# THE EVOLUTION OF NAD83 IN CANADA

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*The North American Datum of 1983 (NAD83) is the national spatial reference system used for georeferencing by most federal and provincial agencies in Canada. The physical realization of this system has undergone several updates since it was first introduced in 1986. It has evolved from a traditional, ground-based horizontal control network to a space-based 3D realization fully supporting more modern positioning techniques and the integration of both horizontal and vertical reference systems. After a brief review of previous reference systems used in Canada, the original definition of NAD83 and its subsequent updates are described, focusing on the definition of the current implementation NAD83(CSRS) and its relationship with other reference systems. Official transformation parameters between NAD83(CSRS) and ITRF (including WGS84) are provided for use throughout Canada. Possible future reference systems for Canada and North America are also examined.*

*Le Système de référence nord-américain de 1983 (NAD83) est le système de référence spatiale national utilisé pour la géoréférence par la plupart des agences fédérales et provinciales au Canada. La réalisation physique de ce système a nécessité plusieurs mises à jour depuis son entrée en vigueur en 1986. Le système a évolué d'un réseau de contrôle horizontal terrestre à une réalisation spatiale tridimensionnelle comprenant des techniques de positionnement plus modernes et intégrant les systèmes de référence horizontale et verticale. Après une brève revue des systèmes de référence utilisés au Canada, la définition originale du NAD83 et ses mises à jour subséquentes sont décrites, en se concentrant sur la définition de la mise en oeuvre actuelle du NAD83 (SCRS) et sa relation avec d'autres systèmes de référence. Les paramètres officiels de transformation entre le NAD83 (SCRS) et l'ITRF (incluant le WGS84) sont accessibles aux usagers pour tout le Canada. On examine aussi d'autres systèmes de référence possibles pour le Canada et l'Amérique du Nord à l'avenir.*

## *Introduction*

The Geodetic Survey Division (GSD) of Natural Resources Canada has a mandate to establish and maintain a geodetic reference system as a national standard for spatial positioning throughout Canada. In general terms, a reference system is an abstract collection of principles, fundamental parameters, and specifications for quantitatively describing the positions of points in space. A reference frame is the physical manifestation or realization of such a prescription. Traditionally, a reference frame consists of a network of geodetic control points on the ground with adopted coordinates that other surveys can be tied and referenced to. Since the introduction of the Global Positioning System, this paradigm has been changing.

Mapping, GIS, scientific and other organizations make large investments in georeferenced data and demand that the integrity of the reference system be maintained and enhanced to keep pace with the way they obtain their positioning data. Consequently, GSD is constantly improving the reference system and periodically publishes new coordinates effectively representing updated realizations of the reference system. Such updates usually result from densification of the network of control points, elimination of blunders and distortions, improvements in accuracies, and the introduction of new positioning methodologies like GPS. At the same time, continuity must be maintained to ensure legacy data, based on previous reference systems and realizations, can be incorporated into the current reference frame.

The current reference system adopted as a national georeferencing standard by most federal and provincial agencies in Canada and endorsed by the Canadian Council on Geomatics [*CCOG* 2006] is the North American Datum of 1983 (NAD83). NAD83 has undergone several updates since its first realization in 1986. This paper describes these changes, focusing on the current implementation and its relationship with other reference systems. It also briefly examines possible future reference systems for Canada and North America.

## *Original Realization of NAD83 – NAD83(Original)*

The first continental reference system for North America was the North American Datum of 1927 (NAD27). It was defined as a reference ellipsoid that was positioned and oriented using classical astronomical observations to best fit North America. The realization of this reference system consisted of a network of thousands of geodetic control monuments (physical makers in the ground) spaced about 20 to 100 km apart at locations chosen for intervisibility but which were usually inconvenient to access. This was only a horizontal network originally built up primarily from triangulation surveys in which systematic errors accumulated resulting in widespread distortions throughout the network. Because of the limited computational resources at the time, densification of the reference frame was performed in a piece-wise fashion by holding existing control points fixed to their published values. This further propagated the accumulation of errors by distorting newer, often more accurate data. For more information about NAD27, see *Junkins and Garrard* [1998].

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In a cooperative effort to reduce the distortions in the reference frame and to obtain a system more compatible with new space-based positioning technologies, Canada, the US, Mexico, and Denmark (Greenland) began a readjustment of the entire continental network using a new reference system called the North American Datum of 1983 (NAD83). The NAD83 system was based on a global reference system known as the BIH Terrestrial System 1984 (BTS84) together with the reference ellipsoid of the Geodetic Reference System 1980 (GRS80). BTS84 was an earth-centred (geocentric) reference frame produced by the Bureau International de l'Heure (BIH) using spaced-based data from lunar laser ranging (LLR), satellite laser ranging (SLR), very long baseline interferometry (VLBI) and the satellite Doppler system. It was the most accurate reference frame available at the time.

Using a relatively dense framework of new Doppler stations across the continent, the NAD83 reference frame was brought into alignment with BTS84 using an internationally adopted transformation between BTS84 and the Doppler reference frame NWL 9D [*Boal and Henderson* 1988]. About a dozen VLBI stations in Canada and the US were also included to provide a connection to the celestial reference frame. As we shall see below, these VLBI sites provide the only link between NAD83 and more modern, stable reference frames. The continental network was then readjusted in 1986 using a stepwise methodology known as Helmert blocking. This initial realization is denoted here as NAD83(1986).

### *Densification*

Although the US included their entire hierarchy of networks in the NAD83(1986) adjustment, from highest accuracy geodetic to the lowest-order municipal networks, Canada included only its primary control network of about 8000 stations. This framework was then densified through subsequent so-called secondary integration adjustments in cooperation with the provincial geodetic agencies [*Parent* 1988]. The first of these was the 1989 Eastern Secondary Integration Helmert Block Adjustment (ESHIBA, now referred to as just SHIBA), that included provincial networks from Ontario eastward. Only a 374-station primary network was included in the Maritimes which had adopted their own new reference system (see below). Shortly after, the Western Secondary Integration Helmert Block Adjustment (WSHIBA) was completed in 1990 with the western provinces. The same year, NAD83 was proclaimed the official geodetic reference frame for federal government operations [*EMR* 1990]. To assist incorporating legacy NAD27 data into NAD83, an official transformation and distortion model called the National Transformation (NT) was developed [*Junkins* 1988].

Immediately after the completion of WSHIBA, some western provinces began major GPS surveying campaigns to densify and improve their networks. There were also many new federal networks in the northern territories. Rather than create confusion by adopting WSHIBA results and subsequently updating them shortly after, it was decided to redo the western adjustment with the new data. This new adjustment, completed and made public in 1993, was called the Network Maintenance Integration Project of 1993 (NMIP93).

The ESHIBA and NMIP93 realizations of NAD83 were the last of the major federal-provincial cooperative adjustment projects and are collectively referred to as NAD83(Original). This network is shown in Figure 1. Based on the ESHIBA and NMIP93 realizations of NAD83, an improved transformation from NAD27 was developed. Known as the National Transformation Version 2 (NTv2) [*Junkins* 1990], this new transformation provided much improved distortion modelling that adapted to the variations in the spatial density of network points.

## Limitations

At about the same time as these traditional adjustment projects, a major advancement was taking place in GPS technology and in the realization of global reference frames. It was at this time that the International GPS Service (IGS), through the cooperative efforts of GSD and several other geodetic agencies around the world, began producing precise GPS satellite orbits that enabled centimetre-level positioning accuracies in 3D [*Beutler et al*. 1999]. These orbits were computed using a collection of permanent GPS tracking stations on the ground, including several in Canada that became the Canadian Active Control System (CACS) [*Duval et al*. 1997]. The number of federal tracking stations has since increased to nearly 50, resulting in even greater improvements in the accuracy of the GPS orbits and positioning results based on them. In essence, the geodetic control network was shifting to the GPS satellites in space (see *Héroux et al*. [this issue]).

At the time of its initial realization, NAD83 (and BTS84) was intended to be a geocentric system and was compatible with the other geocentric systems of the time, including the original realization of WGS84. However, due to the use of more accurate techniques, it is now known that NAD83 is offset by about 2 m from the true geocentre.

