Draft: February 29, 2008

Guidelines for Operating a Real-Time GNSS Network

Chapter 1. Achieving Consistency Among Positional Coordinates and Velocities

1.1 - Introduction

The purpose of this document is to provide guidelines for operating a Real-Time Network (RTN); that is, a network of terrestrial-based Global Navigation Satellite System (GNSS) tracking stations for enabling clients to obtain accurate positional coordinates for points of interest to them, and to do so with a latency of less than a few seconds (once integer ambiguities have been resolved). These guidelines do not address the operation of a RTN for navigational applications.

This first chapter presents guidelines for promoting the consistency of the generated positional coordinates with current realizations of the North American Datum of 1983 (NAD 83), as well as with current realizations of the International Terrestrial Reference System (ITRS). NOAA's National Geodetic Survey (NGS) encourages the use of both of these spatial reference systems for geometric positioning (geodetic latitude, geodetic longitude, ellipsoidal height; or equivalently, geocentric 3-dimensional Cartesian coordinates). Indeed, **NAD 83 is the official spatial reference system for geometric positioning in the United States**.

At present (February 2008), NGS endorses the use of the ITRS realization known as the International Terrestrial Reference Frame of 2000 (ITRF2000) [see Altamimi, Sillard, and Boucher, 2002] for use throughout the United States and its territories. Also, NGS endorses the use of the following NAD 83 realizations:

- NAD 83(CORS96) in CONUS, Alaska, Puerto Rico, and the AmericanVirgin Islands;
- NAD 83(PACP00) in Hawaii, the Marshall Islands, American Samoa and other islands residing on the Pacific tectonic plate; and
- NAD 83(MARP00) in the Mariana Islands (Guam, Saipan, etc.) and other islands residing on the Mariana tectonic plate.

Note that these three realizations of NAD 83 are each related mathematically to ITRF2000 by a 14-parameter Helmert transformation. Hence, if the 3-dimensional ITRF2000 positional coordinates and velocity for a point are known, then its equivalent positional coordinates and velocity can be exactly computed for any of the above three realizations of NAD 83. Conversely, if the positional coordinates and velocity are known for any of the above three realizations of NAD 83, then the corresponding ITRF2000 positional coordinates and velocity can be exactly computed. The transformation between NAD 83(CORS96) and ITRF2000 was published by Soler and Snay [2004]. The transformation between NAD 83(PAC00) and ITRF2000, as well as that between NAD 83(MAR00) and ITRF2000, were published by Snay [2003]. All three transformations are encoded in the Web-based utility known as HTDP at

http://www.ngs.noaa.gov/TOOLS/Htdp/Htdp.shtml . The fact that these three NAD 83 realizations are each mathematically convertible to ITRF2000 implies that RTN operators can work interchangeably in either the ITRS or the NAD 83 reference system. At NGS, all CORS computations are performed in ITRF2000 and the resulting positional coordinates and velocities are transformed to an appropriate NAD 83 realization, if needed, at the end of the process.

NGS has also adopted a realization of NAD 83 called NAD 83(NSRS2007) for use in CONUS, Alaska, and Puerto Rico. This latter realization approximates NAD 83(CORS96). It was obtained by adjusting Global Positioning System (GPS) data collected during various campaign-style geodetic surveys performed between the mid-1980's and 2005. For this adjustment, NAD 83(CORS96) positional coordinates for several continuously operating reference stations (CORS) were held essentially fixed to obtain consistent positional coordinates for about 70,000 passive geodetic reference stations, as described by Vorhauer [2007]. Hence, derived NAD 83(NSRS2007) positional coordinates should be consistent with corresponding NAD 83(CORS96) positional coordinates to within the accuracy of the GPS data involved in the adjustment and the accuracy of the corrections applied to these data for crustal motion, atmospheric refraction, etc. Note that NGS has not adopted NAD 83(NSRS2007) velocities for most of the 70,000 reference stations involved in this adjustment, but their velocities may be predicted using the aforementioned HTDP utility. Note also that the positional coordinates of a reference station should be referred to an "epoch date". This term corresponds to the date for which the positional coordinates are considered valid. A station's positional coordinates referred to one epoch date can be compared with those referred to another epoch date, only if the station's motion between the two epoch dates is known. This motion includes the station's (3-dimensional) velocity. Appendix A presents a procedure for predicting a station's positional coordinates at a specified epoch date by using its positional coordinates for a different epoch date together with the station's velocity.

1.2 - Summary of Recommended Procedures

NGS recommends that the administrator of a RTN follow three procedures so that his/her clients will obtain positional coordinates that are consistent with the NGS-adopted realizations of ITRS and NAD 83.

Recommendation 1. Include a subnetwork of the RTN into the National CORS network.

