Geophysics at the speed of light: EarthScope and the Plate Boundary Observatory

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EarthScope is a proposed new earth science initiative that will dramatically advance our physical understanding of the North American continent by exploring its three-dimensional structure and changes in that structure through time. By integrating scientific information derived from geology, seismology, geodesy, and remote sensing, EarthScope will yield a comprehensive, time-dependent picture of the continent beyond that which any single discipline can achieve. Cutting-edge land- and space-based technologies will, for the first time, resolve earth's structure and measure deformation in real-time at continental scales. These measurements will permit us to relate processes in the earth's interior to their surface expressions, including faults and volcanoes.

The Plate Boundary Observatory. The Plate Boundary Observatory (PBO), one of the core components of EarthScope, is a geodetic observatory designed to study the three-dimensional strain field resulting from plate boundary deformation. Such studies require that plate boundary deformation be adequately characterized over the maximum range of spatial and temporal scales common to active continental tectonic processes. PBO will do this by installing two types of geodetic instruments that overlap in sensitivity yet have broad temporal resolution, and by increasing the spatial scale and density of stations. The core of PBO is a permanent geodetic observatory consisting of a carefully designed and integrated network of strainmeters and GPS (Global Positioning System) receivers (Figure 1). The strainmeters are ideal for recovering short-term transient deformation, from minutes to a month, and will consequently play a central role in observing phenomena that accompany and precede earthquakes and volcanic eruptions. GPS is ideal for time scales greater than a month, thus covering long-period transients, such as those associated with viscoelastic relaxation following an earthquake, as well as decadal estimates of strain accumulation and plate motion and their spatial variations. Only an integrated deployment of these two instrument types is capable of providing temporal resolution over the full set of timescales from minutes to decades, and at the necessary spatial resolution and aerial coverage of the plate-boundary system.

The PBO Facility will consist of four elements. First, a backbone network of 100 new and 20 existing GPS receivers (cyan circles in Figure 1) that will provide a long-wavelength, long-period synoptic view of the entire plate boundary zone. The backbone will cover western North America and Alaska at a receiver spacing of 200 km. The backbone includes another 16 stations in the IRIS Global Seismographic Network (GSN) which will be upgraded with GPS capability (red squares in Figure 1). These stations will house collocated broadband seismometers and GPS instruments, and will extend the reach of PBO to the east coast of the United States. The second element consists of clustered dense deployments of 875 permanent GPS and 175 strainmeters (magenta circles and green triangles, respectively, in Figure 1) in areas where active tectonic phenomena occur. Included in this second element are five long baseline laser strainmeters deployed in southern and central California (blue triangles in Figure 1). The third element of PBO is a pool of 100 portable GPS receivers for temporary deployment and rapid response for volcanic and tectonic crises. The fourth element will include the establishment of a national center for the storage and retrieval of digital imagery and geochronology facilities to support geologic and paleoseismic studies in the region covered by PBO.

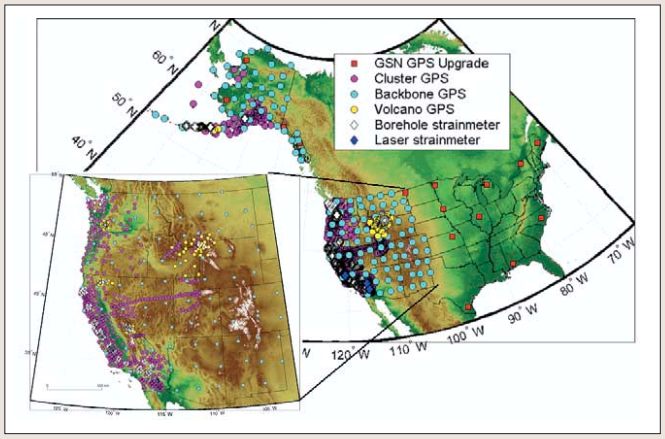

Figure 1. The major instrumentation components of the Plate Boundary Observatory (PBO).

