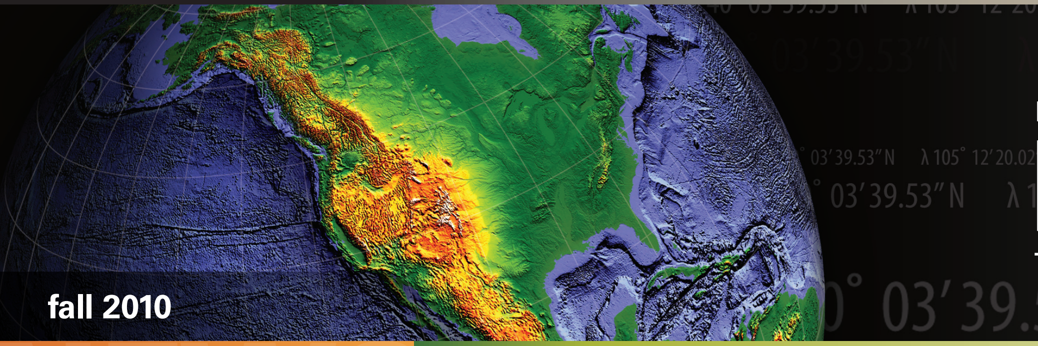

inSights
the EarthScope newsletter

fall 2010

EarthScope News

EarthScope interpretive workshop participants 'make' an earthquake at Yellowstone Lake site H17A, one of the few sites with a co-located seismic station, GPS and borehole strainmeter. Photo: Mike Jackson.

- The **2011 EarthScope National Meeting** will be held May 18-20 at the AT&T Executive and Education Center at the University of Texas at Austin. Pre-meeting workshops will be held on May 17. Details will be posted at www.earthscope.org.
- We welcome a new **EarthScope Program Director**, Dr. Charles Estabrook, who joins Greg Anderson. Dr. Estabrook comes to NSF from CTBTO in Vienna. Many thanks to Dr. Linda Warren, who has left NSF for St. Louis University.
- Please visit the **EarthScope Booth** at the 2010 GSA Meeting October 31-November 3 in Denver and at the 2010 AGU Meeting December 13-17 in San Francisco. AGU Town Hall: December 15 at 12:30 pm.
- Twenty-three graduate students and post-docs participated in the **USArray Data Processing Short Course** held August 25-29 at Northwestern University. This very productive and highly successful course addressed opportunities and challenges in USArray data processing and presented a current practices forum. Presentations at www.iris.edu/hq/es_course/content/2010.html.

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Using GPS to Measure **Soil** Moisture, **Snow** Depth and **Vegetation** Growth

The EarthScope Plate Boundary Observatory (PBO) was created to study the motion of tectonic plates and the deformation of the North American continent. The GPS data collected as part of PBO, though, contain additional information that is very useful in ways unforeseen when the original PBO science plan was created. This article summarizes new ways of using GPS data to study soil moisture, snow cover, and biomass conditions.

The PBO operates ~1100 continuously operating GPS stations and reaches its original goal of studying plate motions and continental deformation by measuring millimeter changes in the position of the GPS stations over time periods that range from months to years. In order to accommodate the needs of the EarthScope science community, UNAVCO developed an analysis plan that provides two kinds of GPS products. The first is a daily position value for the antenna – i.e. latitude, longitude, and height for each GPS site. The second product consists of velocity estimates for each site based on the daily positions, where we assume ground motion can be modeled linearly. In addition to the position and velocity products, geodesists also have access to and analyze the raw GPS observables and the measured distances between the GPS satellites and receivers.

Many factors influence raw GPS observables besides antenna position: satellite orbits, relativity, satellite and receiver clocks, tides, the atmosphere, and reflected signals. The last of these – also known as multipath – is the result of a signal that bounces before it arrives at the antenna. One can think of these reflections as weaker "echoes" of the desired direct signal. PBO does not try to remove the effects of multipath reflections, instead relying on instrument manufacturers who have designed both the GPS receiver and antenna to suppress them. Nevertheless, it is well known by geodesists that the effects of reflected GPS signals can still be observed in PBO data. Engineers actually design radars to detect reflected signals to monitor surface environmental conditions like soil moisture levels. The reflected GPS signal can be used in the same way – to use PBO as an environmental sensing network. Compared to other networks and satellites currently measuring such changes, PBO has the advantage of providing a homogeneous network over most of the western US combined with existing telemetry and archiving.

