IGS reference frames: status and future improvements

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Abstract The hierarchy of reference frames used in the International GPS Service (IGS) and the procedures and rationale for realizing them are reviewed. The Conventions of the International Earth Rotation and Reference Systems Service (IERS) lag developments in the IGS in a number of important respects. Recommendations are offered for changes in the IERS Conventions to recognize geocenter motion (as already implemented by the IGS) and to enforce greater model consistency in order to achieve higher precision for combined reference frame products. Despite large improvements in the internal consistency of IGS product sets, defects remain which should be addressed in future developments. If the IGS is to remain a leader in this area, then a comprehensive, long-range strategy should be formulated and pursued to maintain and enhance the IGS reference frame, as well as to improve its delivery to users. Actions should include the official designation of a high-performance reference tracking network whose stations are expected to meet the highest standards possible.

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Background concepts

All products of the International GPS Service (IGS) depend directly on the underlying reference frame adopted. The numerical values of measured quantities are meaningful only within a well-specified frame and their accuracy is limited, in part, by the quality of the frame realization. The IGS and its users rely on a hierarchy of reference frames. The International Terrestrial Reference Frame (ITRF) provides the "absolute" long-term datum, namely, the definitive realization of the terrestrial origin, scale, orientation, and their time derivatives. To this is attached the IGS GPS-only equivalent long-term realization aligned using a 14-parameter Helmert transformation for a select set of high-quality stations. The higher internal consistency of the IGS realization is the reason for using it rather than ITRF alone. For many applications, where a discrete, rather than secular, frame is needed, the IGS orbit and clock products (sp3 format) provide easy access to nearly instantaneous frame realizations for any user location. Each layer of this framework contributes its own important attributes, but each also has its own errors and characteristics that must be considered. The effects on user results will depend on the specifics of individual applications.

International Terrestrial Reference System and Frame

The International Terrestrial Reference System (ITRS) is the recognized conceptual basis for forming coordinate frames based on earth. The general ITRS precepts are the various resolutions of the International Union of Geodesy and Geophysics (IUGG) and the International Astronomical Union (IAU), as well as historical practice. Except for the general relativistic metric, the Union resolutions are mostly rather broadly worded guidelines. The International Earth Rotation and Reference Systems Service (IERS) is responsible for developing detailed specifications for a concrete realization, and for the formation and maintenance of a practical ITRF. When referring to "ITRF" here, unless otherwise stated, we mean the current ITRF2000 realization (Altamimi et al. 2002) together with the models, constants, and procedures of the IERS Conventions 2003 (McCarthy and Petit 2003).

The main elements that determine an ITRF realization are the contributed space geodetic solutions for global sets of coordinates and velocities that are combined—each

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obliged to adopt IERS conventions—together with a “datum” that specifies how the frame origin, orientation, scale, and their time evolutions are materialized. For the highest accuracy, the origin must be geocentric in the general relativistic sense. This is the only frame “local” to the earth suitable to evaluate the space geodesy observation equations globally to the 1 ppb level or better. “Geocenter” is defined as the center-of-mass (CoM) point of the entire earth system, including all solid and fluid components. (Any technical ambiguity in the definition due to the indistinct upper atmospheric boundary, atmospheric ablation, and meteoroid accretion is inconsequential over historical time scales.) The orientation is consistent with conventions adopted in the early twentieth century maintained through successive overlapping alignments of ever higher accuracy. The net rotational rate of change, integrated over the earth’s surface, is specified to be zero. The scale and its rate should be an inherent physical property of those global geodetic measurements that respect the conventional speed of light (and related quantities) without bias, expressed in the general relativistic geocentric frame. So the only datum aspect that is purely conventional is the orientation; the origin and scale have physical meanings.

For ITRF2000, the scale and scale rate were fixed by the weighted combination of three VLBI and five SLR global solutions. The origin and origin drift were determined from the same five SLR solutions. GPS and DORIS solutions were specifically excluded from these datum specifications due to a lack of confidence in their absolute physical reliability and independence. The ITRF2000 datum is accessible in the form of reference coordinates and linear velocities for about 800 points at about 500 globally distributed sites. Only those ITRF sites equipped with continuous GPS receivers are usable by the IGS, but this covers most of the network.

Table 1 summarizes the estimated accuracy of the ITRF2000 datum, based mostly on the internal agreement of the contributed global solutions. It is possible that the internal consistency (or precision) of each contributing technique may well be better than the ITRF combination, due largely to errors in the local ties connecting colocated systems. Having several independent solutions available within each technique, using mostly common data, is vital as the differences provide the primary means of revealing analysis and modeling effects. Only in the multi-technique combination are the common mode errors within techniques exposed, although interpretation is complicated by the usually significant local tie errors.

Considering, among other things, that only three VLBI solutions, all using the same software, were available, the accuracy estimates in Table 1 are likely to be optimistic as the full magnitude of VLBI analysis errors is probably under-represented. Supporting the view that Table 1 underestimates the true datum errors are the actual large shifts from ITRF97 to ITRF2000 (−7 mm in equatorial origin components, −18.5 mm in axial origin, and 0.9 ppb in scale), though these are certainly due mostly to inaccuracy in the ITRF97 datum (originally established with ITRF94 and propagated via ITRF96). Another indication that the scale rate may be less accurate than the internal measure in Table 1, comes from examining the average vertical motions of stations by technique: 0.5 mm/year for GPS, 0.1 mm/year for VLBI, −3.1 mm/year for SLR, and −0.8 mm/year for DORIS. The select set of 99 stations used by the IGS to realize its internal version of ITRF2000 (see below) has an average vertical rate 1.1 mm/year (compared with 0.5 mm/year for all GPS sites). Part of this dispersion is surely due to the different sampling of local effects, but it is also likely that part of the technique-dependent differences reflect systematic scale errors.

The comparatively large instability in rotational rates is due to the complex relative tectonic motions of the stations combined with poor sampling over the earth’s surface. Proposals for improving the no-net-rotation datum in future ITRF realizations are discussed below. Note that datum differences are primarily important when changing from one ITRF realization to another. For a single fixed application using a single ITRF version, datum errors will be common to all results. In this case, the selection of ITRF reference stations will usually determine how the ITRF errors are seen by the user due to the larger relative station position errors compared with GPS-only frames. For this reason, it is generally advantageous to use as many ITRF

Table 1
Estimated accuracy of ITRF2000 datum

Attribute	Offset error (at 1997.0)	Instability	Datum specification
Origin translations(per component)			Physical: geocenter
Equatorial	0.5 mm	0.1 mm/year	
Axial	0.9 mm	0.3 mm/year	
Scale			
	0.2 ppb	0.03 ppb/year	Physical: earth’s radius
	1.2 mm	0.2 mm/year	
Orientation rotations(per component)			Conventional: no net surface rotation
	0.018 mas	0.065 mas/year	
	0.6 mm	2.0 mm/year	
Station coordinates (3D relative to each other at mean epoch)	2–5 mm	0.5–2 mm/year	

Note: These estimates are based on internal agreement of submitted global solutions (see Altamimi et al. 2002) except that the rotational stability is given by Altamimi et al. (2003), based on the level of agreement among the few available no-net-rotation models. Being internal measures, these accuracy estimates are probably optimistic reference stations as possible when accessing the ITRF datum in order to minimize the net frame alignment errors by averaging over a larger number.

Apart from changes related to its datum accuracy, future ITRF realizations could also differ if the IERS Conventions are altered in their models for station displacements (see below). For instance, if atmospheric pressure loading or temperature-dependent variations are explicitly included in the raw data analyses, then the ITRF reference coordinates will need to be associated with reference pressures and temperatures in addition to the current reference epoch. Any such change will likely cause detectable changes in the ITRF coordinates and possibly in the datum realization.

IGS long-term frame realization

Generally, the IGS and its users do not access ITRF directly, even though it provides the primary reference datum and is certainly the most accurate realization of origin, orientation, scale, and their rates. The reason is that ITRF inter-station vectors (and time derivatives) are not consistent with the IGS' GPS-only frame to the current level of precision. Using ITRF2000 station coordinates and velocities directly to generate IGS products would introduce distortions and inconsistencies that would not otherwise be easily isolated or controlled. Among other problems, this would hinder progress in understanding and reducing existing internal error sources. This does not imply that the GPS frame is necessarily superior to ITRF or those of other techniques, only that it is more self-consistent. Any common mode errors in the IGS frame that are suppressed by the use of GPS-only results (such as possible scale defects) must be investigated separately, for example, in multi-technique combinations.

