IGS

SESSION 7:

REFERENCE FRAME

REGIONAL NETWORKS DENSIFICATION

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ABSTRACT

The core IGS products include a consistent set of station coordinates/velocities, earth rotation parameters (ERPs); GPS satellite orbits and station/satellite clock estimates. These products are generated from the weekly contributions of seven Analysis Centers (COD, EMR, ESA, GFZ, JPL, NGS and SIO). The final station coordinates, ERPs and precise satellite orbits are made available weekly with about two weeks delay after the GPS code and phase measurements are collected. The core products are currently aligned to the IGS realization of ITRS. The agencies generating solutions for regional networks have been using the IGS precise orbits and in some cases ERPs and clock estimates for their work. The reference frame realized by the precise orbits is implicitly used for regional network computations. The orbits, code/phase measurement noise level as well as the processing strategy, impose some limitations on the alignment of the regional networks densification to the ITRF. The resulting reference frame of the regional network, although close to the ITRF, requires some additional considerations. Several methods are available for the regional network densification. Some are presented here and proposed.

The case of the local networks is not specifically discussed here. It is assumed that the responsibility for local network lies either with regional or national agencies. However, the densification approaches discussed here for the regional networks are also likely applicable to local networks.

INTRODUCTION

There has been a need for geodetic network combination/densification/integration since the early days of traditional surveying. In fact, this was a primary incentive to the creation of the IGS itself. International Association of Geodesy (IAG) has also been interested in this subject for a long time, e.g. within Section I through Commission X on Global and Regional Geodetic Networks. Although the scope of Commission X is much broader than that of the RFWG, there are some common objectives when it comes to ITRF densification. Each Sub-commission of Commission X has a continental scope and their interest is not limited only to GPS, although it is undeniably the most widely used densification tool. Here, our interest is limited to networks of continuously operating GPS stations, which can be divided into global networks, i.e., the IGS polyhedron, and regional networks of continental size.

The objective here is limited to provide suggestions and guidelines to agencies with regional networks for the densification of their networks into ITRF, preferably with the use of the IGS products. It is here assumed that this regional network densification will be an ongoing weekly effort to add the most recent information to the continuously observing network.

From its terms of reference, the IGS primary mission is "to provide a service to support, mainly through GPS data products, geodetic and geophysical research activities". This has been achieved with the generation of several official combination products: station coordinates/velocities, ERP's, GPS satellite orbit, station/satellite clock corrections, tropospheric delays, and ionospheric TEC grids. These products are generated from the solutions provided by the IGS Analysis Centers (ACs). Within the IGS, the first four products are also known as the core products. The first two are combined products generated within the Reference Frame Working Group (RFWG). The RFWG charter states, "The group will generate the official IGS station coordinates and velocities, earth rotation parameters (ERP) and geocenter estimates…" The other two core products, i.e., satellite orbits and clock corrections, are generated separately by the AC Coordinator while maintaining full consistency with the station coordinate and ERP combined products from the RFWG. These last two products also instrumental in the densification of ITRF.

The RFWG terms of reference have also set a target of 200-250 stations for a "well distributed and high quality" global network, the so called the IGS polyhedron (Blewitt et al., 1994). This target number of

Polyhedron stations has been independently proposed by several individuals (Zumberge et al., 1994; Blewitt et al., 1994; Beutler et al., 1994). The underlying objective of the polyhedron is to support efficient densification of the ITRF for regional activities. More specifically, the well-distributed 200-250 station polyhedron network yields an average station separation of about 2000 km, which should facilitate precise relative positioning over baselines of 1000 km or shorter (Beutler et al., 1994). In areas where GPS is widely used (E.g.: Europe & North America) the target station separation has easily been met and even exceeded. The covariance information of the weekly and cumulative products is also required.

IGS GLOBAL/POLYHEDRON NETWORK

Originally, the IGS considered creating a global network (~100 stations) and a polyhedron densification network (~100-150 stations), for a total of 200 - 250 stations. The global network was to be generated from the global solutions submitted by ACs, while the densification network was to be assembled from a set of stations selected from the combined solutions of IGS Regional Network Associated Analysis Centers (RNAACs) (Blewitt et al. 1994; Davis, P. 1997). However, with a steady increase in the number of stations included in the AC global solutions, the goal of 200-250 well-distributed polyhedron stations in the cumulative solution has been achieved without the need for regional solutions. There are currently 218 stations available in the cumulative solution. The cumulative solution currently released, is a subset of a more comprehensive cumulative solution that includes over 300 stations. New stations are being added almost weekly. This is a significant development, considerably simplifying and speeding up the generation of the IGS polyhedron network and, in fact, eliminating the necessity for a distinction between the IGS global and polyhedron networks.