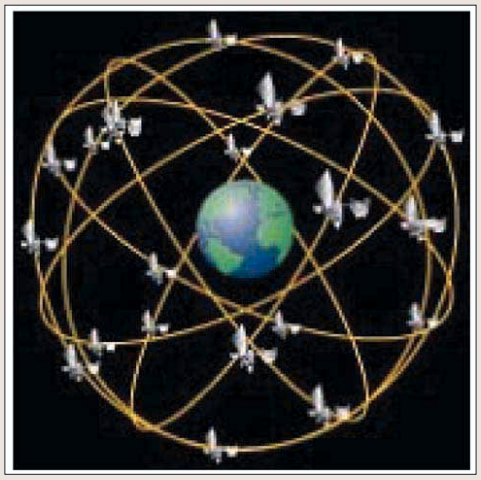

Figure 2. Current GPS constellation of 28 satellites in 6 orbital planes.

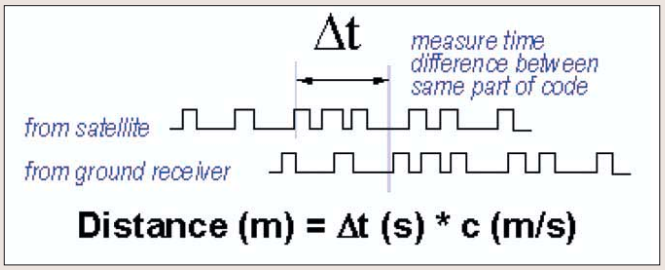

Figure 3. Simplified range calculation based on binary signals from a GPS satellite to a receiver. The constant "c" is the speed of light. Units of the variables and constants are in parentheses.

GPS—the basics. GPS receivers and antennas are well suited for measurements of crustal deformation. GPS provides the

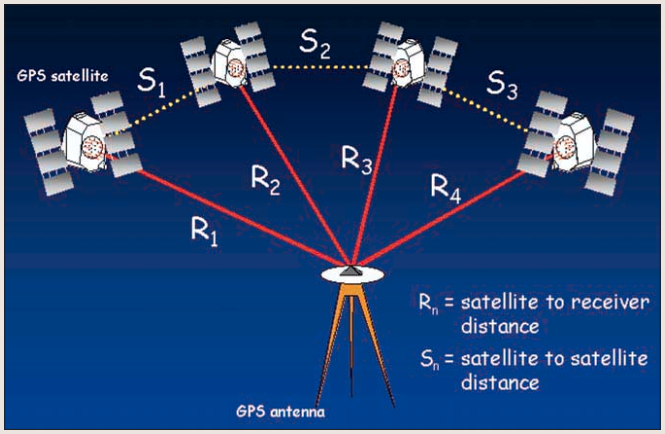

Figure 4. Simplified graphic depiction of how a single-user position is calculated with GPS. Calculation of the receiver to satellite distances R_n is described in the text. Intersatellite distances are known from the satellite broadcast ephemeris. The receiver position is calculated based on a simple resection problem with four distance equations and four unknowns.

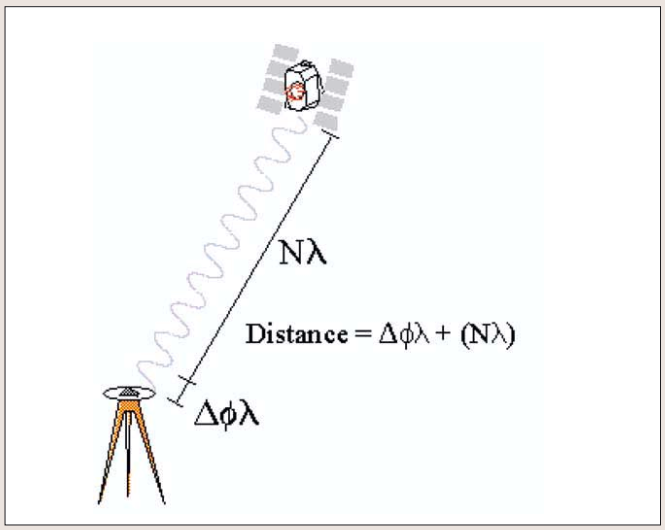

Figure 5. Approximate range between a GPS antenna and satellite based on carrier phase signals. $\Delta\phi\lambda$ is the fractional phase of the carrier expressed in terms of distance. N is an unknown integer number of carrier wavelengths to the satellite.

