Reinforcing and Securing the IGS Reference Tracking Network

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Abstract. The IGS is urged to designate a subset of its global tracking network for the explicit purpose of realizing an improved, more stable terrestrial reference frame. The reference frame, being the foundation upon which all IGS services and products rest, is of primal importance. Therefore, the tracking stations used to form the frame deserve special attention. The current IGS approach uses an *ad hoc* selection of stations made by data analysts from the available network. While this has worked well in the past, to achieve and maintain a future reference frame accurate and stable at the 1-mm level for weekly (or even daily) integrations requires a more rigorous and coordinated approach, enlisting the full and active participation of the station operators and sponsoring agencies. Detailed operational specifications will need to be adopted and long-term supporting commitments sought for up to ~150 highly stable stations. New stations should be invited to fill gaps in the current network geometry, as well as more rigorous installations at existing IGS stations. This will necessarily be an ongoing and very challenging process. But it is also essential if the IGS and its partner agencies are to establish and maintain a new level of reference frame accuracy sufficient to support the most demanding global change research and other applications in the coming years.

Keywords. Reference frames, ITRF, GPS, International GPS Service (IGS)

1 Introduction

All IGS products are expressed with respect to a specific, high-accuracy terrestrial reference frame. The International Terrestrial Reference Frame (ITRF), maintained by the International Earth Rotation and Reference Systems Service (IERS), provides the underlying system to which the IGS Reference Frame (RF) realization is very closely aligned (without internal distortion). The IGS frame is itself a primary contributor to ITRF. The accuracy and stability of the IGS RF (and the underlying ITRF) set a fundamental floor on the accuracy of all IGS products derived therefrom. For this reason it is absolutely essential that the IGS RF be of the highest possible quality, long-term stability, and reliability, and that it provide continuous, easy, and rapid user access (usually via the IGS orbit products).

The time evolution of IGS RFs has steadily moved towards greater numbers of stations, improved geometrical coverage, and higher accuracy. The initial IGS frame used the ITRF92 coordinates and velocities of 13 IGS stations co-located with other space geodetic techniques (see Figure 1). As problems developed at some of the RF stations, the quality of IGS products suffered. That experience showed the need for a much larger, better distributed reference network and led to a series of more robust RF updates between 1998 and 2001. The most recent frame consists of 54 stations (Figure 1) in the IGS00 realization of ITRF2000. Usable data can be obtained for only a portion of the designated RF set, however, usually about 45 out of the full 54. In addition, four RF stations are not monumented to permanent physical markers and other issues affect many others.

While the current *ad hoc* approach to IGS RF realizations has worked fairly well, it is not adequate to ensure the continued improvement needed as IGS orbit accuracies reach the cm level and Earth orientation parameter errors fall below 100 µas (3 mm equatorial rotation). The most ambitious scientific missions that the IGS supports call for reference frame accuracies at the mm level (sub-ppb) with long-term stabilities better than 1 mm/year, a goal not yet reached. Increasingly, other users and even commercial applications are seeking higher RF accuracy, quality, and reliability for a wide range of practical geodetic problems.

This paper proposes to reinforce the current

IGS RF, implement better global coverage and stability, and secure the infrastructure as a committed, long-term, international asset. New stations are sought to fill gaps in the tracking network; this is vital even though they will not be usable immediately as RF stations, until sufficient analysis history is accumulated. Improved configurations at existing IGS stations are also needed, including among the current RF set. The proposal outlined here is highly ambitious and will not be achieved quickly or easily. Maintaining and reinforcing the IGS RF is necessarily an ongoing, permanent task. Working towards this goal will assure not only the future accuracy of IGS products, but other related or derived products, such as ITRF, will also benefit.

2 Current Reference Frame Accuracy

Over the decade around its 1997 reference epoch, the accuracy of ITRF2000 is estimated to be ~0.5 ppb in scale (3 mm height error) and the stability of its geocentric origin and site coordinates are at the few-mm level (Altamimi *et al.*, 2002). Indeed, the formal errors of the ITRF2000 scale and geocenter rates are less than 0.3 mm/year. However, the ITRF formal errors are probably very optimistic, being based solely on the scatter of the solutions included. Some technique solutions were rejected as outliers. For instance, the GPS contributed frames were generally very poor and inconsistent in scale and geocenter, and they were therefore not used to specify these aspects of the ITRF2000 datum. The present ITRF long-term accuracy is thus probably only marginally adequate for such demanding secular applications as monitoring global sea level change.