Within IGS, two Global network solutions are produced, namely, a weekly and a cumulative (multi-year) solution. The weekly solutions include station coordinates, apparent geocenter and daily ERP's. The seven ACs provide the essential building blocks, by generating weekly solutions and making them available using the "Software INdependent Exchange" (SINEX) format. Their combined weekly solutions currently contain station coordinates for up to 150-170 stations (+ implicit geocenter + daily ERP's). Their SINEX files also include full variance-covariance information for all the estimated parameters, the a priori constraints used in their solutions, as well as auxiliary information about the receivers and antennas. The weekly AC solutions are also routinely used by two IGS Global Network Associate Analysis Centers (GNAAC), namely, MIT and NCL. The MIT weekly combination includes station coordinates and daily ERP estimates while the NCL combination is limited to station coordinates. Currently, the GNAAC solutions are used to quality control for the official IGS weekly solution generated within the working Group. The cumulative solutions are updated weekly by rigorously accumulating the unconstrained station coordinates contained in the IGS weekly solutions as discussed above.

The IGS realization of ITRS is defined by a subset of stations from the IGS Global network. For the current IGS realization of ITRS (IGS00), 54 high quality station coordinates and velocities were selected (Ferland, 2001;Weber, 2001), and are generally referred to as the Reference Frame (RF) stations. There are generally between 45 and 50 RF stations in the IGS weekly combinations. The current IGS realization of ITRS was generated using a selected IGS cumulative solution (IGS01P37.snx), which was aligned to ITRF2000 by an unweighted 14-parameters (position/velocity) Helmert transformation using the selected 54 RF stations. The relatively large number of stations, their high quality and good global distribution ensure a stable and precise alignment to ITRF. The alignment of the IGS weekly combined SINEX products is done using all the available RF stations (subject to outliers detection/rejection). The excellent internal consistency between the IGS realization of ITRS and the weekly SINEX products enables their alignment to be precise and stable. In addition, the current IGS realization of ITRS includes data up to September 2001 while ITRF2000 includes IGS data only up to November 2000. Because the IGS realization of ITRS uses up to date data, it also benefits from a shorter extrapolation in time for generating current products, which reduces the effect of errors in the estimated coordinate velocities. This also contributes to the internal stability of the solutions. It is also feasible to update the IGS realization of ITRS only weeks before its implementation to ensure even greater consistency and stability. Weekly solutions with latency of no more than two weeks may also be used. The short latency also allows to quickly taking advantage of new stations.

The interaction between ITRF and IGS is two folds. On one hand, IGS, along with other techniques, provides cumulative solutions for an ITRF realization. This has generally occurred every 2-3 years. On the other hand, once a new ITRF solution is available, it is used every day without requiring "active" IERS intervention/support. This day-to-day interaction is very similar to the global/regional interaction that is discussed above.

As the process of quality improvement continues within the IGS, IVS, ILRS and IDS communities, a convergence of those techniques within the ITRF combinations is expected. The relatively important weight of all the GPS contribution and the weakness of the local ties have contributed to favor GPS stations within the ITRF combination. Each IGS contribution to ITRS is a cumulative solution, thus, determined from GPS measurements only. ITRF is however unique as it takes advantage of multiple techniques, each one having specific strength and weaknesses. IERS is considering adding station coordinates time series as a new ITRF product. Although, the details are not available yet, the weekly IGS solutions can already form the basis to participate to that eventual product. Regional networks will potentially be in a good position to take advantage of this product.

CONTINENTAL/REGIONAL NETWORKS

A continental-size regional network is here arbitrarily defined as having a station spacing of between 100 km and 1000 km and spanning only a limited portion of the globe. The IAG Commission X Sub-commissions should have their own definition of what makes a station "regional". The IGS global network provides up to date accessibility of the ITRF. Most agencies responsible for regional networks already benefit indirectly from the IGS realization of ITRS when using the IGS precise orbit products. Regional networks are generally installed and maintained because the station density of the global network is insufficient for the users applications. This is where regional networks do provide an increased station density and therefore an improved accessibility to the ITRF.

The following paragraphs describe the activities of some of these Sub-commissions and their regional GPS networks that are currently operational or being implemented. Most of these Sub-commissions are acting as official IGS RNAAC's. Two examples of RNAAC continental/regional networks and activities are described below.

