A GUIDE TO USING INTERNATIONAL GPS SERVICE (IGS) PRODUCTS

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February 2003

Abstract

Since 1994 the International GPS Service (IGS) has provided precise GPS orbit products to the scientific community with increased precision and timeliness. Many national geodetic agencies and GPS 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 approach that requires the combination of observations from a minimum of two GPS receivers, with at least one occupying a station with known coordinates is 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 cancel out common GPS 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 GPS 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 products and models systematic effects that cause centimeter variations in the satellite to user range. Furthermore, station tropospheric zenith path delays with cm precision and GPS receiver clock estimates precise to 0.1 nanosecond are also obtained. This paper describes both approaches, summarize the adjustment procedure and specifies the Earth and space based models that must be implemented to achieve cm level positioning, tropospheric zenith path delay and clock solutions.

1. Introduction

The International GPS Service (IGS) 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 GPS 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 article focuses on the advantages and usage of the IGS precise orbits and clocks.

Currently up to eight IGS Analysis Centers (AC) contribute daily ultra-rapid, rapid and final GPS orbit and clock solutions to the IGS combinations. The daily computation of global precise GPS orbits and clocks by IGS, with centimeter accuracy, facilitates a direct link within a globally integrated, reference frame which is consistent with the current ITRF (International Terrestrial Reference Frame). Recently, an ultra-rapid product to serve meteorological applications and support Low Earth Orbiter (LEO) missions has been added to AC product submissions to the IGS. For more information on the IGS combined solution products and their availability see the IGS Central Bureau (see http://igscb.jpl.nasa.gov/components/prods.html).

For GPS users interested in meter level positioning/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 the 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 since the interpolation of the 15-min SA-free satellite clocks given in IGS sp3 files is now possible at a few dm precision level. Furthermore, since December 26, 1999, separate yet consistent clock files, containing new combinations of satellite/station clocks at 5-min sampling intervals have been available and on November 5, 2000, the new clock combinations became the official IGS clock products (Kouba and Springer, 2000). The 5-min clock sampling allows an interpolation of SA-free satellite clocks well below the dm level (Zumberge and Gendt, 2000). For GPS users seeking to achieve geodetic precision, sophisticated processing software packages such as GIPSY (Lichten et al., 1995), BERNESE (Rothacher and Mervart, 1996) and GAMIT (King and Bock, 1999) are required. However, by using the IGS precise orbit products and combining the GPS carrier phase data with nearby IGS station observations, geodetic users can achieve precise positioning within the global frame that is consistent with the current ITRF, with a 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) conventions/ 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 GPS observation file (see e.g. Zumberge, 1999). 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 are utilizing IGS orbit/clock products, there is no need for large and sophisticated global analyses with complex and sophisticated software. This is so since the IGS orbit/clock products retain all the necessary information of the global analyses that have already been done by the IGS AC professionals, using the state of art knowledge and software tools. Thus, the users of the IGS products in fact take the full advantage of the IGS AC global analyses, properly combined and quality checked, all in accordance with the current international conventions and standards.

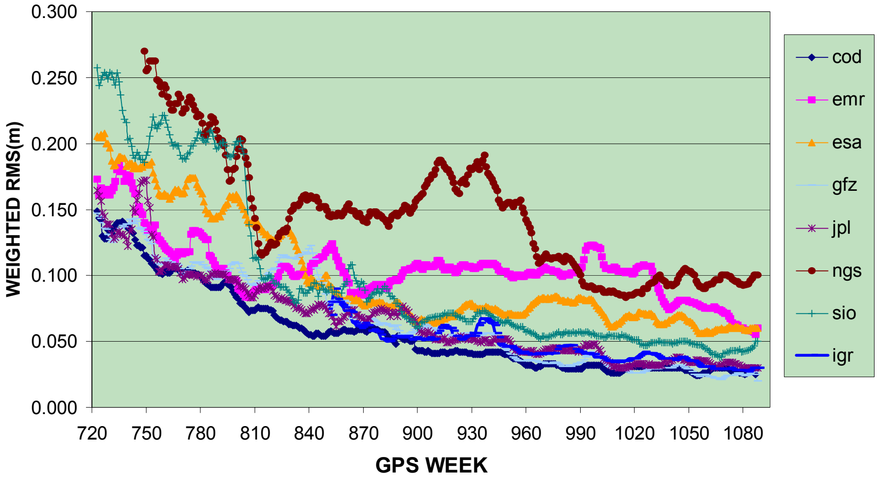
2. IGS GPS Orbit/Clock Combined Products

Even though, strictly speaking, it is illegal 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 Service 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., (1996) who has also shown that, under certain conditions, such orbit combinations represent physically meaningful orbits as they still satisfy the equations of motions. Furthermore, when the orbit weights are also used in the corresponding ERP combinations, 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 to the recently added Ultra-Rapid (IGS Mail #3088 at http://igscb.jpl.nasa.gov/mail/igsmail/igsmail.html), which has become officially available on November 5, 2000 (GPS Wk 1087, MJD 5183). The IGS Ultra-Rapid (IGU) products have replaced the former IGS predicted (IGP) orbit products (IGS Mail #3229). 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 combined from seven (five) contributing IGS Analysis Centers (ACs), using six, largely independent, software packages (i.e. BERNESE, GAMIT, GIPSY, BAHN (Dow et al., 1999), EPOS (Gendt, et al., 1999) and PAGES (Schenewerk et al., 1999)). The IGS Final orbit/clocks are usually available on 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. 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. Recently, 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, that should satisfy the more demanding needs of the meteorological community and future 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., 2002). For more information on the IGS products and their possible applications see e.g. Neilan et al., (1997); Kouba et al., (1998).

From Figure 1, one can see that over the past 8 years the precision of the AC Final orbits has improved from about 30 cm to about 3 - 5 cm, with a concomitant improvement in the Final Combination orbit. It is also interesting to note that the Rapid orbit combined product (IGR), with less tracking stations and faster delivery times, is as precise as the best AC Final solutions. The precision of the corresponding AC/IGS ERP solutions has shown similar improvements since 1993. One element that has not yet received much attention is the quality of the GPS satellite clock estimates included in the IGS orbit products since 1995. Examining the IGS Final summary reports (http://igscb.jpl.nasa.gov/mail/igsreport/igsreport.html), produced weekly by the IGS AC Coordinator one can notice that the satellite clock estimates produced by different AC's agree within 0.1-0.2 nanosecond (ns) RMS, or 3-6 cm. This is also consistent with the orbit precision. The precise GPS 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 correctly implemented.

Figure 1: Weighted orbit RMS of the IGS Rapid and AC final orbit solutions 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; JPL – Jet Propulsion Laboratory; NGS – National Geodetic Surway, NOAA, U.S.A.; SIO- Scripps Institute of Oceanography, U.S.A.)



3. Observation equations

The ionospheric-free combinations of dual-frequency GPS 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:

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

where:

ℓ_P	is the ionosphere-free combination of P1 and P2 pseudoranges ($2.546P_1$-$1.546P_2$),
ℓ_Φ	is the ionosphere-free combination of L1 and L2 carrier-phases ($2.546\lambda_1\phi_1$-$1.546\lambda_2\phi_2$),
dT	is the station receiver clock offset from the GPS time,
dt	is the satellite clock offset from the GPS time,
c	is the vacuum speed of light,
T_r	is the signal path delay due to the neutral-atmosphere (primarily the troposphere),
N	is the non-integer ambiguity of the carrier-phase ionosphere-free combination,
λ_1, λ_2, λ	are the of the carrier- phase L1, L2 and combination (10.7 cm) wavelengths, respectively,
ε_P, ε_Φ	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.

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

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

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

here $\Delta(.)_{ij}^{k}$ denotes the single difference. By subtracting the observation equations (3), (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 observation equations, where the station clock difference errors ΔdT_{ij} , which are the same for both single differences, are also eliminated:

$$\ell_{Pij}^{\,kl} = \Delta\rho_{ij}^{\,kl} + \Delta T_{rij}^{\,kl} + \Delta\varepsilon_{Pij}^{\,kl}, \tag{5}$$
$$\ell_{\Phi ij}^{\,kl} = \Delta\rho_{ij}^{\,kl} + \Delta T_{rij}^{\,kl} + \Delta N_{ij}^{\,kl}\lambda + \Delta\varepsilon_{\Phi ij}^{\,kl}, \tag{6}$$

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 ΔN_{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 double differencing scheme. Consequently, once the $L1$ and $L2$ ambiguities are resolved, the ionospheric-free ambiguities ΔN_{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. Hoffmann-Wellenhof et al., 1992).

