Recently Adopted Changes to the Terrestrial Reference Frames Used in the United States

Neil D. WESTON, Tomás SOLER and Dan ROMAN, United States

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SUMMARY

During the last year, a number of significant milestones related to terrestrial reference frames were achieved. One of the most notable changes took place on April 17, 2011, when the International GNSS Service (IGS) adopted the IGS08 reference frame, a frame defined by a subset of 232 geocentric stations from the International Terrestrial Reference Frame (ITRF2008) network. The IGS also adopted a new set of absolute calibrated antenna parameters and, consequently, slightly modified positions for 65 of the 232 stations.

The other important change to take place was in the United States and is related to the National Spatial Reference System (NSRS). On September 6, 2011, the National Geodetic Survey (NGS) adopted the latest realization of its geodetic reference frame, the North American Datum of 1983 (NAD 83). The frame actually consists of three independent frames consistent with the rotations of three tectonic plates and are officially known as NAD 83 (2011), NAD 83 (MA11) and NAD 83 (PA11) respectively for the North American plate, the Marianas plate and the Pacific plate. The three frame realizations were derived from the recently completed NGS' Multi-Year CORS solution in which GPS data from most of the NGS managed CORS network and a selected number of IGS global tracking stations were processed simultaneously.

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1. Introduction

Several objectives of the International Earth Rotation and Reference Systems Service (IERS) are to provide the International Terrestrial Reference System (ITRS), the International Terrestrial Reference Frame (ITRF) and the Earth orientation parameters to allow transformations between the ITRF and other geodetic or celestial systems. The latest realization of the international terrestrial reference frame is known as ITRF2008 and is derived from several spaced-based, geodetic techniques such as Global Navigation Satellite Systems (GNSS), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), Satellite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI). In addition, the International GNSS Service (IGS) has also recently adopted a new geocentric terrestrial reference frame known as IGS08. Although the ITRF2008 and IGS08 frames are compatible, the latter is based on a significant contribution from the GPS community. The IGS08 frame contains a subset of 232 globally-distributed, stable and well-performing GPS stations from the ITRF2008 network. Before a Helmert transformation to connect the two frames could be derived, several site-specific corrections such as satellite and ground absolute antenna calibrations had to be applied to the ITRF2008 coordinates of 65 IGS08 stations. The remaining 167 IGS08 reference station coordinates are the same as in ITRF2008.

The National Geodetic Survey (NGS), the primary geodetic agency in the United States, is one of nine IGS Analysis Centers which performs a significant contribution to the calculation of GPS determined satellite orbits, a basic ingredient for the materializtion of ITRF and IGS reference frames. As an example, satellite ephemerides, global tracking station coordinates and other pertinent metadata are usually referenced to the latest reference frame adopted by the IGS. There is one exception however, and that is related to multi-year GPS data which has been reprocessed by NGS. The most recent IGS reprocessing campaign included GPS data from 1994 through early 2011. Orbits re-computed during that period are referenced to IGS05 while those computed from April 17, 2011 onward are referenced to IGS08. Ultimately, tracking station coordinates and velocities derived from the reprocessing effort as well as coordinates derived for newly established stations are referenced in the IGS08 frame, epoch 2005.00. As a result of the reprocessing effort, NGS also decided to adopt IGS08 as the primary global reference frame to which satellite ephemerides and tracking stations are referenced.

The other geodetic system of significant importance in the United States is the National Spatial Reference System (NSRS). The latest realization of its terrestrial reference frame is the North American Datum of 1983 which was adopted on September 6, 2011. Officially known as NAD 83 (2011, MA11, PA11) epoch 2010.00, the current realization is actually defined as three independent frames. The NAD 83 (2011) frame is fixed to the North American plate and encompasses the lower 48 states, Alaska, Canada and the Caribbean. The MA11 frame is fixed with respect to the Marianas plate and contains, among others, the Marianas Islands while PA11 is fixed to the Pacific plate and should be used in Hawaii and a number of other US Territories. These realizations were derived from NGS' Multi-Year CORS Solution in which GPS data from most of the NGS managed CORS network and a selected number of IGS global tracking stations were processed simultaneously.