To maintain full internal self-consistency, since 2000 the IGS has formed a secondary GPS-only frame of reference coordinates and linear velocities from the same contributed solutions used for its other products. The "IGS00" frame (currently the second version, IGb00) is aligned via a Helmert transformation (adjusting 14 offset and rate parameters) to ITRF2000 using a selected subset of high-quality stations (recently increased from 54 to 99). This procedure fully preserves the reference datum of ITRF2000 (including scale), but without any internal distortions. IGS00 is then used as the direct basis for all other IGS products.

Many users would prefer the IGS to use ITRF directly in future rather than maintain the separate IGS00 internal frame. However, there is little prospect of doing so without degrading the continuously improving self-consistency, precision, and probably accuracy of IGS products. In order for the ITRF to be directly usable, all other technique solutions and the colocation ties would have to be consistent with the IGS global combined solution to the sub-mm level. Even ignoring systematic differences among the techniques, it seems unlikely that the ties alone will attain the needed level of accuracy within the indefinite future.

Table 2 shows estimates of the uncertainty of the IGS00 long-term frame. The offset estimates and column (1) of the instability estimates are based on a direct comparison between the two realizations (54 vs. 99 reference stations) that had each been separately aligned to ITRF2000 (Ferland 2003). Since the two frames should be significantly correlated, the full amount of their differences is used here as an uncertainty estimate for each rather than being reduced by $\sqrt{2}$. A different set of instability estimates is also listed in Table 2 based on comparisons described in Appendix of sub-networks of IGb00 stations of varying numbers. Column (2) instability estimates are an extrapolation to 100 stations and are very likely to be optimistic. The two different estimates of rotational instability are similar but those for translation and especially scale are rather different. In any case, the IGS internal frame realizations are much more stable rotationally than the underlying no-net-rotational datum and the station coordinates are more consistent than in ITRF2000.

So the "absolute" accuracy of the IGS long-term frame, including the ITRF datum effects (Table 1), is most limited by the ITRF orientation in its net rotational stability; see Table 3. The GPS data and ITRF datum contribute about

Table 2
Estimated internal error of IGb00 long-term realization

Attribute	Offset error (at 1998.0)	Instability error estimates	
		(1)	(2)
Origin translations (per component)	0.15 mm	0.15 mm/year	0.065 mm/year
Scale	0.12 ppb	0.06 ppb/year	0.011 ppb/year
	0.74 mm	0.36 mm/year	0.069 mm/year
Orientation rotations	0.004 mas	0.0037 mas/year	0.0029 mas/year
(per component)	0.13 mm	0.12 mm/year	0.09 mm/year
Station coordinates (relative to each other)			
Horizontal	0.3 mm	0.5 mm/year	
Vertical	0.5 mm	0.8 mm/year	

Note: The offset error estimates and column (1) instability estimates are based on a direct comparison between the two IGS00 realizations (54 and 99 reference stations) using 44 common stations; see Ferland (2003). The instability estimates in column (2) are based on the extrapolation of empirical comparisons described in Appendix; the 3D translational and rotational estimates in Appendix have been converted to 1D values here

Table 3
Estimated accuracy of IGb00 long-term realization

Attribute	Offset error (at 1998.0)	Instability
Origin translations (per component)		
Equatorial	0.5 mm	0.2 mm/year
Axial	1.0 mm	0.35 mm/year
Scale	0.24 ppb	0.07 ppb/year
	1.5 mm	0.4 mm/year
Orientation rotations (per component)	0.068 mas 2.1 mm	0.065 mas/year 2.0 mm/year
Station coordinates (relative to each other)		
Horizontal	0.3 mm	0.5 mm/year
Vertical	0.5 mm	0.8 mm/year

Note: These values are the quadratic sums of values in Tables 1 and 2, using the larger instability uncertainties from Table 2

equally to origin errors, and GPS-related errors probably mostly dominate scale (height) errors at the current epoch. But the internal consistency of the long-term station positions remains at the mm level. Based on this analysis, the largest changes expected in any future ITRF updates would be in the net rotational rates (equivalent to long-term earth orientation shifts).

IGS "instantaneous" reference frames

Except for the IGS Analysis Centers (ACs) and some specialized users, neither ITRF2000 nor IGS00 are easily or conveniently accessible directly, consisting as they do of limited numbers of discrete physical points on the earth's surface. Furthermore, many applications do not lend themselves to long-term solutions, for example, because of limited data spans or in order to study non-linear temporally varying processes. For some short-term needs, the IGS weekly reference frame solutions (see below) may be appropriate, provided that the user has sufficient network overlap with the IGS00 set of 99 reference stations. However, most users rely on a tertiary realization of ITRF that does not depend on having stations in common with the IGS.

GPS data for any location can be analyzed holding the satellite orbits and clocks fixed to values published by the IGS. Taking advantage of the cm-level accuracy and consistency of the IGS products permits autonomous point positioning at the same level (Zumberge et al. 1997), thereby disseminating the ITRF without reference to any other specific point on the earth's surface. This method represents a revolutionary change in the technical means of maintaining and disseminating high-accuracy reference frames to a global community of users. Obviously, the integrity of IGS products is an essential requirement if this approach is to function properly. Furthermore, users must apply analysis methods fully consistent with the IERS standards as well as the additional conventions and practices adopted by the IGS (e.g., satellite antenna offset values); see below for more discussion of these aspects. It is the responsibility of the IGS to ensure that all the necessary information is readily available to users. This must be an ongoing task, which is very difficult to achieve and sustain with sufficient detail and accuracy. Fortunately, Kouba (2003) has written an indispensable user guide that serves as a valuable starting point for future documentation.

Generally, errors associated with this third layer of reference frame realization will dominate the overall user error budget. There are two main reasons. Obviously, the data errors for a relatively short observation period will be much larger than for the long-term integrations used to form ITRF and the equivalent IGS realizations. In addition, the crust-fixed reference frame is neither perfectly rigid nor does it evolve strictly linearly (discussed further in the next section); local, regional, and larger scale deformations occur with variations on all time scales. Short-term positioning results will sense the combination of both effects. In addition, the effects of residual small inconsistencies in the IGS Final products may be noticeable in some high-accuracy applications (see below for a detailed discussion of this topic).

Table 4 gives estimates of the short-term scatter in local station coordinates, for weekly global and daily PPP observing modes. Apart from the different integration times, use of carrier phase ambiguity resolution for the global network improves its east component performance significantly compared to PPP for isolated points. Still, it is not expected that the weekly integrations would improve by as much as $\sqrt{7} = 2.65$ due to well-known temporal correlations in the geodetic results.

Handling non-linear variations

To date, ITRF and the IGS00 realizations have been defined in a strictly secular sense with purely linear temporal changes (apart from the conventional models used in the lowest level data analysis). The linear changes are intended to accommodate primarily unmodeled geophysical motions, mostly of tectonic origin, that cannot be known a priori with sufficient accuracy. In the past, it was not clear as to what extent residual non-linear motions were due to technique-related errors versus geophysical effects not included in the conventional models. For observational spans of long enough duration (greater than 2.5 years

Table 4
Scatter in short-term station coordinates relative to long-term reference frame

Component of local station position	IGS Average weekly SD (mm)[a]	JPL daily SD (mm)[b]
N	2.06	3.7
E	2.13	5.3
U	6.33	10.1

[a] The IGS average scatters are computed from the weekly standard deviations reported by R. Ferland in his IGS Reports series for the 100 weeks from January 27, 2002 through December 27, 2003 for the global IGS combined network

[b] The JPL daily scatters for a large number of point positioned stations are from M. Heflin (2001). Kouba (2003) reports similar PPP results using the IGS combined products

according to Blewitt and Lavalee 2002, to overcome effects of seasonal variations), the non-linear residuals should have minimal influence on the secular ITRF quantities, so the deviations were of secondary interest when the errors in the frame itself were of a similar magnitude.

With the improved accuracy of the observation techniques and easy high-accuracy access to ITRF over short spans (typically from subdaily to about 1 week using GPS), short-term deviations from the secular ITRF quantities can now often be considered significant. They may be important for understanding increasingly subtle geophysical processes, for instance, as well as for better characterizing technique-related errors. Such motions can be considered as global (involving net shifts of the collective frame), large-scale (correlated over continental scales or so), regional, or local, with distinct types of driving processes associated with each.