The equation (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 ΔT_{rij}^{kl} is much smaller than the un-differenced $\Delta T_{r,}$, the noise $\Delta\varepsilon(.)_{ij}^{kl}$ is significantly larger than the original, un-differenced noise $\Delta\varepsilon(.)$, etc. Nevertheless, both un-differenced and double differenced approaches produce identical results, provided that the same set of un-differenced observations and proper correlation, which is derived from the differencing are used. In other words, the double difference position solutions with properly propagated observation weight matrix (see e.g. Hoffmann-Wellenhof et al., 1992), 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 equations (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:

$$f_P = \rho + c\,dT + M\,zpd + \varepsilon_P - \ell_P = 0, \qquad (7)$$

$$f_\Phi = \rho + c\,dT + M\,zpd + N\lambda + \varepsilon_\Phi - \ell_\Phi = 0; \qquad (8)$$

Unlike the equations (1)-(6) that contain unknowns and/or observation differences involving baselines or the whole station network, the equations (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, it makes little or no sense to solve equation (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 (***http://igscb.jpl.nasa.gov/organization/centers.html#RNAAC***), only the observation equation (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 double differenced or even un-differenced observations. For un-differenced network solutions, the resolved *L1, L2* double differenced integer ambiguities are used to derive the ionospheric-free real ambiguities and then the known double differenced integer ambiguities are introduced as condition equations into the corresponding matrix of the normal equations. It is worth to note that point positioning (eqn. (7), (8)) allows position, tropospheric zenith path delay and receiver clock solutions that are consistent with the global reference system implied by the fixed IGS orbit/clock products. The differential approach (eqn. (5), (6)), on the other hand, does not allow for any precise clock solutions, and the tropospheric *zpd* solutions may be biased by a constant (datum) offset, in particular for regional and local baselines/networks (< 500 km). Thus, such regional/local *zpd* solutions, based on double difference network analyses, require external tropspheric *zpd* calibration (at least at one station), e.g. by means of the IGS troposheric combined *zpd* products (Gendt, 1996, 1998).

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 equations (7) and (8) around the a-priori parameter values and observations (X^0, ℓ) in the matrix form becomes:

$$A\,\delta + W - V = 0, \qquad (9)$$

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), troposphere zenith path delay (zpd) and (non-integer) carrier-phase ambiguities (N), form the design matrix A:

$$A = \begin{bmatrix} \frac{\partial f(X,\ell_P)}{\partial X_x} & \frac{\partial f(X,\ell_P)}{\partial X_y} & \frac{\partial f(X,\ell_P)}{\partial X_z} & \frac{\partial f(X,\ell_P)}{\partial X_{dT}} & \frac{\partial f(X,\ell_P)}{\partial X_{zpd}} & \frac{\partial f(X,\ell_P)}{\partial X_{N^j_{(j=1,nsat)}}} \\ \frac{\partial f(X,\ell_\Phi)}{\partial X_x} & \frac{\partial f(X,\ell_\Phi)}{\partial X_y} & \frac{\partial f(X,\ell_\Phi)}{\partial X_z} & \frac{\partial f(X,\ell_\Phi)}{\partial X_{dT}} & \frac{\partial f(X,\ell_\Phi)}{\partial X_{zpd}} & \frac{\partial f(X,\ell_\Phi)}{\partial X_{N^j_{(j=1,nsat)}}} \end{bmatrix}$$

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

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

$$X = \begin{bmatrix} x \\ y \\ z \\ dT \\ zpd \\ N^j_{(j=1,nsat)} \end{bmatrix}.$$

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

$$\delta = -(P_{X^0} + A^T P_\ell A)^{-1} A^T P_\ell W, \qquad (10)$$

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, $\sigma_\Phi \cong 5$ mm and the ratio of $\sigma_P/\sigma_\Phi \cong 100$ 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 $\sigma_o=1$)

$$C_{\hat{X}} = P_{\hat{X}}^{-1} = (P_{X^0} + A^T P_\ell A)^{-1}. \qquad (11)$$

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

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

or from an alternative, but numerically exactly equivalent expression:

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

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

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

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

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

The formal variance-covariance matrices eqn. (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 GPS 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 principal, 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 $df = n\text{-}u$ 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 ($1\text{-}\alpha$) and the phase misclosures:

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

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 $(1\text{-}\alpha)$, 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.

$$\hat{\sigma}\Phi = \hat{\sigma}_0\, \sigma_\Phi \, . \tag{17}$$

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 $(1\text{-}\alpha)$ 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 eqn. (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 eqn. (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 for large number of degrees of freedom, i.e. when $df \Rightarrow \infty$), 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 recognized or edit cycle slips or outliers and such high data samplings are not usually available. (Note that within a geodetic receiver, at least in principal, 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 sec, which is why efficient statistical editing/error detection tests are mandatory, in particular 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 double differenced GPS data analyses. An attractive alternative for un-differenced observation network analyses is a cycle slip detection/editing based on double difference observations, which at the same time could also facilitate the resolution of the initial (double difference) 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 double differenced 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-substitutions or back smoothing is necessary in this case, which makes batch adjustment attractive in particular for double difference approaches. Filter implementations, (for GPS 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* 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* 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 eqns. (7-15) involve four types of parameters: station position (*x, y, z*), receiver clock (*dT*), troposphere zenith path delay (*zpd*) 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 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 (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 double differenced data observed from at least two stations, all clocks including the receiver clock corrections *dT's* 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*:

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

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 $C\varepsilon_{\Delta t}$:

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

where

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

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 zenith path delay $C\varepsilon(zpd)_{\Delta t}$.

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). 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.

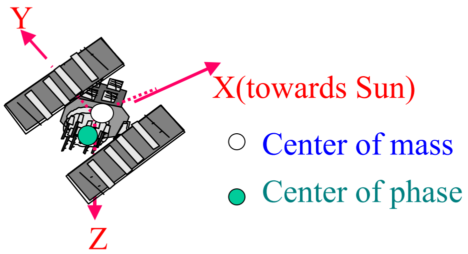
For cm differential positioning and baselines of less than 100 km, all the correction terms discussed below can be safely neglected. The following sections describe additional correction terms often neglected in local relative positioning, that are, however, significant for PPP and all precise global analyses (relative or un-differenced approaches). The correction terms have been grouped under *Satellite attitude effects (5.1), Site displacements effects (5.2)* and *Compatibility considerations (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 GPS 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 GPS precise satellite coordinates and clock products also refer to the satellite center of mass, unlike the orbits broadcast in the GPS navigation message that refer to 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 both in the body *Z*-coordinate direction (towards the Earth) and in the body *X*-coordinate direction which is on the plane containing the Sun (see Figure 2). Note that since all AC estimates of the Block IIR antenna phase center *Z*-offset were much closer to zero than to the specified *Z*-offset value (e.g., Bar-Sever, 1998), the zero value was adopted by IGS as a convention for the Block IIR satellite antenna *Z*-offset listed in Figure 2. Note that a future IGS convention may employ different satellite antenna offsets and also it will likely use satellite antenna phase center variation tables for each of the Block II satellite types (Rothacher and Mader, 2002).

Figure 2: **IGS Conventional antenna phase center offsets in satellite body fixed reference frame**



Antenna phase center offsets adopted by IGS in satellite body fixed reference frame (meters)

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

5.1.2 Phase wind-up

GPS 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 it is oriented towards a 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, 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) 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. Although, it has been shown that it can reach up to 4 cm for a baseline of 4000 km (Wu et al., 1993). However, this effect is quite 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:

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

where $\zeta = \widehat{k}\cdot(\vec{D}'\times\vec{D})$, $\widehat{k}$ 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 ($\widehat{x}', \widehat{y}', \widehat{z}'$) and the local receiver unit vectors (i.e. north, east, up) denoted by ($\widehat{x}, \widehat{y}, \widehat{z}$):

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

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

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

5.2 Site displacement effects

In a global sense, a station undergoes real or apparent periodic movements reaching a few dm that are not included in the corresponding ITRF position. 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. This is accomplished by adding the site displacement correction terms listed below to the conventional ITRF coordinates. Effects with magnitude of less than 1 centimeter, such as atmospheric and ground water and/or snow build-up loading have been neglected and not considered in the following.