2. The IGS Network

2.1 Reference Frame Working Group

The Reference Frame Working Group of the IGS is primarily responsible for designing the network and generating the coordinates and velocities for all the reference stations. They are also responsible for estimating the geo-center, computing daily Earth Rotation Parameters (ERP) and producing and disseminating the corresponding covariance information in SINEX format. Daily solutions performed by the analysis centers (ACs) are stacked in a cumulative fashion and aligned to the current IGS realization of the ITRF to obtain the most accurate set of coordinates and velocities at a specific epoch. As of February 27, 2012, there were 364 active stations in the IGS network.

2.2 Selecting IGS08 Reference Stations

A large number of IGS reference stations were used in defining the ITRF2008. However, to derive the IGS08 frame, a much smaller subset of 232 IGS stations were used. These stations were picked based on velocity accuracies, the number of discontinuities, and each station's overall RMS of its residual time series. Some leeway was given during the selection process to account for the geographic distribution of stations. Figure 1 shows a map with the final selection of the IGS08 reference frame stations chosen by the Reference Frame Working Group.

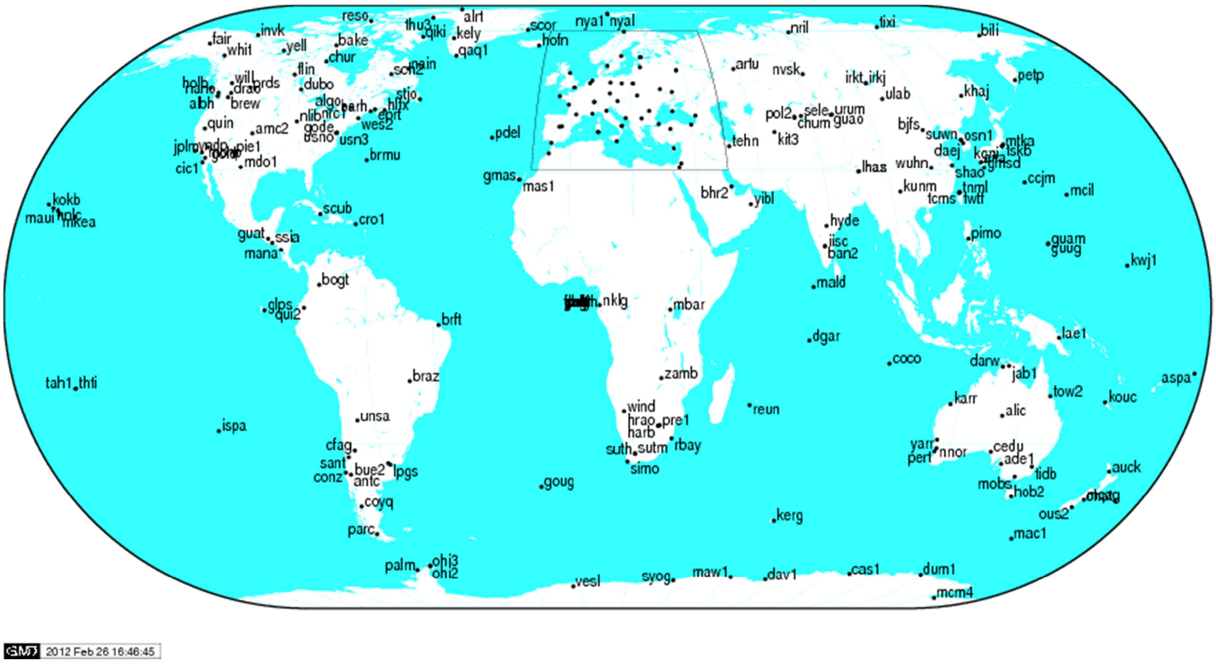

Fig.1. Map showing the location of the 232 reference stations selected for defining the IGS08 reference frame. Courtesy - IGS Central Bureau, JPL, NASA.