Geocenter motion and large-scale displacements

For some years, analyses of SLR data have strongly indicated that the coordinate frame attached to the earth's crust moves detectably relative to the earth's CoM. This translational motion, viewed from a rigid crust-fixed frame, is known as "geocenter motion" and is presumably caused by the mass movement of planetary fluids (atmosphere, oceans, surface hydrology, ice mass, etc.) relative to the solid earth. The motions likely involve tidal, non-tidal (mostly seasonal), and secular components. Since the method of realizing the ITRF origin using long-term SLR solutions senses the combined effect of all secular effects, the contributions due to individual geophysical processes can only be separated by theoretical methods. (In principle, any non-linear geocenter motion, including an acceleration, could be detectable from the linear ITRF frame using time series analysis. Confidently distinguishing such a motion from evolution of the observation techniques might be problematic, however.)

To better understand the magnitude of geocenter motion and the ability of the observation techniques to measure it, the IERS conducted a campaign in 1997–1998 (Ray 1999). The overall impression at that time was that the net motion of the terrestrial reference frame is detectable but small, probably less than about 1 cm in any component. The diurnal and semidiurnal tidal variations appeared to be well determined and in good agreement with modern ocean tidal models (Watkins and Eanes 1997). There was some general agreement about the techniques in detecting seasonal variations, but not enough to justify a combined IERS geocenter time series. Geophysical computations of the expected motions based on global fluid motions were only very roughly consistent with the geodetic observations.

Following the IERS campaign, studies have continued and the capabilities of the GPS technique have greatly improved. Beginning February 27, 2000, the IGS started to account explicitly for apparent geocenter motions in its Final products (Kouba et al. 1998; Springer 2000); see below for further considerations of the IGS procedures. However, the IERS does not do so now, neither in the Conventions (2003) nor in its products. In the following parts of this section, we propose extensions and clarifications of the IERS Conventions for handling geocenter motions.

As pointed out by Blewitt et al. (2001), the redistribution of earth's surface fluids that gives rise to geocenter motions should also be associated with changes in the lithospheric loading and large-scale deformations of the crust. They have analyzed a time series of IGS station coordinates for a global network to infer the seasonal variations in degree one loading coefficients. The net degree one surface deformation can be regarded as equivalent to geocenter motion (Wu et al. 2002; Dong et al. 2003). However, Wu et al. (2002, 2003) argue that a degree one model is inadequate to represent the earth's actual loading deformations; degree and order of at least six are needed.

Celestial transformation modified for geocenter motion

Equation 1 in Chapter 5 of the IERS Conventions 2003 (McCarthy and Petit 2003) relates the terrestrial to the celestial reference system by the product of the traditional precession-nutation (Q), rotation (R), and wobble (W) matrices, which account for the motion of the celestial pole, earth rotation, and polar motion, respectively. In order to accommodate geocenter motions, that expression can be elaborated and applied to the realized celestial and terrestrial frames as:

$$ICRF = Q * R * W * [TRF + O(t)] \tag{1}$$

where $O(t)$ is the offset vector from the center of the "instantaneous" $TRF(t)$ frame to the ITRF origin such that $[TRF+O(t)]$ is aligned to ITRF. The sign (sense) of the geocenter vector, $O(t)$, is arbitrary but it should be fixed by convention to minimize confusion. Note that the formulation proposed in Eq. 1 makes clear that the earth orientation parameters (EOPs) are expressed with respect to the ITRF origin, not the center of the instantaneous crust-fixed frame. (Chapters 4 and 5 of IERS Conventions 2003 can be interpreted as consistent with Eq. 1 if the ITRS used there is viewed as equivalent to our "instantaneous" $TRF(t)$ frame.)

While the conceptual form of Eq. 1 is simple enough, an operational method to extract geocenter offsets from observational results is less obvious. The traditional method has been to use a seven-parameter Helmert similarity transformation to relate each instantaneous $TRF(t)$ to the ITRF datum (or its IGS realization) where the translational offsets are the geocenter vector and where the simultaneous rotational alignment offsets are used to adjust the EOPs in a consistent way. This is the method that has been used in the IGS products since February 27, 2000 (see below).

An alternative method, following the degree one loading development of Blewitt et al. (2001), would augment the traditional Helmert translational terms with three degree-one mass loading terms, which should theoretically capture both the geocenter movement and the largest scale deformations. Both methods require uniform global network coverage to completely avoid biased geocenter estimates. But the degree one loading approach will be further biased if higher order deformations are also not included (through degree and order six according to Wu et al. 2002), which requires dense as well as uniform global coverage. Furthermore, if TRF deformations are explicitly modeled in the formation of the IGS combined SINEX solutions, then the resulting weekly frames will be inconsistent with the associated orbit and clock products (see below).

Therefore, at the IERS-ITRF-IGS level of product formation, we believe it is prudent to avoid the risk of over-manipulating reference frame results in ways that depend on particular model choices. While including deformation effects may soon be practical for GPS, it is clearly not suitable for the much more limited SLR network. Users can always apply their own preferred framework choices provided that the IGS results are adequately documented and the conventional transformations are reversible. Thus, the current IGS procedures for handling geocenter motion are endorsed and no specific provisions are recommended at this time to account for higher order internal deformations within the instantaneous reference frames.

Importantly, the largest possible number of globally well-distributed reference stations should always be considered in measuring geocenter motions to minimize the effects of local non-linear site motions and large-scale displacements. The IGS00 frame serves this function well but it can be improved with better, more uniform global coverage (see below).

Conventional contributions to local station displacements

According to Chapter 4 of the IERS Conventions 2003 (McCarthy and Petit 2003), the modeled instantaneous position of a terrestrial point can be represented as a function of time t as

$$X_m(t) = X_0 + V_0(t - t_0) + \sum_i dX_i(t) \qquad (2)$$

where X_0 and V_0 are regularized coordinates and velocities at reference epoch t_0 and the summation includes various "high-frequency" motions affecting site position. The summation should explicitly include effects for solid earth tides, ocean loading, pole tide, atmospheric loading, and geocenter motion, according to Chapter 4, although the actual frequency range for each is not described. Moreover, Chapter 7 gives complete models for only the first three effects, and does not provide specific models for atmospheric loading or geocenter motion.

This a priori model for station position can be used to linearize the space geodesy observation equations which, after adjustment of various parameters including those for the station position, $X(t)$, gives observed coordinate residuals

$$R(t) = X(t) - X_m(t) \qquad (3)$$

Over time, more geophysical effects have been identified in time series of station residuals, $R(t)$, and subsequently incorporated as new modeled effects in the Eq. 2 summation. In principle, if all relevant effects could be accurately modeled a priori and included in Eq. 2, then $R(t)$ would reflect purely measurement noise. In practice, this does not seem feasible in the near future. What then should be the objective basis for deciding which effects to put into Eq. 2 versus those that are left as residuals for further study a posteriori?

Following traditional practive in treating earth orientation variations, we recommend that the IERS Conventions should be interpreted such that the summation of various model effects for a priori, non-linear station displacements includes only those which (1) have known close-form expressions with high a priori accuracy; and (2) have periods of variation near 1 d or schorter (with jsome exceptions). Currently, these criteria include diurnal and semidiurnal tidal displacements for the solid Earth, ocean loading, and atmospheric loading, as well as the lonber-period Earth and ocean tides and the mostly longer-period pole tide. The ocean tidal loading should account for the whole-body translation of the solid Earth that counter-balances the motion of the ocean mass, in contradiction to Chapter 7 of the IERS Conventions 2003. The "permanent" component of the solid Earth deformation is also included in the tidal model in keeping with longstanding geodetic practice. Currently, the IERS does not provide models for the dirunal/semidurnal displacements due to atmospheric loading or geocenter motion.

Accounting for the geocenter motions in the diurnal and semidiurnal bands, which is conveniently done via the ocean loading corrections, is overdue as these are a direct consequence of the adopted global ocean tide model. Moreover, the magnitude of these motions (Watkins and Eanes 1997) is at least as large as the less well-measured variations at annual and semiannual periods (Eanes et al. 1997; Bouille et al. 2000). So neglect of the diurnal band should be avoided in order to minimize possible aliasing into longer periods or into other 12-h signals and harmonics.