Radars take advantage of the fact that the radar signal penetrates and is reflected by dry soil differently than by wet soil, yielding estimates of shallow soil moisture. This principle is also true for GPS reflections. A radar on a satellite – such as the upcoming NASA SMAP mission (http://smap.jpl.nasa.gov) – typically has a very large spatial footprint (25-600 km^2). In contrast, in situ soil moisture sensors have a very limited spatial sensitivity (on the order of 100 cm^2). The

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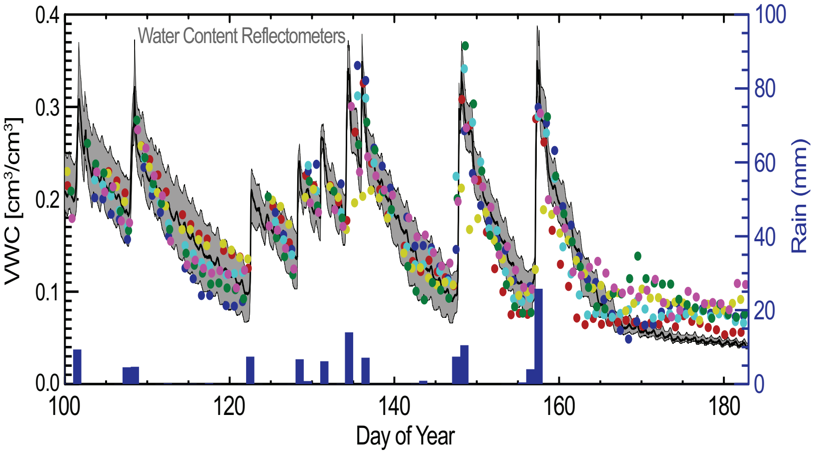

Figure 1: Near-surface variation in volumetric water content (VWC) inferred from multiple GPS satellites (colors) and water content reflectometers (WCR) measured at Marshall, Colorado (PBO site P041) during 2008. The range of the five WCRs (buried at a depth of 2.5 cm) is shown in grey and their mean is the black line. The daily precipitation totals are in blue.

Modeling the **2010 Chile Earthquake** Rupture with USArray

Near real-time earthquake monitoring is of great societal relevance. Agencies such as the National Earthquake Information Center (NEIC) of the US Geological Survey use seismograms recorded by instruments sparsely distributed around the world to determine the location and magnitude of earthquakes globally. Densely spaced seismometer networks, like the EarthScope Transportable Array (TA), on the other hand, can be used like giant inward-looking telescopes focusing seismic energy for imaging the detailed rupture (slip) processes of large earthquakes.

We applied a back-projection technique (see online version for references) to TA data to understand the rupture process of the February 27, 2010 magnitude M_w = 8.8 Maule, Chile, earthquake. The Maule earthquake was the largest earthquake along the Chilean subduction zone since the monumental magnitude 9.5 event in 1960. Its hypocenter, determined within a few tens of minutes by NEIC, was located near the Chilean coast about 100 km north of Concepción and 340 km southwest of Santiago (Figure 1a). A point location, however, does not capture the long rupture duration or the slip distribution over a large fault area that is involved in an M_w = 8.8 earthquake. In contrast, rupture imaging with array data is a simple and efficient technique that reveals the duration, spatial extent, and propagation direction of the earthquake rupture thereby providing crucial information for assessing seismic damage and tsunami generation essential for rapid relief response efforts.

