A GUIDE TO USING INTERNATIONAL GNSS SERVICE (IGS) PRODUCTS

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Abstract

Since 1994, the International GNSS Service (IGS) has provided precise GPS orbit products to the scientific community with increased precision and timeliness.   Many national geodetic agencies and GNSS (Global Navigation Satellite System) users interested in geodetic positioning have adopted the IGS precise orbits to achieve centimeter level accuracy and ensure long-term reference frame stability. Relative positioning approaches that require the combination of observations from a minimum of two GNSS receivers, with at least one occupying a station with known coordinates are commonly used. The user position can then be estimated relative to one or multiple reference stations, using differenced carrier phase observations and a baseline or network estimation approach.   Differencing observations is a popular way to eliminate common GNSS satellite and receiver clock errors.   Baseline or network processing is effective in connecting the user position to the coordinates of the reference stations while the precise orbit virtually eliminates the errors introduced by the GNSS space segment. One drawback is the practical constraint imposed by the requirement that simultaneous observations be made at reference stations. An alternative post-processing approach uses un-differenced dual-frequency pseudorange and carrier phase observations along with IGS precise orbit products, for stand-alone precise geodetic point positioning (static or kinematic) with centimeter precision. This is possible if one takes advantage of the satellite clock estimates available with the satellite coordinates in the IGS precise orbit/clock products and models systematic effects that cause centimeter variations in the satellite to user range. Furthermore, station tropospheric zenith path delays with mm precision and GNSS receiver clock estimates precise to 0.03 nanosecond are also obtained. To achieve the highest accuracy and consistency, users must also implement the GNSS-specific conventions and models adopted by the IGS. This paper describes both post-processing approaches, summarizes the adjustment procedure and specifies the Earth and space based models and conventions that must be implemented to achieve mm-cm level positioning, tropospheric zenith path delay and clock solutions.

1. Introduction

The International GNSS Service (IGS) (Dow et al., 2009), formerly the International GPS Service, is a voluntary collaboration of more than 200 contributing organizations in more than 80 countries. The IGS global tracking network of more than 300 permanent, continuously-operating GNSS stations provides a rich data set to the IGS Analysis Centers, which formulate precise products such as satellite ephemerides and clock solutions. IGS Data Centers freely provide all IGS data and products for the benefit of any investigator. This paper focuses on the advantages and usage of the IGS precise orbits and clocks.

Currently, up to ten IGS Analysis Centers (AC) contribute daily Ultra-rapid, Rapid and Final GPS/GLONASS orbit and clock solutions to the IGS combinations. The daily computation of global precise GPS/GLONASS orbits and clocks by IGS, with centimeter precision, facilitates a direct link within a globally integrated, reference frame which is consistent with the current International Terrestrial Reference Frame (ITRF). Since 2000 the ultra-rapid product originally designed to serve meteorological applications and support Low Earth Orbiter (LEO) missions, has been made available. After several years of pilot project operation, on April 1, 2013, the IGS Real Time Service (RTS) has been officially launched,

providing precise orbit/clocks products in real time. The ultra-rapid and RTS products have since become useful to many other real-time and near real-time users, as well. For more information on the IGS combined solution products and their availability see the IGS Central Bureau (see http://igs.org/products).

For GNSS users interested in meter level positioning and navigation, a simple point positioning interface combining pseudorange data with IGS precise orbits and clocks (given at 15 min intervals) can be used (e.g. Héroux et al., 1993; Héroux and Kouba, 1995). Since May 2, 2000 when GPS Selective Availability (SA) was switched off these products also satisfy GPS users observing at high data rates in either static or kinematic modes for applications requiring meter precision. This is so, because the interpolation of the 15-min SA-free satellite clocks given in IGS sp3 files is possible at the precision level of a few dm. Furthermore, since December 26, 1999, separate, yet consistent, clock files, containing separate combinations of satellite/station clocks at 5-min sampling intervals have been available and on November 5, 2000, the clock combinations became the official IGS clock products (Kouba and Springer, 2001). The 5-min clock sampling allows an interpolation of SA-free satellite clocks well below the dm level (Zumberge and Gendt, 2000). In order to keep clock interpolation errors at or below the cm-level, starting with GPS Week 1410 (January 14, 2007), the IGS Final clock combinations also include additional clock files with 30-sec sampling. For GNSS users seeking to achieve geodetic precision, sophisticated processing software packages such as GIPSY (Lichten et al., 1995), BERNESE (Dach et al., 2007) and GAMIT (King and Bock, 1999) are required. However, by using the IGS precise orbit products and combining the GNSS carrier phase data with nearby IGS station observations, geodetic users can achieve precise relative positioning consistent with the current global International Terrestrial Reference Frame (ITRF), with great ease and efficiency and with relatively simple software. For example, differential software packages provided by receiver manufacturers may also be used, as long as they allow for the input of the station data and orbit products in standard (IGS) formats and conform to the international (IGS and IERS) conventions and standards (see Section 5.3).

The precise point positioning (PPP) algorithms based on un-differenced carrier phase observations have been added to software suites using un-differenced observations such as GIPSY (Zumberge et al., 1997) and more recently even the traditional double-differencing software package such as the BERNESE has been enhanced also to allow precise point positioning. Users now have the option of processing data from a single station to obtain positions with centimeter precision within the reference frame provided by the IGS orbit products. PPP eliminates the need to acquire simultaneous tracking data from a reference (base) station or a network of stations. It has given rise to centralized geodetic positioning services that require from the user a simple submission of a request and a valid GNSS observation file (see e.g., Ghoddousi-Fard and Dare, 2005). An alternative approach is an implementation of simple PPP software that effectively distributes processing by providing portable software that can be used on a personal computer. This software then takes full advantage of consistent conventional modeling and the highly accurate global reference frame, which is made available through the IGS orbit/clock combined products.

For both relative and PPP methods that utilize IGS orbit/clock products, there is no need for large and sophisticated global analyses with complex and sophisticated software. This is so because the IGS orbit/clock products retain all the necessary information of the global analyses that have already been done by the IGS ACs, using the state of art knowledge and software tools. Thus, the users of the IGS products in fact take full advantage of the IGS AC global analyses, properly combined and quality checked, all in accordance with the current international conventions and standards.

2. IGS Orbit/Clock Combined Products

Even though, strictly speaking, it is illegitimate to combine solutions that are based on the same observation data set, the combinations of Earth Rotation Parameters (ERP) and station coordinate solution submissions have been successfully used by the International Earth Rotation and Reference Systems Service (IERS) for many years. Such combinations typically result in more robust and precise solutions, since space technique solutions are quite complex, involving different approaches and modeling that typically generate a random-like noise which is then averaged out within the combination process. This approach is also valid for the combination of IGS orbit solutions as clearly demonstrated by Beutler et al.,

(1995) who have also shown that, under certain conditions, such orbit combinations represent physically meaningful orbits as they still satisfy the equations of motions. Furthermore, when the AC weights resulting from orbit combinations are used in the corresponding ERP combinations (as done for all IGS combinations before February 27, 2000 and currently still being done for the Rapid and Ultra-Rapid ones only), the crucial consistency between the separately combined orbits and ERP solutions is maintained.

The IGS combined orbit/clock products come in various flavors, from the Final, Rapid, the Ultra-Rapid to RTS ones. The IGS Ultra-Rapid (IGU) products replaced the former IGS predicted (IGP) orbit products on November 5, 2000 (GPS Week 1087, MJD 5183), the RTS combined products have been officially made available since April 1, 2013 (GPS Week 1786/Day 2, MJD 56748). The IGS combined orbit/clock products differ mainly by their varying latency and the extent of the tracking network used for their computations. The IGS Final orbits (clocks) are currently combined from up to nine contributing IGS ACs, using seven, largely independent, software packages (i.e. BERNESE, GAMIT, GIPSY, NAPEOS (Springer et al., 2011), EPOS (Gendt et al., 1999), PAGES (Schenewerk et al., 1999) and GINS/Dynamo (Marty 2009). The IGS Final orbit/clocks are usually available before the thirteenth day after the last observation. The Rapid orbit/clock product is combined 17 hours after the end of the day of interest. The latency is mainly due to the varying availability of tracking data from stations of the IGS global tracking network, which use a variety of data acquisition and communication schemes, as well as different levels of quality control. In the past, the IGS products have been based only on a daily model that required submissions of files containing tracking data for 24-hour periods. In 2000, Data Centers have been asked to forward hourly tracking data to accelerate product delivery. This new submission scheme was required for the creation of an Ultra-Rapid product, with a latency of only a few hours (currently 3 hours), which should satisfy the more demanding needs of most real-time users, including the meteorological community and LEO (Low Earth Orbiter) missions. It is expected that IGS products will continue to be delivered with increased timeliness in the future (Weber et al., 2002a). Development of true real-time products, mostly satellite clock corrections, has been accomplished by the IGS Real-Time Pilot Project, which on April 1, 2013 has resulted in the IGS RTS (Caissy et al., 2012). For more information on the IGS products and their possible applications see e.g. Neilan et al. (1997); Kouba et al. (1998b) and Dow et al. (2005).
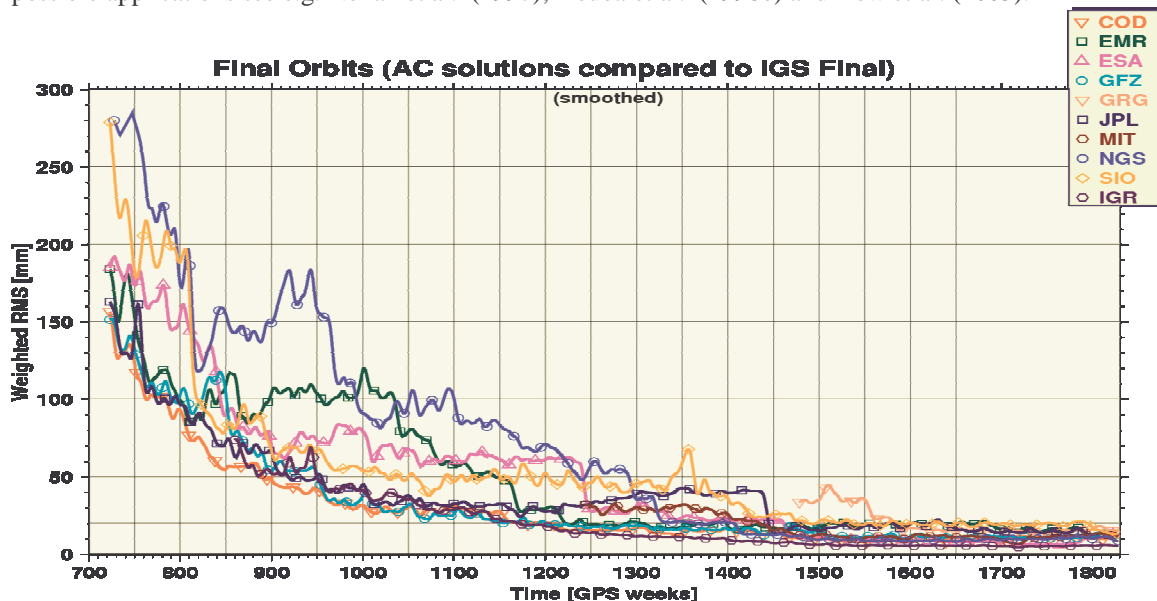

Figure 1: Weighted orbit RMS of the IGS Rapid (*IGR*) products and AC Final orbit solutions during 1994-2015 with respect to the IGS Final orbit products. (*COD* – Center for Orbit Determination in Europe, Switzerland; *EMR* – Natural Resources Canada; *ESA* **-** European Space Agency; *GFZ* – GeoForschungsZentrum Potsdam, Germany; GRG - Groupe de Recherche de Géodésie Spatiale (GRGS)/ Centre National d'Etudes Spatiales (CNES) ; *JPL* – Jet Propulsion Laboratory, U.S.A.; *MIT*- Massachusetts Institute of Technology, U.S.A.; *NGS* – National Geodetic Survey, NOAA, U.S.A.; *SIO* - Scripps Institute of Oceanography, U.S.A.). (Courtesy of the IGS ACC, see http://acc.igs.org/)

From Figure 1, one can see that over the past 15 years the precision of the AC Final orbits has improved from about 30 cm to about 1 - 2 cm, with a concomitant improvement in the IGS Final combined orbit. The current precision of IGS combined orbits has been attained since about GPS Week 1400 (November 5, 2006) when the IGS05 realization of ITRF2005 has been adopted. It is also interesting to note that the IGS Rapid orbit combined product (IGR), with less tracking stations and faster delivery times, is now more precise than the best AC Final solutions. The precision of the corresponding AC/IGS ERP solutions has shown similar improvements since 1994. One element that has received less attention is the quality of the GPS satellite clock estimates included in the IGS orbit products since 1995. Examining the summary plots for IGS Final clock combinations at the IGS AC Coordinator (ACC) web site (http://acc.igs.org/), one can notice that after small biases are removed, the satellite clock estimates produced by different ACs now agree with standard deviations of 0.02 - 0.06 nanosecond (ns) or 1 - 2 cm. This is also consistent with the orbit precision. Any biases in the individual IGS satellite clocks will be absorbed into the phase ambiguity parameters that users must estimate. The precise GNSS orbits and clocks, weighted according to their corresponding precision (sigmas), are the key prerequisites for PPP, given that the proper measurements are made at the user site and the observation models are implemented correctly.

3. Observation equations

The ionospheric-free combinations of dual-frequency (f_1, f_2) GPS (or GNSS) pseudorange (P) and carrier-phase observations (Φ) are related to the user position, clock, troposphere and ambiguity parameters according to the following simplified observation equations:

$$\ell_P = \rho + c(dT\text{-}dt) + T_r + \varepsilon_P \qquad (1)$$
$$\ell_\phi = \rho + c(dT\text{-}dt) + T_r + N\lambda + \varepsilon_\Phi \qquad (2)$$

Where :

$\quad\ell_P (P3)$ is the ionosphere-free combination of P_1 and P_2 pseudoranges $(f_1{}^2 P_1 - f_2{}^2 P_2)/(f_1{}^2\text{-}f_2{}^2)$,

$\quad\ell_\Phi (L3)$ is the ionosphere-free combination of $L1$ and $L2$ carrier-phases $(f_1{}^2\lambda_1\phi_1 - f_2{}^2\lambda_2\phi_2)/(f_1{}^2\text{-}f_2{}^2)$,

$\quad f_1, f_2 \quad$ are the $L1, L2$ frequencies (for GPS 1575.42 and 1227.6 MHz, respectively)

$\quad dT \qquad$ is the station receiver clock offset from the GPS (or GNSS) time,

$\quad dt \qquad$ is the satellite clock offset from the GPS (or GNSS) time,

$\quad c \qquad$ is the vacuum speed of light,

$\quad T_r \qquad$ is the signal path delay due to the neutral-atmosphere (primarily the troposphere),

$\quad N \qquad$ is the non-integer ambiguity of the carrier-phase ionosphere-free combination,

$\quad \lambda_1, \lambda_2, \lambda$ are the of the carrier- phase $L1$, $L2$ and $L3$-combined (10.7cm) wavelengths, respectively,

$\quad \varepsilon_P, \varepsilon_\Phi \quad$ are the relevant measurement noise components, including multipath.

