Teaching High-Accuracy Global Positioning System to Undergraduates Using Online Processing Services

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ABSTRACT

High-accuracy Global Positioning System (GPS) has become an important geoscientific tool used to measure ground motions associated with plate movements, glacial movements, volcanoes, active faults, landslides, subsidence, slow earthquake events, as well as large earthquakes. Complex calculations are required in order to achieve high-precision positions and thereby high-accuracy displacement measurements. It is difficult to familiarize undergraduates with the complex data processing within a period of one semester. Several national organizations offer free online GPS processing services. Using these online services, a GPS beginner can bypass the complex aspect of data processing and focus on applications of the high-accuracy GPS technology. This paper introduces the author's experience using Online Positioning User Service, provided by the National Geodetic Survey (NGS) and Automatic Precise Positioning Service, provided by the Jet Propulsion Laboratory (JPL) in teaching two undergraduate courses, Applications of GPS in Geosciences and Geological Hazards, at the University of Puerto Rico at Mayaguez. Two class projects, "Where is My House?" and "GPS Landslide Monitoring," were designed to practice GPS data collection, processing, and analysis. The enrollments of the two courses were about 10 senior undergraduate students. Online GPS data processing helped both the instructor and students in teaching and learning the intricacies of GPS data processing, understanding different reference frames and coordinate systems, and familiarizing local permanent reference stations. Students who had taken the GPS classes often help professors in the geology department and other departments to survey field sites with centimeter-level accuracy. [DOI: 10.5408/12-295.1]

Key words: APPS, education, OPUS, online processing service, static, high-accuracy GPS, kinematic

INTRODUCTION

Global Positioning System (GPS) is a satellite-based navigation system that was developed by the U.S. Department of Defense in the early 1980s. Initially, it was developed primarily as a military navigational system, but because of its obvious benefits to a wide range of civilian applications, it was opened to general use, and modifications have been made specifically to make the system more user friendly for civilians. GPS has become a widely deployed and useful tool for commerce, scientific uses, tracking, and surveillance. The uses and applications have grown at an incredibly rapid rate. Due to the inherent benefits of obtaining high-precision positions using GPS, and thereby high-accuracy (centimeter, millimeter, sub-millimeter) displacement measurements, this technology is being increasingly used in geoscience applications. Many new disciplines have been developed based on satellite positioning techniques, such as GPS plate tectonics (e.g., Blewitt and Clarke, 2003; Calais et al., 2005; Calais, 2006; Davis et al., 2006), GPS seismology (e.g., Larson et al., 2003; Wang et al., 2007; Bock et al., 2011), GPS glaciology (e.g., Frezzotti et al., 1998), GPS meteorology (e.g., Bevis et al., 1992), GPS geodesy (e.g., Teunissen and Kleusberg, 1998; Herring, 2009), and high-accuracy airborne GPS kinematic tracking for topography, gravity, magnetic, and hyperspectral survey.

GPS also provides high-accuracy and uniform time reference for the vast majority of precision time and frequency products. It has become the world's principal supplier of nanosecond timing. GPS timing technique has been implemented in a global earthquake-monitoring network, which is regarded as an evolution of global earthquake monitoring. In satellite positioning industry, the term "GPS" has been replaced by "GNSS," which stands for Global Navigation Satellite System. GNSS includes several satellite positioning systems developed by different countries or organizations, such as the United States' GPS, Russia's [Global Navigation Satellite System] (GLONASS), Europe's Galileo, and China's Compass systems. Mostly, the term GPS is specific to the United States' GNSS system, the NAVSTAR Global Positioning System. As of 2012, the United States NAVSTAR Global Positioning System remains the only fully operational global satellite positioning system, and most users in the geoscience community only use the United Sates' GNSS signals in data processing. For this reason, this paper only discussed GPS.

PURPOSE OF THIS STUDY

This paper addresses teaching centimeter-, millimeter-, even sub-millimeter–accuracy GPS technologies to geoscience majors. Complex data processing is needed to achieve high-accuracy position or displacement measurements from GPS raw data. In college curricula, GPS is often introduced as a component of geographic information systems (GIS) or land surveying courses. The "On the Cutting Edge Program," funded by the National Science Foundation (NSF) and operated by the Science Education Resource Center

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(SERC) at Carleton College, provides a great number of GIS and GPS teaching materials and modules through their educational Web sites (e.g., Manduca et al., 2010). ESRI also provides some educational materials related to GPS applications (e.g., ESRI, 2009). However, these applications normally require meter-level accuracy, which can be achieved by regular handy GPS units or simple differential GPS techniques. Handy GPS devices automatically process satellite signals in real time, and users can directly read or download final positions (longitude, latitude, and height) from the instruments. No further data processing is needed.

Most GPS professors in the geoscience community learned GPS data processing though self-education. Currently, several geoscience departments teach high-accuracy GPS in graduate courses as a component of conventional geoscience courses, such as the geoscience departments at MIT (by Dr. Tom Herring), Purdue University (by Dr. Eric Calais), Northwest University (by Dr. Seth Stein), Central Washington University (by Dr. Tim Melbourne), University of California–San Diego (by Dr. Yehuda Bock), University of Texas at Dallas (by Dr. Carlos Aiken), University of Alaska at Fairbanks (by Dr. Jeff Freymueller), and University of Texas at Arlington (by Dr. Glen Mattioli). However, there are few geoscience departments offering GPS courses to undergraduate students, though applications of high-accuracy GPS have been introduced in several fundamental undergraduate courses, such as Physical Geology (or Introduction to Geology), Introduction to Geophysics, Seismology, Plate Tectonics, Volcanics, and Geology/Geophysics Field Camp. The author has discussed the feasibility of teaching high-accuracy GPS to undergraduates with several professors who use GPS in their research. The consensus seems to be that the skills involved in high-accuracy GPS data processing are too complex to teach at an undergraduate level. According to author's teaching experience, the fundamental principles of GPS are not too complex for undergraduate students to grasp in three to five lecture hours. However, mastering the skills of processing onerous data is a challenge. This paper introduces a new approach that allows students to bypass complex GPS data-processing operations and focus on data acquisition and applications of high-accuracy GPS measurements.