EUREF

The EUREF GPS Permanent Network (EPN) currently holds about 120 stations in and around Europe. The observations are analyzed according to the distributed processing approach. Local Analysis Centers (LACs) process the observations of a subnet of EPN stations. The Network Coordinator specifies these subnets of stations, and ensures each station to be processed by at least three LACs. Similarly to the IGS, up to date auxiliary information (site logs) is available for all the EPN stations. The EPN Central Bureau checks the consistency between the site logs and the RINEX headers on a daily basis and requests corrections from the station managers. RINEX data from all the EPN stations are available at different Local Data Centres and one Regional Data Center. The EPN data flow is organised following the IGS example. All EPN stations in the SINEX files have valid 4-char IDs and associated DOMES numbers. The receiver and antenna names comply with the IGS standard names and the IGS phase eccentricity tables are applied. The antenna/receiver names and antenna heights used have been crosschecked with the site logs. This is the case for both, the LAC solutions and the combined solution.

The LACs generate a weekly solution of the station coordinates in the SINEX format and submit these files to the Analysis Coordinator (AC). These weekly solutions are generated using the IGS precise orbits. The SINEX files must include the a-priori constraints that had been introduced in the parameter estimation procedure. With it, the constraints could be removed before the combination. It is highly recommended to constrain these solutions to the current ITRF realization. This recommendation yields the best possible consistency of the station specific troposphere parameters, which are submitted by separate SINEX-Troposphere files. The AC combines the weekly subnet solutions of the LACs into the EUREF combined solution. A between LACs comparison of the station coordinates is used to detect and mark outliers by allowing a maximum difference of 5 mm and 10 mm for the horizontal and vertical components. A comparison of the combined solution of seven subsequent weeks is performed to detect outliers in the coordinate time series. A SINEX file of the weekly final combined solution is published at EUREF's Data Center at BKG as official product. The reference frame of this solution is defined by heavily constraining (0.01mm) the current ITRF coordinates of 13 carefully selected stations.

The 'Troposphere Parameter Estimation' special project requires the generation and submission of daily troposphere files in the SINEX Troposphere format. The combination of the troposphere solutions is under responsibility of the Troposphere Coordinator (TC). The 'Time Series Analysis' special project is responsible for the maintenance of the coordinate time series homogeneity of the EPN sites. This SP is keeping track of the station performance and corrects for jumps and outlier periods found in the time series. The information about the jumps and outlier period will be applied for the generation of multi-year EPN solutions; similar to the ones submitted the IERS for the ITRF97 and ITRF2000 realisations. The table of jumps and outlier period can be made available to the IGS in order to guarantee that multi-year IGS and EPN solutions are consistent.

Additionally to the official weekly SINEX file the AC generates two preliminary 'densification products': (1) A weekly solution of the EPN is generated starting week 1136, which is consistent to the weekly global IGS solution, by heavily constraining (0.01mm) the station coordinates of all overlapping stations of IGS and EPN. (2) A cumulative EPN solution is generated starting week 1149, which is consistent to the cumulative global IGS solution by heavily constraining the coordinates of all overlapping stations. These two solutions are no official EUREF products and not publicly available, but could anyway be submitted to IGS. The procedure to generate the regional densification could of course be modified depending of decisions of the IGS. Once the IGS has defined clear guidelines for regional densifications, such products are candidates to become official EUREF products.

NAREF

The North American Reference Frame (NAREF) densification network is a new initiative that operates under the auspices of the NAREF Working Group of the IAG Commission X Sub commission for North America. The objective is to densify the IGS global network in North America through the combination of various existing regional networks and the production of weekly coordinate solutions. Eventually, cumulative solutions with velocities estimates may also be provided. The results are presently available from the NAREF web site at <*www.naref.org*> and will soon be submitted to the IGS Global Data Center.

The selection of stations and solutions for NAREF combinations has involved the adoption of standards and guidelines for station monumentation, station operation, data processing, archiving and redundancy. Most of these standards and guidelines have been adopted from those proposed by the IGS and those used by EUREF. The selection of stations for NAREF has been limited to dual frequency receivers that collect continuous 24 hr data down to a 10 degrees elevation and at a 30 second data rate for a minimum of 5 days a week. They must also have reasonably stable, geodetic quality monumentation. These criteria have been determined primarily by the availability of CORS stations in the U.S. The selection of regional solutions for use in the NAREF combination has been limited to only those using state-of-the-art software and that follow, as much as possible, the processing strategies described in Rothacher et al. [1998]. In particular, fixed IGS precise orbits and Earth rotation parameters should be used for highest accuracy and reference frame consistency. The results must also be provided in the SINEX format. In order to provide some kind of quality check on the regional solutions, there should be significant overlap between the global and regional networks. Ideally, all stations should be included in more than one regional solution to allow for outlier detection. Unfortunately, this redundancy is not met everywhere. Unlike EUREF, most regional solutions are performed by independent organizations with limited budgets and objectives that are often different from those of NAREF. It has been difficult, if not impossible, to enforce such standards.