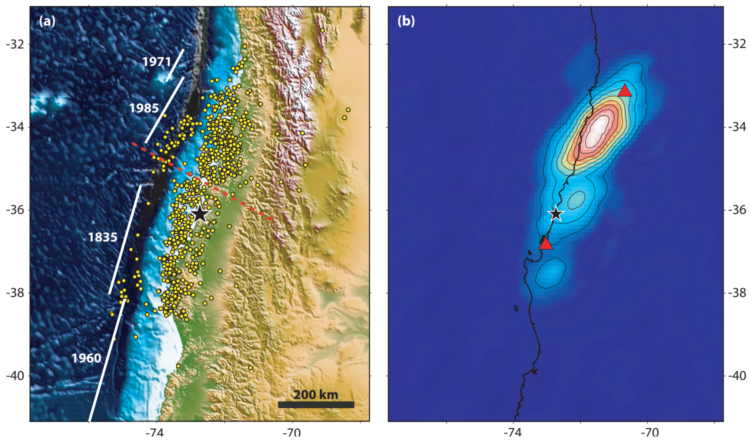

Figure 1: Summary of the 2010 Maule earthquake. (a) Epicenter (black star) of the M_w = 8.8 event and three months of aftershocks (yellow circles) from the NEIC. The white lines on the ocean side of the trench show the latitudinal extent of historical earthquakes. The red dashed line marks a break in the aftershock distribution, which occurs at the boundary between the southern and northern subevents. Background shows the bathymetry/topography. (b) Overall rupture extent from TA data. Colors show relative amplitude of energy release with warm colors for high amplitudes and cold colors for low amplitudes, respectively. Black star is the epicenter and red triangles are the locations of Santiago (north) and Concepción (south).

The back-projection results show that the subduction interface along the Chilean coast slipped a total length of more than 600 km from south of Concepción to north of Santiago (Figure 1b) and rupture lasted for about 120 seconds. The time-space evolution of the rupture (Figure 2) reveals two major slip events on two separate faults. The first event initiates at the hypocenter and rupture propagates bilaterally north- and southward for about 50 seconds, at which point the northward rupture fades away near 35°S, while southward propagation continues for the entire 120 seconds of the earthquake. The second major slip event is triggered up-dip of, and shortly after, the northern terminus of the initial rupture. This event propagates unilaterally northward along the Chilean coast for about 70 seconds, and has a peak energy release near its northern end, close to Santiago.

This segmentation of the 2010 Maule earthquake imaged with the TA data is consistent with past seismicity. The initial southern event coincides with the inferred slip area of the Charles Darwin earthquake in 1835 (M = 8.2), while the northern event has its counterpart in the M_w = 8.0 1985 Valparaiso earthquake (Figure 1a). Our results show that recurrence times of earthquakes along the Chilean subduction zone may vary significantly between different segments. Furthermore, segment boundaries do not necessarily inhibit rupture propagation, and an adjacent fault can be broken by triggering, leading to multiple segment ruptures as observed for the 2010 event.

Similar analysis of other giant subduction zone earthquakes reveals frequent involvement of triggered slip on multiple faults and complicated slip behavior, indicating that small and large earthquakes differ fundamentally. Surprisingly, this conclusion also holds for deep earthquakes, the occurrence and mechanism of which are poorly understood. Availability of high-quality data, such as those from the TA, and further refined analyses will shed light on the earthquake cycle and will help to answer how subduction zone earthquakes evolve with time.

Knowledge about the rupture properties of M = 8+ earthquakes is essential in predicting tsunami generation and areas of shaking-induced damage. To be useful, such information needs to be available immediately after an earthquake. Near real-time implementation of the imaging technique is feasible, but requires access to at least one dense, large-aperture seismic network such as the TA. However, once EarthScope's TA component is completed, the seismological community will lose this powerful telescope in the US for obtaining near real-time information about the extent and characteristics of giant, potentially hazardous, earthquakes. ■

By Eric Kiser and Miaki Ishii, Harvard University.

See online version for expanded article with references.

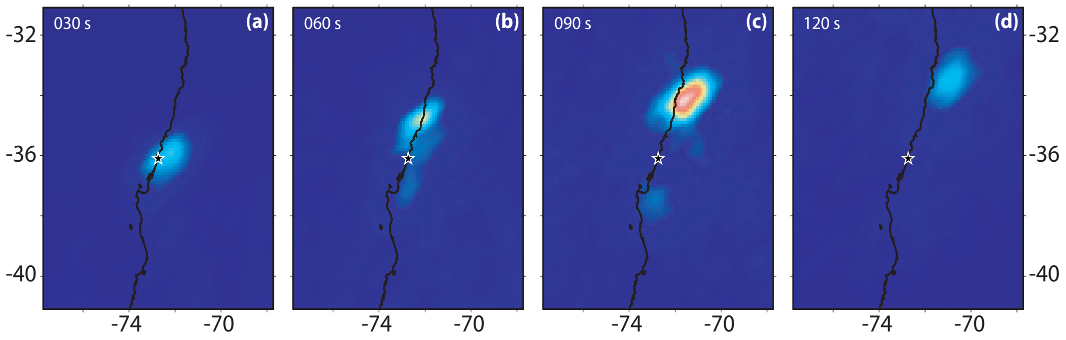

Figure 2: Temporal rupture behavior showing the rupture of the 2010 Maule earthquake at (a) 30 s, (b) 60 s, (c) 90 s, and (d) 120 s after event initiation. See online movie for a complete rupture history.

