Modern Terrestrial Reference Systems
PART 2: The Evolution of NAD 83

Dr. Richard A. Snay and Dr. Tomás Soler

The first realization of NAD 83 was introduced in 1986 by a group of institutions representing the various North American countries to upgrade the previous reference system; that is, the North American Datum of 1927 or NAD 27. In particular, the National Geodetic Survey (NGS) represented the United States, and this federal institution officially refers to the first NAD 83 realization as NAD 83 (1986). For this realization, the group of institutions relied heavily on Doppler satellite observations collected at a few hundred sites to estimate the location of the Earth's center of mass and the orientation of the 3D cartesian axes. They also relied on these same Doppler observations to provide scale for NAD 83 (1986). More precisely, the group of institutions relied on 3D Doppler-derived positions that had been transformed by:

- a translation of 4.5 m along the z-axis
- a clockwise rotation of 0.814 arc seconds about the z-axis
- a scale change of -0.6 ppm

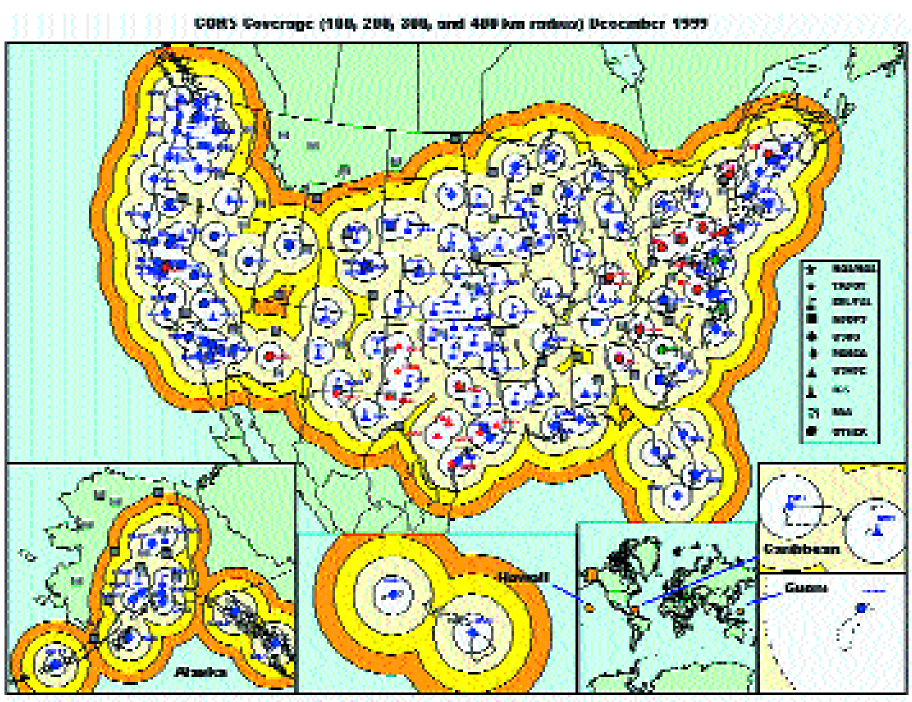
The Doppler-derived positions were so transformed to make them more consistent with the very long baseline interferometry (VLBI), satellite laser ranging (SLR), and terrestrial azimuth measurements that were available in the early 1980s. While NAD 83 (1986) is 3D in scope, NGS adopted only horizontal coordinates (latitude and longitude) for over 99% of the approximately 250,000 U.S. control points that were involved in defining this reference frame. Unfortunately, this first realization of NAD 83 occurred a few years before GPS technology made the vertical dimension economically accessible.