The entire NAREF network presently consists of 110 stations; 23 of which are IGS global stations and 87 represent the NAREF densification stations. Four regional solutions have been contributing to

NAREF since the beginning of 2001. Natural Resources Canada's (NRCan) Geodetic Survey Division (GSD) presently provides two independent Canada-wide solutions. One is based on the Bernese GPS Software with a total of 53 points, about half of which are in neighboring areas in the U.S. The other GSD regional network is based on the GIPSY-OASIS II software with 33 stations, all in Canada. Regional solutions are also obtained from the Scripps Institution of Oceanography for the Plate Boundary Observatory consisting of over 300 points along the West Coast of the U.S. and based on the GAMIT software. Only 53 stations in the northern part of the network are included in NAREF because of limitations in the combination software (this will be rectified in the near future). NRCan's Geological Survey of Canada, Pacific Division also submits a regional solution for their Western Canada Deformation Array (WCDA). This solution is based on the Bernese GPS Software and has 28 stations. Later this year, 4 new permanent GPS stations in the Canadian Arctic and approximately 21 new stations around the Great Lakes will be included in the GSD Bernese solutions. Obviously, this network only covers the northern part of North America. Coverage should improve significantly once solutions for the U.S. CORS network can be obtained from the U.S. National Geodetic Survey.

The weekly regional solutions are combined into a single weekly NAREF "combination" solution using a step-by-step procedure similar to that used to produce the IGS global network combination. All a priori datum constraints are removed from the regional solutions and each is aligned to the IGS weekly solution. During this alignment, the covariance matrix of the regional solution is scaled to make it compatible with that of the IGS solution and the residuals are examined for outliers. The aligned/scaled regional solutions are then combined together by a summation of normal equations and the combination aligned and scaled again with respect to the IGS weekly solution. After a final check for outliers, a minimum constraint is applied (currently, for station DRAO). In addition, a separate "integration" solution is provided where weighted constraints are applied to all common IGS stations based on the IGS global weekly solution (including covariance matrix).

The quality of the weekly NAREF combination solutions is estimated through comparisons with the IGS weekly solution and the residuals for each regional solution. Overall, the RMS of the residuals are less than about 2 mm horizontally (except for PBO which is rather noisy in the east component) and 4 mm vertically. It is important to realize that it is difficult to compare RMS values between different weeks and different regional solutions because different stations are used from week to week and in different regional solutions. Weeks or solutions with a poorly behaved station(s) will exhibit larger RMS values. The RMS of the fit between the NAREF minimum constraint combination and the IGS weekly solution varies from about 1-2 mm horizontally and 2-4 mm vertically. Realizing that the noise level of the IGS solutions is of the order of a few mm, the NAREF weekly combinations can be considered compatible with the IGS. Note that only the coordinates from the IGS global solutions are considered "official" for IGS stations.

DENSIFICATION METHODOLOGIES

Clearly, the IGS cannot assume the responsibility for all the weekly regional network combinations and analyses. However, following its charter, the IGS, should provide guidance for regional network processing and integration. Even though some initial strategies and guidelines were provided to the RNACCs by the IGS (see, e.g., Blewitt et al., 1994; Kouba et al., 1998), more detailed IGS guidelines and conventions are still missing for regional processing and, in particular, integration of regional solutions into the IGS realization of ITRS.

At least in one case, regional network processing has been, well organized at the Sub-commission level (e.g., EUREF). However, at the IGS level, there is a need for more coordination to achieve better consistency among the different regional solutions. For example, an agreed upon recommendation for common processing guidelines. Each regional network has some unique characteristics, some guidelines flexibility. There are two main components to the weekly regional effort. First, within each region, all contributors should follow the existing IGS guidelines for station logs and ID, equipment (receiver/antenna), monumentation, etc… (See "Standard for IGS Station and Operational Centers"). These guidelines are widely accepted and would maximize the consistency with the global IGS network. A copy of the standards (and more) can be found at the IGS web site <*igscb.jpl.nasa.gov*>. The EUREF provides an excellent example of such regional activity, and it should be used as a model. Their strategy is described above, and more details can be found at their website <*www.epncb.oma.be*>. The preference for EUREF has been to align directly to the ITRF, rather than its IGS realization. With the convergence of ITRF and its IGS realization, the distinction is expected to eventually become insignificant. Second, some analysis aspects of the densification issues are discussed below. Some characteristics of the global/regional analysis are reviewed along with their implications eventual densification methodologies.

