IGS Reference Frame Maintenance

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1 ABSTRACT

The Reference Frame maintenance is an ongoing task and influences all the International GPS Service (IGS) core products. This paper proposes some short to medium term improvements to the Reference Frame (RF) related activities and products. It also includes a review of: 1) some procedures to clarify some potential misinterpretation of the products; 2) results from the weekly Software Independent Exchange format (SINEX) combination and 3) the upgrade of the IGS realization (IGb00) of the ITRF; 4) the (ultra) rapid and final orbit and clock products and 5) the current and potential users with often demanding requirements (e.g. Tide Gauge working group (TIGA) for the vertical component). The combination strategy will be reviewed, with emphasis on potential weaknesses. The reported results of weekly SINEX combination will include station coordinates/velocity, scale, Earth Rotation Parameters (ERP's) and apparent geocenter. Large discontinuities in station coordinates time series are currently accounted for, small discontinuities are more difficult to reliably and timely detection; suggestions will be made. Aspects of the realization of the RF using IGS orbits and clocks as well as the TIGA will also be discussed.

2 INTRODUCTION

The maintenance and upgrade of the of the IGS realization of the reference frame depends entirely on the cooperation of a number of agencies worldwide. Those agencies have been installing and are operating equipment contributing to the IGS products. Various types of equipment (GPS receivers/antennas) are used to perform the measurements and make them available in a timely manner. The local environment in which the equipment is installed is also quite diverse and variable. There is ongoing effort by most IGS contributors to ensure the highest standards can be maintained. Various types of local conditions/limitations affect the equipment operating performance, and thus the code and phase measurements. Station and satellite equipment performance is also variable. Few stations meet equally well all the "IGS Site Guidelines" (Moore, 2003). The local conditions between the stations are often correlated and affect estimated parameters such as the station coordinates, specially the height component. To extract the desired information, the Analysis Centers (AC) have to model and/or estimate various effects that are often highly correlated hence, difficult to separate. Detailed information on the maintenance and improvement of the IGS tracking network has been described in detail in Ray, J. (2003). The estimation and modeling strategy selected by each AC to approximate the reality, also introduces some "processing noise". The models used between the AC are not always identical, potentially affecting the estimated parameters in small systematic ways. Each AC has its own criterions/algorithm for the station selection that constitute their network. Within each AC the network configuration varies from epoch to epoch. Between ACs, although their selected networks overlap significantly, they are not identical. For overlapping portions of the network, the ACs will use the same measurements; the estimated station coordinates will be slightly, but often systematically different. The processing strategy used to combine the estimated station coordinates provided by the ACs also influences the results. From the point of view of the station coordinates adjustment, all the effects above contribute to what could be called “external limitations”. The SINEX combination procedure may also introduce some small approximations labeled “internal limitations”. With ever increasing accuracies, one needs from time to time, to review the procedures in place to ensure that none of its components becomes a limiting factor to the ongoing improvement cycle. The ACs final orbit and clock products are also affected by the measurements limitations and modeling / estimation strategies (i.e.: “external limitations”). The combination procedure used on the orbit/clocks also introduces its own set of “internal limitations” and also requires review. Due to practical limitations, the products are not combined simultaneously in a rigorous adjustment. Some approximations are made within and between the products. One objective here is to review the procedures and propose improvements where needed.

3 STATION COORDINATES PRODUCTS

3-1 Internal Limitations

The iterative SINEX combination procedure performs the following functions on the AC & GNAAC solutions: 1) validate; 2) unconstrain; 3) transform to the current IGS realization of ITRF; 4) compare and 5) combine. The weekly combination is presently generated within 12 days after the end of each GPS week. The ACs are submitting solutions that are aligned in orientation to the current realization of the reference frame. The origin of the AC solutions corresponds to the earth center of mass as “observed” with the satellite orbits. The provided solutions are not translated, nor scaled. The provided solutions can be constrained, and if so, the constraints must be removable. The SINEX combination algorithms follow the generally accepted least-squares formulation.

3-1-1 Validation

The format validation ensures that all the files used respect the SINEX V 1.0 (ftp://igscb.jpl.nasa.gov/pub/data/format/sinex.txt). A template generated and maintained at the IGSCB (igs.snx) is also used in the validation process. During the validation process, changes are made to the SINEX files, such that they all use a consistent interpretation of the SINEX format. Corrections for pole tide (esa, ngs) and the addition of the short-term (<35days) effects (LODR-LOD) to the excess of Length of Day (LOD) are applied when appropriate (jpl). An LOD bias correction is estimated and applied for each AC based on a windowed weighted average difference with respect to the IERS Bulletin A (Mireault, Y. et al. 1999). Occasional problems with antenna heights are corrected. The entire process is dependent on the completeness and accuracy of the information that is provided by each AC.

3-1-2 Unconstraining

Most AC & GNAAC weekly estimated solutions are currently providing “loosely” constrained or even unconstrained solutions. The constraints contained in the APRIORI blocks must obviously correspond exactly to the constraints included in the ESTMATE blocks. There is currently no independent way to directly check the reported constraints are the only ones used. Heavy constraints, although perfectly legal, should probably be avoided by the ACs to minimize unconstraining problems. Occasional difficulties with unconstraining or inverting matrices appear to be caused mainly by rounding/truncation problems. Those are fairly minor and are resolved by rescaling the estimated and/or a priori matrix and/or its diagonal. The rescaling is usually below one part per million. More specifically, the rescaling may have one or both of the following objectives: 1) to permit the inversion of the apriori and/or estimated blocks; 2) the inversion of the unconstrained solution. These are expected to have negligible effect on the final weekly products.

Some solutions do contain multiple estimates for a given DOME# marker at a site. Within a solution, they are usually recombined such that for each solution, for one DOME# there is one solution. The coordinate differences between those multiple solutions are generally within a few mm. In the situation where significant differences exist, the outlier is rejected. The IGS apparent geocenter is estimated from the combined AC apparent geocenters (translation components).

Recommendation 1:
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To resolve potential constraints issues, it is proposed that for GPS weeks 1268 to 1270, the ACs contribute SINEX solutions obtained without constraints on any parameters along with their usual SINEX solution. If for any reason, any apriori constraints (orbit, troposphere … etc) are used on any parameters, they must be reported along with their expected influence on SINEX parameters.

3-1-3 Transformation

The alignment of all the unconstrained weekly solutions to ITRF is done with a 7-parameter (3 translations, 3 rotations and 1 scale) similarity transformation. The ERPs are corrected by the appropriate transformation rotation angles and are always referred to the origin. All the common stations between each weekly solution and the RF stations are used to estimate the transformation. Unit weighting is used for the coordinates during the estimation of the transformation parameters. The use of the corresponding weight matrices usually leads to very similar transformation parameters. Occasionally, the estimation of the transformation parameters has shown to be degraded by nearly singular matrices. This raised the concern that the degradation could be gradual and thus not always noticeable. Since the process is to be run as automatically and reliably as possible, the more robust unweighted estimation was preferred for the transformation. Due to the global distribution of the RF stations and to their sigmas being in most cases of similar magnitude, it is not a major approximation. The transformation parameters and combined station coordinates are currently estimated in separate adjustments. One disadvantage is that this is not completely rigorous. On the other hand, due to the almost singular nature of some unconstrained solutions, large transformation parameters are sometimes estimated (generally the RZ rotation), which requires some iterations. With this approach, it is relatively easy to iterate.

Recommendation 2:
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Check/compare the effect of the weighting strategy on the estimated transformation parameters in the current IGS combination strategy by selecting a few GPS weeks.

3-1-4 Comparison

In an effort to produce reliable weekly and updated cumulative solutions, several comparisons are made to detect and reject outliers. The AC/GNAAC are compared with each other, with the RF stations and with the previous week "weekly" and cumulative solutions. During the comparison, it is assumed that the ITRF RF stations, the previous week "weekly" and the cumulative solutions are correct. Those are reasonable assumptions. But, they are from time to time incorrect, mainly in the case of newly added stations in the cumulative solution. The problems can generally be traced back to poor estimated velocity or unreliable metadata. The rejection threshold is currently set at 5 sigmas and 50 mm. These rejection criterions may need "tuning" considering that large residuals often contain biases/systematic effects. To be more effective, the 50 mm threshold needs to be modulated to account for the differences in the expected horizontal and vertical coordinates accuracy. The detection/rejection of ERP outliers is more limited.