The subset consisted of high performing, stable stations whose positions over time remained close to the projected position when advanced by the ITRF piecewise linear velocity model. Additional criteria used to select IGS stations were 1) having a data span greater than five years, 2) having at least three years of data before a discontinuity 3) have less than five discontinuities and 4) having less than 0.3 mm/year error in estimated velocity. In regions where multiple stations were available, selections were made based on which sites had external clocks, multi-constellation receivers and additional collocated positioning techniques. After reviewing the final list of candidate stations, it turned out that most provided data to a central facility on an hourly basis. This was a benefit to those who had applications requiring near real time data access.

In 2008, there were approximately 11 IGS analysis centers (ACs) located around the World that were planning to re-analyze all the GPS data since 1994. One of the principle reasons for this endeavor was because of increasing velocity propagation errors associated with the IGS05 reference frame. Another concern was that ITRF2008 coordinates were consistent with the igs05.atx set of ground antenna calibrations but to move forward in defining IGS08, an updated set of absolute calibrated antennas (igs08.atx) would be needed. The impact of switching from one set of antenna calibrations to another was assessed by using a precise point positioning (PPP) methodology. For most of the stations that were analyzed, the impact was negligible, with differences typically less than 1.2 mm in the East/North and 3 mm in the Up components, but corrections were applied to ITRF2008 coordinates of 65 IGS08 stations.

2.3 Benefits to Reprocessing Data

One of several benefits to reprocessing all of the GPS data was to obtain a consistent set of products such as coordinates (positions and velocities) for all reference stations, daily Earth rotation parameters and satellite ephemerides. Each AC performed their own processing and produced a unique set of cumulatively stacked solutions, each aligned to ITRF2008 via a 14 parameter similarity transformation. The final product was derived using a weighted combination of solutions from all participating ACs. The new IGS08 reference frame and the accompanying antenna calibration information were based on ITRF2008 (released May 2010) and were officially adopted on April 17, 2011.

2.4 Transformation Parameters for the IGS08 Frame

To transform a set of coordinates defined in the IGS05 frame to IGS08, a two step process is required. The first step accounts for station-specific corrections due to antenna pattern updates when switching from igs05.atx to igs08.atx and can be expressed by the following equation:

$$\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix}_{New\ IGS05} = \begin{pmatrix} x \\ y \\ z \end{pmatrix}_{IGS05} + \begin{pmatrix} \delta x \\ \delta y \\ \delta z \end{pmatrix}_{\delta antenna}$$

The second step uses a 14 parameter similarity transformation for the global frame change and is given by the following equation:

$$\begin{pmatrix} x \\ y \\ z \end{pmatrix}_{IGS08} = \begin{pmatrix} x' \\ y' \\ z' \end{pmatrix}_{New\ IGS05} + \boldsymbol{T} + s\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix}_{New\ IGS05} + \boldsymbol{R}\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix}_{New\ IGS05}$$

The rate of change for *x*, *y* and *z* in the IGS08 frame can also be derived from the following equation:

$$\begin{pmatrix} \dot{x} \\ \dot{y} \\ \dot{z} \end{pmatrix}_{IGS08} = \begin{pmatrix} \dot{x}' \\ \dot{y}' \\ \dot{z}' \end{pmatrix}_{New\ IGS05} + \dot{\boldsymbol{T}} + \dot{s}\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix}_{New\ IGS05} + \dot{\boldsymbol{R}}\begin{pmatrix} x' \\ y' \\ z' \end{pmatrix}_{New\ IGS05}$$

For the above equations, **T** is the translation vector, *s* is the scale and **R** is the rotation matrix. Table 1 below contains the elements for **T,** *s* and **R** for the transformation New IGS05 → IGS08. This transformation introduces significant changes in the station geodetic (ellipsoid) height due to the new scale change resulting from the *δantenna* correction. In general, station heights in the northern hemisphere will decrease by approximately 6 mm, due in part, by a decrease in the scale of the IGS05 frame to be consistent with the IGS08 frame and from the change in the *z*-translation. The opposite effect for station heights would be observed in the southern hemisphere.