DATA PROCESSING: A BARRIER TO TEACHING HIGH-ACCURACY GPS

GPS receivers record complex observations of ranges and phases between a GPS antenna and various satellites, the positions of these satellites, as well as other information. Most GPS receivers do not directly provide high-precision position measurements. Extensive calculations are required to obtain high-precision coordinates of a GPS antenna. Three so-called scientific software packages, GIPSY (https://gipsy-oasis.jpl.nasa.gov), GAMIT/GLOBK (http://www-gpsg.mit.edu/~simon/gtgk/), and BERNESE (http://www.bernese.unibe.ch), have been widely used by researchers to calculate high-precision positions of GPS antennas. The advanced models and processing techniques applied in these packages enable high-precision positions for long baselines, such as hundreds or even thousands of kilometers in baseline length, forming part of large geodetic networks. However, these software packages are not simple to understand and master. It is difficult to familiarize students with these software packages in the span of a single semester. There are user-friendly, commercial software packages, such as Trimble Business Center (http://www.trimble.com), TopconTools (http://www.topconpositioning.com), and Leica Geo Office (http://www.geotex.com), which provide high-precision results for short baselines (e.g., <100 km). However, it is difficult to gain access to these commercial software packages for a large group of students in a laboratory environment. Fortunately, a number of national organizations have developed free online GPS data post-processing services. A user just needs to send GPS raw data files to an online GPS data-processing provider through the Internet; within a few minutes, the calculated positions are sent back to the user via e-mail.

The author taught a senior elective course, GEOL4060 Applications of GPS in Geosciences, at the Geology Department of University of Puerto Rico at Mayaguez, from 2007 to 2011. This is a research-focused senior course comprising two 1-h lectures and 1.5 h of laboratory per week. The enrollment was about 10 senior students. They had experience with handy GPS for navigation and field mapping before taking this course. The Online Positioning User Service (OPUS) was used in this class for GPS data post–static processing. OPUS was selected because of its user-friendly interface, and the high precision of the positions referred to several reference frames and coordinate systems. As a result, students can learn commonly used geodetic datums, reference frames, and coordinates by simply analyzing the OPUS outputs. The details of OPUS are discussed in the following section. For kinematic GPS data processing, the kinematic mode of Automatic Precise Positioning Service (kinematic mode) (APPS; https://apps.gdgps.net) provided by the Jet Propulsion Laboratory (JPL) of National Aeronautics and Space Administration (NASA) was used.

ONLINE POSITIONING USER SERVICE

OPUS is a free, automated, and Web-based GPS data post-processing utility that delivers accurate and reliable positional coordinates in the United States and its territories (e.g., Weston et al. 2007). OPUS has become one of the most popular geodetic tools provided by the National Geodetic Survey (NGS). OPUS provides its users with accurate and reliable positional coordinates in a timely fashion by processing each user's GPS data with corresponding GPS data from the Continuously Operating Reference Stations (CORS) network operated by the NGS. Detailed information about CORS and OPUS can be obtained in a number of recent articles included in a monography edited by Soler (2011). The CORS network is a multipurpose cooperative permanent GPS network contributed by over 200 different organizations, including local government, academia, and private organizations. As of February 2012, the CORS network contains over 1,800 continuous GPS stations distributed throughout the United States, its territories, and a few foreign countries (Sella et al., 2011). The infrastructure foundation of OPUS is CORS. At the time that the author taught the last GPS class in the fall of 2010, there were 15 CORS stations in the Puerto Rico and the U.S. Virgin Islands region. The number had increased to 19 by the summer of 2011 (Fig. 1). This dense permanent GPS network provides a precise and robust geodetic reference

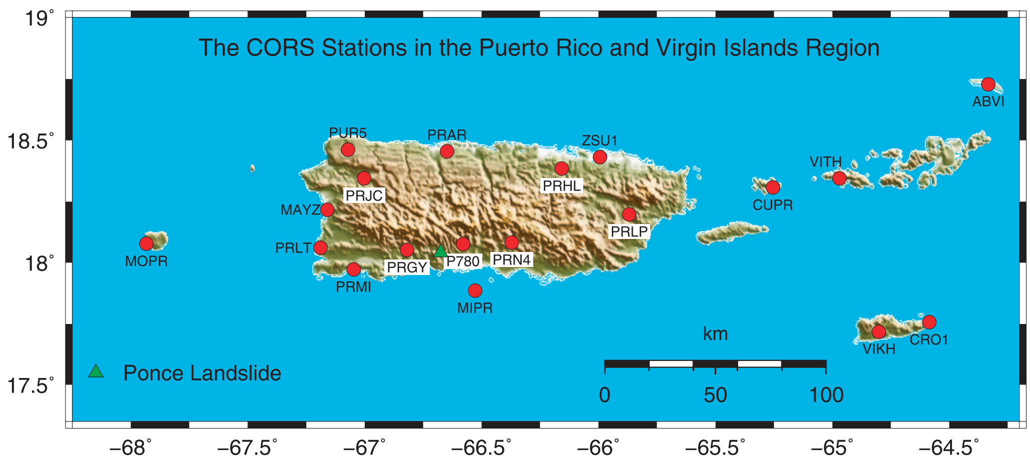

FIGURE 1: CORS permanent GPS stations in the Puerto Rico and Virgin Islands region as the summer of 2011. The location of the landslide is marked with a filled triangle.

frame for local positioning activities. The primary access to CORS information is via the Web site http://www.ngs.noaa.gov/CORS.

OPUS, in general, provides accurate, reliable, and consistent geodetic coordinates relevant to the U.S. National Spatial Reference System (NSRS), which constitutes the official civilian government system for enabling a user to determine geodetic latitude, longitude and height, as well as other geodetic measurements at any point within the United States and its territories. The NSRS also contains information about its orientation and scale relative to international reference frames and the precise orbits of all satellites used in defining or accessing the NSRS (Snay and Soler, 2008). GPS is now the primary means of referencing surveys and mapping projects to NSRS. OPUS provides static (OPUS-S) or rapid static (OPUS-RS) solutions, based on the length of the data session submitted by users. Data files with observation sessions longer than or equal to 2 h are processed with OPUS-S. Shorter, dual-frequency data files, with sessions between 15 min and 2 h in duration, are processed by OPUS-RS (Weston et al., 2007). OPUS employs the software package Program for the Adjustment of GPS Ephemerides, developed by Schenewerk and Hilla (1999). Inherent to the results of OPUS-S is the calculated average of three separated single-baseline solutions, using three CORS sites as fixed stations. A double-differenced, ionosphere-free mathematical model is implemented during each single-baseline processing. In general, OPUS-S selects three closest CORS stations based on the availability and quality of data at CORS network (Soler et al., 2006). The Web interface and format of the final report of OPUS-RS are the same as that of OPUS-S, though OPUS-RS uses different base-station selection criteria and algorithms and processing methods. OPUS-RS uses a software package specifically designed for processing short session GPS data sets, which achieves high accuracy by computing the atmospheric delays of a local CORS network composed of three to nine stations to predict the atmospheric delays experienced at the rover GPS site (Lazio, 2007; Martin, 2007; Schwarz et al., 2008, 2009). OPUS-RS also uses a more restrictive algorithm for selecting reference stations, and it places more restrictions on the data sets to be processed. Furthermore, OPUS-RS uses the least-squares ambiguity decorrelation adjustment (LAMBDA) algorithm to fix ambiguities. The LAMBDA algorithm has been found to be superior to other ambiguity search algorithms in many applications (Jonge de and Tiberius, 1994).