A pair-wise comparison between the weekly AC and GNAAC ensures that they are consistent. Detected outliers are by default rejected in both files. This process reveals station coordinates with significant inconsistencies. The weekly AC and GNAAC solutions are also compared with the previous week combined solution to detect significant station coordinates variations between consecutive weeks. This comparison detects significant station coordinates variations from week to week. The outlier stations are rejected from the offending solutions. The weekly AC and GNAAC solutions are finally compared with the cumulative solution to detect outliers in the station coordinates time series. Improvements have been made and are still possible in the rejection procedures. The rejection process is also extensively used during the transformation and combination processes. The rejection process is iterative, in the sense that only the most significant outliers are rejected using predefined significances levels.

Any station deleted is reported with the residuals and the solutions involved. All the weekly solutions matrices are also rescaled by a variance factor (Chi**2/(degrees of freedom)) determined during a comparison with the combined cumulative solution after the transformation/comparison/combination process is completed. The applied scale factors are reported. Cases of “multiple minimum” variance factors are sometimes encountered, where during successive iterations, the variance factor jumps between two estimated values. This is caused by marginal station coordinates in the offending solutions.

3-1-5 Combination

The weekly AC solutions are combined to produce the weekly and the cumulative solutions. The full covariance information is used to combine the station coordinates, geocenter and daily ERP. Standard least squares procedure is used (Vanicek, P. et al., 1982). The combined weekly and cumulative solutions are aligned to ITRF using respectively 7 and 14 transformation parameters. The station coordinates and ERP consistency are maintained during the transformation. The results are checked and the process is repeated if necessary. The estimated rotations and rates are not reported, and are most likely irrelevant, as they do not contain meaningful information. The total translation is reported under the “Apparent Geocenter” section. The transformation parameters between the weekly AC solutions and the IGS realization of ITRF are estimated and reported. Those are shown in Figure 1. The figure also shows the IGS combined “apparent geocenter”. The agreement between the AC and combined solutions is generally within 10 mm in the X and Y-axis and 20 mm for the Z-axis for the best centers. The time series also include some discontinuities due to reference frame realizations updates (GPS week 1021, 1143). The solutions before GPS week 1051 were during the pilot phase, when changes were occurring almost weekly. They are reported here for completeness. Note that the gfz solution is currently not included in the “apparent geocenter” combination due to some unremovable constraints. Some AC pole rates also have to be excluded due to similar situations. The IGS weekly solution scale change needs to be reported as it may contain valuable information for further analysis. Figure 2 shows the weekly AC estimated scale. Unfortunately, the estimated scale needs to be applied to each AC at the combination stage to minimize the differences between the ACs and the reference frame realizations. A rigorous combined scale is not possible without negatively affecting the quality of the combined station coordinates height.

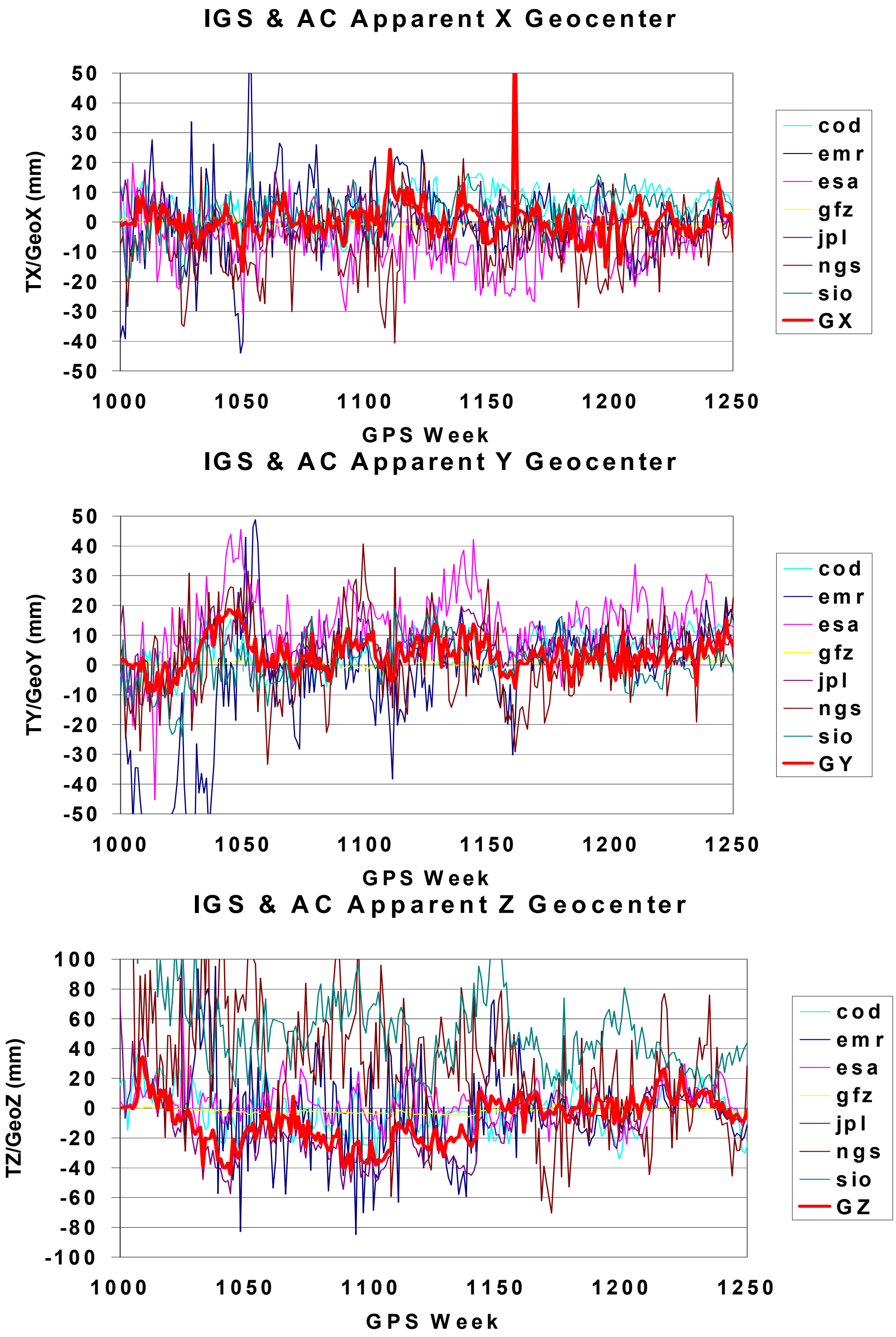

Figure 1: Weekly estimated transformation parameters using AC solutions and IGS "apparent geocenter".

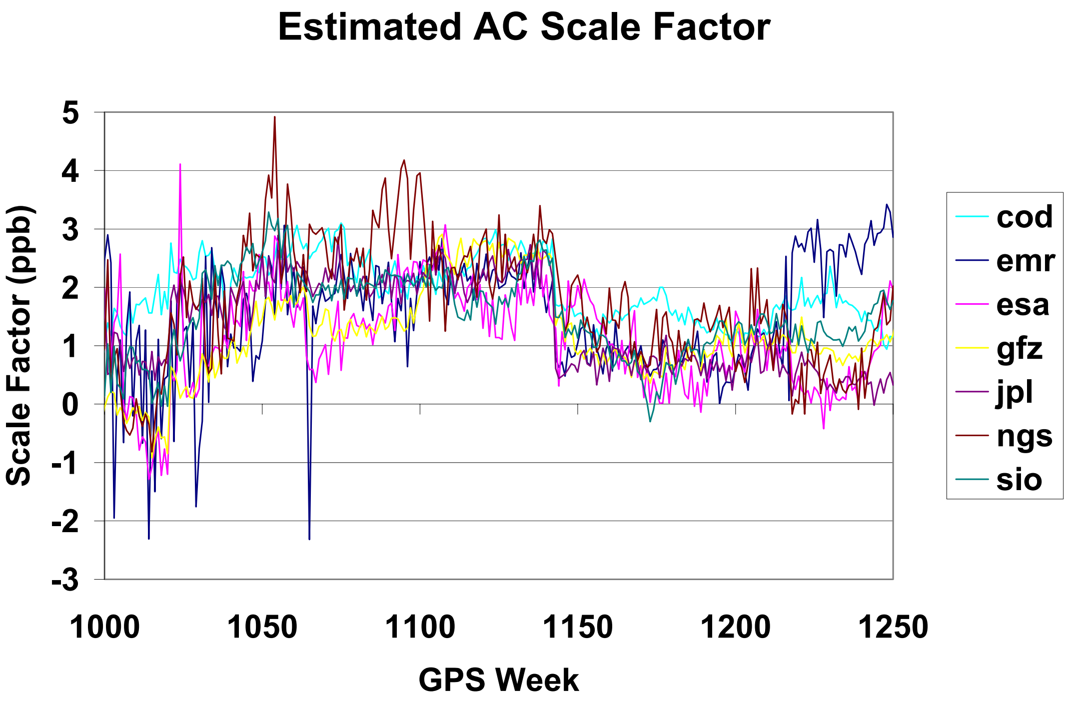

Figure 2: Weekly estimated AC scale

An approximate combined scale factor can be obtained by computing a weighted average of the AC scales. The standard deviation of the height residuals between each AC and the IGS weekly could be used as a weight. Since GPS week 1143 the average scale offset is about 1.1ppb (±0.6 ppb). Note also the scale shift caused by the reference frame realization changes from IGS97 to IGS00 (GPS week 1143).