Symbol ρ is the geometrical range computed by iteration from the satellite position (Xs, Ys, Zs) at the transmission epoch t and the station position (x, y, z) at the reception epoch $T = t + \rho/c$, i.e.

$$\rho = \sqrt{(Xs\text{-}x)^2 + (Ys\text{-}y)^2 + (Zs\text{-}z)^2} \quad .$$

Alternatively, for relative positioning between two stations (i, j) the satellite clock errors dt can be eliminated simply by subtracting the corresponding observation Eqs. (1) and (2) made from the two stations (i, j) to the same satellite (k), i.e.:

$$\ell_{Pij}{}^k = \Delta\rho_{ij}{}^k + c\Delta dT_{ij} + \Delta T_{rij}{}^k + \Delta\varepsilon_{Pij}{}^k , \qquad (3)$$
$$\ell_{\Phi ij}{}^k = \Delta\rho_{ij}{}^k + c\Delta dT_{ij} + \Delta T_{rij}{}^k + \Delta N_{ij}{}^k \lambda + \Delta\varepsilon_{\Phi ij}{}^k , \qquad (4)$$

where $\Delta(.)_{ij}{}^k$ denotes the single difference. By subtracting the observation Eqs. (3) and (4) pertaining to the stations (i, j) and the satellite k from the corresponding equations of the stations (i, j) to the satellite l, we

can form so called double differenced (DD) observation equations, where the station clock difference errors ΔdT_{ij}, which are the same for both single differences, are also eliminated, which is generally true for GPS where all the satellites use common carrier frequencies:

$$\ell_{P_{ij}}{}^{kl} = \Delta\rho_{ij}{}^{kl} + \Delta T_{rij}{}^{kl} + \Delta\varepsilon_{Pij}{}^{kl}, \tag{5}$$

$$\ell_{\Phi_{ij}}{}^{kl} = \Delta\rho_{ij}{}^{kl} + \Delta T_{rij}{}^{kl} + \Delta N_{ij}{}^{kl}\lambda + \Delta\varepsilon_{\Phi_{ij}}{}^{kl}, \tag{6}$$

where $\Delta(.)_{ij}{}^{kl}$ represents the respective double difference for the (i, j) station and (k, l) satellite pairs. Furthermore, the initial L1 and L2 phase ambiguities that are used to evaluate the ionospheric-free ambiguities $\Delta N_{ij}{}^{kl}$ become integers. This is so since the fractional phase initializations on L1 & L2 for the station (i, j) and satellite (k, l) pairs, much like station/satellite clock errors, are also eliminated by the above DD scheme. Consequently, once the L1 and L2 ambiguities are resolved, the ionospheric-free ambiguities $\Delta N_{ij}{}^{kl}$ become known and can thus be removed from the equation (6), which then becomes equivalent to the pseudorange equation (5), i.e. double differenced phase observations with fixed ambiguities become precise pseudorange observations that are derived from unambiguous precise phase measurement differences. That is why fixed ambiguity solutions yield relative positioning of the highest possible precision, typically at or below the mm precision level (e.g. Hofmann-Wellenhof et al., 1997).

The above integer phase ambiguity resolution may be compromised for GLONASS, since, unlike GPS and other GNSS', GLONASS satellites use slightly different carrier frequencies (frequency channels). Then, a small offset between pseudorange and phase observation epochs, constant and usually known within a receiver, causes small, frequency channel dependent phase biases (Sleewaegen et al., 2012). However, *when GLONASS data phase and pseudorange observations refer to the same epoch (clock) as required by the RINEX format, there are no GLONASS inter channel phase biases!* If uncorrected (i.e., improperly RINEXed) GLONASS data is used, DD phase observations no longer have integer character and the GLONASS channel phase biases are absorbed into the real phase ambiguity solutions. Note that the GLONASS frequency dependent pseudorange biases, which can reach up to several m, unlike the phase ones, are real and cannot be removed during RINEXing. They have to be either externally calibrated, or mitigated by an appropriately increased standard deviation of GLONASS pseudorange observations.

The equations (1), (2) and (5), (6) appear to be quite different, with a different number of unknowns and different magnitudes of the individual terms. For example, the double differenced tropospheric delay $\Delta T_{rij}{}^{kl}$ is much smaller than the un-differenced $T_{r,}$ the noise $\Delta\varepsilon(.)_{ij}{}^{kl}$ is significantly larger than the original, un-differenced noise $\varepsilon(.)$, etc. Nevertheless, both un-differenced and DD approaches produce identical results, provided that the same set of un-differenced observations and proper correlation derived from the differencing, are used. In other words, the DD difference position solutions with properly propagated observation weight matrix (see e.g. Hofmann-Wellenhof et al., 1997), are completely equivalent to un-correlated, un-differenced solutions where the (satellite/station) clock unknowns are solved for each observation epoch.

Since we are using the IGS orbit/clock products, the satellite clocks (dt) in Eqs. (1) and (2) can be fixed (considered known) and thus can be removed. Furthermore, expressing the tropospheric path delay (T_r) as a product of the zenith path delay (zpd) and mapping function (M), which relates slant path delay to zpd, gives the point positioning mathematical model functions for pseudorange and phase observations:

$$f_P = \rho + c\, dT + M\, zpd + \varepsilon_P - \ell_P = 0, \tag{7}$$

$$f_\Phi = \rho + c\, dT + M\, zpd + N\lambda + \varepsilon_\Phi - \ell_\Phi = 0; \tag{8}$$

The tropospheric path delay ($M\, zpd$) is separated in a predominant and well-behaved hydrostatic part ($M_h\, zpd_h$) and a much smaller and volatile wet part ($M_w\, zpd_w$). While zpd_h can be modeled and considered known, zpd_w has to be estimated. For most precise solutions, temporarily varying zpd_h, M_h and M_w have to be based either on global seasonal models (Boehm et al., 2006; Boehm et al., 2007), NWM - numerical weather models (Boehm and Schuh, 2004; Kouba, 2007), or alternatively (and potentially more precisely)

zpd_h can be computed from measured station atmospheric pressure (see e.g., Kouba, 2009). For a concise summary of precise zpd modeling, consult the IERS Conventions Chapter 9 (IERS 2010).

Unlike the Eqs. (1) - (6) that contain unknowns and/or observation differences involving baselines or the whole station network, the Eqs. (7) and (8), after fixing known satellite clocks and positions, contain observations and unknowns pertaining to a single station only. Note that satellite clock and orbit weighting does not require the satellite clock and position parameterizations, since the satellite clock and position weighting can be effectively accounted for by satellite specific pseudorange/phase observation weighting. So, unless attempting to fix integer ambiguities (see below), it makes little or no sense to solve Eqs. (7) and (8) in a network solution as it would still result in uncorrelated station solutions that are exactly identical to independent, single station, point positioning solutions.

Conversely, if a network station solution with a full variance-covariance matrix is required, such as is the case of a Regional Network Associated Analysis Center (RNAAC) processing (see e.g., http://www.ngs.noaa.gov/IGSWorkshop2008/docs/IGSACWS_TAH_RNAAC.ppt), only the observation Eqs. (1) - (6) are meaningful and should be used. Also note that in single point positioning solutions it is not possible to fix *L1, L2* integer ambiguities, unlike for the network solutions utilizing DD or even un-differenced observations. For un-differenced network solutions, the resolved *L1, L2* DD integer ambiguities are used to derive the ionospheric-free real ambiguities and then the known DD integer ambiguities are introduced as condition equations into the corresponding matrix of the normal equations. An alternative and more efficient approach is to generate satellite phase clocks and satellite wide-lane biases that are made consistent with the resolved integer *L1, L2* phase ambiguities. Then even a single PPP user can resolve and fix integer phase ambiguities without any need of additional station network data (Laurichesse and Mercier 2007). The Decoupled Clock Model of Collins (2008), in addition to the above phase clocks and wide-lane biases, also generates separate satellite pseudorange clocks, in order to remove common mode pseudorange biases. It is worth to note that PPP (Eqs. (7) and (8)) allows position, tropospheric zenith path delay and receiver clock solutions that are consistent with the global reference system, implied by the fixed orbit/clock products. The differential (Eqs. (5) and (6)), on the other hand, does not allow for any precise clock solutions, and the tropospheric zpd_w solutions may be biased by a constant (datum) offset, in particular for regional and local baselines/networks (< 500 km). Thus, such regional/local zpd_w solutions, based on DD network analyses, require external tropspheric zpd_w calibration (at least at one station), e.g. by means of PPP, or the IGS troposheric combined zpd products (Gendt, 1996, 1998; Byun and Bar-Sever, 2009).

4. Adjustment models

For the sake of simplicity, only the point positioning approach is discussed in this section. However, the adjustments of un-differenced or differenced data in network solutions are quite analogous to this rather simple, yet still precise point positioning case.

Linearization of the observation Eqs. (7) and (8) around the a-priori parameter values and observations (X^0, ℓ) in the matrix form becomes:

$$A \ \delta + W - V = 0, \tag{9}$$

where *A* is the design matrix, δ is the vector of corrections to the unknown parameters *X*, $W = f(X^0, \ell)$ is the misclosure vector and *V* is the vector of residuals.

The partial derivatives of the observation equations with respect to *X*, which in the case of PPP consist of four types of parameters: station position (*x, y, z*), receiver clock (*dT*), wet troposphere zenith path delay (zpd_w) and (non-integer) carrier-phase ambiguities (*N*), form the design matrix *A*:

$$A = \begin{bmatrix} \dfrac{\partial f(X,\ell_P)}{\partial X_x} & \dfrac{\partial f(X,\ell_P)}{\partial X_y} & \dfrac{\partial f(X,\ell_P)}{\partial X_z} & \dfrac{\partial f(X,\ell_P)}{\partial X_{dT}} & \dfrac{\partial f(X,\ell_P)}{\partial X_{zpd_w}} & \dfrac{\partial f(X,\ell_P)}{\partial X_{N^j_{(j=1,nsat)}}} \\[4mm] \dfrac{\partial f(X,\ell_\Phi)}{\partial X_x} & \dfrac{\partial f(X,\ell_\Phi)}{\partial X_y} & \dfrac{\partial f(X,\ell_\Phi)}{\partial X_z} & \dfrac{\partial f(X,\ell_\Phi)}{\partial X_{dT}} & \dfrac{\partial f(X,\ell_\Phi)}{\partial X_{zpd_w}} & \dfrac{\partial f(X,\ell_\Phi)}{\partial X_{N^j_{(j=1,nsat)}}} \end{bmatrix}$$

$$with: \frac{\partial f}{\partial X_x} = \frac{x - Xs}{\rho}, \quad \frac{\partial f}{\partial X_y} = \frac{y - Ys}{\rho}, \quad \frac{\partial f}{\partial X_z} = \frac{z - Zs}{\rho},$$

$$\frac{\partial f}{\partial X_{dT}} = c, \quad \frac{\partial f}{\partial X_{zpd_w}} = M_w, \quad \frac{\partial f}{\partial X_{N^j_{(j=1,nsat)}}} = 0 \quad or \quad 1$$

$$X = \begin{bmatrix} x \\ y \\ z \\ dT \\ zpd_w \\ j \\ N_{(j=1,nsat)} \end{bmatrix}.$$

The least squares solution with *a-priori* weighted parameter constraints (P_{X^o}) is given by:

$$\delta = -(P_{X0} + A^T P_\ell A)^{-1} A^T P_\ell W, \tag{10}$$

where P_ℓ is the observation weight matrix. For un-differenced observations it is usually a diagonal matrix with the diagonal terms equal to $(\sigma_o/\sigma_P)^2$ and $(\sigma_o/\sigma_\Phi)^2$, where σ_o is the standard deviation of the unit weight, σ_P and σ_Φ are the standard deviations (sigmas) of pseudorange and phase observations, respectively. Typically, $\sigma_\Phi \cong 10$ mm and the ratio of $\sigma_P/\sigma_\Phi \geq 100$ are used for ionospheric-free un-differenced phase and pseudorange observations. Then the estimated parameters are

$$\hat{X} = X^0 + \delta,$$

with the corresponding weight coefficient matrix (the a priori variance-covariance matrix when $\sigma_o=1$)

$$C_{\hat{X}} = P_{\hat{X}}^{-1} = (P_{X0} + A^T P_\ell A)^{-1}. \tag{11}$$

The weighted square sum of residuals is obtained from the residuals, evaluated from Eq. (9) and the parameter correction vector (Eq. 10) as follows:

$$V^T PV = \delta^T P_{X0} \delta + V^T P_\ell V, \tag{12}$$

or from an alternative, but numerically exactly equivalent expression:

$$V^T PV = V^T P_\ell W. \tag{13}$$

Both expressions can be used to check the numerical stability of the solution (Eq. 10). Finally, the a posteriori variance-covariance matrix of the estimated parameters is

$$\Sigma_{\hat{X}} = \hat{\sigma}_0^2 (P_{X0} + A^T P_\ell A)^{-1}, \tag{14}$$

where the a posteriori variance factor is estimated from the square sum of residuals and the degrees of freedom $df = n - u$; (n , u are the number of observations and the number of effective unknowns, respectively):

$$\hat{\sigma}_0^2 = \frac{V^T P V}{(n-u)} .$$ (15)

The formal variance-covariance matrices Eq. (14) are usually too optimistic (with too small variances), typically by a factor 5 or more, depending on the data sampling and the complexity of error modeling used in GNSS analyses. The longer the data sampling interval and the more sophisticated error modeling are, the smaller (and closer to 1) the factor tends to be.

A note on non-integer number of degrees of freedom is due at this point, since, in principle, all or none of the parameters X^0 can be weighted. Thus the trace (u') of the a priori parameter weight matrix P_x effectively determines an equivalent of the number of observations, so that the effective number of unknowns $u = u_x - u'$ (u_x is the dimension of the parameter vector X^0) can be a real number attaining values between 0 and u_x. This can make the number of degrees of freedom $df = n - u$ a non integer number.

4.1 Statistical testing, data editing

The simplest statistical testing/data editing usually involves uni-variate statistical tests of the misclosures W and residuals V that are based on limits equal to a constant multiple (k) of sigmas, i.e. using the probability P at the probability level ($1-\alpha$) and the phase misclosures:

$$P\{ -k\,\sigma_{\Phi} < w_{\Phi j} < k\,\sigma_{\Phi} \} = (1-\alpha); \quad j=1, n \qquad (n\text{- number of observations}),$$ (16)

where α is the probability that the variable $|w_{\Phi j}| > k\,\sigma_{\Phi}$. For example, for the Normal Distribution (ND) and the 99% probability level $k = 2.58$. The *Chebyshev* inequality, which is consistent with a wide range of error distributions, states that for all general (non Normal) error distributions the probability P that the variable is within the limits of $\pm k\,\sigma_{\Phi}$ is greater or equal to $(1-\alpha)$, provided that $k = (\alpha)^{-1/2}$ (e.g. Hamilton, 1964). When $\alpha = 0.05$ is assumed then $k = 4.47$. That is why the sigma multipliers of 5 and 3 are usually chosen for the outlier testing of misclosures and residuals, respectively. Note that in the above tests, strictly speaking, a posteriori estimates of the observation sigmas should be used, i.e.

$$\hat{\sigma}_{\Phi} = \hat{\sigma}_0\,\sigma_{\Phi} .$$ (17)

When assuming the ND, the square sum of residuals (12), (13) are distributed according to the well known χ^2 variable, thus the square sums can be effectively tested, at the $(1-\alpha)$ probability level, against the statistical limit of $\hat{\sigma}_0^2 \chi^2_{df, \alpha/2}$. This test can also be applied to the square sum of weighted parameters (the first term on the right hand side of Eq. (12)), or to other subgroups of the weighted parameters and/or residuals. E.g., the residuals pertaining to a specific satellite and/or station can be tested in this way. Alternatively, the above χ^2 test could be applied to a single epoch increment of the square sum of residuals Eqs. (12) or (13). The power of this test is increasing with the decreasing group size (i.e. the increment of the number of degrees of freedom). For a single residual and/or parameter this χ^2 test becomes exactly equivalent to the well-known Student's t_α test (equivalent to the above ND test (Eq. 16) for large number of degrees of freedom, i.e. when $df => \infty$), since $\chi^2_{1,\alpha} = (t_\alpha)^2$. For more details and an extended bibliography on statistical testing in geodetic applications see e.g. Vaníček and Krakiwsky (1986).

Data editing and cycle slip detection for un-differenced, single station observations is, indeed, a major challenge, in particular during periods of high ionospheric activities and/or station in the ionospherically disturbed polar or equatorial regions. This is so, since the difference between *L1* and *L2* phase observations are usually used to check and edit cycle slips and outliers. However, in the extreme cases, this editing approach would need data sampling higher than 1 Hz in order to safely recognize or edit cycle slips or outliers and such high data samplings are not usually available. (Note that within a geodetic receiver, at least in principle, it should be possible to do an efficient and reliable data cleaning/editing based on the *(L1-L2)* or *L1, L2* phase fitting, since data samplings much higher than 1 Hz are internally available). Most of

IGS stations have data sampling of only 30 s, which is why efficient statistical editing/error detection tests are mandatory, especially for un-differenced, single station observation analyses.