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 an accuracy of 1 mm is desired in determining station positions (see e.g. IERS Conventions (IERS, 1996)). However, for 5-mm precision, only the second-degree tides and a height correction term are necessary (IERS, 1989). Thus, at this precision, the site displacement vector in Cartesian coordinates $\Delta\vec{r}^{\,T} = \left|\Delta x, \Delta y, \Delta z\right|$ is:

$$\Delta\vec{r} = \sum_{j=2}^{3}\frac{GM_j}{GM}\frac{r^4}{R_j^3}\left\{\left[3l_2\left(\widehat{R}_j\cdot\widehat{r}\right)\right]\widehat{R}_j + \left[3\left(\frac{h_2}{2}-l_2\right)\left(\widehat{R}_j\cdot\widehat{r}\right)^2 - \frac{h_2}{2}\right]\widehat{r}\right\} + \left[-0.025m\cdot\sin\phi\cdot\cos\phi\cdot\sin\left(\theta_g+\lambda\right)\right]\cdot\widehat{r}, \qquad (21)$$

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 $\widehat{r}$ and $\widehat{R}_j$, respectively; l_2 and h_2 are the nominal second degree Love and Shida dimensionless numbers (about 0.609, 0.085); ϕ, λ are the site latitude and longitude (positive east) and θ_g is Greenwich Mean Sidereal Time. The tidal correction (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-hour period. However, the permanent part, which can reach up to 12 cm in mid latitudes (along the radial direction) remains in such a 24h average position. The permanent tidal distortion, according to the adopted ITRF convention has to be removed as well (IERS, 1996). In other words, the complete correction (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 (21) in point positioning would result in systematic position errors of up to 12.5 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 that 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 (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 deformations, 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, longitude (+east) and height in mm is approximately equal to (IERS, 1996):

$$\Delta\phi = -9\cos 2\phi\ (X_p \cos\lambda - Y_p \sin\lambda);$$

$$\Delta\lambda = \quad 9\cos\phi\ (X_p \sin\lambda + Y_p \cos\lambda);$$

$$\Delta h = -32\sin 2\phi\,(X_p \cos\lambda - Y_p \sin\lambda),$$

where X_p *and* Y_p are the pole position coordinates in seconds of arc. Since most ACs are utilizing 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 accuracy the above polar tide corrections need to be applied to obtain an apparent station position, or alternatively the above corrections have to be subtracted from the position solutions in order to be consistent with ITRF. Unlike the solid earth tides (5.2.1) and the ocean loading effects (see 5.2.3 below) the pole tides do not average down 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 as it is dominated by diurnal and semi diurnal periods, but it results from the load of the ocean tides. While ocean loading is almost an order of magnitude smaller than solid Earth tides, it 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 intervals significantly shorter than 24h, this effect has to be taken into account. Note that when the tropospheric *zpd* 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* (Dragert et al., 2000) and station clocks. The ocean load effects can be modeled in each principal direction by the following correction term (IERS, 1996):

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

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 $S_{sa.;}\omega_j$ 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 can be readily evaluated by a FORTRAN routine *ARG* available from the IERS Convention ftp site: *ftp://maia.usno.navy.mil/conventions/chapter7/arg.f*.

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 functions utilizing the latest global ocean tide models as well as refined coastline database (e.g. Scherneck, 1991; Pagiatakis, 1992; Agnew, 1996). A table of the amplitudes A_{cj} and phases Φ_{cj} for most ITRF stations, computed by Scherneck (1993), is also available from the above ftp site (*ftp://maia.usno.navy.mil/conventions/chapter7/olls25.blq*). Alternatively, software for evaluation of A_{cj} and Φ_{cj} at any site is available from Pagiatakis (1992). 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 accuracy it is also necessary to augment the global tidal model with local ocean tides digitized, for example, from the local tidal charts. Future ITRF convention will likely also require a model for the geocenter variation (at a cm level), which is also of tidal origin. Consequently, the station specific amplitude A_{cj} and phases Φ_{cj} would then also include the geocenter (tidal) variation. A consequence of this new convention/approach would be that for cm station position precision, the ocean load effect corrections would have to be included at all stations, even for those far from the ocean.

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 GPS analysis (see e.g. IERS, 1996). 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, are required and should be used.

Even for PPP processing formulated within the terrestrial frame, with precise orbits held fixed, the so called sub-daily ERP model, which is also dominated by diurnal and sub-diurnal periods of ocean tide origin, may still be required to attain sub-cm positioning precision. This is resulting from the IERS convention for ERP, i.e. the IERS/IGS ERP series as well as ITRF positions do not include the sub-daily ERP variations, which can reach up to 3 cm at the surface of the earth. The IGS orbits are derived with the complete ERP; i.e. the conventional ERP plus the sub-daily ERP model so that no sub-daily ERP modeling is required in ITRF. However, some AC orbits may not employ the sub-daily ERP variation in transformation from inertial to ITRF. Consequently, in order to be consistent, in particular for precise static positioning over intervals much shorter than 24 h, this sub-daily effect needs to be taken into account by a user of such AC orbits, given in the current ITRF. Note that much like the ocean tide loading, the sub-daily ERP effects are averaged out to nearly zero over a 24-h period only for position solutions. However, for *zpd* and clock solutions, the sub-daily ERP effects do not average out and may be significant (Kouba, 2002b).

This effect can be modeled, like all the tidal displacements, as apparent corrections (Δx, Δy, Δz) to the conventional (ITRF) station coordinates (x, y, z), evaluated from the instantaneous sub-daily ERP corrections (δXp, δYp, $\delta UT1$), i.e.

$$\Delta x = + y \cdot \delta UT1 + z \cdot \delta Xp \,, \tag{23}$$

$$\Delta y = - x \cdot \delta UT1 - z \cdot \delta Yp, \tag{24}$$

$$\Delta z = - x \cdot \delta Xp + y \cdot \delta Yp, \tag{25}$$

where each of the sub-daily ERP component corrections (δXp, δYp, $\delta UT1$) is obtained from the following approximation form, e.g. for the *Xp* pole component:

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

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 (IERS, 1996) ftp site: *ftp://maia.usno.navy.mil/conventions/chapter8/ray.f* . For more information on the sub-daily ERP effects when using IGS products see Kouba (2002b).

5.3 Compatibility and IGS conventions

Positioning and GPS 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) etc. Note that, in general, all Analysis Center (AC) solutions and thus IGS combined products follow the current IERS conventions (IERS, 1996). 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 (2002) 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://igscb.jpl.nasa.gov/igscb/center/analysis/), or to Weber at al., (2002).

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 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	GPS data/ 30 sec	ftp://igscb.jpl.nasa.gov/igscb/data/format/rinex210.txt
RINEX-clock ext.	Sat./Sta. Clock / 5 min.	ftp://igscb.jpl.nasa.gov/igscb/data/format/rinex_clock.txt
SP3	Orbits/Clocks/ 15 min.	ftp://igscb.jpl.nasa.gov/igscb/data/format/sp3c.txt
IGS ERP Format	IGS ERP/ 1 day	ftp://igscb.jpl.nasa.gov/igscb/data/format/erp.txt
SINEX	Sta. Pos.(ERP) 7(1) day	ftp://igscb.jpl.nasa.gov/igscb/data/format/sinex.txt
SINEX-tropo ext.	Tropo. ZPD 2 h	ftp://igscb.jpl.nasa.gov/igscb/data/format/sinex_tropo.txt
IONEX	Iono. maps/sat DCB 2 h	ftp://igscb.jpl.nasa.gov/igscb/data/format/ionex1.ps

5.3.2 IGS reference frames

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 International Terrestrial Reference Frame (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 data) be in the same reference frame even when unconstrained relative position solutions are combined or being constrained 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 Wk 1051) when the SINEX station/ERP combinations became official, all the IGS combined Final products (including orbits/clocks and SINEX station/ERP), are also fully consistent and minimally constrained with respect to IGS position/velocity coordinate solutions of a set of more than 50 Reference Frame Station (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 the most precise applications, there was no noticeable discontinuity and no transformation should be necessary on February 27, 2000, when this internal IGS realization of ITRF was adopted. (see ftp://igscb.jpl.nasa.gov/igscb/mail/igsmail/2750, 2751 and also Ferland, 2000; 2001).

Since December 2, 2001 (GPS Wk 1143, MJD 52245) the IGS ITRF2000 realization (IGS00) is used and it is accomplished through a 54 RS subset of the Wk 1131 IGS cumulative station/ERP solution product. (See files IGS01P37_RS54.SNX and IGS01P37_RS54.notes on the IGS CB archives at ftp://igscb.jpl.nasa.gov/igscb/station/coord/). This solution is minimally constrained with the 14 transformation parameters (seven transformation parameters and 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 (ftp://lareg.ensg.ign.fr/pub/itrf/itrf2000). 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 six different, official realizations of ITRF (ITRF92, ITRF93, ITRF94, ITRF96, ITRF97 and ITRF2000). The exact dates of the ITRF changes, estimated transformation parameters and a simple Fortran 77 transformation program are available at the following ftp site: ftp://macs.geod.emr.ca/pub/requests/itrf96_97 (also 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), ITRF97-00 (December 2, 2001) and any future 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 (.0001") accuracy level only.

The ITRF convention allows linear station movements only, i.e. dated initial station positions and the station velocities, which is not adequate at the mm-level precision, as even stable stations exhibit real and apparent non-linear departures that can exceed the 10 mm level. Often, the station movements are of periodical (e.g. seasonal and semi-seasonal) character. The non-linear station movements can be induced e.g. by various uncorrected loading effects (atmospheric, snow), or by the real variation of geocenter and scale (i.e. the Earth's dimension). Currently, a new ITRF convention is being considered, where an ITRF conventional origin, approximating a mean geocenter would be adopted. Then the geocenter variations would have to be monitored and become part of the new ITRF convention (much like ERP monitoring is an integral part of ITRF). This new convention, after accounting for all the loading effects, should provide an ITRF realization of stable station positions at the mm level. Alternatively, if such "conventional" geocenter movements can be modeled, they can be included into the (ocean) loading effects as discussed above. Then ocean loading corrections would become mandatory for all stations, since all stations, even those far from oceans will undergo "ocean loading" effects at the 10 mm level.