The ITRF is currently only defined in a secular sense, assuming strictly linear evolution (except for occasional discontinuities in station coordinates). The weekly IGS combinations of global station coordinates and daily Earth orientation parameters are attached to the secular ITRF frame by a Helmert transformation for the 54 selected RF stations. Blewitt (2003) and Dong *et al.* (2003) have discussed some conceptual weaknesses of this approach that will probably require future RF refinements.

Meanwhile, the weekly IGS translational parameters represent nominal geocenter motion; that is, net displacements of the Earth's crust relative to the ITRF origin aligned to the total center of mass. To what extent the observed IGS offsets reflect genuine geophysical signals is an area of active research, but it is clear that problems in the GPS orbit modeling can be a significant source of error. Therefore, for the time being, satellite laser ranging (SLR) continues to be important to maintain the ITRF secular origin and to monitor shorter-term geocenter motions.

Likewise, the IGS combined frame consistently differs from ITRF2000 in scale by 1 to 2 ppb. This is widely thought to be an effect of

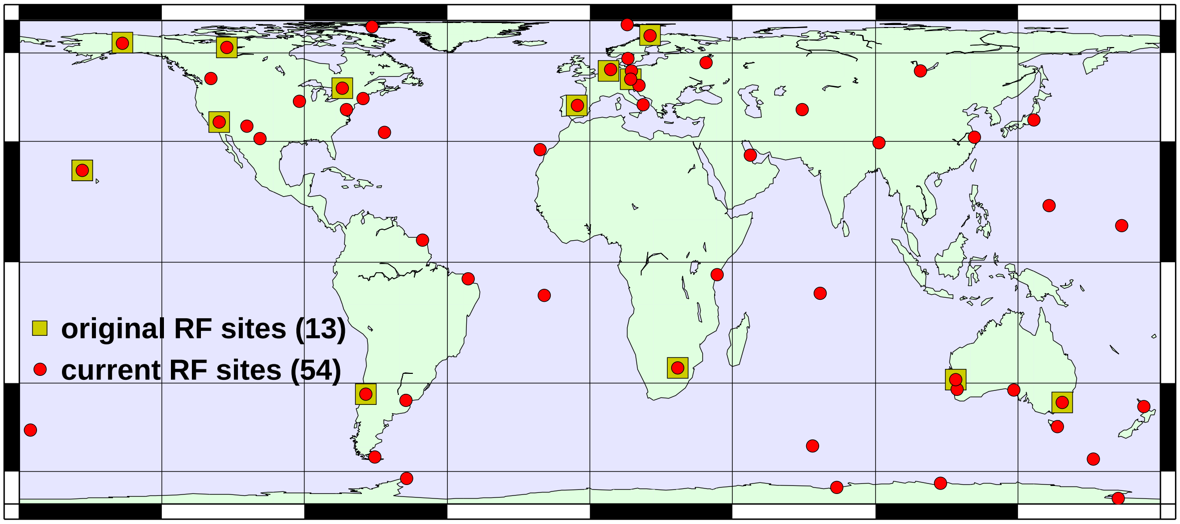

Fig. 1 Distribution of IGS Reference Frame stations, originally (yellow boxes) using ITRF92 and currently (red dots) based on ITRF2000

unmodeled variations in the antenna beam patterns of the GPS satellites and tracking stations. Therefore, contributions from SLR and very long baseline interferometry (VLBI) will likely continue to be needed to specify the ITRF absolute scale.

In these ways the IGS RF is dependent on ITRF for its "absolute" datum even though the GPS contribution in terms of density and accessibility is indispensable. The resulting accuracy is consequently a combination of the underlying ITRF accuracy and the effect of IGS frame alignment, which globally adds about 2 mm more random uncertainty for each weekly realization (ignoring possible systematic errors), based on routine IGS reports.