The general objective of network densification is to provide a more convenient and accurate access to the reference frame. A desirable characteristic is to have the coordinates in the ITRF, since over the last few years it has become the global standard. Regional activities may prefer to use other reference frames for their own reasons (E.g. the North American Datum is currently fixed to the North American Plate). In those cases, transformation parameters are generally available for conversion.

Combining all the code and phase measurements available from all the stations in a rigorous adjustment would be the optimal approach in the least-squares sense, but is clearly not feasible. Also, it is not possible to rigorously subdivide this type of analysis into manageable subsets, leading to sub-optimal results. The general practice has been to break down the analysis spatially and temporally and to ignore the correlation between the subsets. Therefore, the analysis task is generally broken down spatially in sub-networks (several global and several regional); and temporally, in daily data sets. In the case of the station coordinate parameters, this potentially leads to multiple global and regional solutions for some stations, when ideally, a unique "optimal" set of station coordinates (velocity) is desired. The necessary overlap required to integrate the networks forces the reuse of the code and phase observations at selected common stations. For example, for GPS week 1152, the code and phase observations for station WTZR were used in the global analysis by six IGS ACs and within EUREF by four LACs.

The regional networks can be combined directly with the ITRF, or alternatively, with the IGS global network, in one adjustment by making use of all the available covariance information. If we assume the global/regional networks as uncorrelated, this alternative has the advantage of being optimal in the least-squares sense. The coordinates of all the stations are adjusted during the combination. The change in coordinates of the global stations during the adjustment can be alleviated by tightly constraining them. One side effect is to produce unrealistically small covariance information. However, even this approach may potentially become demanding, even prohibitive in some cases, specially considering (1) that the number of regional solutions may be increasing as well as (2) the number of stations within each regional solution is also very likely to gradually increase (3) that this effort may be required every week. There is a necessity to share the effort. Although, the processing load would potentially become demanding, most could probably be accommodated. However, the computational load is only one aspect of the total effort. From the IGS weekly experience, significant analysis/trouble shooting/reporting effort is also necessary especially in the early phase. The regional contributors have also a personal stake in the quality of the regional networks. The distributed effort also allows raising the level of expertise and interest within local/regional agencies. Each regional group also has some unique requirements, concerns and interests to address within the region, including the number of contributing agencies, resources limitations, number of stations network size, etc.

At the global level, there is generally significant overlap/redundancy between the global solutions being combined. This situation generally provides the necessary information for the detection/resolution of problems, and to also estimate statistics. The situation is quite different between the regional networks. There is little or even no overlap between the regional solutions. This lack of overlap significantly limits the ability to detect problems when comparing regional networks. The regional solutions can be compared/combined to the global solutions simultaneously or sequentially with limited effect on each other. This also suggests that a densification scheme could consider regional networks separately. This alternative is somewhat less rigorous, but can significantly simplify the whole integration process. This type of tradeoff has been proposed in the past within IGS … "IGS should provide the means to make the procedure as simple as possible without significantly compromising regional accuracy" (Blewitt, 1993). Additionally, this approach can easily be adapted to a decentralized densification effort.

There are several alternative approaches to integrate the regional (combined) solutions into ITRF. ITRF can be accessed directly or via the IGS realization of ITRS. If the IGS realization of ITRS is preferred, it can use the weekly or the cumulative solution. The use of the weekly solutions is suitable for series representations where non-linear station position departures are considered important. The use of the cumulative solutions, which assumes a linear station motion model, is the traditional realization.

When non-linear stations behavior is required, the series of IGS weekly combined solutions should be used to integration of regional solutions. The IGS weekly solution series do not have velocity estimates; but since an independent solution for each global station is generally available each week, it is only a matter of matching corresponding weekly solutions with the regional solutions of the same epoch. The IGS weekly and the regional station coordinates solutions should experience very similar non-linear temporal (real and apparent) behavior for the common stations. After estimating and applying a 7-parameters similarity transformation, the residual differences at the common stations should be small (2-3mm horizontally, 5-10mm vertically), which is a very desirable attribute to achieve maximum integration stability. Since the same code and phase measurements should be used, the residuals differences should be originating mainly from the differences in network geometry and processing strategy. Station with abnormal differences should be resolved or rejected. In fact, with this alternative, the integration instability to ITRF would be coming partly from (1) the number and the geometry of the overlapping stations between the two weekly solutions, and (2) the uncertainty in the alignment of the IGS weekly solution to ITRF. The first source of instability (Regional-IGS weekly) is very much networks/processing dependent and may be highly variable. As discussed above, the second source of instability (IGS weekly–ITRF) is minimized with a careful selection of reference stations. Recent tests have indicated that horizontally, the level of instability is sub-millimeter. The common stations in the global and regional networks should have their coordinates/covariances fixed to the global values (Blewitt, 1993) for the published solutions. This can be done with a back substitution. Inner constraints also known as datum constraints should also be applied to each transformed solution and properly reflected in the APRIORI SINEX block. These constraints can be applied as part of the transformation process (Altamimi, 2002) or separately as is currently done for the IGS weekly and cumulative solutions. The use of inner constraints avoids the distortion of the global and local solutions as well as their covariance information. Ideally, the covariances of the global and regional solutions also need to be made compatible by potentially rescaling one (preferably the regional) or both matrices. The use of heavy constraints on the global station coordinates or subset of, as is currently done within EUREF achieves similar results on the coordinates. However, it distorts the covariance information. Again, independent solutions could/should be maintained regionally. Comparisons with available GNAAC combinations could also be used to provide some independent quality assurance. These alternatives do not prevent the regional analysis centers from generating independent regional cumulative solutions. This type of parallel analysis is actually encouraged.