The IERS Special Bureau for Loading (van Dam et al. 2003) has published a model for the S1 atmospheric pressure thermal tides having the form:

$$P(\phi, t) = P_{\max} \cos^3(\phi) \sin(t + 12^\circ) \qquad (4)$$

where $P_{\max}$ is the maximum loading amplitude at the equator, ϕ is the latitude, and the longitudinal variation depends on the time of day, t, with a phase offset of 12^o. Assuming a non-inverted barometer ocean earth model, $P_{\max}$ is −0.8 mm for the S1 tide and about −1.5 mm for S2. Presumably, an updated model of this type can be prepared for data analysts, taking into account the recent work of Ponte and Ray (2002) on handling atmospheric pressure tides.

Apart from the effects listed above, all other longer period motions will be observed as residuals to the Eq. 2 model. The types of effects include those local to individual tracking stations as well as the larger scale deformations associated with loading by global fluid motions. A major unresolved question is whether non-tidal pressure loading at subdaily periods can be safely ignored without adding excessive noise to the daily (or subdaily) geodetic results.

If not, rapid analysis of GPS data could become vastly more cumbersome.

IGS combination procedures

During the first years of the IGS, the combined products were formed by a simple weighted averaging procedure, with robust outlier and reliability checking. The product sets included satellite orbits and clocks tabulated at 15-min intervals, together with daily earth rotation parameters (ERPs, namely polar motion coordinates, their rates, and length of day). The terrestrial reference frame was rigidly constrained to the adopted epoch coordinates of a set of agreed fiducial stations. Originally, only 13 fiducial GPS stations colocated with SLR or VLBI were used with coordinates taken from ITRF92, ITRF93, and ITRF94 successively. By 1997, the quality of IGS results was clearly being limited by the small number, limited distribution and availability, and performance of this fiducial network. With the introduction of ITRF96 on March 1, 1998, the set of fixed fiducial reference stations was expanded and improved to 47 sites; it later increased to 51 with ITRF97 on August 1, 1999.

In 2000, two important changes were made in the IGS product set that forced fundamental changes in this simple combination methodology. On February 27, 2000, the quasi-rigorous approach of Kouba et al. (1998) was fully implemented operationally in the IGS Final products to permit the introduction of new terrestrial reference frame products. The weekly combined (and accumulated) sets of station coordinates require use of the full variance-covariance information for the tracking network provided in a fiducial-free form. At that same time, the internal IGS97 realization of ITRF97 was adopted. It was necessary to slightly modify the combination procedures for the classical products to ensure the highest level of overall consistency between the terrestrial frames, orbits, and clocks (Kouba et al. 1998). Then, on October 22, 2000, the clock combination procedures were changed to add station clocks and to improve the time resolution for all clocks to 5 min (Kouba and Springer 2001). The approach to the final products has remained unchanged since that time.

The IGS products generated in the Rapid and the Ultra-rapid modes continue to use the fiducial-fixed methods of the earlier period. However, the internal IGS00 realization and reference frame stations are used to enforce a high degree of compatibility and consistency among products.

Quasi-rigorous methodology

We review briefly the current IGS Final product combination procedures in place since 2000. It is assumed as necessary that the product submissions from the individual ACs are internally self-consistent and either minimally constrained or unconstrained. At the combination level, the IGS attempts to maintain product consistency with the highest level of rigor feasible. Presently, the full variance-covariance information is carried only for the terrestrial reference frame and ERPs in SINEX-format files; orbit, clock, and troposphere parameters are too numerous and variably modeled to be treated the same way.

At the first stage of combination, the Reference Frame Coordinator (R. Ferland, Natural Resources Canada) reconstructs the submitted weekly solution files, deconstrains them if necessary, checks for outliers and discrepant metadata, rescales the individual weighting based on comparison with the IGS00 frame, aligns all frames to IGS00 using a 7-parameter Helmert transformation, and forms the IGS combination from the rescaled, realigned inputs. The weekly datum (orientation, scale, origin) matches that of the long-term IGS00 frame, and hence ITRF2000; that is, each weekly IGS frame has been shifted by the amount of the apparent geocenter motion from its "instantaneous" location with respect to the CoM. It has also been rescaled by a significant amount, usually around 1 ppb (6 mm height change) to 2 ppb depending on the AC. In this way, the official IGS ERP series is sure to be fully consistent with the IGS00 (ITRF2000) datum.

It is noteworthy that the IGS weekly frames are translated from their displaced CoM locations to the IGS00 origin, which has the benefit of removing these global variations from the time series of individual station residuals. The remaining variations in IGS station residuals should therefore be interpreted as arising from other effects.

The second combination stage applies for the satellite orbits and clocks, and station clocks. (The classical ERP combination also continues to be produced as before, but these are no longer the official series.) The former orbit combination process was changed to enforce consistent rotational alignment of the final orbits to the weekly IGS reference frame produced in the first stage combination (Springer 2000). Rotational offsets are applied to each AC orbit set prior to the orbit combination based on the differences between individual AC frame/ERP estimates and the IGS combined frame/ERP values from the SINEX combination. On the other hand, the SINEX translational and scale offsets are not applied in the orbit combination. So the IGS Final orbits continue to be consistent with a weekly terrestrial frame that has not been shifted to the IGS00 origin.

In the accompanying second stage combination for the satellite and station clocks, it was originally proposed that adjustments should be made to each AC submission to account for geometric differences in their solutions compared to the IGS combinations for stations (based on the first stage SINEX process) and satellites (Kouba and Springer 2001). The proposed geometric correction was also supposed to account for the apparent geocenter offset of each AC solution from IGS00. So, while the IGS orbits are not explicitly corrected for the geocenter offsets from the SINEX combination, the associated satellite clocks would be (Kouba and Springer 2001). Such a geocenter correction was not actually implemented in the IGS clock combination, however (G. Gendt, private communication). The geometrical corrections are only for differences in radial satellite positions among the various ACs.

Consequently, use of the IGS Final orbits and clocks for PPP will give user positions that are in an "instantaneous" frame, shifted in origin and scaled differently from the IGS weekly

SINEX frame (aligned and scaled to IGS00). Likewise, if only the orbits are used, for instance, in a global double-differenced analysis, the same result will be obtained. As discussed already, user coordinates, $X(t)$, can be compensated (approximately) for the apparent geocenter shift by applying the reported IGS geocenter offset, $O(t)$, for that week; that is, $[X(t)+O(t)]$ should be aligned to IGS00 and the IGS weekly frame. The adjustment is only approximately valid if the user coordinates are not averaged for the same 1-week period as the IGS weekly SINEX frames. However, the scaling factor for the IGS weekly frame is not reported and therefore the appropriate rescaling cannot be done. In principle, the fact that the scale adjustments from the first stage SINEX frame combinations are not applied to the orbits or the clocks would seem to be a basic inconsistency in the IGS Final products that remains to be addressed (Kouba 2003). In actual fact, the problem does not seem to be so serious, as discussed further below.

A third stage of the IGS Final product formation applies for station zenith tropospheric delays and ionospheric map grids. In both cases, these combinations are done independently of the other IGS products. In the case of the ionosphere, this is justifiable on practical grounds since the predominate errors are mostly unrelated to the reference frame and are at a much larger level. (Some important datum connections do exist, however, particularly between inter-modulation signal biases and clock offsets. So, the best handling of ionospheric products and datum factors should be reconsidered from time to time.)

For the troposphere products, adjustments for differences in station heights and scale corrections from the IGS weekly SINEX combination should ideally be applied in their combination to maintain full consistency (Kouba et al. 1998). However, the station height adjustments will usually be tiny (1 m of height change near sea level corresponds to about 0.3 mm of zenith path delay). The scale inconsistency will be discussed further below.

For the IGS Rapid and Ultra-rapid products, the ACs are expected to use the IGS00 reference frame with tight fiducial constraints. So, all the resulting IGS combined products for these series should be nominally consistent with the IGS00 (ITRF2000) datum, including origin and scale. However, the orbital dynamics will still sense the actual geocenter. So, if the tracking network is displaced from the IGS00 origin due to geocenter motion, the resulting errors will have to be accommodated in the data analysis in some way. The true frame of the orbits will therefore be ambiguous at some level, which is difficult to evaluate and depends on the degree to which phase ambiguities have been resolved in the data analysis (Ferland et al. 2004).

The various reference frames used in different IGS product sets are summarized in Table 5. Nominally, there seem to be significant frame inconsistencies within the Finals and between the Finals and other products. However, the actual significance of these differences is less obvious, as discussed next.