On the other hand, the double difference of *L1, L2*, or even the doubled differenced ionosphere-free *L3* measurement combinations are much easier to edit/correct for cycle slips and outliers; consequently statistical error detection/corrections may not be as important or even needed in DD GNSS data analyses. An attractive alternative for un-differenced observation network analyses is a cycle slip detection/editing based on DD observations, which at the same time could also facilitate the resolution of the initial DD phase ambiguities. The resolved phase ambiguities are then introduced into an un-differenced analysis as the condition equations of the new un-differenced observations that are formed from the reconstructed, unambiguous and edited DD observations, obtained in the previous step.

4.2 Adjustment procedures/filters

The above outlined adjustment can be done in a single step, so called batch adjustment (with iterations), or alternatively within a sequential adjustment/filter (with or without iterations) that can be adapted to varying user dynamics. The disadvantage of a batch adjustment is that it may become too large even for modern and powerful computers, in particular for un-differenced observations involving a large network of stations. However, no back-substitution or back smoothing is necessary in this case, which makes batch adjustment attractive in particular for DD approaches. Filter implementations, (for GNSS positioning, equivalent to sequential adjustments with steps coinciding with observation epochs), are usually much more efficient and of smaller size than the batch adjustment implementations, at least, as far as the position solutions with un-differenced observations are concerned. This is so, since parameters that appear only at a particular observation epoch, such as station/satellite clock and even zpd_w parameters, can be pre-eliminated. However, filter (sequential adjustment) implementations then require backward smoothing (back substitutions) for the parameters that are not retained from epoch to epoch, (e.g. the clock and zpd_w parameters).

Furthermore, filter/sequential approaches can also model variations in the states of the parameters between observation epochs with appropriate stochastic processes that also update parameter variances from epoch to epoch. For example, the PPP observation model and adjustment Eqs. (7) through (15) involve four types of parameters: station position (*x, y, z*), receiver clock (*dT*), troposphere zenith path delay (zpd_w) and non-integer carrier-phase ambiguities (*N*). The station position may be constant or change over time depending on the user dynamics. These dynamics could vary from tens of meters per second in the case of a land vehicle to a few kilometers per second for a Low Earth Orbiter (LEO). The receiver clock will drift according to the quality of its oscillator, e.g. about 0.1 ns/sec (equivalent to several cm/sec) in the case of an internal quartz clock with frequency stability of about 10^{-10}. Comparatively, the tropospheric zenith path delay (*zpd*) will vary in time by a relatively small amount, in the order of a few cm/hour. Finally, the carrier-phase ambiguities (*N*) will remain constant as long as the satellite is not being reoriented (e.g., during an eclipsing period, see the phase wind-up correction, Section 5.1.2) and the carrier phases are free of cycle-slips, a condition that requires close monitoring. Note that only for DD data observed from at least two stations, all clocks *dT's*, including the receiver clock corrections are practically eliminated by the double differencing.

Using subscript *i* to denote a specific time epoch, we see that without observations between epochs, initial parameter estimates at epoch *i* are equal to the ones obtained at the previous epoch *i-1*:

$$X_i^0 = \hat{X}_{i-1}.$$ (18)

To propagate the covariance information from the epoch *i-1* to *i*, during an interval *Δt*, $C_{\hat{x}_{i-1}}$ has to be updated to include process noise represented by the covariance matrix $C\varepsilon_{\Delta t}$:

$$P_{X_i^0} = [C_{\hat{x}_{i-1}} + C\varepsilon_{\Delta t}]^{-1}$$ (19)

where

$$
C\varepsilon_{\Delta t} = \begin{bmatrix} C\varepsilon(x)_{\Delta t} & 0 & 0 & 0 & 0 & 0 \\ 0 & C\varepsilon(y)_{\Delta t} & 0 & 0 & 0 & 0 \\ 0 & 0 & C\varepsilon(z)_{\Delta t} & 0 & 0 & 0 \\ 0 & 0 & 0 & C\varepsilon(dT)_{\Delta t} & 0 & 0 \\ 0 & 0 & 0 & 0 & C\varepsilon(zpd_w)_{\Delta t} & 0 \\ 0 & 0 & 0 & 0 & 0 & C\varepsilon(N^j_{(j=1,nsat)})_{\Delta t} \end{bmatrix}.
$$

Process noise can be adjusted according to user dynamics, receiver clock behavior and atmospheric activity. In all instances $C\varepsilon(N^j_{(j=1,nsat)})_{\Delta t} = 0$ since the carrier-phase ambiguities remain constant over time. In static mode, the user position is also constant and consequently $C\varepsilon(x)_{\Delta t} = C\varepsilon(y)_{\Delta t}= C\varepsilon(z)_{\Delta t} = 0$. In kinematic mode, it is increased as a function of user dynamics. The receiver clock process noise can vary as a function of frequency stability but is usually set to white noise with a large $C\varepsilon(dT)_{\Delta t}$ value to accommodate the unpredictable occurrence of clock resets. A random walk process noise of about 2-5 mm/√hour is usually assigned and used to derive the wet zenith path delay $C\varepsilon(zpd_w)_{\Delta t}$.

5. Precise positioning correction models

Developers of GPS software are generally well aware of corrections they must apply to pseudorange or carrier-phase observations to eliminate effects such as special and general relativity, Sagnac delay, satellite clock offsets, atmospheric delays, etc. (e.g. ION, 1980; ICD-GPS-200, 1991). All these effects are quite large, exceeding several meters, and must be considered even for pseudorange positioning at the meter precision level. When attempting to combine satellite positions and clocks precise to a few cm with ionospheric-free carrier phase observations (with mm resolution), it is important to account for some effects that may not have been considered in pseudorange or even precise differential phase processing modes.

For cm differential positioning and baselines of less than 100 km, all the correction terms discussed below can be safely neglected. The following sections describe additional correction terms often neglected in local relative positioning, that are, however, significant for PPP and all precise global analyses (relative or un-differenced approaches). The correction terms have been grouped under *Satellite effects (5.1), Site displacements effects (5.2)* and *Compatibility and IGS conventions (5.3)*. A number of the corrections listed below require the Moon or the Sun positions which can be obtained from readily available planetary ephemeredes files, or more conveniently from simple formulas since a relative precision of about 1/1000 is sufficient for corrections at the mm precision level.

5.1 Satellite effects

5.1.1 Satellite antenna offsets

The requirement for satellite-based corrections originates from the separation between the satellite center of mass and the phase center of its antenna. Because the force models used for satellite orbit modeling refer to the satellite center of mass, the IGS precise satellite coordinates and clock products also refer to the satellite center of mass, unlike the orbit ephemeredes in the GPS broadcast navigation message, which refer to the satellite antenna phase center. However, the measurements are made to the antenna phase center, thus one must know the satellite phase center offsets and monitor the orientation of the offset vector in space as the satellite orbits the Earth. The phase centers for most satellites are offset in the body *Z*-coordinate direction (towards the Earth) and for some satellites also in the body *X*-coordinate direction which is on the plane containing the Sun (see Figure 2). Since all AC estimates of the GPS Block IIR antenna phase center *Z*-offsets (with zero phase center variations (PCV)) were much closer to zero than to the specified *Z*-offset value published by the GPS operators (e.g., Bar-Sever, 1998), the zero value was adopted and used by IGS up to November 4, 2006 (GPS Week 1399) (Fig. 2). Starting November 5, 2006 (GPS Week 1400), however, the IGS convention employs different, so called "absolute", phase center

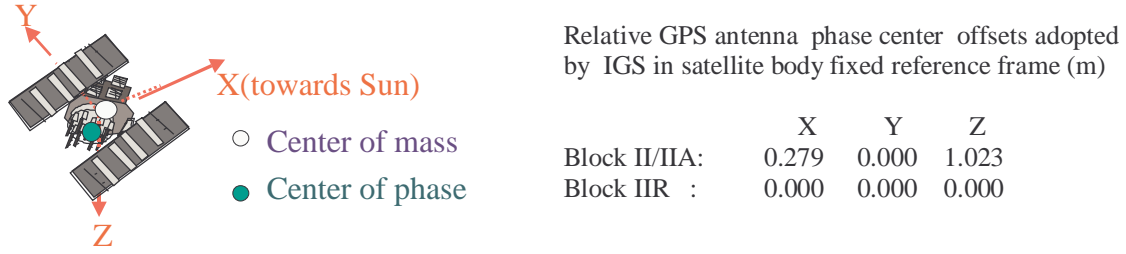offsets and non-zero PCVs for both satellite and all station antennas, in the *igsXX.atx* file, corresponding to the current *igsXX* reference frame realization (ftp://ftp.igs.org/pub/station/general/; Schmid et al., 2007).

Relative GPS antenna phase center offsets adopted by IGS in satellite body fixed reference frame (m)

	X	Y	Z
Block II/IIA:	0.279	0.000	1.023
Block IIR :	0.000	0.000	0.000

Figure 2: IGS conventional (relative) GPS satellite antenna phase center offsets in satellite body fixed reference frame, used up to Nov. 4, 2006 (GPS Week 1399) and consistent with the relative *igs01.pcv* and *igs01.atx* PCV's.

5.1.2 Phase wind-up

GPS/GLONASS satellites transmit right circularly polarized (RCP) radio waves and therefore, the observed carrier-phase depends on the mutual orientation of the satellite and receiver antennas. A rotation of either receiver or satellite antenna around its bore (vertical) axis will change the carrier-phase up to one cycle (one wavelength), which corresponds to one complete revolution of the antenna. This effect is called "phase wind-up" (Wu et al., 1993). A receiver antenna, unless mobile, does not rotate and remains oriented towards a fixed reference direction (usually north). However, satellite antennas undergo slow rotations as their solar panels are being oriented towards the Sun and the station-satellite geometry changes. Furthermore, in order to reorient their solar panels towards the Sun during eclipsing seasons, satellites are also subjected to rapid rotations, so called "noon" (when a straight line, starting from the Sun, intersects the satellite and then the center of the Earth) and "midnight turns" (when the line intersects the center of the Earth, then the satellite). This can represent antenna rotations of up to one revolution within less than half an hour. During such noon or midnight turns, phase data needs to be corrected for this effect (Bar-Sever, 1996; Kouba 2008) or simply edited out.

The phase wind-up correction has been generally neglected even in the most precise differential positioning software, as it is quite negligible for double difference positioning on baselines/networks spanning up to a few hundred kilometers. However, it has been shown to reach up to 4 cm for a baseline of 4000 km (Wu et al., 1993). This effect is significant for un-differenced point positioning when fixing IGS satellite clocks, since it can reach up to one half of the wavelength. Since about 1994, most of the IGS Analysis Centers (and therefore the IGS orbit/clock combined products) apply this phase wind-up correction. Neglecting it and fixing IGS orbits/clocks will result in position and clock errors at the dm level. For receiver antenna rotations (e.g. during kinematic positioning/navigation) the phase wind-up is fully absorbed into station clock solutions (or eliminated by double differencing).

The phase wind-up correction (in radians) can be evaluated from dot (·) and vector (×) products according to (Wu at al., 1993) as follows:

$$\Delta\phi = sign(\zeta) \ \cos^{-1}(\vec{D}'\cdot\vec{D} \ / \ |\vec{D}'| |\vec{D}|) , \tag{20}$$

where $\zeta = \hat{k} \cdot (\vec{D}' \times \vec{D})$, $\hat{k}$ is the satellite to receiver unit vector and $\vec{D}', \vec{D}$ are the effective dipole vectors of the satellite and receiver computed from the current satellite body coordinate unit vectors ($\hat{x}', \hat{y}', \hat{z}'$) and the local receiver unit vectors (i.e. north, east, up) denoted by ($\hat{x}, \hat{y}, \hat{z}$):

$$\vec{D}' = \hat{x}' - \hat{k}(\hat{k} \cdot \hat{x}') - \hat{k} \times \hat{y}' ,$$

$$\vec{D} = \hat{x} - \hat{k}(\hat{k} \cdot \hat{x}) + \hat{k} \times \hat{y} .$$

Continuity between consecutive phase observation segments must be ensured by adding full cycle terms of $\pm 2\pi$ to the correction (Eq. 20).

5.2 Site displacement effects

In a global sense, a station undergoes periodic movements (real or apparent) reaching a few dm that are not included in the corresponding ITRF "regularized" positions, from which "high-frequency" have been removed using models. Since most of the periodical station movements are nearly the same over broad areas of the Earth, they nearly cancel in relative positioning over short (<100 km) baselines and thus need not be considered. However, if one is to obtain a precise station coordinate solution consistent with the current ITRF conventions in PPP, using un-differenced approaches, or in relative positioning over long baselines (> 500 km), the above station movements must be modeled as recommended in the IERS Conventions. This is accomplished by adding the site displacement correction terms listed below to the regularized ITRF coordinates. Site displacement effects with magnitude of less than 1 centimeter, such as atmospheric and ground water and/or snow build-up loading, have been neglected and are not considered here.

5.2.1 Solid earth tides

The "solid" Earth is in fact pliable enough to respond to the same gravitational forces that generate the ocean tides. The periodic vertical and horizontal site displacements caused by tides are represented by spherical harmonics of degree and order (n, m) characterized by the Love number h_{nm} and the Shida number l_{nm}. The effective values of these numbers weakly depend on station latitude and tidal frequency (Wahr, 1981) and need to be taken into account when a position precision of 1 mm is desired. For details, including a standard FORTRAN subroutine *dehanttideinel.f*, see the Chapter 7 of the IERS Conventions (IERS, 2010). This self-contained and easily to implement standard FORTRAN subroutine should be used in all precise analyses. However, for 5-mm precision, only the second-degree tides and a height correction term are necessary (IERS, 1989). Thus, at the 5-mm level of precision, the site displacement vector in Cartesian coordinates $\Delta \bar{r}^T = |\Delta x, \Delta y, \Delta z|$ is:

$$\Delta \vec{r} = \sum_{j=2}^{3} \frac{GM_j}{GM} \frac{r^4}{R_j^3} \left\{ \left[3l_2 \left(\hat{R}_j \cdot \hat{r} \right) \right] \hat{R}_j + \left[3 \left(\frac{h_2}{2} - l_2 \right) \left(\hat{R}_j \cdot \hat{r} \right)^2 - \frac{h_2}{2} \right] \hat{r} \right\} +$$

$$\left[-0.025m \cdot \sin \phi \cdot \cos \phi \cdot \sin \left(\theta_g + \lambda \right) \right] \cdot \hat{r}, \tag{21}$$

where GM, GM_j are the gravitational parameters of the Earth, the Moon ($j=2$) and the Sun ($j=3$); r, R_j are the geocentric state vectors of the station, the Moon and the Sun with the corresponding unit vectors $\hat{r}$ and $\hat{R}_j$, respectively; (l_2, h_2) are the nominal second degree Love and Shida dimensionless numbers (about 0.608, 0.085); ϕ, λ are the site latitude and longitude (positive east) and θ_g is Greenwich Mean Sidereal Time. The tidal correction (Eq. 21) can reach about 30 cm in the radial and 5 cm in the horizontal direction. It consists of a latitude dependent permanent displacement and a periodic part with predominantly semi diurnal and diurnal periods of changing amplitudes. The periodic part is largely averaged out for static positioning over a 24-h period. However, the permanent part, which can reach up to 12 cm in mid latitudes (along the radial direction) remains in such a 24-h average position. The permanent tidal distortion, according to the adopted ITRF convention has to be included as well in the tidal correction (IERS, 2010). In other words, the complete correction (Eq. 21), which includes both the permanent and periodical tidal displacements, must be applied to be consistent with the ITRF (so called "Tide-free") tidal reference system convention. Even when averaging over long periods, neglecting the correction (Eq. 21) in point positioning would result in systematic position errors of up to 12 and 5 cm in the radial and north directions, respectively. For differential positioning over short baseline (<100km), both stations have almost identical tidal displacements so the relative positions over short baselines will be largely unaffected by the solid Earth tides. If the tidal displacements in the north, east and vertical directions are required, they can be readily obtained by multiplying (Eq. 21) by the respective unit vectors.

