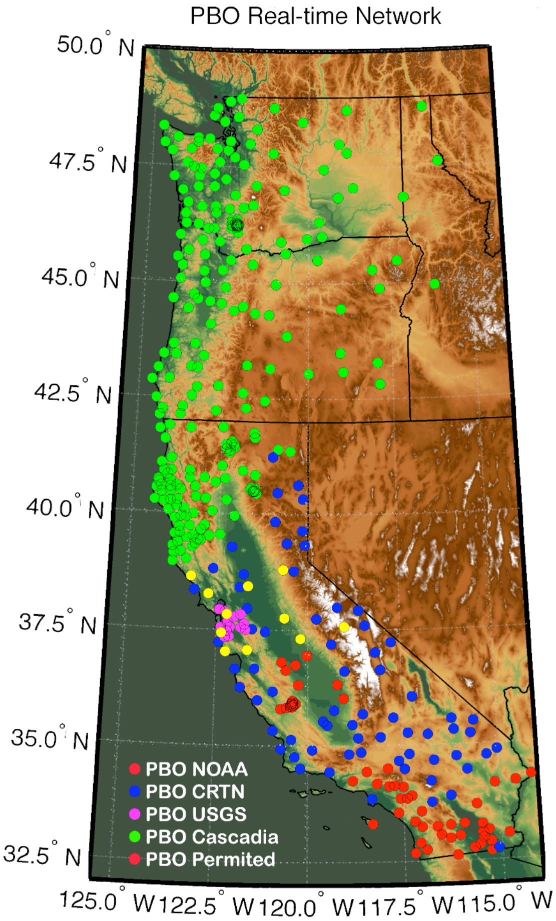

Figure 2 (left). Location of EarthScope Plate Boundary Observatory GPS sites in the western United States that are now, or are presently being upgraded to, high rate and low-latency data streams. In all there are 232 Cascadia, 12 NOAA, 79 CRTN, 8 USGS, and 54 PBO stations where data streams are part of the land use permit.

Figure 3 (below). The GDGPS network which provides global real-time GPS coverage for research and applications. GDGPS provides streams of positions for all sites at 1 sample per second. Figure from http://www.gdgps.net/ courtesy of Yoaz Bar-Sever.

From a scientific standpoint, most of the benefits of high-rate and low-latency (i.e. "real-time") data derive from the inherent value of having high-rate information, allowing better temporal resolution in the observations of natural processes in Earth systems. In most other types of geophysical instrumentation (e.g. seismometers, borehole strainmeters, laser strainmeters, meteorological instruments, tilt-meters, etc.) the need for sample intervals well below 1 second has been acknowledged and fulfilled for decades. The advantages of having these data apply to the study of numerous processes, including earthquakes, seismic wave propagation, volcanic eruptions, magmatic intrusions, structure and dynamics of the atmosphere and ionosphere, landslides, etc.

For scientific research, the availability of low-latency data is generally welcome, even if it is not strictly needed for reconstructing events after they occur. However, in some cases the availability of low-latency data will substantially enhance the outcome of research. The first advantage is that low-latency delivery assures that high-rate data are properly and safely transmitted to the laboratories that use them. In some events instrumentation or data transmission lines can be disabled or destroyed and thus immediate delivery can save the data that are the most precious, e.g. near-field measurements that record the largest displacements during a volcanic eruption, earthquake, landslide, etc. For this and other engineering reasons, the delivery of high-rate data is best done with low-latency. Second, the availability of low-latency data allows for the targeting and coordination of rapid scientific response to events. For example, new stations can be deployed, settings for other instrumentation can be changed, or other disciplines brought into the response (depending on the nature of the event) and brought to focus on areas that are inferred from early data to be the center of the phenomenon.

Real-time data allow for real-time science and have a place in an increasingly real-time society. The analogy with seismic data is instructive. Today it is possible for anyone to receive notification of hypocentral and moment tensor information for earthquakes, placed into geographic and tectonic context, within minutes of their occurrence. How would the science of seismology change if seismic data from stations in the western US and globally would slowly trickle in with various latency times ranging from seconds to months? It is likely that this would reduce seismologists ability to do science with these data. Providing the data rapidly has had a profound impact on the awareness that scientists have of their planet, and has an impact on how scientific inquiry is focused. The availability of low-latency data created a new set of opportunities and challenges that changed the face of seismology. Thus it is expected that GPS data and higher level products provided in real-time will greatly enhance distribution and use of the data for scientific and other uses.