Parameters at 2005.0		Rates of Parameters	
T_x mm	+1.5 ± 0.2	$\dot{T}_x$ mm/year	-0.1 ± 0.2
T_y mm	+0.0 ± 0.2	$\dot{T}_y$ mm/year	+0.0 ± 0.2
T_z mm	+5.8 ± 0.2	$\dot{T}_z$ mm/year	-0.1 ± 0.2
s ppb	-1.04 ± 0.04	$\dot{s}$ ppb/year	+0.01 ± 0.04
R_x mas	-0.012 ± 0.009	$\dot{R}_x$ mas/year	-0.002 ± 0.009
R_y mas	+0.014 ± 0.009	$\dot{R}_y$ mas/year	-0.003 ± 0.009
R_z mas	+0.014 ± 0.010	$\dot{R}_z$ mas/year	+0.001 ± 0.010

Table 1. Transformation parameters needed to convert coordinates from New IGS05 to IGS08.
[From Rebischung et al., 2012]

3. The National Spatial Reference System

One of the main objectives of NOAA's National Geodetic Survey is to define, maintain and provide access to the National Spatial Reference System (NSRS). The fundamental components of the NSRS are latitude, longitude, geodetic height, orthometric height, gravity and with extension to shoreline information. For this article however, the primary focus will only be on the first three, which are sometimes informally known as the geometric components. The latest realization of the reference frame adopted on September 6, 2011, as mentioned before is the North American Datum of 1983 and is officially known as NAD 83 (2011, MA11, PA11) epoch 2010.00.

3.1 The CORS Network

The CORS network managed by NGS is a multi-purpose cooperative endeavor involving government, academic and private organizations (Snay and Soler, 2008). As of February 2012, the CORS network consisted of approximately 1,750 operating stations, most contributed from over 226 different organizations. The sites are independently owned and operated and support numerous applications. Each agency shares their data with NGS and NGS in turn analyzes and distributes the data free of charge. Some of the more prolific users of CORS data come from the positioning and geophysics communities, transportation sectors, meteorology and space weather agencies, as well as from the construction, mining and petroleum and natural gas industries. Most positioning and navigation applications are mandated at the federal, state and local levels to use the latest NAD 83 reference frame coordinates while those that require tying to the global network (geophysics, space weather) will prefer to work with the latest IGS realization – IGS08. NGS publishes both NAD 83 (2011) epoch 2010.00 and IGS08 epoch 2005.0 coordinates for all of the CORS.

3.2 Connecting to the Global Network

The IGS08 global network illustrated in Fig.2 was primarily designed to yield a robust terrestrial framework and to allow for the production of the most accurate GPS satellite orbits. Since the network of CORS stations in the United States is significantly denser than other networks around the globe, care must be taken when designing the connections to the IGS reference frame stations. The global and CORS networks were integrated by forming many single baselines radiating from the global stations to the CORS (see Fig.3). This design, regulated by a Delaunay triangulation algorithm, was implemented to minimize frame distortions due to local effects from dense regional less stringent networks.