5.2.2   Rotational deformation due to polar motion (polar tides)

Much like deformations due to Sun and Moon attractions that cause periodical station position displacements, the changes of the Earth's spin axis with respect to Earth's crust, i.e. the polar motion, causes periodical deformations due to minute changes in the Earth centrifugal potential. Using the above second degree Love and Shida numbers, the corrections to latitude (+north), longitude (+east) and height (+up) in mm is approximately equal to (IERS, 2010):

$$\Delta\phi = -9\cos 2\phi\,[(X_p - \bar{X}_p)\cos\lambda - (Y_p - \bar{Y}_p)\sin\lambda];$$

$$\Delta\lambda = \quad 9\sin\phi\,[(X_p - \bar{X}_p)\sin\lambda + (Y_p - \bar{Y}_p)\cos\lambda];$$

$$\Delta h = -33\sin 2\phi\,[(X_p - \bar{X}_p)\cos\lambda - (Y_p - \bar{Y}_p)\sin\lambda],$$

where $(X_p - \bar{X}_p)$ and $(Y_p - \bar{Y}_p)$ are the pole coordinate variations from the mean poles $(\bar{X}_p, \bar{Y}_p)$ in seconds of arc (for the mean pole values, see the Eq. 7.25 of the IERS 2010 Conventions, Chapter 7). Since most ACs utilize this correction when generating their orbit/clock solutions, the IGS combined orbits/clocks are consistent with these station position corrections. In other words, for sub-centimeter position precision the above polar tide corrections need to be applied to obtain an apparent station position, that is, the above corrections have to be subtracted from the position solutions in order to be consistent with ITRF. Unlike the solid earth tides (Section 5.2.1) and the ocean loading effects (see Section 5.2.3 below) the pole tides do not average to nearly zero over a 24h period. As seen above they are slowly changing according to the polar motion, i.e. they have predominately seasonal and Chandler (~430 day) periods. Since the polar motion can reach up to 0.8 arc sec, the maximum polar tide displacements can reach about 25 mm in the height and about 7 mm in the horizontal directions.

5.2.3 Ocean loading

Ocean loading is similar to solid Earth tides, it is dominated by diurnal and semi diurnal periods, but it results from the load of the ocean tides on the underlying crust. While the displacements due to ocean loading are almost an order of magnitude smaller than those due to solid Earth tides, ocean loading is more localized, and by convention it does not have a permanent part. For single epoch positioning at the 5-cm precision level or mm static positioning over 24h period and/or for stations that are far from the oceans, ocean loading can be safely neglected. On the other hand, for cm precise kinematic point positioning or precise static positioning along coastal regions over observation intervals significantly shorter than 24h, this effect has to be taken into account. Note that when the tropospheric zpd_w or clock solutions are required, the ocean load effects also have to be taken into account even for a 24h static point positioning processing, unless the station is far (> 1000 km) from the nearest coast line. Otherwise, the ocean load effects will map into the solutions for tropospheric zpd_w (Dragert et al., 2000) and station clocks. The ocean load effects can be modeled in each principal direction by the following correction term (IERS, 2010):

$$\Delta c = \sum_j f_j A_{cj}cos(\omega_j t + \chi_j + u_j - \Phi_{cj}) \tag{22}$$

where f_j and u_j depend on the longitude of the lunar node, however for 1-3 mm precision one can set f_j =1 and u_j =0; the summation of j represents the 11 tidal waves designated as M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1, M_f, M_m and S_{sa}; ω_j and χ_j are the angular velocity and the astronomical arguments at time $t=0h$, corresponding to the tidal wave component j. The argument χ_j and eq. (22) can be readily evaluated by FORTRAN routines *ARG2.f* and *hardisp.f*, respectively, both are available from the IERS Convention ftp site: ftp://tai.bipm.org/iers/convupdt/chapter7/.

The station specific amplitudes A_{cj} and phases Φ_{cj} for the radial, south (positive) and west (positive) directions are computed by convolution of Green's functions utilizing the latest global ocean tide models as well as refined coastline database (e.g. Scherneck, 1991; Pagiatakis, 1992; Agnew, 1996). A software for evaluation of A_{cj} and Φ_{cj} at any site is available from Pagiatakis (1992), or the amplitudes/phases for any site can be evaluated by the on-line ocean loading service (http://holt.oso.chalmers.se/loading/). Typically, the

M_2 amplitudes are the largest and do not exceed 5 cm in the radial and 2 cm in the horizontal directions for coastal stations. For cm precision, one should use a recent global ocean tide model, such as FES2004 (Lyard et al., 2006) and it may even be necessary to augment the global tidal model with local ocean tides digitized, for example, from the local tidal charts. The station specific amplitude A_{cj} and phases Φ_{cj} can also include the sub-daily center of mass (CoM) tidal variations. In that case, for cm station position precision, ocean load effect corrections have to be included at all stations, even for those far from the ocean. Consistently with the sub-daily earth rotation parameter convention (see the next Section 5.2.4), the current IGS convention also requires that the sub-daily tidal CoM is included in ocean loading corrections when generating IGS AC orbit/clock solutions. Most ACs have complied and since 2007 they are including CoM in ocean loading corrections and in their ITRF transformations of orbit/clock solutions (Ray and Griffiths, 2008). Consequently, when the IGS solution products are used directly in ITRF (such as in a PPP), the ocean-loading corrections *should not* include the CoM.

5.2.4 Earth rotation parameters (ERP)

The Earth Rotation Parameters (i.e. pole position *Xp*, *Yp* and *UT1-UTC*), along with the conventions for sidereal time, precession and nutation facilitate accurate transformations between terrestrial and inertial reference frames that are required in global GNSS analysis (see e.g. IERS, 2010). Then, the resulting orbits in the terrestrial conventional reference frame (ITRF), much like the IGS orbit products, imply, quite precisely, the underlying ERP. Consequently, IGS users who fix or heavily constrain the IGS orbits and work directly in ITRF need not worry about ERP. However, when using software formulated in an inertial frame, the ERP, corresponding to the fixed orbits, augmented with the so called sub-daily ERP model, are required and must be used. This is so, since ERP, according to the IERS convention are regularized and do not include the sub-daily, tidally induced, ERP variations.

The sub-daily ERP is also dominated by diurnal and sub-diurnal periods of ocean tide origin, and can reach up to 0.1 mas (~3 cm on the Earth surface). Each of the sub-daily ERP component corrections *(δXp, δYp, δUT1)* is obtained from the following approximation form, e.g. for the *Xp* pole component:

$$\delta Xp = \sum_{j=1}^{8} F_j \sin \xi_j + G_j \cos \xi_j, \qquad (26)$$

where ξ_j is the astronomical argument at the current epoch for the tidal wave component *j* of the eight diurnal and semi-diurnal tidal waves considered (*M_2, S_2, N_2, K_2, K_1, O_1, P_1, Q_1*), augmented with $n \cdot \pi/2$ (*n= 0, 1* or *–1*) and F_j and G_j are the tidal wave coefficients derived from the latest global ocean tide models for each of the three ERP components. The above (conventional) FORTRAN routine, evaluating the sub-daily ERP corrections can also be obtained at the Chapter 8 of IERS (2010). When ITRF satellite orbits are generated without the sub-daily ERP model (not the case for IGS/AC orbits), then even PPPs, formulated in ITRF need to take the sub-daily ERP variations into account, for more details see Kouba (2002b).

5.3 Compatibility and IGS conventions

Positioning and GNSS analyses that constrain or fix any external solutions/products need to apply consistent conventions, orbit/clock weighting and models. This is in particular true for PPP and clock solutions/products, however even for cm precision differential positioning over continental baselines, the consistency with the IGS global solutions also needs to be considered. This includes issues such as the respective version of ITRF, the IGS ERP corresponding to the IGS orbit and station solutions used, station logs (antenna offsets), antenna PCV etc. Note that, in general, all AC solutions and thus IGS combined products follow the current IERS conventions (IERS, 2010). Thus, all the error-modeling effects discussed above are generally implemented with little or no approximation with respect to the current IERS conventions. The only exceptions are the atmospheric and snow loading effects, which currently (2015) are neglected by all ACs. For specific and detail information on each AC global solution strategy, modeling and departures from the conventions, in a standardized format, refer to the IGS CB archives (ftp://ftp.igs.org/pub/center/analysis/ , or to Ray and Griffiths (2008) as well as Weber at al. (2002b).

5.3.1 IGS formats

Perhaps the most important prerequisite for a successful service and the ease of utilization of its products is the standardization of data and product formats. IGS has adopted and developed a number of standard formats, which for convenience are listed below in Table 1. Also listed here are the relevant IGS Central Bureau (CB) URL's, where the detail description of a particular format can be found. (Note: some formats, like RINEX, SP3 and SINEX undergo regular revisions to accommodate receiver/satellite upgrades, or multi-technique solutions, respectively).

Table 1. Data/product formats adopted by IGS

Format name	IGS Product/Sampling	Reference/URL
RINEX	GNSS data/ 30 sec	ftp://ftp.igs.org/pub/data/format/rinex211.txt
RINEX-clock ext.	Sat./Sta. Clock/5 min/30s	ftp://ftp.igs.org/pub/data/format/rinex_clock302.txt
SP3	Orbits/Clocks/ 15 min.	ftp://ftp.igs.org/pub/data/format/sp3c.txt
IGS ERP Format	IGS ERP/ 1 day	ftp://ftp.igs.org/pub/data/format/erp.txt
SINEX	Sta. Pos.(ERP) 7(1) day	ftp://ftp.igs.org/pub/data/format/sinex.txt
SINEX-tropo ext.	Tropo. ZPD 2 h/5 min.	ftp://ftp.igs.org/pub/data/format/sinex_tropo.txt
IONEX	Iono. maps/sat DCB* 2 h	ftp://ftp.igs.org/pub/data/format/ionex1.pdf

* Differential Code Bias (DCB)

5.3.2 IGS reference frames

The use of the IGS orbit/clock products imply positioning, orientation and scale of a precise reference frame, so that PPP position solutions (with the IGS orbits/clocks held fixed) are directly in the IGS global reference frame which conforms to the ITRF. In fact, the PPP approach represents the simplest and the most direct access (interface) to the IGS realization of ITRF (as well as the global tropospheric *zpd* and time reference frames). In unconstrained or minimally constrained regional relative positioning, only the precise orientation and scale are strongly implied by fixing IGS orbits. However, in global differenced data solutions, the implied reference frame positioning (origin/geocenter solution) is equally strong, but it is much weaker in regional (~1000 km) and nearly non existent (i.e., singular) for local (<100 km) network solutions. So, *it is also important that all network station solutions (including the one using un-differenced observations) be in the same reference frame, even when unconstrained relative position solutions are constrained or being combined with external positions*, or with other IGS station position solutions, such as is the case of the IGS Global Network Associated Analysis Center (GNAAC) or Regional Associated Analysis Center (RNAAC) analyses/combinations (Ferland, 2000, Ferland et al., 2002).

Since February 27, 2000 (GPS Week 1051) when the SINEX station/ERP combinations became official, all the IGS combined Final products (including orbits/clocks and SINEX station/ERP solutions), are also fully consistent and minimally constrained with respect to IGS position/velocity coordinate solutions of a set of more than 50 Reference Frame Stations (RS). These IGS RS solutions, in turn are minimally constrained to the current ITRF. These IGS RS coordinate sets are internally more consistent than the original ITRF one, yet in orientation, translation and scale (including the corresponding rates) it is completely equivalent to the ITRF solution station set, thus, the IGS Final products can still be considered to be nominally in the current ITRF. Note that for all, even for most of precise applications, there usually are no noticeable discontinuities and no transformation should be necessary for internal IGS realizations of ITRF changes. (e.g., for the ITRF97/ITRF2000 change, see Ferland, 2000; 2001).

Starting on December 2, 2001 (GPS Week 1143, MJD 52245) till November 4, 2006 (GPS Week 1399) the IGS00 (the IGS of ITRF2000) was used. Initially, IGS00 was accomplished through a 54 RS subset of the Week 1131 IGS cumulative station/ERP solution product. (See IGS Mail #3605 at http://igs.org/mail/). This solution was minimally constrained with the 14 transformation parameters (seven transformation parameters and their respective rates) that were derived from the comparison with the corresponding 54 RS ITRF2000 station position/velocity set, which is available at the IERS ITRF ftp site

(http://itrf.ensg.ign.fr/ITRF_solutions/index.php). On January 11, 2004 (GPS Week 1253, MJD 53015) an improved ITRF2000 realization IGb00, based on more recent cumulative station/ERP solution product and more than 100 RS, was adopted by IGS (see IGS Mail #4748). Since November 5, 2006 (GPS Week 1400) the IGS05 realization of ITRF2005 has been used. It was obtained analogously to IGS00 and IGb00 from a recent IGS cumulative station/ERP solution product, corrected for small absolute antenna PCV position changes and 132 RS ITRF2005 station positions (see IGSMail #5438). Consequently, mainly due to the adoption of the absolute PCV modeling, there could be small discontinuities at some stations on November 5, 2006. Starting on April 17, 2011 (GPS Week 1632) IGS has adopted the IGS08 - the IGS realization of ITRF2008 with the corresponding absolute satellite and ground antenna PCVs (igs08.atx). On October 7, 2012 (GPS week 1709) the improved IGb08 has officially replaced the IGS08 reference frame by recovering 33 station coordinates affected by position discontinuities and adding 3 co-located sites. (see IGS Mail #6663).

The IGS SINEX station/ERP products also take into account full variance-covariance matrices. However, all the IGS orbit/clock users, interested in a long series of station position solutions and the mm-precision level, still need to take into account all the ITRF changes. This is particularly true for PPP and global or continental relative station positioning. More specifically, since its beginning in 1994, IGS has used *eight* different, official realizations of ITRF (ITRF92, ITRF93, ITRF94, ITRF96, ITRF97, ITRF2000, ITRF2005 and ITRF2008). For the exact dates of the ITRF changes, estimated transformation parameters and a simple Fortran 77 transformation program see Kouba (2002a). Most of the ITRF changes are at or below the 10-mm level, with the notable exception of the ITRF92-93 and ITRF93-94 transformations, where rotational changes of more than .001" (30 mm) were introduced due to a convention change in the orientation evolution of ITRF93 (see e.g. Kouba and Popelar, 1994). It is important to note that only the ITRF96-97 (on August 1, 1999), ITRF97-2000 (December 2, 2001), ITRF2000-2005 (November 5, 2006) and any subsequent ITRF changes have virtually exact transformations (due to the minimum constraining used since 1998). However, all the preceding transformations (i.e. prior the ITRF96-97 change) are only approximate and can be used for transformations at the 1-3 mm (0.0001" for ERP) precision level only.

To minimize the above discontinuities as well as to increase precision and consistency of IGS products, IGS has undertaken two reprocessing campaigns of all the data starting from 1994 (see http://acc.igs.org/reprocess.html and http://acc.igs.org/reprocess2.html). The reprocessed orbits/clocks and SINEX station/ERP solutions are available at the IGS Data centers (e.g., ftp://cddis.gsfc.nasa.gov/gps/products/repro1/ and ftp://cddis.gsfc.nasa.gov/gps/products/repro2/). The first reprocessing (*repro1*) combinations (*IG1*) cover the GPS weeks 730-1459 (1994-2007) and together with the IGS Final products between the GPS Weeks 1460 and 1631 (up to April 16, 2011), represent a homogenous continuous series, consistent with the IGS05 reference frame and igs05.atx PCV. The second reprocessing (*repro2, IG2*) includes the period of the GPS Week 730 to 1772 (1994-2014) and together with the IGS Final products after the GPS week 1772 forms a homogenous series, consistent with the IGb08 (ITRF2008) reference frame, igs08.atx PCV and also features daily SINEX station/ ERP combinations. Note that from the GPS Week 1702 (Aug 19, 2012) IGS has switched from weekly to daily SINEX combinations. During 2016 IGS is likely to switch to the ITRF2014 reference frame, however the discontinuity between IGb08 and ITRF2014, (as well as subsequent reference frame changes) will likely be insignificant for most applications.