Another limitation of the original realizations of NAD83 was that access to it was provided mainly through a horizontal control network. Today, many applications of GPS require a 3D reference frame. Yet another problem revealed by GPS was the limited accuracy of conventional horizontal control networks. The significant accumulation of errors in both the observations and methods of network integration were being revealed by the use of new GPS survey techniques. Figure 2 illustrates these errors at points across Canada by comparing NAD83(Original) coordinates to those based on high accuracy GPS surveys tied almost directly to the fundamental reference frame of NAD83. Errors in the horizontal network are about 0.3 m on average but can exceed 1 m in the northern parts of many provinces.

**Figure 1: Traditional horizontal control network comprising the original realization of NAD83.**

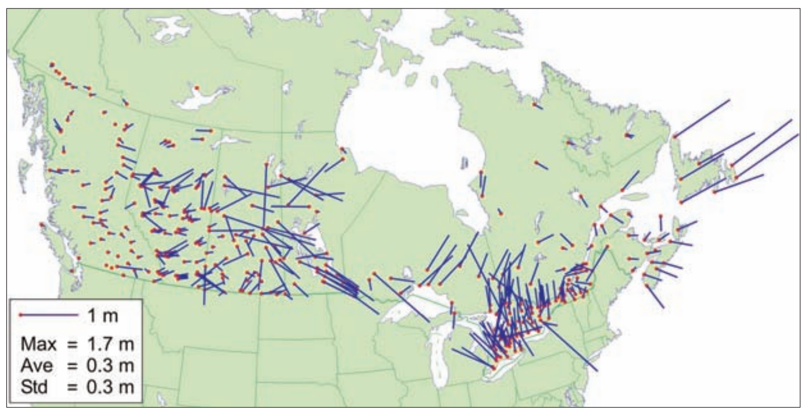


**Figure 2: Errors in NAD83(Original) as revealed by high accuracy GPS observations in NAD83(CSRS).**

## 3D Realization of NAD83 – NAD83(CSRS)

In light of the above limitations of NAD83(Original), a more accurate, true 3D realization of the NAD83 reference frame was clearly needed which enabled users to relate their positions more directly to the fundamental definition of the NAD83 reference frame. Together with a high accuracy geoid (see *Veronneau et al*. [this issue]), a complete 3D reference frame would also enable the convergence of traditional horizontal and vertical reference systems into a single unified system able to support all aspects of spatial positioning (see *Héroux et al*. [this issue] and *Veronneau et al*. [this issue]).

Since 1990 the most accurate and stable reference frames available are the successive versions of the International Terrestrial Reference Frame (ITRF) produced by the International Earth Rotation and Reference Systems Service (IERS). Individual realizations are denoted by ITRFxx, where xx represents the last year for which data was included in a particular solution. These reference frames are based primarily on SLR, VLBI, GPS and a system called DORIS (Détermination d'Orbite et Radiopositionement Intégré par

Satellite) [*Boucher and Altamimi* 1996]. A key difference with previous reference systems is the dynamic nature of the reference frame. Coordinates for stations are valid for a specific date (epoch) and are accompanied by velocity estimates for propagating coordinates to other epochs.

During the first several years, new realizations of ITRF were introduced on a nearly annual interval as significant amounts of new data were added. Now that well over 15 years of data are available, the realizations of ITRF have stabilized to about a centimetre. Consequently, new versions are released less frequently. Presently, the last two releases were ITRF97 and ITRF2000 [*Altamimi et al*. 2002]. A new ITRF2005 is due sometime this year and is likely to be the last official public version for several years. Scientific updates are expected to be released more frequently to densify the reference frame and improve velocity estimation for new stations.

Realizing the benefits of using such a highly stable global reference frame, at the 20th General Assembly of the International Union of Geodesy and Geophysics in 1991, the International Association of Geodesy (IAG) adopted Resolution No. 1 which, among other things, made the following two recommendations [*IAG* 1992]:

> "1) that groups making highly accurate geodetic, geodynamic or oceanographic analysis should either use the ITRF directly or carefully tie their own systems to it"

> "4) that for high accuracy in continental areas, a system moving with a rigid [tectonic] plate may be used to eliminate unnecessary velocities provided it coincides exactly with the ITRS at a specific epoch"

*Unfortunately …Canada and the US chose different methods of updating the transformation to new ITRF realizations.*

Considering recommendation (4), it was assumed that recommendation (1) also allowed for the use of other systems such as NAD83 providing they are carefully tied to the ITRS. Note that the ITRF coordinates of points are constantly changing due to the motions of the individual tectonic plates. It is therefore necessary to specify which epoch ITRF coordinates refer to and to account for tectonic motion when propagating coordinates to other epochs.

Rather than abandon NAD83 altogether in favour of ITRF (as some countries have done), it was decided to define NAD83 by its precise relationship with ITRF which would comply with the IAG resolution. A precise connection between ITRF and NAD83 was made possible by the common VLBI stations in both systems. This allowed for the determination of a conformal 3D seven-parameter similarity (Helmert) transformation between the two reference frames. The transformation effectively provides a more accurate realization of the fundamental NAD83 3D reference frame in terms of the ITRF. It also provides any user with convenient and nearly direct access to the highest levels of the NAD83 reference frame. This enables users to determine accurate positions that are highly consistent across the entire continent. Moreover, GPS orbits can be transformed to NAD83 allowing users to position themselves directly in NAD83 through applications such as Precise Point Positioning (PPP) [*Héroux et al*. this issue].

## *1996 Realization – NAD83(CSRS96)*

The first ITRF-NAD83 transformation adopted by both Canada and the US was determined with respect to ITRF89 in the early 1990s [*Soler et al*. 1992]. The scale of ITRF, derived in part from VLBI stations in Canada and the US, was adopted for compatibility with more recent versions of WGS84 by setting the estimated scale parameter to zero. This realization of the NAD83 reference frame was denoted as NAD83(CSRS96), where "96" indicates the year the transformation was introduced (not any particular coordinate epoch). The transformation was used to produce NAD83 coordinates for CACS stations and allowed for GPS orbits to be generated in NAD83.

Unfortunately, following the adoption of this first ITRF-NAD83 transformation, Canada and the US chose different methods of updating the transformation to new ITRF realizations. Canada used the official incremental transformations between different versions of ITRF as published by the IERS. The US, on the other hand, recomputed the transformation for each new ITRF, adopting the slightly different scale of each ITRF. Consequently, the updated transformations differed slightly, mainly in scale. This resulted in ellipsoidal height discrepancies of about 5 cm along the common borders by the time ITRF96 was introduced in 1998.

## *1998 Realization – NAD83(CSRS)*

In order to reconcile the slightly different realizations of NAD83 in Canada and the US arising from these different ITRF-NAD83 transformations, a new common NAD83 transformation was derived with respect to ITRF96, the most recent at the time. The data used in determining the transformation were the NAD83(Original) and ITRF96 coordinates at 12 VLBI stations in Canada and the US (see Figure 3). These are the only fundamental points in the original definition of NAD83 with 3D coordinates in both NAD83 and ITRF96.

Using the ITRF96 coordinates at epoch 1997.0, a new seven-parameter similarity (Helmert) transformation was determined [*Craymer et al*. 2000]. The scale of ITRF96 was adopted for this realization of NAD83 by setting the scale parameter to zero after estimation. This ensures the scale of NAD83 will be compatible with the more accurate scale defined by ITRF96 and used by other systems such as WGS84. The estimated parameters are given in Table 1.

In order to correctly account for the tectonic motion of the North American tectonic plate when transforming from/to ITRF96 positions at any arbitrary epoch, the NNR-NUVEL-1A plate motion model was adopted [*DeMets et al*. 1994] as recommended by the IERS [*McCarthy* 1996]. *Larson et al*. [1997] had shown NNR-NUVEL-1A to be in relatively good agreement with velocities estimated from GPS in North America at that time (based on more data it is now known to be slightly biased). The effect of this motion can be treated as additional rotations of the reference frame defined by

$$\begin{bmatrix} R_X \\ R_Y \\ R_Z \end{bmatrix} = \begin{bmatrix} 0.0532 \\ -0.7423 \\ -0.0316 \end{bmatrix} \text{mas/y} \tag{1}$$

where $R_X$,$R_Y$,$R_Z$ are rotations about the geocentric Cartesian coordinate axes in units of milliarcseconds per year (mas/y).