The benefit that low-latency information provides to society is perhaps more direct and obvious. For example, people who live in the path of natural hazards require information about catastrophic events to be delivered as quickly as possible. The ability to detect and characterize events rapidly can make all the difference in the critical minutes to hours that follow an event. This point was clearly made following mega-disasters that occurred during the last decade (e.g. the 2004 Sumatra earthquake and tsunami where near 230,000 are thought to have lost their lives). However, the distinction between pure science and hazard research is often blurred and history has shown that value to society comes from basic Earth science. For example, knowledge of earthquake physics and recurrence was accelerated by the development of the instrumentation needed for quantitative seismology. Pure science and hazard research are inextricably linked, since preparing for disasters requires knowledge of the hazards, which requires understanding of the where, when and how of catastrophic events.

As in astronomy and other fields, inquiry often drives yet follows the observation technologies. In this regard it is essential that barriers to observations be successively removed so that the pace of discovery can increase. In this document we outline our expectations for where rapid advances will be made by using real-time GPS systems. In some cases this boils down to a report on the status of a field, and where next steps might be most immediately obvious. We aim to provide a representative, but not necessarily complete sample of research topics that can be addressed with real-time GPS data.

What is meant by "real-time" GPS?

GPS was originally designed to be a "real-time" system, intended to provide accurate positioning anywhere on the Earth's surface within seconds. Accuracy of these systems was typically measured in meters. In the 1980's and 1990's, through various systems and analysis improvements, the accuracy of positioning improved to the cm level, but usually required collecting data continuously for 24 hours or longer periods (e.g. *Larson et al.*, 1991; *Blewitt et al.*, 1992; *Segall and Davis*, 1997). Over the past decade the science of geodetic positioning has continued to press the boundary of accuracy and speed 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. One rule of thumb is that the accuracy of geodetic precision has improved by approximately one order of magnitude every decade for the past 4 decades (*LaBrecque*, 2006).