The IGS Rapid products are consistent with the current ITRF convention, i.e. IGS00 positions of the IGS RS stations are fixed in all 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, but also in anticipation of the new ITRF convention, since June 28, 1998 are based on minimal rotational constraints only. Note that unconstrained global GPS solutions are nearly singular only in orientation, they contain a strong origin (geocenter) and scale information due to orbit dynamics (i.e. the adopted gravity field). So after June 28, 1998, all the IGS orbit/clock, at least nominally, refer to the real geocenter and scale that undergo small (~10mm) variations with respect to the adopted ITRF origin and scale. The new ITRF convention has in fact already been adopted for the IGS00 RS station set, as well as for all the IGS weekly (IGSYYPWWWW.SNX) and cumulative (IGSYYPWW.SNX) SINEX products. Since the geocenter positions and scale biases are solved for and published every week when the IGS accumulated product are being augmented with the current week (independent from week to week) SINEX combinations, which contain the weekly mean solutions of the implied geocenters. However, currently (2003) no geocenter/scale variation removal has been done for the corresponding IGS Final orbit combinations. 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, are made highly consistent with the IGS SINEX/ERP cumulative combinations as outlined in Kouba et al. (1998), the scale variations are not yet accounted for (Kouba and Springer, 2000). Note that the apparent geocenter variations are accounted for only in the current IGS clock combinations as discussed in Section 7.1. The IGS Final and all AC orbit/clock solutions are not transformed, thus they fully reflect (i.e. with respect to) apparent or real geocenter/scale variations. Thus all *global* analysis 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 geocenter and scale variations as the geocenter/scale variations are fully implied by the IGS Final orbits. On the other hand, regional relative positioning with fixed IGS Final orbits and from November 5, 2000, PPP's with the IGS Final orbits/clock products held fixed, should show only small weekly scale (height) variations. This is so, since relative regional analyses are less sensitive to orbit origin and in case of PPP, the apparent geocenter variation is properly accounted for in the current IGS Final clock combinations. Thus, since November 5, 2000, the IGS Final orbit/clock PPP users will only have to consider (with respect to IGS00 (ITRF00)) small (~cm) weekly scale (height) biases, which are not yet accounted for in the new now official IGS Final clock/orbit combinations.

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 date (week), thus small (weekly) variations in origin/scale with respect to ITRF could be seen. After November 5, 2000 all PPP solutions based on the IGS Final products should show only small weekly scale (height) variations since IGS Final orbit origin variations are accounted for in the current Final clock combinations. At about 10-mm precision level, when using the IGS Final products, all the above origin/scale variations can be safely neglected. The above small weekly 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 IGS CB (http://igscb.jpl.nasa.gov/mail/igsreport/igsreport.html). 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 (2000).

5.3.3 IGS receiver antenna phase center offsets/tables

For PPP, unless using Dorne-Margolin (D/M) antennas, the adopted IGS antenna phase center variation (*pcv*) table (*igs_01.pcv*) that are available at the IGS Central Bureau (http://igscb.jpl.nasa.gov) must always be used (see below). For precise relative positioning with different antenna types even over short baselines, and in particular when solving for tropospheric *zpd*'s, the IGS antenna calibration table is also mandatory, otherwise, large errors up to 10 cm in height and *zpd* 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* solutions does not require the use of the antenna calibration table. Since PPP in fact is 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 IGS antenna calibration table to ensure compatibility with the IGS antenna *pcv* convention. Currently (2003), the IGS antenna *pcv* table (*igs_01.pcv)* is relative to the D/M antenna type, thus the IGS orbit/clock products are consistent with the D/M antennas and all the PPP's involving D/M antennas can safely neglect the *igs_01.pcv* table. However, note that this IGS convention is subject to change, as in the near future IGS may adopt absolute antenna calibration tables so that no antenna is favored (e.g. with assumed zero *pcv's*). In this case every PPP, even with D/M antennas, would have to use a specific antenna calibration table adopted by IGS. Note that even when no *pcv* tables are necessary (e.g. for cm relative positioning with no *zpd* solutions), the constant antenna phase center height offsets, adopted by IGS and also given in the *IGS_01.pcv* table, are still mandatory even in this case. Similarly, although currently not used, satellite specific antenna *pcv* tables and offsets will likely be implemented by IGS in the near future (Rothacher and Mader, 2002). This may mitigate, or even fully eliminate, the apparent (terrestrial) scale bias of about 15 ppb, seen when an absolute antenna calibration *pcv* is introduced into a global GPS analysis, while solving for both stations and GPS orbits (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

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

is to be applied by all GPS users (ION, 1980; ICD-GPS-200, 1991). Here $\vec{X}s$, $\vec{V}s$ 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 or 10^{-14} level for time and frequency, respectively (e.g. Kouba, 2002c).

By an agreed convention, there are no L1-L2 (or P1-P2) Differential Calibration Bias (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* and P_1 code pseudoranges, which can reach up to 2 ns (60 cm). 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*):

$P_{C/A}$ and $P'_2 = P_{C/A} + (P_2 - P_1)$	*Up to April 02, 2000 (GPS Week 1056),*
P_1 and P_2	*After April 02, 2000 (GPS Week 1056).*

For *C/A* and *P*–code carrier phase observations ($L_{C/A}$ 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. 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 the IGS CB Archives: http://igscb.jpl.nasa.gov/mail/igsmail/2000/.

6. Single frequency positioning

Precise, 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 offer little or no benefit over the broadcast orbits. With ionospheric delay corrections, e.g. derived from the IGS ionospheric grid maps generated by the IGS Ionospheric Working Group (ftp://gage.upc.es/pub/gps_data/GPS_IONO/cmpcmb), 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 the above-derived ionospheric delay corrections along with the corresponding satellite (L1-L2) Differential Calibration Delays (DCB); even then only precision at about 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 (L1-L2) 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 soluyions (Heroux, 1993, personal com.). This is so, since the IGS clocks are consistent with the (L1-L2) DCB convention, i.e. the single frequency IGS users have to first correct the IGS satellite clocks by

$$-1.55\ (L1\text{-}L2)\ DCB, \tag{28}$$

in order to make them compatible with the single frequency observations. (Note the different sign convention for the broadcast (L1-L2) group delays T_{GD}, which after April 29, 1999 are quite precise and can also be used even in the most precise applications (http://maia.usno.navy.mil/gpst/mail/11Jun99.1). 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 on, a single frequency 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.

7. Solution precision/accuracy with IGS combined products

Accuracy is an elusive word and it is difficult to comprehend. 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.

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 shows a compilation of AC/GNAAC position standard deviations (sigmas) with respect to the IGS cumulative (combined) station SINEX product (IGS00P39.SNX in this case), during the period of more than 4 years (Wk 0837-1081). Currently, only AC weekly unconstrained SINEX final 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).

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.), nevertheless it is already an indication of the position accuracy that can be achieved with the IGS combined products. This is so since the AC sigmas include real and apparent station movements and the statistics was 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 are 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 one-week period, accounting for a small geocenter and scale offset and fixing the best ACs and/or the IGS orbits/clock products should achieve comparable precision/accuracy levels. This is so because PPP is an approximation (a back substitution) of the station position solution within the corresponding global (AC or IGS) solution. However, the daily PPP position standard deviations should be larger than the weekly ones shown in Figure 3, up to $(7)^{1/2}$=2.6 times when only random errors are assumed.

More recent results are summarized in Table 2, which was adopted from the Wk 1081 SINEX combination report (ftp://igscb.jpl.nasa.gov/igscb/mail/igsreport/7641). They indicate that some ACs have improved significantly, still, the above implied precision level (i.e. 5mm horizontally and 10 mm vertically) should be applicable to the best daily PPP and AC global solutions. Also shown is the RMS agreement with the IGS97 51 Reference frame station (RS) position/velocity set (ITR denotes IGS00P04_RS51.SNX). This is a subset of the IGS cumulative product IGS00P04.SNX, minimally constrained to ITRF97 (through a 14 parameter transformation) which was used for the IGS realization of ITRF up to December 2, 2001

(Ferland, 2000). It is encouraging to see that even after 245 days both IGS cumulative station/position SINEX combination solutions were still consistent within 1mm horizontally and 4 mm vertically.

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 (GPS Wk 0837-1081).