To ensure a consistent application of the transformation to other ITRF realizations, both Canada and the US also agreed to adopt the most current IERS values for transforming between ITRF96 and other ITRF reference frames. The only exception was the incremental transformation between ITRF96 and ITRF97 where the GPS-based IGS transformation was used to account for a systematic bias in the GPS networks used in ITRF97.

This new realization of NAD83 was originally denoted as NAD83(CSRS98) to distinguish it from the 1996 realization. Like the 1996 realization, "98" refers to the year it was adopted and not to any coordinate epoch. However, because the NAD83(CSRS96) realization saw very limited use, the name of the new realization has since been shorted to just NAD83(CSRS).

The main advantage of this improved NAD83(CSRS) realization is that it provides almost direct access to the highest level of the NAD83 reference frame through ties to the CACS and collocated VLBI stations that form part of the ITRF network. These stations effectively act as both ITRF and NAD83 datum points for geospatial positioning, thereby enabling more accurate, convenient, and direct integration of user data with practically no accumulation of error typically found in classical horizontal control networks.

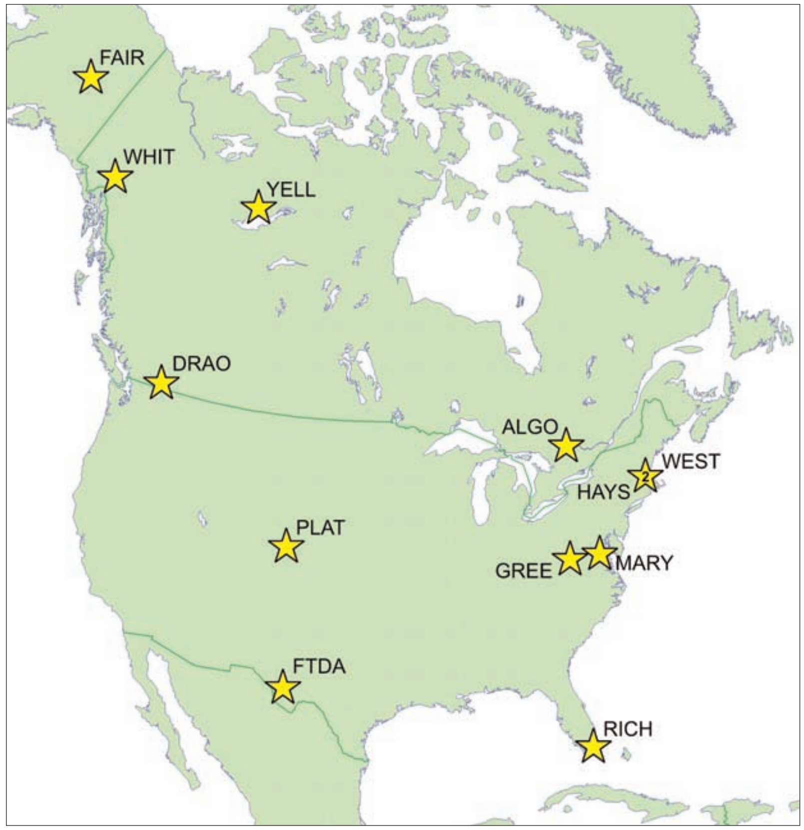


**Figure 3: VLBI stations included in NAD83(Original) and used in the ITRF96 transformation.**

It is important to bear in mind that the NAD83 reference system itself has not changed. It is only the method of physically defining or realizing it that has been updated to make NAD83 more accurate and stable, and more easily accessible to more users. Any differences between NAD83(Original) and NAD83(CSRS) reflect primarily the much larger errors in the original. Each successive update is generally more accurate than, but fully consistent with, previous realizations.

## *Hierarchy of NAD83(CSRS) Networks*

The new NAD83(CSRS) realization was accompanied by a transition to a new reference frame structure for Canada (see Figure 4). The traditional horizontal network hierarchy that constituted the original realization of NAD83 was replaced with a more modern framework that takes advantage of advanced GPS methods and enables more

**Table 1: ITRF to NAD83 transformation parameters at an epoch of 1997.0 and their rates of change (mas = milliarcsec, ppb = parts per billion).**

| | $T_X$ m<br>$dT_X$ m/y | $T_Y$ m<br>$dT_Y$ m/y | $T_Z$ m<br>$dT_Z$ m/y | $R_X$ mas<br>$dR_X$ mas/y | $R_Y$ mas<br>$dR_Y$ mas/y | $R_Z$ mas<br>$dR_Z$ mas/y | $DS$ ppb<br>$dDS$ ppb/y |
|---|---|---|---|---|---|---|---|
| ITRF88 | 0.9730 | -1.9072 | -0.4209 | -25.890 | -9.650 | -11.660 | -7.400 |
| | 0.0000 | 0.0000 | 0.0000 | -0.053 | 0.742 | 0.032 | 0.000 |
| ITRF89 | 0.9680 | -1.9432 | -0.4449 | -25.790 | -9.650 | -11.660 | -4.300 |
| | 0.0000 | 0.0000 | 0.0000 | -0.053 | 0.742 | 0.032 | 0.000 |
| ITRF90 | 0.9730 | -1.9192 | -0.4829 | -25.790 | -9.650 | -11.660 | -0.900 |
| | 0.0000 | 0.0000 | 0.0000 | -0.053 | 0.742 | 0.032 | 0.000 |
| ITRF91 | 0.9710 | -1.9232 | -0.4989 | -25.790 | -9.650 | -11.660 | -0.600 |
| WGS84(G730) | 0.0000 | 0.0000 | 0.0000 | -0.053 | 0.742 | 0.032 | 0.000 |
| ITRF92 | 0.9830 | -1.9092 | -0.5049 | -25.790 | -9.650 | -11.660 | 0.800 |
| | 0.0000 | 0.0000 | 0.0000 | -0.053 | 0.742 | 0.032 | 0.000 |
| ITRF93 | 1.0111 | -1.9058 | -0.5051 | -24.410 | -8.740 | -11.150 | -0.400 |
| | 0.0029 | -0.0004 | -0.0008 | 0.057 | 0.932 | -0.018 | 0.000 |
| ITRF94 | 0.9910 | -1.9072 | -0.5129 | -25.790 | -9.650 | -11.660 | 0.000 |
| WGS84(G873) | 0.0000 | 0.0000 | 0.0000 | -0.053 | 0.742 | 0.032 | 0.000 |
| ITRF96 | 0.9910 | -1.9072 | -0.5129 | -25.790 | -9.650 | -11.660 | 0.000 |
| | 0.0000 | 0.0000 | 0.0000 | -0.0532 | 0.7423 | 0.0316 | 0.000 |
| ITRF97 | 0.9889 | -1.9074 | -0.5030 | -25.915 | -9.426 | -11.599 | -0.935 |
| | 0.0007 | -0.0001 | 0.0019 | -0.067 | 0.757 | 0.031 | -0.192 |
| ITRF2000 | 0.9956 | -1.9013 | -0.5214 | -25.915 | -9.426 | -11.599 | 0.615 |
| WGS84(G1150) | 0.0007 | -0.0007 | 0.0005 | -0.067 | 0.757 | 0.051 | -0.182 |

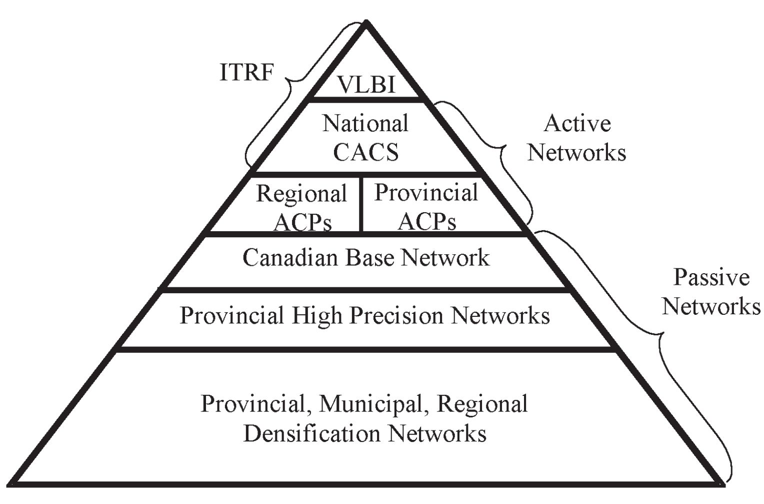


**Figure 4: Hierarchy of NAD83(CSRS) reference frame.**

accurate and more convenient access to the NAD83(CSRS) reference frame.