The use of the cumulative solutions may appear advantageous to combine regional networks directly to ITRF; but there are some disadvantages. Namely that (1) there is a significant lag between the time of the most recent observations are made and the time the solution is available (one to two years) (2) real or apparent temporal variations other than the linear station velocity and discontinuities are not modeled in ITRF. The first disadvantage can be mitigated with the high quality of the ITRF estimated velocities. The second disadvantage, i.e. non-linear station movements other than discontinuities, cannot be accounted for in the current ITRF. This problem is not unique to the ITRF solution; it is shared with all the cumulative solutions currently available. The IGS cumulative solution mitigates the extrapolation time problem, because it is updated every week and lags by at most two weeks. The non-linear temporal variations would not be accounted for, except for new stations with a very short history. A constraining/back substitution strategy similar to the one describe above can be applied here.

The "how" the regional solution should be integrated can take several forms. Before the combination, the common stations have two sets of coordinates/velocity with relatively small differences. The simplest way is to align the regional solution using 7/14 parameters (or a subset of) Helmert transformation using a selected set of stations coordinates and covariance. Alternatively, making use of their respective covariance information can combine the global and the regional solutions. Depending on the final objective, the weighting scheme can be altered to give preponderance to the coordinates of the global or regional solutions. Alternatively, a backward substitution can be used to fix one set of coordinates. To avoid confusion, the coordinates from the global station solutions, which should be more precise than the regional solutions, should be fixed in the integration. It is relatively simple to implement, making it possible for the regional agencies to do their own integration. Considering that the regional solutions have a continental scope, the number (>10) and distribution of stations should be sufficient for all continents. In the case of Africa, stations around the continent could also be included. A carefully selected subset of the common stations may also be used when many stations are common between the global and regional solutions.

Practical issues related to standard least squares such as variance factor estimation; outliers detection/rejection, numerical stability, etc…also need to be taken into account. Those are well documented in the geodesy literature. This short procedure provides the main steps that are/should be required to produce weekly regional products. It is concise version of the IGS weekly combination procedure described in (Ferland et al. 2000).

1) Validation:
- Compliance with the SINEX format
- Naming issues
- Correct modeling inconsistencies

2) Unconstraining:
- Remove inner and/or coordinates constraints
- Check for numerical problems

3) Transformation (Helmert)/Combination:
- Compute misclosures:
- Check abnormalities (Investigate/Reject/Fix)
- Compute partials/normals/estimated corrections/Residuals:
    - Check residuals (Investigate/Reject/Fix)
- Iterate if necessary:

4) Prepare/distribute final statistics/reports.

A similar procedure is described in the NAREF section. Other alternatives may be provided by the Regional Networks Associate Analysis Centers (RNAAC) at MIT (Herring, 1996; Herring 1998) and NCL (Davis et al., 1996, Kawar et al, 1998ab) for example or by some effort by (U. of Colorado (Blewitt)).

CONCLUSION/RECOMMENDATIONS

1) The current IGS SINEX cumulative combination satisfies the IGS Polyhedron network (~200 stations). The originally planned use of the regional networks to complement the global network is no longer necessary. This allows for the densification of ITRF using the regional networks to be simplified.

2) Various regional networks densification alternatives have been proposed and discussed by the authors to integrate the regional solutions to the global IGS network. All the proposed solutions have strength and weaknesses. In an effort to keep the process simple and to provide internally consistent solutions, the weekly/cumulative regional SINEX solutions should be aligned using a Helmert transformation (7/14) to the appropriate weekly or cumulative IGS SINEX solution. For stations coordinates appearing in global and regional solutions, their differences should be within the noise level. This type of approach is currently being used to align the IGS weekly and cumulative solutions to its realization of ITRF. To avoid potential confusions, the common stations in the global and regional networks should also have their coordinates/covariances fixed to the global values.