Concerning scale, it should be noted that plans under IGS consideration for handling satellite antenna phase patterns and the "absolute" calibration of tracking station antennas (Schmid and Rothacher 2003) will have a major impact. As the method of estimating satellite antenna patterns from GPS data is nearly singular unless the terrestrial scale is fixed, operational implemention of a set of absolute antenna patterns determined using ITRF2000 fixed will have the effect of enforcing a single consistent scale on all IGS products and approximately eliminating the scale inconsistencies discussed above. However, one caveat should be kept in mind: A variety of other analysis choices also affect the resulting system scale, including elevation cutoff angle, tropospheric mapping function and parameter partials, tropospheric parameterization and estimation strategy, handling of atmospheric gradients, orbit estimation strategy, etc. If the effective scale of the analysis used to derive the absolute antenna patterns is not very close to the weighted average scale of the IGS ACs, then the overall scale of the combined products will not necessarily be exactly fixed to ITRF2000. This aspect should be evaluated and verified when absolute antenna patterns are implemented by the IGS.

Remaining inconsistencies in IGS products

Consider first the apparent scale inconsistency between the IGS Final orbits and the weekly SINEX terrestrial reference frames. Following the adoption of IGS00 on December 2, 2001, all the IGS AC SINEX solutions have been rescaled

Table 5
Nominal reference frames of IGS combined products

Product set	Origin	Scale
Finals		
Terrestrial frame (SINEX)	IGS00 (shifted)	VLBI/SLR via ITRF2000 & IGS00
Orbits	CoM for terrestrial frame with weekly geocenter offset from IGS00	GPS[a] (IGS AC average scale)
Clocks	CoM for terrestrial frame with weekly geocenter offset from IGS00	GPS[a] (IGS AC average scale)
Troposphere	Ambiguous (but probably not significantly so)	GPS[a] (IGS AC average scale)
Rapids and Ultra-rapids		
All	IGS00[b]	VLBI/SLR via ITRF2000 & IGS00[b]

[a] The scale of all products could be shifted to IGS00 when the IGS adopts "absolute" antenna phase patterns for satellites and tracking stations

[b] The Rapid and Ultra-rapid tracking frames are rigidly fixed to IGS00 but there is a partial response of the orbital dynamics to geocenter displacement (Ferland et al. 2004)

upward by 0–2 ppb, except during the last year when the NRCanada frames required scale changes of 2–3.5 ppb (see results posted by R. Ferland at ftp://macs.geod.nrcan.gc.ca/pub/requests /sinex/sum/). During this period, the mean "natural" scale of the GPS solutions seems to have been about 1–2 ppb smaller than ITRF2000/IGS00. However, the associated Final orbit solutions have not been scaled in any way. Springer (2000) found that doing so degraded the orbit combination.

If we compare the IGS Rapid orbits (which use the IGS00 frame rigidly) with the Final orbits (fiducial-free), we find that the scales match to within about 0.1 ppb, based on weekly reports from the Analysis Coordinator (see plots posted at http://www.gfz-potsdam.de/igsacc). This is equivalent to a difference in satellite radial positions of less than about 2.5 mm on average. (For comparison, the 1D WRMS differences in the two orbits are about 1 cm.) Such a high level of orbit scale agreement is incompatible with any significant influence by the adopted terrestrial scale. The same conclusion is reinforced by examining the orbit and frame scale differences among ACs. There is no obvious correlation in the relative behavior of individual ACs between the two sets of scale differences. The overall dispersion in orbit scales has been about 1 ppb during recent years but about 2 ppb (increasing to 3 ppb lately) for terrestrial frames.

Zhu et al. (2003) have shown how some types of errors can affect the GPS terrestrial scale (and troposphere estimates) but have no effect on the scale of the orbits. It is tempting to conclude that, since the estimation of GPS orbits relies heavily on dynamical modeling rather than kinematic positioning, Kepler's third law (relating orbital period with semi-major axis) overrides any influence of the scale of the tracking network. (As shown by Zhu et al. (2003) errors in the adopted value of GM can also impact the orbit scale.) In the absence of any evidence to the contrary, we conclude, therefore, that the apparent inconsistencies in the handling of the scale of IGS orbits (see Table 5) are immaterial. However, this conclusion should really be verified by using IGS Final products in long-term PPP comparisons. When the IGS adopts absolute antenna phase patterns (with an inherent scale choice fixed by design), then the scale inconsistencies should be mostly removed.

The other main inconsistency discussed above concerns geocenter offsets. The IGS Final orbits and clocks correspond to a terrestrial frame displaced from the IGS00 origin by the amount of the weekly observed geocenter offsets. The corresponding weekly terrestrial frame has been shifted, however, to match the IGS00. Users can compensate for this inconsistency by applying the same geocenter offset obtained from the SINEX combination. In some cases, the offset will be only approximately valid since the IGS geocenter offsets are 1-week averages and users may have results for other intervals.

The other IGS products that seem inconsistent with the IGS00 frame are the troposphere zenith path delays. The effects of geocenter offset and station coordinate differences from the weekly SINEX frames are probably very minor. However, the inconsistency in scale, unlike for the GPS orbits, is probably not negligible. Generally, the terrestrial scale (and station heights) are very tightly correlated with tropospheric parameter estimates. So the rescaling of the IGS SINEX frame by 1–2 ppb (6.4–12.8 mm height changes) could reasonably be expected to require a compensating change in the tropospheric products at the mm level or greater (Kouba et al. 1998).

One other type of product inconsistency deserves mention. The IGS (and IERS) changes in reference frame from time to time have caused the time series of products to be inhomogeneous, especially in the earlier years. Kouba (1998) developed a transformation utility (trnfsp3n) that is useful to shift sp3 orbit files from one official IGS frame to another. However, users should be aware that any such attempt is limited in its accuracy, at least in the period before quasi-rigorous consistency was enforced for the products. In particular, orbits of the ITRF93 era (Kouba 1995) remain discontinuous compared to other years, even after being transformed. This is because the IERS earth orientation series and ITRF93 were shifted in their own relative consistency with respect to realizations before and after. So, even if users attempt to align the IGS sp3 files to a consistent reference frame for long-term solutions where the orbits are held fixed, small daily rotational and translational offsets should be adjusted to ensure the fullest consistency, if a global or nearly global network is observed.

It should be mentioned in passing that the weights used for input solutions to the various IGS combinations are set independently for each product type. This probably contributes additionally to IGS product inconsistencies since AC biases will be expressed differently for different products. However, there is probably no better way to adjust meaningful weights while recognizing that each AC quality is not usually equal across all products. Indeed, not all ACs contribute to all IGS products.

Table 6 is a summary of the IGS product inconsistencies that may have tangible effects for some users. There is, at present, no completely satisfactory solution to resolve discrepancies in all cases. For global networks using double-differenced data and fixed IGS Final orbits, the published weekly geocenter offsets from the SINEX combination process can be used as an approximation of the offsets needed to relate user results to the IGS weekly combined terrestrial frame (if this is needed). For the IGS troposphere products, no procedure can be recommended to resolve current inconsistencies until studies have been made of the precise relationship between the terrestrial frame scale and the associated zenith path delay in the presence of other complicating effects (such as elevation angle coverage and antenna phase patterns).

Improvements in analysis center procedures

Apart from the conceptual and procedural aspects discussed in the previous sections, the IGS reference frame

Table 6
Summary of IGS product inconsistencies for users

Usage	Inconsistency	Remedy
Precise point positioning with fixed IGS Final & clocks	Origin offset from IGS weekly SINEX frame by apparent geocenter offsets (approximately); scale difference from weekly SINEX frame	Apply weekly IGS geocenter offsets when needed (approximate only); none available currently
Double-differenced positioning of global network with fixed IGS Final orbits	Origin offset from IGS weekly SINEX frame by apparent geocenter offsets (approximately)	Apply weekly IGS geocenter offsets when needed (approximate only)
Long-term positioning with fixed IGS Final orbits	sp3 files aligned to different IGS reference frame realizations	Apply transformations with trnfsp3n and adjust rotational and translational offsets
Tropospheric path delays	Origin and scale not precisely defined (but origin defect is probably insignificant)	None available currently

Note: Inconsistencies are relative to the origin and scale of the IGS00 (ITRF2000) reference frame, and assume that the apparent scale difference between the weekly SINEX frames and the orbits is not significant. The scale inconsistencies could be resolved when the IGS adopts "absolute" antenna phase patterns for satellites and tracking stations, thereby fixing the frame of all products to IGS00

(in the broadest sense, including datum effects in all products) is highly influenced by many details of the methods and models used by the individual ACs. In some cases, consistency within the overall IGS framework is sufficient, which merely requires that ACs agree to the same conventional constants and procedures. These should not be changed without very strong compulsion because of the difficulties and confusion caused for users. In other cases, the best possible physical model for a given effect is required if tangible errors are to be avoided. Ordinarily, these procedures must be implemented and updated as often as necessary, although coordination among the ACs may be useful sometimes. We consider below a number of areas where changes in analysis have recently been proposed.

