# Topic 3: IGS Reference Frame Realisation and Contributions to ITRF

# IGS REFERENCE FRAME REALIZATION

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## ABSTRACT

The current set of 13 ITRF94 stations and the IGS approach to ITRF realization are no longer adequate for high precision frame reference definition. A new set of 52 Reference Frame (RF) Stations has been identified and is proposed to be used for a new IGS realization of ITRF. The new approach of ITRF realization is based on a nearly rigorous accumulated combination of weekly GNAAC SINEX solutions for station positions and EOPS of the current week. The orbit/clock solutions can then be obtained by an approximation of back substitution. This way the consistency of all IGS products, including the future IGS SINEX products, is enforced. It is proposed that this new, nearly optimal IGS realization of ITRF should be implemented preferably by June 28, 1998, but not later than January 3, 1999. The ITRF96 station coordinates and velocities for the set of 52 RF stations were evaluated and compared to an accumulated combination of GNAAC SINEX solutions, resulting in an rms agreement of a few mm horizontally and less than 10 mm vertically. For an interim and immediate improvement of the IGS realization of ITRF, it is suggested that a large subset of 47 ITRF96 station positions and velocities be selected and used, starting as early as March 1, 1998. This new set of ITRF96 stations is to replace the current 13 ITRF94 station set.

## INTRODUCTION

The prime objective of IGS is to provide a global IGS reference system, including realization, maintenance, and easy accessibility for all IGS users and GPS applications.

"A global IGS reference system" here is used in a broad sense. It encompasses not only a traditional reference system (with its imbedded reference frames, e.g. ITRF, ICRF, etc.), but also the standards and calibrations for ionosphere, troposphere and other, yet unforeseen, GPS-related information. Such a reference system, in addition to traditional theory, constants, conventions, documentation and monitoring, can be realized and represented in discrete and/or model forms. As with any global reference system, the IGS reference system must strive for global coverage and the utmost accuracy and consistency, both internally and with respect to the internationally adopted standards (e.g. IERS, BIPM, etc.). This is precisely what the IGS Terms of Reference imply. Even the components which contribute to the IGS reference system are listed, giving the specific IGS products for its realization, namely, orbits, EOP, station coordinates, clocks, along with (global) tropospheric and ionospheric information. The first four components (orbits/EOP/station coordinates/clocks) are fundamental in nature, although only the first three are generally considered to be absolutely essential, thus requiring the utmost precision to support IGS users. However, the recent precise point positioning approach (Zumberge et al., 1997) and the precise time transfer initiative (Ray, 1998) make the IGS clock product component equally important and fundamental in nature. Thus, the IGS quadruplet orbits/EOP/station coordinates/clocks must all be consistent and highly accurate. They should include GPS (and possibly GLONASS) satellites only and about 200 (polyhedron) stations, Not all possible (e.g. LEO) satellites and not all possible stations computed by ACS /AACs or observed by IGS users should or need to be included in the above IGS (reference system) product components. The tropospheric/ionospheric delay products should also be global (i.e. with global resolution), highly accurate and consistent within the IGS reference system. For more discussions on clock/orbit consistency and possible product additions and/or enhancements, see the other position papers and presentations at this workshop (e.g. Springer et al., 1998; Ray, 1998; Gendt, 1998; Schaer and Feltens, 1998).

The stability of the underlying reference frame (lT'RF), realized by the global GPS network, is crucial and an integral part of, perhaps the basis of the whole IGS reference system as described above. However, the current IGS realization of ITRF has been gradually degrading due to the decrease in quality and availability of some of the 13 ITRF stations that are used for the current IGS realization of ITRF94. More specifically, the ITRF94 realization is obtained by constraining the 13 ITRF station coordinates and velocities (Kouba and Mireault, 1997, p. 56). More and better ITRF station position/velocities and new approaches are required to solve this urgent problem. The future IGS reference frame realization should not only be precise, robust, consistent, and stable but it should also take advantage of the GNAAC station combinations (G-SINEXes). Furthermore, the IGS reference frame realization should ensure a high product consistency, in particular for the core products, viz., the IGS orbit, EOP, station coordinate (G-SINEX and P-SINEX) and clock combinations. The new ITRF96, which was recent] y released, can contribute significantly to the IGS reference frame realization, thus it is also discussed here.

## CONSISTENCY OF IGS REFERENCE SYSTEM AND IGS PRODUCTS

Some constants and models defining a reference frame may not be accurately known, however the reference system should always be consistent, i.e. all the derived constants and reference system components must be consistent with these, albeit not accurately known, constants. Then transformation and relations to a new and improved reference system can be realized with greater precision and ease. The same is true for the underlying reference frames (i.e. positioned, oriented and scaled coordinate systems). A good example of the importance of reference system/frame consistency is the case of the core IGS products. The IGS orbit and IGS station solutions imply two realizations of IGS reference frame; i.e. they imply two sets of reference frame positions, orientations and scales that are not necessarily identical. Furthermore, the IGS EOPS imply an orientation for the reference frame. Clearly the implied reference frames should all be the same so that IGS users, when using any combination of the core products, will not detect any conflicts and (statistically speaking) will obtain the same results. For example, users of the new precise point positioning approach (Zumberge et al., 1997) realize the ITRF implied by the IGS orbits and clocks rather than a mixture of the two reference frames implied by stations and orbits, which is the case for more traditional GPS positioning approaches. This example also demonstrates the importance not only of the IGS orbits, EOPS, and stations but also clock solutions must be consistent with the other IGS products. It should be mentioned that the consistency of orbits and EOPS has been attempted from the very beginning, as evident from the fact that the initial IGS orbit combination enforced orbit/EOP consistency by rotating submitted orbits to adopted IERS (Bull. A and B) EOPS prior to the IGS combinations (Beutler et al., 1995). This was later abandoned in favor of separate orbit and EOP combinations as the AC orbits and EOPS were (and still are) considered to be sufficiently consistent (Kouba and Mireault, 1997). The need for EOP/station consistency, i.e. the need to include EOP in the SINEX station solutions, has also been recognized at an early stage (Blewitt et al., 1994). However, so far, less than half of ACS include EOPS in their SINEX submissions and the SINEX submissions for most ACS are not consistent with the orbits/EOPs submitted to IGS and the AC EOPS submitted to IERS! This is clearly unacceptable and a serious deficiency, which should be corrected as soon as possible!

The need for clock/orbits/EOP/station solution consistency is nowadays quite accepted, as it became evident thanks to the modem precise point positioning mentioned above. This will be even more accentuated with the time transfer project. However, that the tropospheric and ionospheric IGS products must also be consistent with the IGS core products is not as widely appreciated, but the same condition applies to these two atmospheric products. Specifically, tropospheric delays require the corresponding station solutions and (radial station error) corrections prior to the IGS tropospheric delay combinations (Gend, 1996). Clearly, IGS tropospheric delays should be harmonized (refer to) the IGS station coordinates (combined), or the adopted station solutions. Similarly for the ionospheric delay combination, the crucial component here is the (LI -L2) calibration delay for both satellite and station hardware. This is important not only for single frequency (L1 ) users who use the ionospheric delay information for improved position determinations (largely free of the ionospheric effects) (Huot et al., 1998), but it also has significant implications for precise time transfers. All the IGS clock products (be it the current satellite clock or the future station clock products) have the L1/L2 delays imprinted in them; consequently the L1/L2 calibrations are required and need to be applied when compared to external (time transfer) measurements at the ns and sub-ns level. Clearly, the L1/L2 station/satellite biases and L1/L2 satellite and station clock corrections, be they implied or externally corrected for independent clock comparisons/time transfer such as in the proposed pilot project (Ray, 1998), must be precise and consistent (preferably the same, in this case). So we also have a strong "connection" of ionospheric and clock products and in turn a strong connection between clocks and the orbit/station position products (the station positions are required for receiver clocks, too).

## REVIEW OF CURRENT STATUS OF IGS REFERENCE FRAME REALIZATION

Since the official start of IGS, the IGS reference frame realization has been accomplished by simply fixing, constraining or aligning IGS/AC solutions to the adopted ITRF coordinates of the same 13 stations: ALGO, FAIR, GOLD, HART, KOKB, KOSG, MADR, SAINT, TIDB, TROM, WETI', YAR1, YELL (see Figure 1). All the 13 stations have, or have had multi-technique (in most cases VLBI) collocations. Since January 1994, three official versions of ITRF have been used (ITRF92, ITRF93 and ITRF94). Changes of ITRF versions introduced apparent station coordinate discontinuities that can reach up to 3 cm, in particular the changes to and from ITRF93, which was differently aligned by up to 1 mas with respect to the other ITRFs (Boucher et al., 1994). For more details and the specific estimates of transformation parameters between different ITRF versions used by IGS, please consult the Analysis Coordinator Report in the 1996 IGS Annual Report (Kouba & Mireault, 1997). Consult also the IGSMail#1391 (http: //igscb.jpl.nasa.gov//igscb/mail/mess.1 391) which gives the information about a simple program facilitating the transformation of the current IGS sp3 orbit files to and from one of the above ITRF versions. In order to aid its users and prevent possible misuse and confusions connected with the past and future ITRF changes, IGS should consider transforming all past products based on previous ITRF realizations into the currently adopted ITRF. Even better, IGS should consider implementing, at the DC level, a simple user interface, e.g. based on the transformation program mentioned above, which would allow users to get all the IGS core products in an ITRFyy of their choice. However, it should be noted here that all such ITRF transformations of IGS products are only approximate due to limitations of the past and current ITRF realizations as discussed below.

Due to systematic errors in ITRF and GPS solutions, as well as the limited number, distribution and precision of the 13 (ITRF94) stations, the **station** position errors are mapped into the constrained IGS/AC solutions (and the implied reference frame), The distortions and reference frame variations vary amongst ACS and also in time, with possible small, periodical systematic and random effects. Even when a more optimal approach, such as applying minimum datum constraints to unconstrained ("fiducial free") AC solutions (see e.g. Heflin et al. 1997; Jefferson et al., 1997), the ITRF and GPS systematic errors as well as changes in station geometry and of processing approaches cause systematic reference frame variations (errors). For example, the current deficiency of the (13) ITRF station distribution is responsible for an increased noise and a decrease of the stability of IGS and AC solutions for PM y especially (Springer, 1998 personal comm.). More recently, the problems have been magnified since at least two or three ITRF stations have become unusable (e.g. TROM, MADR), leaving at times only 9 or even 8 ITRF stations available and usable as fiducials. Such a low number of stations can compromise all the IGS/AC products as reference frame errors can easily exceed the formal errors. The situation is particularly acute for the IGS Rapid products where timely availability of data is critical.