A summary of the combination is prepared and made available weekly. To facilitate the quick access to the summary information, tabular and graphical form of the summaries are available by ftp (Appendix II) and will soon be available using a web interface. Some of the information is “frame” sensitive. In its current form the table/graphics are not corrected for frame changes.

It is possible to get an estimate of the “processing noise” by comparing IGS weekly with the corresponding GNAAC (mit & ncl) solutions. Both GNAAC solutions also combine the AC weekly solutions using independent software and procedures. One of the most apparent differences between the two GNAAC resides in the differences between number of stations combined and reported. The ncl solution includes only the global solutions (Kouba et al. 1998), while the mit solution includes all the stations. Figure 3 shows the weekly estimated coordinates residuals standard deviations between the mit and ncl solutions and the IGS weekly solution. The GNAAC solutions are realigned to the IGS reference frame realization and the rejection process using the procedure described above is also applied. The comparison indicates that the processing noise is at about 1 mm for the horizontal components and about 3 mm for the vertical component. Although small, those differences are not negligible. They are yet to be explained/resolved.

The cumulative solution contains several years (0837 – now) of weekly solutions. Older data (0837-0978) are currently receiving marginal weight. The covariance information in the cumulative solution is

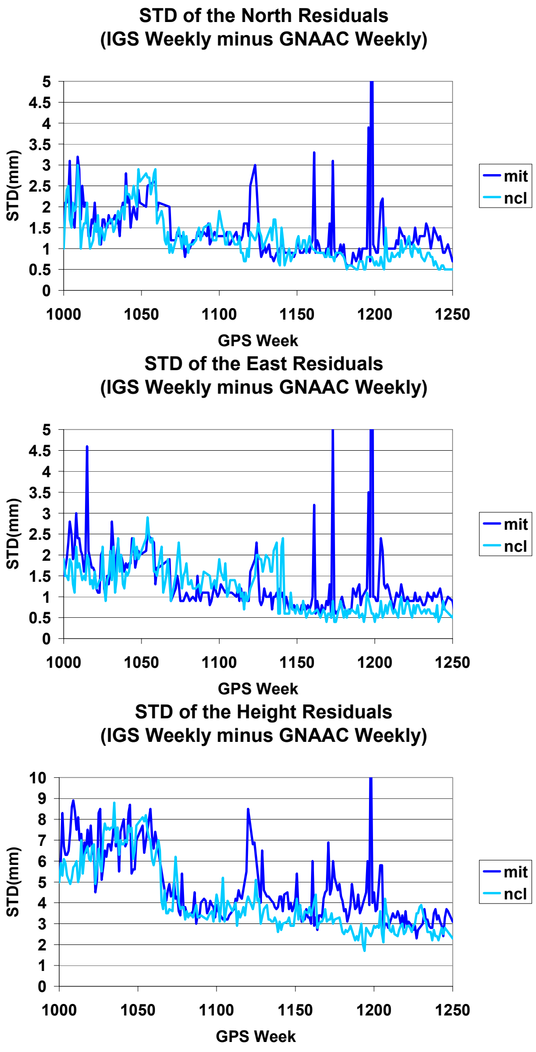

Figure 3: Weekly estimated coordinates residuals standard deviations between the MIT and NCL solutions and the IGS weekly solution.

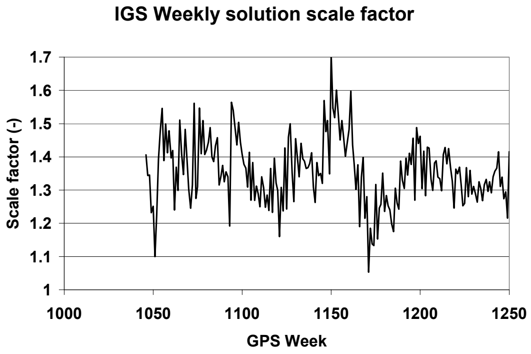

Figure 4: Estimated IGS weekly SINEX solution scale factor (sqrt (variance factor)).

based on the accumulation of the scaled weekly covariance information following standard least-squares practices. The coordinates uncertainty (1 sigma) are on average at about 3 mm at the reference epoch (1998.0), the best ones are at about 0.5 mm, while the velocity uncertainty is on average about 1.5 mm/y, with the best ones reaching 0.3 mm/y. Although the station coordinates/velocity estimates are most likely very good, it is doubtful that they are stable or have reached that formal accuracy. These types of solutions generally have optimistic formal errors. The analysis indicated that station coordinates time series used in the estimation of velocity do not have the “white noise” behavior expected by the standard least squares. The estimation of the combined weekly station coordinates from the AC solutions also assumes that those are not correlated and are characterized by random noise. This is not the case as the ACs reuse the same data. This shortcoming is approximately accounted for by rescaling the weekly combined product by estimating the variance factor with respect to the cumulative solution (Figure 4). On average, the scale factor is about 1.36. This indicates (as expected) that the AC solutions are significantly correlated. The approximation made by not considering the solution correlations probably doesn’t have significant impact at this time. It is recommended to continue using the current procedure.

The cumulative solution does contain well over 2000 AC weekly solutions. From each solution a full covariance matrix was available and used. Occasionally, some AC solutions were tuned (see above) to prevent singularity. Overall, numerical aspects seem to have remained under control. The matrix has so far remained positive definite and does show expected behavior for this type of solution (e.g. horizontal components are 2-3 times better than the vertical components). Residuals between the AC&GNAAC and the weekly/cumulative solutions are reported weekly. If we consider the combination as filter, the reported residuals are always with respect to the filtering. The residuals resulting from the “smoothing” are not estimated. For the station where the coordinates have reached a steady state the differences are expected to be negligible. For the new stations there may be significant differences.

Recommendation 3:
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Estimate and report a scale factor between the IGS weekly combined solution and the IGS realization of ITRF.

Recommendation 4:
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Review the combination procedures with the GNAACs, to better explain and possibly reduce the observed differences. Ideally, in this type of analysis, the processing noise should be kept well below (one order of magnitude) the signal.

3-2 External Limitations

Most ACs have developed and use their own “in house” software to generate their products for IGS. This is an ongoing improvements process. The diversity of software provides a much needed quality assurance. The agreement between the AC SINEX products and the combined weekly and cumulative solutions can provide a measure of the consistency of the products. Most (if not all) ACs are doing some form of approximation when they generate their weekly products from their daily solutions. Those processes are generally repeated with little changes from week to week.

A look at the time series residuals indicates that the week-to-week differences between the ACs have a “noise” like component that is often added to significant biases. This is generally more apparent in the height component. Figure 5 shows two examples (ALGO & YELL) of such a time series residuals for the north, east and height components for the period (GPS weeks 0999 - 1250). Note that those are usual time series behavior. The time series show the estimated residuals as well as polynomials (4th order) fits. The fits show clearly some systematic differences between the ACs. The horizontal “biases” are generally within 1-2 mm of the combined solution, and the vertical components are within 5-10 mm of the average. These “biases” have a number of important implications. When an AC doesn’t include a station or the AC solution is missing altogether, its absence will generate some potentially significant bias/discontinuity (up to a few mm in the vertical component). Abrupt bias changes have sometimes been observed before/after equipment upgrade. When those equipment changes are also associated with discontinuities, the resulting estimated discontinuity from the combined solution may be different than the one that may be estimated by an ACs by potentially several mm. The differences between the AC modeling and estimation strategies have a certain influence on the observed small biases. A summary of all the AC processing is being put together in an effort to better understand the biases. Preliminary comparison of the ACs modeling strategies indicates, for example, that for the station displacement (Solid Earth, Pole Tide, Ocean Loading) (information extracted from the AC “*.acn” files) there is a variety of models that is used. The differences between the models need to be better understood as well as their effect on the AC products. Those effects are considered random in the SINEX least-squares combination, but it is unlikely to be the case. The detailed understanding of the differences in the models is beyond the scope of this position paper, but needs to be addressed.