At the time that the author taught the GPS class in the fall of 2010 or earlier, OPUS results were referred to the International Terrestrial Reference Frame of 2000 (ITRF00) and also to the North American Datum of 1983 (NAD_83) if the user's GPS receiver was within an area in which NAD_83 was defined. OPUS changed the reference frames to IGS08 (2011) on 6 September 2011 (http://geodesy.noaa.gov/CORS/coords.shtml). GPS data used in this article were processed before the update of the reference frames. OPUS provides position coordinates in both three-dimensional Cartesian and geodetic ("geographic") coordinate systems. OPUS report also includes positions in two-dimensional Cartesian coordinates, Universal Transverse Mercator (UTM) and State Plane Coordinate (SPC). An example of an OPUS output is listed in Appendix 1. One benefit of using OPUS in a class is that many local CORS stations can be involved and, as a byproduct, students will become familiar with the geographic distribution of local CORS stations.

CLASS PROJECT I: WHERE IS MY HOUSE?

The primary advantage in using OPUS is that even GPS beginners can execute a professional surveying job by using only a single-receiver–antenna combination. Two class projects were developed in order to practice GPS data acquisition and processing.

The first project was titled "Where Is My House?" At the beginning of each semester, students were taken to a CORS site to learn GPS instrumentation. Students were taught to (1) install a "CORS-style" permanent GPS monument at an ideal site on the roof of their houses, (2) collect GPS data with a Topcon GB1000 GPS unit using both static and rapid static surveying methods, (3) convert GPS raw data (e.g., in Topcon TPS format) to the Receiver Independent Exchange (RINEX) format, (4) submit RINEX files to OPUS, and finally (5) plot the OPUS output on Google Earth. The entire training can be completed in two laboratory classes (1.5 h

FIGURE 2: Typical "roof-style" GPS monuments installed by students for the first class project, "Where Is My House?"

per class). Students are able to conduct a GPS survey independently after the training. Most students can build a satisfactory permanent GPS monument with help from their parents or friends. Figure 2 shows two typical GPS monuments that students installed on their houses. Two or three students worked as a team. Each team was required to survey their houses at least 10 times, with static and rapid static methods on different occasions and different days. They were then taught to do a basic statistical study, using the OPUS outputs for the same site. This included using Microsoft Excel to calculate the average, standard deviation, and root mean square (RMS). The RMS is also called the repeatability, or precision, of GPS measurements in the GPS literature. Almost all groups were able to finish their homework, with little help from the instructor. Students and their families were very happy to get precise positions of their houses. Several students even used the high-accuracy GPS equipment to survey the sizes of their land properties.

Students could further identify major issues affecting GPS precision by analysis of the repeated measurements from the same site. For example, all students recognized that longer sessions have higher precision (closer to the average measurement), and a few students even reported finding higher precision during night-time surveys than day-time surveys. Students were also taught to judge the quality of GPS data according to the quality-control parameters reported in OPUS reports (see Appendix 1). According to the author's experience, a sub–centimeter-horizontal-accuracy GPS survey requires that at least 90% of observations be used, 85% of the ambiguities be fixed, and that overall RMS seldom exceeds 0.03 m. This was used as a rule of thumb to evaluate the quality of raw data and the precision of OPUS results in the GPS class. Students also learned details of GPS data quality and OPUS processing from their failed surveying experiences. For rapid static surveys using sessions less than 2 h, students sometimes received "OPUS aborting" reports saying, "OPUS could not process the data file that was submitted. The data was (sic) either very noisy or it was collected in kinematic mode." Students were forced to think about what they did in the field. One common mistake was launching the survey first then adjusting and tightening the GPS antenna. Some students made the mistake of checking the battery too often. They went to the site and blocked satellite signals. It is true that students learned more from their failed experience than successful experience.

CLASS PROJECT II: GPS LANDSLIDE MONITORING

Students were able to conduct an independent survey after finishing the first class project. At this point, they were assigned the second project, "GPS Landslide Monitoring." Students were trained to analyze continuous GPS data collected at a local active landslide site. Location of the landslide is plotted in Fig. 1. The details of this landslide were introduced in a recent publication (Wang, 2012). There were 1.5 years of continuous data available to the most recent GPS class, the fall semester of 2010. Students were trained to study the kinematics of this landslide, using continuous GPS data.

The first step of the GPS landslide monitoring project was to visit the landslide site. It is very important for students to understand the geological background of the landslide and field GPS instrumentation. Next, continuous GPS raw data recorded at the landslide site were assigned to students, with two or three students working as a team. Each team would then submit daily GPS data (RINEX format) to OPUS. The third step was to process and plot OPUS outputs with Microsoft Excel or other tools. It does take time to teach students Excel and CoPlot (http://www.cohort.com), a plot tool for scientific graphs and maps. Fortunately, most students became comfortable with Excel preprocessing and CoPlot plotting in two or three laboratory classes. A couple of students with advanced computer skills even wrote an automatic uploading program to submit landslide GPS data to OPUS Web site, and a Linux shell script to extract GPS positions from a group of OPUS outputs as received by email.

Students were also taught to retrieve local rainfall data from a nearby USGS weather station in order to study the effect of rainfall on landslide movements. Figure 3 shows local rainfall data and the landslide movement derived from OPUS solutions. Northing and easting coordinates in UTM coordinates and orthometric height were used to plot the three-component movements of the landslide GPS antenna. At the end of this project, all the groups were able to produce a plot similar to the one presented here (Fig. 3), which indicated sub-millimeter horizontal accuracy and 2-mm vertical precision for 24-h continuous sessions (Wang, et al., 2012). Using this plot, students would further pursue the kinematics of the landslide and the correlation between rainfall and landslide movements.