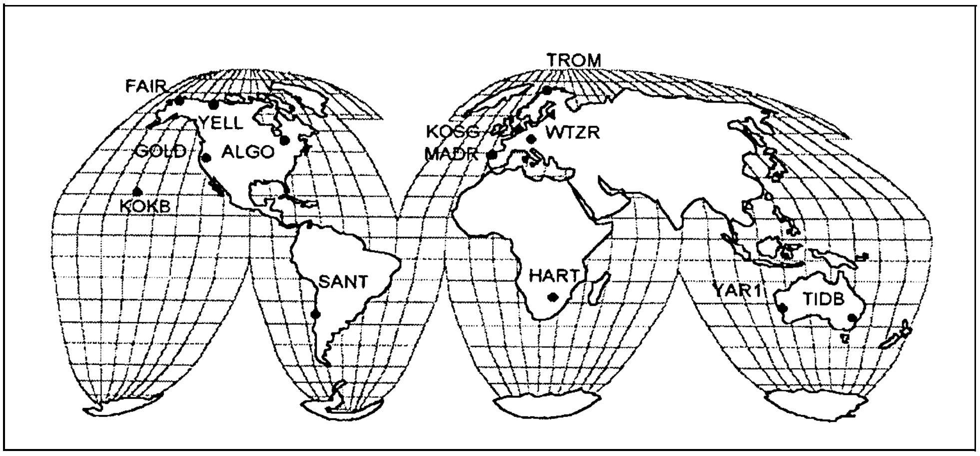

**Fig. 1. The** set of the 13 ITRF stations used by IGS for the current ITRF94 realization

Clearly, a much larger number of ITRF stations and more consistent set of ITRF station coordinates than the currently adopted ITR94 coordinate/velocity set are urgently needed, That is why a search for a new much larger set of ITRF station was initiated during the AC Workshop held in March 1997 at JPL. An initial set of about 50, well distributed global stations, was identified as potential candidates at the workshop and the discussions continued by e-mail until August 1997 when a more definitive set of 52 stations was identified and agreed upon by all ACS (Figure 2). All the 52 stations survived a rigorous test and criteria of GPS data and solution quality, consistency and timeliness. Unlike for the 13 ITRF station selection, good multi-technique and ITRF coordinates, though important, are not as essential as long as there is a sufficient number of multi-technique stations remaining in the station set. This is so because there is already a sufficient number of GPS-only stations with a very high level of internal consistency which can effectively and reliably interpolate/realize ITRF even when some of the few crucial ITRF stations are missing, thus mitigating the current reference frame problems discussed above. Accordingly, this new set is termed reference frame (RF) station set, rather than an ITRF station set - the term used for the current 13 (ITRF/multi-technique) station set. For more details on the RF station list, the selection criteria as well as the individual station "performance", please refer to Appendix I.

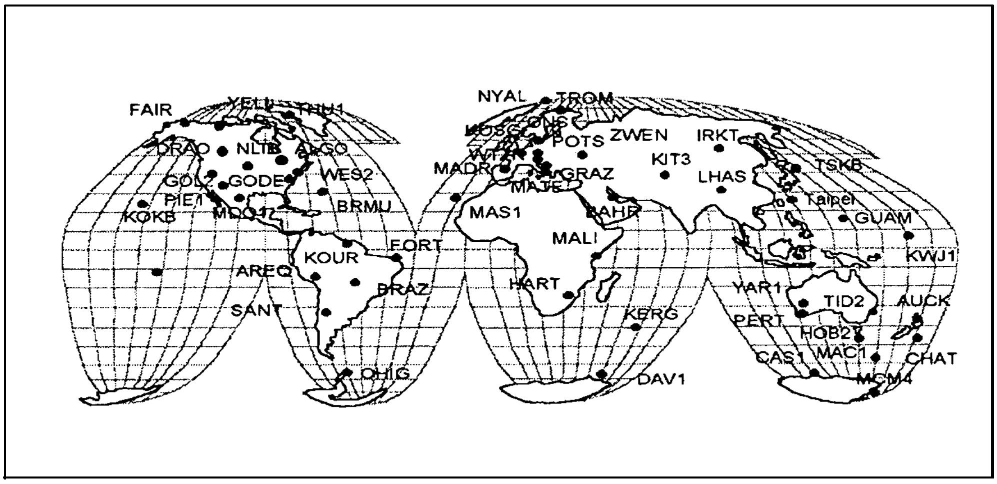

**Fig.** 2. The **Proposed set of 52 Reference Frame (RF) stations for future ITRF realization** of IGS

Currently IGS does not produce any official (combined) IGS station coordinate product, though it is well positioned to do so thanks to the significant effort invested into the ITRF Densification Pilot Project (e.g. Kouba, 1997) which is nearing maturity. Based on the earlier discussions here, it is essential that there is also an official IGS station position/velocity product (after all it is one of the four "core" products!) which is consistent with the current IGS products (orbits/EOP/clocks). Actually the SINEX approach developed and perfected in the ITRF Densification project may significantly enhance IGS ITRF realization/maintenance, and even provide the IGS contribution to ITRF (see the following sections for more detailed discussions on this subject).

## INTERIM (IMMEDIATE) IMPROVEMENTS OF IGS REFERENCE FRAME (ITRF) REALIZATION

During the selection and discussions of RF stations it was contemplated that an a GPS-only solution, with properly positioned, oriented and scaled reference frame, would be used for the new IGS ITRF reference frame realization. With the release of an improved version of ITRF (ITRF96) in August 1997 it became clear that the new ITRF version is indeed internally quite consistent with precision comparable to the best IGS station position solutions and can be used in place of the 13 ITRF stations. Note that, unlike the previous ITRF (yearly) realizations of IERS, the ITRF96 datum (i.e. frame positioning, orientation and scale) is supposed to be (at least nominally) the same as that of ITRF94 (Boucher, 1997, personal comm.; Ray, 1997). The final version of ITRF96, released in December 1997, has corrected a small misalignment and the time evolution (with respect to ITRF94) as well as a few outliers contained in the preliminary (August 97) ITRF96 version (Altamimi, 1997, pers. comm.). At the IAG Rio97 Meeting in September 1997 the IERS Directing Board officially accepted ITRF96.

A relatively fast and efficient resolution of the current IGS reference frame “crisis” is to replace the 13 ITRF stations with ITRF96 station coordinate/velocity set for most if not all the selected 52 RF stations. This is only an interim step as it does not address nor incorporate the ITRF Densification project and its potential impact and improvements in IGS ITRF realization. Before using the RF station ITRF96 coordinates and velocities they must first be evaluated and tested for precision and consistency. That indeed the new ITRF96 version is highly consistent with ITRF94 is evident from Table 1, where the ITRF96/ITRF94 alignment and coordinates/velocities for the 13 ITRF stations are compared, As one can see in Table 1, both ITRF94 and ITRF96 are almost identical in translation and orientation with the exception of small misorientations (of about -0.2 mas) in Rx and Rz, which are barely statistically significant (the formal sigmas are about 3 mm, 0.1 mas, 0.4 ppb). Even more encouraging is that the rates are practically zeros (equal or less than the formal sigmas of about 1 mm y-l, 0.03 mas $y^{-1}$, 0.2 ppb y-]). In the second part of Table 1, the alignment of each ITRF94 & 96 is checked with respect to NNR NUVELIA (McCarthy, 1996), using only the respective ITRF station velocities. Also shown are position/velocity rrns after the transformations, Both ITRF solutions are well aligned in velocity, with nearly zero rates. The differences between ITRF96 and ITRF94 rates in the last line of Table 1 compare quite well to the relative transformation rates in the second line, The formal sigmas for these NNR alignments are about the same as above, i.e. 1 mm $y^{-1}$, 0.03 mas y-l and 0.2 ppb $y^{-1}$ . This should be no surprise as ITRF94 and ITRF96 time evolution should, by definition, be consistent with the NNR NUVELIA (Boucher, 1990).

**Table 1: Transformation ITRF94 to ITRF96 (using the 13 ITRF** station positions/velocities)

| Epoch | Tx | Ty | Tz | Rx | Ry | Rz | Scl | rms (mm) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | mm | mm | mm | mas | mas | mas | ppb | dN | dE | dH |
| Param 1997 | 0.1 | 0.5 | 0.8 | -0.190 | -0.005 | -0.230 | -0.5 | 8.2 | 8.4 | 10.5 |
| Rate ./y | -0.5 | -0.2 | -0.6 | 0.018 | 0.033 | -0.002 | -0.01 | 2.4 | 1.3 | 2.9 |

Rates with respect to NNR Nuvel1A, computed from the velocities of 11 of the 13 ITRF stations; SANT & GOLD excluded due to plate margin effects .

| | mm/y | mm/y | mm/y | mas/y | ma s/y | mas/y | ppb/y | rms (mm/y) | | |
|---|---|---|---|---|---|---|---|---|---|---|
| ITRF96 | -0.6 | -1.8 | -0.3 | -0.03 | 0.02 | 0.02 | 0.00 | 1.6 | 2.2 | 2.7 |
| ITRF94 | 0.2 | -1.2 | -0.6 | -0.03 | 0.00 | 0.01 | 0.12 | 1.7 | 1.5 | 2.5 |
| ITRF96-94 | -0.8 | -0.6 | 0.3 | 0.00 | 0.02 | 0.01 | -0.12 | | | |

*The* ITRF96 station coordinates of the newly selected 52 RF station set are evaluated in Table 2 and Fig. 3 where the ITRF96 solution is compared to a combination of more than 100 GNAAC SINEX weekly combinations (GPS Weeks 830-933). The weekly GNAAC (G-SINEX) files are routinely produced by the three GNAACs (i.e. MIT, NCL and JPL) as a part of the ITRF Densification Project (Herring, 1997; Davies and Blewitt, 1997; Heflin et al., 1997). Remi Ferland of NRCan AC (formerly EMR) kindly produced this “IGS SINEX” combined solutions (labeled here as IGS97P05), using his SINEX combination software. As seen from Table 2 and Fig. 3, both ITRF96 and IGS station positions are highly consistent and precise, at least for the 52 RF station set and for the epoch of 1997.0. The station position rms agreement (after a 14-parameter transformation) is at the 2-mm and 7-mm level for horizontal and vertical directions, respectively. Even for a more representative and useful epoch of 1998.0 the rms agreement is still at about 4-mm horizontal and about 10-mm vertical precision levels, which is significantly better than the ITRF94/ITRF96 position agreement (see Table 1). For completeness, position rms values for epoch 1999.0 are also shown in Table 2 and Fig. 3. Individual station position residuals are listed in the Appendix II. It is expected that, except for one or two questionable ITRF96 station velocities, the rms increases for the 1998 and 1999 epochs are largely due to weaker station velocities for the IGS97P05 solution, since they are based on less than two years of GPS data. This can be seen in Fig. 3 but also in Table 3 where the ITRF96 and IGS97P05 station velocity solutions are compared to the NNR NUVEL1 A plate motion model.