3) Within each region, the IGS standards (monumentation/logs/naming/etc.) should be used <*igscb.jpl.nasa.gov*>.

4) The general strategy and structure used within EUREF <*www.epncb.oma.be*> should be followed and adapted as required by the other regions.

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Satellite Antenna Phase Center Offsets and Scale Errors in GPS Solutions

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Abstract

This paper studied two scale factors, which may affect GPS solutions: gravitational constant GM and satellite antenna phase center offset in z-direction. GM affects the scale of the orbits of satellites by 1/3 of dGM/GM. But its effect on the scale of a terrestrial frame realized by GPS technique is much small. The reason is, that the scale errors in the orbits are (largely) canceled in the double differences, or absorbed in the clock solutions. For example, we first fix a set of (IGS) GPS orbits and solve the station positions, afterwards we deliberately enlarge the orbit coordinates by a factor of (1+5.e-9), that is, to change the scale of orbits by 5 ppb, and solve the site position again by fixing the enlarged orbits. Comparing these two sets of station positions, one finds only less than 1 ppb scale variation. The conclusion is: **the scale of GPS orbits (just like the orbit of other satellites, such as LAGEOS) is sensitive to GM, but the scale of the GPS terrestrial frame is much less sensitive**! When one talks about the scale of GPS, one MUST distinguish clearly between the scale of the orbit and that of the terrestrial frame!

As far as the terrestrial frame is concerned**, the uncertainty in the satellite antenna phase center offset (z-direction) is almost equivalent to the scale error in the GPS orbits caused by the error in GM.** But **the uncertainty of the current available GM value is very small, while the errors in the z-off could be very large. This is the essential difference between these two factors.** Therefore although most of the z-off errors are canceled in the double differences, or absorbed in the clock solutions, the rest effect on the scale of the terrestrial frame is not ignorable small. Approximately, **delta scale = 7.8 dz**, where dz is the error of z-off in unit meter, while the scale change is in ppb. That is, 7 cm of dz in the BLOCK II and IIA satellites could produce 0.5 ppb scale variation. For BLOCK IIR dz could reach 1 m. The number of these satellites increases from year to year. ITRF2000 solutions (see Lareg, 2001) have shown that there are ppb level scale differences between GPS and other techniques, and between various GPS Analysis Centers (AC). The trends of the scale differences reach 0.2 ppb per year. Our study has shown that the uncertainty in the satellite antenna phase center offset **could be** one of the major reasons for these problems.

Densification of the ITRF: The NAREF Experience in North America

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In an effort to densify the ITRF, the IGS initiated a program of distributed regional processing to better manage the computational effort. In 2000, the North American Subcommission of the International Association of Geodesy's Commission X formed a North American Reference Frame (NAREF) Working Group to promote and coordinate such regional processing in North America. This coordination has involved the adoption of standards and guidelines for station selection, operation, data processing, archiving, redundancy, and the combination and integration of regional solutions within the ITRF and IGS global network. Most of these standards and guidelines have been adopted from those proposed by the IGS and those used by the European Reference Frame (EUREF) Technical Working Group.

In support of this densification initiative, the Geodetic Survey Division (GSD) of Natural Resources Canada has been contributing on two fronts: the provision of weekly regional solutions for Canada and the combination of regional solutions from other agencies across North America. Since the beginning of 2001, GSD has been computing two independent Canada-wide weekly solutions using GIPSY-OASIS II and the Bernese GPS Software. In addition to all IGS stations in the northern half of North America, the solutions also include all stations of the Canadian Active Control System (CACS), the Western Canada Deformation Array (WCDA), as well as a some selected stations of the US CORS network, the Alaska Deformation Array (AKDA), the Pacific Northwest Geodetic Array (PANGA), the Eastern Basin Range Yellowstone Array (EBRY). Also included until the end of 2001 were selected stations from the British Columbia Active Control System (BCACS) and the Quebec Permanent GPS Network. In additional to our own regional solutions, we have been receiving regional weekly solutions from the Geological Survey of Canada - Pacific Division for their WCDA and from the Scripps Institution of Oceanography for the Plate Boundary Observatory (PBO). We also expect to soon be receiving weekly solutions from the US National Geodetic Survey for their CORS network. This contribution will make NAREF truly North American in scope.

GSD has also been combining these regional solutions into weekly NAREF combinations. Overlap among these regional networks provide redundancy checks and allow for the determination of correct relative weighting of the different solutions relative to each other. The agreement among the regional solutions is generally less than a couple of mm horizontally and about 4 mm vertically. Agreement of the minimally constrained weekly NAREF combinations with the IGS weekly combinations is of the order of 1-3 mm horizontally and 3-6 mm vertically.