GPS Changed Everything

Around the same time that NGS adopted NAD 83 (1986), the agency had begun using GPS technology, instead of triangulation and/or trilateration, for horizontal positioning. The fact that GPS technology also provided accurate ellipsoidal heights was somewhat overlooked in the 1980s because surveyors, hydrologists, and other users of vertical positions required orthometric heights relative to mean sea level, as obtained with tide gauges and spirit leveling, and not geometric heights relative to an abstract mathematical surface (the ellipsoid), as obtained with GPS. The attitude towards using GPS to measure heights gradually evolved, however, as NGS and other institutions developed improved geoidal models for determining the spatial separation between mean sea level and the ellipsoid. These improvements enabled people to convert ellipsoidal heights into orthometric heights with greater and greater accuracy. Moreover, practitioners can measure heights much more economically with GPS than with spirit leveling.

As GPS matured, so did other space-age geodetic technologies; in particular, SLR and VLBI. Within a few years after 1986, both GPS and SLR measurements had allowed geodesists to locate Earth's center of mass with a precision of a few centimeters. In doing so, these technologies revealed that the center of mass that was adopted for NAD 83 (1986) is displaced by about 2 m from the true geocenter. Similarly, GPS, SLR, and VLBI revealed that the orientation of the NAD 83 (1986) cartesian axes is misaligned by over 0.03 arc seconds relative to their true orientation, and that the NAD 83 (1986) scale differs by about 0.0871 ppm from the true definition of a meter. These discrepancies caused significant concern as the use of highly accurate GPS measurements proliferated. In particular, starting with Tennessee in 1989, each state–in collaboration with NGS and various other institutions–used GPS technology to establish regional reference frames that were to be consistent with NAD 83. The corresponding networks of GPS control points were originally called High Precision Geodetic Networks (HPGN). Currently, they are referred to as High Accuracy Reference Networks (HARN). This latter name reflects the fact that relative accuracies among HARN control points are better than 1 ppm, whereas relative accuracies among pre-existing control points were nominally only 10 ppm.

For defining these regional reference frames, NGS retained the location of the geocenter and the orientation of the 3D cartesian axes which had been derived in 1986 from the transformed Doppler observations. This agency, however, opted to introduce a new scale that would be consistent with the scale of the then cur-



rent ITRS realization which is known as the International Terrestrial Reference Frame of 1989 (ITRF89). As we shall discuss later, the ITRF89 scale was based on a combination of GPS, SLR, VLBI, and lunar-laser-ranging (LLR) measurements. The resulting scale change, equal to -0.0871 ppm, altered existing NAD 83 latitudes and longitudes insignificantly, but it systematically decreased all ellipsoidal heights by about 0.6 m (= 0.0871•10-6 • R where R is the radius of the Earth). Nevertheless, this change to a more accurate scale facilitated the migration toward using GPS technology for deriving accurate heights. Let us call this second realization NAD 83 (HPGN) or NAD 83 (HARN); but keep in mind that this second realization is actually a collection of regional realizations that were formulated over a period of several years (1989-1997) with each new regional realization being "adjusted" to fit with those that preceded it.

Third Realization of NAD 83 Incorporated CORS

In late 1994, NGS introduced a third realization of NAD 83 when the agency organized a network of continuously operating reference stations (CORS). Each CORS includes a GPS receiver whose data NGS collects, processes, and disseminates for public use. Surveyors and other professionals can apply CORS data to position points at which other GPS data have been collected with accuracies that approach a few centimeters, both horizontally and vertically. The CORS system started with about a dozen sites in December 1994, and it has grown at a rate of about three sites per month. Figure 2 depicts the recent status of the National CORS network. Positional coordinates of the early CORS sites were first computed in the ITRS realization known as ITRF93. Equivalent NAD 83 coordinates were then computed by applying a Helmert transformation; that is, a transformation of the form