Table 2: ITRF96 and combined (IGS97P05) station coordinates residuals for 52 RF stations at 1997.0 (IGS97P05-ITRF96) after 14-parameter transformation.

|  | Dx mm | Dy mm | Dz mm | dN mm | dE mm | dH mm | Epoch | Excluded from means & sig. |
|---|---|---|---|---|---|---|---|---|
| Mean | 0.4 | -0.7 | 0.1 | -0.2 | -0.3 | 0.0 | 1997 | none |
| Sig | 4.9 | 5.2 | 5.5 | 1.6 | 2.3 | 7.2 |  |  |
| Mean | 1.8 | 0.4 | 1.9 | 0.2 | 0.0 | 0.0 | 1998 | AUCK , CHAT dE |
| Sig | 7.0 | 7.8 | 11.3 | 3.7 | 4.2 | 10.8 |  | & MCM4 dH |
| Mean | 3.1 | 1.5 | 3.6 | 0.5 | 0.0 | -0.1 | 1999 | AUCK, CHAT dE |
| Sig | 10.3 | 12.6 | 19.1 | 6.0 | 7.2 | 17.4 |  | & MCM4 dH |

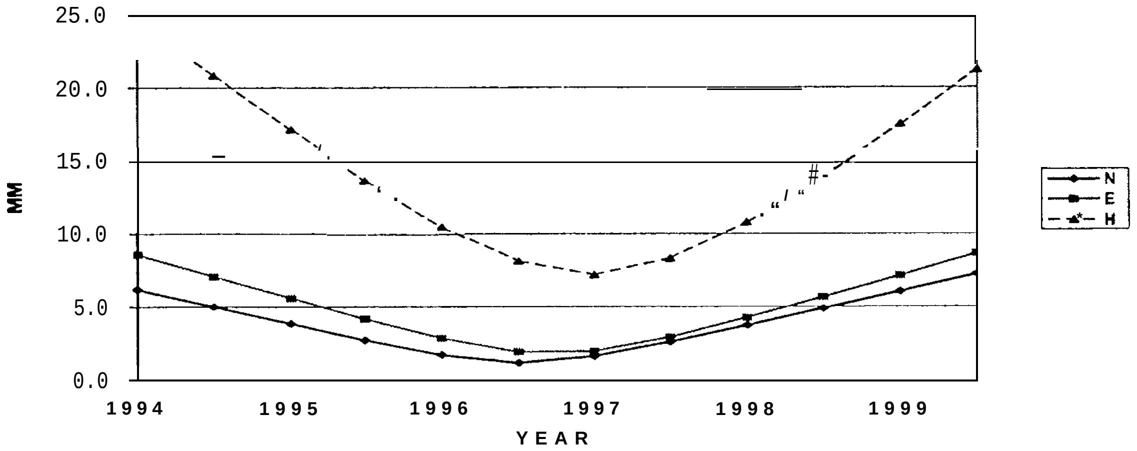

**Fig.3**: ITRF96 and combined (IGS97P05) station coordinates rms for 52 RF stations after a 14-parameter transformation.

While the IGS97P05 horizontal velocities compare equally well to NNR NUVEL1A, the vertical velocities show considerably worse agreement than ITRF96 (i.e. assuming the zero vertical motion which is implied by NNR NUVEL1 A). However, two ITRF96 station velocities (for AUCK and CHAT) appear to be anomalous (see the Appendix III, where individual station velocity residuals are listed), thus likely cannot be included in the new ITRF station coordinate/velocity set. Also, two Antarctic stations (MCM4 and CAS 1) appear to have erroneous vertical ITRF96 velocities. Thus the stations AUCK, CHAT, MCM4 and CAS 1, together with BAHR, which has rather large ITRF96 residuals, were not recommended for inclusion into the new ITRF96 station set. Altogether 47 RF stations has been recommended for the new ITRF96 station set (Altamimi, 1998). IGS97P05, in addition to the same two Antarctic stations above, has additional problems with the vertical velocities at stations GRAZ, TROM, NYAL and LHAS (see Appendix III).

**Table 3: ITRF96 and IGS97P05 differences from NNR NUVELIA (EURA, NOAM, AUST, ANTA, SOAM Plates)** for RF stations (see the Appendix III for specific station exclusions to mitigate plate margin effects on the means and sigmas below).

| STATION | PLATE | IGS97P05 - NNR NUVEL1A | | | ITRF96 - NNR NUVELIA | | |
|---|---|---|---|---|---|---|---|
| | | N(mm/y) | E(mm/y) | H(mm/y) | N(mm/y) | E(mm/y) | H(mm/y) |
| Mean | EURA | 1.75 | -2.18 | 3.81 | 1.37 | 0.36 | 0.52 |
| Sigma | EURA | 3.50 | 2.74 | 9,53 | 1.89 | 2.05 | 1.98 |
| Mean | NOAM | -1.09 | 0.04 | -0.63 | -1.07 | 0.82 | -0.52 |
| Sigma | NOAM | 1.45 | 1.80 | 4.85 | 1.07 | 1.52 | 2.34 |
| Mean | AUST | 2.53 | -3.93 | -3.74 | -0.75 | 4.70 | -1.40 |
| Sigma | AUST | 2.43 | 1.91 | 3.72 | 3.10 | 0.74 | 1.60 |
| Mean | ANTA | -0.98 | -3.17 | 0,75 | -4.36 | 0.05 | 10.27 |
| Sigma | ANTA | 1.97 | 4.49 | 17.40 | 3.77 | 6.21 | 10.84 |
| Mean | SOAM | 1.12 | 1.73 | 3.18 | -0.70 | 2.53 | -2.50 |
| Sigma | SOAM | 0.57 | 2.38 | 4,97 | 1.42 | 3.08 | 6.64 |

It would be very useful if all ACS compare their best station position/velocity solutions to the ITRF96 coordinates/velocities of the 52 RF stations above, in particular for the problematic station solutions in both ITRF96 and/or IGS97P05 solutions. It is hoped that exclusions of stations (e.g. AUCK, CHAT, MCM4, CAS 1, BAHR) from the new ITRF96 station set could be finalized at the workshop so that the new RF set of 47 stations could be adopted by IGS and used instead of the ailing 13 ITRF94 stations. It is proposed that this finalized RF station set, with the ITRF96 coordinates/velocities, together with the official igs.snx (SINEX Header template of antenna heights), is then used, starting as early as March 1, 1998, as an interim IGS realization of ITRF96. Since some small discontinuities of about 0.2 mas are expected, it is essential that, as in the past, all ACS and the IGS products make this ITRF96 change at the same time. Also note that it would be preferable that all ACS use minimum datum constraints (e.g. Blaha, 1971), based on this new ITRF96 set, as recommended in the following sections. It is, however, recognized that, given the rather short time frame and the urgency, the usual (sigma) constraining should be acceptable. Besides, since the new set is highly consistent it is no longer so important (to apply the minimum datum constraints). In fact it may even be advantageous to apply sigma constraints, as the new ITRF set may be less prone to systematic effects (biases) than individual, minimally constrained AC and IGS solutions. This is applicable and important to IGS and AC Rapid solutions. Note that all stations of the new RF set, including some stations with possibly questionable ITRF96 collocations, can be used for the new and nearly optimal IGS ITRF realization proposed in the next section because the new RF set is so internally consistent. Thus the IGS ITRF96 realization will be defined by the adopted ITRF96 positions/velocities of a large subset (47) of the RF stations, together with the current igs.snx template containing the antenna heights and offsets, The igs.snx file is maintained and available at the following IGSCB WWW site:

ftp:/ /igscb.jpl.nasa. gov/igscb/station/general/igs.snx

The adoption of the new ITRF96 station set should result in significant improvements of stability and precision of all IGS core products and EOPS, in particular.

## PROPOSED IGS REFERENCE FRAME REALIZATION AND MAINTENANCE

As already discussed above, it is essential that all IGS reference system components, i.e. all IGS combined products, be consistent and precise. In an ideal case this can be accomplished when all the submitted AC solutions are combined in a single rigorous (SINEX) adjustment of all the IGS products as unknown parameters. However this is not possible both for theoretical as well as practical reasons. Namely, strictly speaking, GPS global analyses cannot be (rigorously) subdivided into overlapping portions of networks (stations). In addition, it is very difficult to parametrize global adjustments and yet allow different and innovative approaches, For example, satellite state vectors are generally incompatible amongst ACS unless identical models and (stochastic) error models are employed, and yet satellite ITRF positions are largely independent of the modeling effects and thus are better suited for exchange, comparisons and combinations. Only approximations to an ideal and rigorous method are possible. There are several possible approaches, each with varying degrees of complexit y and approximation.