LEARN GEODETIC DATUM AND COORDINATE SYSTEMS FROM OPUS OUTPUTS

Teaching geodetic datums and coordinates is one of the difficult parts of an introductory geodesy course. The OPUS report provides positions with Earth-centered, Earth-fixed Cartesian coordinates (*X, Y, Z*) and geodetic coordinates (longitude, latitude, and ellipsoid height) referred to the International Terrestrial Reference Frame of year 2000 (ITRF00) at the mean epoch of observation, and the North American Datum of 1983 (CORS96), at epoch 2002.00.

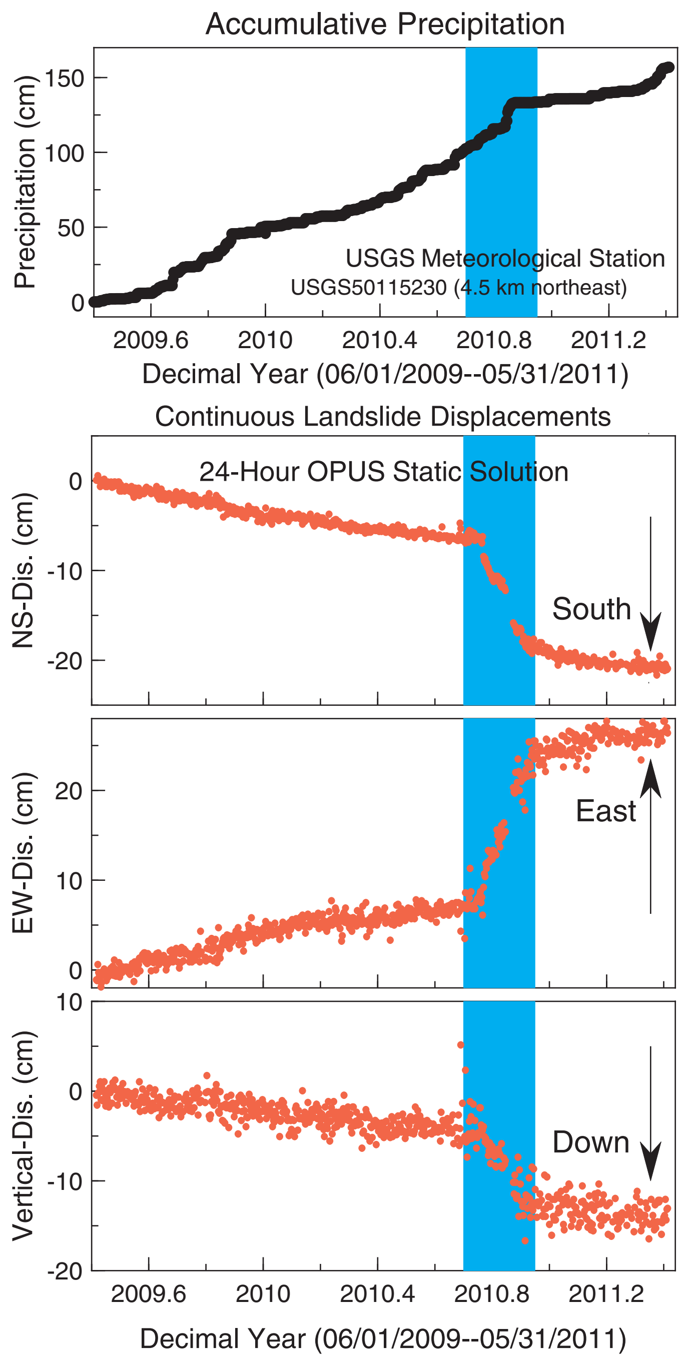

FIGURE 3. Continuous landslide movements during a 2-year period from 1 June 2009 to May 31, 2011, derived from OPUS results for 24-h sessions. The rainfall data were recorded by a nearby USGS weather station.

OPUS also provides positions in two-dimensional Cartesian coordinates: the UTM and the SPC systems. There are many classic documents (e.g., Bomford 1980) explaining datum and coordinate systems, but just listening to or reading the explanations can easily confuse students. Furthermore, it seemed that the more they were taught in lectures, the more confused they became. The author found that it is easier for students to learn different reference frames and coordinate systems by comparing the different plots derived from OPUS outputs. As a part of the second class project, "GPS Landslide Monitoring," students were required to plot landslide movements within different reference frames and coordinate systems. Most students can produce nice plots similar to Figs. 4–6. They truly understood datums and coordinates after they finished these plots by themselves. The Geodetic Glossary Web page available at the NGS website was recommended to learn details about geodetic datums and coordinates (http://www.ngs.noaa.gov/CORS-Proxy/Glossary/xml/NGS_Glossary.xml).

NAD_83 Versus ITRF00

Figure 4 shows the Cartesian and geodetic coordinate time series of the landslide GPS over 2 years (1 June 2009 to 31 May 2011) referred to as the North American Datum of 1983 (NAD_83) and the International Terrestrial Reference Frame of 2000 (ITRF00). The initial positions on 1 June 2009 were initialized to zeros. The NAD_83 (CORS96) reference frame is the current control datum for the United States and its territories. The NAD_83 datum is based on the 1980 Geodetic Reference System (GRS80 ellipsoid), an Earth-centered (or "geocentric") datum (spheroid) with a 6,378,137-m semi-major axis and a 1:298.257 flattening. The GRS80 and the WGS84 ellipsoids are the most common reference surfaces used in geodetic positioning by GPS. The ITRF00 is defined by a set of physical points with precisely determined coordinates (e.g., GPS stations operated by International GNSS Service) located on the Earth's surface. ITRF00 solutions are specified by Cartesian geocentric coordinates X, Y, and Z and do not directly use a specific ellipsoid. The landslide GPS coordinates provided by OPUS for 1 June 2009 (Appendix 1) indicate that the ITRF00 and NAD_83 reference frames are comparable, with differences at the level of 1 m or less along the three axes. In practice, ITRF00 coordinates and velocities can be transformed to corresponding NAD_83 coordinates and velocities, using equations and parameters described by Soler and Snay (2004). Figure 4 further indicates that the differences are increasing over time. This is particularly clear in the Z direction within the Cartesian coordinate system and latitude direction within the geographic coordinate system. This is because of the fact that the positions referred to the NAD_83 (CORS96) frame are North American Plate fixed, while the positions referred to the ITRF00 are not. The over-time difference of the horizontal displacements between the two reference frames indicates the occurrence of relative horizontal plate motions between the North American and Caribbean Plates. There is no visible over-time difference in the ellipsoidal heights measured within the two reference frames, which implies insignificant vertical movements of the North American datum (NAD_83) around the Caribbean Plate. The NAD_83 is set to remain essentially constant over time to points on the North American tectonic plate. In other words, the North American Plate is fixed within the NAD_83 reference frame. The displacements derived from the NAD_83 positions are a combination of the local landslide displacements and relative plate displacements between the North American Plate and the Caribbean Plate. ITRF00 is a spatial reference system co-rotating with the Earth in its diurnal motion through space. In such a system, plate motions have been considered. The ITRF00 position of a point anchored on the Earth's solid surface is described by X, Y, Z and the velocities in X, Y, Z