Recommendation 2. For each reference station contained in the RTN, adopt values for its 3-dimensional positional coordinates (at a selected epoch date) and a velocity that are consistent with corresponding values adopted by NGS for reference stations in the National CORS network.

Recommendation 3. For each reference station in the RTN, use the Online Positioning User Service (OPUS) at http://www.ngs.noaa.gov/OPUS/ to test for the continued

DRAFT

consistency of its adopted positional coordinates and velocity on a daily basis, and revise the station's adopted coordinates and/or velocity if the tests reveal a need to do so.

1.3 – Implementing Recommendation 1

If the RTN contains at least 30 reference stations, then NGS recommends that the RTN administrator include at least 10% of these reference stations into the National CORS network. If the RTN contains less than 30 reference stations, then NGS recommends that the RTN administrator include at least three of them in the National CORS network. In either case, the RTN administrator and NGS may agree to include more than the recommended number of his/her RTN reference stations into the National CORS network. Also, the included reference stations should be well distributed throughout the RTN.

For each station contained in the National CORS network, NGS will determine its positional coordinates and velocity for each pertinent realization of NAD 83 and ITRS. Moreover, NGS will monitor the accuracy of these positional coordinates and velocities on a daily basis. NGS will also make available all GNSS data collected at these stations to the public for post-processing activities. NGS will NOT distribute these data in real time to individuals and/or organizations unless NGS has received permission to do so from the RTN sponsor. Even with permission, NGS would broadcast only the GNSS data without correctors.

Information about including a reference station into the National CORS network and guidelines for establishing and operating these stations may be found at http://www.ngs.noaa.gov/CORS/ .

As will be addressed later, one advantage of including RTN stations into the National CORS network is to allow RTN administrators to easily test for the consistency of the positional coordinates that they have adopted for their RTN reference stations via OPUS and in such a way that OPUS uses only reference stations from this RTN as control stations.

1.4 – Implementing Recommendation 2

For each RTN reference station contained in the National CORS network, NGS encourages the RTN administrator to adopt values for the station's 3-dimensional positional coordinates (at an operated-selected epoch date) and velocity which will agree with the corresponding NGS-adopted values for this station's positional coordinates (at the NGS-selected epoch date) and velocity in the following sense:

> The administrator-adopted values will predict positional coordinates that differ by no more than 2 cm in each horizontal dimension (north-south and east-west) and by no more than 4 cm in ellipsoidal height from the positional coordinates, predicted with the corresponding NGS-adopted values, for each day that both the administrator-adopted values and the NGS-adopted values are in actual use.

As mentioned previously, a procedure for predicting positional coordinates at one epoch date using positional coordinates for a different epoch date is presented in Appendix A.

It would be convenient if the administrator-adopted values were identical to the NGS-adopted values, but the administrator is likely to have more available resources than NGS to monitor the positional coordinates of his/her RTN reference stations. Hence, the administrator will probably be the first to detect when positional coordinates and/or velocities need to be revised. The administrator should then advise NGS at ngs.cors@noaa.gov as to the discrepancy, for it may be the case that the administrator-adopted values are more accurate than the NGS-adopted values, whereupon NGS would need to revise its adopted values.

The RTN administrator may also want to adopt values that differ (within the above tolerances) from the NGS-adopted values because RTN technology requires a higher level of internal consistency among positional coordinates than what is required for standard CORS applications. This internal consistency enhances the ability to determine accurate corrections to the GNSS data for the systematic errors associated with orbits, clocks, atmospheric refraction, and other phenomena. These accurate corrections will better enable rapid and reliable resolution of the integer ambiguities, as is needed for cm-level positioning. In many cases, the RTN administrator will have more available resources than NGS to determine internally consistent positional coordinates for his/her RTN reference stations.

The RTN administrator may use any procedure that he/she deems appropriate to determine positional coordinates (at a selected epoch date) and velocities for all reference stations contained in his/her RTN, provided the resulting values yield positional coordinates that are consistent with those yielded by OPUS in the following sense:

> If--for any period of time spanning 60 consecutive days--a person submits daily (24-hour) GPS data files from a RTN reference station to OPUS, then the average coordinates from these 60 OPUS solutions should differ by no more than 2 cm in each horizontal dimension nor by no more than 4 cm in ellipsoidal height from the average positional coordinates for these 60 days, as predicted by the administrator-adopted values.

Appendix B provides some suggestions as to how a RTN administrator may determine positional coordinates (at a selected epoch date) and velocities for his/her RTN reference stations.