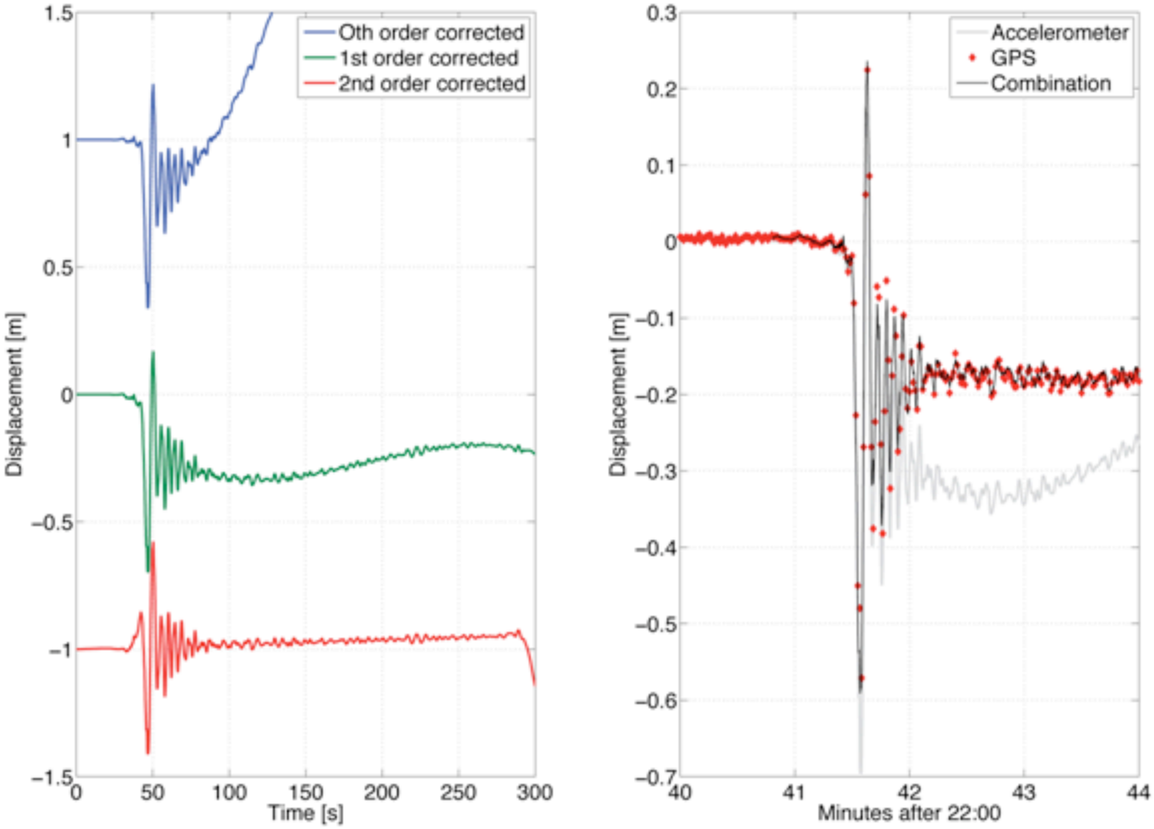

Figure 4. (Left) Zeroth, first- and second-order corrected north displacement waveforms obtained for a strong motion recording from the Mw 7.2 El Mayor-Cucapah Earthquake, for station WES (~71 km from epicenter) using the scheme proposed by *Boore et al.* (2002). The zeroth-order corrected signal has a sizable drift which explains the need for the first-order correction. Due to the proximity of the station to the source a static offset signal is expected. The first-order corrected time series shows an offset but it also contains a long period component that hinders the interpretation. Applying the second -order correction, the long period component is removed, but the static deformation is lost. (Right) 1 Hz total GPS displacement waveform, the first-order corrected integrated 100 Hz accelerometer data, and 100 Hz multi-rate Kalman filter combination of the zero-order corrected accelerometer data and the CGPS displacements using the approach of *Smyth and Wu* (2006). Compared to the post-processed GPS static offset the integrated accelerometer static offset is overestimated and there is has a small long period component. It is clear that the 100 Hz Kalman filter record at provides a more accurate and physically plausible displacement waveform and has the advantage of being able to be performed in real-time. Figure courtesy of Yehuda Bock and Diego Melgar, Scripps Institution of Oceanography.

In general, GPS is now referred to as "real-time" when position solutions arrive with both high rate (e.g., at 1 Hz or higher), and low-latency (e.g., on the order of seconds or less). Because high precision geodetic measurements traditionally have used daily or weekly position estimates, solutions estimated more frequently than daily are often considered high-rate. In the “standard” mode, receivers are set to sample raw GPS satellite observations at 15 or 30 second intervals, and the data are subsequently processed into a daily position. However, because high precision methods rely on signal phase, there is no immediately obvious limit to how frequently this observation can be made, and sample rates of 100 Hz have been demonstrated. Latency is limited by data transfer systems and has been demonstrated in PBO to be below 0.3 seconds from receiver acquisition to availability for pickup at UNAVCO archives.

Science that will benefit from real-time GPS

Earthquake Studies: The Seismic Source

Integration of seismic and GPS data at the time series level promises to push forward the science of very broad band seismology. The study of seismic sources has much to gain from the inclusion of longest periods, including parts of the deformation sequence that do not necessarily generate seismic waves. For example, recent earthquake clusters near Lake Tahoe (*Smith et al*., 2004), and Reno, Nevada (*Anderson et al*., 2008; *Blewitt et al*., 2008) indicated that while hundreds to thousands of small to medium earthquakes occurred, most of the deformationoccurred aseismically. Studies of "seismic" sources will be increasingly viewed as studies of Earth deformation events, only a part of which are illuminated via energy propagated as elastic waves from the source. Many deformation processes associated with the earthquake cycle (including fault slip, viscous flow of rocks, fluid flow and postseismic deformation), volcanic activity and non-tectonic deformation processes do not produce seismic waves and can occur over a very wide range of time scales. The use of high-rate geodetic monitoring in these cases is absolutely essential to understand the nature of the event.