Subdaily variations

Subdaily effects are particularly insidious for GPS because many geophysical phenomena have periods linked to the solar day and are therefore commensurate with the satellite orbital period. Any subdaily errors that do not alias into the orbit parameters can affect position estimates or other parameters. Diurnal and semidiurnal station height errors can in turn alias into longer period signals. As Penna and Stewart (2003) show, a 10-mm height error at most of the eight largest diurnal/semidiurnal tidal periods can map into annual or semiannual aliases at levels up to 1–2 mm. Thus, models for the subdaily effects should be as accurate as possible, considering that planned GNSS expansions (Galileo and GLONASS) will add new orbital periods not commensurate with the solar day.

Subdaily EOP tidal variations

As already discussed at the IGS Ottawa workshop in 2002, ACs are urged to adopt the improved subdaily EOP tidal model in the IERS Conventions 2003. The tidal model itself is unchanged from the 1996 version; the coefficients of the eight main tidal constituents are nominally the same. But the new model is more complete in using a frequency-dependent admittance function to account for a total of 71 diurnal and semidiurnal terms. Comparison of the 2003 and 1996 models for year the 1997 shows peak differences of 0.1 mas for PM-x, more than 0.08 mas for PM-y, and about 0.012 ms for UT1. The RMS differences are 0.033 mas, 0.030 mas, and 0.0041 ms, respectively. The effect applies in evaluating the GPS observation equation as well as in the rotation of the AC orbit solutions into an earth crust-fixed frame. A subroutine is available from the IERS at <ftp://maia.usno.navy.mil/conv2000/chapter8/ortho_eop.f.>

The 2003 model uses the same geophysical analysis as in 1996, simply extended to more tidal terms. The original work by R. Ray in 1995 was unpublished although it followed the same development as Ray et al. (1994). More than likely, the subdaily EOP variations could be improved using results from recently enhanced global ocean circulation models. Atmospheric tides, especially S1, should also be considered.

High-frequency nutation in polar motion

In Resolution B1.7 (2000) adopted at its 24th General Assembly, the IAU redefined the celestial pole to eliminate ambiguities in the distinction between "high-frequency nutation" and polar motion. Effects previously regarded as nutations with periods less than 2 days (viewed from the celestial frame) are to be considered using a model for the corresponding polar motion. The forced nutations due to the lunisolar torque on the triaxial earth, having prograde diurnal and prograde semidiurnal terms, are therefore now regarded as polar motion effects. The prograde diurnal nutations correspond to long-period polar motions and are thus already contained in the measured daily values; no changes are required for these. The prograde semidiurnal nutations correspond to prograde diurnal polar motions; these should be accounted for in data analysis in the same way as the subdaily EOP tidal variations. The IERS Conventions 2003 lists 10 diurnal polar motion terms with amplitudes up to about 0.015 mas, but no subroutine is provided. When a validated routine becomes available, ACs should implement it as with their subdaily EOP model.

New solid earth tide model

The IERS 1996 solid earth tide model was updated slightly for the 2003 edition. It is consistent with the new IAU2000 nutation model and incorporates a more complete handling of frequency-dependent effects. Based on comparisons between the old and new models at mid-latitude sites, changes in local vertical are at the level of 1–2 mm while horizontal differences are below 0.5 mm. A subroutine is available at <ftp://ftpserver.oma.be/dist/astro/dehant/IERS/dehanttideinel.f.> However, the inline documentation is limited. Note that the input arguments seem to require geocentric station coordinates in the ITRF frame (meters); geocentric coordinates for the sun and the moon in an earth crust-fixed frame (meters); year, month, day, and day-fraction using UTC; and the output local displacements are XYZ vectors in the ITRF frame (meters).

Subdaily geocenter variations

As shown by Watkins and Eanes (1997) using SLR data, the large-scale mass redistribution due to the ocean tides causes a counterbalancing motion of the solid earth. The magnitudes of the largest tidal terms reach the level of about 5 mm in the Z component and 2–3 mm in the equatorial, similar in size to the expected annual and semiannual variations. This subdaily geocenter motion is somewhat analogous to the subdaily tidal EOP variations discussed above, except that it is translational rather than rotational. To account for this effect most simply in the GPS observation equation, appropriate ocean loading coefficients can be used. At the automated ocean loading site operated by M.S. Bos and H.-G. Scherneck (see http://www.oso.chalmers.se/~loading/), users can select coefficients with such a correction already applied. In Chapter 7, the IERS Conventions 2003 seem to recommend against this approach—"The displacement model does not include the translation of the solid earth that counterbalances the motion of the oceans' center of mass."—while Chapter 4 suggests the opposite.

As already discussed above, our recommendation is to account for the subdaily geocenter motion due to the oceans. Otherwise, the motion will be heavily aliased into the GPS orbits. Use of the geocenter-corrected ocean loading coefficients is an attractive option for doing this partially. However, as with the subdaily EOP variations, a standalone model for the subdaily geocenter motion is still needed to transform the inertial orbits into the earth crust-fixed frame required by the IGS. Such a model is not yet available.

In principle, all analysis models and procedures involving ocean tides should be formulated with a consistent global ocean model. (More detailed coastal models are often also needed for ocean loading.) It is unlikely that the current IERS Conventions satisfy this requirement.

Subdaily atmospheric loading model

As already discussed above, our interpretation of Chapter 4 of the IERS Conventions 2003 calls for an a priori model for subdaily atmospheric pressure loading displacements among the various conventional contributions to be added to regularized station coordinates. At present, no such model is available, though the height variations are expected to be near 1–2 mm for the S1 and S2 tides.

Pole tide

The IERS Conventions have historically been unclear about which reference pole to use in computing the centrifugal deformation of the earth due to polar motion, known as the pole tide. In the 2003 edition, the ambiguity was largely resolved: a moving average pole position should first be removed from the instantaneous polar coordinates before computing the pole tide. The appropriate averaging time is not stated but it should presumably be sufficient to remove the annual and Chandler wobbles. In any case, two concrete realizations of the mean pole are provided, a numerical file of annual coordinates and a linear trend (apparently fitted to filtered pole coordinates for the period from about 1975 to 2000; G. Petit, private communication). The tabular file ends at year 2000 making its current use problematic. The sensitivity of the effect is such that about 30 mas of polar offset corresponds to a maximum station displacement of about 1 mm.

The critical requirement is for all analysis groups of all techniques to handle this effect the same way. Otherwise, the results of the combined products will be uninterpretable. The agreement in mean pole position needs to be at the level of 10 mas or better. Owing to inherent difficulties in filtering out the annual and Chandler variations for the most recent data, the requirement is most conveniently satisfied by adopting a conventional model for the mean pole position, namely, the linear trend given in IERS Conventions 2003.

Nutation model errors

It is well known that satellite orbit tracking is highly insensitive to offsets in the celestial pole position. Modest rotations of the whole earth in inertial space do not affect, to lowest order, the orbits as observed from an earth-fixed frame. Much like UT1 and LOD, however, the rates of change of the celestial pole correspond to an unmodeled acceleration of the orbital dynamics and can be formally estimated together with the classical elements (Rothacher et al. 1999). The resulting nutation rate estimates will be subject to similar unmodeled acceleration errors which will usually limit their accuracy, compared to measurements from truly inertially based systems (i.e., VLBI). Conversely, errors in assumed nutation rates, if sufficiently large, can adversely affect GPS analyses and should therefore be controlled.

The IAU1980 nutation model has a particularly large prograde fortnightly (13.66 d) error corresponding to about 0.07 mas/d (J. Kouba, unpublished). Viewed from the terrestrial frame, this variation will appear as a nearly diurnal polar motion rate signal with the same amplitude and, for 24-h averaging, will alias into a retrograde fortnightly (13.66 d) polar motion rate error with slightly reduced amplitude (J. Kouba, unpublished). In the time domain, the fortnightly polar motion error will have an amplitude of about 0.15 mas.