The stations selected (their number, their distribution, their quality, etc…) by each AC in their analysis also influence the solution; this is the so-called “network effect”. Finally, ITRF and the cumulative solution also used to generate the IGS realization of ITRF have some noise. The noise from both solutions propagates into the IGS realization of ITRF. Which in turn propagates into the weekly SINEX products alignment to ITRF. Those two have a significant influence on the final results.

All the above contribute to the observed small but real differences between the station coordinates.

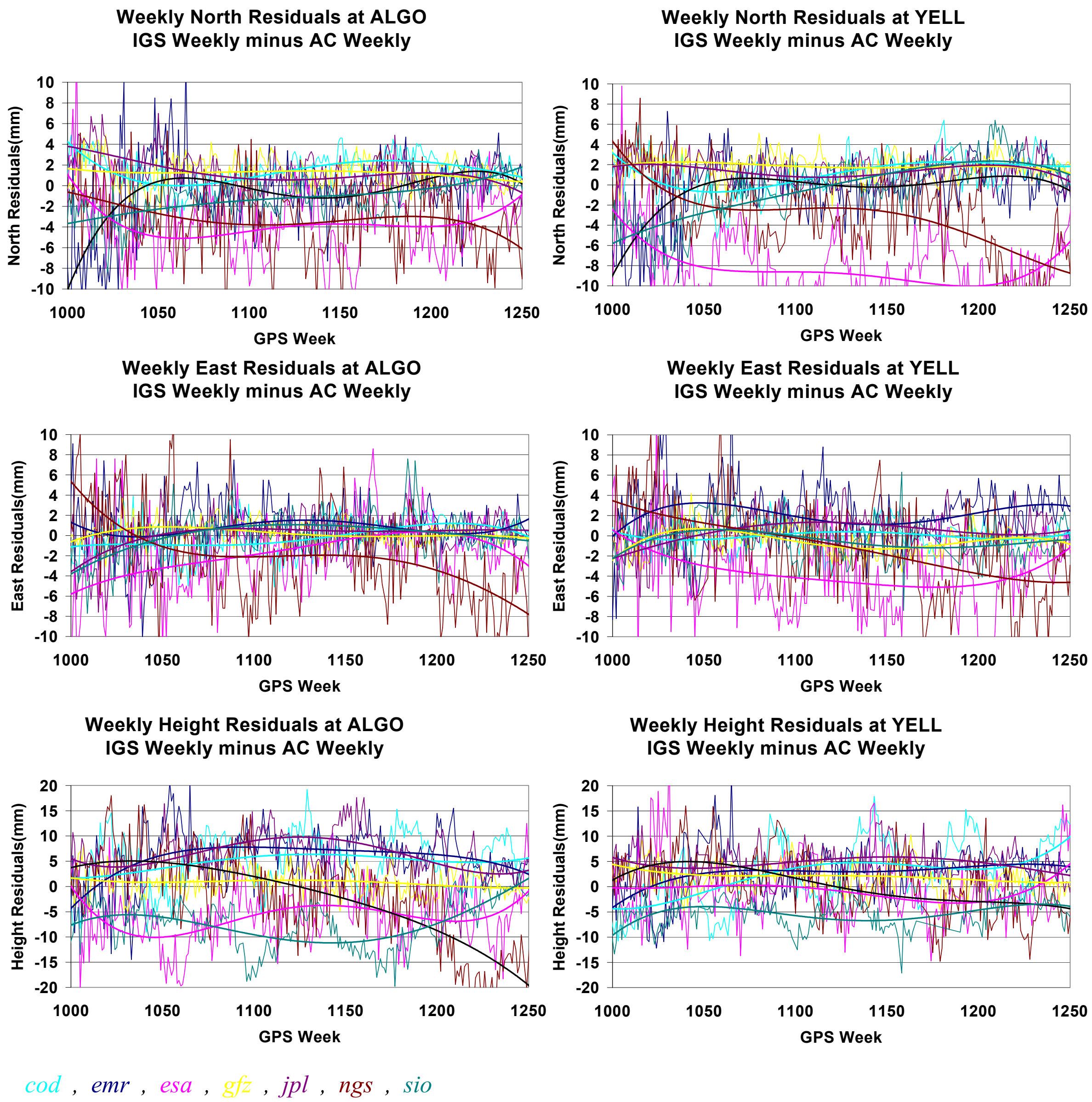

Figure 5: Weekly estimated coordinates (N, E, H) residuals time series between the AC solutions and the IGS weekly solution for stations ALGO and YELL. The figures also include 4th order fits on the residuals.

Recommendation 5:
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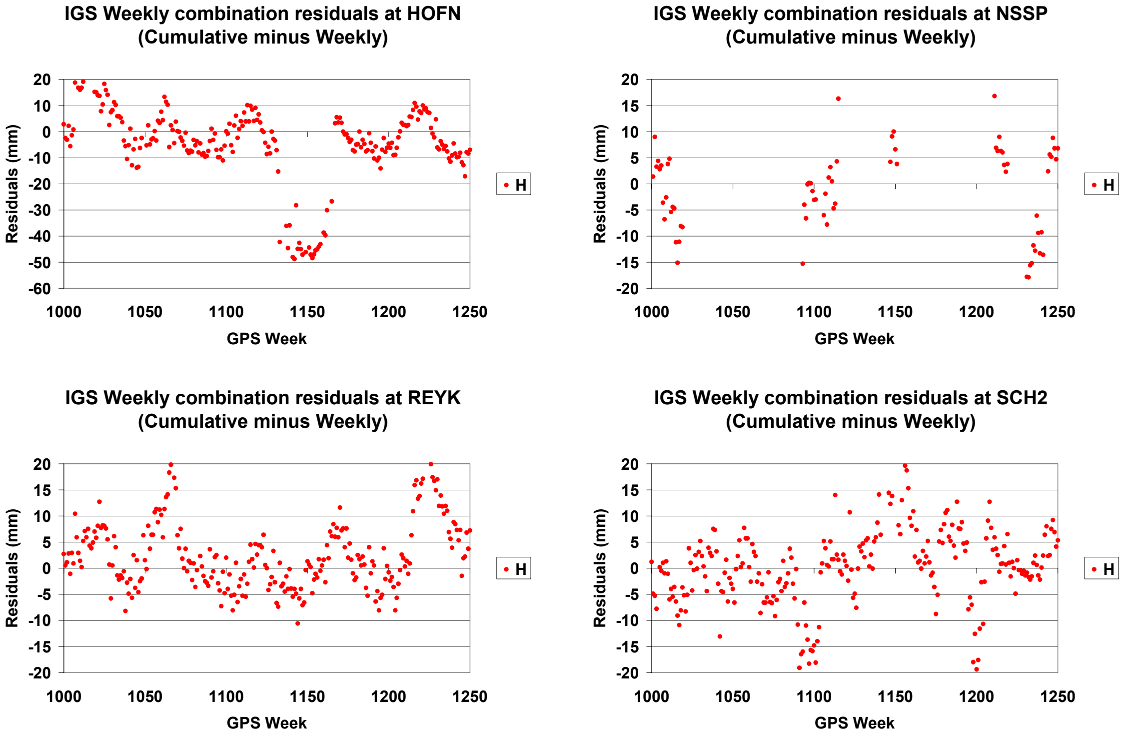
The modeling differences between ACs need to be compared to understand the observed small systematic differences between the AC station coordinates, orbits and clocks. As a starting point, a summary of all the AC processing/modeling is being compiled. The information available from the *.acn files is used for this compilation. The ACs should update the file every time any significant analysis change is made.

3-2-1 Time Series

Since 1999, (between GPS weeks 0999 and now) residuals have been estimated between AC&GNAAC coordinates and the weekly and cumulative solutions. Altogether, close to half million coordinates (N, E, H) residuals have been accumulated. There are also a few thousand rejections; many of those are in the early days of the project. Graphical as well as tabular forms for the residuals are available, details can be found in Appendix I. Time series derived from for the summary reports are also available see Appendix II for details.