In the future the level of integration between seismic and geodetic methods will likely deepen as researchers take advantage of the increasing quantities of real-time GPS data that are available from their regions of interest. High-rate GPS data can effectively serve as a strong motion displacement instrument that never saturates, which reduces potential problems in the double integration of strong motion records (e.g. *Larson*, 2009). Inertial accelerometers cannot distinguish between accelerations caused by rectilinear motions and accelerations that arise when a seismometer is tilted in the Earth’s gravity field. In addition, double integration of seismic data also requires extreme linearity of the seismometer system as well as knowledge of the initial ground velocity at the start of integration. This means that most strong motion records are high-pass filtered to remove spurious long-period signals. Unfortunately, the process of high-pass filtering also removes critical information about the rupture process. GPS systems do not suffer from these shortcomings. *Larson et al.,* (2003), *Bock et al*., (2004), *Ji et al*. (2004), *Miyazaki et al*. (2004) demonstrated that 1 Hz GPS data can be incorporated in finite-source inversions in the same manner as traditional seismic waveforms, and can provide direct measurements of arbitrarily large dynamic and static ground horizontal displacements. *Genrich and Bock* (2006) using methodology developed by *Bock et al.* (2000) and *Nikolaidis et al.* (2001) to show that GPS position time series with sample rates as high as 50 Hz are obtainable, increasing the potential for integration with traditional seismology. Figure 4 shows an example for the El Mayor-Cucapah earthquake, where accelerometer and GPS data were integrated into a singe time series having both 100 Hz sampling and accurate static offset.

Earthquake Studies: Early Event Characterization and Warning

GPS-measured static displacements and waveforms can be used to produce improved and rapidly available models of earthquake slip and associated surface deformation and strong ground motion. Such data are of scientific value for first-response efforts that require knowledge of areas of greatest strong ground motion and surface rupture (*Crowell et al*., 2009). Maps of ground deformation and shaking can help emergency responders and planners identify locations where disruption to infrastructure is likely. The primary benefit of high-rate and real-time GPS data for such studies lies in the rapid availability of high-quality earthquake source and shaking models for early scientific field investigations and response and rescue efforts.

Access to high-rate GPS data and estimated static offsets can help constrain automated finite-source models, which in current operations depend on seismic waveform data alone. With GPS-measured surface displacements from an earthquake, joint inversions of seismic waveforms and static deformation can improve kinematic models (e.g., *Rolandone et al*. 2006). Rapidly determined finite-source models may be used to characterize near-fault strong ground shaking, which can be important in areas where strong motion stations do not exist, or where they may have been knocked offline (*Dreger et al*., 2005). The advantage of GPS data is that it may independently determine the location and orientation of the rupture plane, and therefore is not subject to inherent errors in seismically determined event location, magnitude estimates, or moment tensor solutions. However, slip models obtained solely from GPS coseismic offsets cannot be used to directly predict near-fault strong ground motions. For this a model of the rupture kinematics is needed (*Rhie et al.,* 2009).

Thus in the future we can expect better event information to reach citizens and emergency responders after an earthquake, for example seeing maps of the permanent displacement fields associated with earthquake events, and maps of shaking that are informed by models derived in part from real-time GPS data. Such maps can help emergency responders and planners identify locations where disruption to infrastructure is likely. Seismic early warning systems are intended to provide information about an ongoing earthquake so quickly that many locations may receive a prediction of shaking before it occurs. The Japan Meteorological Agency and National Research Institute for Earthquake Science and Disaster Prevention have been operating a public early warning system for approximately two years. The USGS is currently supporting development of a prototype early warning system in California. While current systems are based on real-time seismic data, it seems clear that real-time GPS data will play a vital role in early warning for large events with long ruptures (*Böse and Heaton*, 2010). In particular, having pairs of GPS stations on opposite sides of important faults (e.g., the San Andreas) will provide the ability to track an ongoing long rupture in real-time.

Earthquake Studies: The Built Environment

While it is generally believed that buildings only respond at periods close to their natural period, this is often not the case when they experience plastic behavior at large deformations. In these instances, it is very important to understand the true displacement of the building in an inertial reference frame. The problem is particularly severe if static offsets as well as the dynamic far-field motions are desired. It is only through high-sample rate GPS data that we can hope to document the motion of large buildings and bridges (e.g *Kogan et al*., 2008) in an inertial reference frame. In fact, for structures such as a bridge with several piers, it is important to know the true relative displacements of the piers. This is best achieved using high-rate GPS.

Developments in early warning of tsunamis have many parallels with earthquake early detection and warning. Tsunami warning also has particular requirements with regard to calculating an accurate magnitude, propagation direction, and vertical and horizontal motion of the sea floor. The goal of tsunami warning systems currently under development is to reduce the amount of time required to recognize that a tsunami event is occurring and improve the prediction of where the wave will rise on near and distant coasts (*Titov et al.,* 2005; *Bar-Sever et al.*, 2009). The models require information about the motion of the sea floor to predict how an ocean wave will propagate. Displacements at GPS sites are used to infer sea-bottom motion by constraining a fault slip model, which in turn predicts motion of the sea floor and continental shelf (*Song et al*., 2008).