In order to avoid polar motion errors of this type, it is necessary that the Analysis Centers apply a priori nutation models of modestly high quality. By itself, the IAU1980 model is not adequate. On the other hand, the new IAU2000A model is probably unnecessary, considering its computational burden and the fact that it does not include the variable free core nutation. Suitable compromise solutions would be to use the IERS1996 model or the IAU1980 model together with the IERS published nutation offsets (interpolated to the epoch of date). The latter should provide the highest quality since it includes the observed free core nutation.

Neglected ionospheric corrections

Only the lowest order ionospheric correction (inverse frequency-squared term) is ordinarily applied in radiometric analyses. Kedar et al. (2003) have considered the effect of the neglected second-order correction, which depends on the earth's magnetic field and varies as the inverse of frequency-cubed, on GPS positioning. They find that estimated station latitudes are affected at the few-mm level, with the main variations being mainly diurnal, semiannual, and decadal. Errors are largest near equatorial sites and when the ionospheric delay is greatest. These north-south distortions in apparent station location can consequently also influence the axial component of estimated geocenter motions.

Relativistic effects

The IAU advocates the use of Geocentric Coordinate Time (TCG) for the analysis of near-earth satellite data. TCG differs by a constant rate from TAI (or UTC). However, most (if not all) analysis groups continue to use the prior Terrestrial Dynamical Time (TDT), now known as Terrestrial Time (TT), which differs from TAI only by an offset, as observational data are normally time-tagged using a scale linked to TAI. While formally deficient, the TT results will differ at a practical level from a TCG analysis only in scale, being smaller by about 0.7 ppb. Recognizing this, the ITRF2000 datum is explicitly fixed using TT time with the understanding that users needing a TCG frame should apply the appropriate rescaling (see IERS Conventions 2003, Chapter 4). When using the TT time scale, the appropriate value for GM in the data analysis is 398600.4415 km^3/s^2; with TCG time, GM is 398600.4418 km^3/s^2.

Three types of relativistic corrections are usually applied in GPS data analyses: (1) The first-order effects on the clock frequencies due to time dilation and gravitational potential shifts have already been accounted for by offsets in the oscillator settings aboard the spacecraft (assuming nominal orbital elements). The second-order effects due to non-circular GPS orbits must be handled by the user by applying a correction of magnitude $2(R * V)/c^2$, where R is the satellite position, V its velocity, and c is the speed of light. (2) A "dynamical" correction to the acceleration of near-earth satellites is given in Eq. 1 of IERS Conventions 2003, Chapter 10. This version differs from earlier editions by the addition of terms for the Lense-Thirring precession (frame dragging) and geodesic (de Sitter) precession, which are probably negligible for the short arcs used in most GPS analyses. The main dynamical correction term should be applied, however. The IERS formulation neglects the earth's oblateness, an effect estimated by J. Kouba (submitted to *GPS Solutions*) to be about the same level as the IGS clock accuracy with periodic variations at 6 hours and near 14 days. (3) The coordinate time of propagation, including the gravitational delay, is given by Eq. (17) in IERS Conventions 2003, Chapter 11.

Improvements in ITRF

Current situation

Over a decade, the stability of the ITRF2000 geocentric origin (defined by SLR) is estimated to be at the few-mm level and its absolute scale (defined by SLR and VLBI) is around 0.5 ppb (equivalent to a shift of approximately 3 mm in station heights); see above. Improvements of scale and geocenter estimates are expected from ongoing technique and modeling enhancements. While SLR currently provides the most accurate realization of the earth's long-term CoM for the ITRF origin, measurement of geocenter motion still needs more refinement by the analysis centers of all satellite techniques. Some technique-specific effects seem to have impacts on CoM estimates, judging from the relatively poor agreement in results between SLR, GPS, and DORIS. Possibly, the inclusion of LEO satellites in IGS analyses will improve GPS CoM results.

From the ITRF2000 results (Altamimi et al. 2002), it was found that the best scale agreement was between VLBI and SLR solutions. Meanwhile, some recent GPS time series analyses show improved agreement with SLR and VLBI. The scale is generally affected by station vertical motions, which are closely linked to troposphere estimation strategy, antenna-related effects for VLBI, GPS and DORIS, and station-dependent range biases for SLR. Relatively frequent GPS equipment changes can adversely impact station height estimates and thus the frame scale.

The ITRF2000 orientation time evolution is believed to satisfy the no-net-rotation (NNR) condition at about the 2 mm/year level. This is also the current level of NNR stability of the few existing NNR plate motion models, as discussed by Altamimi et al. (2003).

The number and distribution of inter-technique colocation sites and the quality of the local ties is a major limitation of the current ITRF. Even with major improvements within the individual techniques, the potential benefits for the ITRF combination may be constrained by the ties.

Future ITRF improvements

The ITRF combination of global long-term solutions of station positions and linear velocities, as traditionally provided by the various techniques, prevents accounting for possible non-linear station motions at the combination level. One aspect that will certainly contribute to the improvement of ITRF and its datum definition will be the use of time series of station positions and EOPs for future ITRF solutions.

One of the most challenging tasks is still to be able to discriminate between real geophysical signals and technique-specific, analysis, or tie errors. The impact of GPS equipment changes on time series of station positions is one specific example. Meanwhile, the IERS has initiated a new surveying effort to try to improve the quality of ties at existing colocation sites.

In terms of datum definition, it is expected that the ITRF origin definition will still rely on SLR and the scale will probably be determined by weighted contributions from VLBI, SLR, and possibly some consistent GPS solutions. Concerning the orientation time evolution, it is of course essential to preserve the NNR condition for future ITRF releases. Newly available NNR geophysical models should be tested and evaluated, particularly those using space geodesy data, to replace the deficient NNR-NUVEL-1A model used in the past. Moreover, the selection of reference sites to be used in the application of the NNR condition should be reviewed to integrate, as appropriate, IGS reference stations in order to minimize any possible rotational effect on the IGS frame. We expect better implementation of the NNR condition because of more stations and longer observational time spans available since the ITRF2000 release, as well as better sampling of tectonic plates.

Time series of TRF and EOP simultaneous combinations

Similar to the IGS, several technique analysis centers have begun to make available time series of daily or weekly solutions of station positions and daily EOPs provided in the SINEX format. Unlike the previous ITRF solutions, it is expected that the next ITRF solution would be based on such time series of station positions and EOPs. Weekly (GPS, SLR, DORIS) and daily (VLBI) solutions will allow better monitoring of non-linear station motions and other kinds of discontinuities in the time series. The EOP parameters resulting from this combination should be used to recalibrate the current IERS operational C04 series so that ITRF and EOP consistency will be finally ensured, minimizing, by the way, IGS and IERS polar motion discrepancies.

The recent multi-technique combination analysis by Altamimi et al. (2004) shows that IGS polar motion estimates appear to dominate other technique results. This is mainly because the IGS solution is a robust combination of seven or eight Analysis Centers and is based on continuous observations from more than 200 homogenously distributed sites.

Improvements in IGS reference frame realizations

During its first decade of service, the IGS and its collaborating groups have made huge strides in advancing a modern, space geodesy-based reference frame that is both highly precise and readily accessible. However, the progress in the most recent years has stalled to some extent and has not kept pace with general improvements in GPS data analysis. This threatens to limit the potential usefulness of IGS products in fully addressing the most demanding geophysical, scientific, and societal applications in future. Fortunately, certain improvements are clear and can be implemented in straightforward, if not always easy, ways. Some basic steps are suggested here.

Designate official reference frame stations

The current ad hoc process used by the ACs to pick reference frame stations from the available network is inadequate. The most serious shortcoming now is the lack of commitment by the chosen stations to meet the necessary operational standards. Many station operators may not even be aware of the needs or the fact that their station has been chosen for this purpose. A fully informed and committed collaborative approach is required, building upon the mutual consent of data analysts and station operators. This means the IGS should adopt accepted standards for the installation and operation of reference frame stations specifically. The standards should not be merely those of the data analysts. In recent years, there has been a growing erosion of the awareness of reference frame requirements as many of the pioneers in space geodesy retire. One important objective is to re-instill the level of care and concern evident in the early IGS. A set of proposed specifications has been published by Ray (2004).

The reference frame specifications and guidelines should then be strictly enforced once stations are officially designated with this status. Many of the current reference stations need to improve their performance or stability. Evidence of long-term committed support should be requested for all such stations. And concerted efforts are needed to fill the remaining gaps in global coverage, especially in the Pacific region.