The ITRF convention allows linear station movements only (apart from the conventionally modeled high-frequency tidal variations), i.e. dated initial station positions and the station velocities, which is not adequate at the mm-level precision, as even stable stations may exhibit real and apparent non-linear departures that can exceed 10 mm. Often, the station movements are of periodical (e.g. seasonal and semi-seasonal) character. The non-linear station movements can be induced, for example, by various uncorrected loading effects (atmospheric, snow), or by the real non-tidal variation of geocenter and scale (i.e. the Earth's dimension).

The IGS Rapid products are consistent with the current ITRF convention, i.e. IGb08 positions of the IGS RS stations are fixed in all the IGS AC Rapid solutions, thus no geocenter or scale variations are allowed and none should show up in the solutions when using IGS Rapid/clock products. However, all the IGS Final solutions and products, mainly to facilitate higher internal precision/consistency, since June 28, 1998

are based on minimal rotational constraints only. Note that unconstrained global GNSS solutions are nearly singular only in orientation, they still contain a strong origin (geocenter) and scale information due to orbit dynamics (i.e. the adopted gravity field). So, *IG1*, *IG2* and after June 28, 1998, all the IGS Final orbits/clocks, at least nominally, refer to the real geocenter and scale that undergo small (~10mm) variations with respect to the adopted ITRF origin and scale. Starting with the IGS00 RS station set, geocenter positions and scale biases are solved for and published every week for all the IGS (IGSYYPWWWW.snx, where YY is last 2 digit of year, WWWW is GPS week) and cumulative (IGSYYPww.snx, where ww is the week number of the year) weekly SINEX products. However, currently (2015) the corresponding IGS Final orbit combinations are not corrected for the daily geocenter/scale variation. Even in the new IGS Final clock combinations, which has become official on November 5, 2000 (IGS Mail #3087) and which, in every other aspect was made highly consistent with the IGS SINEX/ERP cumulative combinations as outlined in Kouba et al. (1998a) and Kouba and Springer (2001), the geocenter clock corrections were not implemented. The IGS Final and all AC orbit/clock solutions were not transformed, thus they fully reflected (i.e. they are with respect to) the apparent or real geocenter/scale variations. However, since November 5, 2006 AC and IGS clocks are supposed to be transferred to the ITRF origin. Thus all *global* analyses utilizing differenced observations and using only the IGS Final orbits (unlike the IGS Rapid orbits) still have to take into consideration the small (~10 mm) weekly (daily after GPS Week 1701 and *IG2*) geocenter and scale variations as the geocenter/scale variations are fully implied by the IGS combined orbits. On the other hand, regional relative positioning with fixed Final orbits and from November 5, 2006 PPP's with the *IG1, IG2* or the IGS orbit/clock products held fixed, should show only small weekly (daily) scale (height) variations. This is so, since relative regional analyses are less sensitive to orbit origin and in the case of PPP, the apparent geocenter variation should be properly accounted for in the *IG1, IG2* and the current IGS Final clock combinations. Thus, since November 5, 2006, the IGS Final orbit/clock PPP users will only have to consider (with respect to the current IGS reference frame small (~cm) daily scale (height) biases, which are not yet accounted for in the official, IGS Final orbit/clock combinations, or reprocessing.

In summary, all (global) applications involving IGR rapid orbit/clock products should be directly in the conventional ITRF and no origin/scale variations should be seen. On the other hand, all global applications using (i.e. fixing) the IGS Final orbit products will refer to a mean geocenter and scale of the week, thus small weekly variations in origin/scale with respect to ITRF could be seen. However, for the *IG1*, *IG2* and after November 5, 2006 for the IGS Final products, all PPP solutions should show only small weekly (daily) scale (height) variations, since orbit origin variations should be accounted for in the clock combinations. At the precision level of about 10-mm, when using the IGS Final products, all the above origin/scale variations can likely be neglected. The above small weekly/daily IGS geocenter (origin) variation can be found in the corresponding GPS week (WWWW) SINEX combinations and summary files (IGSYYPWWWW.sum), which are also available at the IGSREPORT Archives (http://www.igs.org/mail/). Perhaps, a more acceptable and consistent approach would be also to remove, if possible, from the IGS Final combined orbit products all the origin/scale variations with respect to the adopted ITRF. This has already been suggested in Kouba and Springer (2001).

5.3.3 IGS receiver antenna phase center offsets/tables

Prior to November 5, 2006, unless using Dorne-Margolin (D/M) antennas, the relative IGS antenna PCV table (*igs_01.pcv*) that are available at the IGS Central Bureau (ftp://www.igs.org/pub/station/general/) and the conventional satellite antenna offset of Fig.2 should be used with the IGS solution products. After November 5, 2006, (and/or for any reprocessed IGS orbits/clocks) the absolute receiver and satellite antenna PCV and offsets, corresponding to the IGS reference frame should be used (i.e., *igs05.atx* and igs08.atx for the IGS05 and IGS08/IGb08 reference frames, respectively). If a receiver antenna type is not contained in the current igs05.atx or igs08.atx, the GPS satellite antenna offsets of Fig.2 and the zero or relative PCV/offsets (*igs_01.pcv*) should be used for the receiver antenna. *The relative and absolute satellite and receiver antenna PCVs and offsets should never be mixed,* as such an inconsistent use of satellite/receiver PCVs and offsets will result in position biases (mainly in height) up to 10 cm. Note that when the relative PCVs and offsets (*igs_01.pcv*) are used for receiver antennas together with the satellite antenna offsets of Fig. 2, acceptable (cm-precision) results are still obtained even when the orbits/clocks were generated with the absolute satellite antenna PCVs and offsets.

For precise relative positioning with different antenna types even over short baselines, and in particular when solving for tropospheric zpd's, the IGS antenna PCV tables (either absolute or relative) are also mandatory, otherwise, large errors up to 10 cm in height and zpd_w solutions may result. On the other hand, relative positioning with the same antenna type over short to medium length baselines (<1000 km), with or without the zpd_w solutions does not require the use of the antenna PCV. Since PPP is in fact equivalent to a station position solution within a global (IGS) network solutions (but conveniently condensed within the IGS precise orbit/clock products), it must always use the appropriate IGS antenna PCV to ensure compatibility with the IGS antenna PCV convention. Before November 5, 2006, the IGS antenna PCV table (*igs_01.pcv*) was relative to the D/M antenna type, thus the IGS orbit/clock products were consistent with the D/M antennas and all the PPP's involving D/M antennas could safely neglect the *igs_01.pcv* table. However, for best results, after November 5, 2006 and/or for the reprocessed IGS products, every PPP, even with D/M antennas, should use for both receiver and satellite antennas, specific (absolute) antenna PCV tables, adopted by IGS (*igs05.atx*, or *igs08.at*x). Note that even if no PCV tables are necessary (e.g. for cm relative positioning with no zpd_w solutions), the constant receiver antenna height offsets, given in the *igs_01.pcv* table, along with the offsets of Fig.2, are still mandatory in this case. The absolute satellite antenna PCVs (e.g., *igs05.atx*) have nearly eliminated the apparent station scale bias of about 15 ppb, seen in global unconstrained GPS station/orbit solutions when absolute receiver antenna PCVs and the (relative) satellite antenna offsets of Fig. 2 were used (see e.g. Rothacher et al., 1995; Springer, 1999; Rothacher and Mader, 2002).

5.3.4 Modeling/observation conventions

The GPS System already has some well developed modeling conventions, e.g., that only the periodic relativity correction

$$\Delta t_{rel} = -2\bar{X}s \cdot \vec{V}s / c^2 \tag{27}$$

is to be applied by all GPS users (ION, 1980; ICD-GPS-200, 1991). Here $\bar{X}s, \vec{V}s$ are the satellite position and velocity vectors and c is the speed of light. The same convention has also been adopted by IGS, i.e., all the IGS satellite clock solutions are consistent with and require this correction. Approximation errors of this standard GPS relativity treatment are well below the 0.1 ns and 10^{-14} level for time and frequency, respectively (e.g. Kouba, 2002c; 2004).

By an agreed convention, there are no (P_1-P_2) Differential Code Bias (P1P2 DCB) corrections applied in all the IGS AC analyses, thus no such DCB calibrations are to be applied when the IGS clock products are held fixed or constrained in dual frequency PPP or time transfers. Furthermore, a specific set of pseudorange observations, consistent with the IGS clock products, needs to be used, otherwise the station clock and position solutions would be degraded. This is a result of significant satellite dependent differences between *C/A (C_1)* and P_1 code pseudoranges, which can reach up to 2 ns (60 cm). For receives observing only C_1, P_2 pseudorrange observations, satellite P1C1 DCB's are required to transform C_1 to P_1 pseudoranges. Note that IGS has been using the following conventional pseudorange observation sets, which needs to be used with the IGS orbit/clock products (*IGS Mail #2744*):

C_1 and $P'_2 = C_1 + (P_2-P_1)$ *Up to April 02, 2000 (GPS Week 1056),*
P_1 and P_2 *After April 02, 2000 (GPS Week 1056).*

For C_1 and P–code carrier phase observations (L_{C1} and L_{P1}) there is no such problem and no need for any such convention, since according to the GPS system specifications (ICD-GPS200, 1991, p.11) the difference between the two types of $L1$ phase observations is the same for all satellites and it is equal to a quarter of the $L1$ wavelength. This phase difference is then fully absorbed by the initial real phase ambiguities. However, early on, most receiver manufactures have agreed to align L_{C1} and L_{P1} phase observations (J. Ray, person. comm. 2009). For more information on this pseudorange observation convention and how to form the conventional pseudorange observation set for receivers, which do not give all the necessary pseudorange observations, see the *IGS Mail #2744* at (http://www.igs.org/mail/). The 30-day moving averages of P1C1 and P1P2 DCB's are readily available from CODE AC (ftp://ftp.unibe.ch/aiub/CODE/P1C1.DCB, ftp://ftp.unibe.ch/aiub/CODE/P1P2.DCB).

6. Single-frequency positioning

Precise, i.e., mm-level, positioning with single-frequency and without any external ionospheric delay corrections, is only possible for relative positioning over very short (<10 km) baselines. For such short baselines using IGS precise orbits offers little or no benefit over the broadcast orbits. With ionospheric delay corrections, derived, for example, from the IGS ionospheric grid maps generated by the IGS Ionospheric Working Group (http://igs.org/projects-working-groups/iwg), relative single-frequency cm-positioning could be extended up to a few hundred km when using the IGS precise orbits. Here the IGS precise orbits already could offer some accuracy improvements over the broadcast orbits.

Single-frequency PPP must also use ionospheric delay corrections along with the corresponding satellite P1P2 DCB; even then only precision at about the 0.5 m level is possible with the IGS orbits/clocks, which is mainly due to a limited resolution and precision of the IGS ionospheric grid maps. Neglecting the satellite P1P2 DCB's, which are nearly constant in time, but vary from satellite to satellite and can reach up to 12 ns, (i.e., using only the ionospheric delay corrections), would result in significant positioning errors that may be even larger (several meters) than the errors of uncorrected, single-frequency PPP solutions (Héroux, 1993, personal com.). This is so, since the IGS clocks are consistent with the P1P2 DCB convention (this is also true for the GPS broadcast clocks), i.e. the single-frequency IGS users have to first correct the IGS satellite clocks by *-1.55 P1P2 DCB* in order to make them compatible with the single-frequency observations. (Note the different sign convention for the broadcast P_1-P_2 group delays T_{GD}, which after April 29, 1999 are quite precise and can also be used even in the most precise applications (IGS Mail #2304 at http://www.igs.org/mail/). For static single-frequency PPP at this precision level, the IGS precise orbits/clocks offer only marginal improvements with respect to the broadcast orbits and clocks, in particularly with SA switched off i.e., after May 02, 2000. However, before May 02, 2000 with SA switched on, a single-frequency GPS static or kinematic (navigation) PPP, with the IGS precise orbits and clocks could offer about an order of magnitude precision improvements over the broadcast orbits and clocks. A more precise alternative to single-frequency PPP is to use the ambiguous ionspheric-free combination of *(L1+P_1)/2* and the P_1 (with appropriately large noise) in place of ℓ_ϕ *(L3)* and ℓ_P *(P3)* in a "regular" PPP (Eqs. 7 - 8). Here, *C/A (C_1)* pseudoranges can be used in place of P_1, too. This single-frequency PPP usually yields dm precision and thanks to the ambiguity solutions, it is also less sensitive to any inconsistency (or even neglect) of *P1C1* and *P1P2* DCBs, as well as satellite antenna PCVs/offsets.

7. Solution precision/accuracy with IGS Combined Products

Accuracy is an elusive word and it is difficult to quantify. In this context, by accuracy here it is meant the measure of a solution uncertainty with respect to a global, internationally adopted, conventional reference frame or system. Precision, on the other hand, is much easier to understand and attainable and here it can be interpreted as solution repeatability within a limited area and over a limited period of time. So, in this way, precise solutions may be biased and therefore may not be accurate. Formal solutions sigmas (standard deviations) are most often representative of solution precision rather than accuracy. For IGS users, the accuracy is perhaps the most important factor, though for some applications, precision may be equally or even more important, e.g. for crustal deformation or relative movement studies during short periods of time. It is also important to note that the precision/accuracy of IGS combined products is not constant and that it has been improving steadily (see Fig. 1) due to both better data quality and quantity (coverage) as well as significant analysis improvements realized by all ACs.