Studies after the 2004 Sumatra event showed that GPS data, if it had been processed and interpreted in real-time, could have estimated the true magnitude of the event in less than 15 minutes (*Blewitt et al*., 2006 - Figure 5). This would have been an improvement over seismic methods that took over 45 minutes to estimate the magnitude as >M9 (*Kerr*, 2005). Though new techniques to estimate true magnitude using very long period P-wave data have significantly improved the ability of the tsunami warning centers to respond more rapidly to tsunamigenic earthquakes (e.g. *Kanamori and Rivera*, 2008), GPS data should provide a basis for robust tsunami prediction, possibly even while an earthquake is still rupturing. GPS is currently being evaluated by the Pacific Tsunami Warning Center as an additional tool to complement existing tsunami early warning systems.

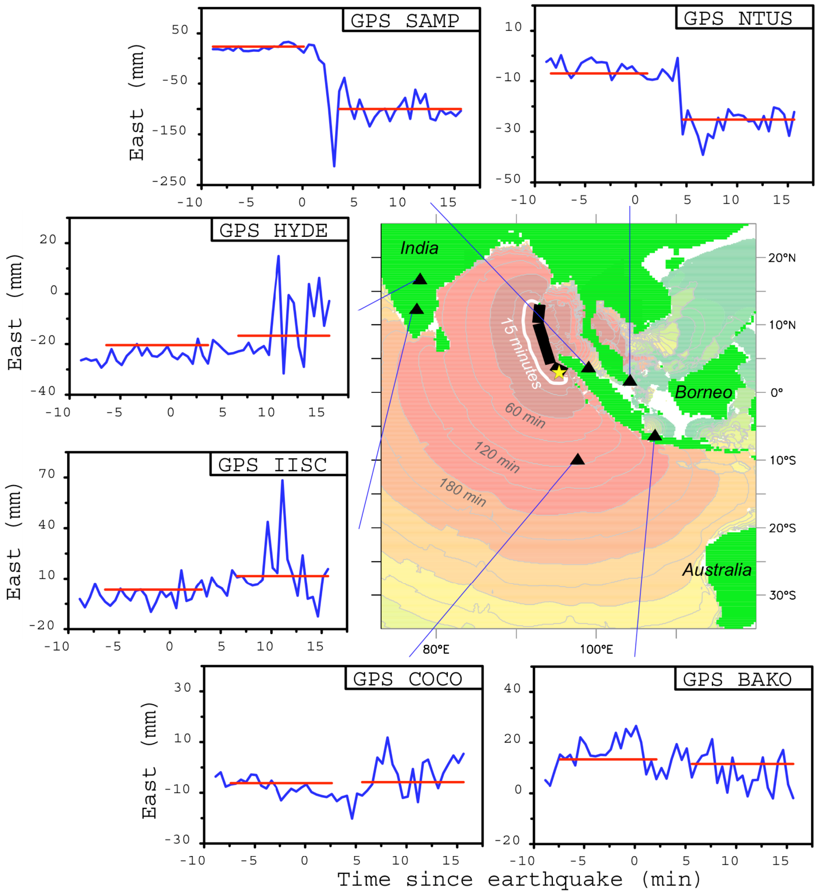

Figure 5 (left). Time series (blue lines) of east component of ground displacements after the December 2004 Sumatra great earthquake, recorded by continuous GPS sites (black triangles) in southeast Asia. The earthquake produced changes in site positions that are large enough to allow the magnitude of the earthquake to be assessed within 15 minutes, faster than was possible with seismic data alone. This time interval is shorter than the time required by the tsunami to cross the Indian Ocean, illustrating that GPS data can contribute to tsunami warning by assessing whether an earthquake is large enough to generate an oceanwide tsunami. The tsunami arrival times (color contours on map) are made available by NOAA Center for Tsunami Research. Figure from GRL issue cover containing *Blewitt et al*., (2006).