3 History of IGS RF Realizations

3.1 ITRF92,93,94/13 RF Sites — Early RFs

Initially the IGS adopted the ITRF92 coordinates and velocities for a set of 13 co-location sites with established SLR and/or VLBI histories; see Figure 1. When ITRF93 and ITRF94 were issued, the IGS successively updated its RF accordingly. ITRF93 was problematic because it did not obey the usual global no-net-rotation condition (in order to try to reduce inconsistencies with the long-term IERS Earth orientation parameters). This caused significant rotational discontinuities in IGS products associated with each frame change.

The 13 original RF stations were located in N. America (ALGO, FAIR, GOLD, YELL), Europe (KOSG, MADR, TROM, WTZR), Australia (TIDB, YAR1), S. America (SANT), Africa (HART), and the Pacific (KOKB). The overall global coverage was poor, with no RF stations in Asia, the Atlantic or Indian Oceans, or Antarctica. As equipment problems, data losses, or other disruptions developed at some of these stations, the limited number and distribution of RF sites caused noticeable degradations of IGS products. By 1998, these problems had become severe (Kouba *et al.*, 1998).

Figure 2 illustrates one manifestation of the RF effect, in this case seen by comparing the polar motion results from the IGS Rapid (delivered with 17 hours delay) and Final (available after ~2 weeks) series. Polar motion measurements reflect the global quality, robustness, and stability of the RF, as well as possible systematic errors due to orbit mismodeling, etc. During the ITRF94 era with only 13 or fewer RF stations, delays in the reporting of some RF data contributed to large polar motion biases and much greater scatter in the Rapids compared to the Finals.

3.2 ITRF96/47 RF Sites — 1 March 1998

To address the limitations of using only 13 RF stations, Kouba *et al.* (1998) proposed a much enlarged network of 47 stations selected according to an objective set of criteria. This plan was adopted by the IGS Analysis Centers and implemented on 1 March 1998 (GPS week 947) using ITRF96 coordinates and velocities. The nominal datum of ITRF96 was fixed to that of ITRF94 in origin, scale, orientation, and their time derivatives. So IGS products were affected by only minor shifts.

The improved results from the better distributed, more robust RF coverage were dramatic, as seen for instance in the Figure 2 polar motion comparison. Notably, however, this *ad hoc* approach by the IGS data analysts had no official sanction and bestowed no recognized status on the RF stations, unlike those stations designated as "global" in the IGS Terms of Reference. Perhaps even more important, the consent and active cooperation of the RF station operators was never sought.

The Kouba *et al.* (1998) plan for RF realization was more ambitious than simply enlarging the set of RF stations. A scheme was also developed to permit a nearly rigorous combination of all IGS products to ensure the highest degree of internal consistency. That larger plan was implemented in stages and was fully completed on 27 February 2000 (see below).

3.3 ITRF97/51 RF Sites — 1 August 1999

The approach used for ITRF96 was simply updated when ITRF97 was released, except that the IGS RF set was enlarged from 47 to 51 stations. The same ITRF94 datum was propagated by a 14-parameter Helmert alignment to ITRF96. Nevertheless, significant shifts occurred in the origin translation along the z-axis (-14.7 mm), scale (+1.43 ppb), and rotations about the x- (0.159 mas), and y-axes (-0.263 mas). These datum shifts must be accounted for in long-term analyses using IGS products.