$$xNAD83 = Tx + (1+s) \cdot xITRF + Rz \cdot yITRF - Ry \cdot zITRF \quad (1a)$$

$$yNAD83 = Ty - Rz \cdot xITRF + (1+s) \cdot yITRF + Rx \cdot zITRF \quad (1b)$$

$$zNAD83 = Tz + Ry \cdot xITRF - Rx \cdot yITRF + (1+s) \cdot zITRF \quad (1c)$$

where Tx, Ty, and Tz represent three translation along the x-axis, y-axis, and z-axis, respectively, which will bring the origin of the two frames into coincidence. Rx, Ry, and Rz represent three rotations about the x-axis, y-axis, and z-axis, respectively, which, in combination, will bring the three axes of one frame into parallel alignment with their corresponding axes in the other frame. Finally, s represents the difference in scale between the two frames. The values of Tx, Ty, Tz, Rx, Ry, and Rz had been estimated so that the ITRF93 positional coordinates of nine VLBI sites in the United States would transform as best as possible (in a least squares sense) to their adopted NAD 83 (HARN) positional coordinates. The scale difference, s, was set to equal zero. These VLBI sites were used because they had highly accurate positions (cm-level) in both ITRF93 and NAD 83 (HARN). Let us use the label NAD 83 (CORS93) to identify the reference frame obtained by applying this transformation to convert CORS positions from ITFR93 to NAD 83.

In the spring of 1996, NGS computed positional coordinates for all the then existing CORS in yet another ITRS realization, known as ITRF94. Similarly, the agency developed a Helmert transformation from ITRF94 to NAD 83 using eight of the same VLBI sites (a VLBI site in California was not used here because of crustal motion concerns). Again, the scale difference was set to equal zero. NGS applied this new transformation to convert ITRF94 coordinates for the CORS sites to a fourth NAD 83 realization which we call NAD 83 (CORS94).

Most recently in the fall of 1998, NGS computed positional coordinates for all the then existing CORS in the ITRS realization known as ITRF96. This time, however, NGS collaborated with representatives from Canada's Geodetic Survey Division to derive a Helmert transformation based on eight VLBI sites in the United States and four VLBI sites in Canada. Again, a scale difference equal to zero was enforced. Other adopted parameters for this transformation are presented in the sidebar box. NGS applied the resulting transformation to convert ITRF96 positional coordinates for the CORS sites to a fifth NAD 83 realization which we call NAD 83 (CORS96). NGS, however, continues to use NAD 83 (CORS94) positions for all CORS sites, except those that have come online since the fall of 1998 and those whose NAD 83 (CORS96) position differs from their corresponding NAD 83 (CORS94) position by more than 2 cm horizontally or 4 cm vertically.

In summary, surveyors and others have witnessed five realizations of NAD 83 in the United States. A similar evolution occurred in Canada, but the two countries at least agree on their first and last realizations. The five U.S. realizations are consistent in their choice of origin and orientation; they differ, however, in their choice of scale. While the scale difference between NAD 83 (1986) and NAD 83 (HARN) equals -0.0871 ppm, the scale difference between NAD 83 (HARN) and any NAD 83 (CORSxx) is smaller than 0.005 ppm in magnitude. It should be noted that the NAD 83 (HARN) latitude and/or longitude of a given control point may differ by up to a meter from its corresponding NAD 83 (1986) coordinate. Fortunately, the horizontal discrepancy between the NAD 83 (CORS93) and NAD 83 (HARN) positions for a control point is almost always less than 10 cm, and the horizontal discrepancy between any two NAD 83 (CORSxx) positions for a control point is almost always less than 2 cm. In addition, as NAD 83 has evolved from mostly a horizontal reference system to a full 3D reference system, the number of control points with measured ellipsoidal heights has grown dramatically.

Finally, for the present discussion, we intentionally omitted the role of crustal motion on the evolution of NAD 83. We will address this topic in some detail, however, after discussing the evolution of ITRS, as this international reference system provides the global perspective that will help us understand certain concepts associated with crustal motion.

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

DR. TOMÁS SOLER *is Chief, Global Positioning System Branch, Spatial Reference Systems Division, National Geodetic Survey.*

