# Modern Terrestrial Reference Systems
## PART 3: WGS 84 and ITRS

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The Department of Defense (DoD) developed the WGS 84 reference system to support global activities involving mapping, charting, positioning, and navigation. More specifically, DoD introduced WGS 84 to express satellite orbits; that is, satellite positions as a function of time. Accordingly, WGS 84 is widely used for "absolute" positioning activities whereby people assume that satellite orbits are sufficiently accurate to serve as the sole source of control for positioning points of interest. In particular, absolute positioning does not rely on using positional coordinates for pre-existing terrestrial points for control, except indirectly in that orbits are derived from adopted positions for a small set of tracking stations (Fig. 3). The general user, however, never needs to know the positions of these tracking stations.

DoD provides both "predicted" and "postfit" orbits in the WGS 84 reference system. As implied by the name, predicted orbits are calculated ahead of time by applying physical principles to extrapolate currently observed satellite positions. On the other hand, postfit orbits are calculated from previously observed satellite positions. Postfit orbits are more precise than predicted orbits both because they do not involve predicting the future and because they are usually derived using a larger number of tracking stations. GPS predicted orbits and satellite clock parameters are generated by the Air Force at the GPS Operational Control Segment, located at Schriever AFB, Colorado. The Air Force then uploads these predicted quantities to the GPS satellites so that this information may be included in the radio signal transmitted by these satellites. These predicted orbits support all real-time positioning and navigation activities involving GPS. Postfit GPS orbits and satellite clock parameters are generated by the National Imagery and Mapping Agency (NIMA), who currently makes this information available on its Geodesy and Geophysics World Wide Web pages. A number of other organizations also generate postfit GPS orbits which they usually express in a particular

realization of the International Terrestrial Reference System (ITRS).

The original WGS 84 realization essentially agrees with NAD 83 (1986). Subsequent WGS 84 realizations, however, approximate certain ITRS realizations. Because GPS satellites broadcast the predicted WGS 84 orbits, people who use this broadcast information for positioning points automatically obtain coordinates that are consistent with WGS 84. Hence, the popularity of using GPS for real-time positioning has promoted greater use of WGS 84. Despite its popularity, people generally do not use WGS 84 for high-precision positioning activities, because such activities require the use of highly accurate positions on pre-existing terrestrial points for control. For example, various differential GPS techniques use known positions for one or more pre-existing terrestrial points to remove certain systematic errors in computing highly precise positions for new points. Consequently, before WGS 84 can support high-precision positioning activities, a rather extensive network of accurately positioned WGS 84 terrestrial control points would have to be established.

DoD established the original WGS 84 reference frame in 1987 using Doppler observations from the Navy Navigation Satellite System (NNSS) or TRANSIT. The WGS 84 frames have evolved significantly since the mid-1980s. In 1994, DoD introduced a realization of WGS 84 that is based completely on GPS observations, instead of Doppler observations. This new realization is officially known as WGS 84 (G730) where the letter G stands for "GPS" and "730" denotes the GPS week number

(starting at 0h UTC, 2 January 1994) when NIMA started expressing their derived GPS orbits in this frame. The latest WGS 84 realization, called WGS 84 (G873), is also based completely on GPS observations. Again, the letter G reflects this fact, and "873" refers to the GPS week number starting at 0h UTC, 29 September 1996. Although NIMA started computing GPS orbits in this frame on this date, the GPS Operational Control Segment did not adopt WGS 84 (G873) until 29 January 1997.

The origin, orientation, and scale of WGS 84 (G873) are determined relative to adopted positional coordinates for 15 GPS tracking stations: five of them are maintained by the Air Force and ten by NIMA (see Fig. 3). NIMA chose their sites to complement the somewhat equatorial distribution of the Air Force sites and to optimize multiple station visibility from each GPS satellite. People may anticipate further improvements of WGS 84 in the future, as new GPS tracking sites may be added or existing antennas may be relocated or replaced. NIMA is dedicated to take appropriate measures to guarantee the highest possible degree of quality and to perpetuate the accuracy of WGS 84. As mentioned earlier, however, most regions lack a network of accessible reference points that might serve as control points from which highly accurate WGS 84 coordinates may be propagated using an appropriate static differential GPS technique involving carrier phase observables. Another minor drawback affecting accurate GPS work is the unavailability to the general GPS user of the crustal velocities at the WGS 84 tracking stations. More information about WGS 84 may be obtained via the Internet by accessing: http://164.214.2.59/GandG/tr8350_2.html
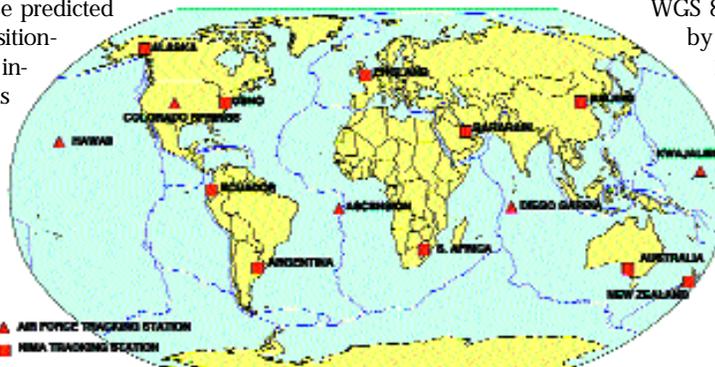
### The Evolution of ITRS