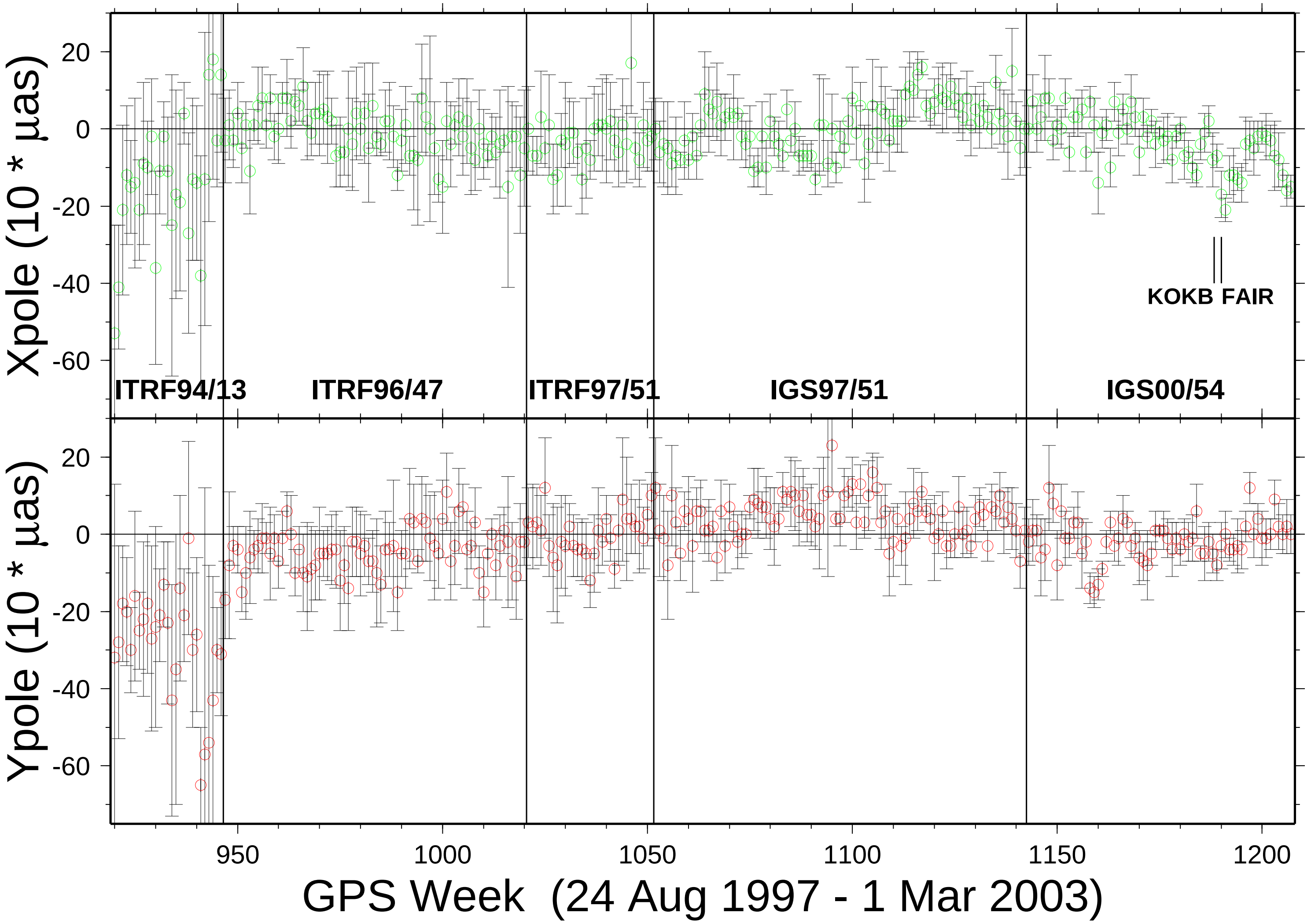

Fig. 2 Comparison of IGS Rapid and Final polar motion differences. Each point is the weekly mean difference and the error bars show seven-day standard deviations. The various IGS RF realizations are indicated. Displacement events at KOKB and FAIR are indicated.

3.4 IGS97/51 RF Sites — 27 February 2000

The quasi-rigorous methodology of Kouba *et al.* (1998) was fully implemented on 27 February 2000 when the RF coordinates and velocities were replaced with the IGS97 internally self-consistent realization of ITRF97. The frames were closely aligned using the 51 RF stations so that no significant shifts were observed. The weekly IGS combined terrestrial frame was determined simultaneously with the Earth orientation parameters using the full covariance information from all the Analysis Centers provided in SINEX format. The orbit combination continued to be performed separately, for practical reasons, but rotational offsets from the SINEX combination were applied to the orbits to enforce consistency. The matching translational offsets were not used, however.