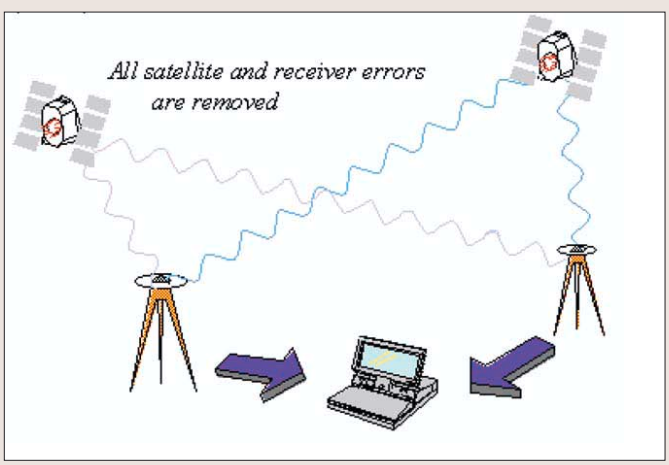

Figure 6. Data received at a single GPS antenna from two satellites are contaminated with the same receiver clock error. Data from the same satellite received at distant antennas are contaminated with the same satellite error. Such errors are analogous to source and receiver statics in exploration seismology. Differencing the data in GPS processing software removes the common errors.

needed temporal resolution (weeks to decades) and can track mm level changes in distance over a few hundred meters to thousands of kilometers. So, just what is this system and how does it work?

The U.S. Department of Defense (DOD) originally established the NAVSTAR GPS for military purposes. Fortuitously, a bunch of smart scientists and engineers were able to exploit the signals for public use and produce a great side benefit for scientific, surveying, air and marine navigation, and timing applications. The system can deliver a cruise missile onto a hostile bunker, help the blind navigate safely down an unknown street, and yet resolve tectonic deformation to better than the width of a coin. A very diverse system indeed—in fact, it could be said that the GPS is one of the great success stories of the U.S. taxation system. The following article provides a brief glimpse at the versatility of the GPS. We first discuss its general workings, explaining in lay terms how low- and high-precision positioning works, followed by a cutting edge example illustrating how the system is used to better understand the inner workings of the earth.

What is GPS? GPS is a space-based one-way (satellite to user) radio navigation system. GPS is based on a constellation of 24 active satellites and four spares orbiting the earth in six orbital planes at an altitude of 20 200 km (Figure 2). The satellites broadcast radio frequency signals that allow users to position and navigate anywhere in the world, in all weather conditions, at any time of the day. The system does this by broadcasting precise but complex binary codes (Figure 3) superimposed upon two sinusoidal carrier waves (called L1 and L2). Other unique characteristics of the system are that precise timing information on when the various signals left the satellites are embedded in the signals and precise information on the location of the satellites in time and space are included in what space scientists call a satellite ephemeris. To position or navigate in real-time, ground based receivers mark the time the signals are received, decrypt the binary information carried on the sinusoids, and contrast it with copies of the same information generated internally on the receiver. The receiver correlates the two sets of identical but time-offset signals and measures the time delay, or time of flight of the signal from the satellite to the receiver. The distance from the satellite to the antenna is computed by multiplying the time of flight by the speed of light, which is the speed that the radio signals travel from the satellite to the receiver. The resulting distance calculation (Figure 3) is compromised by errors inherent in the system such as errors in the satellite positions, signal delays due to propagation errors in the ionosphere and troposphere, receiver noise, and the fact that the receiver clock is not perfectly synchronized with satellite clocks. Because of these contaminating errors, the calculated distance is often called a pseudodistance or pseudorange. The synchronization error between satellite and receiver clocks is particularly important given that an error of only 0.1 microsecond in the satellite or receiver clocks results in distance error on the order of 30 m! Given four independent measurements of pseudorange from four satellites, the three receiver coordinates and synchronization errors between satellite and receiver clocks can be computed (Figure 4). The geometry in Figure 4 is a high-tech rendition of the classic resection of triangles problem encountered by early surveyors and topographers. In the not so distant past a surveyor, given a topographic map, three identifiable peaks, and three compass bearings, could draw resection lines on a map, the intersection of which represented the person's