In the late 1980s, the International Earth Rotation Service (IERS) introduced ITRS to support those scientific activities that require highly accurate positional coordinates; for example, monitoring crustal motion and the motion of Earth's rotational axis. The initial ITRS realization was called the International Ter-



Figure 3. Combined DoD tracking network that defines WGS 84.

restrial Reference Frame of 1988 (ITRF88). Accordingly, IERS published positions and velocities for a worldwide network of several hundred stations. The IERS, with the help of several cooperating institutions, derived these positions and velocities using various highly precise geodetic techniques including GPS, VLBI, SLR, LLR, and DORIS (Doppler orbitography and radiopositioning integrated by satellite). Every year or so since introducing ITRF88, the IERS has developed a new ITRS realization –ITRF89, ITRF90, ..., ITRF97– whereby they have published revised positions and velocities for previously existing sites, as well as new positions and velocities for those sites that had been established since after earlier realizations had been developed. Each new realization not only incorporated at least an additional year of data, but also the most current understanding of Earth's dynamic behavior. The ITRF96 frame is defined by the positions and velocities of 508 stations dispersed among 290 globally distributed sites (Fig. 4). Recall that a particular site may involve one or more co-located instruments employing various space-related techniques (e.g., GPS, VLBI, SLR, LLR, and DORIS). The accuracy and rigor of ITRS has proven contagious, and its popularity is steadily growing among those who engage in positioning activities.

Furthermore, ITRS is the first major international reference system to directly address plate tectonics and other forms of crustal motion by publishing velocities as well as positions for its control points. To appreciate the need for velocities, consider the theory of plate tectonics. According to this theory, Earth's outer shell consists of about 20 plates that are essentially rigid, and these plates move mostly laterally relative to one another like several large sheets of ice on a body of water. The relative motion between points on different plates are, in some cases, as large as 150 mm/yr, which is easily detectable using GPS and other modern day positioning techniques.

Given the fact that each tectonic plate is moving relative to the others, one may ask how crustal velocities may be expressed in "absolute" terms. The people responsible for ITRS currently address this
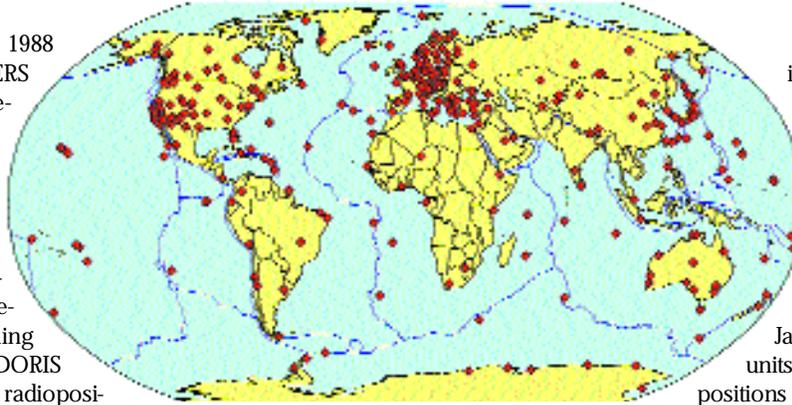


Figure 4. Sites defining ITRF96.

dilemma by assuming that the Earth's surface, as a whole, does not move "on average" relative to Earth's interior. Said differently, the ITRS developers assume that the total angular momentum of Earth's outer shell is zero. Hence, the angular momentum associated with the motion of any one plate is compensated by the combined angular momentum associated with the motions of the remaining plates. Consequently, points on the North American plate generally move horizontally at measurable rates according to the ITRS definition of absolute motion. In particular, horizontal ITRF96 velocities have magnitudes between 10 and 20 mm/yr in the coterminous 48 states. Moreover, horizontal ITRF96 velocities have even greater magnitudes in Alaska and Hawaii.