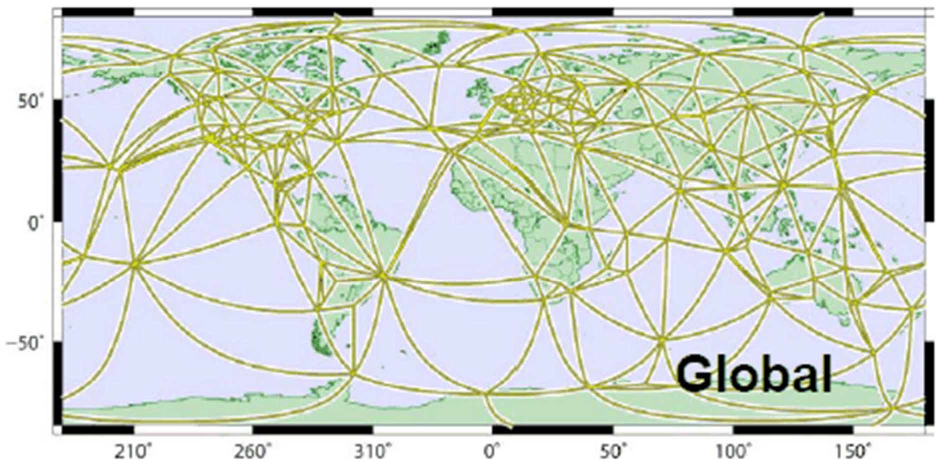

Fig. 2. IGS08 global reference frame showing optimal connections between stations.

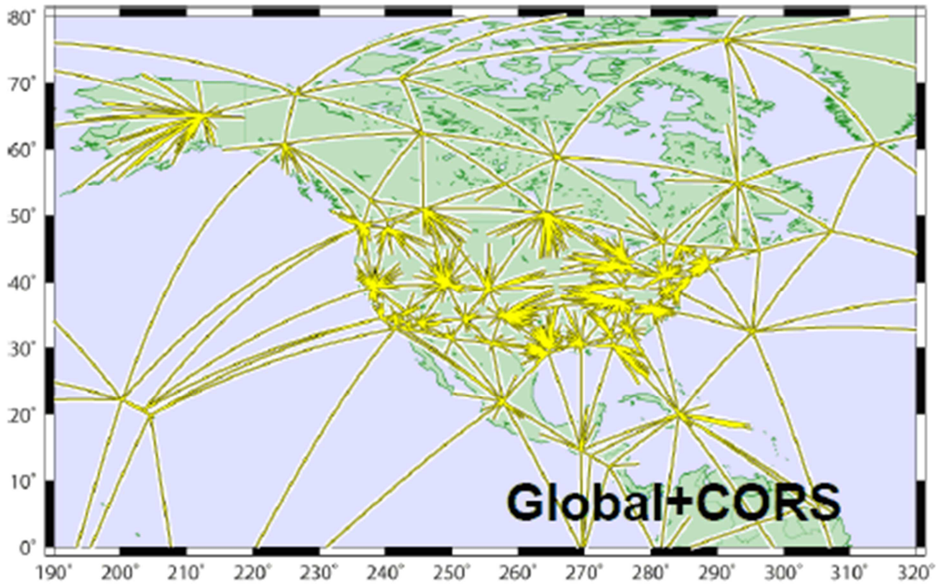

Fig. 3. Integration of global and CORS networks across North America. Global IGS08 stations often connect in a radial configuration to many CORS.

3.3 Processing CORS Data

One of the most resource-intensive operations at NGS is the daily processing of GPS data from the CORS network. The primary purpose of this effort is to compute a set of coordinates for each CORS, add the derived coordinates consecutively to the time series and then compare the results with previous positions derived over time. If the coordinates for the CORS deviate from the mean or accepted position by a specified tolerance, the site is flagged for further analysis and review.

A second set of analyses takes place a week after the data are collected where all CORS are processed together with many of the IGS reference stations in North America. The RINEX files from the CORS are processed in the global frame using absolute antenna calibrations, reprocessed orbits, Earth orientation parameters from NGS and global station coordinates from the IGS. The daily CORS solutions are "stacked" into a weekly SINEX format file where the x, y and z coordinates and their full variance-covariance information for each CORS are preserved.

3.4 Multi-Year Processing Using CATREF

The objective of the Multi-Year effort was to reprocess all GPS data collected from the CORS and IGS networks since 1994.0. The first step would be to review previously computed weekly SINEX solutions from 1994.0 to 2010.5 to identify discontinuities in the time series such as those caused by physical events (earthquakes, subsidence), equipment changes or jumps due to software and model changes and to make sure all CORS were tied to the global frame. The next step would involve stacking the weekly SINEX files using the CATREF software from the Institut Géographique National (IGN). The stacking procedure used unbiased Helmert transformation parameters to align GPS stations, common to all SINEX solutions, to the ITRF2008 frame. ITRF2008 to IGS08 position corrections were then applied at several stations to account for absolute antenna calibration changes with certain antennas. The final step was to run the CATREF program to produce a SINEX solution file, containing new IGS08 positions, velocities and variance-covariance information for all CORS and IGS stations.