7.1 Positioning

In order to demonstrate the possible precision and accuracy achievable with IGS products, it is useful to examine the precision level that is being routinely achieved by ACs in their daily global analyses. Figure 3 represents the precision of weekly station position solutions achieved by IGS and ACs prior to 2000. It shows a compilation of AC/GNAAC position sigmas (standard deviations) with respect to the IGS cumulative (combined) station SINEX product (IGS00P39.snx in this case), during the period of more than

4 years (1996-2000; GPS Weeks 0837-1081). Currently, only daily unconstrained AC final SINEX station/ERP solutions are used in the IGS SINEX station/ERP combinations; the GNAAC SINEX combinations (*JPL, mit, ncl*) are used only for comparisons and quality control (Ferland, 2000). (Note that the *JPL* GNAAC is no longer operational and currently *mit* GNAAC has the acronym of *mig*)

Although Figure 3 still represents solution precision only, (it does not include the real and/or apparent geocenter/scale variations, constant station position and velocity biases that are common to all AC solutions, etc.), it is already an indication of the position accuracy that could be achieved with the IGS combined products prior to 2000. This is because the AC sigmas include real and apparent station movements and the statistics were obtained from a large number of globally distributed stations over relatively long period of time (more than 4 years). Furthermore, both reference frame transformation errors and mean residuals are small, at or below the mm level, and the geocenter variations along with the IGS position solution biases are also expected to be at the sub-cm level. More specifically, as seen from Figure 3, the best ACs, GNAACs and the IGS independent weekly combinations (*igs*) solutions were likely accurate at or below the 5-mm and 10-mm accuracy level in the horizontal and vertical components, respectively. This also implies that the daily static PPP during a one-week period, accounting for a small geocenter (before Nov. 2006) and scale offset, and fixing the best ACs and/or the IGS orbits/clock products should achieve comparable precision/accuracy levels. This is because PPP is an approximation (a back substitution) of the station position solution within the corresponding global (AC or IGS) solution. However, the corresponding daily PPP position standard deviations should be larger than the weekly ones shown in Figure 3, by up to $(7)^{1/2} \approx 2.6$ times when only random errors are assumed.
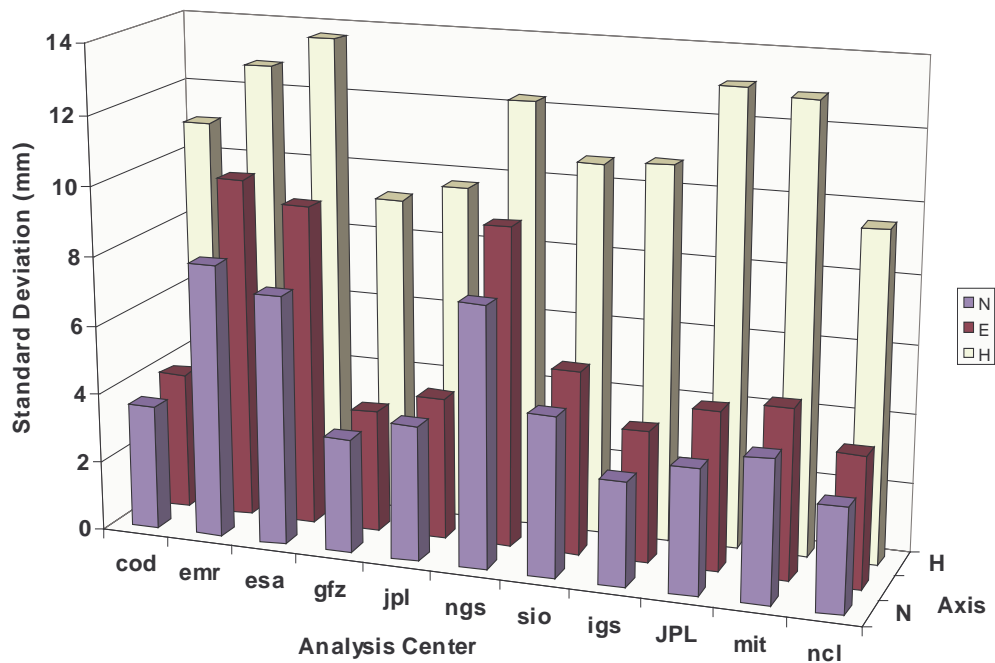

Figure 3. Standard deviations of SINEX weekly position solutions for the contributing *ACs (cod, emr, esa, gfz, jpl, ngs, sio)*, the IGS weekly combined products (*igs*) and the GNAAC combinations (*JPL, mit, ncl*) with respect to the IGS cumulative SINEX product during 1996-2000 (GPS Week 0837-1081).

More recent results of May 10, 2015 (IGS Week 1844, Day 0) are summarized in Table 2, which was adopted from the GPS Week 1844 SINEX combination report (see IGSREPORT #23616). Table 2 indicates the daily position solution precision/accuracy that is currently being achieved by IGS and have improved significantly since the period of 1996-2000 shown in Fig. 3. Namely, the current daily SINEX solutions are at the same precision level as the weekly ones shown in Fig. 3. This is a consequence of more and better data coverage as well as significant analysis improvements. Also shown here is the RMS agreement with the IGb08 Reference frame station (RS) position/velocity set (*ITR* denotes *IGb08.snx*). *IGb08.snx* is a subset of the IGS cumulative SINEX product, minimally constrained to ITRF2008 (through

a 14-parameter transformation) and corrected for some absolute antenna PCV solution differences (see IGS Mail #6663). The IGb08 realization of ITRF2008 has been adopted by IGS on October 7, 2012 (GPS week 1709).

Table 2. Daily means and standard deviations (RMS) of ACs SINEX residuals on May 10, 2015 with respect to the IGS cumulative SINEX combination of the GPS Week 1844 (May 10-16, 2015) (*IGS15P20.snx*). The GNAAC (*mig, ncl*), the IGS daily SINEX combinations (*igs = igs15P18440.snx*) and the IGb08 (ITRF2008) RS station set (*ITR = IGb08.snx*) are included for comparisons only (from the IGSREPORT #23616).

```
|          |     Weighted average (mm) |     Weighted RMS (mm)     |
| AC  #sta |    N        E        U    |    N        E        U    |
|----------|---------------------------|---------------------------|
| cod  240 |   -1.1      0.4      6.0  |    2.6      6.9      8.9   |
| emr   73 |   -0.8     -0.1      6.2  |    2.7      2.5      9.1   |
| esa  142 |   -1.2     -0.1      6.0  |    2.8      2.6      8.6   |
| gfz  200 |   -1.2      0.4      6.7  |    2.9      8.5      9.2   |
| grg   87 |   -0.4     -0.7      4.6  |    4.0      3.2      9.4   |
| jpl   68 |   -0.7      0.4      4.1  |    2.8      3.2      7.0   |
| mit  286 |   -1.8      0.3      7.1  |    3.1      8.1      9.3   |
| ngs  215 |   -0.0      0.3      4.7  |    3.3      3.4      8.9   |
| sio  285 |   -0.1     -0.2      6.9  |    3.4      4.0     10.1   |
| mig  386 |   -1.2      0.2      6.3  |    2.8      5.7      8.5   |
| ncl  213 |   -0.4      0.6      6.6  |    2.3      6.9      8.7   |
| igs  462 |   -1.3      0.2      6.0  |    2.9      5.9      8.3   |
| ITR  164 |   -0.1      0.8      0.9  |    4.1      3.3      6.3   |
|----------|---------------------------|---------------------------|
```

For PPP position accuracy testing, *three independent software* packages and *three different periods* of seven days, with different numbers of globally distributed stations, were used here. The primary motivation was to demonstrate that the IGS combined products give the most reliable and accurate results, and that any software, not only the one used to generate the fixed precise orbit/clock solutions, can be used, provided the software is consistent with the IGS standards and conventions. Furthermore, the three seven-day periods should also show the expected improvements of the IGS combined products realized from 1999 to 2009.

The first test used data from the GPS Week 0995 (January 24 -30, 1999) from four stations (AUCK, BRUS, WILL, USUD) on four continents (Australia, Europe, North America and Asia) and static daily GIPSY PPP's with various AC, IGS orbits/clock orbit products fixed. Note that since the NGS and SIO ACs have not been solving for any satellite clock corrections, and ESA clock solutions at that time were rather noisy, they were not used in this first PPP test. Furthermore, since most AC orbit/clock solutions, including the IGS Final Combined Orbit/Clock Products exhibited "apparent" daily geocenter (origin) variations at the cm level, an origin offset was estimated and removed for each day and AC as the average of all PPP-ITRF97 station coordinate differences of that day. No daily scale (height bias) was estimated here. The geocenter/scale variations, as already discussed above, are the consequence of the minimal constraints (rotations only) that were adopted for all ACs and IGS Final products after June 28, 1998 (Kouba et al. 1998a). (After November 4, 2006 and for the reprocessing campaigns *repro1/repro2*, such daily origin offset corrections should not be necessary for PPPs, since they are included in the AC and combined clocks). Then the PPP RMS with respect to the conventional ITRF station positions will also represent the achievable positioning accuracy. Note that, unlike the PPP repeatability around the weekly mean station position, PPP RMS results corrected for daily origins still contain the ITRF97 station position/velocity errors and constant or slowly varying real and/or apparent station position movements/biases. Such (real) station movements/biases can be due, for example, to unmodeled loading effects, such as those due to the atmosphere, snow and ground water.
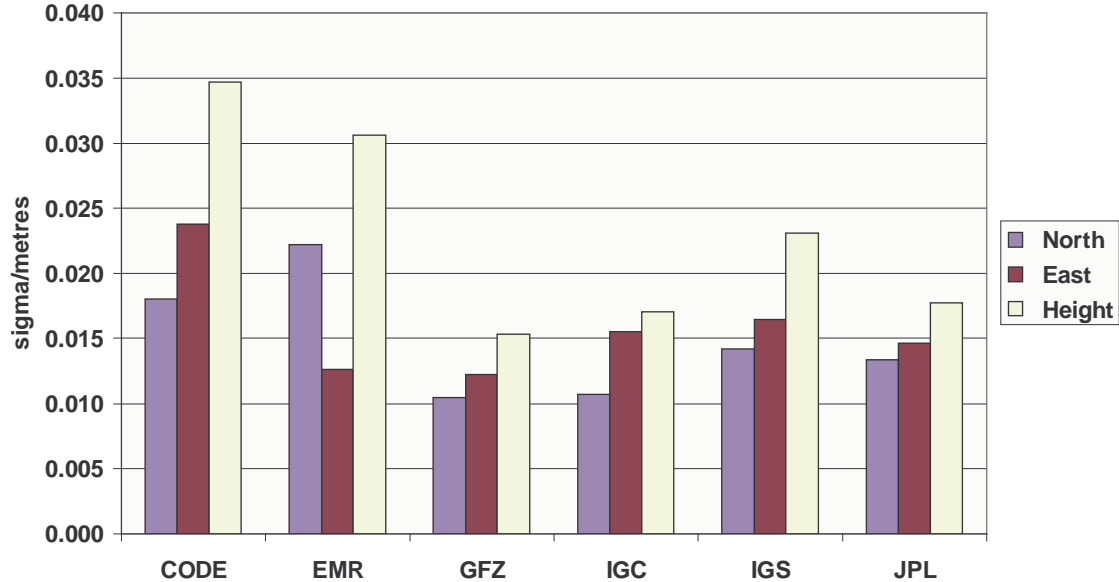
Figure 4: Static GIPSY PPP sigmas (RMS of PPP-ITRF97 position differences) for stations AUCK, BRUS, USUD, WILL with IGS, AC orbit/clock solutions and the new clock combination *IGC* for GPS Wk 0995 (corrected for daily geocenter origin offsets; IGC represents the new clock combination, adopted by IGS on November 5, 2000)

Figure 4 shows the RMS of the PPP-ITRF97 position differences for static GIPSY PPP's with various AC and IGS Final orbit/clock products, after correcting for the daily origin offsets. Also shown here are the results of the IGS Final orbits augmented with 15-min satellite clocks from the new, more consistent and robust, 5-min satellite/station clock combination (*IGC*) which has replaced the IGS satellite clock combinations on November 5, 2000 (Kouba and Springer, 2001). As one can see here the PPP RMS (accuracy) for the IGS products and the best ACs was between 10 and 15 mm for the horizontal, and between 15 and 25 mm for the vertical components.

This is quite consistent with the corresponding weekly SINEX results after assuming daily random variations, i.e. after increasing the weekly SINEX RMS' of Figure 3 by a factor of up to 2.6. It is encouraging to see that the IGS Final orbits augmented with the new clock combinations (*IGC*) were slightly better than the original IGS Final orbit/clock products (prior November 5, 2000). Note that when only the PPP repeatability around the respective weekly mean station positions are concerned, i.e. once the weekly mean station position biases are excluded, the same PPP repeatability performance as reported in Zumberge at al. (1997) was obtained, i.e. about 5 mm-horizontal and 10 mm-vertical repeatability. It is interesting to note that the horizontal JPL orbit/clock PPP RMS in Figure 4 were in fact quite equivalent to the GIPSY position service (Zumberge et al., 1999), since the same software, orbits/clocks orbits and six transformation parameters (3 shifts and 3 rotations) were used. The height RMS of Figure 4 should be slightly higher, since no daily scale (height) biases were applied here.

The second PPP test (Fig. 5) was performed at the Astronomical Institute of the University of Berne by the former IGS AC Coordinator, Dr. T. Springer, in order to check and verify the final implementation of then new (now operational) IGS satellite/station clock combinations (Kouba and Springer, 2001), labeled here *IGC*. Dr. Springer has kindly made available his complete PPP results for three stations (BRUS, WILL, TOW2) from the GPS Week 1081 (September 24-30, 2000) and he obtained them with the BERNESE software operating in the static PPP processing mode. The corresponding AC weekly origin/scale and *IGC* scale biases of the GPS Week 1081 SINEX combination (*IGS00P1081.sum*) that are compiled in Table 3, were accounted for in these PPP results. The weekly IGS origin/scale and *IGC* scale biases were not yet

available in the IGS SINEX combinations so they were approximated by a weekly average of each of the 5 AC solutions listed in Table 3.
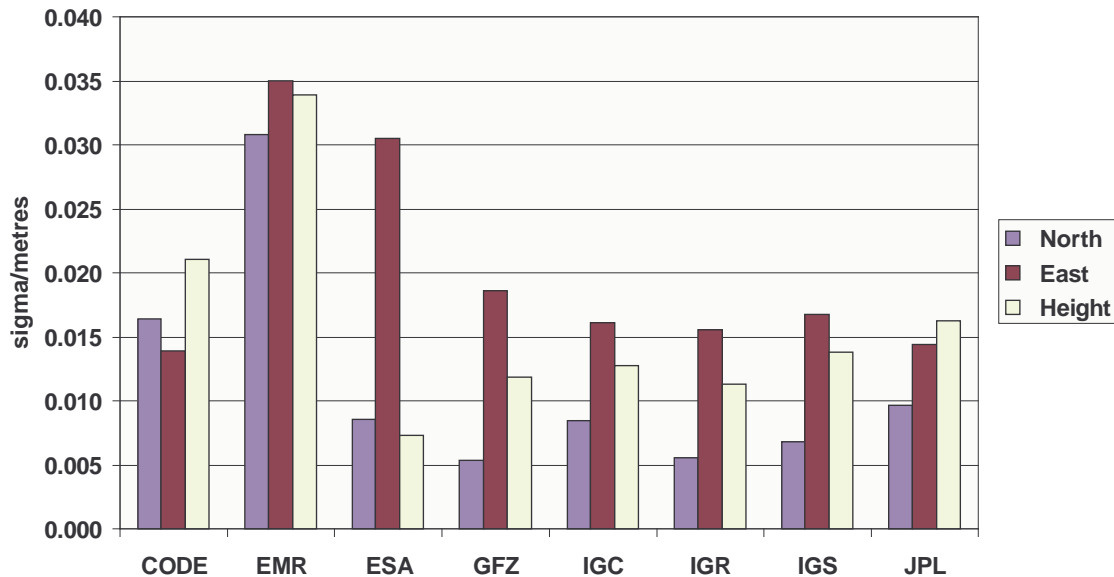

Figure 5: Static BERNESE PPP sigma (RMS of position differences) for stations BRUS, WILL, TOW2, with IGS, IGR, AC orbit/clock solutions and the new clock combination IGC for GPS Week 1081 (September 24-30, 2000; corrected for a weekly geocenter origin offset of Tab. 3)

Table 3. Weekly origin and scale offsets available from the IGS SINEX combination and removed from the GPS Week 1081 PPP RMS comparisons. (The *IGC* scale and *IGS* origin/scale offsets that are not available in *IGS00P1081.sum* were approximated by the averages of all AC origin/scale biases).