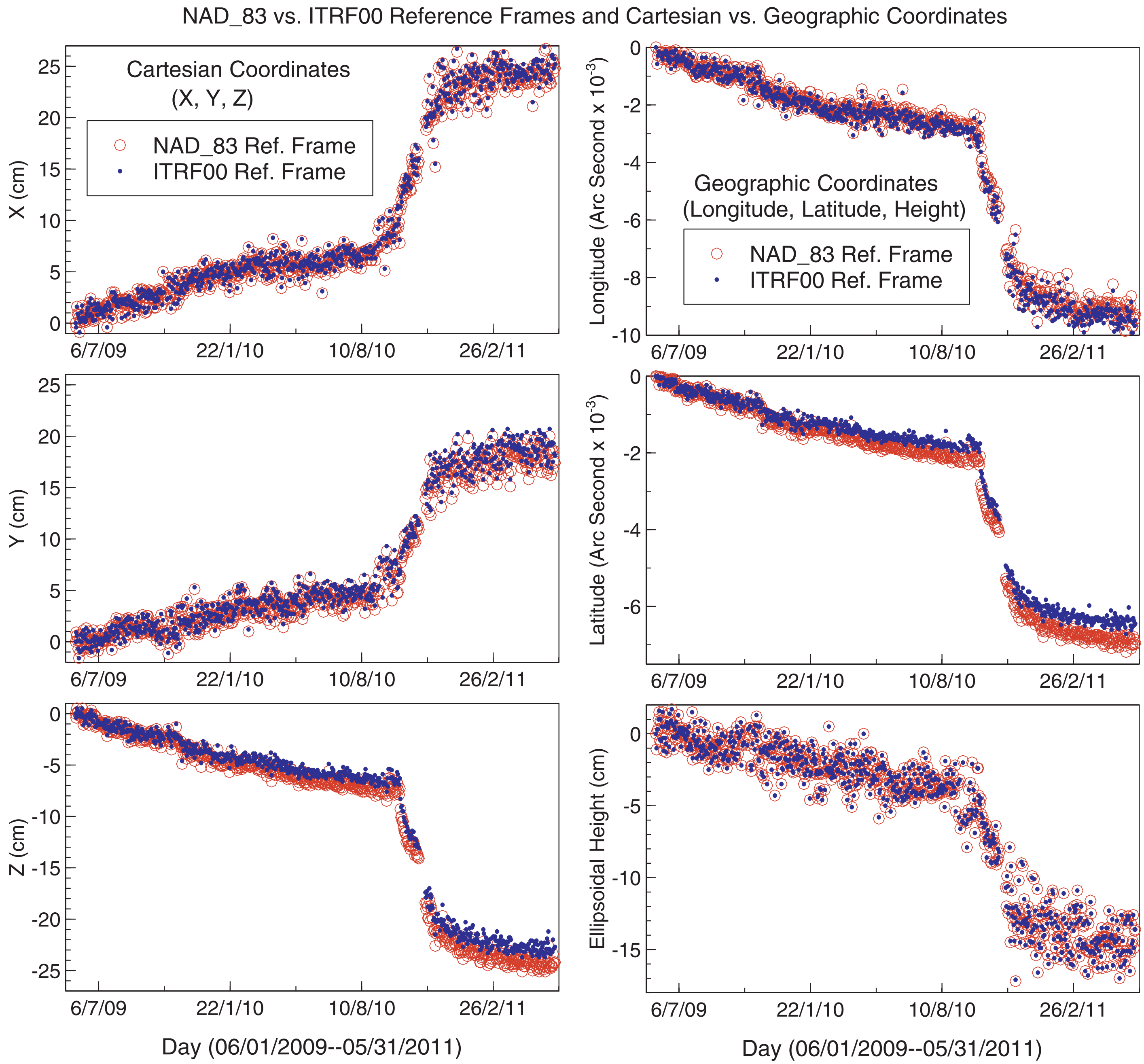

FIGURE 4: Comparisons of the landslide movements derived from OPUS outputs in the three-dimensional Cartesian coordinates and geodetic coordinates within the NAD_83 and the ITRF00 reference frames. The position time series are initialized by the positions (*X*, *Y*, *Z*, or longitude, latitude, ellipsoidal height) on the first day (1 June 2009).

directions, and a specific epoch. Students also gained experience of studying relative motions between two tectonic plates by plotting Fig. 4.

UTM Versus SPC

Figure 5 illustrates the northing and easting position time series of the landslide derived from GPS data given in the UTM and the SPC systems. Both UTM and SPC are defined in a two-dimensional Cartesian coordinate system. The initial positions were initialized to zeros. The absolute coordinates under the two measuring systems are largely different. For example the northing and easting position values within the UTM coordinates on 1 June 2009 are 1,996,261.289 and 746,058.406 m, respectively, while the corresponding positions within the SPC coordinates are 222,995.001 and 174,341.954 m, respectively. However, the changes in the positions, or landslide displacements, within the two coordinate systems are the same. The differences of UTM and SPC coordinates do not affect the measurements of local horizontal displacements.