1.5 – Implementing Recommendation 3

For each reference station contained in his/her RTN, the administrator should submit a 24-hour GPS data set (spanning the time from UTC midnight to the following UTC midnight) to OPUS for each day of operation. Moreover, the operator should submit these data to OPUS at least 24 hours after the end of the UTC day so that OPUS will use

DRAFT

the Rapid Precise Orbits, provided by the International GNSS Service (IGS), when processing these GPS data.

For each day, the administrator should then compare the OPUS-generated positional coordinates for the station with the positional coordinates predicted for that day using the administrator-adopted values for the station's positional coordinates (at the administrator-selected epoch date) and velocity. If the two sets of positional coordinates differ "in a consistent manner" by more than 2 cm in either horizontal dimension and/or by more than 4 cm in ellipsoidal height, then the RTN administrator may want to contact NGS at ngs.cors@noaa.gov to help him/her determine the cause of the discrepancy. For example, the discrepancy may be caused by

- an error in the administrator-adopted values for the RTN station's coordinates and/or velocity,
- an error in the NGS-adopted values for the coordinates and/or velocities of the National CORS being used by OPUS, and/or
- an error in the OPUS software.

In some cases, the cause of the discrepancy may be rather obvious; for example, the reference station's antenna was displaced by an earthquake or by vandals. In such cases, the administrator need only determine new values for the reference station's coordinates. In other cases, the cause may be extremely subtle; for example, gradual subsidence due to sediment compaction or seasonal variations in the station's location due to hydrological effects. In such cases, the motion of the station may need to be modeled more accurately or perhaps the station should be replaced with another station whose crustal motion would be better understood.

Note that OPUS allows its users to select one or more of the three CORS that this software will use in processing the user-submitted GPS data. Hence, a RTN administrator may instruct OPUS to use any of the three or more reference stations that he/she opted to include in the National CORS network in accordance with Recommendation 1. This action would promote internal consistency among the positional coordinates of the stations in this RTN.

Appendix A – Transforming positional coordinates from one epoch date to another

Let $[x(t_1), y(t_1), z(t_1)]$ denote the geocentric Cartesian coordinates of a specified terrestrial point at time t_1 relative to a specified reference frame, for example, some realization of NAD 83 or some realization of ITRS.

Furthermore, let $[x(t_2), y(t_2), z(t_2)]$ denote the geocentric Cartesian coordinates of this same point at time t_2 relative to the same reference frame.

Then

$$\begin{aligned} x(t_2) &= x(t_1) + v_x \bullet (t_2 - t_1) \\ y(t_2) &= y(t_1) + v_y \bullet (t_2 - t_1) \\ z(t_2) &= z(t_1) + v_z \bullet (t_2 - t_1) \end{aligned} \qquad \text{(A1)}$$

where [v_x, v_y, v_z] denotes the x-, y-, and z-components of the point's velocity relative to the specified reference frame.

The above equations assume that the motion of the specified terrestrial point between times t_1 and t_2 is adequately characterized by a constant velocity. In particular, the point has not been suddenly displaced by an earthquake or by a bulldozer; nor has the point's location fluctuated significantly due to thermal or hydrological effects, nor has any other motion occurred which is better represented by a non-constant velocity.

Equations similar to Equations A1 can also be formulated to update given geodetic coordinates (latitude, longitude, and ellipsoidal height) at time t_1 to corresponding geodetic coordinates at time t_2, if the velocity components [v_{north}, v_{east}, v_{up}] are available. Alternatively, the geodetic coordinates at time t_1 can be converted to their equivalent geocentric Cartesian coordinates and the north-east-up velocity can be converted to its equivalent geocentric Cartesian velocity, so that Equations A1 may be used to compute the geocentric Cartesian coordinates at time t_2. These Cartesian coordinates can then be converted into their equivalent geodetic coordinates at time t_2.

It should be noted that the HTDP Web-based utility residing at

http://www.ngs.noaa.gov/TOOLS/Htdp/Htdp.shtml

enables its users to update given positional coordinates at time t_1 to corresponding positional coordinates at time t_2 in any of several popular reference frames. The user simply needs to enter either the geocentric Cartesian coordinates or the geodetic coordinates at time t_1 and the velocity. If the user does not know the velocity, then HTDP will predict a velocity based on numerical models encoded into this utility and this utility will allow the user to use this predicted velocity. Finally, HTDP also incorporates numerical models for several major earthquakes, and this utility can apply these models to determine the positional coordinates at time t_2 given the corresponding positional coordinates at time t_1, if the point has been displaced by one of the modeled earthquakes occurring between these times.

Appendix B – Suggestions for determining positional coordinates and velocities for RTN reference stations

The positional coordinates for a RTN reference station may be obtained by processing some of the station's GPS data with the OPUS utility at

http://www.ngs.noaa.gov/OPUS/ .