3-2-2 Discontinuities

One important objective with detection of the discontinuities/abnormal behavior is to separate the geophysically meaningful "signal" from systematic errors. This is probably one of the more problematic aspects in the analysis of the station coordinates time series. The easiest ones to deal with are those that have an identifiable cause, that occur at a specified time and that cause an abrupt and permanent discontinuity. Those can generally easily be identified, even with automated procedures. They are probably a minority of events occurring in the station coordinates time series. Unfortunately, not all the "anomalies" that are detected are discontinuities that have the above characteristics. The Figure 6 shows four (HOFN, NSSP, REYK and SCH2) examples of height residuals time series between the IGS weekly and the IGS cumulative. Those represent a small sample of the type of behavior that is often encountered. The first discontinuity in the HOFN residual time series is caused by an equipment change, which is often the case. However, the second discontinuity in the same time series cannot be associated with any reported event. The first and the last segments appear to be reasonably continuous; but there is no certainty of this. Should two or three segments be identified? Sometimes, because of various operational reasons, a station may not provide any data (see NSSP) for long periods of time. In those


IGS Weekly combination residuals at HOFN (Cumulative minus Weekly)

IGS Weekly combination residuals at NSSP (Cumulative minus Weekly)

IGS Weekly combination residuals at REYK (Cumulative minus Weekly)

IGS Weekly combination residuals at SCH2 (Cumulative minus Weekly)

Figure 6: Station height residuals at four stations (HOFN, NSSP, REYK and SCH2).

cases the time series does not provide enough information to identify potential discontinuities. Should a discontinuity be identified every time there is an uncertainty about the discontinuity in a time series? External information such as plate motion models may sometimes be of some help to reach a conclusion. The stations with only white noise residuals tend to be the exceptions. Stations with time series like those for REYK and SCH2 tend to be fairly common. In those cases, the anomalous behavior of the time series residuals is gradual, and most often cannot be easily related to specific events that are usually reported in the station logs. Many stations contain a seasonal signature in the time series residuals, which may also vary significantly from year to year. In some cases, the seasonal variations may even have the appearance of a discontinuity SCH2 (1090-1103). Should these cases be treated as discontinuities or seasonal variations? Where do one start and the other ends? Generally, the smaller the anomaly, the longer a time series is required to identify a discontinuity with a high degree of confidence. This can be problematic when a timely identification is desired. Even in the case where a clear discontinuity can be identified, it may be temporary. The identification of the cause could resolve the temporary/permanent nature of the discontinuity. Usually, the discontinuity can be related to local environment, equipment change/malfunction, processing changes. In the case of temporary discontinuity (~ one month??), a new solution should probably not be started. The anomalous solutions should simply be discarded. The anomalous behavior interval may sometimes be difficult to determine. To make the decision process even more interesting, more than one cause of perturbation can occur over a short time span. When they are identified, their characteristics can be tabulated. Altamimi, Z. 2004 suggested the format in Appendix III to tabulate those discontinuities. It was also suggested to compile/update two of those tables. The first table would contain the discontinuities that are clearly established. The second table would contain the questionable discontinuities. Those tables also need to be publicly available.

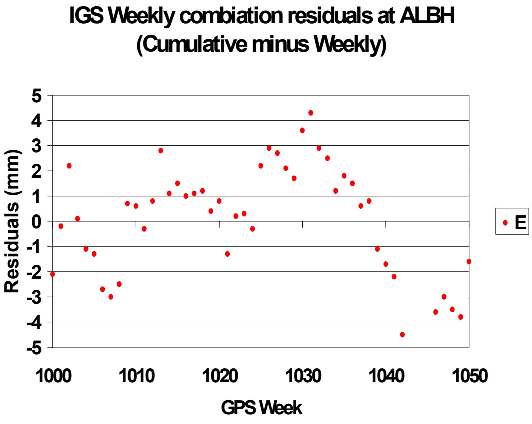


Figure 7: Station east residuals at station ALBH.

A uniform decision threshold may not be practical or even desirable. Some small real discontinuities may actually be approaching the processing noise level. Figure 7 shows the residual time series (IGS cumulative minus IGS weekly) at station ALBH for the east component between GPS weeks 1000 and 1050. If one looks very carefully (and with some imagination), it may be possible to identify a small discontinuity (2-3 mm) around GPS week 1023. ALBH was one of several stations that did experience in 1999 (GPS week 1023) a so called "silent slip" (Dragert et al. 2001) about 2-3 mm but, without prior knowledge or very detailed analysis, these types of events cannot be identified. For a first iteration of the detection and inclusion of small discontinuities will not be included. In the uncertain cases, it becomes a judgment case.

The identified discontinuities need to be included in the cumulative solution. A few possibilities have been proposed (some requiring SINEX format extension). The larger discontinuities are already accounted for by estimating a new coordinate/velocity pair. This is the most natural and flexible way to include such discontinuity. The existing format can readily handle this. It is proposed to handle all discontinuities this way. The inclusion of a large number of discontinuities will also have a significant impact on the number of parameters in the cumulative solution and the processing requirements (see also section 4-4). Various conditions could potentially be imposed on the position/velocity estimates (height difference condition, equal horizontal position, equal velocity condition). It is suggested not to impose any conditions in the official IGS cumulative solution. Those conditions should instead serve to quality control the official solution. Those conditions could be imposed on “derived” products. For example, velocity conditions were imposed on a cumulative solution when the most recent (IGb00) reference frame realization was prepared.

The inclusion of the discontinuities is unavoidable it was even included in the first version of the SINEX format. It makes it possible to have multiple solutions for a single physical marker (DOME#). It is used to account for real sudden motion such as those caused by earthquakes. It is also used to account for technique specific time series discontinuities (see above). For collocated sites, the local markers used by each technique are connected with local survey. The technique specific discontinuities at collocated sites may become problematic for multi-technique combinations. In those cases, some techniques may have a single solution while others may have several for the same time span and with a constant local tie. In those cases, the selection of the solution (if any) referring to the physical marker may often be problematic.

Recommendation 6:
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Generate two lists of station position discontinuities: one with “known/certain” station position discontinuities and another one with “suspected/probable” discontinuities. Some AC have already identified a number of discontinuities, their contribution is certainly welcomed. A related activity is to recombine the weekly/cumulative solutions to include the discontinuities.

3-2-3 Reference Frame

The objective is to provide the most stable and reliable reference frame realization for the IGS current and future products, using all the available past and present information. In the past and current realization of the reference frame (IGS96, IGS97, IGS00, IGb00) several criterions were used for the selection of station (Kouba et al. 1998). The most frequently used criterions are:

- Usage/performance (RMS/Years)
- Monumentation/geology
- Geometry
- Collocation
- Coordinates/velocity quality
- Hardware

The most important criterion considered was the station performance. Stations down or not providing timely and quality data could generally not be included. Those stations were generally rejected without further considerations, except for those experiencing temporary problems. Geometry was also an important criterion. For regions such as North America and Europe, it was rather easy to find enough quality stations to provide a good coverage. In other areas, the choice was much more limited. The “IGS Site Guidelines” (Moore, 2003) provide clarifications for the IGS community. As was the case in the past, few stations met equally well all the selection criterions. During the selection process, it was felt that the “subjective” weighting of the selection criterions was far from ideal. However, an objective selection criterion may only provide partial guidance to the process.

One alternative, could be to include all the stations…. and hope for the least squares process to provide the solution. In the current state of the Reference Frame realization, most of the quality stations are already included. The quality stations left out are mainly in North America and Europe, where their density exceeds the IGS requirements. To ensure continuity, between the successive realizations, a maximum overlap is desired; however the use of the best stations may and does require that some stations be replaced.

In the current AC (ultra) rapid orbit/clock estimation procedure, the stations are fixed. Occasionally, for various reasons, the coordinates of a station may change well beyond the usual noise level. This can potentially cause significant distortions in the estimation of the orbit/clock/ERP’s parameters. This is most critical for the ERP's because they are approaching the mm accuracy (at present the orbits and clocks have not yet reached the sensibility as the ERPs). In the final SINEX combination, those problem stations can generally be identified and removed automatically. In principle, if the ACs solve for the stations coordinates in their analysis (more parameters to solve in their (ultra) rapid solutions), then the estimated station coordinates can be tested against their expected reference frame values to a given confidence level; any outlier station can then be: 1) removed before constraining to the reference frame, or, 2) simply not constrained to the reference frame. This should prevent abnormal behavior of the orbit/clock/ERP’s estimates. With appropriate constraints, results very similar to the current procedure could be obtained. Alternatively, the station coordinates can be constrained to a realistic level (e.g.: ~10 mm) during the processing to allow for expected daily variations. With the current number (~100) of stations, the solution should be relatively insensitive to outliers of up to a 2-3 cm. The estimated station coordinates can be tested, and the outliers can simply be unconstrained. The reference frame realization accuracy should approach the mm level.