UTM can be understood as a two-dimensional horizontal map representation of the three-dimensional Earth surface (ellipsoid). A map projection is often used to convert from the three-dimensional geodetic coordinate system to a

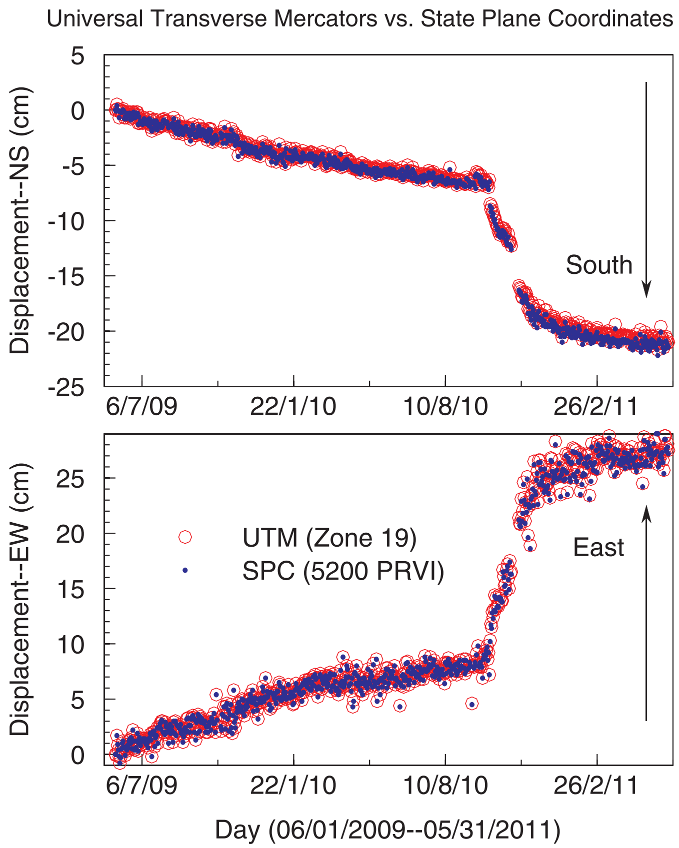

FIGURE 5: Comparisons of the northing and easting displacements under UTM coordinates and SPC. The absolute coordinates within the UTM and SPC coordinates are largely different (see Appendix 1), while the changes of positions, or horizontal displacements, are the same.

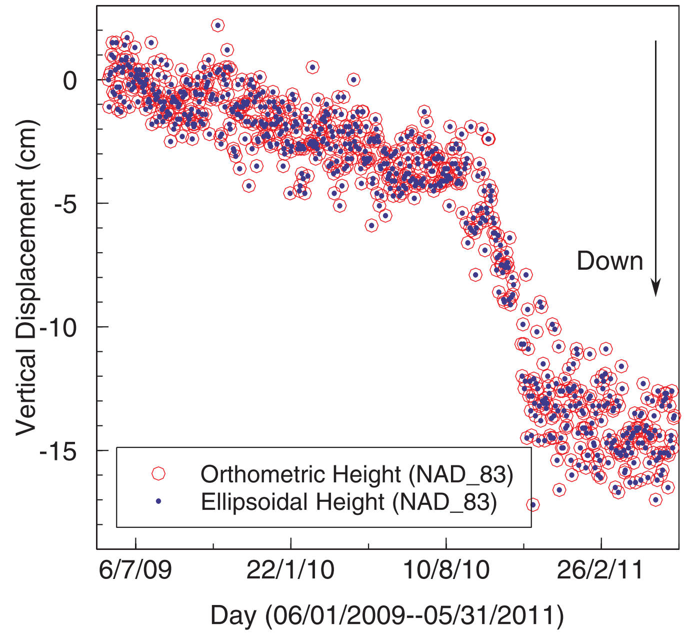

FIGURE 6: Comparisons of ellipsoidal height and orthometric height within the same reference frame (NAD_83).

two-dimensional projected Cartesian coordinate system. UTM uses a grid-based method of specifying locations on the surface of the Earth. A UTM position is referenced in the UTM system by the UTM zone, and the easting and northing coordinate pair. The easting is the projected distance of the position eastward of the central meridian, while the northing is the projected distance of the point north of the equator (in the northern hemisphere). The SPC system is also a two-dimensional Cartesian coordinate system. SPC was designed for specific regions of the United States. Each state contains one or more state plane zones. There is one SPC zone (5200) in Puerto Rico and the U.S. Virgin Islands. The SPC system is widely used by state and local governments for practical mapping purposes, largely because SPC uses a simple plane Cartesian coordinate system to specify locations rather than a more complex spherical coordinate system. By thus ignoring the curvature of the Earth, "plane surveying" methods can be used, speeding up and simplifying calculations. Another advantage of SPC coordinates is its high accuracy within each zone. However, the accuracy rapidly declines outside a specific state plane zone, meaning that the SPC system is not useful for regional or national mapping.

Vertical Position Measurements

For height measurements, OPUS provides ellipsoidal heights referred to the NAD_83 and ITRF00 reference frames, and orthometric height with respect to the NAD_83 reference frame. Figure 6 illustrates the orthometric and ellipsoidal height measurements referred to the NAD_83 reference frame. The height on the first day (1 June 2009) was initialized to zero. Orthometric height is the distance measured above the geoid. Ellipsoidal height is the distance above the ellipsoidal surface. The ellipsoidal heights under the NAD_83 and ITRF00 reference frames are slightly different. They are 172.492 and 170.612 m, respectively, at the landslide GPS site according to the OPUS-S report for the 24-h data on 1 June 2009. The difference is 1.88 m. The difference between orthometric height (NAD_83) and ellipsoidal height (NAD_83) is called the geoidal height, or geoidal separation. There is a simple mathematical relationship among orthometric height, ellipsoidal height, and geoidal height:

$$H = h - N, \quad (1)$$

where H represents orthometric height (above geoid), h represents ellipsoidal height (above the ellipsoid), and N represents geoidal height. According to Eq. 1, geoidal height at the landslide GPS site is −39.7 m. Figure 6 illustrates the changes in the orthometric height and the ellipsoidal height over a 2-year range. It is clear that the changes, or the vertical displacements, derived from orthometric heights and ellipsoidal heights have an equivalent interpretation at the landslide site. The comparisons of the ellipsoidal heights within the NAD_83 and ITRF00 reference frames are plotted in Fig. 4. There are invisible differences between the two heights over the 2-year range. Accordingly, the differences in reference frames and measuring methods (orthometric or

