GETSI module on GPS, Strain, and Earthquakes

<slide 1> My thanks to Dave Gosselin for organizing this session, to Cathy Manduca and all the others associated with InTeGrate, <slide 2> to the team who helped build this GETSI module, and to all the folks at UNAVCO and SERC who have supported this work.

<slide 3> Geoscience is intrinsically interdisciplinary. The scientific resource at the heart of my presentation involves mathematics, geodesy, structural geology and tectonics, physics, very big data, and information-and-communications technology. It is an exemplary model of open, research-grade data shared in real time through the web.

<slide 4> GPS geodesy can help us recognize and quantify the direction and speed that Earth's plates move, allows us to measure the way Earth's crust deforms or strains, and provides a literally vital tool as part of an early warning system for earthquakes.

<slide 5> The STEM educational resource I will tell you about today brings this scientific resource into the undergraduate classroom, where it has been used from introductory to graduate courses, from community colleges to research universities and graduate schools.

I want to tell you about something that I think is truly amazing. I'm going to leave out most of the details for lack of time, but I want to give you a feel for what an undergraduate student can learn to do because of the InTeGrate/GETSI module we have developed.

<slide 6> When I was an undergraduate, we had no option but to use surveying equipment to find the location of points on the landscape.

<slide 7> Geodesists needed to create trilateration arrays with permanent benchmarks so they could use theodolites and laser distance meters to measure location over large areas in support of fault or earthquake studies.

<slide 8> To measure change, these surveys would have to be repeated year after year, but high cost and variable resolution were always issues. The critical limitations of this approach became abundantly clear in the run-up to the eruption of Mt. St. Helens in 1980, when lives were endangered because we lacked the capability to measure the changing shape of the volcano with sufficient speed and accuracy.

<slide 9> Based on earlier efforts by the USGS, NASA, and university-based geoscientists, the National Science Foundation funded a network of research-grade GPS receivers that are fixed to bedrock at around 1324 sites throughout the United States. Each of the bright blue dots on this map is a PBO GPS site. Installation of this Plate Boundary Observatory began in 2004.

The installation of networks of GPS stations like the Plate Boundary Observatory is a development of almost unimaginable importance to our ability to understand the deformation of Earth's crust and the geology of earthquakes. The Plate Boundary Observatory is a national treasure.

<slide 10> These devices generate data that allow us to calculate the location of the site to at least millimeter accuracy. Those data are continuously transmitted to remote sites for analysis, and location solutions are made available in near-real-time on the web. The data produced at a given site allows us to compute the location of that site 4 times a minute routinely, and as many as 5 times per second in emergency situations. A daily average location is published online.

<slide 11> We can compute the average velocity of any given PBO station as observed from the stable cratonic interior of North America (or from other reference frames) in units of millimeters per year. Here's how.

Let's find the data for PBO station BEMT at Twentynine Palms, California. First we go to the map of PBO stations and zoom-in to the area we are interested in.

<slide 12> Twentynine Palms is over on the right or eastern edge of the map.

<slide 13> We click on the blue circle over station BEMT, and an information box pops up. Clicking on the blue BEMT link in the information box <slide 14> gets us to the overview page for BEMT, which is a portal for all the data we need for this site.

<slide 15> We can look at a photograph of the instruments installed at the site <slide 16> which includes solar panels, communications equipment, an electronics cabinet, and the GPS receiver under that gray dome in the background.

<slide 17> Elsewhere on the overview page is the location of the site, <slide 18> in latitude, longitude, and elevation in meters.

<slide 19> The final data we need from the overview page are the mean site velocities, <slide 20> which are given relative to north, east, and up. We will focus on the horizontal components of motion.

You can see that the site is moving at 5.24 mm/yr toward north and 5.11 mm/yr toward the west –– all relative to a reference frame that is fixed to the stable interior of the North American Plate. (The negative number indicates a westward motion.)

<slide 21> We show students how to use the Pythagorean theorem to compute the total motion of the site, which turns out to be 7.32 mm/yr toward azimuth 316°.

<slide 22> If a student can do this once, she can do it again for a site near Mission Viejo, California, labeled SBCC.

<slide 23> This site is moving much faster, and in about the same direction, as the other station. Why do you think that is so?

<slide 24> We can show students how to use an important resource maintained by the US Geological Survey in partnership with many State surveys –– the Quaternary Fault and Fold Database of the United States. This interactive map and the database it is linked to constitute another great tool students can use in the future, either as a geoscientist or maybe just as someone looking for a seismically quiet place to live.

<slide 25> The reason why SBCC is not moving at the same speed as BEMT is that the San Andreas Fault and other active faults lie between the two GPS sites. Station SBCC at Mission Viejo is moving with the Pacific Plate, west of the San Andreas Fault System, and BEMT is located on the soft western edge of the North American Plate.