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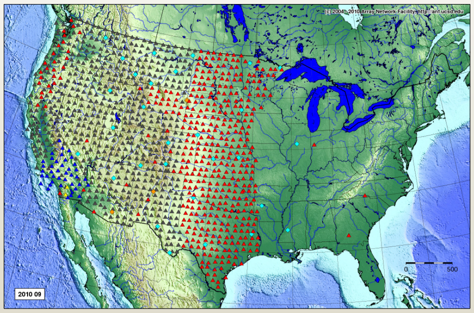
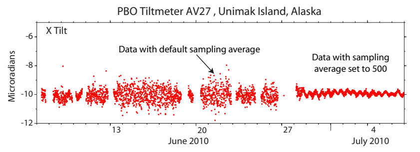


- More than **1000 Transportable Array** sites have been commissioned since 2004. The initial 400-station footprint was completed in August 2007. Since then, the TA has rolled from the west coast, across the Rocky Mountains, and into the Central Plains. Early 2011 installations will begin east of the Mississippi River! See deployment history at: http://anf.ucsd.edu/stations/deployment_history.php.

- Summer is a busy time for **PBO field work in Alaska**. PBO engineers completed 31 maintenance visits. A bout of bad weather on Unimak Island, accessible only for 11 days through a US Fish and Wildlife Service Special Use Permit, added extra challenges. All maintenance tasks were completed, including a tilt meter reconfiguration at site AV27 that reduced time series noise (compare before and after June 27 on figure below).



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Using GPS to Measure **Soil** Moisture, **Snow** Depth and **Vegetation** Growth

PBO GPS sites have a footprint of ~1000 m^2, providing a bridge between in situ probes and satellites. Figure 1 shows the first demonstration that reflected GPS measurements correlate well with in situ soil moisture probes. The soil responds immediately to large precipitation events, followed by long dry-downs of days to weeks. Soil moisture data are important to weather forecasters, hydrologists, and climate scientists so that they can properly initialize their models.

If GPS can detect when soil is wet vs. dry, it is not too surprising that we have also been able to detect snow. In fact, snow effects are far easier to measure with GPS reflections than soil moisture. Figure 2 shows GPS estimates of snow depth from a winter storm at a PBO site near Boulder, Colorado. The GPS method is able to capture both the rapid snow accumulation and the melting of the snow over two days. Although snow is currently measured by NOAA and state agencies, many of these measurements are either infrequent (monthly) or focus on very small footprints (10 m^2). Using PBO to measure snow has the advantages of a large footprint, which provides a more representative measurement of snow accumulation, and of a continuously operating sensor. Snowpack and melt rate information are essential for management of the water supply and flood control systems, particularly in the more arid western US.

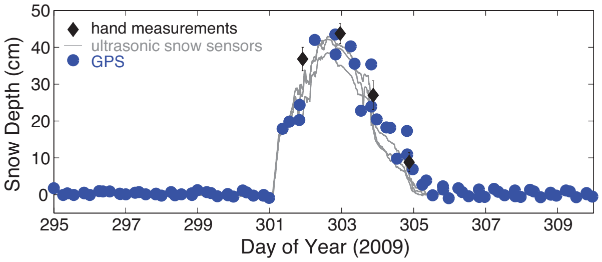

Figure 2: Variation in snow depth measured at Marshall, Colorado (PBO site P041) by GPS satellites (blue), three ultrasonic snow depth sensors (gray lines), and using a meter-stick over a 50-meter transect (bars on black diamonds are one standard deviation of the hand measurements).