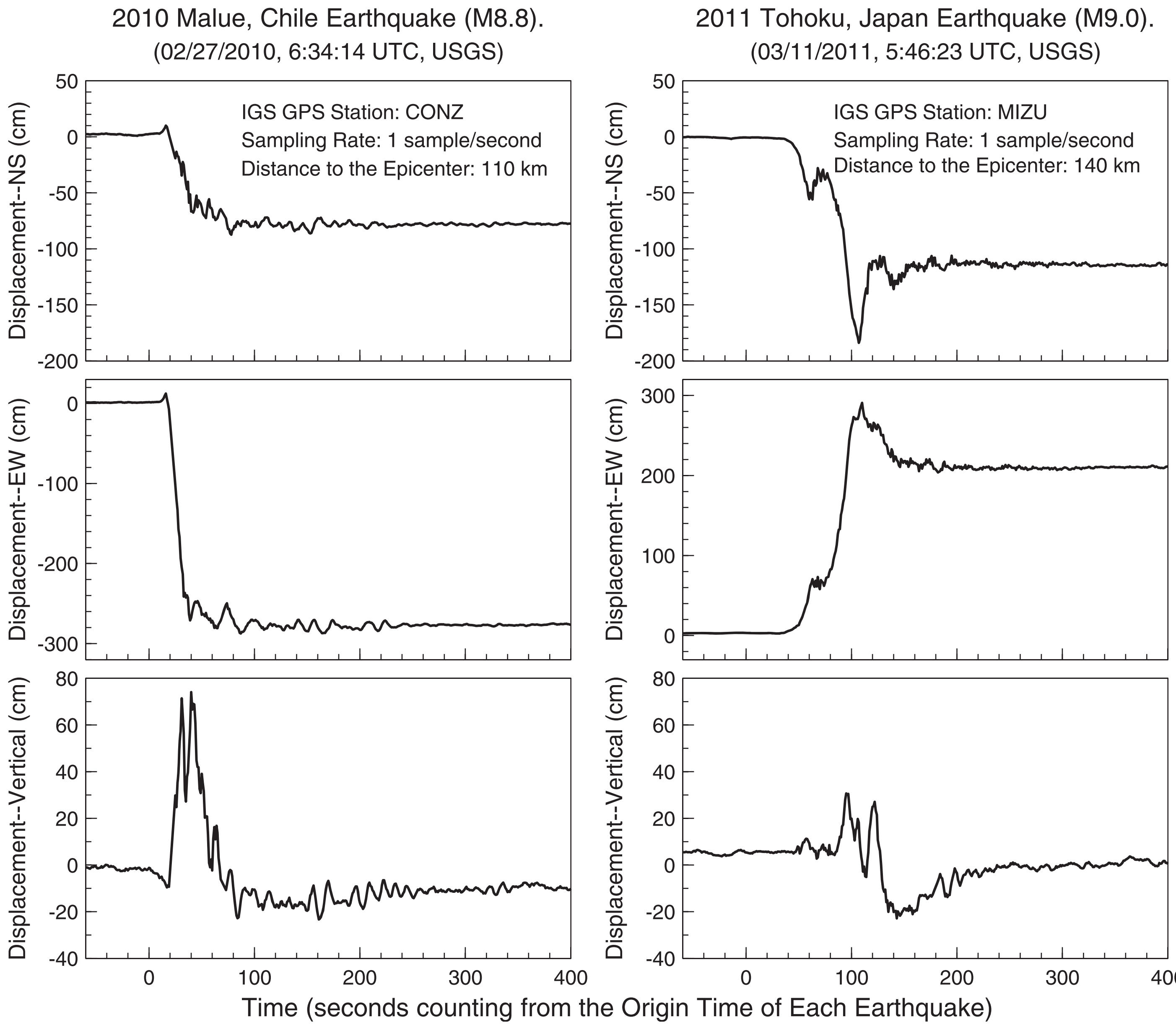

FIGURE 7: Three component GPS seismograms recorded at International GNSS Service (IGS) GPS station CONZ during the 2010 Maule, Chile Earthquake (*M* 8.8) and at IGS GPS station MIZU during the 2011 Tohoku, Japan Earthquake (*M* 9.0).

ellipsoidal) do not affect the landslide study. OPUS outputs really help students to understand the correlation between absolute and relative measurements

ONLINE KINEMATIC PROCESSING

High-rate GPS has been recognized as a new technology useful in measuring strong earthquake ground motions and with the potential of identifying tsunamigenic earthquakes and being employed in global tsunami early warning system (e.g., Blewitt et al., 2006, 2009; Crowell et al., 2009; Allen and Ziv, 2011; Wright et al., 2012). Many researchers have discussed the potential for GPS seismology (e.g., Ge, 1999; 2000; Nikolaidis et al., 2001; Larson et al., 2003; Bock et al., 2004; Emore et al., 2007; Wang et al., 2007; Bilich et al., 2008; Larson, 2009; Smalley 2009). It would be significant to demonstrate the new seismic sensor to geosciences students. High-rate (1-sample per s) GPS data collected during large earthquakes such as the 2010 Maule, Chile Earthquake (*M* 8.8) and the 2011 Tohoku, Japan Earthquake (*M* 9.0) were used in the recent GPS classes. APPS, operated by NASA's JPL, was applied for post-kinematic GPS data processing. Students can obtain nice seismograms from high-rate GPS data recorded during large earthquakes by using APPS without knowing so much about the details of kinematic GPS data processing. Figure 7 shows two examples of three-component GPS seismograms recorded during the Chile and Japan Earthquakes. Almost all students can produce a similar plot to Fig. 7 at the end of this class. GPS seismographs provide long-period and permanent ground motion information that cannot be provided by conventional seismic sensors. By using the satellite-based seismic "sensor," students could realize the great impacts of new technologies on traditional scientific disciplines.

CONCLUDING REMARKS

The expansion of permanent GPS observing stations over the last decade, through regional, national, and global networks, has enabled not only the free availability of GPS raw data and associated geodetic products (e.g., satellite orbits and clock information, atmospheric products, international terrestrial reference frame, etc.), but also the free availability of high-quality post-processing services, even real-time or near-real-time processing services. Recently, a number of national and international organizations (e.g., NGS, JPL, Scripps Orbit and Permanent Array Center, Natural Resources Canada, Geoscience Australia) developed free online GPS data-processing services. These services provide the opportunity for a user to obtain high-precision coordinates in a recognized datum (e.g., IGS08) without advanced knowledge and responsibility for GPS data processing. The author has been applying OPUS and other online services to research and education for several years. Each online service has certain advantages and disadvantages, which have been investigated by several publications (e.g., Ghoddousi-Fard and Dare, 2006; Liu and Shih, 2007; Tsakiri, 2008; Martin et al., 2011). This paper demonstrates the efficiency of using OPUS and APPS in teaching high-accuracy GPS technology to undergraduate students. Nevertheless, other online services can also be used in GPS education.