	DX	DY	DZ	SCL
Center	(cm)	(cm)	(cm)	(ppb)
COD	-0.29	0.05	-1.05	2.52
EMR	0.78	-0.15	4.81	2.00
ESA	-0.08	1.86	0.02	1.32
GFZ	0.01	0.00	-0.24	1.34
IGC	0.00	0.00	0.00	1.86
IGR	0.00	0.00	0.00	0.00
IGS	-0.02	0.46	0.28	1.86
JPL	-0.53	0.53	-2.12	2.02

As discussed before (Section 5.3.2), zero origin/scale and zero origin offsets should be expected and used for IGR and *IGC*, respectively. This application of origin/scale offsets represents a proper use of the orbit/clock products of the ACs and IGS (prior Nov. 5, 2006) with the corresponding IGS ITRF convention (i.e. the weekly monitoring of "geocenter" and scale biases). Also note that the IGS cumulative SINEX (*IGS00P04.snx*) products was also used here as a ground truth in all the position comparisons. The RMS PPP results of this second test, shown in Figure 5, in fact, represent the achievable accuracy with the IGS products prior November 2006, once the small daily or weekly origin/scale offsets are accounted for.
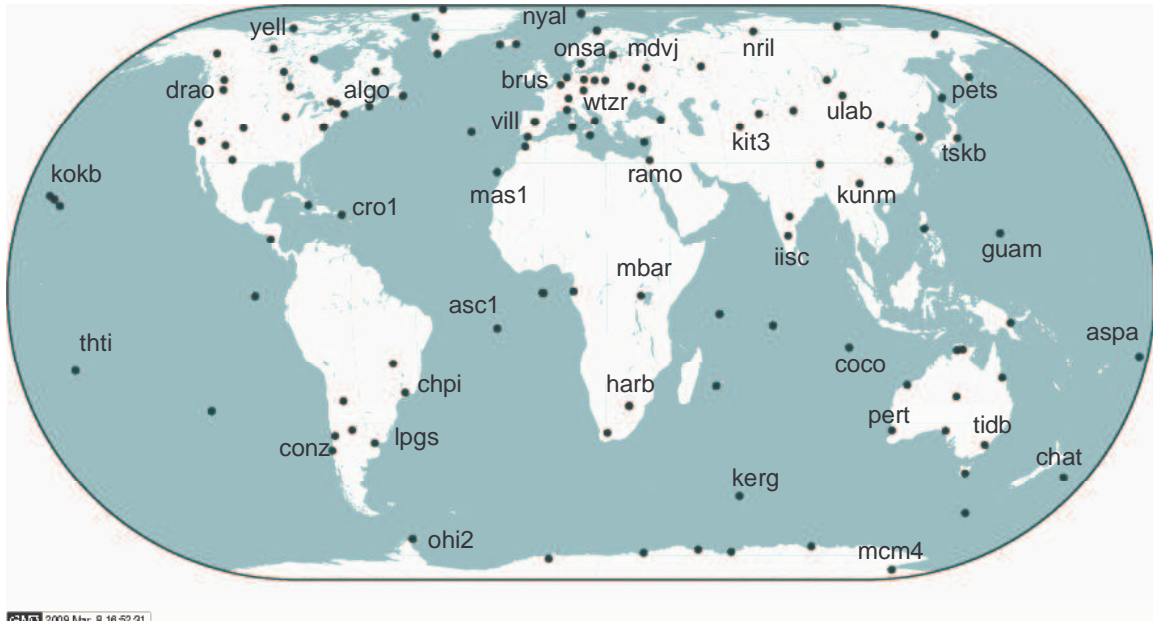
Figure 6. IGS Reference Frame Stations (RS) (*dots*) used for IGS ITRF realizations in 2009 and the names of the 36 RS selected for the PPP evaluations during the GPS Week 1516 (January 25 - 31, 2009)

The third, more extensive PPP test, used GPS data from a subset of 36, globally well-distributed Reference frame stations (RS) (Fig. 6) with good tracking during the GPS Week 1516 (January 25 - 31, 2009). It also involved a different PPP software, namely GPS Pace (Héroux and Kouba, 1995), which was enhanced to account for all the modeling effects and approximations at the mm- precision level as discussed above (Héroux and Kouba, 2000; Kouba and Héroux, 2001). The IGS05 station positions/velocities of the IGS cumulative SINEX combination product (*IGS09P04.snx*) were used as a ground truth in this PPP solution comparison. Since November 5, 2006 all the AC clock solutions should be transformed (translated) to current ITRF (here IGS05), consequently all the PPP results in Figure 7 include no geocenter/scale corrections. As one can see the RMS agreement of Fig. 7 has improved considerably when compared to the GIPSY and BERNESE PPP results of Figure 4 and 5. This is likely due to significant improvements of IGS and AC orbit/clock solutions realized after the GPS week 1400 (November 2006) (see Fig. 1). Note that the results of Figure 7 were obtained with a rather simple PC based PPP software, that is completely independent from the IGS solutions since it was not used to generate any of the AC and IGS solutions. Both IGS and all the AC solutions, except for the two new ACs (*GRG* and *MIT*) show nearly the same RMS in Fig. 7. Note that the two ACs, in particular GRG, have improved significantly around GPS Week 1600 (Fig. 1). This indicates that the IGS and most AC clocks indeed refer to the ITRF origin and no geocenter corrections need to be applied. The slightly higher PPP RMS for the vertical component is due to a scale bias of about 1.5 ppb (~10 mm). Note here, that the IGS Rapid (IGR) orbit/clock products, which were constraining about 100 (or more) RS at the IGS05 coordinates and which were available with only a 17-hour delay, have performed equally well as the best AC and the IGS Final orbit/clock products. This figure also indicates that all AC clock solutions were more consistent with the corresponding daily AC orbits and the weekly SINEX station solutions, than it was the case in 2000. Furthermore, that all the IGS orbit/clock combined products gave the best accuracy and that the accuracy of PPP's with the IGS orbit/clock combined products should currently be at or below the 10-mm level.
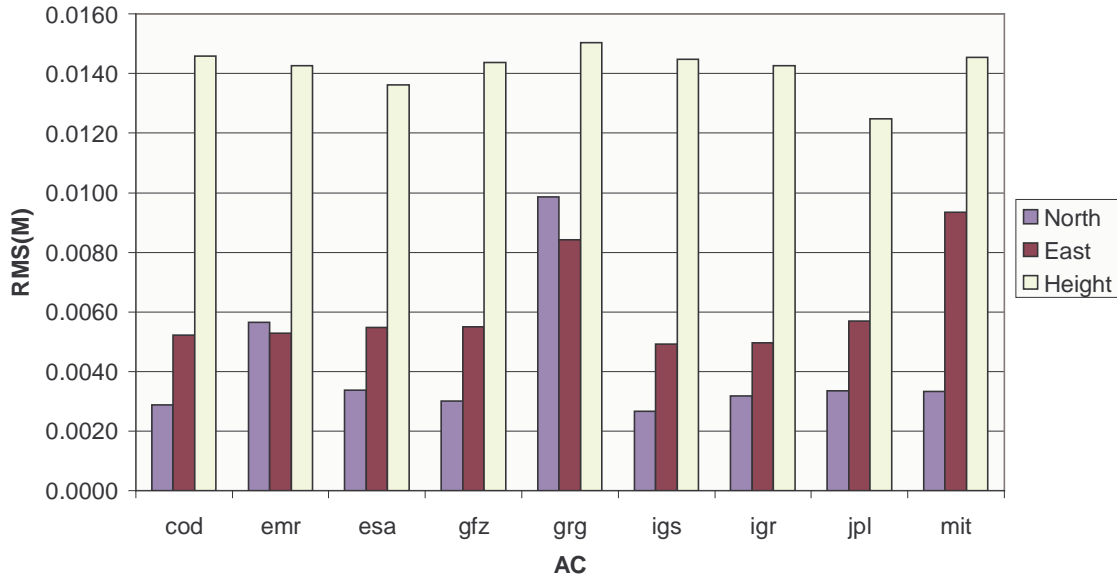
Figure 7: Static GPS Pace PPP RMS at 36 Reference frame stations (RS) with IGS, IGR and AC orbit/clock solutions for GPS Week 1516 (January 25 - 31, 2009; no geocenter origin/scale offset corrections)
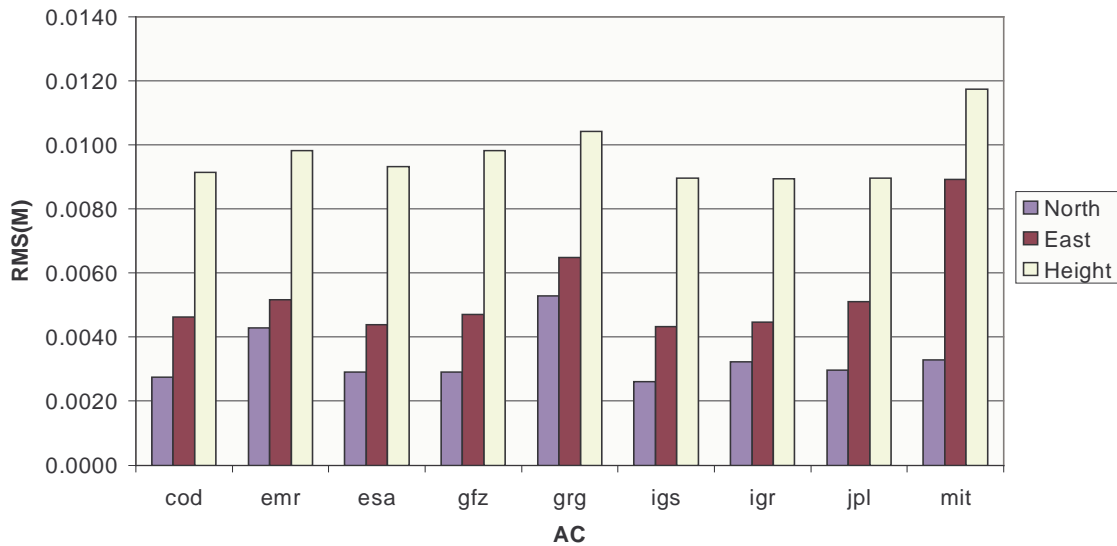

Figure 8: Static GPS Pace PPP RMS at 36 Reference frame stations (RS) with IGS, IGR and AC orbit/clock solutions for GPS Week 1516 (January 25-31, 2009; *corrected* for daily geocenter origin/scale offsets)

The relatively high horizontal RMS for GRG orbit/clock PPP solutions (in Fig. 7) are partly due to a small (~ 6 mm) *dz*-origin offset. After daily geocenter and scale offsets (computed as daily averages over the 36 RS) are accounted for here, the GRG PPP results become more comparable to the rest (see Fig. 8). Except for GRG (and to a smaller extent also EMR), the horizontal RMS of Fig. 8 are practically the same as in Fig. 7, where no geocenter offset corrections were applied. After nearly constant daily scale biases of about 1.5 ppm have been removed, the vertical RMS of Fig. 8 are significantly smaller. Comparing Fig. 8 with Table 2, one can see that the daily (SINEX) IGS/AC solutions of 2015, after 7-parameter Helmert transformations, gave RMS, which are about the same as daily PPP RMS. Fig. 8 is also comparable to the continuous daily PPP results, compiled on the ACC website (http://acc.igs.org/), where all the (~ 100) RS are processed with BERNESE PPP and 7-parameter transformations are used daily.

To demonstrate the high precision and consistency of most of the AC orbit/clock solutions, the weekly repeatability's at each station (i.e., the standard deviations (sigmas) with respect to weekly (biased) mean station positions) are compiled in Figure 9. This figure shows rather small repeatability sigmas, well below the 10-mm level, for all the ACs and IGS orbit/clock products. The IGS and the best AC orbit/clock solutions gave the daily position repeatability 1-2 mm in the horizontal and about 5 mm in the vertical components.
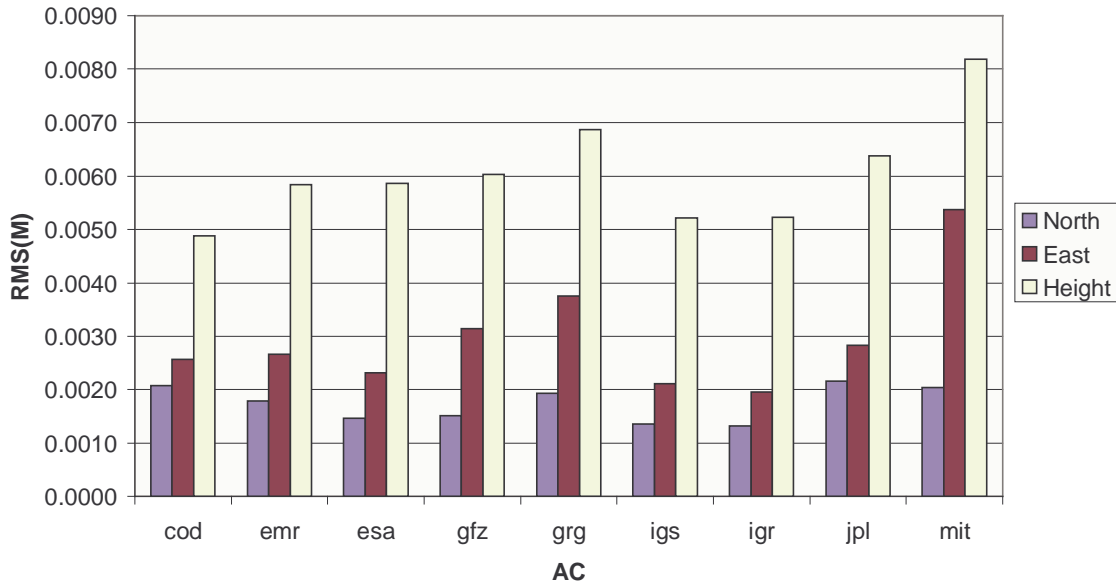
Figure 9: Static GPS Pace PPP repeatability sigma (RMS) at 36 Reference frame stations (RS) with respect to weekly average positions, using IGS, IGR and AC orbit/clock solutions for GPS Week 1516 (January 25 - 31, 2009)
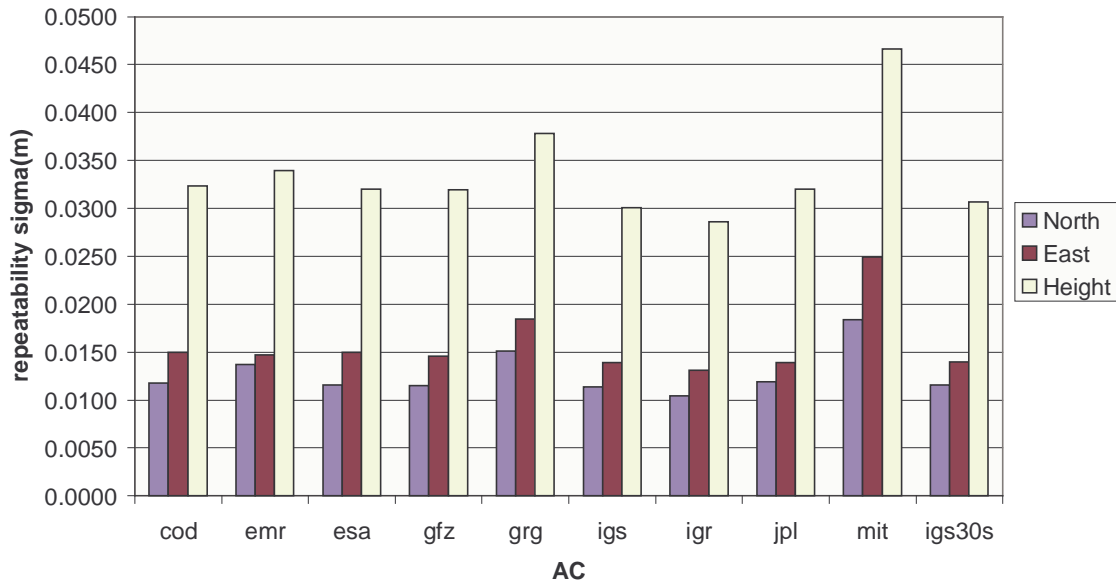
Figure 10: Average kinematic (navigation) GPS Pace PPP repeatability sigmas at 36 Reference frame stations (RS) with respect to daily average positions, using IGS, IGR and AC orbit/clock solutions for GPS Week 1516 (January 25 - 31, 2009)

PPP software and the IGS orbit/clock products can also be used for efficient and accurate kinematic positioning (navigation) at each epoch at any place on the Earth and for any user dynamics. In fact, thanks to the availability of IGS orbit/clock products, there is no need for any base stations and/or differential GPS

(DGPS) corrections in post-processing mode at the cm accuracy level. This point is demonstrated by Figure 10, which shows GPS Pace RMS' of independent epoch position solutions ("simulated navigation") with respect to daily means of the 36 RS with the AC and IGS combined products during the GPS Week 1516 (January 25 - 31, 2009). Unlike for the static PPPs in Figs. 7 - 9, where no solution was rejected, the Fig. 10 does not include a problem data of January 26, 2009 at the reference station PETS, where kinematic RMS values were rather large (0.1 to 0.4 m). To avoid clock interpolation errors, only the clock sampling epochs (either 5-min or 30-sec for COD, EMR and MIT) were used in Fig. 10. The IGS Final clock combinations with 30-sec sampling, which are available since 2007 and which were then based on COD, EMR and MIT clocks only are also shown in Fig. 10. Note that the 30-sec clock sampling allows precise interpolation of satellite clocks, so that nearly the same kinematic PPP repeatability shown in Fig.10 is now achievable for any clock sampling with IGS 30-sec clocks. Kinematic PPPs at 3 IGS stations (currently BRUX, WILL, TOW2) are also included as a quality check in every IGS orbit/clock weekly combinations (Kouba and Mireault, 1999).