<slide 26> What we have just done is to put some new tools in the student's scientific toolbox. They can use GPS velocities from the Plate Boundary Observatory to compute the total horizontal velocity of a site in a given reference frame, and can access reliable information about active faults.

Now, we can work on describing how the crust deforms between three or more GPS sites. At this point, an introductory course might take a different path through the analysis than would a graduate course, but both will converge on the same basic results.

<slide 27> Let me give you a brief conceptual sketch of the process, using three PBO sites just west of Portland, Oregon, shown as green dots in the red box. These are on a part of the North American Plate under which the Juan de Fuca Plate is subducting.

<slide 28> We zoom in to see the three points on a Google-style map.

<slide 29> Using the most current data (vintage a few hours ago), we graph the north and south velocity data for each site.

<slide 30> That allows us to determine the horizontal velocity of each site relative to the stable interior of the North American Plate. Shedding the information we don't need <slide 31> we see the three GPS sites and their instantaneous velocity vectors.

<slide 32> They form a triangle, and we imagine that we can draw a circle in the middle of that triangle before deformation.

<slide 33> Then we visualize the strain that results when the three sites move in the direction and at the speed indicated by the GPS velocities.

<slide 34> We subtract the translational part of that strain <slide 35> and are left with the distortional part of the strain. If you have good eyesight, you might be able to see that the original black circle has been distorted into a red ellipse.

<slide 36> Higher-level students learn that this is the infinitesimal strain ellipse, but all students can visualize that this reflects a shortening in the northeast-southwest direction, and a slight lengthening in the northwest-southeast direction.

<slide 37> We can then put a graphic depiction of these results back on the map between the three GPS sites <slide 38> and look at the regional structural or tectonic setting to see that the leading edge of the North American Plate is being elastically shortened or squeezed like a rubber sponge by the sliding of the Juan de Fuca Plate under North America along the Cascadia Subduction Zone.

<slide 39> The mathematical process that generates the quantitative results of this analysis can be handled in several ways, and teachers can choose the most appropriate method for their students. On the simple end, students can input the location and velocity data for three GPS sites into an Excel spreadsheet, which computes the answers. Similar calculators are available in MatLab and Mathematica. On the opposite end, students can be supplied with a written algorithm for the analysis, and they are required to write the corresponding code.

<slide 40> On January 26, 1700, with elastic strain built up like it is today, the Cascadia Subduction Zone generated a magnitude 9 earthquake that sent a tsunami across the Pacific Ocean Basin, where it destroyed communities and drowned people in Japan. The geological record of that earthquake can still be seen along the Washington, Oregon, and northern California coasts.

<slide 41> More than three hundred years later in 2011, a similar magnitude 9 earthquake occurred along a subduction zone under Japan that is broadly similar to the Cascadia Subduction Zone under North America.

<slide 42> Approximately 16,000 people have been confirmed dead, more that 2500 remain missing, and 127,000 buildings were destroyed in the Tohoku earthquake and tsunami. These events also destroyed the Fukushima-Daichi nuclear power station, rendering part of Japan uninhabitable and causing significant water pollution in the ocean near the destroyed nuclear plant.

<slide 43> The GPS sites in Japan rebounded toward the subduction zone, like the snap of a rubber band, during the earthquake. We expect the same sort of elastic rebound to occur along the Cascadia Subduction Zone during a future magnitude 9 earthquake like the one it generated in 1700. Geoscientists want the public to be aware of this danger so that we can take reasonable steps to lessen the effect of an inevitable natural event.

We have been working on GPS-based earthquake early warning systems that would operate in tandem with our seismograph networks. Current proposals to eliminate or reduce Federal support for this work will simply lead to avoidable casualties when large earthquakes occur in Cascadia or along the San Andreas Fault System, as is inevitable.

<slide 44> As an optional sub-module, students can learn about how the Plate Boundary Observatory and other GPS networks recorded the magnitude 6 earthquake that occurred in 2014 in Napa, California. Estimates of total damage in the Napa area range from around $400 million to as much as $1 billion, with one person killed and 200 injured.

<slide 45> Students use the techniques they learned earlier in the main module to investigate the crustal strain before, during, and after the earthquake.

<slide 46> This is a very flexible educational resource that can be adapted to a wide variety of settings. It allows students of widely varying backgrounds and levels of preparation to access fresh research-grade data, perform an analysis, reach tentative conclusions, and consider the human and societal implications of their findings. And everything necessary to take advantage of this resource is available for free on the web.

Our students inherit a world in which there are many significant challenges facing humanity, several of which are existential. The solutions to our largest problems require interdisciplinary science, effective engineering, and cooperative engagement throughout society.

We must do our best to facilitate the growth of a society where even non-scientists have a rudimentary understanding of science, and respect for the reliable knowledge that science provides. It is our responsibility to help undergraduates in general (and novice geoscientists in particular) to begin developing their understanding of these problems so they can join in their solution or mitigation.