This new reference frame hierarchy is divided into active and passive components as illustrated in Figure 4. The active component consists of networks of continuously operating GPS receivers and products derived from them, such as precise orbits and broadcast corrections. The passive component is comprised of more traditional monumented control points that users can occupy with their own equipment.

## *Active Component*

At the top of the "active" reference frame hierarchy are the VLBI and CACS stations that are part of the global ITRF reference frame. Using the adopted transformation, the ITRF coordinates for these stations can be converted to NAD83 without any loss of accuracy or continuity with previous ITRF or NAD83(CSRS) realizations. Moreover, the data for these GPS stations are available to the general public thereby enabling users for the first time to tie directly to the highest level of NAD83 reference frame. In the old hierarchal network structure, users were generally only able to connect to control points in the lower levels of the network hierarchy with their attendant lower accuracies.

At the level below the CACS sites are additional continuously operating GPS receivers, collectively referred to as regional ACPs. These regional ACP networks were installed in support of specific local and regional projects to determine crustal motions and monitor sea level rise. They can be considered a densification of the ITRF and IGS global networks. Some examples of these regional networks are the Western Arctic Deformation Network (WARDEN) and the Western Canada Deformation Array (WCDA) (some of these regional ACPs have recently been incorporated into the ITRF global network) See *Henton et al.* [this issue] for more discussion of these networks.

In addition to the federally operated CACS stations, some provinces have implemented their own network of active GPS stations that provide data and DGPS corrections to the general public. Some examples of such systems can be found in British Columbia, Quebec, and soon New Brunswick. A few private companies have also installed DGPS system in various regions. Most of these services charge a fee for access to the DGPS corrections. Although the provincial systems generally tie their DGPS stations to NAD83(CSRS), not all private systems do. Some systems have only been tied to the original realization of NAD83 and thus their accuracies will be degraded by any local distortions. In some areas the distortions are fairly coherent enabling accurate relative positioning (cf. Figure 2). However, problems might arise if using such services across areas where the distortions are quite different.

Note that a Canada-wide DGPS Service (CDGPS) has also been created through collaboration between all the provincial and federal geodetic agencies based on NRCan's wide-area GPS Corrections (GPS•C). Broadcast nationwide via Canada's own MSAT communication satellite, this service provides sub-metre positions directly in NAD83(CSRS) nearly everywhere in Canada. For more information about CDGPS and GPS•C see *Héroux et al*. [this issue] and the CDGPS web site at *www.cdgps.com*.

In addition to providing the link to the global reference frame, the CACS stations and some regional ACPs contribute to the International GNSS Service (IGS) efforts to produce, among other products, the most accurate GPS orbits available. Although computed in the ITRF reference frame of date, these orbits are easily transformed to NAD83(CSRS) like any other coordinates using the adopted ITRF-NAD83(CSRS) transformation. By using such precise IGS orbits, users can determine point positions directly in NAD83(CSRS). For more information about these products see *Héroux et al*. [this issue]. In essence, the satellites themselves have effectively become an extension of the NAD83(CSRS) reference frame available to users.

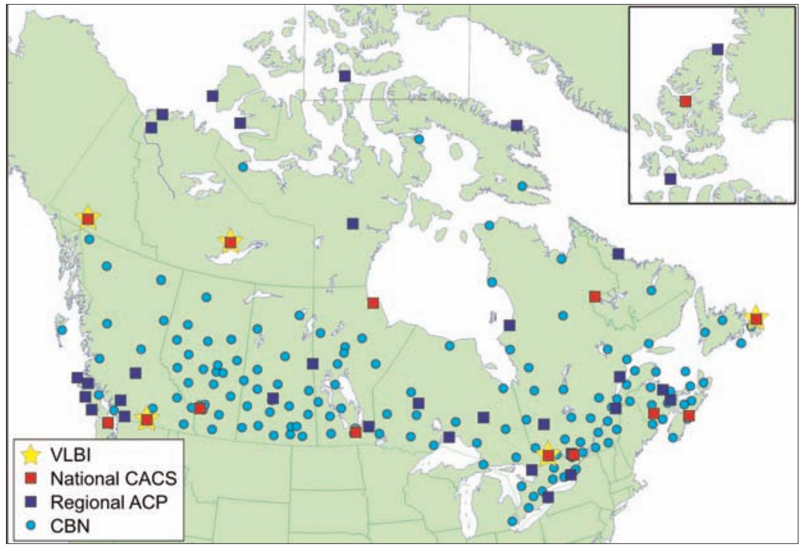


**Figure 5: Federal component of the NAD83(CSRS) reference frame.**

## *Passive Component*

In order to assist with the integration of the older horizontal control networks into NAD83(CSRS) a new, much sparser but more stable network of "passive" control points was established and tied directly to the CACS stations (see Figure 5). Called the Canadian Base Network (CBN), this network forms the next level of the reference frame hierarchy below the CACS. It is the highest level of the passive component of the CSRS reference frame.

The CBN consists of approximately 160 highly stable, forced-centering pillars. This network was originally conceived as an interim measure or transition during the move to a CACS-only reference frame. However, the CBN has proven to be invaluable for monitoring the on-going deformation of the Canadian landmass for scientific studies and the long-term maintenance of the reference frame. To date, there have been three complete measurements of the CBN. The quality of these surveys has been held in high regard by many scientists because of the unprecedented spatial detail the results have revealed about the motions of the Earth's crust (see *Henton et al*. [this issue]). Public interest has also been very high as indicated by much media interest [*AP* 2004; *CanWest* 2004; *The Globe and Mail* 2004; *The Guardian* 2004; *The Independent* 2004; *The New Scientist* 2004; *UPI* 2004; *The Washington Post* 2004].

During the establishment of the CBN, the provincial agencies began densifying the network for their own requirements. These densifications are often referred to as a provincial high precision networks (HPNs). High accuracy ties between the CBN and various HPNs were made during the first measurement campaign of the CBN enabling the provinces to integrate their traditional networks into NAD83(CSRS).

The 8000 stations of the primary horizontal control network were not entirely abandoned by this new reference frame structure. Rather the provinces assumed the responsibility for their maintenance and integration into NAD83(CSRS). Most provinces have readjusted this data together with their own (secondary) horizontal control networks. These networks provided the main source of information for the development of NTv2 distortion models for converting large holdings of georeferenced data from NAD83(Original) to NAD83(CSRS).