The ACs could also continue with their current approach, and add PPP solutions using the estimated orbits & clocks to check for any abnormal behavior of the stations. If such an approach would not be feasible at the AC level (too high burden) sub-optimal approaches can be put in place. After each Rapid combination the Analysis Coordinator can perform a PPP using the combined orbits and clocks to check all stations. For practical reasons, the network could be restricted to the core stations (about 100), i.e. in this case the ACs must not constrain a non-core station. Even if this can only be done with a delay of 1 day, it would be a step forward. It should be up to the ACs to find their optimal approach.

Recommendation 7:
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Provide updates to the reprocessed weekly SINEX solutions. It is suggested to keep those solutions separate from the official ones (CDDIS), and with a distinct, but similar naming convention. Updates should be provided when significant improvements have been made.

3-2-4 Reanalysis

As is sometimes the case, at the time of the official SINEX combination (less than 2 weeks after the end of each GPS week), incomplete, or even erroneous information is available. Improved combination is often possible following detailed analysis. One obvious case of this is the resolution of the station coordinates discontinuity. Reanalysis has been an ongoing process. Improved solutions have been made available for some ERP studies. Improved cumulative solutions are from time to time included as part of the weekly updates. Just recently, as the MIT AC solutions were officially included in the official weekly processing, almost one year tests solutions received in 2003 were also included in the cumulative solution (+used IGb00). These ongoing improvements should probably be made publicly available. Precautions need to be taken to ensure that there is no possibility of confusion between those and the official SINEX combination products available at CDDIS. They should be put in a separate location and probably using a different naming convention. They need only to be updated as required. It must be done such that there cannot be confusion with the existing official products.

The reanalysis by the ACs of the code/phase measurements is another matter. This was suggested several times in the past. To get consistent weekly SINEX products over the whole IGS history would certainly contribute to an improved ITRF realization. The ACs should get ready to reprocess in the future the global data periodically. The introduction of significantly improved models would justify reprocessing.

Recommendation 8:
==============

The ACs need to verify the stability of the RF stations before constraining them during the generation of the (ultra) rapid orbit/clock products. Additionally, a PPP will be applied after the combination to check the RF station positions.

Recommendation 9:
==============

The AC should be prepared to reprocess the IGS data. The detailed procedure should be discussed after the absolute antenna phase center variation models are decided (see Antenna session).

3-2-5 TIGA

In 2001 the Tide Gauge Benchmark Monitoring Pilot Project (TIGA, http://op.gfz-potsdam.de/tiga/) was established, focusing on the analysis of GPS data near tide gauges. The project was initiated because the current IGS solutions are not fully fulfilling the requirements of the sea level community in terms of: (a) completeness, several GPS stations near or at tide gauges are not part of the IGS network, and (b) accuracy for the vertical component. The uncertainty of the vertical rate required for sea level studies need to be better than 1 mm/yr. This value is still not reached for most of the stations.

Currently six TIGA analysis centers (TAC) are processing GPS data not limited to IGS stations. Processing is done with about 460 days latency. In addition, a reanalysis of past data is performed by some TACs leading to a homogeneous data set. The TACs are using almost identical processing strategies as the ACs, thus later solutions are comparable but past solutions are supposed to be less affected by e.g. software changes or late detected hardware failures. A particular problem of TIGA is the difference in the network coverage of the individual TAC solutions, ranging from global to regional.

For TIGA it is necessary to select subsets of reference frame stations for the analysis. Here, the project benefits from the IGS reference frame. With a large number of weeks that are reprocessed, the individual time series of all stations can be analyzed prior to defining a set (or all) RF stations. Tests need to be performed to find stations with a reliable and stable history (see “IGS Site Guidelines”, Moore, 2003), and sufficient data span. Moreover, a combination of the vertical time series with tide gauge measurements may be useful for the selection of RF stations. Preliminary studies indicate that a lot of attention is required in the selection of the reference frame stations to provide meaningful interpretation of the time series. Improper selection of RF stations may easily lead to vertical rates that are inconsistent with tide gauge measurements (i.e. sea level rise to fall or vice versa). In order to find differences in the solutions provided by the TACs correction models used (e.g. load) should be analyzed to eliminate of small inconsistencies not addressable to e.g. hardware changes. For models which cannot be harmonized between the TACs for various reasons, the tabulated values for all points should be made available to allow further analyzes. In addition, to further minimize seasonal or aliasing effects, resulting from different modeling of e.g. tides, studies should be carried out how to remove these effects before any combination for TIGA is started.

4 ORBIT AND CLOCK PRODUCTS

Now we would like to discuss some aspects on accessing the RF using the IGS combined orbits and satellite clocks.

Abbreviations used in this section:

CoM	: Center of Mass (including ocean, atmosphere)
CoN_{RF}	: Reference Frame (RF)-Origin (center of RF network)

X_{AC}, X_{IGS} : Station coordinates from AC and IGS SINEX combination
Y_{AC}, Y_{IGS} : SP3 satellite positions from AC and IGS Combination

To get a better understanding, how different strategies in handling constraints on RF defining stations are influencing the orbit and clock solution, small studies were performed. In the study the RF was shifted and tightly constrained to the new position to investigate the behavior of the adjusted solution. The results are:

S1. The Center of Mass (CoM) determined by the GPS orbits (SP3) will follow the RF shift only by:

> (dx dy dz) ~ (10% 10% 20%) if the solution is ambiguity fixed[**]
> (dx dy dz) ~ (40% 40% 50%) if real ambiguities are solved for
> [**] about 90% percent of ambiguities fixed
>
> i.e. in any case the SP3 orbits are referenced to the CoM, and in case of fixing the RF the deviation "CoM-CoN_{RF}" influences the CoM determination by about 10% of that deviation.
>
> The scale and the rotations are not affected.

S2. If the SP3 orbits and satellites clocks are used for a Precise Point Positioning (PPP) (Zumberge, et al., 1997), the resulting station coordinates are in the shifted RF, more precise they follow the RF shift by:

> (dx dy dz) ~ (90% 90% 100%)
>
> i.e. the clocks adopt for the RF shift.

Additionally, the discussion below uses the following statements (Kouba, 2000):

> If the orbits and satellite clocks are given in Frame A ($SP3_A$ and CLK_A), and the PPP station coordinates are wanted in Frame B, then two options are possible:
>
> V1) Shift $SP3_A$ to Frame B ($SP3_B$)
> ==> PPP with $SP3_B$ and CLK_A gives station coordinates in Frame B
>
> V2) Transformation of CLK_A to Frame B (CLK_B)
> ==> PPP with $SP3_A$ and CLK_B gives station coordinates in Frame B
> *Attention: PPP with $SP3_B$ and CLK_B gives station coordinates in Frame A.*

4-1 Final Combination (Status: end 2003)

The weekly final solutions from all ACs are consistent in either unconstrained or minimum datum constrained.

The AC final orbits and satellite clocks ($SP3_{AC}$, CLK_{AC}) are referenced to the instantaneous CoM_{AC}. The combined Final orbits ($SP3_{FIN}$) are then in the weighted mean CoM from all the AC solutions (CoM_{FIN}). During the clock combination the input clocks CLK_{AC} are corrected with

$$dCLK_{AC}= (Y_{AC}-Y_{IGS})^{*}\ Y_{AC})/Rsat/c \ , \qquad (1)$$

which accounts at the same time for the radial differences between $SP3_{AC}$ and $SP3_{FIN}$ and the difference "CoM_{AC} - CoM_{FIN}". Therefore, finally the CLK_{FIN} are referenced to the CoM_{FIN}.

Final products:

- $SP3_{FIN}$ in CoM_{FIN} (mean of all CoM_{AC})
- CLK_{FIN} in CoM_{FIN}
- PPP gives station coordinates in CoM_{FIN}

This describes the ideal case. In reality, some ACs are handling their product generation in several steps, to ensure in their daily products the consistency to the weekly SINEX solution. Those processes may give some small effects, but possibly significant for the level of accuracy we are aiming in near future, or different references for the clocks (CoM_{AC} or CoN_{ITRF}). Therefore, the AC procedures have to be evaluated and checked, if any calibration has to be applied during the combination.