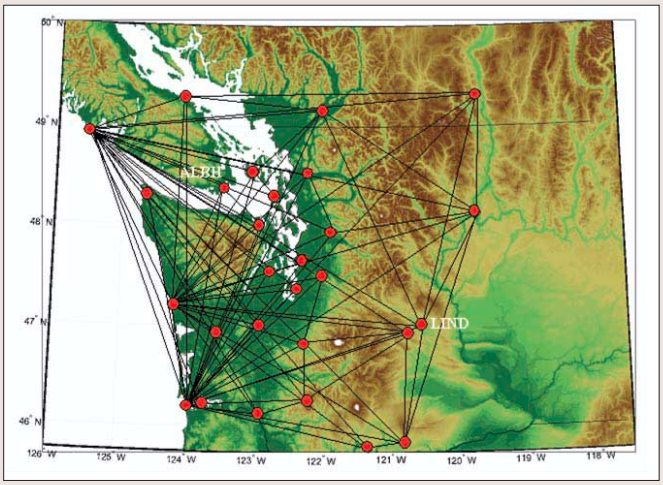

Figure 7. An example geodetic array from the PANGA network in Washington and southwest Canada. Red dots = GPS stations in the network. Black lines = precise interstation distances that are measured daily. Some lines have been omitted for clarity. Stations LIND and ALBH are discussed later in the text.

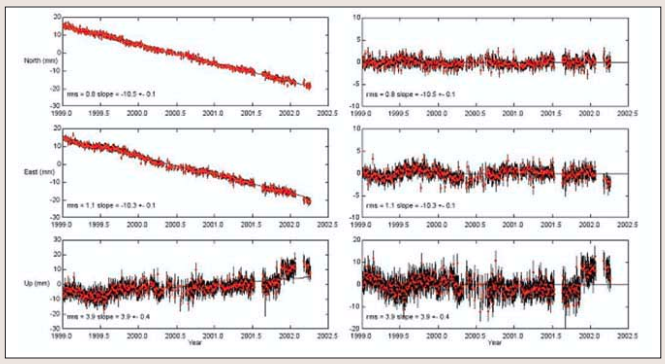

Figure 8. Raw (left) and detrended (right) time series of daily north (top), east (middle), and up (bottom) position components for station LIND. The slopes of the north and east components of the time series on the left diagram represent the long-term northeast motion of stations in the Pacific Northwest due to oblique convergence on the Cascadia subduction zone. The detrended time series on the right is useful for determining the noise in the station and to help identify any systematic variations in the station position. Note the root mean square values of the position are 0.8, 1.1, and 3.9 mm respectively. The systematic variations in the position components (right diagram) are likely due to seasonal changes in weather patterns. Time series courtesy of Scripps Orbit and Permanent Array Center (SOPAC).

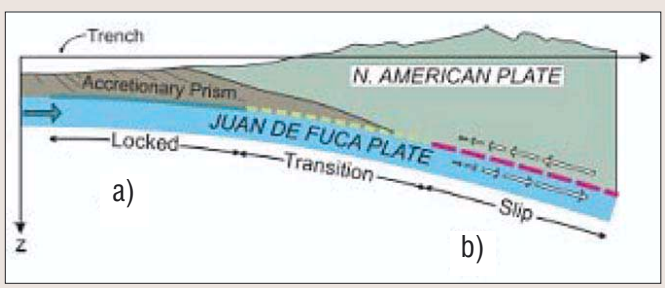

Figure 9. Cross-section of the Cascadia subduction zone. (a) Seismogenic locked segment. (b) Deep segment with episodic slip. (From Dragert et al., 2001.)

topographic position. In a single-user GPS scenario, the various error terms combine, resulting in a position in error of a few meters to tens of meters. This level of accuracy is sufficient to navigate a hunter back to his camp at the end of the day for a cold Budweiser, but it hardly provides the slivers of millimeters necessary for resolving, for example, Basin and Range extension. How then do we eke more precision out of the system?