## Relationship to Other Reference Frames

### ITRF

The transformation between NAD83(CSRS) and any realization of ITRF at any arbitrary epoch ($t$) can be obtained by combining the definitive ITRF96-NAD83 transformation previously described together with the incremental between-ITRF transformations and the NNR-NUVEL-1A rotations defining the motion of the North American tectonic plate. The resulting Helmert transformation can be written as [*Craymer et al*. 2000]

$$\begin{bmatrix} X_N \\ Y_N \\ Z_N \end{bmatrix} = \begin{bmatrix} T_X(t) \\ T_Y(t) \\ T_Z(t) \end{bmatrix} + \begin{bmatrix} 1+DS(t) & -R_Z(t) & R_Y(t) \\ R_Z(t) & 1+DS(t) & -R_X(t) \\ -R_Y(t) & R_X(t) & 1+DS(t) \end{bmatrix} \begin{bmatrix} X_I(t) \\ Y_I(t) \\ Z_I(t) \end{bmatrix} \quad (2)$$

where

$X_N, Y_N, Z_N$ are the geocentric Cartesian coordinates in NAD83(CSRS)

$X_I(t), Y_I(t), Z_I(t)$ are the geocentric Cartesian coordinates in ITRF at epoch $t$

$T_X(t) = T_X + dT_X \cdot (t\text{-}1997.0)$ m

$T_Y(t) = T_Y + dT_Y \cdot (t\text{-}1997.0)$ m

$T_Z(t) = T_Z + dT_Z \cdot (t\text{-}1997.0)$ m

$R_X(t) = [R_X + dR_X \cdot (t\text{-}1997.0)] \cdot k$ rad

$R_Y(t) = [R_Y + dR_Y \cdot (t\text{-}1997.0)] \cdot k$ rad

$R_Z(t) = [R_Z + dR_Z \cdot (t\text{-}1997.0)] \cdot k$ rad

$DS(t) = DS + dDS \cdot (t\text{-}1997.0)$ ppb

$t$ = epoch of ITRF coordinates

$k = 4.84813681 \times 10^{-9}$ rad/mas

All these parameters are time-dependent due to tectonic plate motion and the rates of change of some of the incremental transformation parameters between different ITRFs. Note that the rotations in these expressions are given as positive in a clockwise direction following the non-standard convention used by the IERS. Table 1 summarizes these parameters for all ITRF realizations available at the time of this paper (ITRF2005 is expected to be released this year). See also *Soler and Snay* [2004] for further discussion of the ITRF2000-NAD83 transformation.

In addition to transforming coordinates, it is also possible to transform GPS baseline vectors. Because vectors contain no absolute positional information, the translational part of the transformation is not used. Only the rotations and scale change are applied to the vector coordinate differences as follows:

$$\begin{bmatrix} \Delta X_N \\ \Delta Y_N \\ \Delta Z_N \end{bmatrix} = \begin{bmatrix} 1+DS(t) & -R_Z(t) & R_Y(t) \\ R_Z(t) & 1+DS(t) & -R_X(t) \\ -R_Y(t) & R_X(t) & 1+DS(t) \end{bmatrix} \begin{bmatrix} \Delta X_I(t) \\ \Delta Y_I(t) \\ \Delta Z_I(t) \end{bmatrix} \quad (3)$$

where

$\Delta X_N, \Delta Y_N, \Delta Z_N$ are the geocentric Cartesian coordinate differences in NAD83(CSRS)

$\Delta X_I(t), \Delta Y_I(t), \Delta Z_I(t)$ are the geocentric Cartesian coordinate differences in ITRF at epoch $t$

Although the effect of the rotations and scale change on baseline vectors is relatively small (of the order of 0.1 ppm) and may be neglected in some cases, they systematically accumulate throughout a network and can amount to a significant error in some situations. Because the application of the transformation is relatively simple, it is recommended to always transform baseline vectors unless one is sure they will never be assembled to construct larger networks.

Velocities in ITRF can also be transformed into NAD83(CSRS). This involves only the rates of change of the transformation parameters defined in eqn. (2) and Table 1. These parameters represent the NNR-NUVEL-1A velocity for the North American plate and some small drifts in the origin, orientation, and scale of different realizations of the ITRF. The transformation can be expressed as

$$\begin{bmatrix} V_{X_N} \\ V_{Y_N} \\ V_{Z_N} \end{bmatrix} = \begin{bmatrix} V_{X_I} \\ V_{Y_I} \\ V_{Z_I} \end{bmatrix} + \begin{bmatrix} dT_X \\ dT_Y \\ dT_Z \end{bmatrix} + \begin{bmatrix} dDS & -dR_Z{\cdot}k & dR_Y{\cdot}k \\ dR_Z{\cdot}k & dDS & -dR_X{\cdot}k \\ -dR_Y{\cdot}k & dR_X{\cdot}k & dDS \end{bmatrix} \begin{bmatrix} X_I(t) \\ Y_I(t) \\ Z_I(t) \end{bmatrix} \tag{4}$$

where

$V_{X_N}, V_{Y_N}, V_{Z_N}$ are the geocentric Cartesian velocities in NAD83(CSRS)

$V_{X_I}, V_{Y_I}, V_{Z_I}$ are the geocentric Cartesian velocities in ITRF at epoch $t$

These ITRFxx-NAD83(CSRS) transformations have been implemented in software available from GSD and the US National Geodetic Survey (NGS). GSD's software is called TRNOBS and will transform input data files of positions and position differences for GSD's own GHOST adjustment software as well as for the commercial GeoLab™ software. For US users, the HTDP (Horizontal Time Dependent Positioning) software will transform data files of positions and velocities in NGS Blue Book format. On-line versions and Fortran source code for both TRNOBS and HTDP are available at the respective agency's web sites.

## *WGS84*

The World Geodetic System 1984 [*NIMA* 2004] is a global reference frame originally developed by the US Defense Mapping Agency (subsequently renamed the National Imagery and Mapping Agency (NIMA) and now called the National Geospatial-Intelligence Agency (NGA)). It was used for mapping campaigns around the world and is the "native" reference frame used by GPS.

WGS84 is unique in that there is no physical network of ground points that can be used as geodetic control. The only control points available to the public are the satellites themselves, defined by the broadcast orbits. Because of the relative inaccuracy of these orbits and further degradation prior to May 1, 2000 due to the implementation of selective availability (S/A), public users could not get true WGS84 positions to better than about 10-50 m. Accuracies improved to about 3-5 m when S/A was turned off and even better accuracies of a metre or less can now be achieved with correction services such as the Wide Area Augmentation System (WAAS). It was at this time that many users began to notice a systematic bias between WGS84 and NAD83 of about 1.5 m in the horizontal and a metre in the vertical.

Originally, WGS84 was defined in a similar manner as NAD83. It used a global network of Doppler stations to align itself with the same BTS84 reference frame used by NAD83. Thus, WGS84 was identical with NAD83 in the beginning. Based on this original realization, NIMA determined simple average geocentric Cartesian coordinate shifts (translations) between WGS84 and many local datums around the world. Because NAD83 and WGS84 were defined by the same BTS84 reference frame, the shift between these systems was zero [*NIMA* 2004].

Several years later, in an effort to improve its stability and accuracy, WGS84 was redefined in terms of ITRF [*Slater and Malys* 1998; *NIMA* 2004]. In doing so, the WGS84 reference frame was shifted by about two metres and rotated slightly to align it with the ITRF reference frame. Figure 6 illustrates the differences between this new WGS84 and NAD83 in Canada for both horizontal and vertical components. This realignment with ITRF occurred three different times [*Slater and Malys* 1998; *Merrigan et al.* 2002; *NIMA* 2004; *NGA* 2004]. These WGS84 realizations are denoted with a "G" followed by the GPS week the frame was put into use. Table 2 lists the different ITRF-based realizations of WGS84 giving the particular version of ITRF used and the dates they were put into use. Of particular importance to GPS users are the dates used to produce the broadcast orbits. Users can transform WGS84 positions or baseline vectors to NAD83 by simply using the parameters for the associated ITRF.

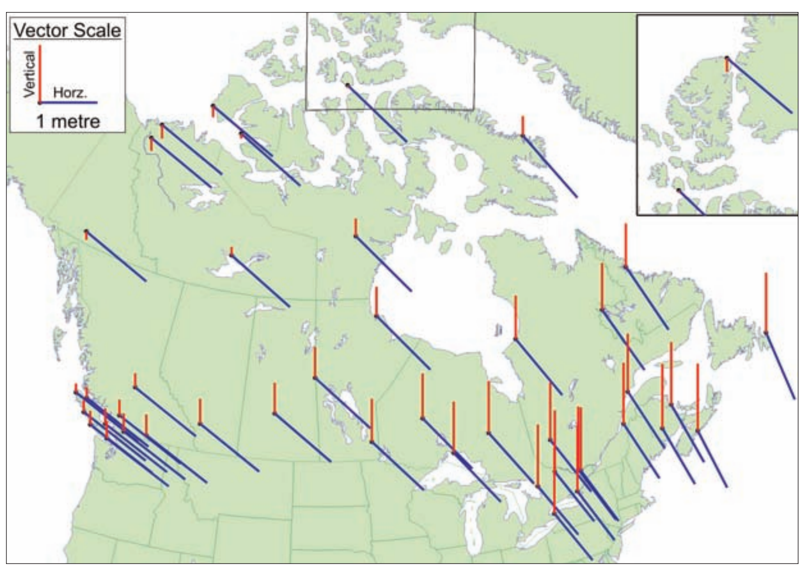


**Figure 6: Horizontal (blue) and vertical (red) differences between NAD83(CSRS) and WGS84 in the sense NAD83(CSRS) minus WGS84.**