As part of this process, the IGS must officially recognize the vital role of the reference frame stations. The obsolete status of “global station” should be replaced. Other tangible steps should be taken to promote the visibility of reference frame stations. At the same time, other tracking stations will continue to be needed for a wide range of specialized applications. They should not be discouraged, although all stations would benefit by adopting the reference station standards where feasible and appropriate.

Develop quality assessment system

Any reference frame strategy will be only as effective as the quality actually attained. Therefore, it is vital that mechanisms be established to continuously monitor and report the performance of reference stations. The monitoring tools must be automated, but most corrective actions will probably require manual interventions. The proper lines of communication must be reliable and effective. Many of the elements of this system are already in place.

A related aspect of monitoring has hardly been addressed, however. It concerns the quality and reliability of IGS products. There is no quality assurance or control system within the IGS to quickly detect and correct errors caused by reference frame stations or any other related problems. It would be straightforward to dedicate a sparse subnet of stations to check IGS product performance by continuous evaluation of PPP solutions. Such quality control stations must meet similar standards as reference stations, but be treated separately in order to maintain data independence. Some progress along these lines should become a high priority for the IGS.

Improve user interfaces

One of the weakest aspects of IGS service generally is in its interface to the broader user community. Many of the procedures, methods, and standards are poorly or incompletely documented. This applies particularly to the reference frame. The current expert system severely limits its greater utility, while creating large risks of mistakes or misunderstandings among non-specialists. This can be viewed in part as a need for better educational outreach. One approach to improve the situation would be to invite collaborations with outside groups or even commercial services to provide value-added user interfaces.

Develop long-range, proactive reference frame strategy

The IGS needs a new, long-range vision of how best to maintain and improve its reference frame. Many of its users need and expect the highest levels of stability over indefinitely long periods. An expanded view is needed from the IGS to really advance the state-of-the-art in major ways, to satisfy such long-term commitments.

Perhaps most important of all, the IGS must assume an active posture towards securing and maintaining an optimal reference frame rather than merely making the most of what is available. The reference frame must be recognized as the foundation of everything the IGS does and therefore deserving of special attention. A major difficulty is the cross-cutting nature of this task, involving all components of the organization. Without a single person or component being responsible and aware of all its aspects, the reference frame presents a unique structural challenge for the IGS.

Summary of recommendations

Develop reinforced IGS reference frame strategy

The IGS should officially designate reference frame stations according to a set of operating standards mutually accepted by all components of the organization. The station operators must be actively involved and committed to this process. The IGS needs to develop a long-range, proactive strategy to reinforce and secure the long-term stability of a sustainable and robust reference frame incorporating appropriate quality assessment systems and much improved user interfaces.

Verification of IGS PPP consistency

The IGS should commission a thorough study of the consistency of its Final orbits and clocks for global precise point positioning relative to the associated weekly sets of station coordinates. In particular, the effects of possible geocenter and scale differences should be well studied and remedies for any defects found should be developed. Ideally, an ongoing quality-checking process should be implemented to continuously monitor the consistency and precision of IGS products.

IGS precise point positioning (PPP) service

The IGS should institute procedures to maintain the documentation of all necessary analysis methods, conventions, and constants so that non-specialized users can use IGS products with maximum accuracy and minimum effort. Ideally, a freely available, open software package and other automated electronic tools should be provided as a service for precise point positioning by general and expert users. The IGS should consider inviting agencies to provide such services operationally, where the quality and integrity would be continuously monitored by the IGS.

Absolute antenna patterns and the IGS scale

When the IGS implements absolute antenna phase patterns for the satellites and tracking network, the effect on the average scale and consistency of the combined products should be carefully evaluted to verify that it closely matches ITRF2000/IGS00.

Handling geocenter motions

The IERS is encouraged to clarify the celestial–terrestrial transformation using the form:

$$ICRF = Q * R * W * [TRF + O(t)]$$

to explicitly account for geocenter motion. The sense of the geocenter offset vector is from the center of the "instantaneous" TRF(t) frame to the ITRF origin such that $[TRF{+}O(t)]$ is aligned to ITRF. This should be the understanding of the geocenter parameters in the SINEX format. Realization of geocenter offsets using a Helmert transformation approach, as already implemented by the IGS, is also recommended.

Conventional contributions to station displacements

Following traditional practice in treating earth orientation variations, the IERS Conventions should be interpreted such that the summation of various model effects for a priori, non-linear station displacements includes only those which (1) have known closed-form expressions with high a priori accuracy; and (2) have periods of variation near 1 day or shorter (with some exceptions). Currently, these criteria include diurnal and semidiurnal tidal displacements for the solid earth, ocean loading, and atmospheric loading, as well as the longer period earth and ocean tides and the mostly longer period pole tide. The ocean tidal loading should account for the whole-body translation of the solid earth that counterbalances the motion of the ocean mass, in contradiction to Chapter 7 of the IERS Conventions 2003. The "permanent" component of the solid earth deformation is also included in the tidal model in keeping with longstanding geodetic practice. Currently, the IERS does not provide models for the diurnal/semidiurnal displacements that occur due to atmospheric loading or geocenter motion.

Tropospheric path delay products

The IGS Troposphere Working Group should consider measures to ensure the highest possible accuracy, precision, and consistency of its zenith path delay products with the IGS00 reference frame. In particular, the station coordinates used for tropospheric products should match those of the IGS weekly terrestrial reference and methods to account for the current differences in scale should be developed and applied.

Handling subdaily variations

Analysis Centers should ensure that they are using the newest IERS models for subdaily EOP and solid earth tidal variations. The Analysis Coordinator is asked to work with the IERS to develop suitable models for the effects of high-frequency nutation in polar motion, subdaily geocenter variations, and subdaily atmospheric loading. Centers should prepare to implement these models as soon as they become available.

Handling pole tide deformations

Analysis Centers should ensure that they remove the mean pole position from the instantaneous polar motion before computing the pole tide effect. The linear trend provided in IERS Conventions 2003, Chapter 7, Eq. 23a and b is recommended for this purpose.

Nutation models

Analysis Centers should not rely on the IAU1980 nutation model alone. To do so will cause longer period polar motion errors. If the IAU1980 model is used, corrections from the published IERS nutation offsets should also be applied. Alternatively, a more accurate nutation model (with or without observed offsets) can be considered.

Neglected ionospheric corrections

The IGS and Analysis Centers should consider methods to attenuate the present level of error caused by the neglect of higher order ionospheric delay corrections.

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Appendix: IGS00 stability tests

Tests have been carried out in an attempt to assess the long-term stability of IGS reference frame realizations as the number of fiducial stations is varied. We start with the IGb00 frame consisting of about 99 stations (more, including some decommissioned stations). Four independent subnetworks of about 25 stations each were selected, trying to keep each equally well distributed globally. The IGS weekly SINEX files were then combined into individual long-term solutions over the period from week 999 (February 28, 1999) through 1,240 (October 18, 2003) while minimally attaching in turn each 25-station frame as a datum. Then, the Helmert parameter differences for all six possible pairs of independent realizations of IGb00 were examined. The average rate differences are shown in Table 7. The same procedure was repeated using three pairs of 50-station realizations, also shown in Table 7. Surprisingly, we found that the improvement in stability in going from 25 to 50 reference stations was very close to a factor of two. Obviously, the results could be limited by the small number of independent realizations available. Nevertheless, using the results available, we have extrapolated the apparent 1/N behavior to infer an estimated instability for the full IGb00 network, shown in the rightmost column of Table 7.

Table 7
Estimated instability in IGS global networks versus number of reference stations

Attribute	Estimated instability error		Inferred error
	25 RF Stations	50 RF Stations	100 RF Stations
Translations (3D)	0.515 mm/year	0.224 mm/year	0.112 mm/year
Scale	0.042 ppb/year	0.022 ppb/year	0.011 ppb/year
	0.266 mm/year	0.138 mm/year	0.069 mm/year
Rotations (3D)	0.02014 mas/year	0.01014 mas/year	0.00507 mas/year
	0.624 mm/year	0.314 mm/year	0.157 mm/year

Note: Estimated empirical instability errors are the average values for differences among test global networks with independent station selections from the IGb00 set of 99 reference frame stations. Four different 25-station networks were used for six different pairwise comparisons. The 50-station comparisons used three independent pairwise comparisons of various combinations of the 25-station networks. The inferred instability error for a 100-station network is based on a 1/*N* extrapolation of the error estimates for the smaller networks

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