3.5 Impacts from the Multi-Year Solution

The results from the Multi-Year solution showed that no significant impact to the NGS derived reference frame was observed when data from the CORS was added to the solution. The transformation from the global frame (IGS08) to the global frame plus CORS was essentially zero - all Helmert transformation parameters were zero. For cases where there were station coordinate differences, most were below 10 mm along the horizontal components and up to 25 mm for the vertical direction and were probably due to weaker portions of the reference frame prior to 1997, and inaccuracies in the velocities for a number of sites in certain areas. The average differences between all stations used in the alignment of IGS08 reference frame with the one produced by NGS using CATREF, when including all the CORS, was 0.00 ± 0.12 mm for the east component, 0.00 ± 0.19 mm for the north component and 0.05 ± 0.41 mm for the up component.

3.6 New NAD 83 Positions

The official adoption of the IGS08 reference frame is compatible with the ITRF2008. There are slight differences where some of the coordinates at several reference stations were updated to account for changes to the absolute antenna calibration patterns. However, the IGS considers the 14 parameter transformation between ITRF2008 and IGS08 to be the identity function – all transformation parameters are zero. Furthermore, the transformation from IGS08 to NAD 83 is also assumed identical to the transformation from ITRF2008 to NAD 83.

A 14 parameter similarity transformation was therefore used to define the relationships between ITRF2008 epoch 2005.00 and NAD 83 (2011) epoch 2010.0 coordinates. The equations below were used to compute new NAD 83 coordinates for all CORS at the completion of the Multi-Year effort. The NAD 83 velocities, on the other hand, are essentially zero by definition because the three plates (North American, Pacific, Marianas) move as a whole and individual points on the plates are assumed to be fixed at a specific epoch. The full equations including the variations with respect to time of the seven parameters are available at (Soler and Snay, 2004; Pearson and Snay, 2012)

$$x(t)_{NAD83} = T_x\,(t) + [1 + s(t)] \cdot x(t)_{ITRF2008} + \omega_z(t) \cdot y(t)_{ITRF2008} - \omega_y(t) \cdot z(t)_{ITRF2008}$$

$$y(t)_{NAD83} = T_y\,(t) - \omega_z(t) \cdot x(t)_{ITRF2008} + [1 + s(t)] \cdot y(t)_{ITRF2008} + \omega_x(t) \cdot z(t)_{ITRF2008}$$

$$z(t)_{NAD83} = T_z\,(t) + \omega_y(t) \cdot x(t)_{ITRF2008} - \omega_x(t) \cdot y(t)_{ITRF2008} + [1 + s(t)] \cdot z(t)_{ITRF2008}$$

For the equations given above, T_x , T_y and T_z are the translational components along the three ITRF2008 orthogonal axes, ω_x , ω_y and ω_z are the rotations about the same axes and *s*(*t*) is the differential scale factor. The numerical values for the parameters to use in the transformation equations to obtain any of the NAD 83 realizations are given in Table 2.

Parameter	ITRF2008->NAD 83	ITRF2008->NAD 83 (MA11)	ITRF2008->NAD 83 (PA11)
T_x m	+0.99343	+0.908	+0.908
T_y m	-1.90331	-2.0161	-2.0161
T_z m	-0.52655	-0.5653	-0.5653
s ppb	+1.71504	+1.1	+1.1
ω_x mas	+25.91467	+28.971	+27.741
ω_y mas	+9.42645	+10.42	+13.469
ω_z mas	+11.59935	+8.928	+2.712

Table 2. Transformation parameters to convert coordinates from ITRF2008 to NAD 83. [From Pearson and Snay, 2012]