Taking GPS to the next level. To get the highest levels of precision and accuracy out of the GPS system requires the use of receivers that can exploit the sinusoidal or carrier wave signals in addition to the binary code signals. Also, care must be taken to remove error terms that are modeled or ignored in a single-user position and to use the highest precision estimates for the satellite positions.

For the most part, the high-precision positioning model is identical to the satellite to GPS antenna distance model used for a single-user position with the exception that we now use the phase of the L1 and L2 carrier frequencies. At the time a receiver first locks onto a satellite signal, a simplified model for the distance between GPS antenna and the satellite can be expressed:

$$\text{Distance (m)} = \Delta\phi\lambda \text{ (m)} + N\lambda \text{ (m)} + \text{errors} \qquad (1)$$

where $\Delta\phi\lambda$ is the fractional phase of the carrier expressed in terms of distance (Figure 5). This fractional phase measurement is derived by mixing a reference frequency generated in the receiver with the incoming GPS carrier signal. Modern geodetic quality receivers can resolve the phase of a GPS carrier to better than a fraction of 1%. For example, the phase of an L1 cycle with a wavelength of 0.19 m can be resolved to submillimeter level establishing the fundamental level of precision attainable by GPS. The value of N represents the number of integer wavelengths from the receiver to each satellite at the moment the receiver first acquires a signal from a satellite. This value cannot be measured directly and must be calculated from many observations; the value of N in equation 1 is inherently ambiguous and is therefore called the integer ambiguity. The equation presented above and the graphical representation given in Figure 5 is only valid at the instant the receiver locks onto the satellite. Since the satellite continues to move in space relative to the receiver, another term, which we will conveniently ignore here, is needed to represent subsequent changes in the measured ranges.

As mentioned above, the theoretical precision of the phase range measurement is at the submillimeter level. However, various error sources such as receiver and satellite clock offsets, error in the position of the satellites, interaction of the signals with the ionosphere and troposphere, and multipath, or the reflection and refraction of signals as they reach the antenna all conspire to degrade the measurement. To attain the millimeter level of precision required for tectonic studies, these biases must be accounted for. For high-precision applications these error sources are modeled, solved for, or removed through data processing techniques. For example, satellite and receiver clock errors can be removed by differencing one station's GPS observations with adjacent sites (Figure 6). Since the satellite clock errors are common between stations and satellites, these common-mode errors are removed when the signals are differenced with adjacent stations. Differencing results in networks of interconnected stations where the vector distance between stations is known to the millimeter level.

Another source of error occurs when the GPS signals pass through the ionosphere and the troposphere on their way to a GPS antenna. The ionosphere is a layer of high electron content in the upper atmosphere between GPS receivers and satellites that cause delays in the signals. These delays can result in phase range errors of tens of meters. The ionosphere delay is frequency dependent, meaning that it will