When adding a new reference station to the National CORS network, NGS processes 24 hours of this station's data for at least 10 different days and then computes the arithmetic mean of all these solutions (after editing out any anomalous results). NGS, however, processes these GPS data in the context of a rigorous least squares adjustment of the entire CORS network, rather than use OPUS.

The problem with using OPUS to determine positional coordinates for a new reference station is that the accuracy of the OPUS solution depends on the accuracy of the

DRAFT

positional coordinates of the three CORS that were used in the OPUS solution. CORS coordinates may be in error because the CORS antenna may have moved since the time when NGS adopted the stations coordinates. As part of its QA/QC process, NGS does monitor the values of all CORS coordinates on a daily basis by performing an adjustment of all CORS data collected during the given day. Using these daily values for the coordinates, NGS will revise the adopted CORS coordinates of a particular station only if the daily values differ consistently from the station's adopted coordinates by more than 1 cm in one of the horizontal dimensions and/or by more than 2 cm in ellipsoidal height. Daily differences for each station in the National CORS network are publicly displayed, for the past 60 days, at http://www.ngs.noaa.gov/CORS/.

As an alternative to using multiple OPUS solutions for determining coordinates for a reference station, NGS recommends that the RTN administrator uses a network adjustment involving GPS data for several days and from several RTN reference stations, including as many National CORS sites in this adjustment as is reasonable. Appropriate adjustment software may be obtained from any of several commercial vendors. Also, the ADJUST software is available for this purpose from NGS at

http://www.ngs.noaa.gov/PC_PROD/ADJUST/ .

In the network adjustment, the RTN administrator should constrain the coordinates of all National CORS sites, contained in the RTN, to the values that are currently adopted by NGS, as updated to the epoch date selected by the RTN administrator. For convenience, the RTN administrator may want to select an epoch date that is reasonably close (less than one year) from the time period spanned by the GPS data included in the adjustment. NGS recommends that the RTN administrator weights the constraints on the CORS coordinates to allow them to adjust by as much as 1 cm in each horizontal dimension and by as much as 2 cm in ellipsoidal height. (Constraints on CORS coordinates should be eliminated whenever the adjusted residuals of these coordinates significantly exceed these tolerances, because this would indicate that the NGS-adopted CORS coordinates are in error. Please contact NGS at ngs.cors@noaa.gov, if this is the case.) Weighted constraints are preferred rather than absolute constraints that hold the CORS coordinates rigidly fixed. With weighted constraints, errors in the CORS coordinates will not significantly distort the computed coordinates for the other RTN reference stations involved in the adjustment.

The advantage of using a network adjustment, as opposed to using multiple OPUS solutions, is that the resulting positional coordinates will be consistent among all reference stations contained in the RTN. Such internal consistency is important because any coordinate discrepancies among the RTN stations would corrupt the GPS correctors being distributed to RTN users. For the sake of internal network consistency, the RTN administrator may want to adopt his/her adjusted values for the CORS coordinates rather than use the NGS-adopted values. This is okay, as long as Recommendation 2 is satisfied.

In summary, NGS recommends a network adjustment to achieve good local accuracy among the RTN reference stations. Furthermore, the adjustment should be constrained so

DRAFT

that the resulting coordinates of all included CORS stations agree reasonably well with the corresponding coordinates adopted by NGS. Consequently, the adjusted coordinates will exhibit good global accuracy with respect to the National Spatial Reference System.

As discussed throughout this chapter, terrestrial points move. The dominant motion is often associated with a constant velocity, but other types of motion also exist. To address possible motion, NGS recommends that RTN administrators adopt a constant velocity for each reference station in their network. The HTDP software at

http://www.ngs.noaa.gov/TOOLS/Htdp/Htdp.shtml

may be used to predict such a velocity in any of several popular reference frames. After a reference station has been in operation for several years, NGS recommends that its velocity be computed from the GPS data that has been collected over the lifespan of this reference station. Such a computed velocity should be more accurate than the HTDP-predicted velocity, if the station's GPS data span more than three years. Computing such velocities is not an easy task, even for NGS. If an accurate velocity for a moving reference station can not be obtained, then the RTN administrator will need to update the station's positional coordinates relatively frequently.

References:

Altamimi, Z., P. Sillard, and C. Boucher (2002) "ITRF2000: A new release of the International Terrestrial Reference Frame for Earth science applications", *J. Geophysical Research*, 107(B10), ETG2/1-19.

Snay, R.A. (2003) "Introducing two spatial reference frames for regions of the Pacific Ocean", *Surveying and Land Information Science*, 63(1), 5-12.

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

Vorhauer, M.L. (2007) "National readjustment of 2007", *The American Surveyor*, May 2007, 48-54.

DRAFT