Horizontal Time-Dependent Positioning

Richard Snay

The earth is like a soft-boiled egg in that it consists of three major layers. The outer layer, dubbed the *crust*, is rather brittle and comprises only about one percent of the earth's radius. The intermediate layer, called the *mantle*, has a consistency somewhat like toothpaste. The innermost layer is referred to as the *core*. Ongoing radioactivity within the earth causes temperatures to become hotter with increasing depth, and this heat causes the mantle's material to undergo convective flow. The crust is too stiff to flow, so it has fractured into more than 20 tectonic plates that drift somewhat rigidly upon the mantle at relatively constant rates of a few centimeters per year. These plates deform elastically whenever two of them collide or grind laterally past each other. Stresses that accumulate as a result of this deformation can be released catastrophically as an earthquake when these stresses overcome frictional forces along interplate boundaries. In a period of a few minutes, adjacent plates will each rebound in an effort to regain their undeformed shape. Thus, points on the earth's surface move horizontally with relatively constant velocities that are interrupted by episodic displacements associated with earthquakes.

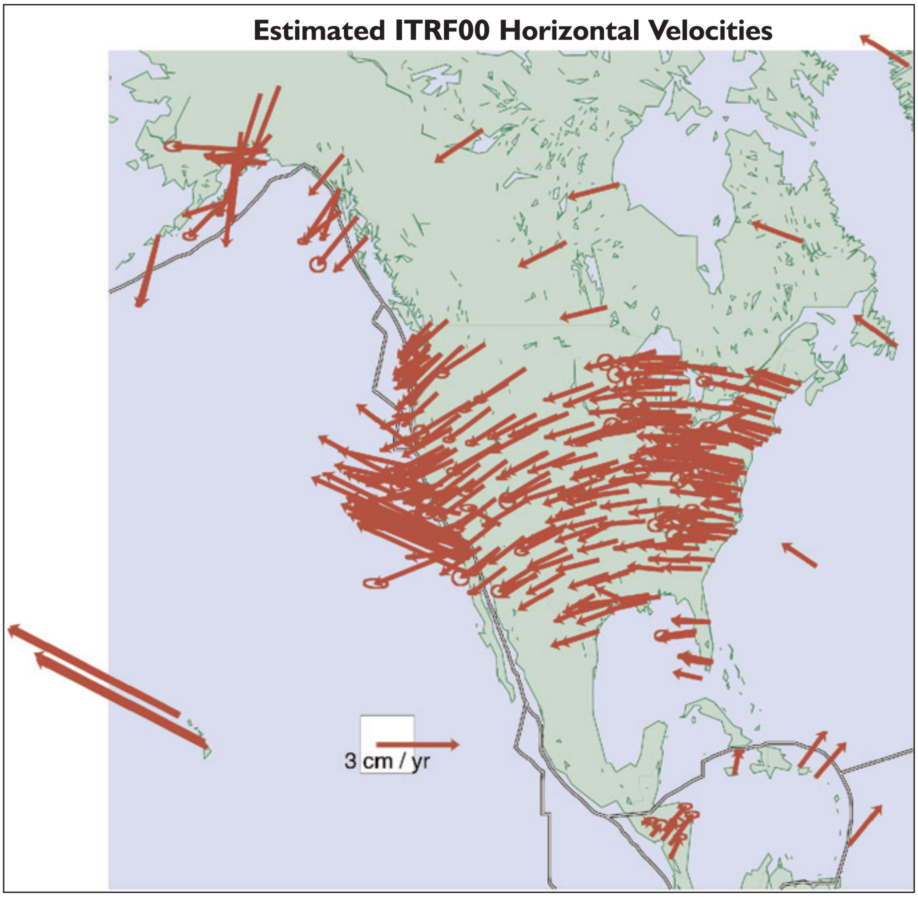

***Figure 1:** ITRF00 horizontal velocities for points in and around North America. Double lines approximate plate boundaries. Note how the interior of the North American plate is rotating counterclockwise about a "pole," through the earth's center, that pierces the earth's surface at a point just west of Ecuador.*

HTDP Software

To help surveyors and others cope with the changes in positional coordinates associated with such crustal motion, NOAA's National Geodetic Survey (NGS) has developed a software package known as the Horizontal Time-Dependent Positioning (HTDP) utility which has been incorporated into NGS's Geodetic Tool Kit. While HTDP addresses that motion associated with drifting tectonic plates and earthquakes, NGS recognizes the need to develop a more comprehensive tool that will address other forms of crustal motion as that associated with volcanic/magmatic activity, land subsidence, postglacial rebound, and crustal loading/unloading.