**Table 2: ITRF-based realizations of the WGS84 reference frame.**

| Version | Based on | Implemented at NIMA | Implemented in Orbits |
|---|---|---|---|
| WGS84(G730) | ITRF91 | 1994-01-02 | 1994-06-20 |
| WGS84(G873) | ITRF94 | 1996-09-29 | 1997-01-29 |
| WGS84(G1150) | ITRF2000 | 2002-01-20 | 2002-01-20 |

Unfortunately, NGA still considers the G-series realizations of WGS84 to be identical with the original realization. Thus, the zero transformation with respect to NAD83 has never been revised in spite of the bias being clearly measurable. This has created problems when using WGS84-based correction services and trying to convert results to NAD83. Most receiver manufactures include only the original NIMA coordinate shifts (translations) in their receiver firmware, which are zero for NAD83. Consequently, many receivers are producing so-called NAD83 coordinates that are actually still in WGS84 and biased by 1.5 to 2 metres with respect to the true NAD83 reference frame. Great care must therefore be exercised when using the transformations built into receiver firmware and post-processing software.

### *NAD83(Original)*

To assist in the conversion of large amounts of data tied to the original realization of NAD83 and in cases where it is impractical or impossible to readjust existing NAD83(Original) networks in NAD83(CSRS), many provinces have developed NTv2-type distortion models to convert such data to NAD83(CSRS). This task first involved the readjustment of provincial networks in NAD83(CSRS). This provided coordinate discrepancies between the original and CSRS realizations of NAD83 with a greater spatial density to better model the distortions. In some cases it was necessary to perform surveys to provide additional connections between the old and new realizations.

It is important to emphasize again that NAD83(Original) and NAD83(CSRS) do not represent different reference systems. NAD83(CSRS) is essentially an updated physical realization (network) of the same NAD83 reference system, fully consistent with NAD83(Original) but with much greater accuracy. The provincial NTv2 distortion models therefore do not reflect any changes in the reference system. Rather they represent the errors (distortions) in the networks comprising the original realization of NAD83. Because these distortions are about half a metre on average, users should consider the accuracy of their georeferencing before deciding whether data holdings need to be converted from NAD83(original) to NAD83(CSRS).

### *NAD27/CGQ77/ATS77*

For similar reasons, transformations to NAD83(CSRS) have also been developed for other older reference systems. The system with the greatest amount of legacy data was NAD27 and so an NTv2 to NAD83(Original) transformation and distortion model was developed as discussed earlier. This transformation can also be used for NAD83(CSRS). This is because the differences between the original and CSRS versions of NAD83 are insignificant compared to the relatively low accuracy of the NAD27-NAD83(Original) transformation. These minor differences can therefore be safely ignored without introducing any systematic bias in the results.

In order to reduce the distortions in NAD27, Quebec performed a readjustment of their provincial networks based on the NAD27 reference frame several years before NAD83 was introduced. This realization was denoted as NAD27(CGQ77) or CGQ77. Quebec developed their own NTv2-compatible transformations and distortion models between NAD27, CGQ77, NAD83(Original), and NAD83(CSRS) which are implemented in their SYREQ software.

At about the same time CGQ77 was implemented, the Maritime Provinces introduced yet another reference system called the Atlantic Terrestrial System of 1977 (ATS77) [*Gillis et al.* 2000]. Unlike CGQ77, this was a geocentric system. It was adopted in New Brunswick and Nova Scotia in 1979 and continued to be used after the introduction of the original realization of NAD83. An NTv2-based transformation between NAD27 and ATS77 was developed as was a transformation between ATS77 and NAD83(Original). However, the latter used only the federal primary control stations in the Maritimes. When the 1998 realization of NAD83(CSRS) was introduced in 1998 it was soon adopted or was used unofficially for most positioning applications. New Brunswick, Nova Scotia, and Prince Edward Island have since developed their own NTv2-compatible transformations and distortion models between ATS77 and NAD83(CSRS).

## *Maintenance of NAD83(CSRS)*

In general, geodetic reference frames and networks need periodic maintenance or updating of their coordinates for a variety of reasons. Some of these include the addition of new densification networks, the correction of survey blunders, unstable or disturbed monumentation, the effects of crustal motion both locally and regionally, and to keep pace with ever increasing accuracy requirements.

Crustal motions are especially troublesome along the west coast and in central and eastern Canada (see *Henton et al*. [this issue]). Vertical movements up to 2 cm/y due to post-glacial rebound can quickly make positions outdated. In the case of NAD83(CSRS), it is now known that the NNR-NUVEL-1A plate motion used in the defining ITRF-NAD83 transformation is in error by about 2 mm/y (see Figure 7). Over several years this can accumulate to well over a centimetre which becomes problematic for high accuracy and scientific applications.

In an effort to ensure the NAD83(CSRS) reference frame keeps pace with future requirements, coordinates are periodically updated as new versions of the ITRF are released. New ITRF coordinates for Canadian stations are transformed to NAD83(CSRS) using the adopted transformation. This periodic updating of the reference frame is sometimes referred to as a semi-dynamic approach to maintenance where positions are valid for only a defined period of time.

Another method of reference frame maintenance is a purely dynamic approach where positions are assumed to be dynamic and are valid only for a specific epoch. Estimated velocities are then used to propagate the positions to any other date. Such an approach is often required for scientific applications demanding the highest accuracies. The ITRF is the prime example of a dynamic global reference frame as is the new Stable North American Reference Frame (SNARF) discussed below.

## *Evolving from NAD83*

To many, our current NAD83(CSRS) spatial reference system appears to be adequate for most positioning activities in North America. However, history has repeatedly shown that reference systems need to evolve to keep pace with the ever-increasing accuracy with which we are able to locate points on and near the Earth, and to enable the proper integration of georeferenced data from various sources and from different times.

As previously mentioned, it is now known that NAD83 is offset from the true geocentre by about two metres. It is therefore incompatible with the newer realizations of WGS84, the native reference frame for GPS. As discussed above, this can cause problems when treating the two frames as the same. In addition, the adopted NNR-NUVEL-1A plate motion model overestimates the magnitude of the rotation of the North American plate (see Figure 7). This can accumulate to magnitudes that are detectible in high accuracy GPS surveys. Finally, intra-plate crustal deformations such as post-glacial rebound can cause coordinates to quickly go out of date.

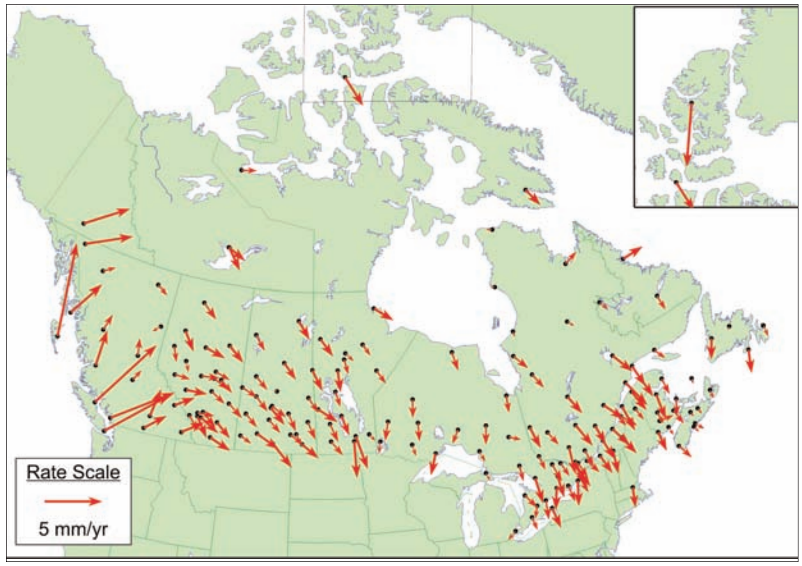


**Figure 7: GPS horizontal velocities from repeated high accuracy GPS observations with respect to the NNR-NUVEL-1A plate motion estimate for North America. The coherent pattern reveals a bias in NNR-NUVEL-1A of about 2 mm/y.**

One option of dealing with these problems is to simply use the most recent ITRF realization as done in some countries (e.g., South America). The advantage of this is that it would be completely compatible with the WGS84 system used by GPS. However, the relentless movement of the North American continent due to plate tectonics will slowly but surely ensure that all coordinates systematically change by about 2.5 cm/y. This amounts to a quarter of a metre in only 10 years. If this motion is not accounted for it would result in coordinate discrepancies at a level unacceptable for most users.