It is important to free the IGS products from changes and errors in the fiducial stations set. These changes can occur either from upgrades in ITRF or the RF station set, which involved improvement of the relative site positions, or from errors either due to blunders at the AC's or due to unplanned configuration changes at fiducial sites. All of these have occurred in the last few years with the 13 ITRF stations, Therefore it is suggested to ACS and to GNAACS that always only minimum constraints (not "sigma constraints") are used

**in the final solutions. The ITRF frame is then realized from a Helmert transformation of unconstrained solutions with proper outlier detection in the computation of the transformation parameters. This means a site by site review of station residuals after the transformation, and editing out any outlying site, and re-computing the transformation. This makes it possible to reduce or remove the "warping" like effect of an anomalous site. As seen from the above discussion, it is essential for precise, robust solutions in a consistent reference frame to have a large set of highly consistent RF station set.**

Another relatively simple but well proven approach is an extension to the IGS combination of the "fiducial free" method which has been developed and used at JPL for a number years (see e.g. Jefferson et al., 1997). Here "fiducial free" orbit solutions are requested and then combined, resulting in a "fiducial free" IGS orbits and clocks. Then using a sufficiently large and well-distributed subset of IGS stations with the combined "fiducial free" orbits held fixed in a regular global analysis for "fiducial free" station positions and other pertinent parameters. In order to economize, the new precise point positioning approach can be used here, provided that the IGS clock information is precise, consistent and frequent enough. Finally, a reference frame is attached, i.e. the "fiducial free" combined orbits are transformed according to the transformation between the "fiducial free" station positions and the adopted set of ITRF stations. The advantage of this approach is the relative insensitivity to problems or changes of ITRF (i.e. "fiducial") stations of the individual AC orbit solutions; i.e. the corresponding AC "fiducial free" station solutions need not to be used. However, the disadvantages are that the method does not use the valuable information contained in AC station/EOP SINEX solutions. The current orbit (and future station) reference frame consistency feedback to ACS, contained in the current IGS summary Tables 1, 2 and 4, would not be possible. Furthermore, the method relies on single software to provide the station/orbit datum connection, which could potentially result in a decrease of reliability and precision; and there is additional processing workload at the raw data level (even when the efficient point position method is used).

The approach highlighted here is based on a nearly rigorous (SINEX) combination of station positions/velocities/EOP (Blewitt et al., 1997). It is a method endorsed by the recent IERS/ITRF workshop held in October 1996 in Paris, Fr. (Reigber and Feissel, 1997). It was developed during the ITRF densification pilot project, thus it is fully compatible with the project. It also closely approximates a simultaneous adjustment of all the core IGS products, i.e. orbits/EOP/clocks and stations, while it maintains the core product consistency, as long as the submitted AC products themselves are consistent. The scheme is outlined below:

*a.* First, assume that all the submitted AC core solutions -- i.e. orbits/clocks/EOP (in SP3 and ERP files) and A-SINEX files also containing EOP -- are consistent, either unconstrained, or minimum datum constrained. For a detail description of the method of the minimum datum constraints see (e.g. Blaha, 1971; Vaníček and Krakiwsky, 1982, p.275). Note that this condition is not currently satisfied.

***b.*** All the A-SINEX files (with station/EOP) are combined weekly by GNAACS and the resulting combinations (G-SINEXes) are then timely submitted (with EOP!) for a weekly IGS cumulative, unconstrained solution for station position/velocities and EOP (for the current week EOP only). This combination is called "accumulated kinematic solution" in Blewitt et al. (1997). Note that the A-SINEXes could alternatively be used here, but this may not be optimal, as it would not take advantage of the GNAAC combinations, thus potentially it could be less robust and precise. This combination of G-SINEXes is, in fact, equivalent to a simultaneous station/velocity adjustment of all A-SINEXes, or all the GPS data accumulated from the start to the current week.

c. An ITRF reference frame is then attached to the unconstrained IGS combined SINEX solution of station/velocity and EOP (of the current week only). The reference frame attachment can be e.g. accomplished by minimum datum constraints, based on the soon to be finalized list of 47 RF stations with good ITRF96 positions/velocities. (See the previous section for detail discussions on the ITRF96 station set). Altogether 14 minimum datum constraints are required (7 Helmert parameters and the corresponding rates). The values and sigmas used (derived at least from the ITRF96 sigmas (or matrix) and the IGS matrix) should be entered in the SINEX apriori block, so that the original unconstrained SINEX file can be recovered. The above constrained file can be designated e.g. as IGS(SSC/SSV/EOP)yyPww (yy-year; ww-the week of the year), and considered the official (Final) IGS station/position and EOP product, and it would, in fact, represent the current and official IGS realization of ITRF as well. Note that Blewitt et al. (1997) also propose independent weekly combinations which, once lTRF is attached in a way which is consistent to the accumulated solution above, represent another type of IGS realization of ITRF. This discrete (weekly) realization should have a distinct IERS designation, e.g. IGSyyPwwww, here wwww could stand for the GPS week.

***d.*** Using the weekly A-SINEXes (the short (SSC) AC SINEX files would be preferred here) a 7-parameter transformation between the IGSyyPww above and each of the AC solutions is computed. The AC transformation parameters are then used to transform the submitted AC orbits and EOP (one transformation per each week and AC) to be consistent with the IGSyyPww. Furthermore, the AC orbits for each day are rotated according the AC PM differences between AC and IGS EOP (of step c, i.e. the IGS(EOP)yyPww), very much as it used to be done during the initial years for the IGS Rapid using IERS Bull A and the IGS Final using IERS Bull B orbit combinations (Beutler et al., 1995), Note that here, in place of or in addition to the daily PM rotations, full 7-parameter transformations can also be applied to AC orbit, while maintaining the history of transformation parameters in Tables 1 and 2 of the IGS (Final) combinations. This forms an important AC feedback on solution datum connections and consistency amongst orbit, EOP and station coordinate solutions. The check of consistency here is that the weekly mean PM x, y differences and the corresponding Ry, Rx rotations are statistically the same.

e. Finally, the transformed AC orbits (i.e. weekly by the 7-parameter transformations and daily by the AC PM y,x differences) are then combined into the consistent IGS orbits. Subsequently the AC clocks are corrected for the AC-IGS orbit radial differences as it is already being done for the current IGS orbit/clocks combinations.

In this way, a new and unique official IGSyyPww SINEX product would be introduced which would also contribute to much higher consistency of the other IGS core products as well as more precise and stable IGS ITRF realization (through the IGS core products) than it is the case today. ACS would be well advised to use the IGSyyPww station position/velocities of RF stations for their ITRF needs, in particular for the AC and IGS Rapid solutions. In fact the above concept of ITRF realization is, due to its complexity and inherent delays, only practical for the IGS Final products. Timely (i.e. the weekly) IGSyyPww station/EOP solutions would greatly benefit all IGS users and the AC Rapid analyses and the IGS Rapid products generation in particular, including the IGS timely contributions to ITRF. When attaching a reference frame to the IGS Final SINEX "cumulative kinematic" solution it is important that the accumulation include weekly solution for geocenter and scale and this information is also entered into the in IGSyyPww SINEX file. This way a precise geocenter and monitoring is maintained as well as unique and exact (i.e. stable with no drift) reference frame attachment is enforced.

**It should be noted here that the above "accumulated kinematic solution" (IGSyyPww) is optimal in terms of station positions/velocities only, as it uses all past and present GPS data in a rigorous way (Helmert blocking). While, the above proposed orbit solutions with minimum or no constraints (i.e. "fiducial free") are,** strictly speaking, sub-optimal as only GPS data from the current day or week is utilized in AC orbit solutions. The IGS (Final) orbit solution would be optimal only if the IGSyyPww position/velocity matrix (of the previous week) is used for constraining in the AC solutions (of the current week) in this way all data, including the past data are used in a rigorous way.

Although the AC solutions, constrained according to sigmas as it is currently done by most ACS, or according to the IGSyyPww matrix, can in principle, be used here, it is recommended that AC apply minimum or no datum constraints in all AC Final solutions. Currently, the sigma/matrix constraining can potentially introduce small reference frame inconsistency even when a highly consistent and precise station coordinate set such as the future IGSyyPww set is used. This situation, as discussed above, should change fairly quickly with proper and efficient feedback on AC orbit/EOP and station solution consistency and frame relative biases, That is why the proposed scheme of orbit combination ("back-substitution") and the question of sigma/matrix versus minimum or no constraints in AC Final solutions, should be reviewed after several years of operation of the proposed scheme, or when AC Rapid solutions that use sigma/matrix become more precise and stable than the corresponding AC Final ones.

For the AC/IGS Rapid solutions, the sigma/matrix constraining of RF stations with IGSyyPww positions/velocities, could be quite acceptable or even desirable due to lack of data availability. Besides it is only meaningful to maintain and realize IGS realization of ITRF from more definite and also more precise IGS/AC Final solutions. By using the recent IGSyyPww station positions/velocity maximum consistency between IGS Rapid and Final products is ensured. Note that regardless of which method of constraining ACS

**choose** (unconstrained, minimum) to apply for their Final solutions, their orbit/EOP/clocks (i.e. SP3 and ERP files) must be transformed to be consistent with the corresponding weekly AC SINEX/EOP files.. This should not be a major effort, and in fact should have been enforced from the beginning, and besides, it has already been the case for some ACS for several years now! (See the Appendix VI for more detail information and practical suggestions on AC product consistency).

It is important that a unique (and official) IGS station polyhedron product is established, In that regard it would be preferable if the GNAAC polyhedron combinations (i.e. P-SINEXes) are used instead of G-SINEXes in the step *b* above, however the use of P-SINEXes would introduce delays of up to several weeks which may not be acceptable. Besides it is advantageous that RNAACS, as it is currently required, use the IGS Final orbit/clock/EOP products in their (R-SINEX) analyses. In this regard, it is far more efficient and convenient to obtain an official IGS station polyhedron product (P-SINEX) by a back substitution, using the above IGSyyPww global solution. The IGS P-SINEX products would then have the same IERS designation, i.e. IGSyyPww.

## SUMMARY AND RECOMMENDATIONS

It is essential that all the IGS products are made highly consistent and in particular the IGS core products (i.e. orbits/EOP/clocks and station positions) must be consistent as they are used in various combinations for different applications or realizations of the IGS reference frame. This necessitates that all the AC core products submitted to IGS and IERS must be self-consistent, The urgent need for a larger and more precise ITRF station set than is the case for the currently used 13 ITRF94 stations can quickly and sufficiently be met by adopting ITRF96 positions/velocities of a new ITRF set of about 47 stations. This interim step should be adopted as early as March 1, 1998.