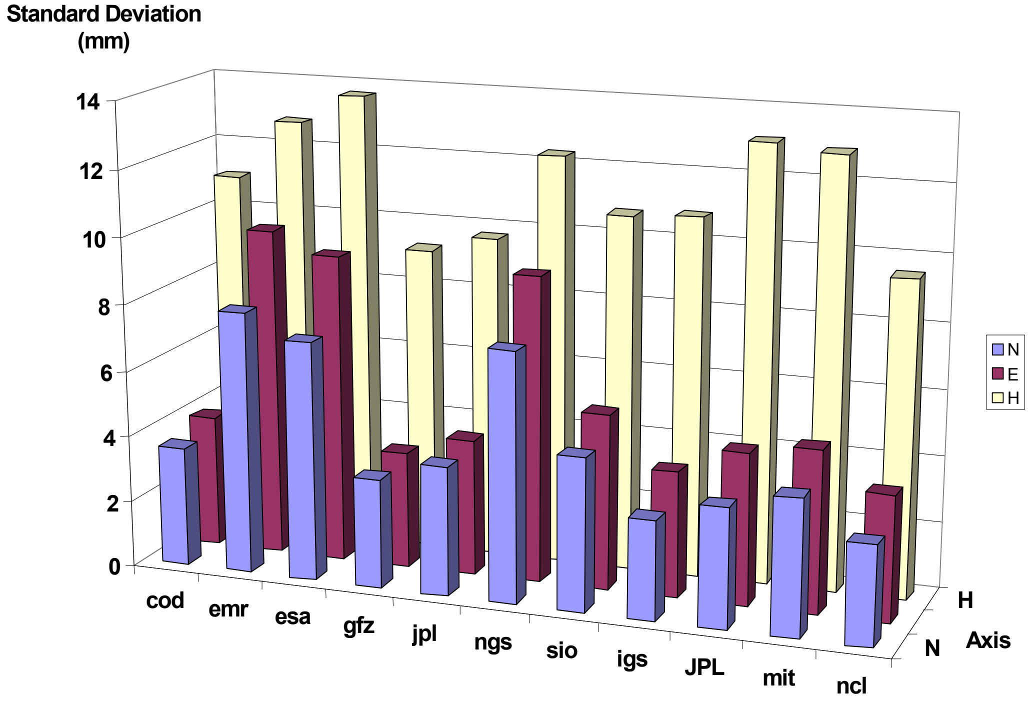


Table 2. Means and standard deviations of ACs SINEX residuals with respect to the IGS cumulative SINEX combination of the Wk 1081 (IGS00P39.snx). The GNAAC (mit, ncl), the IGS weekly SINEX combinations (igs = igs00P1081.snx) and the IGS97 (ITRF97) RS station set (ITR = IGS00P04_RS51.SNX) are included for comparisons only (from the IGS Report#7641)**.**

Solution		Weighted Average (mm)			Standard dev. (mm)		
	#Sta	N	E	U	N	E	U
cod	124	0.0	0.8	-1.6	3.8	4.3	9.3
emr	46	-0.6	0.6	-0.9	3.3	7.0	8.8
esa	49	0.2	-0.5	-1.1	6.2	6.1	11.3
gfz	69	1.1	0.6	0.2	2.6	2.8	8.4
jpl	58	-1.3	0.4	0.0	3.2	3.8	7.5
ngs	75	-3.0	-0.4	-1.0	5.0	7.2	9.5
sio	122	-0.7	0.2	-1.1	3.1	3.2	8.2
mit	30	1.1	-0.1	-1.5	2.3	2.6	6.9
ncl	95	0.3	-0.1	0.0	2.4	2.9	6.0
igs	136	0.0	-0.1	-1.4	2.0	2.6	6.5
ITR	51	-0.1	0.1	-0.2	0.8	1.2	3.7

For PPP position accuracy testing, *three independent software* packages and *three different periods* of seven days, during one and half years 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 January 1999 to September 2000.

The first test used data from Wk 0995 (January 24 -30, 1999) from four stations on the three continents (AUCK, BRUS, WILL, USUD) and static daily GIPSY PPP's with various AC, IGS orbits/clock orbit products fixed. Note that since NGS, 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 the AC and IGS Final products after June 28, 1998 (Kouba et al, 1998). When the AC orbit modeling and the consistency with weekly SINEX solutions are improved and the weekly geocenter/scale offsets are monitored and accounted for with respect to the adopted conventional ITRF origin, then such daily origin offset corrections will not be necessary. Then, the PPP RMS with respect to the conventional ITRF station positions will also represent the achievable positioning accuracy. Note that such PPP results corrected for daily origins still contain, unlike the PPP repeatability around the weekly mean station position, the ITRF97 station position/velocity errors, constant or slowly varying real and/or apparent station position movements/biases. Such (real) station movements/biases can be due to e.g. unmodeled loading effects (atmosphere, snow, ground water, etc.).

Figure 4: Static GIPSY PPP RMS (stations AUCK, BRUS, USUD, WILL) with IGS, AC orbit/clock solutions and the new clock combination IGC for Wk 0995 (corrected for daily geocenter origin offsets; IGC represents the new clock combination, adopted by IGS on November 5, 2000)

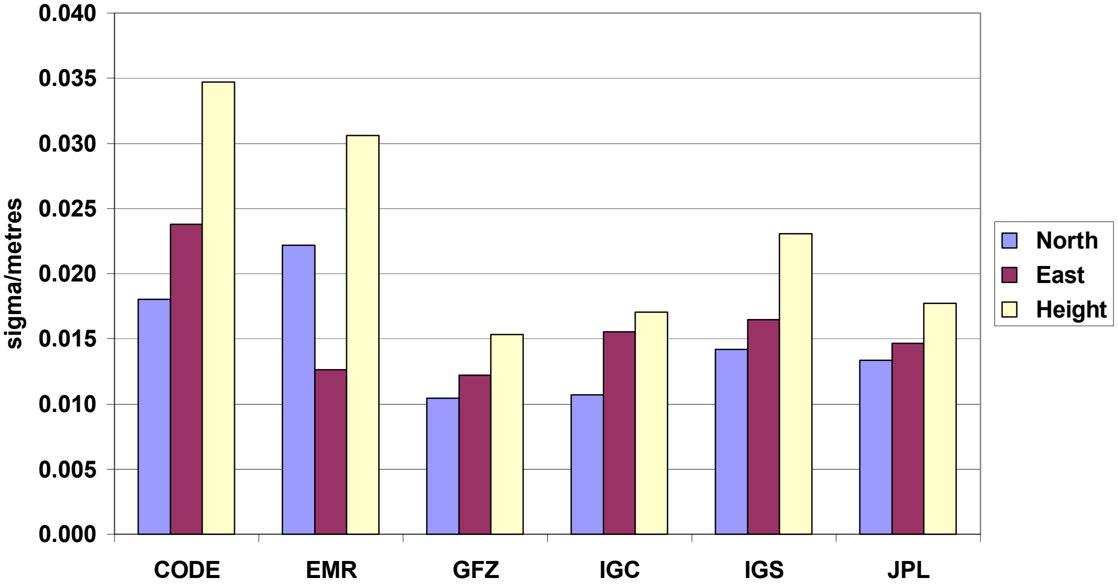
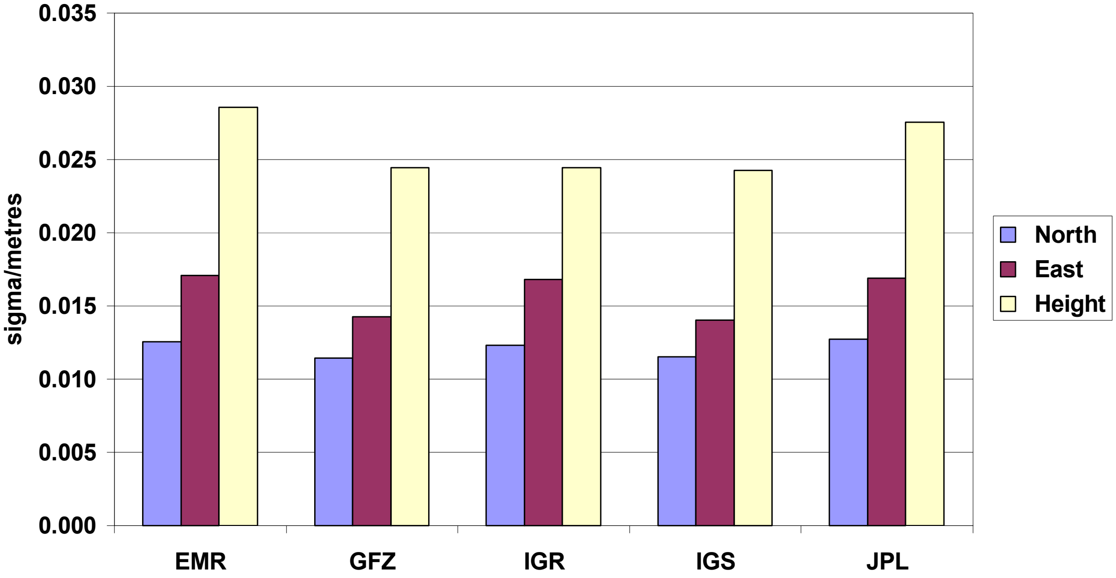