The accumulating coordinate discrepancies due to tectonic motion could be somewhat reduced by simply updating the ITRF coordinates on a regular basis following the semi-dynamic approach to maintenance. However, it would still be difficult to relate data from different time periods. At the very least, this approach would require significant efforts to inform and educate the public.

Another approach would be to adopt a version of ITRF at a specific epoch and to keep this realization fixed to North America as recommended by the *IAG* [1992]. Such coordinates can be related to ITRF coordinates at any other epoch using an estimate of the motion of the North American tectonic plate as done for NAD83(CSRS). This is the approach recently used to define the so-called Stable North American Reference Frame (SNARF) [*Blewitt et al*. 2005; *Craymer et al.* 2005]. Under the joint auspices of UNAVCO, Inc. in the US and IAG Sub-Commission 1.3c for North America, a working group was established with the goal of defining such a regional reference frame that is consistent and stable at the sub-mm-level throughout North America. This reference frame fixes ITRF2000 to the stable part of North America to facilitate geophysical interpretation and inter-comparison of geodetic solutions of crustal motions.

The SNARF reference frame is essentially defined by a rotation vector that models the tectonic motion of North America in the ITRF2000 reference frame. The rotations transform ITRF2000 positions and velocities at any epoch into the SNARF frame fixed to the stable part of North American. Thus, just like NAD83(CSRS), SNARF is defined in relation to the ITRF. The advantage of SNARF is that it is truly geocentric and also uses a rotation vector that more accurately models the motion of stable North America. Previous plate rotation estimates have used stations in areas of intra-plate crustal deformations which can bias the estimation of the rotation vector.

The SNARF plate rotations were determined using ITRF2000-based velocities of 17 stations in geophysically stable areas. The following are the rotations adopted for SNARF v1.0 which transform ITRF2000 coordinates into the SNARF frame:

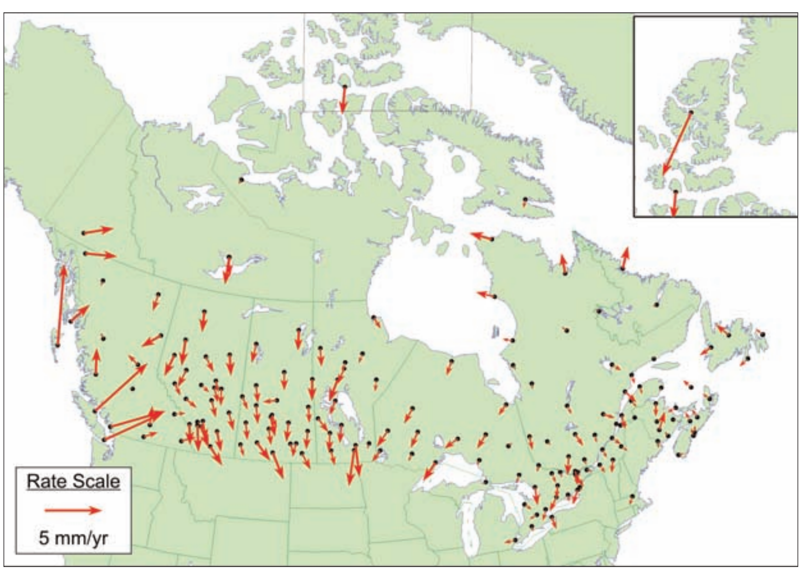


**Figure 8: GPS horizontal velocities from repeated high accuracy GPS observations with respect to the SNARF 1.0 plate motion estimate for North America.**

$$\begin{bmatrix} R_X \\ R_Y \\ R_Z \end{bmatrix} = \begin{bmatrix} 0.06588 \\ -0.66708 \\ -0.08676 \end{bmatrix} \text{mas/y} \tag{5}$$

This rotation vector is equivalent to a horizontal surface velocity of about 2 cm/y in Canada.

Velocities of CBN stations with respect to the SNARF reference frame are plotted in Figure 8. In this reference frame the expected outward pattern of intra-plate horizontal velocities from post-glacial rebound is small but clearly visible. This model of plate motion is an improvement over NNR-NUVEL-1A for North America (compare Figures 7 and 8).

The first release of SNARF also includes an empirical model of post-glacial rebound based on a novel combination of GPS velocities with a geophysical model. It has been adopted as the official reference frame for the Plate Boundary Observatory of the EarthScope project along the west coast of North America. Over the next few years SNARF will be incrementally improved and refined and could become a de facto standard for many applications. Sometime in the future it is possible that, after further analysis and consultation with stakeholders, SNARF or some variation of it may eventually replace NAD83 as the official datum for georeferencing in both Canada and the US.

## Acknowledgements

Parts of this paper were based on an in-house report prepared by Don Junkins, recently retired from GSD. His contribution is gratefully acknowledged. I am also indebted to Joe Henton (GSD) for preparing most of the figures using the GMT software [*Wessel and Smith* 1998]. I would also like to thank Allen Flemming (Nova Scotia Geomatics Centre), Leo-Guy LeBlanc (Service New Brunswick) and Serge Bernard (PEI Transportation and Public Works) for kindly providing information about the Maritime networks, and especially Norman Beck and Robert Duval (GSD) for their many constructive comments and suggestions while reviewing this paper.

## Disclaimer

Any reference to commercial products in not intended to convey an endorsement of any kind.

## References

Altamimi, Z., P. Sillard and C. Boucher. 2002. ITRF2000: A new release of the International Terrestrial Reference Frame for earth science applications. *Journal of Geophysical Research*, Vol. 107, No. B10, DOI: 10.1029/2001JB000561.

Associated Press (AP). 2004. Scientists say Chicago sinking a millimeter a year. *The Associated Press State and Local Wire*, May 20.

Beutler, G., M. Rothacher, S. Schaer, T.A. Springer, J. Kouba and R.E. Neilan. 1999. The International GPS Service (IGS): An Interdisciplinary Service in Support of Earth Sciences, *Advances in Space Research*, 23(4), pp. 631-635.

Blewitt, G., D. Argus, R. Bennett, Y. Bock, E. Calais, M. Craymer, J. Davis, T. Dixon, J. Freymueller, T. Herring, D. Johnson, K. Larson, M. Miller, G. Sella, R. Snay, and M. Tamisiea. 2005. A Stable North American Reference Frame (SNARF): First Release, Proceedings of the Joint UNAVCO/IRIS Workshop, Stevenson, WA, USA, June 9-11.

Boal, J.D. and J.P. Henderson. 1988. The NAD 83 Project - Status and Background. In J.R. Adams (ed.), *Papers for the CISM Seminars on the NAD '83 Redefinition in Canada and the Impact on Users*, Canadian Institute of Surveying and Mapping, Ottawa, pp. 59-78.

Boucher, C. and Z. Altamimi. 1996. International Terrestrial Reference Frame. *GPS World*, 7(9), September, pp. 71-74.

Canadian Council on Geomatics (CCOG). 2006. CCOG Resolution S05-10: National Standard for Integrated Surveys. CCOG Spring Meeting, Ottawa, April 6-7.

CanWest. 2004. Satellite shows North America bulging upward. *CanWest News Service*, May 15.

Craymer, M., R. Ferland and R. Snay. 2000. Realization and Unification of NAD83 in Canada and the U.S. via the ITRF. In R. Rummel, H. Drewes, W. Bosch, H. Hornik (eds.), *Towards an Integrated Global Geodetic Observing System (IGGOS)*, IAG Section II Symposium, Munich, October 5-9, 1998, International Association of Geodesy Symposia Volume 120, Springer-Verlag, Berlin, pp. 118-121.