A new and nearly optimal ITRF realization should utilize the GNAAC combinations. It is nearly optimal in terms of station positions/velocities and EOPS; in fact it is the same approach recently recommended by IERS for simultaneous solutions of EOP and positions. In order to increase the IGS product consistency and to prepare ground for adaptation of the new approach of ITRF realizations, the following recommendations are offered for consideration to the workshop:

1. **That IGS adopts ITRF96 as early as March 1, 1998 to replace the currently ailing and problematic IGS realization of ITRF94, which currently is based only on less than 13 ITRF stations.**

2. **As an interim measure and to facilitate an immediate ITRF realization improvement it is recommended that the selection of the new ITRF96 station positions and velocities for a large subset of the RF station is finalized at this workshop. This newly selected ITRF96 set of the 47 globally distributed IGS stations is to be used for ITRF96 realization in all IGS products beginning as early**

**as March 1, 1998. IGS realization of ITRF is then accomplished by the above ITRF96 station coordinates/velocities together with the current official igs.snx, which contains antenna offset and height information in the SINEX format.**

3. **That all weekly submitted AC SINEX solutions (A-SINEXes) contain the EOP of the current week and that the submitted AC orbits/clocks (sp3) and EOP (erp) files are consistent with the above A-SINEX solutions. This is essential not only for the increased IGS product consistency but also for the future (improved) ITRF realization and IGS products. It is recommended that this is implemented and ensured by all ACS by June 28, 1998.**

4. **That the GNAAC combinations retain (and adjust) the submitted AC EOP information of the current week in their G-SINEX combined products, along with the usual station position solutions. It is recommended to be implemented by June 28,1998.**

5. **The SINEX extensions as outlined in the Appendix IV, allowing the minimum datum and transformation parameter constraints to be coded in the SINEX format, are accepted and used by IGS on or before March 1, 1998. Furthermore, that IGS submits the SINEX extension for acceptance to Prof. Tom Herring of CSTG, who is currently responsible for the SINEX format. This will provide a means and encouragement to ACS and other IGS users to use (minimum) datum constraints, as well as it allow an efficient and safe monitoring of geocenter and scale changes (e.g. Ray, 1997). It is further recommended that only the AC Final products, which are based on minimum or no datum constraints, be accepted for the IGS Final orbit/clock/EOP/station combinations after June 28, 1998. (See the** Appendix V for more details and suggestions on coding the minimum datum constraints in the AC (A-SINEX) submissions).

6. That a (super) combination of **G-SINEXes** for station coordinates and EOP is **researched and initiated on behalf of IGS. This EOP (G-SINEX combination) cumulative solution would replace the current IGS EOP combination and it would lead to an official SINEX station solution product (both for global as well as the polyhedron stations). The polyhedron SINEX solutions could be produced by back substitution when P-SINEXes are made available to produce the IGS P-SINEX products (station positions/velocities only). The implementation goal should also be by June 28, with the official IGS SINEX (G and P) products on or before January 3, 1999!**

Remarks: The current IGS orbit/clock combination would require only minor modifications, i.e. the prior transformations based on one set of (up to 7) transformation parameters for each week and AC, and for each AC a pair of daily PM x,y difference rotations (and/or up to 7 transformation parameters), all with respect to the current IGSyyPww SINEX solution. This step can be viewed as an approximation of a back substitution adjustment process for the (IGS Final) satellite obit solutions. Due to annual

**and** semiannual effects for some stations in most current AC solutions (see the AC poster presentations at this workshop), it is mandatory that, until these effects are removed or mitigated, that the new ITRF realization use only the IGSyyPww solutions that are only derived from an exact multiple of years.

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# APPENDIX I

(August 15, 1997)

ITRF station selection criteria. (For fuller explanations, see the Remarks at the bottom of the table.)

1) Stable and permanent monumentation, possibly with local stability nets (not used, but see Remarks below)
2) ACS *not* including site in SINEX submissions
3) High quality and reliable station hardware
4) Performance including timely data communications; based on igsnet and G-SNX GCOMP Reports: >0 - above, <0 below average; (#)- # of inclusions in GCOMP (=22 max; 0- local or not operating station (Wk 0878-900))
5) Favorable station data quality (RFI, multipath, etc.) based on igsnet includes phase/Code quality: >0- above; <0 below average.
6) Supportive and responsive station staff
7) Good quality ITRF94 position and velocity
8) Multi-techniques collocations (R=VLBI, L=SLR, D=DORIS G= absolute G)
9) Established GPS observing history (> 2 years) (not used)
10) Comments from CODE Analysis Center

[For explanation of notations, see Remarks below]

Europe:

| CODE | 1) | 2) Used | 3) Hrdw. | 4) Perf. | 5) Qual. | 6) Staff | 7) ITRF | 8) Tech. | 9) | 10) AC |
|---|---|---|---|---|---|---|---|---|---|---|
| *KOSG | | | R12 | 1.0(22) | 0.6 | | A | 1 | | Move ! |
| * MADR | | | R8 | -.5(4) | -1.7 | X | A | R | | x |
| MATE | | r,e,j,s | TR | -1.3(11) | -1.7 | | A | RL | | |
| NYAL | | r | R8 | -5.6(7) | -3.1 | | B | R D | | x |
| ONSA | | r,j | TR | 0.7(22) | 0.5 | | A | R | | |
| * TROM | | | R8 | -3.0(13) | -3.0 | | B E-V | r | | Rec. |
| VILL | | c,r,g,j,n,s | TR | 2.5(0) | 0.7 | | NONE | | | x |
| *WTZR | | | TR | 0.1(22) | 0.0 | | A | RL | | |
| GRAZ | | | TR | -1.7(2) | -1.7 | | A | L | | |
| POTS | | | TR | 1.9(16) | 1.9 | | A | L | | |
| ZWEN | | | TR | -4.7(16) | -0.8 | | NONE | | | |

Asia:

| CODE | 1) | 2) Used | 3) Hrdw. | 4) Perf. | 5) Qual. | 6) Staff | 7) ITRF | 8) Tech. | 9) | 10) AC |
|---|---|---|---|---|---|---|---|---|---|---|
| KIT3 | | | TR | -0.3(13) | 0.2 | | CT | D | | |
| SHAO | | r,g | TR | 0.3(15) | 0.2 | | CT | RL | | |
| TSKB | | | TR | 2.3(19) | 0.6 | | B | r | | |
| IRKT | | | TR | -2.0(9) | 0.5 | | NONE | | | |
| LHAS | | | TR | -1.3(16) | -0.5 | | NONE | | | |

Africa/Arabia :

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| BAHR | r,e,n,s | Z12 | 0.9(5) | -0.2 | | NONE | | New |
| * HART | | TR | -0.7(18) | 0.0 | | B | RLD | |
| MALI | | RC | -4.3(8) | -3.7 | | NONE | | Rec. |
| MAS1 | r,n,j,s | TR | N/A (to be completed ASAP) | | | | | |

N. America

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| *ALGO | | TR | 2.7(22) | 0.6 | | B | R | |
| BRMU | r,j | TR | 2.7(22) | 0.6 | | CT | r | |
| DRAO | e,j | TR | 2.6(15) | 0.7 | | Z | r | |
| *FAIR | | R8 | 2.6(20) | 0.6 | | B | R D | X |
| * GOLD | | R8 | -1.6(19) | -1.6 | X | CT | RLD | X |
| MDO1 | r,j,s | TR | 2.3(20) | 0.6 | | A | RL | |
| NLIB | r,e,j,s | TR | 2.1(6) | 0.7 | | B | R | |
| PIE1 | r,e,g,n,s | TR | 2.6(0) | 0.7 | | B | R | |
| THU1 | r,e,n | R12 | -0.6(0) | 0.7 | | NONE | | |
| *YELL | | TR | 2.0(22) | 0.1 | | B | R D | |
| GODE | | TR | 2.4(0) | 0.6 | | A | rL | |
| WES2 | | TR | 1.3(20) | 0.3 | | dU=4cm | Rl | |

S. America

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| AREQ | | TR | -1.0(17) | 0.4 | | B | L D | |
| FORT | | TR | -0.5(18) | -0.5 | | B | R | |
| * SANT | | TR | 1.1(17) | -0.3 | | B | R D | |
| BRAZ | | TR | -1.3(12) | -0.3 | | NONE | | |
| KOUR | | RC | 0.1(14) | -1.9 | | B | D | Rec. |

Astralia:

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| HOB2 | r,e | TR | -2.0(18) | -0.2 | | CT | R | |
| *TID2 | | TR | 2.2(21) | 0.7 | X | ? | RLD | X |
| *YAR1 | | R8 | -2.1(21) | -1.9 | | B | LD | Rec. |
| MAC1 | r | TR | -1.4(12) | 0.1 | | NONE | | |
| PERT | | TR | 2.4(22) | 0.6 | | NONE | | |
| CHAT | | TR | 0.4(2) | -0.2 | | NONE | | |
| AUCK | | TR | 1.3(0) | 0.2 | | NONE | | |

Antarctica:

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| CAS1 | r,e | TR | -1.1(20) | 0.0 | | C | | |
| DAV1 | | TR | -1.4(17) | -0.4 | | C | | |
| KERG | | RC | -2.5(19) | -2.3 | | B | D | Rec. |
| MCM4 | | TR | 1.7(19) | 0.4 | | C | | |
| OHIG | r | TR | -2.3(18) | -1.0 | | Z | R | |

Pacific

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| * KOKB | | TR | 2.2(21) | 0.5 | B | R D | |
| KWJ1 | r | TR | 2.4(2) | 0.6 | NONE | r | New |
| GUAM | | TR | 1.0(12) | 0.5 | NONE | D | |

* current fiducial stations

Columns Remarks:

1) Some stations have large antenna heights (> 2m) eg, NYAL, TROM, BAHR HART and MATE is mounted on a roof.

2) This column lists the analysis centers not using the station. The Information was obtained from the AC's weekly analysis report. (Letter code represents first letter of AC's name except for EMR which is "r")

3) Hardware codes are:
   - R8 for big rogue,
   - RC for mini rogue,
   - TR for 8 channel turborogue
   - R12 for 12 channel turborogue
   - Z12 for 12 channel ashtech
   - TE for 8 channel Trimble SSE

4) and 5) The code used are the average of the "igsnet" latency and quality code respectively. The average was computed using 4 randomly selected weeks of 1997.