Figure 4 shows RMS of the PPP-ITRF97 differences for static GIPSY PPP's with various AC and IGS Final orbit/clock products, after correcting for the daily origin offsets. Also shown here are the results of the IGS Final orbits augmented with 15-min satellite clocks from the new, more consistent and robust,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

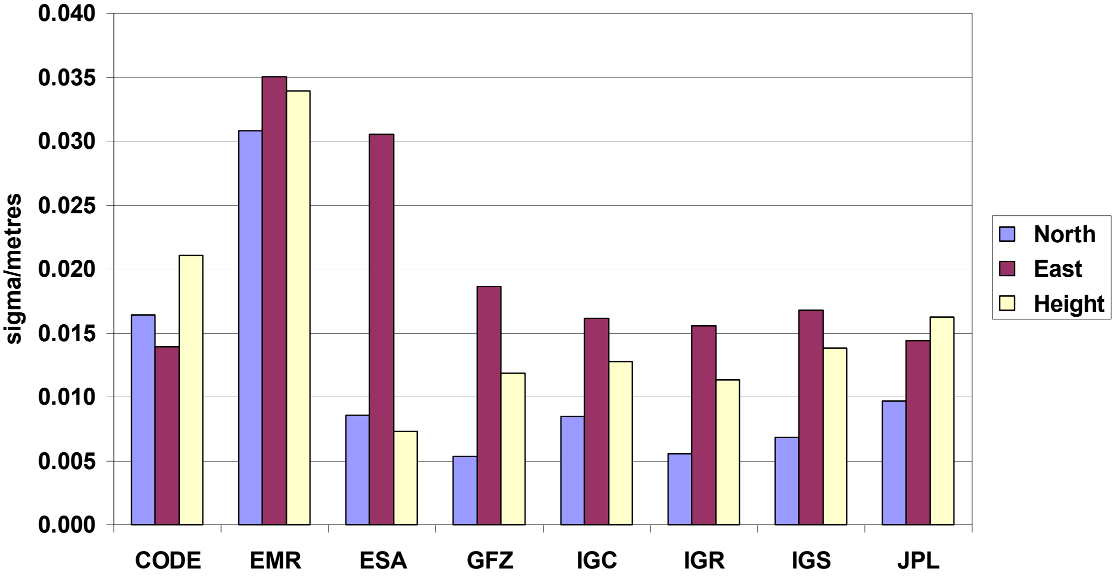
This is quite consistent with the weekly SINEX results after assuming daily random variations, i.e. after increasing the weekly SINEX RMS' of Figure 3 or Table 2 by a factor of 2.6. It is encouraging to see that the IGS Final orbits augmented with the new clock combinations (IGC) are slightly better 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) is 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 are 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.

Figure 5: Static GPS Pace PPP RMS (36 Reference frame (RS) stations) with IGS, IGR and AC orbit/clock solutions for Wk 1039 (corrected for daily geocenter origin offsets)



The second, more extensive PPP test, used GPS data from 36 globally distributed Reference frame (RS) stations with tracking data of acceptable quality and continuity of the Wk 1039 (December 5-11, 1999). It also involved a different PPP software, namely GPS Pace (Heroux and Kouba, 1995), which was enhanced to account for all the modeling effects and approximations at the cm-level as discussed above, except for the ocean loading, polar tides and sub-daily ERP effects (Heroux and Kouba, 2000; Kouba and Heroux, 2001). Also, instead of the ITRF97 RS station coordinate set used in the previous PPP test, here the IGS97 station positions/velocities were used in all PPP solution comparisons. Since, at that time, ESA and CODE clocks still were not fully consistent with the respective orbit and SINEX station solutions, they were not used in this extensive test. Furthermore, since no new clock combination was available for this period, IGC also is not included here. During December 1999 some of the ACs and IGS orbit/clock solutions still had daily cm origin variations, so all the PPP results in Figure 5 also include the daily origin corrections computed for each AC from the PPP-IGS97 station position differences. As one can see the RMS accuracy is comparable to GIPSY PPP results of Figure 4. However, the results of Figure 5 were obtained with a rather simple PC based software, that is completely independent from the IGS solutions since it was not used to generate any of the AC and IGS solutions. The slightly higher PPP RMS, in particular for the vertical component, most likely is due to a much larger number of stations, in more remote and weakly tracked parts of the IGS station network. To a smaller extent, it could also be due to the above mentioned effects (ocean loading and polar tides in particular), which were not yet accounted in the software at the time of testing, since the station repeatability (precision) around the corresponding station weekly mean positions was quite comparable to the GIPSY PPP repeatability seen during Wk 0995 (Kouba and Heroux, 2001). It is interesting to note here, that the IGS Rapid (IGR) orbit/clock products, which were constraining up to the 51 ITRF97 RS station coordinates and which are available with only a 17 hour delay, have performed equally well as the best AC and the IGS Final orbit/clock products.

Figure 6: Static BERNESE PPP RMS (stations BRUS, WILL, TOW2), with IGS, IGR, AC orbit/clock solutions and the new clock combination IGC for Wk 1081 (corrected for a weekly geocenter origin offset)



The *final PPP test* was performed by the former IGS AC Coordinator, Dr. T. Springer of the Astronomical Institute, the University of Berne, in order to check and verify the final implementation of then new (now current) IGS satellite/station clock combination, labeled here IGC (Kouba and Springer, 2000). Dr Springer has kindly made available his complete PPP results for three stations (BRUS, WILL, TOW2) from the Wk 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 wk 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. 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 current orbit/clock products of the ACs and IGS (prior Nov. 5, 2000) within the current IGS ITRF convention (i.e. the weekly monitoring of "geocenter" and scale biases). Also note that the IGS cumulative SINEX (IGS00P04.SNX) products also was used here as a ground truth in all the position comparisons. The RMS PPP results of this third test, shown in Figure 6, in fact, represent the currently achievable accuracy with the IGS products. This Figure also indicates that all AC clock solutions are now more consistent with the corresponding daily AC orbits and the weekly SINEX station solutions, than it was the case in December 1999. 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 be at the 10-mm level.

The high RMS for EMR orbit/clock PPP is solely due to the large (up to 4 cm) origin variations of the EMR daily orbits. However, the PPP RMS performance of EMR orbits/clocks becomes comparable to the other AC orbit/clocks once the EMR orbit/clocks are corrected for the daily orbit origin (apparent geocenter) offsets. As a point of interest, and to demonstrate the positioning accuracy obtained when the above geocenter and scale monitoring is not taken into account (i.e. neglected), the Figure 7 shows the corresponding PPP RMS results with no weekly origin/scale offsets applied. As one see from Figure 7 all the IGS product PPP results are still at a quite acceptable accuracy level of about 15 mm.

Figure 7: Static BERNESE PPP RMS (stations BRUS, WILL, TOW2) with IGS, IGR, AC orbit/clock solutions and the new clock combination IGC for Wk 1081 (NOT corrected for a weekly geocenter origin offset)

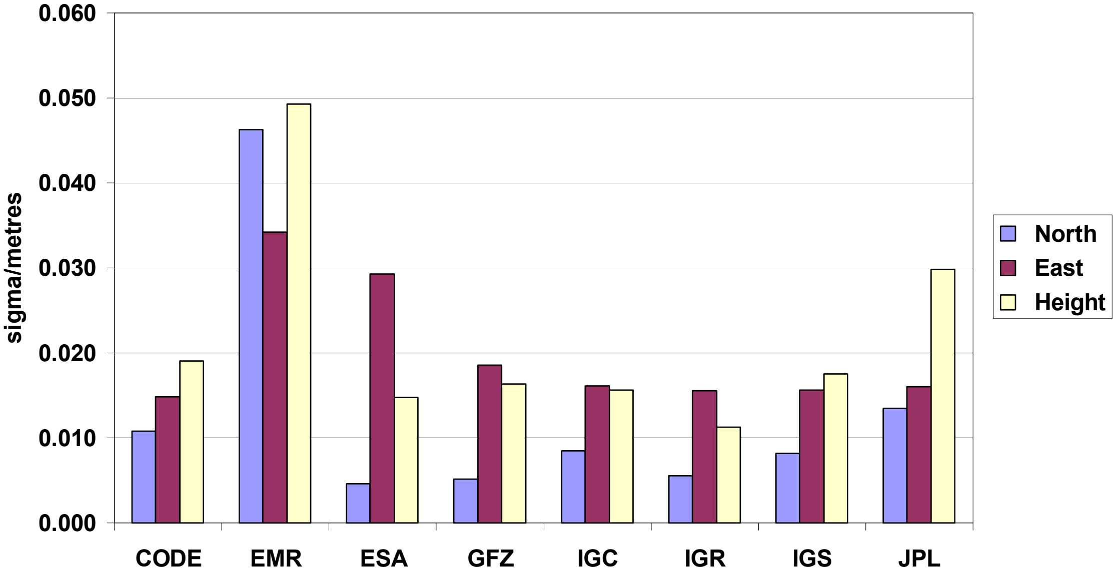


Table 3: Weekly origin and scale offsets available from the IGS SINEX combination and removed from the Wk 1081 PPP RMS comparisons. (The IGC scale and IGS origin/scale offsets that are not available in IGS00P1081.SUM were approximated by the averages of all AC origin/scale biases).