A key factor in the success of such a system is the geographic distribution of GPS sites in the vicinity of the rupture. An adequate near-field network is essential for constraining the slip distribution, even though M9 events can produce measurable displacement up to 4500 km from the epicenter (*Banerjee et al*., 2005; *Kreemer et al*., 2006). For example, for the 2004 Sumatra earthquake, inversions for the slip distribution required near-field sites (<100 km from the fault) to reliably estimate the magnitude (*Blewitt et al*., 2006; *Sobolev et al.,* 2007). Another key factor is a sufficiently high rate of GPS sampling to 1) estimate displacements rapidly enough to produce a timely warning, and 2) distinguish the seismic shaking from the permanent displacement at the GPS sites. The temporal evolution of the slip in the 2004 earthquake was constrained by 30-s GPS time series from stations in Thailand by *Vigny et al*. (2005). If this had been accomplished in real-time, a kinematic slip model and tsunami prediction could have been produced hours before the tsunami devastated coastal regions around the Indian Ocean. Timely position estimates must be provided, at least every minute, though more frequently is preferable.

Volcanic and Magmatic Events

Volcano magmatic activity, i.e. magma chamber inflation/deflation, dike intrusion, effusive and/or explosive eruption, is often accompanied by measurable surface deformation that can vary rapidly in space and time (*Dzurisin*, 2007). For example, GPS stations either side of Kilauea rift zone dike emplacement events have recently exhibited more than 10s of cms baseline changes accruing over a few to 10s of hours (*Segall et al*., 2001; *Poland et al*., 2008). Because these types of events are often precursory to, or accompany hazardous eruptions, telemetered GPS networks combined with low-latency processing strategies are major components of the well-established volcano observatories worldwide such as in Hawaii, the Cascades, Yellowstone, and Italy.

More generally, the deformation data provide information about the physical processes that occur inside the magmatic plumbing system and that ultimately control eruption type and the kinds of rocks placed at the surface. These links between observation, process and hazard were articulated in the EarthScope Science Plan:

> "Recent studies show that magma storage depths obtained through experimental petrology methods compare quite well with those derived from geodetic studies, providing strong impetus for continuation of interdisciplinary work. Magma ascent time scales can also be cross-correlated across disciplines, with important implications for eruption predication. For example, 60 to 90 days prior to the onset of the 2006 eruption of Augustine Volcano in Alaska, PBO crustal deformation data revealed magma ascent to shallow levels, a time scale that was corroborated by petrological data. The enormous amount of information collected by many researchers over the course of the 2006 Augustine eruption illustrates the potential of an integrated geophysical and petrological/geochemical approach to studying active volcanoes, especially those "caught in the act" of erupting. Future PBO data may clarify the details of magma accumulation and ascent and the onset of eruption at several instrumented volcanoes." (*Williams et al.,* 2010)

It is not only the direct magmatic related signal associated with a volcano that warrants low-latency GPS observations, however. It is well known that the steep slopes of island volcanoes can fail catastrophically and generate a tsunami with the potential to substantially impact coastal populations (*Day et al*., 1999; *Ward*, 2002; *Mattia et al*., 2004). The extremely large displacements associated with a catastrophic volcanic sector collapse likely accumulate over time-scales from seconds to minutes. Additionally, as with subaerial landslides, some ocean island volcano mobile flanks exhibit non-catastrophic slow-slip (*Cervelli et al*., 2002) and very little is known about the presumed precursory transition from stable to catastrophic failure. Further complicating matters, volcanic edifice stability and magmatic processes may be closely related. For example, *Brooks et al.*, (2008) showed that 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. Thus, high-rate data are needed to avoid temporal aliasing of flank motion signal and low-latency data transmission is needed for detection of precursory motion. Furthermore, because the stations are likely to be destroyed during a catastrophic event, rapid transmission of their data will be critical in order to use them for either scientific or hazards purposes.

The extremely rare, flank-collapse scenario notwithstanding, the case for high-rate GPS at volcanoes is not yet as clear as for low-latency GPS. Recently, *Larson et al.*, (2010) (and references therein) found that even when high-rate data are collected, to characterize most volcanic processes, workers typically decimate their processed results to the time-scale of minutes (with the appropriate combination of site-specific filtering, multipath characterization, and tropospheric mitigation efforts). However, given the low-cost of storing high-rate GPS data on *in situ* buffers, *Larson et al.* (2010) see no reason to not collect high-rate data for potential later uses.