Most recently, our group showed that vegetation changes are also sensed by reflected GPS signals. In contrast to soil moisture and snow signals, which are dominated by coherent reflections, vegetation primarily scatters radar returns. Figure 3 shows daily multipath scattering statistics at a PBO site in western Idaho. There is a strong negative correlation between the GPS scattering statistics and vegetation indices as measured by satellite – consistent with expectations that when vegetation is high, fewer signals will be reflected back to the antenna. Estimates of vegetation state are required for hydro-meteorological modeling and for validation of satellite surveys of land surface conditions. We are currently conducting experiments at agricultural sites in Boulder County to further validate our results. For example, we will compare the height and water content of an alfalfa field, measured weekly by a field crew, with GPS scattering statistics.

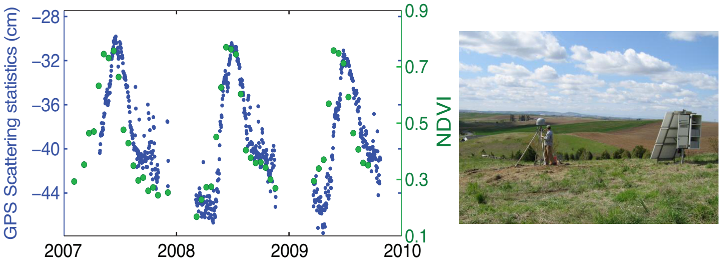

Figure 3: At left: GPS multipath scattering statistics MP1 in blue plotted with NDVI (Normalized Difference Vegetation Indices) in green from PBO site P422. The lag between the NDVI and MP1 data is due to the physical lag between vegetation greenness (measured by NDVI) and vegetation water content (sensed by GPS). We found similar NDVI-MP1 correlations for PBO grassland and shrubland sites as for the cropland site P422. Right, P422 (near Moscow, Idaho).

The original science goals of PBO were very much oriented towards understanding deformation of the solid Earth. Recently EarthScope updated its science goals (www.earthscope.org/ESSP) to include water cycle studies. Observing and monitoring spatial and temporal changes in the water cycle are needed to understand and predict a future climate. This new EarthScope initiative is another demonstration of how PBO contributes to solving problems of societal importance and with significant consequences for our future. Our work also shows how development of infrastructure for one purpose can yield inadvertent and "free" science products for other disciplines. In fact, our studies using PBO data could be applied to other GPS networks globally, adding crucial water cycle and vegetation information at intermediate scales (1000 m^2) augmenting existing in-situ and remote-sensing systems. ■

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See online version for expanded article with references.

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the EarthScope newsletter

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Inside this issue...

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Teaching Teachers: **Illinois EarthScope Workshop**

About 30 Transportable Array stations will be deployed in Illinois in 2011, placing a research-caliber seismometer within 50 km distance of every school in the state. Anticipating this unique opportunity, the Illinois EarthScope partnership, which includes Illinois State University, several school districts, and the Illinois Association of Aggregate Producers, was formed. A series of professional development workshops will increase knowledge and develop skills of middle and high school science and Earth science teachers. They will then have the tools to bring the excitement of a large-scale research project into classrooms, raising their students' interest in science and increasing Earth science literacy.

Teachers from across Illinois attended the first workshop – July 26 to August 6 – hosted by Illinois State University (ISU). Classroom activities focused on EarthScope observations and their interpretations that lead to a better understanding of Earth's interior and the geologic assembly of North America. Exposure to practical applications played an important role. After introducing the seismic refraction technique, teachers helped shoot a seismic line on the ISU football practice field. Applying the same principles, they used seismograms from the April 2008 Wabash Valley $M_w = 5.5$ earthquake to determine crustal thickness in Illinois. A highlight was a three-day field trip across southern Illinois to experience Precambrian basement, Illinois Basin closure-related faulting, and effects of magmatic fluids. Stops included a production blast (equivalent to M = 3.2) at the Anna Quarry and fluorite collection at the only remaining fluorite operation in the US. The next workshop in November will focus on plate margin and hot spot volcanism. In time for the bicentennial of the 1811-1812 earthquakes, the New Madrid Fault Zone will be the topic of the February 2011 workshop. ■

Illinois EarthScope is headed by Skip Nelson (ISU) and is funded by the US Department of Education through the Illinois State Board of Education.

Workshop participants and instructors show how GPS station HDIL, located in the stable continental interior, moves relative to Europe. HDIL, 25 km west of ISU, hosts a permanent ANSS (Advanced National Seismic System) seismometer and a PBO GPS sensor.