Center	DX (cm)	DY (cm)	DZ (cm)	SCL (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

To demonstrate the high precision and consistency of most of the AC orbit/clock solutions, the weekly repeatability at each station, i.e. standard deviations with respect to a weekly (biased) mean station positions, are compiled in Figure 8. This figure shows rather small repeatability sigmas, well below the 10 mm level, for all ACs and IGS orbit/clock products with the only notable exception of CODE and EMR. In particular EMR repeatability sigmas are rather large, about 30 mm and they also are due to the unaccounted daily origin variations in EMR orbit/clock solutions as already discussed above. Note that once the EMR daily origin offsets are accounted for, the EMR PPP repeatability is comparable to the rest of ACs. It is also interesting to note that despite the origin offset problem, the EMR clocks still have contributed quite significantly (at 18%) to the new IGS clock combinations (IGC) of the wk 1081 (Kouba and Springer, 2000). The IGC clock combination precision (repeatability) was not compromised by EMR contributions, as can be seen in Figure 8.

Figure 8: Static BERNESE PPP repeatability (stations BRUS, WILL, TOW2), with IGS, IGR, AC orbit/clock solutions and the IGC clock combinations (representing the current IGS clock combinations) for Wk 1081

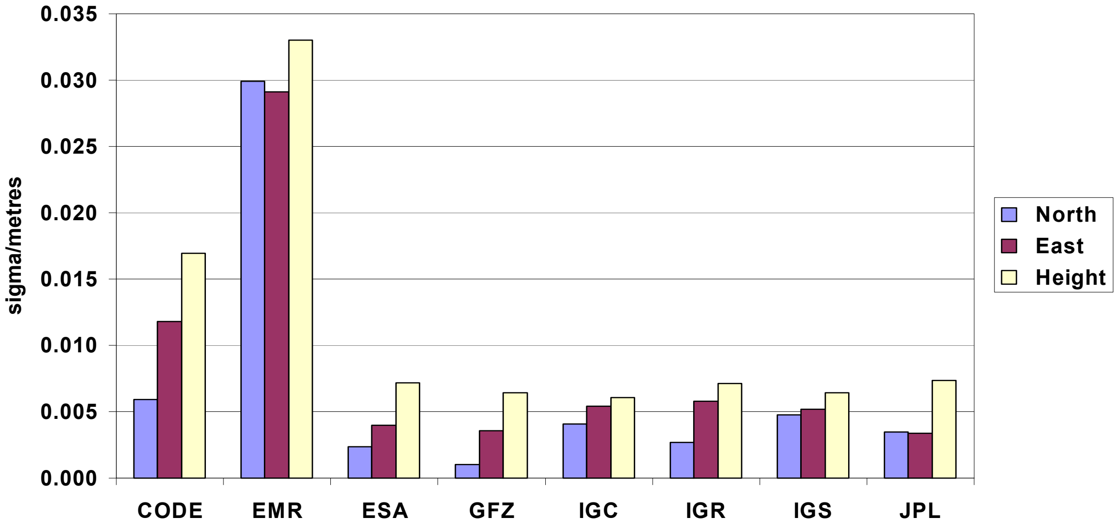
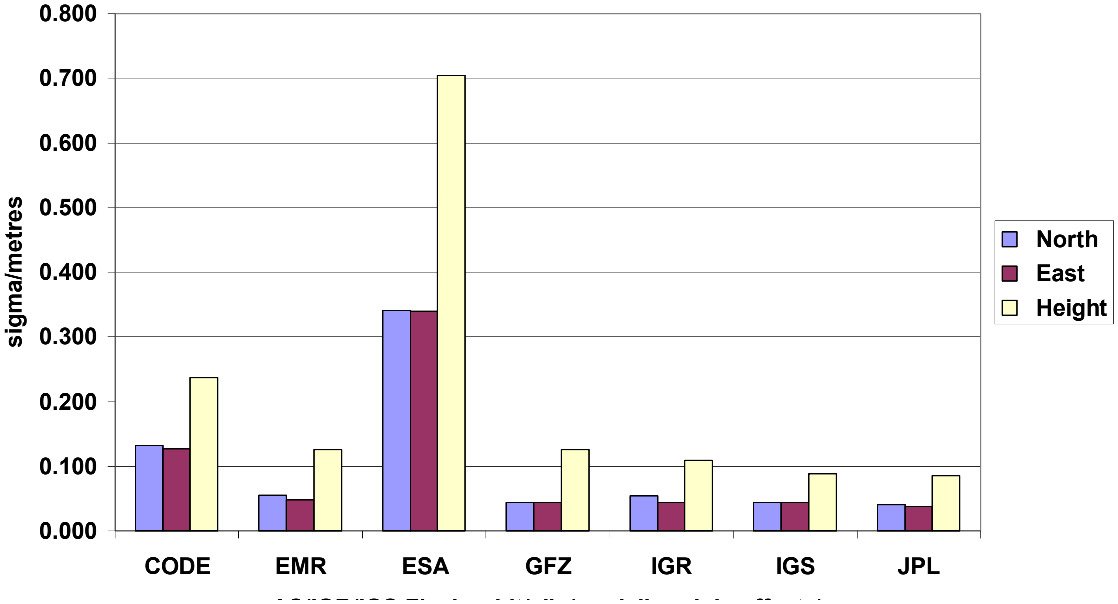


Figure 9: Navigation GIPSY PPP RMS (stations BRUS, USUD, WILL) with IGS, IGR and AC orbit/clock solutions for Wks 0940-0990 (not corrected for any origin offsets).



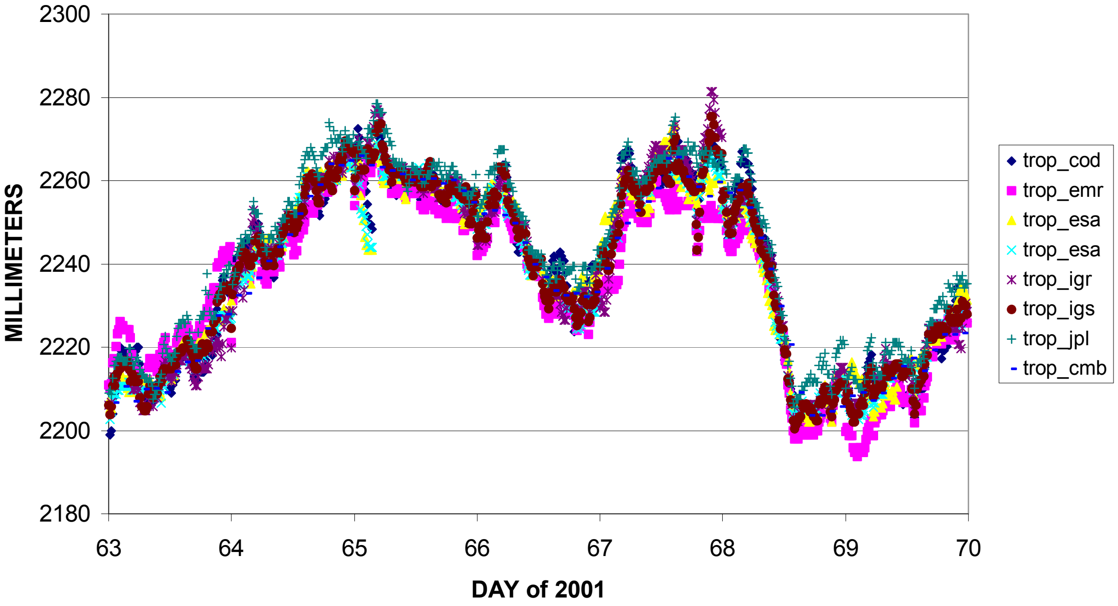
PPP software and the IGS orbit/clock products can also be used for efficient and accurate kinematic positioning (navigation) at 15-min epochs at any place on the Earth and for any user dynamics. In fact, thanks to the availability of IGS orbit/clock products, there is no need for any base stations and/or differential GPS (DGPS) corrections at the 10 cm accuracy level in post processing mode. This point is demonstrated in Figure 9, which shows GIPSY PPP RMS' of independent 15 min position solutions ("simulated navigation") with the AC and IGS combined products for almost a year (weeks 0940-0990, March 8, 1998-January 2, 1999). The RMS results for three IGS stations (BRUS, WILL, USUD) shown here were adapted from Kouba and Mireault, (1999), where the navigation PPP orbit/clock evaluations results, that were included in the IGS orbit/clock combinations for 1998, were compiled.

Furthermore, 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 new 5-min IGS satellite/station clock products (IGC) has become official on November 05, 2000, it is now possible to linearly interpolate the IGS satellite clocks at about 0.1 ns and thus also to obtain navigation solutions at or below the 10-cm accuracy level at any place and for any interval.