In contrast, the NAD 83 reference system addresses plate motion under the assumption that the North American plate, as a whole, does not move "on average" relative to Earth's interior. Hence, points on the North American plate generally have no horizontal velocity relative to NAD 83 unless they are located near the plate's margin (California, Oregon, Washington, and Alaska) and/or they are affected by some other deformational process (volcanic/magmatic activity, postglacial rebound, etc.). The NAD 83 reference system, however, does make special accommodations for certain U.S. regions that are located completely on another plate. In Hawaii, for example, NAD 83 positional coordinates are defined as if the Pacific plate is not moving. This approach is convenient for people who are involved with positioning activities solely in Hawaii. This approach, however, introduces a layer of complexity for people who are involved in positioning points in Hawaii relative to points in North America.

In the realm of crustal motion, it is inappropriate to specify positional coordinates without specifying the "epoch date" for these coordinates; that is, the date to which these coordinates correspond. Accordingly, ITRF96 positions are usually specified for the epoch date of 1 January 1997 (often denoted in units of years as 1997.0). To obtain positions for another time, t, people need to apply the formula

$$x(t) = x(1997.0) + vx \cdot ( t - 1997.0 ) \quad (2)$$

and similar formulas for y(t) and z(t). Here, x(t) denotes the point's x-coordinate at time t, x(1997.0) denotes the point's x-coordinate on 1 January 1997, and vx denotes the x-component of the point's velocity.

NGS furnishes easy access to the ITRF96 reference frame through a set of over 170 stations belonging to the National CORS network (recall Fig. 2). Positions, velocities, and other pertinent information for these stations are available via the Internet by accessing: *ftp://www.ngs.noaa. gov/cors/coord/coord_96*.

**Transforming Between Reference Frames**

In 1998, U.S. and Canadian officials jointly adopted a Helmert transformation to convert positional coordinates between ITRF96 and NAD 83 (CORS96). The IERS has also adopted appropriate Helmert transformations for converting between ITRF96 and other ITRS realizations. NGS has encoded all these transformations into a software package, called HTDP (Horizontal Time-Dependent Positioning), which is freely available via the Internet: *http://www.ngs.noaa.gov/TOOLS/ Htdp/Htdp.html*

This software enables people to transform individual positions entered interactively or a collection of positions entered as a formatted file. Also, if people expect to transform only a few positions, then they may run HTDP interactively from this web page.

While Helmert transformations, as encoded into HTDP, are appropriate for transforming positions between any two ITRS realizations or between any ITRS realization and NAD 83 (CORS96), more complicated transformations are required

for conversions that involve NAD 27, NAD 83 (1986), or NAD 83 (HARN). These complications arise because these frames contain large local and regional distortions that can not be quantified by a simple Helmert transformation. For instance, NAD 27 contains distortions at the 10 m level. That is, if one applied the best possible Helmert transformation from NAD 27 to NAD 83 (CORS96), then the converted NAD 27 positions may still be in error by as much as 10 m. In a similar manner, NAD 83 (1986) contains distortions at the 1 m level, and NAD 83 (HARN) contains distortions at the 0.1 m level.

NGS has developed a software package, called NADCON (), that embodies rather intricate transformations to convert positional coordinates between any pair of the following reference frames: NAD 27, NAD 83 (1986), and NAD 83 (HARN). Referring to a pair of 2D grids that span the United States, NADCON contains appropriate values for each grid node to transform its positional coordinates from one reference frame to another. Furthermore, NADCON interpolates these gridded values to transform points located within the grid's span. It should be noted that NADCON may be used only to transform horizontal coordinates (latitude and longitude), because ellipsoidal heights—relative to NAD 27 or NAD 83 (1986)—have never been adopted for most control points.

While HTDP may be used with pairs of certain reference frames (NAD 83 (CORS96), ITRF88, ITRF89,. . . , and ITRF97) and NADCON with pairs of other reference frames (NAD 27, NAD 83 (1986), and NAD 83 (HARN)), no NGS-sanctioned software exists for transforming coordinates from any member of one set to any member of the other. Also, no NGS-sanctioned software exists for transforming NAD 83 (CORS93) and/or NAD 83 (CORS94) positions to other reference frames. Regarding the WGS 84 reference system, it is generally assumed that WGS 84 (original) is identical to NAD 83 (1986), that WGS 84 (G730) is identical to ITRF92, and that WGS 84 (G873) is identical to ITRF96. Other transformations between pairs of the WGS 84 realizations, however, have also appeared in the literature. ⬇

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