4-2 Rapid combination *(Status: end 2003)*

During the Rapid analysis the ACs are fixing the RF to the given ITRF realization. Then, reflecting to the above-mentioned study the AC products are:

- $SP3_{AC}$ in CoM_{AC} (approximately, depending on the level of phase ambiguities fixed)
- CLK_{AC} in CoN_{ITRF}.

The combined orbits ($SP3_{RAP}$) are given in the weighted mean CoM from the ACs solutions (CoM_{RAP}). During the clock combination the input clocks CLK_{AC} are again corrected with formula (1), which corrects only for radial differences and the differences "CoM_{AC} - CoM_{RAP}". i.e. the CLK_{RAP} will keep in CoN_{ITRF}.

Rapid Products:

- $SP3_{RAP}$ in CoM_{RAP} (mean of all CoM_{AC}) (approximately, depending on the level of phase ambiguities fixed)
- CLK_{RAP} in CoN_{ITRF}
- PPP gives station coordinates in CoN_{ITRF}

4-3 Discussion

From the above summary it can be seen that the SP3 orbits are in both cases in the CoM. The different reference for the satellite clocks yields station coordinates in different frames, either CoN_{ITRF} or CoM_{FIN}, using Rapid or Final combined IGS products in PPP, respectively.

The CoM_{FIN} should be consistent with the geocenter motion derived from the SINEX combination using the CoN_{AC}. This can only be proven if one would regularly perform PPP using the Final products. Therefore it should be recommended to include into the Final combination a step validating the orbit and clock products by PPP using a sufficiently dense global network, e.g. all the core stations of the latest IGS ITRF realization. A similar procedure can be applied to the Rapid products.

To overcome the divergence between Final and Rapid based PPP one has to introduce some changes into the combination process. Shifting the Final clocks would be one possibility to solve the problem, i.e. (Kouba, 1998)

$$dCLK_{AC}= (Y_{AC}-Y_{IGS})^{*}\ Y_{AC} - DX)/R_{sat}/c, \qquad (2)$$

with

$$DX = \text{"}CoM_{FIN} - CoN_{ITRF}\text{"} = \text{IGS Geocenter motions in ITRF.}$$

DX could be computed from the SINEX combination result "CoN_{Combi} - CoN_{ITRF}" supposing that the AC results are consistent, and that the CoN_{AC} approximates the CoM_{AC} and similar weights in orbit and SINEX combination are used (then $CoN_{Combi} \cong CoM_{FIN}$). Finally the CLK_{FIN} and hence the station coordinates derived by PPP would be in ITRF. But this can only be proven applying the already mentioned PPP with the Final products. As a result we would have both for Rapid and for Final the orbits in $\text{CoM}_{\text{Combi}}$ and satellite clocks in CoN_{ITRF}, which will yield station coordinates in ITRF using PPP (but only by PPP).

This raises also a more general question, if the orbits are in CoM and the clocks in ITRF, then the PPP gives results in ITRF. But, if the user takes only the orbits, then his solution will be in CoM. Even if we have here an inconsistency, it should be recommended to keep the orbits in CoM. CoM-orbits offer a more consistent solution with other satellite geodetic applications, and users mixing IGS orbits into their analysis (e.g. LEOs) will have a consistent handling of all parts.

For the application of (2), it has to be checked, if CoN_{AC} approximates with sufficient accuracy CoM_{AC}. The error of this approximation cannot be accessed directly from the information available (this will change if in future PPP results are available). One can only get an impression on the overall quality, if one compares the time series of "CoM_{AC} - CoM_{FIN}" from the Final orbit combination with that of "CoN_{AC} – $\text{CoN}_{\text{Combi}}$" from the SINEX combination. If they do not agree reasonably, then CoM_{AC} and CoN_{AC} may not be in good agreement, and the SINEX geocenter solution cannot be used to approximate DX. From Figure 8 and Table 1 one can see that the quality in the agreement between the two series is not sufficient over the whole time interval, so that at present the application of (2) is not feasible. The differences are often larger than the geocenter motion itself. Here some more investigations are needed to find the reasons for that differences in general, and especially for the ACs where we see larger deviations now.

Table 1: Comparison of differences "CoM_{AC} - CoM_{FIN}" and "CoN_{AC} – CoN_{Combi}" (units: mm)

AC	Orbit "CoM_{AC} - CoM_{FIN}"			SINEX "CoN_{AC} – $\text{CoN}_{\text{Combi}}$"			Orbit - SINEX		
	X	Y	Z	X	Y	Y	X	Y	Z
COD	1 ± 1	0 ± 1	-1 ± 8	8 ± 8	6 ± 5	-4 ± 12	-7 ± 8	-6 ± 4	2 ± 7
EMR	0 ± 3	0 ± 3	2 ± 7	-2 ± 10	1 ± 8	-2 ± 14	2 ± 10	-2 ± 7	4 ± 9
ESA	-2 ± 4	2 ± 2	-5 ± 8	-10± 12	12 ± 8	0 ± 11	8 ± 13	-10 ± 8	-4 ± 13
JPL	0 ± 3	2 ± 3	0 ± 4	-2 ± 10	3 ± 5	-6 ± 8	2 ± 10	-1 ± 5	6 ± 8
NGS	-5 ± 4	-3 ± 5	9 ± 20	-6 ± 9	-2 ± 8	6 ± 30	1 ± 8	-1 ± 7	3 ± 14
SIO	-2 ± 3	-1 ± 4	-4 ± 12	6 ± 9	-2 ± 5	41 ± 25	-8 ± 9	1 ± 7	-45 ± 19

The variety of approaches by the ACs makes it rather complicated, if not impossible, to get a clean combined clock solution in the ITRF. Therefore it is welcome, and should be recommended, that all ACs will generate clocks in the ITRF.

Recommendation 10:
===============

All IGS satellite clocks should be in ITRF center of network. This is the case for the (Ultra) Rapid products and should be realized for the Final product too. ACs should fix their shifted station coordinates (use of AC station solutions transformed into RF by Helmert transformation) while back substituting for final clocks (short term).

Recommendation 11:
==============

The quality of the PPP realization of ITRF using IGS products (Rapid and Final) will be monitored; changes in the combination have to be prepared. For the most demanding users, the 7-parameters transformations will be made available.

5 RECOMMENDATIONS

1) To resolve potential constraints issues, it is proposed that for GPS weeks 1268 to 1270, the ACs contribute SINEX solutions obtained without constraints on any parameters along with their usual SINEX solution. If for any reason, any apriori constraints (orbit, troposphere … etc) are used on any parameters, they must be reported along with their expected influence on SINEX parameters.
2) Check/compare the effect of the weighting strategy on the estimated transformation parameters in the current IGS combination strategy by selecting a few GPS weeks.
3) Estimate and report a scale factor between the IGS weekly combined solution and the IGS realization of ITRF.
4) Review the combination procedures with the GNAACs, to better explain and possibly reduce the observed differences. Ideally, in this type of analysis, the processing noise should be kept well below (one order of magnitude) the signal.
5) The modeling differences between ACs need to be compared to understand the observed small systematic differences between the AC station coordinates, orbits and clocks. As a starting point, a summary of all the AC processing/modeling is being compiled. The information available from the *.acn files is used for this compilation. The ACs should update the file every time any significant analysis change is made.
6) Generate two lists of station position discontinuities: one with "known/certain" station position discontinuities and another one with "suspected/probable" discontinuities. Some AC have already identified a number of discontinuities, their contribution is certainly welcomed. A related activity is to recombine the weekly/cumulative solutions to include the discontinuities.
7) Provide updates to the reprocessed weekly SINEX solutions. It is suggested to keep those solutions separate from the official ones (CDDIS), and with a distinct, but similar naming convention. Updates should be provided when significant improvements have been made.
8) The ACs need to verify the stability of the RF stations before constraining them during the generation of the (ultra) rapid orbit/clock products. Additionally, a PPP will be applied after the combination to check the RF station positions.
9) The AC should be prepared to reprocess the IGS data. The detailed procedure should be discussed after the absolute antenna phase center variation models are decided (see Antenna session).
10) All IGS satellite clocks should be in ITRF center of network. This is the case for the (Ultra) Rapid products and should be realized for the Final product too. ACs should fix their shifted station coordinates while back substituting for final clocks (use of AC station solutions transformed into RF by Helmert transformation) (short term).