Glaciology

In just the last few years GPS has had a remarkable impact on the study of glacier volume, flow, and history, leading to improvements in measurements of gross flow velocities, rates of surface snowfall, and isostatic adjustment associated with glacial mass change. High-rate monitoring of the cryosphere in particular has had a transformational effect on our understanding of dynamic glaciology. Since the advent of these types of measurements, it has become apparent that glaciers can change flow speed and direction on time-scales that were once thought impossible: seasonal, fortnightly, daily, and even on the scale of minutes (*Wiens et al.* 2007; *Winberry et al.* 2009; *Nettles et al.* 2008; *Anandakrishnan et al.*; 2003). The processes associated with these changes are poorly-understood and not included in current models of ice-sheet flow. As a result, estimates of glacial contribution to sea-level are poor (*IPCC*, 2007). The ocean and the atmosphere are the source of the forces that produce these high-frequency changes in glacier flow (e.g., see *Zwally et al,* 2002). RTGPS can contribute to a better understanding of the dynamics of glaciers by allowing researchers to collect and analyze glacier flow data along with the ocean and atmospheric data.

Atmospheric Sciences: Tropospheric Modeling and Weather Forecasting

Studies of the troposphere are generally focused toward improved understanding of weather and climate processes, and ultimately improved weather forecasting. The atmospheric sciences rely heavily on circulation models, in which the physics of dynamic transport of both mass and energy (as well as radiative and other forcing) must be addressed. Energetics and buoyancy in troposphere dynamics is vastly complicated by rapid phase changes of the water constituent between solid, liquid and vapor forms.

GPS measurements have the potential to contribute to tropospheric weather modeling, climate modeling, and/or weather forecasting in up to four different ways. In order of increasing tenuousness, these include: (1) integrative measurement of atmospheric water vapor in GPS signal delays; (2) localized sensing of soil moisture and snow depth from satellite to antenna multipath; (3) large-scale sensing of water mass from elastic deformation signals, and (4) imaging of hydrometeor scattering.

(1) Water Vapor Sensing

Because water vapor is key to energy transport and buoyancy, assimilation of water vapor measurements is vital to weather modeling. Operational weather forecasts routinely assimilate observations of relative humidity along with pressure and temperature collected using radiosondes (weather balloons), rocketsondes and surface meteorological sensors. In most continental regions, such measurements sample adequately to prevent significant aliasing of pressure and temperature fields (which covary on large spatial and temporal scales) but can undersample the relatively short temporal- and small spatial-scale variability of humidity. Microwave frequencies are particularly sensitive to the presence of water vapor (*Bevis et al*., 1992; *Herring*, 1992), and much effort has been devoted to estimation of water vapor along GPS signal propagation paths from phase delays (*Businger et al*., 1996; *Braun et al*., 2001). The dry hydrostatic contribution to troposphere delay can be determined accurately from measurements of temperature and pressure at the GPS site, so isolation of the water vapor signal is straightforward (~100 PBO sites are equipped with met instruments suitable for this purpose). Applications of water vapor sensing include estimates of locally-averaged (~15-20 km scale) precipitable water vapor (PWV) using all GPS phase delays averaged over periods of order 0.5 hours, and tomographic applications using intersecting slant-paths of closely-spaced sites (e.g., *Xie et al*., 2005).

Atmospheric scientists, including both operational forecasters and academic researchers, use PWV or slant (SWV) GPS measurements sparingly though increasingly. For forecasters, the reason is obvious: Without low-latency measurements, there is little motivation to develop assimilation strategies for GPS data, which will require new metrics to accommodate the integral nature of GPS observables in place of current approaches that emphasize high vertical resolution achievable with sondes. Academic researchers more typically perform case studies of significant weather events after-the-fact, but the automated systems they use to collect radar, satellite and surface observation data streams are real-time. These groups would be far more likely to incorporate GPS data into their analyses if the data were arriving at similar latency. For these and other reasons, respondents to a recent survey of the atmospheric community (*J. Braun*, *pers. comm*., 2010) suggested higher-rate sampling and lower-latency data products as being equally important to future development of GPS PWV/SWV products, with greater station density also identified as important. This perception is quantified in a recent simulation of operational forecasting (*Fabry*, 2010), which placed GPS PWV products from Suominet and NOAA near the bottom of the list of desirable measurements to assimilate into short-term (<24 hour) forecasts, largely because those products average over half-hour timescales. Microwave radiometers ranked much higher because they sample once every five minutes. Hence, the future of GPS water vapor sensing will involve migration to SWV sensing using high-rate, low-latency data from multi-constellation (GPS, GLONASS, GALILEO, etc) receivers.