6) X = poor response, likely should not be recommended

7) A = Class A: collocated sites with quality <2 cm at 1988 and 1993
B = Class B: collocated sites with quality <3 cm at 1993
C = Class C: not Class A or B, with no large residuals
Z = Class Z: sites with large residual (blunder or poor determination); DRAO & OHIG have large height discrepancies
T = local tie to GPS not available
? = TID2 not in ITRF94 (although TIDB is) and no site log available
NONE = not included in ITRF94
E-V = East velocity inconsistency with VLBI
dU=4cm = GPS vs. VLBI height discrepancy of -4 cm at WES2

8) R=VLBI, L=SLR, D=DORIS G=absolute G; lower case letters indicate mobile site, poor data quality, or discontinued operations

10) X-means : Do NOT use as fiducial station.
New Relatively new station
Rec. Receiver change necessary (big or mini rogue)
Move Site will be moved!
KOSG will be moved to Westerbork (tens of kilometers away).

However there will be something like a year “overlap” using both receivers; the old one in KOSG and new one at new site Westerbork.

NOTE BY JF Zumberege’s performance & quality coefficient determination

Col. 4:
Based on 169 daily IGSnet reports spanning the period October 12, 1996 through April 11, 1997, we show in Table 1 a summary of statistics. Scores from each of the following three categories have been normalized to zero mean and unit sigma: (1) number of times the site occurred with non-trivial entry in the daily IGSnet reports; (2) the quality field from the daily report; and (3) the latency field from the daily report (only nonzero latencies are considered). The sum of the three normalized numbers is then averaged for each site. Roughly, positive scores are above average.

Col. 4 (xx) # of weeks station survided GCOMP's (max 22); see GCOMP for rejection criteria

Col.5 the same as Col 4. except that only IGSnet quality considered

## APPENDIX 11

**ITRF96 and combined (IGS97P05) station coordinates residuals for 52 RF stations at 1997.0 (IGS97P05-ITRF96) after 14-parameter transformation.**

1997.0 IGS97P05-ITRF96 (nun)

| | Dx | Dy | Dz | dN | dE | dH |
|---|---|---|---|---|---|---|
| ALGO | -1.0 | 0.0 | -2.2 | -1.4 | -1.0 | -1.8 |
| AREQ | -0.4 | -6.7 | 1.1 | 2.8 | -2.5 | 5.7 |
| AUCK | 13.7 | 4.6 | 8.6 | -0.9 | -5.8 | -15.7 |
| BAHR | -7.0 | -7.1 | -5.4 | -0.5 | 0.9 | -11.3 |
| BRAZ | 0.8 | -1.7 | 1.9 | 2.3 | -0.5 | 1.2 |
| BRMU | -0.6 | -0.3 | -0.9 | -0.8 | -0.7 | -0.5 |
| CAS1 | -3.1 | 4.8 | -10.6 | 0.8 | 1.2 | 11.9 |
| CHAT | 3.9 | 8.9 | 3.1 | -0.8 | -8.7 | -5.4 |
| DAV1 | -2.6 | 3.8 | -1.6 | 2.4 | 3.3 | 2.6 |
| DRAO | 1.2 | -0.8 | -2.5 | -1.7 | 1.4 | -1.8 |
| FAIR | 3.7 | 1.3 | -7.7 | 0.2 | 0,9 | -8.6 |
| FORT | -1.4 | -0.5 | 1.5 | 1.4 | -1.3 | -0.9 |
| GODE | 5.5 | -15.3 | 10.7 | -1.8 | 1.8 | 19.2 |
| GOL2 | 2.4 | -5.1 | 1.9 | -0.4 | 4.5 | 4.0 |
| GRAZ | -13.3 | -4.3 | -14.3 | 0.4 | -0.6 | -20.0 |
| GUAM | -1.1 | -1.8 | -1.2 | -1.2 | 2.2 | -0.4 |
| HART | -0.1 | -0.5 | -3.5 | -3.3 | -0.4 | 1.3 |
| HOB2 | 0.1 | 1.0 | -3.5 | -2.3 | -0.9 | 2.7 |
| IRKT | -1.6 | 0.8 | 1.2 | -0.1 | 1.3 | 1.6 |
| KERG | -4.7 | 0.4 | 3.0 | 1.1 | 4.6 | -3.0 |
| KIT3 | 1.2 | -2.0 | -1.1 | 0.0 | -1.8 | -1.7 |
| KOKB | 5.0 | 0.3 | -3.9 | -1.8 | 1.4 | -5.9 |
| KOSG | -1.1 | -1.1 | -1.3 | 0.2 | -1.0 | -1.8 |
| KOUR | 1.4 | -9.8 | 1.9 | 1.1 | -4.8 | 8.8 |
| KWJ1 | 2.2 | -2.8 | -2.8 | -2.4 | 2.3 | -3.1 |
| LHAS | 0.4 | 19.6 | 9.6 | -1.3 | -0.7 | 21.8 |
| MAC 1 | 0.1 | 3.5 | -1.2 | 0.2 | -3.3 | 1.7 |
| MADR | -2.7 | 3.1 | -9.9 | -5.7 | 2.9 | -8.7 |
| MALI | -2.5 | -0.1 | -0.2 | -0.3 | 1.6 | -2.0 |
| MAS1 | -3.6 | 0.7 | -2.6 | -0.6 | -0.3 | -4.4 |
| MATE | -0.4 | -1.4 | -1.1 | -0.3 | -1.2 | -1.3 |
| MCM4 | 1.2 | 0.9 | 5.9 | 0.3 | -1.1 | -4.9 |
| MDO1 | 0.5 | -2.3 | 1.7 | 0.4 | 1.0 | 2.7 |
| NLIB | 0.7 | -1.7 | 0.4 | -0.8 | 0.7 | 1.5 |
| NYAL | 1.8 | -0.8 | 6.7 | -0.3 | -1.1 | 6.9 |
| OHIG | 0.3 | -4.6 | 0.0 | 3.6 | -2.2 | 1.8 |
| ONSA | 1.5 | 0.0 | 4.0 | 1.0 | -0.3 | 4.2 |
| PERT | 2.8 | 1.1 | -0.5 | -0.6 | -3.0 | 0.1 |
| PIE1 | -0.7 | -6.7 | 5.5 | 0.9 | 1.5 | 8.5 |
| POTS | -1.6 | -1.0 | -1.8 | 0.3 | -0.6 | -2.5 |
| SANT | 0.2 | -0.8 | 4.2 | 4.0 | -0.1 | -1.6 |
| SHAO | -0.5 | -0.6 | -0.6 | -0.3 | 0.7 | -0.6 |
| THU1 | 0.9 | -2.7 | 4.5 | -1.8 | -0.1 | 5.1 |
| TID2 | 5.3 | -3.4 | 3.4 | -0.9 | 0.2 | -7.1 |

|  |  |  |  |  |  |  | Epoch | Excluded |
|---|---|---|---|---|---|---|---|---|
| TROM | 1.4 | 0.8 | 6.4 | 0.8 | 0.3 | 6.5 |  |  |
| TSKB | 0.1 | -0.7 | -0.5 | -0.1 | 0.5 | -0.7 |  |  |
| VILL | -3.7 | 0.4 | -2.1 | 0.8 | 0.1 | -4.2 |  |  |
| WES2 | -2.3 | -3,0 | 2.6 | 0.5 | -3.1 | 3.3 |  |  |
| WTZR | -2.3 | -1.2 | -2.1 | 0.6 | -0.6 | -3.2 |  |  |
| YAR1 | -0.3 | 8.7 | -4.3 | 0.1 | -3.5 | 9.1 |  |  |
| YELL | 2.2 | 2.2 | -7.0 | -0.7 | 1.1 | -7.6 |  |  |
| ZWEN | -3.5 | 0.1 | -3.3 | 0.4 | 2.2 | -4.3 |  |  |
| Mean | 0.4 | -0.7 | 0.1 | -0.2 | -0.3 | 0.0 | 1997 | none |
| Sig | 4.9 | 5.2 | 5.5 | 1.6 | 2.3 | 7.2 |  |  |
| Mean | 1.8 | 0.4 | 1.9 | 0.2 | 0.0 | 0.0 | 1998 | AUCK, CHAT |
| Sig | 7.0 | 7.8 | 11.3 | 3.7 | 4.2 | 10.8 |  | dE, MCM4 dH |
| Mean | 3.1 | 1.5 | 3.6 | 0.5 | 0.0 | -0.1 | 1999 | AUCK, CHAT |
| Sig | 10.3 | 12.6 | 19.1 | 6.0 | 7.2 | 17.4 |  | dE, MCM4 dH |

# APPENDIX III

**ITRF96 and IGS97P05 differences from NNR NUVEL1 A for RF stations. (* stations excluded from the averages and sigmas below)**