Predicting horizontal velocities for a user-specified location is one of two primary functions supported by HTDP. The software's second primary function is to predict horizontal displacements for a user-specified location and a user-specified period of time. For this second function, HTDP multiplies the predicted velocity by the time difference and then adds any earthquake-related displacements that occurred during the specified time period. In predicting velocities and/or displacements, HTDP applies numerical models for horizontal crustal motion that have been derived from repeated geodetic observations, as well as from geological, seismological, and other geophysical information.

HTDP primarily predicts velocities and displacements relative to the North American Datum of 1983 (NAD 83), but it is able to convert these predicted values to equivalent values in other popular reference frames including all realizations of the International Terrestrial Reference Frame (ITRF) and all realizations of the World Geodetic System of 1984 (WGS 84). NAD 83 is defined so that points interior to the North American tectonic plate will (on average) have zero horizontal velocities relative to this reference frame. Points within a few hundred kilometers of the North American plate boundary (California, Nevada, Oregon, Washington, and Alaska) usually will have nonzero horizontal NAD 83 velocities, some approximately 50 mm/yr in magnitude.

Both the ITRF and WGS 84 reference frames are defined so that the average horizontal velocity, when integrated over the entire surface of the earth, is zero. Consequently, almost all points on the earth's surface have significant nonzero horizontal velocities relative to each of these two reference frames. In the contiguous 48 states, horizontal ITRF/WGS 84 horizontal velocities have magnitudes that range from 9 mm/yr to 22 mm/yr, except for points located near the North American plate boundary where horizontal velocities usually exceed 22 mm/yr in magnitude. Horizontal ITRF/WGS 84 velocities in Alaska and Hawaii also exceed 22 mm/yr in magnitude, as shown in **Figure 1**.

The reality of crustal motion implies that positional coordinates in many locations change as a function of time. Hence, it is inappropriate to specify positional coordinates for these locations without also specifying the date for which these coordinates correspond. This date is called the epoch date for the given coordinates. For instance, NAD 83 positional coordinates for Continuously Operating Reference Stations (CORS) are currently specified for an epoch date of January 1, 2002 (except in Alaska where an epoch date of January 1, 2003 is used because of a major earthquake in November 2002), and ITRF coordinates for CORS are currently specified for January 1, 1997. People may apply HTDP to update (or backdate) coordinates from one epoch date to corresponding coordinates for another epoch date for CORS or, for that matter, any geodetic reference station. This software simply adds (or subtracts) the station's predicted displacement between the two dates to the positional coordinates for the starting epoch date.

HTDP also enables its users to update (or backdate) certain types of geodetic observations (differential GPS, distances, azimuths, horizontal angles, horizontal directions) from the value that was measured on the day of observation to the value that would have been measured on some other date. Indeed, NGS updated a copy of all pertinent geodetic observations that were observed in California before 1983 to corresponding values that would have been observed on December 31, 1983. NGS then performed a simultaneous (fixed-Earth) adjustment of these updated observations to determine the NAD 83 positional coordinates for the more than 10,000 reference stations that had provided horizontal geodetic control for California during the 1850-1983 period. As a result, the derived coordinates have an epoch date of December 31, 1983. On a few more recent occasions, NGS—in cooperation with several California organizations—has updated pertinent geodetic observations to a few more current epoch dates for determining corresponding reference-station coordinates. The need to update observations to a common date, called data homogenization, is a burden of living in earthquake country; but this need is not unique to California. NGS performed a highly precise GPS survey in 1991 to establish the High Accuracy Reference Network (HARN) for the state of Washington. Some consternation was expressed when this network was re-observed in 1998 and the newer GPS measurements were inconsistent with the positional coordinates that had been derived from the 1991 GPS survey. This consternation was only dispelled when people realized that points in western Washington are moving horizontally about 10 mm/yr relative to points in eastern Washington as a consequence of ongoing collision between the Juan de Fuca plate and the North American plate. These two plates first meet about 100 km west of the Pacific Coast where the more dense Juan de Fuca plate dives or subducts beneath the North American plate, thus causing both horizontal and vertical crustal deformation in Washington, Oregon, and northern California. As illustrated in **Figure 2**, large regions of the western United States are moving horizontally at speeds in excess of 5 mm/yr relative to the NAD 83 reference frame. Such motion is easily detectible with repeated GPS observations that span a few years. Similar deformation is occurring in Alaska, but it has yet to be adequately quantified due to a lack of repeated geodetic observations.