Craymer, M., G. Blewitt, D. Argus, R. Bennett, Y. Bock, E. Calais, J. Davis, T. Dixon, J. Freymueller, T. Herring, D. Johnson, K. Larson, M. Miller, G. Sella, R. Snay and M. Tamisiea. 2005. Defining a Plate-Fixed Regional Reference Frame: The SNARF Experience. Dynamic Planet 2005, IAG/IAPSO/IABO Joint Assembly, Cairns, Australia, August 22-26.

DeMets, C., R.G. Gordon, D.F. Argus and S. Stein. 1994. Effect of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions. *Geophysical Research Letters*, 21(20), pp. 2191-2194.

Duval, R., P. Heroux and N. Beck. 1997. Canadian Active Control System—Delivering the Canadian Spatial Reference System. Presented at GIS'96, Vancouver, March 1996 (revised).

Energy, Mines and Resources, Department of (EMR). 1990. New Reference System of Latitudes and Longitudes for Canada - Notice of Adoption. *Canada Gazette*, Part I, Vol. 124, No. 21, May 26, pp. 1808-1809.

Globe and Mail, The. 2004. Canada is rising. *The Globe and Mail*, June 1.

Guardian, The. 2004. The earth moves, and you can watch. *The Guardian* (U.K.), May 20.

Gillis, D., A. Hamilton, R.J. Gaudet, J. Ramsay, B. Seely, S. Blackie, A. Flemming, C. Carlin, S. Bernard and L.-G. LeBlanc. 2000. The Selection and Implementation of a New Spatial Reference System for Canada's Maritime Provinces. *Geomatica*, 54(1), pp. 25-41.

Henton, J., M. Craymer, H. Dragert, S. Mazzotti, R. Ferland and D.L. Forbes. 2006. Crustal Motion and Deformation Monitoring of the Canadian Landmass. *Geomatica*, this issue.

Héroux, P., J. Kouba, N. Beck, F. Lahaye, Y. Mireault, P.Tétreault, P.Collins, K. MacLeod and M. Caissy. 2006. Space Geodetic Techniques and the CSRS Evolution, Status and Possibilities. *Geomatica*, this issue.

IAG. 1992. International Association of Geodesy Resolutions adopted at the XXth IUGG General Assembly in Vienna. In "The Geodesist's Handbook". *Bulletin Geodesique*, 66(2), pp. 132-133.

Independent, The. 2004. Chicago feels chill of the ice age as geologists say Windy City is sinking. *The Independent*, London, The Independent, May 22.

Junkins, D.R. 1988. Transforming to NAD 83. In J.R. Adams (ed.), *Papers for the CISM Seminars on the NAD '83 Redefinition in Canada and the Impact on Users*, Canadian Institute of Surveying and Mapping, Ottawa, pp.94-105.

Junkins, D.R. 1990. The National Transformation for Converting Between NAD27 and NAD83 in Canada. In D.C. Barnes (ed.), *Moving to NAD '83: The New Address for Georeferenced Data in Canada*, The Canadian Institute of Surveying and Mapping, Ottawa, pp. 16-40.

Junkins, D. and G. Garrard. 1998. Demystifying Reference Systems: A Chronicle of Spatial Reference Systems in Canada. *Geomatica*, 52(4), pp. 468-473.

Larson, K.M., J.T. Freymueller and S. Philipsen. 1997. Global plate velocities from the Global Positioning System. *Journal of Geophysical Research*, Vol. 102, No. B5, pp. 9961-9982.

McCarthy, D.D. (ed.). 1996. IERS Conventions. 1996. Technical Note 21, International Earth Rotation Service, Paris Observatory, Paris.

Merrigan, M.J., E.R. Swift, R.F. Wong and J.T. Saffel. 2002. A Refinement to the World Geodetic System 1984 Reference Frame. *Proceedings of the ION GPS 2002*, September 24-27, pp. 1519-1529.

New Scientist, The. 2004. Canada's on the up – US is going down. *The New Scientist*, May 20.

NGA. 2004. *Addendum to NIMA TR 8350.2: Implementation of the World Geodetic System 1984 (WGS 84) Reference Frame G1150*. National Geospatial-Intelligence Agency.

NIMA. 2004. Department of Defence World Geodetic System 1984: Its Definition and Relationship with Local Geodetic Systems. Technical Report 8350.2, Third Edition, Amendment 2, National Imagery and Mapping Agency (NIMA), Bethesda, MD.

Parent, C. 1988. NAD83 Secondary Integration. *CISM Journal ACSGC*, 42(4), pp. 331-340.

Slater, J.A. and S. Malys. 1998. WGS 84 - Past, Present and Future. In F.K. Brunner (ed.), *Advances in Positioning and Reference Frames*, IAG Scientific Assembly, Rio de Janeiro, Brazil, September 3-9, 1997, International Association of Geodesy Symposia Volume 118, Springer-Verlag, Berlin, pp. 1-7.

Soler, T., J.D. Love, L.W. Hall and R.H. Foote. 1992. GPS Results from Statewide High Precision Networks in the United States. *Proceedings of the 6th International Geodetic Symposium on Satellite Positioning*, The Ohio State University, Columbus, OH, March 17-20, pp. 573-582.

Soler, T. and R.A. Snay. 2004. Transforming Positions and Velocities between the International Terrestrial Reference Frame of 2000 and North American Datum of 1983. *Journal of Surveying Engineering*, 130(2), pp. 49-55.

United Press International (UPI). 2004. Researchers see North America moving. *United Press International*, May 14.

Véronneau, M., R. Duval and J. Huang. 2006. A Gravimetric Geoid Model as a Vertical Datum in Canada. *Geomatica*, this issue.

Washington Post, The. 2004. Chicago is sinking! In Coast to Coast: A national briefing of people, issues and events around the country. *The Washington Post*, May 30.

Wessel, P. and W.H.F. Smith. 1998. New, improved version of the Generic Mapping Tools released. *Eos Trans. Amer. Geophys. U.*, 79(47), p. 329.

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# The Evolution of NAD83 in Canada: Addendum

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Since the publication of the paper “The Evolution of NAD83 in Canada” in *Geomatica* Vol. 60, No. 2, 2006, [*Craymer* 2006] the ITRF2005, a new version of the International Terrestrial Reference Frame, was released. The transformation parameters from ITRF2005 to NAD83(CSRS) are provided in the table below as an update to Table 1 in *Craymer* [2006].

I would also like to take this opportunity to correct the following two passages in *Craymer* [2006]:

p. 159, 2nd column, 3rd paragraph. “...the WGS84 reference frame was shifted by about two metres and rotated slightly to align it with the ITRF...” should be changed to “...the WGS84 reference frame was shifted, rotated and scaled by about 1.5 metres to align it with the ITRF...”

p. 160, 2nd column, 2nd paragraph. “...an NTv2 to NAD83(Original) transformation...” should be changed to “...a NAD27 to NAD83(Original) transformation...”

**Table: ITRF2005 to NAD83(CSRS) transformation parameters at an epoch of 1997.0 and their rates of change (mas = milliarcsec, ppb = parts per billion).**

| | $T_X$ m<br>$dT_X$ m/y | $mT_Y$ m<br>$dT_Y$ m/y | $T_Z$ m<br>$dT_Z$ m/y | $R_X$ mas<br>$dR_X$ mas/y | $R_Y$ mas<br>$dR_Y$ mas/y | $R_Z$ mas<br>$dR_Z$ mas/y | $DS$ ppb<br>$dDS$ ppb/y |
|---|---|---|---|---|---|---|---|
| ITRF2005 | 0.9963<br>0.0005 | -1.9024<br>-0.0006 | -0.5219<br>-0.0013 | -25.915<br>-0.067 | -9.426<br>0.757 | -11.599<br>0.051 | 0.775<br>-0.102 |

## References

Craymer, M.R. 2006. The Evolution of NAD83 in Canada. *Geomatica*, 60(2), pp. 151-164.