| STATION | PLATE | IGS97P05- NNR NUVEL1A | | | ITRF96 -NNR NUVEL1A | | |
|---|---|---|---|---|---|---|---|
| | | N(mm/y) | E(mm/y) | H(mm/y) | N(mm/y) | E(mm/y) | H(mm/y) |
| GRAZ | EURA | 0.7 | -1.7 | 22.9 | 1.1 | 1.5 | 0.8 |
| KOSG | EURA | 2.2 | -4.1 | -0.3 | 0.6 | -0.4 | 0.8 |
| MADR | EURA | -7.0 | 1.9 | -1.6 | -0.5 | 1.4 | 3.9 |
| VILL | EURA | -1.8 | -4.7 | -9.1 | -0.9 | 0.1 | 1.5 |
| WTZR | EURA | 1.5 | -3.3 | -2.3 | -0.3 | 0.7 | -2.4 |
| POTS | EURA | 1.8 | -3.2 | -1.1 | 0.5 | 0.7 | 4.2 |
| ONSA | EURA | 1.7 | -3.7 | 3.6 | -0.6 | -0.7 | 0.1 |
| MATE | EURA | 7.1 | -2.8 | 2.6 | 5.6 | 2.3 | -0.7 |
| TROM | EURA | 4.8 | -6.0 | 19.5 | 3.0 | -3.8 | -0.8 |
| NYAL | EURA | 1.5 | -4.0 | 14.8 | 1.1 | -1.4 | -2.0 |
| ZWEN | EURA | 5.5 | -0.7 | 3.7 | 2.4 | -1.8 | -0.5 |
| IRKT | EURA | 1.0 | 3.1 | 1.8 | 2.6 | 2.3 | -0.1 |
| KIT3 | EURA | 3.8 | 0.9 | -5.0 | 3.3 | 4.0 | 1.8 |
| SHAO * | EURA | 0.9 | 6.9 | 1.4 | -0.6 | 10.2 | -1.0 |
| TSKB* | EURA | 5.8 | -26.7 | -4.1 | 4.6 | -21.0 | -5.3 |
| | | | | | | | |
| Mean | EURA | 1.75 | -2.18 | 3.81 | 1.37 | 0.36 | 0.52 |
| Sigma | EURA | 3.50 | 2.74 | 9.53 | 1.89 | 2.05 | 1.98 |
| | | | | | | | |
| ALGO | NOAM | -1.9 | 0.4 | -1.1 | -2.2 | 1.2 | -0.5 |
| DRAO | NOAM | 0.0 | 0.3 | 0.5 | 1.5 | 2.7 | 1.2 |
| FAIR | NOAM | -3.4 | 1.4 | -8.1 | -2.4 | 2.3 | -0.1 |
| GODE | NOAM | -2.5 | 0.8 | -3.3 | -0.4 | -2.1 | -3.8 |
| MDO1 | NOAM | -0.9 | 0.7 | -5.2 | -1.5 | 1.4 | 2.0 |
| NLIB | NOAM | -0.6 | -0.3 | -3.7 | -1.2 | 0.9 | -3.7 |
| THU1 | NOAM | -2.6 | -0.4 | 9.0 | -0.7 | -1.9 | -3.8 |
| PIE1 | NOAM | 0.4 | 0.0 | 0.1 | -1.5 | 1.0 | 1.2 |
| WES2 | NOAM | 1.4 | -5.0 | 6.0 | -1.9 | 1.2 | -1.4 |
| BRMU | NOAM | -1.6 | 0.9 | 0.3 | -0.5 | 0.8 | 2.4 |
| YELL | NOAM | -0.3 | 1.5 | -1.4 | -0.9 | 1.7 | 0.7 |
| GOL2* | NOAM | 5.8 | -6.0 | -9.7 | 6.8 | -2.5 | 0.1 |
| | | | | | | | |
| Mean | NOAM | -1.09 | 0.04 | -0.63 | -1.07 | 0.82 | -0.52 |
| Sigma | NOAM | 1.45 | 1.80 | 4.85 | 1.07 | 1.52 | 2.34 |
| | | | | | | | |
| HOB2 | AUST | 2.6 | -5.1 | -5.9 | 1.5 | 5.2 | -1.1 |
| PERT | AUST | 2.0 | -4.2 | -3.8 | -3.4 | 4.9 | -0.1 |
| TID2 | AUST | 5.7 | -1.1 | -6.8 | 2.3 | 5.1 | -3.7 |
| YAR1 | AUST | -0.2 | -5.3 | 1.5 | -3.5 | 3.6 | -0.6 |
| AUCK* | AUST | 2.9 | -4.8 | -8.8 | 2.3 | 17.1 | -0.6 |
| MAC1* | AUST | -16.0 | -6.7 | -6.6 | -17.9 | 3.8 | 0.8 |
| | | | | | | | |
| Mean | AUST | 2.53 | -3.93 | -3.74 | -0.75 | 4.70 | -1.40 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Sigma | AUST | 2.43 | 1.91 | 3.72 | 3.10 | 0.74 | 1.60 |
| CAS1 | ANTA | -3.0 | -0.1 | 29.7 | -7.3 | 2.2 | 13.9 |
| DAV1 | ANTA | -1.9 | -5.1 | -3.9 | -8.0 | -4.0 | 1.3 |
| MCM4 | ANTA | 1.7 | 3.1 | -16.5 | 0.3 | 9.5 | 27.4 |
| OHIG | ANTA | 0.5 | -6.3 | -6.7 | -1.1 | -0.8 | 1.8 |
| KERG | ANTA | -2.2 | -7.5 | 1.1 | -5.7 | -6.5 | 6.9 |
| Mean | ANTA | -0.98 | -3.17 | 0.75 | -4.36 | 0.05 | 10.27 |
| Sigma | ANTA | 1..97 | 4.49 | 17.40 | 3.77 | 6.21 | 10.84 |
| BRAZ | SOAM | 1.5 | 0.6 | -2.2 | -2.3 | -0.9 | -10.1 |
| FORT | SOAM | 0.5 | **0.1** | 7.6 | -0.1 | 3.3 | 2.3 |
| KOUR | SOAM | 1.4 | 4.5 | 4.2 | 0.3 | 5.1 | 0.3 |
| AREQ* | SOAM | 7.7 | 10.4 | 1.3 | 3.1 | 14.6 | -1.1 |
| SANT* | SOAM | 7.4 | 18.9 | -1.1. | 4.2 | 19.1 | 8.1 |
| Mean | SOAM | 1.12 | 1.73 | 3.18 | -0.70 | 2.53 | -2.50 |
| Sigma | SOAM | 0.57 | 2.38 | 4.97 | 1.42 | 3.08 | 6.64 |
| BAHR | AFRC | 12.1 | 2.5 | 1.0 | 15.6 | 1.9 | 2.0 |
| HART | AFRC | -5.2 | -15.8 | 0.3 | -1.2 | -4.1 | 1.5 |
| MAS1 | AFRC | -1.6 | -4.2 | -1.3 | -1.8 | -0.1 | 3.1 |
| KOKB | PCFC | 3.6 | -6.5 | -8.9 | 0.9 | -2.5 | -1.6 |
| KWJ1 | PCFC | 1.6 | -11.3 | -6.0 | 3.2 | -7.7 | -4.2 |
| CHAT | PCFC | 3.5 | -3.7 | -7.6 | 2.5 | 25.3 | -0.4 |
| MALI | INDI | -4.2 | -9.8 | 2.4 | -5.6 | -4.2 | 2.7 |
| LHAS | INDI | -28.1 | 8.4 | -20.6 | -25.2 | 6.5 | 1.8 |
| GUAM | PHIL | 7.2 | 28.5 | 3.0 | 4.7 | 32.1 | -0.5 |

# APPENDIX IV

## PROPOSED SINEX 1.00 EXTENSION EXTENSIONS FOR DATUM CONSTRAINTS AND TRANSFORMATION PARAMETER SOLUTION

By

Remi Ferland, NRCan

(Nov 20, 1997)

Transformation parameters and inner constraints are routinely estimated/applied during coordinates computations. Currently, there is no explicit definition to incorporate those in SINEX. This is an attempt to correct this minor problem by proposing standard names and usage.

The transformation parameters may be estimated and/or applied or their sigmas used to constrain the solution

When the transformations parameters are estimated, they can appear in the ESTIMATE block and optionally in the APRIORI block as is currently done for the station parameters. The sign convention should follow IERS convention.

When the transformation parameter sigmas are used to provide the reference frame constraint with the inner constraints technique, those constraints are unfortunately not explicitly provided.

The general SINEX practice has been to have a one to one explicit correspondence between APRIORI and ESTIMATED parameters. For the inner constraints case, the transformation parameters would only appear in the SOLUTION/APRIORI and optionally in the SOLUTION/MATRIX_APRIORI blocks. This would provide the 7 (or less) constraints to apply and code explicitly in the SINEX format.

Names should be reserved for the transformation parameters and their rates (units) such as:
RX RY RZ TX TY TZ SC ( mas mas mas m m m ppb )
RXR RYR RZR TXR TYR TZR SCR ( ma/y ma/y ma/y m/y m/y m/y pb/y )

When used as inner constraints, the variables Code, Point and Solution could be respectively '----' '--' '----' The apriori values would not be needed.

Example #1:

Minimum datum (rotational) constraints only:

```
*-------------------------------------------------------------------------------
+SOLUTION/APRIORI
*Index _Type_ Code Pt Soln _Ref_Epoch__ Unit S _Apriori Value______ _Std_Dev___
     1 RX     ----- ---- - 00:000:00000 mas  0  .000000000000000E+00 .1000000E+0
     2 RY   ----   --  ---- 00:000:00000 mas  0  .000000000000000E+00 .1000000E+0
     3 RZ     ----- ---- - 00:000:00000 mas  0  .000000000000000E+00 .1000000E+0
-SOLUTION/APRIORI
*-------------------------------------------------------------------------------
```

Example #2:

Transformation from ITRF94 to ITRF93:

```
*-------------------------------------------------------------------------------
+SOLUTION/APRIORI
*Index _Type_ Code Pt Soln _Ref_Epoch__ Unit S _Apriori Value______ _Std_Dev___
     1  RX  ----  --  ---- 88:000:00000 mas   0 -.390000000000000E+00 .1000000E-1
     2  RY  ----  --  ---- 88:000:00000 mas   0  .800000000000000E+00 .1000000E-1
     3  RZ  ----  --  ---- 88:000:00000 mas   0 -.960000000000000E+00 .1000000E-1
     4  TX  ----  --  ---- 88:000:00000 m     0  .006000000000000E+00 .1000000E-1
     5 TY     ----- ---- - 88:000:00000 m    0 -.005000000000000E+00 .1000000E-1
     6 TZ     ------ ----  88:000:00000 m     0 -.015000000000000E+00 .1000000E-1
     7   se   ----  -- ---- 88:000:00000 ppb 0  .400000000000000E+00 .1000000E-1
     8  RXR ----  --  ---- 88:000:00000 ma/y 0 -.110000000000000E+00 .1000000E-1
     9  RYR ----  --  ---- 88:000:00000 ma/y 0 -.190000000000000E+00 .1000000E-1
    10 RZR    ----- ---- - 88:000:00000 ma/y 0  .050000000000000E+00 .1000000E-1
    11  TXR ----  --  ---- 88:000:00000 m/y  0 -.002900000000000E+00 .1000000E-1
    12  TYR ----  --  ---- 88:000:00000 m/y  0  .000400000000000E+00 .1000000E-1
    13 TZR  ----  --  ---- 88:000:00000 m/y  0  .000800000000000E+00 .1000000E-1
    14  SCR ----  --  ---- 88:000:00000 pb/y 0  .000000000000000E+00 .1000000E-1
-SOLUTION/APRIORI
*-------------------------------------------------------------------------------
(The Apriori Values are real but the Std_Dev were made-up for this example
```

# APPENDIX V

## SUGGESTIONS FOR AC SUBMISSIONS OF MINIMUM DATUM CONSTRAINT A- SINEX SOLUTIONS

As proposed in the paper it is recommended that the ACS final orbit/EOP/station/clock solutions be only minimally constrained and that they be consistent. More details on possible approaches and suggestions on how to make all the AC solutions consistent can be found in the Appendix VI. Here it is only suggested how a minimum constrained AC Final (A-SINEX) station/EOP solution can be coded in the SINEX format.