4. Conclusion

There are a number of things to consider when switching to IGS08 and the accompanying new antenna calibration information. First, the most important change will be to each station's position due in part by the global effect of a datum change in going from ITRF2005 to ITRF2008. Depending on a station's latitude and which hemisphere it is in, a station's height could differ by as much as ±6 mm. There will also be station-dependent changes due to the antenna if the antenna pattern for the site had an updated calibration pattern. To transform a set of coordinates from IGS05 to IGS08, the first step must account for corrections to include IGS05 offsets from the ground antenna calibration update (igs05.atx to igs08.atx). The second step will consist of two 14 parameter similarity transformations to obtain the positions and rates at the station.

New NAD 83 positions for the CORS in the United States were also made available on October 6, 2011. The changes between the two, NAD 83 (CORS96) epoch 2002.0 and NAD 83 (2011) epoch 2010.0 are primarily due to a number of factors. The first is that eight more years of data became available for analysis. Another concern became evident when predicted positions were computed using modeled (estimated) velocities to advance a set of positions at a published epoch to a new epoch. Deviations between computed and predicted positions usually occur when the period between the published and new epoch is large, for example 8 or more years, or if the velocities used to advance the positions are not accurate and do not reflect what geophysical phenomena are occurring at the CORS or region of interest. Last but not least, new improvements in GPS processing software (e.g. improved ocean loading models, etc.) should not be discarded.

REFERENCES

Altamimi Z., and Collilieux X., (2009), IGS contribution to ITRF. *J. Geodesy*, 83(3-4):375-383

Altamimi Z., Collilieux X., and Métivier L., (2011), ITRF2008: an improved solution of the International Terrestrial Reference Frame. *J. Geodesy*, 85(8):457-473.

Collilieux X., Métivier L., Altamimi Z., van Dam T., and Ray J., (2011a), Quality assessment of GPS reprocessed terrestrial reference frame. *GPS Solutions*. 15(3):219-231.

Dow J.M., Neilan R. E., and Rizos C., (2009), The International GNSS Service in a changing landscape of Global Navigation Satellite Systems. *J. Geodesy,* 83(3-4):191–198, DOI: 10.1007/s00190-008-0300-3

Rebischung P., Griffiths J., Ray J., Schmid R., Collilieux X., and Garayt B., (2012), IGS08: the IGS realization of ITRF2008. *GPS Solutions*. (in press) DOI 10.1007/s10291-011-0248-2.

Pearson C., and Snay R., (2012), Introducing HTDP 3.1 to transform coordinates across time and spatial reference frames. *GPS Solutions*. (in press) DOI 10.1007/s10291-012-0255-y.

Snay R.A., and Soler T., (2008), Continuously Operating Reference Station (CORS): History, applications, and future enhancements. *J. Surv. Eng.*, 134(4): 95-104.

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

BIOGRAPHICAL NOTES

Dr. Neil D. Weston is the Chief of the Spatial Reference System Division at the National Geodetic Survey. His team is responsible for defining and maintaining the National Spatial Reference System in the United States. His other interests are in GNSS software development, 3-D imaging and motion analysis.

Dr. Tomás Soler has served as an NGS scientist since 1979. Tom supervised the GPS Branch from 1990 – 2003 and currently serves as the Chief Technical Officer in the Spatial Reference System Division of the National Geodetic Survey.

Dr. Daniel Roman has been a Research Geodesist since 1999. He is the Team Lead for Geoid Modeling Research and is the Principle Investigator for The Gravity for Redefinition of the American Vertical Datum (GRAV-D). He developed Geoid99, Geoid03, Geoid06, Geoid09 and other associated models.

CONTACTS

Dr. Neil D. Weston
National Geodetic Survey, NOAA
1315 East West Hwy, SSMC#3, Room 8813
Silver Spring, Maryland
United States
Tel. +1-301-713-3191
Fax +1-301-713-4324
Email: neil.d.weston@noaa.gov
Web site: www.ngs.noaa.gov