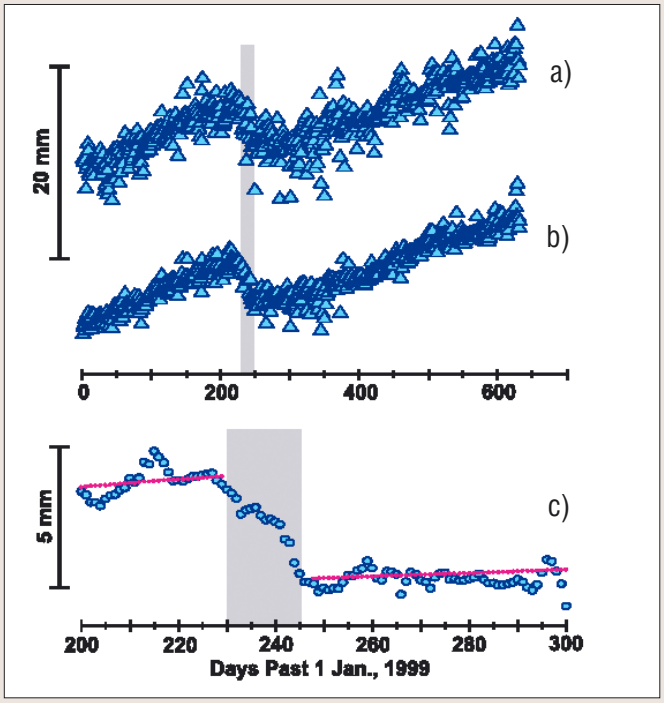

Figure 10. Daily changes in longitude at station ALBH. (a) Raw time series from which the magnitude of the transient displacement were estimated. (b) a cleaned time series where averaged daily residuals have been removed. (c) an expanded view of the transient displacement from which the start and duration of transient (shaded area) were estimated. (From Dragert et al., 2001).

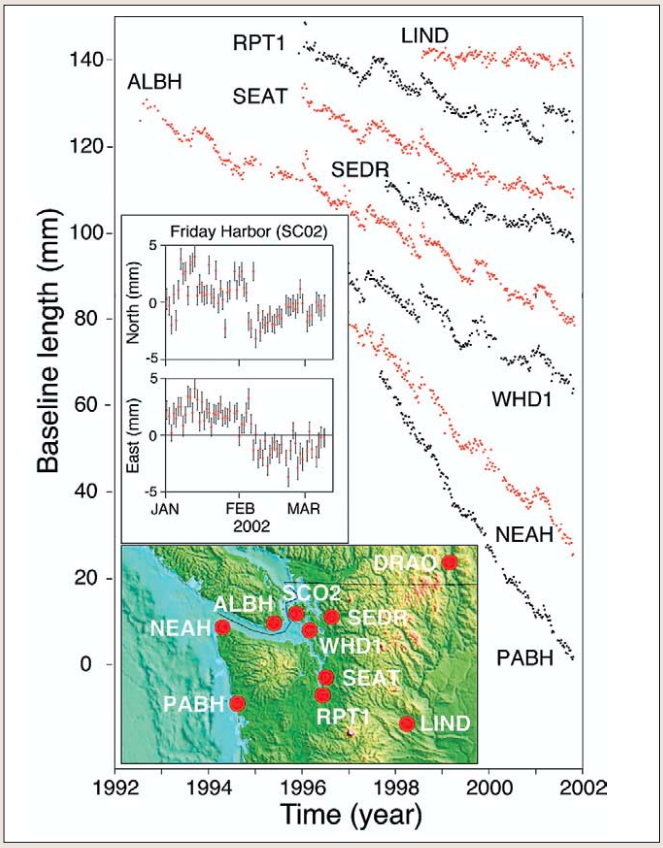

Figure 11. Time series for GPS stations along the Cascadia margin. Baseline lengths are from weekly station positions with respect to Penticton (DRAO). The crenulations in the time series indicate slow earthquake sequences. The inset time series shows daily positions for Friday Harbor (SC02) for 2002 and illustrates the onset of the latest sequence. (From Miller et al., 2002).

delay signals of different frequency by different amounts. Fortuitously, the planners of the GPS system took this into account and designed the satellites to broadcast on two frequencies, L1 and L2. By combining these signals in data processing, a combined signal, often called the ionosphere free combination, is created. This removes any residual delay due to the ionosphere. The troposphere behaves differently—in the L-band it is frequency independent so both signals are delayed the same amount. In this case, a correction is calculated from models and the data to mitigate delays due to tropospheric water vapor. The sensitivity of GPS to tropospheric and ionospheric delays is being exploited by both atmospheric scientists and meteorologists, further proof that one person's signal is another's noise.

In most GPS networks, the data are downloaded daily and automated processing routines reduce the data to precise station positions and interstation distances. The daily estimates of position and distances create an interlocking, three-dimensional deformation-monitoring web (Figure 7) so that any tectonic perturbation resulting in ground deformation, such as a large earthquake or volcanic eruption, can be detected, monitored, and modeled. To aid in this analysis, station positions are generally displayed as north, east, and up time series components relative to a mean position (Figure 8). For example, the trend seen in the north and east components of the time series on the left of Figure 8 represent the long-term northeast motion of stations in the Pacific Northwest due to oblique convergence on the Cascadia subduction zone. The detrended time series on the right is useful for determining the noise in the station and to help identify any systematic variations in the station position. Note the root mean square values of the position are 0.8, 1.1, and 3.9 mm in the north, east, and up components, more than adequate to resolve the long-term convergence rate, and as we will see in the next section, to identify repeated, silent, deep earthquake events.