Although in principle unconstrained (consistent) solutions could be used, it is convenient or even necessary to constrain (i.e. attach a datum to) the AC solutions for several reasons. As already discussed in the paper, at least for the time being it is essential that the datum constraints be minimal in order to preserve the relative station/orbit precision and/or datum connections. In this way it is hoped that an efficient feedback on orbit/EOP/station consistency can result in significant consistency improvements .

Since only the three orientation parameters (Rx, Ry, Rz) are nearly singular (with sigmas of a few 10's of mas), by definition, the minimum datum constraints can only include the three rotational parameters. In fact the example #1 of the Appendix IV already demonstrates how such a minimum (datum) constraint A-SINEX submission could be coded. In this way, the important geocenter and scale information implied from the Global AC analysis is preserved. Note that in principle (due to near singularity) any values Rx, Ry, and Rz can be used, so they are of little significance and need not even be coded (i.e. zero values could be used instead) . However the apriori sigmas, or the apriori matrix used, must be coded properly in the apriori SINEX blocks, so that the original (unconstrained) matrix can be recovered. The apriori minimum (rotation) constraints are thus somewhat arbitrary and could be based on e.g. a transformation between the original unconstrained station solution and the IGSyyPww solutions of the 52 RF station set. Alternatively, until IGSyyPww becomes available, the new ITRF96 station set of 47 stations can be used instead.

Analogously for the GNAAC weekly combined SINEXes only the minimum (i.e. rotation) datum constraints could also used, or alternatively, a complete 7-parameter solution (and the corresponding apriori information) could be coded (see e.g. the example #2 of the Appendix IV). When the IGSyyPww RF set becomes available it could be used for the transformation solutions/apriori or alternatively it can be used directly as apriori information. The important consideration here is that all apriori (datum) constraints be fully removable and the original geocenter and scale information be retained.

# APPENDIX VI

## SUGGESTIONS AND DISCUSSIONS ON AC SOLUTION/PRODUCT CONSISTENCY

It is essential that the consistency of all AC solutions be maintained. This is true for the proposed new ITRF realization in particular. The consistency of the Final orbit, EOP, station, clock and tropospheric delay solutions are to be maintained regardless of whether minimum datum or no constraints are used. (Note that after June 28, 1998 it is proposed that only minimum or no constraints be used for all Final AC solutions; see the Appendix V for more details and the proposed coding in the SINEX format). Since ionospheric delays are not sensitive to reference frame changes and are only needed to connect the IGS clock solutions to external standards, they are not discussed here.

The fact that AC station solutions are currently accumulated and submitted to the IGS on a weekly basis somewhat complicates the product consistency. (Note that weekly-accumulated station solutions were adopted by IGS as a compromise between daily and yearly station submissions.) Depending on the degree of sophistication and the additional CPU time expense, there are at least three possible approaches available to ACS:

1. A rigorous adjustment for all products based on the whole weeklong period. Though preferable, for practical considerations and given the current submission and CPU limitations, this is difficult to realize.

2. A rigorous adjustment for a part of the AC products, e.g. station positions and EOP, accumulated over a one-week period. Then the remaining parameters are obtained by a rigorous back-substitution. This approach may already be feasible for some ACs; in fact, some ACS are already doing this. Note that the solutions for the remaining parameters, while fixing all the relevant parameters obtained from the above-accumulated rigorous (partial parameter) solution, are equivalent to rigorous back-substitution in terms of the parameter values only, but not in terms of the corresponding covariance matrix. So, if the matrix is not required (as is currently the case for the AC orbit/clock/tropo solutions), this back-substitution by parameter fixing could also be a practically viable alternative.

3. A rigorous adjustment for a part of the AC products, e.g. Station positions and EOP, accumulated over a one-week period. All the remaining parameters are then obtained by approximations of back-substitution. More specifically, approximate solutions consistent with the weekly-accumulated SINEX station/EOP solutions can be obtained by applying appropriate parameter transformations computed between the daily (minimum datum or no constraint) station solutions and the accumulated AC A-SINEX solution for the current week. Since this is relatively easy to implement and likely will be a choice for most ACS, below are more details for all the relevant AC product solutions.

EOP (erp-format): The EOP and sigmas from the A-SINEX solution are coded in the erp weekly file, which accompanies the sp3 daily orbit files.

Orbits (sp3 format): 7 parameter transformations between each daily (minimum or no constraint) station solutions and the weekly A-SINEX solution are applied to the corresponding (minimum or no datum constraint) daily orbits. In this way the daily transformed orbits approximate back-substitutions and are consistent with the A-SINEX.

**Satellite clocks:** The (minimum or no datum constraint) daily clocks are increased by the height corrections computed from the daily station dx, dy, dz shift and scale (Se) transformations. I.e. the following consistency corrections are added to the daily satellite clock solutions:

$$Dt= ((dx.Xs + dy.Ys + dz.Zs)/Rs + Sc.Rs)/c;$$

where Xs, Ys, Zs, are the ITRF SV coordinates, Rs is the SV radius vector and c is the speed of light. Note this correction accounts for the origin changes of the daily station solutions. The second correction, based on the orbit height errors (with respect to the daily station origin) also needs to be applied but with the opposite sign (see the test below for more details), however this is already being done during the current IGS orbit/clock combinations.

**Station** clocks: the daily station clocks (to be submitted for some stations in the near future, in a yet to be specified format) need to be corrected only for relative height errors, i.e. the daily station height residuals after 7 parameter transformation between the daily and the A-SINEX station solution. The daily station height residuals with respect to the A-SINEX, expressed in time units, are subtracted from the corresponding daily (minimum or no datum constraint) station clock solutions. Note that the daily transformation parameters (shift and scale) should not be included in this correction.

Tropospheric delays: The tropospheric (tropo) delay corrections are completely analogous to the station daily clocks, i.e. the only difference is that the daily station height residuals are scaled by an empirical scaling factor of about .15 to .30. This factor is likely COnStant for an AC, but could vary from AC to AC. It may be a function of the elevation cut-off and/or elevation dependent weighting used.

EXAMPLE: Consistency transformation between EMR sigma constrained and unconstrained solution for Feb 02, 1998 (Wk 0943, day 01)

In addition to the regular EMR09431 Final solution, which uses the ITR94 position and sigmas of the 13 ITRF stations as apriori constraints, the second, unconstrained solution was generated with large (at least 10 m) apriori position sigmas for all stations. The Table 1 summarizes the parameter transformations between the corresponding orbit as well as between station solutions.

Table 1: 7 parameter orbit and station transformations for unconstrained -constrained solutions

| Product | dx | dy | dz | Sc | R x | Ry | Rz | 2D | H |
|---|---|---|---|---|---|---|---|---|---|
| | mm | mm | mm | ppb | mas | mas | mas | RMs(mm) | |
| Orbits | -3 | 66 | 43 | 0.0 | .48 | -.36 | .26 | 73 | 40 |
| Stations | -4 | 140 | 84 | -0.1 | .76 | -.42 | .24 | 9 | 13 |
| Difference | 1 | -74 | -41 | 0.1 | -.28 | .06 | .02 | | |

As one can see, except for the shift parameters dy, dz and the rotation Rx, both the orbit and station transformations are quite consistent. The large and disturbing dy bias, typically also seen for the EMR unconstrained (weekly SINEX) solutions (see the weekly GNAAC summary reports by JPL, MIT and NCL) is also seen for this daily solution. The smaller dy, dz orbit shifts are likely due to orbit dynamics and gravity field which should mitigate (or resist to) any geocentre offset, more than for the station solution. For most ACS the geocentre offsets of unconstrained solutions are much better behaved and usually they are small, within 10-20 mm. This EMR example, in fact, could represent a worst scenario case. The differences in Table 1 also indicate the need for daily 7 parameter transformations in the IGS orbit combinations to account for larger variations in the shift and orientation biases for some AC (minimum or no constraint) solutions.

As outlined above, the approximate transformations/corrections were applied to the unconstrained clock and tropo delay solutions and then they were compared to the constrained solution. The results of comparisons are summarized in Table 2. Note that for the satellite clocks, the orbit height error (which includes the daily orbit offsets and scales) were subtracted in addition to adding the above height corrections based on the daily stations offsets and scale transformations . The first (orbit height error) correction, in fact simulates the orbit height corrections available and applied in the current IGS clock combinations. In other words the orbit height corrections applied here effectively only include the differential dx, dy, dz and scale offsets listed in the last row of Table 1.

As one can see the consistency transformations/corrections of step 3) seem to be quite acceptable with respect to the formal sigmas. Although the formal sigmas are likely rather pessimistic due to significant correlation amongst the above solution parameters.

Table 2. Comparisons of the unconstrained and constrained clock, tropo EMR Final solutions for Feb 02, 1998.

| Solution | RMS (unconstrained - constrained) | | Average formal |
|---|---|---|---|
| | Original | transformed | sigma |
| Sat. clocks | .195 ns | .061 ns | .123 ns |
| Sta. clocks | .056 ns | .040 ns | .087 ns |
| Tropo delays | 2.7 mm | 1.7 mm | 4.6mm |

A final note on the 7-parameter transformation between unconstrained daily solution and the minimally constrained A-SINEX solution: Due to the near rotational singularity of the daily unconstrained solutions one can only use the identity matrix weighting. Alternatively, if matrix weighting is desired, one should first “condition* the unconstrained matrix by applying minimum rotation datum constraints, with the daily rotation solution values unchanged (see the example #1 of Appendix IV) .