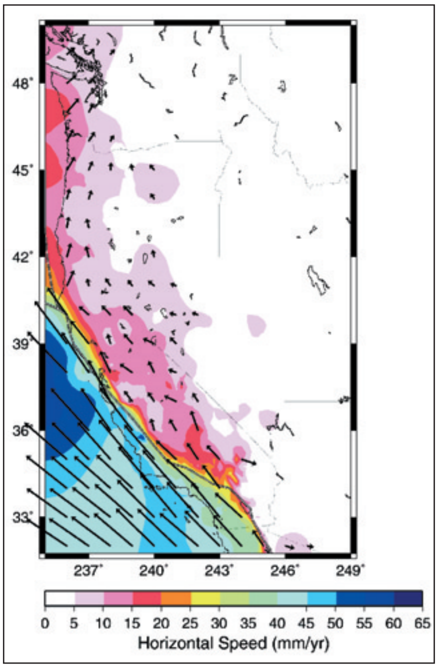

Figure 2: *NAD 83 horizontal velocities across the western United States. Colors specify speed in mm/yr and arrows specify corresponding directions of motion.*

Dynamic Evolution

As implied earlier, HTDP can be used to transform positional coordinates from one reference frame to another. It is important to realize that two reference frames may be moving relative to one another, and so the transformation parameters encoded into HTDP involve time-dependent terms. For example, points located in the eastern United States generally do not move relative to NAD 83, but they do move at speeds in excess of 9 mm/yr relative to ITRF (and WGS 84). Hence, the NAD 83 coordinates for a single point will transform into two different ITRF coordinates for two different epoch dates.

To consider a particular application of HTDP's capability to transform coordinates between reference frames, let us assume that a highly precise GPS survey was performed today and that, for control, this survey included the occupation of some previously established reference stations, each with known NAD 83 positional coordinates at an epoch date of

January 1, 2002. Assume, furthermore, that the satellite ephemerides (orbits) to be used in processing the GPS data are expressed in ITRF00. Thus, to be rigorous, the known NAD 83 positional coordinates of the reference stations would be transformed to ITRF00, such that the epoch date of these transformed coordinates equals the survey date, namely, today. Hence, the GPS processing software can perform all computations in ITRF00, and the positional coordinates for any newly established reference stations will also be expressed in ITRF00 with their epoch date equal to the survey date. Subsequently, HTDP can be applied to transform derived positional coordinates from ITRF00 to another reference frame and to another epoch date, as desired.

The word "dynamic" may be attributed to the HTDP software for several reasons. The software merits this attribute primarily because it enables surveyors and others to deal rigorously with time-dependent positions on our dynamic planet. This attribute is also merited because the software has evolved rather dynamically over time. Since June 1992 when NGS released the initial version of HTDP, this agency has enhanced the software through a progression of 18 subsequent versions. Collectively, these subsequent versions have introduced numerous new and/or improved numerical models for crustal motion. They have also introduced new capabilities, most notably, the capability to work with the various ITRF realizations and WGS 84 realizations as well as with NAD 83. As in the past, HTDP may be expected to continue evolving, so as to keep pace with the continually improving accuracy with which surveyors and others can position points. For a more detailed presentation on HTDP, see the article, "Using the HTDP Software to Transform Spatial Coordinates Across Time and Between Reference Frames," which can be downloaded and/or viewed at *www.ngs.noaa.gov* by clicking on "Geodetic tool kit" and then "HTDP."

DR. RICHARD A. SNAY *is Manager of the National Continuously Operating Reference Station (CORS) program and a geodesist with the National Geodetic Survey.*