(2) Multipath Sensing of the Site Environment

Energy and mass fluxes into and out of the troposphere are also crucial to the forcing of weather and climate system models. Observations relating to flux of water to- and from- the land surface can be gleaned from GPS multipath measurements of, e.g., snow depth (*Larson et al.*, 2009) and soil moisture (*Larson et al*., 2008). These measurements derive changes in properties of the site environment from changes in the amplitude and frequency of multipath interference (relating, respectively, to attenuation properties and position of reflective surfaces). Multipath observations do not directly measure fluxes. For example, reduction of soil moisture partitions between downward percolation and upward evapotranspiration, and converting snow depth to mass loss/addition requires independent constraint of snow density. However multipath measurements could be combined with GPS water vapor sensing and meteorological modeling (e.g., *Valeo et al.*, 2005) to help quantify fluxes due to sublimation, ablation and evapotranspiration. Multipath measurements benefit greatly from high-rate sampling. They do not require low-latency, but one might anticipate that their utility for both operational and academic purposes would be enhanced by low-latency, for reasons similar to those cited above for SWV measurements.

(3) Water Mass from Elastic Load Response

Accurate estimates of large-scale continental water mass changes are useful for a wide variety of reasons, and the GRACE (Gravity Recovery and Climate Experiment) satellite mission has been a flagship for geodetic measurements of water mass changes (e.g., *Swenson and Wahr*, 2003). However GRACE measurements of Earth's gravity field have limited utility on spatial scales less than 500 km and timescales less than a month, and data are far from low-latency. Predictions derived from GRACE measurement fields are sufficiently correlative with GPS positions to suggest that elastic load response is the largest source of nonlinear variation (*Tregoning et al.*, 2009). This would imply that GPS-measured deformation could be used to estimate water mass variations on much shorter temporal and spatial scales than GRACE provides (and with low-latency), while averaging over much larger spatial scales than afforded by multipath amplitude measurements.

(4) Hydrometeor Scattering

Passive and active microwave-frequency sensing is already employed by radiometers to estimate liquid- (rain) and solid-phase (ice) integrated water content (e.g., *Kummerow et al.*, 1996). Scattering can be expected to affect microwave signals via both attenuation of amplitudes and delay of signals, and moreover is dispersive (showing up as a slight phase-advance in "ionosphere-free" linear combinations of L1-L2 frequency signals). Little effort has been made thus far to evaluate the utility of GPS scattering for hydrometeor sensing, but implementation may be made more tractable with the addition of a third (L5) civilian GPS signal. A third signal will enable more effective separation of dispersion resulting from scatterers versus that occurring in the ionosphere.

Atmospheric Sciences: Ionosphere and Space Weather

Ionospheric modeling seeks to address interactions of solar radiation with the Earth's outermost atmosphere. The properties of ionospheric plasma depend on electron density, temperature of ions and electrons, and composition of ions. Modeling ionospheric processes emphasizes solar forcing of the outer atmosphere and plasma in addition to mass and energy transport. Analogous to studies of the troposphere, scientists devote their efforts to both space weather (operational forecasting, with implications for communications and satellite maintenance) and post-mortem research designed to better understand the physical conditions of past "significant events". Also analogous to troposphere studies, both types of efforts entail assimilation (via Kalman filtering) of observations into a physics-based dynamical model. The observations include ground-based radar "sounders", and satellite data (including GPS occultation data), but the primary data source consists of ground-based GPS slant measurements of total electron content (TEC) derived from differences in L1 and L2-frequency phase delays (*D. Thompson*, *pers. comm*., 2010). GPS estimates of slant TEC are by far the most plentiful observations of ionospheric processes and provide the bulk of global spatial sampling, so global models necessarily rely on them heavily.

Because virtually all aspects of ionosphere studies already use GPS observations, the increased potential for research activity with high-rate/low-latency data anticipated in tropospheric studies is less likely here. Clearly low-latency will aid in the development of operational forecasting, but is unlikely to impact studies of historical data. Higher sampling rates are not anticipated to have tremendous impact either, except perhaps in studies of traveling ionospheric disturbances (TIDs) and other wave phenomena, including ionospheric disturbances from earthquakes and tsunamis (e.g., *Jakowski et al.*, 2006).

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