7.2 Tropospheric zenith path delay (*zpd*)

It is important to note that unless double differenced GPS analyses are based on a sufficiently large area (e.g. >500km), it is not possible to obtain meaningful zpd solutions. For small or regional areas (< 500 km) it is possible to precisely estimate only *zpd* differences, (e.g. with respect to a reference station, or with respect to the IGS combined *zpd* products). PPP solutions, on the other hand, are quite capable, even from a single station, to determine the total *zpd* quite precisely within the IGS reference frame (ITRF). It is also important to note that *zpd* 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. About a third to one fifth of the station height errors (variations) maps directly into the *zpd* 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).

Figure 10. IGS tropospheric *zpd* combinations (CMB) at station DRAO and PPP *zpd* solutions with IGS, IGR, COD, EMR, ESA, GFZ and JPL orbits/clocks



To evaluate accuracy of troposheric *zpd* solutions is even more difficult than the evaluation of positioning accuracy as there are no ground truth. To demonstrate the quality and consistency of PPP *zpd* solutions, the estimated *zpd's* for GPS week 1104 with different AC and IGS orbit/clock products were compared with the IGS combined tropospheric *zpd* product (Gendt, 1998). IGS currently combines *zpd*'s at 2-hour intervals from contributions made by the seven ACs for up to 200 globally distributed GPS tracking stations. 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).

Figure 10 shows a 7-day time series of *zpd's* obtained from the GPS Pace PPP at the IGS station DRAO during the GPS week 1104, using precise orbit/clock solutions from COD, EMR, ESA, GFZ, JPL, IGS and IGR. The official IGS combined estimates (CMB) (Gendt, 1996) are also included here. A general agreement for all time series is obvious, although the 2 hr CMB series exhibits a stronger smoothing.

To get a more global view of the quality of the PPP *zpd* estimates, daily comparisons with the IGS *zpd* products at approximately 30 IGS stations over the 7 days of the second test period (GPS week 1039), was performed by Heroux and Kouba (2000). The daily mean biases did not exceed 5 mm and standard deviations varied from 5 to 8 mm depending on the orbit/clock solutions used. This is comparable to AC *zpd* solutions contributed to IGS *zpd* product combinations (Gendt, 1998). The above PPP *zpd* solution precision corresponds to about 1 mm of integrated precipitable water.

7.3 Station clock solutions

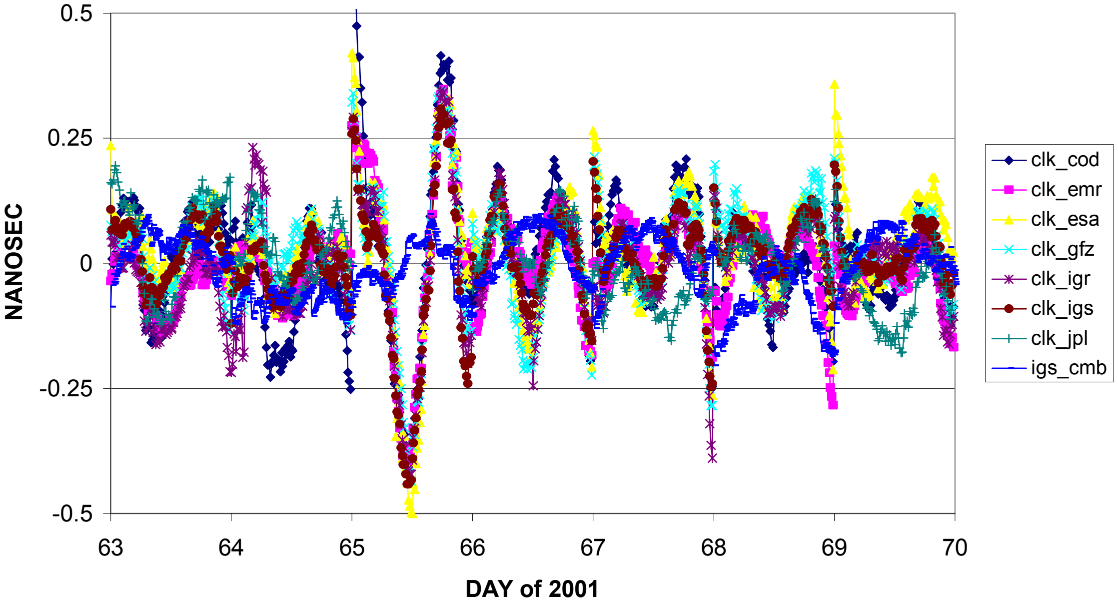
It is important to note that it is not possible to get any meaningful clock solutions from double difference GPS analyses, which is the penalty paid for the significant simplification and efficiency of double differenced GPS observations. The clock solutions are only possible in un-differenced global and PPP solutions. Since the clock solution parameters are perhaps the most sensitive to a wide range of effects and thus can be significantly biased unless proper modeling all the effects discussed above (Section 5) are taken into account, including the ocean loading effects. For these reasons, discussions in Section 5.3.2 should also be carefully consulted.

Evaluating the quality of PPP estimated station clocks 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 between the PPP station clock solutions of the GPS week 1104 with the corresponding IGS clock combination of the AC clock solutions. The IGS station DRAO was selected for the clock comparison since it is equipped with a Hydrogen MASER (HM) clock and was processed by the all ACs for most days of the GPS week 1104. ACs used ALGO, NRC1, or USNO as the reference clocks (all of them are equipped with HM's) so that all the DRAO station clock estimates will contain effects from both DRAO and the reference clocks.

This PPP test used the 15-minute precise GPS satellite clocks stored in the AC final orbit product. Since the AC/IGS orbit/clock product files in sp3 format do not contain any clock accuracy codes, the AC clock solutions could not be weighted. To remove the effect introduced by the different reference clocks offsets and drifts, and to check the solution quality, a daily linear regression was applied to the IGS combined clock (igs_cmb) and the PPP station clock estimates (clk_igs, clk_igr, clk_cod, clk_emr, clk_esa, clk_gfz, clk_jpl) for DRAO. Since DRAO and all the clock reference stations are equipped with high quality HM clocks, the RMS of 24-hour straight line fit of only a few cm should be expected. The AC and PPP solutions of the DRAO clock have regression RMS at the 1-6 cm level (30-200 picoseconds), which is consistent with the expected HM clock stability at or below 10^{-14}/100s.

Figure 11 shows the residuals for the 8 different solutions over the 7 days of the Wk 1104. There is a systematic effect with peak-to-peak amplitude of ~ 600 picosecond that corresponds well to what would be expected from station GPS antenna cable temperature sensitivity (Larson, 2000). The larger residuals on day 65 seen for all PPP solutions is caused by tracking problems at DRAO during parts of the day, which was further alleviated with the 15 min data sampling used in PPP. As expected the IGS combined orbit/clocks and the IGS combined clocks (igs_cmb) in particular show the best performance since it is a combination of all AC clock solutions.

Figure 11. 24-h linear regression clock residuals from IGS combined and PPP estimates for station DRAO clock, GPS week 1104



Currently, (2003) the IGS combined clock products are aligned daily to GPS time, approximated by the daily averages of the broadcast satellite clock corrections. This is not acceptable since it introduces significant daily alignment and discontinuity errors at a few ns. Consequently, IGS is to adopt a new IGS time scale and UTC alignment approach, developed by Senior et al. (2001) as a part of the IGS/BIPM Pilot Project. This significant development will mitigate alignment and daily discontinuity errors (Ray and Senior, 2002). See also Weber et al. (2002) for specific recommendations relating to the new IGS time scale and UTC clock alignment.

8. Conclusions

The primary goal of this compilation of well-known and not so well known aspects of GPS analyses was to aid IGS product users both at practical and scientific levels. It should also help IGS users to use the existing GPS 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 can 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 orbit/clock combined products and dual-frequency pseudorange and carrier-phase observations from a single GPS receiver to estimates station coordinates, tropospheric zenith path delays and clock parameters at the 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 details, 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-dm precision level as is being demonstrated daily within IGS combination summary reports (see IGS Rapid and Final Combination Summary Reports at the IGS CB archives http://igscb.jpl.nasa.gov/mail/igsreport/igsreport.html). Since November 5, 2000 when the new 5-min combined clock products become available and with no S/A, it is possible to precisely interpolate satellite clocks which enables also cm-dm global kinematic positioning/navigation at any interval sampling.

Acknowledgements

IGS data and products are the result of an unprecedented voluntary, yet coordinated effort of many individuals and organizations that continues to provide an invaluable service to scientific and technical community. A part of the above information, mainly pertaining to the PPP modeling and some of the result evaluations, have already been presented and published in a summary form at the 2000 IGS Network Workshop (Héroux and Kouba, 2000) and in Kouba and Héroux (2001). The former Analysis Center Coordinator, R. Weber of Technical University of Vienna, has read this paper and provided the author with a number of corrections and useful suggestions.

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