Online services are "black boxes" for users, and the results of online services are not user controlled, but all of the processing employs well-known recognized standards and strict quality control. The results are often credible. Using online GPS processing services, a GPS learner can speed through the complex aspects of data processing and focus on the scientific applications of high-accuracy GPS. The author also taught a geological hazards course (GEOL5605 Geological Hazards) at the University of Puerto Rico. This was an elective course for senior undergraduate and graduate students. The enrollment was about 15 students. GPS was taught in the laboratory section of this course. GPS and other satellite remote sensing technologies have been frequently applied to studies of natural hazards. It is therefore reasonable to teach GPS in the laboratory section of this course. The second project introduced in this article was also implemented in the Geological Hazards class as a semester-long, research-based group project. By using OPUS, most students can independently process GPS raw data and plot the landslide displacement time series. Students were happy to learn both natural hazards and centimeter-accuracy GPS from one course. OPUS helped both the instructor and students in preparing and learning the intricacies of GPS data processing, understanding different reference frames and coordinate systems, and studying the kinematics of landslide movements. The enrollment of both classes was small (about 10 senior undergraduates) because of the fact that they were elective courses, and total undergraduate population at that department was not large. However, online processing service can be definitely implemented in classes with a large enrollment. Online GPS data processing can be done using computers maintained at NGS headquarters. Users do not need to install any GPS-processing software packages on personal computers. GPS software is frequently improved; it is difficult for an occasional practitioner to keep up with the habitual updates. The convenience and high quality of online GPS processing services has led to their increased usage in educational, research, and industry communities. It is evident that online GPS data processing will become a popular and powerful tool for GPS education in the near future.

Finally, from the perspective of an educator, implementing OPUS into GPS education is rewarding, because students benefit noticeably and promptly. Several years ago, a colleague at the National Astronomy and Ionosphere Center (http://www.naic.edu), Arecibo Observatory in Puerto Rico, needed to precisely locate the position of a critical instrument. He requested me to do a professional surveying. I sent an undergraduate student from my GPS class to do the surveying after I figured out that they need about 2-cm horizontal accuracy and 5-cm vertical accuracy. The student had just finished the first project, "Where Is My House?" He learned the skills necessary for surveying a point with static GPS. He drove to the site and conducted a 4-h static GPS survey with a single GPS unit (Topcon GB1000). During the 4 h that he waited for the GPS receiver to collect data, the colleague at the observatory altruistically gave him a free tour and a free lunch. The student submitted the data to OPUS the next day and sent the OPUS output to the observatory. His "client" was very happy, and the student was very proud of his professional service. In fact, students who have taken my GPS classes often help professors in the geology department and other departments to survey field sites.

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APPENDIX 1. An example of OPUS output.

```
FILE: ponc1520.09o 000207040

 1008   NOTE:  Antenna offsets supplied by the user were zero.  Coordinates
 1008   returned will be for the antenna reference point (ARP).
 1008
                    NGS OPUS SOLUTION REPORT
                    ========================

All computed coordinate accuracies are listed as peak-to-peak values.
For additional information: http://www.ngs.noaa.gov/OPUS/about.html#accuracy

    USER: guoquan.wang2011@gmail.com            DATE: April 20, 2011
RINEX FILE: ponc1520.09o                        TIME: 00:11:04 UTC


  SOFTWARE: page5  1009.28 master2.pl 1215103      START: 2009/06/01  00:00:00
 EPHEMERIS: igs15341.eph [precise]                  STOP: 2009/06/01  23:59:00
  NAV FILE: brdc1520.09n                        OBS USED: 57203 / 58789   :  97%
  ANT NAME: TRM49700.00     NONE            # FIXED AMB:   185 /   222   :  83%
ARP HEIGHT: 0.0                            OVERALL RMS: 0.019(m)


 REF FRAME: NAD_83(CORS96)(EPOCH:2002.0000)           ITRF00 (EPOCH:2009.4151)

       X:      2402010.784(m)   0.009(m)          2402010.162(m)   0.009(m)
       Y:     -5570892.070(m)   0.010(m)         -5570890.256(m)   0.010(m)
       Z:      1962746.889(m)   0.007(m)          1962746.690(m)   0.007(m)

     LAT:   18  2 27.38423      0.008(m)        18  2 27.39734      0.008(m)
   E LON:  293 19 27.61066      0.008(m)       293 19 27.61566      0.008(m)
   W LON:   66 40 32.38934      0.008(m)        66 40 32.38434      0.008(m)
  EL HGT:          172.492(m)   0.010(m)               170.612(m)   0.010(m)
 ORTHO HGT:         212.198(m)   D.N.E. [No official datum supported (FAQs 19,20).]

                    UTM COORDINATES    STATE PLANE COORDINATES
                     UTM (Zone 19)         SPC (5200 PRVI)
Northing (Y) [meters]     1996261.289          222995.001
Easting (X)  [meters]      746058.406          174341.954
Convergence  [degrees]     0.72020254         -0.07582231
Point Scale                1.00034859          0.99999955
Combined Factor            1.00032147          0.99997243

US NATIONAL GRID DESIGNATOR: 19QGV4605896261(NAD 83)

                         BASE STATIONS USED
PID       DESIGNATION                        LATITUDE    LONGITUDE DISTANCE(m)
DI4790 PUR5 PUERTO RICO 5 CORS ARP        N182746.702 W0670401.051   62406.0
DH9349 PRMI MAGUEYES ISLAND CORS ARP       N175813.418 W0670243.343   39924.6
DF8978 ZSU1 SAN JUAN WAAS 1 CORS ARP       N182552.803 W0655936.517   84100.1

               NEAREST NGS PUBLISHED CONTROL POINT
TV1246      PENUELAS USGS 1934            N180222.211 W0664207.818    2810.4

This position and the above vector components were computed without any knowledge by the National
Geodetic Survey regarding the equipment or field operating procedures used.
```