Discovery of slow and silent earthquakes in the Pacific Northwest using GPS. We anticipate that installation of the PBO network will begin in 2004 and take five years to complete. To provide the reader with insight on the kind of information that PBO will provide, I will present some groundbreaking results by GPS workers using the much smaller 28-station array in the Pacific Northwest.

The subduction of the Juan de Fuca plate at a rate of 37 mm/yr beneath North America has caused great earthquakes (moment magnitude, Mw > 8) along the entire 1500 km length of the Cascadia Margin from central British Columbia to northern California. The shallow part of the fault, characterized by cooler temperatures and greater friction, has been shown to rupture in great earthquakes every few hundred years, the last of which occurred in 1700. In between these large events, the motion of plates is arrested across the locked portion of the fault, and the overlying North American Plate crustal margin is squeezed in a northeast direction (Figure 9). Since 1992, continuously operating GPS stations in Canada and the Pacific Northwest have been recording a fairly steady state northeast migration of the stations landward (for example left side of Figure 8). In the summer of 1999, Herb Dragert and his colleagues at the Geological Survey of Canada noticed that a cluster of seven GPS sites briefly reversed their direction of motion. They believe this reversal is a consequence of aseismic, episodic slip on the deeper portion of the fault beneath North America (b in Figure 9). The slip event initiated near Seattle and propagated to the northwest along the plate boundary, eventually affecting a 50 × 300 km fault area over a period of 35

days. The slip event was not instantaneous but lasted between 5 and 16 days depending on station location—positively glacial compared to the speed of seismogenic slip events (Figure 10). If this slip had occurred as a seismic rupture, it would have been a magnitude 6.7 earthquake, similar in energy to the recent Nisqually earthquake near Seattle. Meghan Miller and her colleagues at Central Washington University looked farther back into the Pacific Northwest GPS record and noted that no less than eight of these slow and silent earthquakes have occurred since 1992 (Figure 11). Each event started over a three-week period and lasted 2-4 weeks at any one station. Propagation of the slow earthquakes across the affected region may last for up to eight weeks. The slow earthquakes occur on average every 14.5 ± 1 months over the past 10 years and typically begin in the Puget Lowlands near the arch in the descending Juan de Fuca plate. Modeling of the slow earthquake sequences indicates slip of a few centimeters per event occurring along the plate interface at a depth of 30-50 km.

The work of Dragert and Miller provides convincing evidence that slow and silent earthquakes occur at convergent margins. But what this says about the very vocal, lightning fast, and dangerous earthquakes that occur farther up in the seismogenic zone is still unclear. When the locked segment of a thrust-plate interface becomes unstuck, large earthquakes occur sometimes with devastating consequences. The energy released by slow and silent earthquakes could reduce the energy available for periodic large seismic events. On the other hand, it is conceivable that a silent slip event may propagate updip and trigger a great subduction thrust earthquake. What is clear is that the frequency, duration, and mode of strain release of slow earthquake invites an assessment of the role of transient, aseismic creep events in plate boundary deformation processes. The Plate Boundary Observatory under the banner of the EarthScope initiative will further study these transient phenomena as well as the dynamics and kinematics associated with convergent, transform, and extensional tectonics.

Suggested reading. "Periodic slow earthquakes from the Cascadia Subduction Zone" Miller et al. (*Science*, 2002). "A silent slip event on the deeper Cascadia subduction interface" by Dragert et al. (*Science*, 2001). *Understanding GPS Principles and Applications* edited by Kaplin (Artech House, 1996). *Global Positioning System, Signals, Measurements, and Performance* by Misra and Enge (Ganga-Jamuna Press, 2001). *Linear Algebra, Geodesy, and GPS* by Strang and Borre (Wellesley-Cambridge Press, 1997). *GPS for Geodesy* edited by Teunissen and Kleusberg (Springer-Verlag, 1998). TLE

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