Different methods of integrating the combined NAREF solutions into the IGS global network were also investigated. It was decided to us a combination of Helmert transformation and a priori weighting of the IGS global stations. The later uses the full covariance matrix from the IGS solutions to propagate the global accuracies into the NAREF combination. Agreement of these integrated NAREF combinations with the IGS solutions is about 1 mm horizontally and 3 mm vertically. We presently have a time series of NAREF combinations from GPS week 1095 to present and soon hope to begin estimation cumulative solutions in an effort to determine velocities at the regional sites. More information can be obtained at www.naref.org.

How to Express a Regional GPS Solution in the ITRF ?

Zuheir ALTAMIMI

The usefulness of the densification of the International Terrestrial Reference Frame (ITRF) is to facilitate its access by users interested on small (regional or local) networks. Although a regional GPS solution is usually derived using IGS products (Orbits, Clocks,...), which are nominally expressed in the ITRF, its corresponding datum definition could be far from that of ITRF due mainly to the network configuration. The main question to be answered here is how to optimally express station positions of a regional network in the global frame of ITRF. This could be achieved by mainly (1) constraining coordinates of a subset of stations to their ITRF values or (2) aligning the regional solution to ITRF using a transformation formula. This paper will focus on the second method, based on minimum constraints approach yielding an optimal datum definition together with preserving the original characteristic of the regional solution.

The advantage of method (1) is that the regional solution is well expressed in the ITRF frame, while its disadvantage is that the selected stations will have their coordinates entirely determined by the ITRF selected values. Given the nature of a regional network and its effect on the estimation of the transformation parameters, its extremely important to be very careful when using method (2). In fact, the most efficient way to use is the transformation parameter alignment using minimum constraints approach as described hereafter.

The relation between a regional solution (X_R) and ITRF (X_I), over selected stations, could be written as:

$$X_I = X_R + A\theta \tag{1}$$

where A and θ are respectively the design matrix of partial derivatives and the vector of 7 transformation parameters:

$$A = \begin{pmatrix} . & . & . & . & . & . & . \\ 1 & 0 & 0 & x_a^i & 0 & z_a^i & -y_a^i \\ 0 & 1 & 0 & y_a^i & -z_a^i & 0 & x_a^i \\ 0 & 0 & 1 & z_a^i & y_a^i & -x_a^i & 0 \\ . & . & . & . & . & . & . \end{pmatrix}, \quad \theta = \begin{pmatrix} T_x \\ T_y \\ T_z \\ D \\ R_x \\ R_y \\ R_z \end{pmatrix}$$

1

Un-weighted least squares adjustment yields a solution for θ as:

$$\theta = (A^T A)^{-1} A^T (X_I - X_R) \tag{2}$$

The approach of minimum constraints consists in using the matrix $B = (A^T A)^{-1} A^T$ in such a way that X_R will be expressed in the same frame as the ITRF solution X_I. Therefore to have X_R be expressed in the ITRF at Σ_θ level, a "datum definition" equation could be written as:

$$B(X_I - X_R) = 0 \qquad (\Sigma_\theta) \tag{3}$$

where Σ_θ is the variance matrix at which equation (3) is satisfied. Σ_θ is a diagonal matrix containing small variances (to be selected at the user level) for each one of the 14 transformation parameters.

In terms of normal equation, we then can write:

$$B^T \Sigma_\theta^{-1} B(X_I - X_R) = 0 \tag{4}$$

Using IGS product (orbits, clocks, etc.), the initial normal equation system of a regional solution before adding any kind of constraints could be written as:

$$N_{unc}(DX) = K \tag{5}$$

where $DX = X - X_{apr}$, N_{unc} is the unconstrained normal matrix and K is the right side vector.

The normal equation system (5) could be obtained also after removing classical constraints applied to a given regional solution.

Selecting ITRF subset of stations (X_I), the equation of minimum constraints (or datum definition) is:

$$B^T \Sigma_\theta^{-1} B(DX) = B^T \Sigma_\theta^{-1} B(X_I - X_{apr}) \tag{6}$$

Note that if the the ITRF values are used as a priori values, the right hand side of eq. (6) vanishes. Cumulating (5) and (6) yields:

$$(N_{unc} + B^T \Sigma_\theta^{-1} B)(DX) = K + B^T \Sigma_\theta^{-1} B(X_I - X_{apr}) \tag{7}$$

Solving for eq. (7) yields a regional TRF solution expressed in the ITRF at the Σ_θ level.