11) The quality of the PPP realization of ITRF using IGS products (Rapid and Final) will be monitored; changes in the combination have to be prepared. For the most demanding users, the 7-parameters transformations will be made available.

6 ACKNOWLEDGEMENTS

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8 APPENDICES

Appendix I

RESIDUAL Tables/Plots

```
ftp     macs.geod.emr.ca
cd      /pub/requests/sinex/res/
```

The residual files tables are identified by:

1) Station code (4 character)
2) AC or GNAAC (or igs weekly if applicable)
3) Igs (weekly) or IGS (cumulative)
4) .res

For example in the file "ALGO_igs_IGS.res"
(1) (2) (3) (4)

Their contents has the form:

```
Week Center Station         dN        dE       dH       sN       sE       sH
```

Example:

```
0999    igs     ALGO        -2.3     -1.5       .5      1.8      1.9      3.8
1000    igs     ALGO         -.9      -.8      4.0      2.1      2.2      3.8
1001    igs     ALGO        -2.0     -1.0       .3      1.9      1.8      3.5
1002    igs     ALGO        -1.6      -.8       .7      1.7      1.6      3.3
1003    igs     ALGO         -.5     -1.1     -3.9      1.7      1.7      3.4
1004    igs     ALGO         -.4       .7     -4.5      1.8      1.7      3.2
```

....

(dN, dE, dH) = residuals for station ALGO between the cumulative solution and the weekly solution (IGS99P10.snx - igs99P1000.snx).

(sN, sE, sH) = Standard deviation for station ALGO based on the weekly solution (igs99P1000.snx) covariance information.

Corresponding postscript (*.ps) files are also available in the same directory. Similar name convention is used with the addition of the axis (_N, _E, _h) between (3) and (4).

Appendix II

SUMMARY Tables/Plots

ftp macs.geod.emr.ca
cd /pub/requests/sinex/sum/

The summary file tables are identified by:

1) Summary section # (5-1,5-2-1,5-2-2,5-2-3,5-3-1,5-3-2,5-3-3,5-4,5-5-1,5-5-2)
2) AC or GNAAC or igs centers
3) .sum

For example: 5-2-1_cod.sum
(1) (2) (3)

The content varies from section to section, and is identical to the corresponding section in the summary reports.

The summary postscripts (*ps) plots are identified by:

1) Summary section # (5-1,5-2-1,5-2-2,5-2-3,5-3-1,5-3-2,5-3-3,5-4,5-5-1,5-5-2)
2) An acronym for each column within each section.
3) .ps

Appendix III

The purpose of this format is to keep a record of station coordinates time series discontinuities. This proposed format is based on the SINEX format. It is a variant of the “SOLUTION/EPOCH” currently in the version 1.0 of the format description. To avoid any possibility of misunderstanding, this block should be accompanied with the “SITE/ID” block. This allows to physically relate the information to a “DOME#”.

```
+ SOLUTION/DISCONTINUITY
*CODE PT SOLN T _DATA_START_ __DATA_END__ ________COMMENTS__________
 BRMU  A    2 P 03:071:69300 00:000:00000 Antenna & Receiver Changes
 FAIR  A    2 P 02:308:00000 00:000:00000 Denali earthquake
 ....
- SOLUTION/DISCONTINUITY
```

S O L U T I O N D I S C O N T I N U I T Y D A T A L I N E		
Field	Description	Format
[Site Code]	Site code for which some parameters are estimated.	1X,A4
[Point Code]	Point Code at a site for which some parameters are estimated.	1X,A2
[Solution ID]	Solution Number at a Site/Point code for which some parameters are estimated.	1X,A4
[Observation Code]	Identification of the observation technique used.	1X,A1
[Time]	Start time for which a discontinuity has been identified.	1X,I2.2, 1H:,I3.3, 1H:,I5.5
[Time]	End time for which a discontinuity has been identified.	1X,I2.2, 1H:,I3.3, 1H:,I5.5
[Comment]	Short explanation describing the cause of the discontinuity.	1X,A41
		80

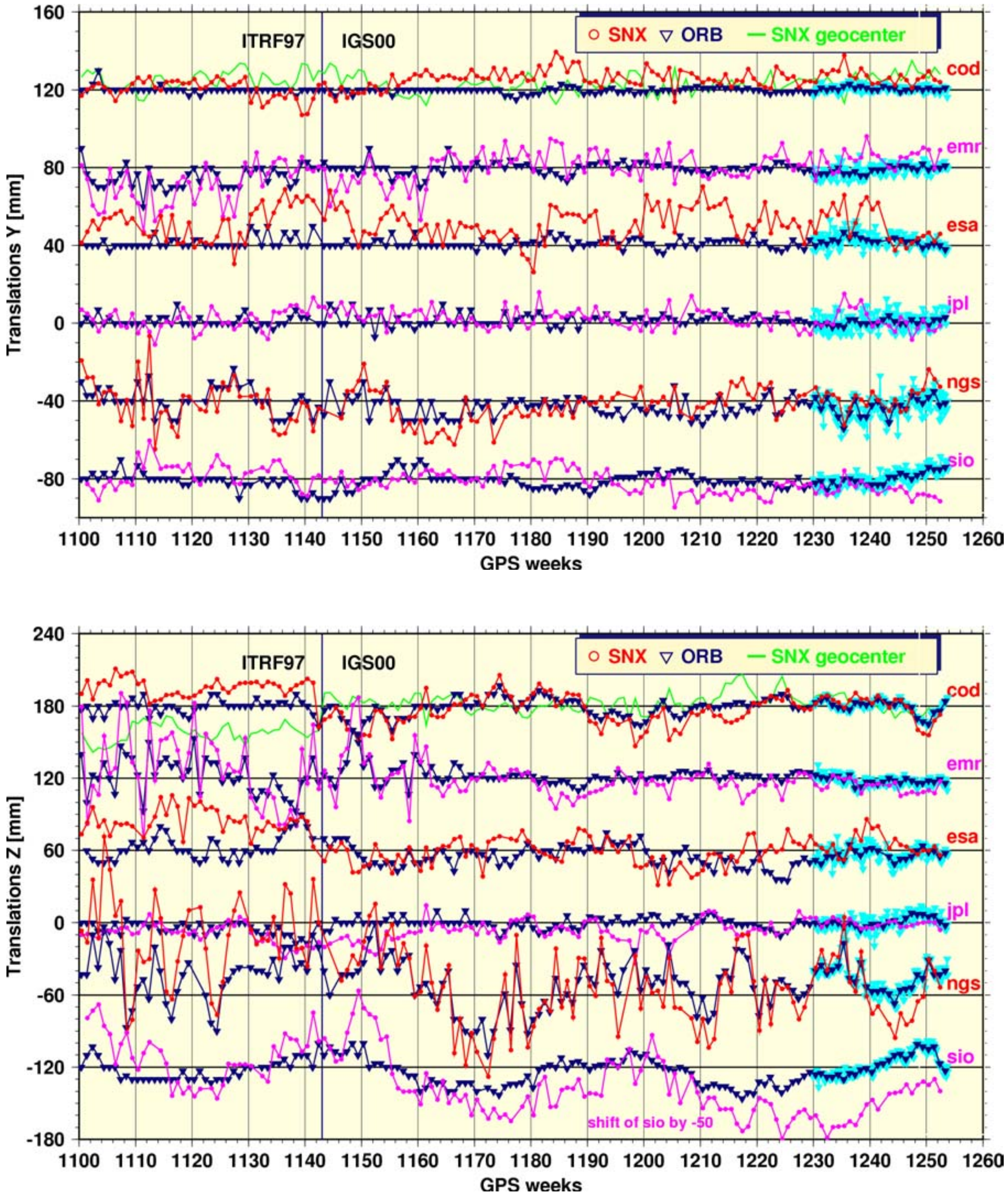

Figure 8: AC apparent geocenter motion derived from weekly AC SINEX solutions (SNX) (difference to weekly mean SINEX geocenter, see also. Fig. 1) compared to geocenter motion derived from orbit combination (ORB) (difference to combined Final orbits, weekly mean). The daily scatter for the ORB values are indicated at the end of each curve. The weekly mean SINEX geocenter is given in the 'cod' example as additional information. Note: the translation for the X component has been omitted here because it is very similar to the Y component.