By using the IGS products one ensures the highest possible consistency within the current ITRF. Since the Selective Availability (SA) was switched off permanently on May 02, 2000 and the 5-min IGS satellite/station clock products (IGC) has become official on November 05, 2000, it is possible to linearly interpolate the IGS satellite clocks at about 0.1 ns. Thus, also possible to obtain navigation solutions at or below the accuracy level of about 10-cm at any place and for any observation interval. Furthermore, since the GPS Week 1410 (January 14, 2007), when IGS Final clock combinations also include separate clock files with 30-sec sampling, it is possible to interpolate satellite clocks at about 0.03 ns and obtain navigation solutions at the accuracy level of a cm at any place and for any sampling interval.

7.2 Tropospheric zenith path delay (zpd)

The zpd_w solutions have been found useful in meteorology to determine vertical atmospheric integrated precipitable water content (Bevis et al., 1992). The zpd ($zpd_h + zpd_w$) could also provide accurate control (a reference, consistent with ITRF) for the combined hydrostatic and water vapor pressure in numerical weather modeling (Kouba, 2009).

It is important to note that unless DD GNSS analyses are based on a sufficiently large area (e.g. > 500 km), it is impossible to obtain meaningful solutions for zpd_w. For such small or regional areas (< 500 km) it is only possible to estimate precisely differences of zpd_w with respect to a reference station zpd_w. So, reference station zpd_w's have to be obtained externally, e.g. from the IGS. PPP solutions, on the other hand, are capable of determining quite precisely the value of zpd_w within the IGS reference frame (ITRF), even from a single station. It is also important to note that zpd_w solutions are correlated with station heights, thus for the highest precision a careful consideration should be given to the variations and monitoring of the origin/scale (if applicable), as discussed in Section 5.3.2. Depending on elevation angle cut off angle and/or elevation weighting, about a third to one fifth of the station height errors (variations) map directly into the zpd_w solutions (Gendt, 1996, 1998). This is why it is also important that station loading effects and the ocean loading, in particular for stations in coastal areas, are correctly modeled as well (Dragert et al., 2000). An error (bias) or unmodeled temporal variations of M_h, M_w and/or a priori zpd_h, can also cause systematic errors in heights and the total zpd ($zpd_h + zpd_w$) of more than 10 mm (Kouba, 2009).

Evaluating the accuracy of troposheric zpd solutions is even more difficult than the evaluation of positioning accuracy. The IGS combined zpd's at 2-hour intervals, derived from the contributions made by up to eight ACs for up to 200 globally distributed GPS tracking stations, are available only up to GPS Week 1399 (November 4, 2006) (see ftp://cddis.gsfc.nasa.gov/gps/products/troposphere/old/). The IGS combined station zpd's have been compared with estimates derived from other techniques and have proven to be quite precise (~7 to 8 mm) and accurate (Gendt, 1996). After November 4, 2006, the combined zpd products have been replaced with the "IGSnew" zpd products, which have 5-min sampling, are available from 2000 for all IGS stations and are based on GIPSY PPP with IGS Final orbits/clocks (Byun and Bar-Sever, 2009; ftp://cddis.gsfc.nasa.gov/gps/products/troposphere/new/).
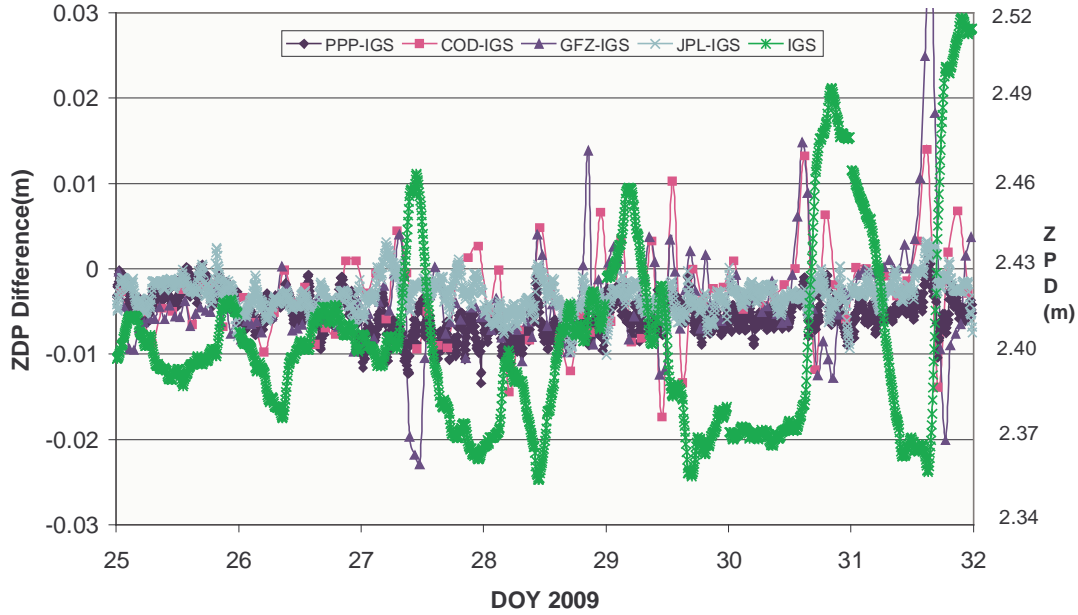
Figure 11. GPS Pace PPP and AC *zpd* (z*pd_h*+ z*pd_w*) differences with respect to the "IGSnew" *zpd* (*IGS*) at the New Zealand RS CHAT during the GPS Week 1516 (January 25 - 31, 2009). Also shown is the IGSnew *zpd* variation (see the right-hand scale).

To demonstrate the quality and consistency of recent PPP z*pd_w* solutions utilizing IGS orbits/clocks, the estimated (total) *zpd's* (z*pd_h* + z*pd_w*) for the GPS Week 1516 (January 25 - 31, 2009), obtained by three different ACs and from PPP with IGS orbit/clock products were compared to the IGSnew *zpd's*. Figure 11 shows the 7-day time series of the differences with respect to IGSnew *zpd's* for COD, GFZ and JPL AC *zpd's* and GPS Pace PPP *zpd's* at the New Zealand RS CHAT. For completeness and convenience the IGSnew *zpd's* are also plotted here, utilizing the scale on the right. One can see a very good agreement with IGSnew *zpd* for both PPP and JPL AC *zpd's*, with a standard deviation of about 2 mm in both cases, though both PPP and JPL AC show a small systematic (negative) offset. This is likely due to the IGSnew *zpd*, since it used an old Mapping Function (MF) (Neill) and only a constant, height dependent pressure for z*pd_h* (Byun and Bar-Sever, 2009), while JPL used the global seasonal MF (GMF) model with z*pd_h* based on a global pressure model (GPT) (see Boehm at al., 2006 and Boehm at al., 2007, respectively) and the GPS Pace PPP is using temporally and specially varying NWM (Gridded Vienna Mapping Function 1) values for M_h, M_w and z*pd_h* (Kouba, 2007).

COD and GFZ AC *zpd's* in Fig. 11 also exhibit a similar negative bias, however the agreement is much worse, with standard deviations of 6 and 7 mm, respectively. This is mainly due to smoothing, caused by COD hourly or GFZ half-hourly estimations, which could not depict the rapid changes of CHAT *zpd* on this day. Furthermore, continuity constraints at the hourly and half-hourly *zpd* estimation boundaries likely cause the large, compensating spikes for both COD and GFZ *zpd's* (see Fig. 11).

To get a more global view of the quality of the PPP *zpd* estimates, the *zpd's* of the above 36 RS static PPP test have been compared with the IGSnew *zpd* products. IGSnew *zpd* products are missing for three RS (NYAL, MDVJ and ASPA) during this GPS Week 1516. Furthermore, on each day and at every station the last two 5-min epochs (23:50 and 23:55) are also missing in IGSnew *zpd's* and thus could not be included in the comparisons. The 7-day mean *zpd* differences (PPP-IGSnew) varied from -3 to 4 mm and the standard deviations varied from 1 to 3 mm, with an average standard deviation of 1.9 mm. However, the IGSnew *zpd's* had to be first corrected for height errors by *dH*/4, where *dH* is the error (with respect to the IGS05) of the IGSnew daily (i.e., GIPSY PPP) height solutions, which are also available in the IGSnew *zpd* files. Otherwise, without the height corrections, the mean *zpd* biases were between –12 (at MCM4) and 3 mm. This is likely a consequence of the old MF and a constant, height dependent station pressures (used for z*pd_h*) utilized for the IGSnew. Recall that the GPS Pace PPP has used temporally and spatially varying

zpd_h and the MF's of the gridded VMF1 (Kouba 2007). The zpd_w solution precision of 3 mm corresponds to about 0.5 mm of integrated precipitable water (Bevis et al., 1992).

7.3 Station clock solutions

It is important to note that it is impossible to get any clock solutions from DD GNSS analyses, which is the penalty paid for the significant simplification and efficiency of DD GNSS observations. The clock solutions are only possible in un-differenced global and PPP solutions. The clock solution parameters are perhaps the most sensitive to a wide range of effects and thus can be significantly biased unless properly modeling all the effects discussed above (Section 5), including the ocean loading effects. For these reasons, discussions in Section 5.2.3 should also be carefully consulted.

Evaluating the quality of PPP station clock solutions is also somewhat complicated by the absence of an absolute standard for comparison and the fact that different reference clocks and alignment values are used by the ACs in the computation of their daily solutions. Therefore, the following evaluation is an internal comparison of the above (static) GPS Pace PPP station clock solutions, based on the combined IGS Final (*igs*) and Rapid (*igr*) satellite orbits/clocks at only one of the 36 RS, during the GPS Week 1516. The IGS RS BRUS was selected for this clock comparison since it is equipped with a Hydrogen MASER (HM) clock and was processed by most ACs during this week.
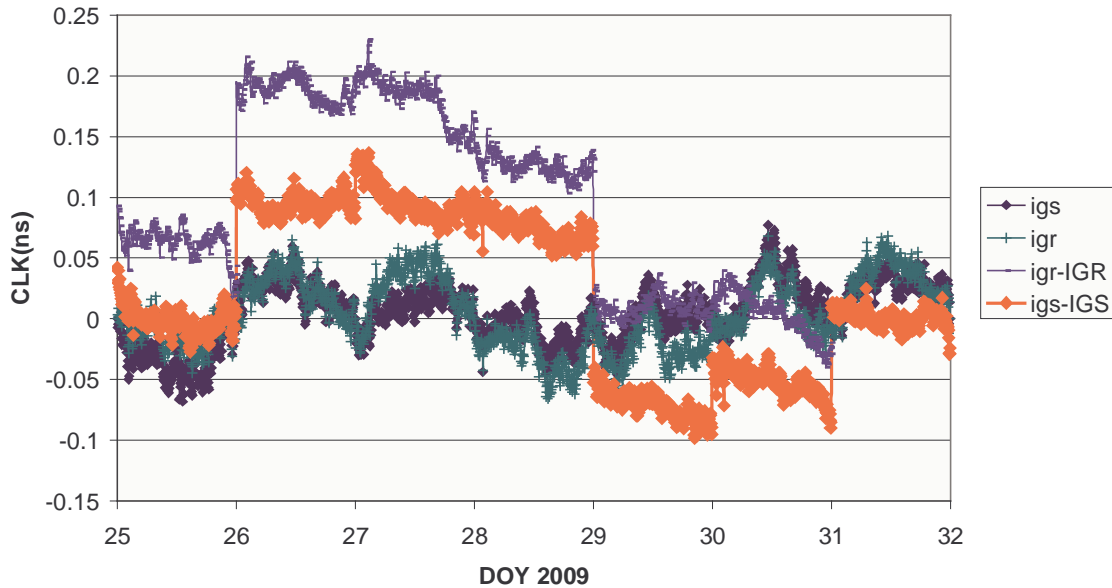

Figure 12. 24-h linear regression clock residuals for GPS Pace PPP station clock solutions with IGS Final (*igs*) and IGS Rapid (*igr*) orbits/clocks at the European RS BRUS during the GPS Week 1516. Also shown are the PPP clock solution differences with respect to the IGS Final (*IGS*) and Rapid (*IGR*) combined station clocks with no offsets or drifts removed.

Figure 12 shows the *igr* and *igs* BRUS station PPP clock solutions and their differences with respect to the IGS Final (*IGS*) and Rapid (*IGR*) combined clocks during the 7 days of the GPS Wk 1516. Except for small offsets and drifts, both the *igr* and *igs* PPP clocks agree very well with the *IGS* and *IGR* ones, namely at the 12 and 14 picosecond levels (one standard deviation), respectively. The small daily jumps and drifts should be expected and are mainly due to the PPP clocks, since PPP (as well as AC) clocks are aligned daily by pseudorange averages for PPP observed only at a single station, but for ambiguity fixed AC solutions also pseudoranges observed at the neighbouring stations. Consequently AC station clocks should have smaller jumps and drifts than the corresponding PPP ones. Furthermore, the current IGS clock combination and time scale alignment (Senior et al., 2001) was designed to minimize the daily AC clock jumps, which otherwise could exceed 1 ns at some stations for some AC solutions (Ray and Senior, 2003). To minimize the HM aging and other non-liner effects (such as residual reference clock errors (instabilities)

of the IGS/AC clocks, the *igs* and *igr* PPP clocks, shown in Fig. 12 were corrected for small daily offsets and drifts. After correcting for the daily offsets and drifts, the *igs* and *igr* PPP clock solutions were linear to within 50 picoseconds, with standard deviations of 25 and 29 picoseconds, respectively.   This is already smaller than the formal PPP solution sigmas of about 30 picoseconds, furthermore it is also consistent with the expected HM clock stability (Larson et al., 2000).   Note that the BRUS PPPs have benefited from a dense network of surrounding European IGS stations; for a remote station, the PPP clock solutions and comparisons could be significantly worse than the ones seen in Fig. 12.

8. Conclusions

The primary goal of this compilation of well-known and not so well known aspects of GNSS analyses was to aid IGS product users at both practical and scientific levels. It should also help IGS users to employ the existing GNSS software more efficiently or even to develop practical, scientific or commercial software that would allow an efficient and consistent utilization of IGS products. It should also be useful for technical and scientific interpretations of results obtained with IGS Combined Products.

The observation equations, estimation technique and station/satellite models used for the implementation of GPS precise point positioning (PPP) using IGS orbit/clock products were described. Past and current conventions and compatibility issues were compiled together with discussions and tests of precision and accuracy that could and can now be obtained with IGS products. The main emphasis was on simple, yet efficient PPP solutions with IGS products. It was demonstrated that different PPP software can be used with IGS GPS Orbit/Clock combined products and dual-frequency pseudorange and carrier-phase observations from a single GPS receiver to estimate station coordinates, tropospheric zenith path delays and clock parameters at the mm-cm accuracy level, directly in ITRF. Typically, PPP with IGS Orbit/Clock Combined Products gave the best accuracy and more robust/complete results, which are better than the ones obtained with the individual Analysis Center orbit/clock solutions. The PPP processing mode, described and tested here in detail, forms an ideal interface to the IGS orbit/clock products and ITRF for both practical and scientific applications. The PPP approach utilizing IGS orbit/clock combined products is equally applicable to global kinematic positioning/navigation at the cm precision level as was demonstrated here and also is demonstrated every week within IGS combination summary reports. (See IGS Rapid and Final Combination Summary Reports at the IGSREPORT archives (http://www.igs.org/mail/)). Since 2007 when the 30-sec IGS combined clock products have become available and with no SA, it is possible to precisely interpolate satellite clocks, which enables also cm global kinematic positioning (navigation) at any interval sampling, anywhere in the world and without any need of base stations.

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