3.5 IGS00/54 RF Sites — 2 December 2001

When ITRF2000 was published a new IGS00 realization was produced with the only significant change being an update of the RF set from 51 to 54 stations. However, ITRF2000 adopted somewhat revised datum specifications. The most significant change was in departing from the IUGG recommendation to use the TCG geocentric time scale in order to conform with the practice of all IERS analysis groups. This caused a systematic scale shift of -0.7 ppb. In addition, the rotational rates were affected slightly by an improved implementation of the global no-net-rotation condition. Actual shifts in the RF origin were found to be -6.0, -5.6, and 20.1 mm in x, y, and z, respectively, and the full scale shift was -1.40 ppb, double the effect of the time scale change. The translation and scale changes were probably due mostly to accumulated errors since the previous ITRF datum specification in 1994.

4 Current Status

4.1 Overall Assessment

Overall, the global RF coverage is now quite good. The effects of RF weaknesses on the IGS products is clearly much smaller than before 1998. Still, some sizable network gaps remain, especially in the Pacific region and to a lesser extent in Africa, S. America, S. Asia, and the Southern Ocean. The number of usable RF stations has gradually decayed with time, from 54 originally to typically 40 to 45 on most days. Station configuration changes and other events can still have serious impacts on the RF and IGS product quality. Two events illustrating this are marked in Figure 2. The KOKB radome was removed in week 1188 leading to a few-cm apparent displacement, and the Denali earthquake near FAIR in week 1190 shifted its position by ~5 cm. Since the Rapid solutions use tightly constrained IGS00 coordinates and there was some delay before the Analysis Centers responded to the changes, the Rapid polar motion x component was biased for a couple of weeks.

Evidence of continued RF improvements since the ITRF96/47 change in March 1998 is lacking. The polar motion comparisons in Figure 2 do not show any overall improvement with time. While the polar motion consistency within each week has improved *(i.e.*, smaller error bars in Figure 2) the mean weekly differences have not. It is evident that the polar motion differences are not white noise distributed. The magnitude of the rotational variations since week 947 corresponds to net weekly RF shifts at about the 2-mm level. The errors for one-day realizations would be larger, but probably not as much as $\sqrt{7}$ due to temporal correlations.

It might be argued that polar motion results, while a globally integrated measure of RF accuracy, are also affected by other sources of error, such as analysis methods, which might be more important. However, during the same period the Rapid and Final orbits have grown steadily closer in rms agreement (after removing a 7-parameter Helmert transformation). This is shown in Table 1 which gives the means and standard deviations for differences between Rapid and Final polar motion and orbits. There has been a monotonic and dramatic drop in mean orbit wrms differences from 6.0 cm during GPS weeks 920-946 to 1.9 cm in the most recent period; the scatter in the orbit wrms values has also declined from 1.5 cm to 0.3 cm. This probably reflects overall improvements in the analysis methods used in the IGS rather than any RF effect since the stagnation in the polar motion quality since 1998 is a better measure of overall RF conditions.

The continued susceptibility of the IGS products to single-station problems, such as those at KOKB and FAIR, must be considered as an aspect of RF weakness. Any mishandling of RF information, including antenna eccentricities and phase center variations, by the IGS Analysis Centers can also play a role. Even conceptual ambiguities with the current RF definition should be considered. For example, the Rapid products are rigidly expressed within a secular frame aligned to ITRF whereas the Finals use weekly frame realizations that translate and deform compared to the secular frame. All such facets, taken together with number, selection, and stability of individual RF stations, can influence the quality of the IGS products.

Table 1. Comparison of IGS Rapid and Final polar motion (PM-x,y) and orbit (weighted rms) differences

IGS RF	GPS weeks	PM-x (µas) mean std dev	PM-y (µas) mean std dev	orbit wrms (cm) mean std dev
ITRF94/13	920-946	-139.6	-284.1	6.0
		±165.5	±140.9	±1.5
ITRF96/47	947-1020	-11.1	-44.1	4.1
		±57.4	±55.1	±0.7
ITRF97/51	1021-1051	-28.7	-1.0	3.8
		±56.9	±54.1	±0.6
IGS97/51	1052-1142	7.6	43.2	3.0
		±64.6	±54.3	±0.4
IGS00/54	1143-1223	-33.3	-16.4	1.9
		±64.1	±48.6	±0.3

4.2 Other Issues

Among the complications in the practical maintenance of the IGS RF are discontinuities in station coordinates (or less commonly in velocity). Since the secular ITRF and the long-term accumulated IGS frames assume linear site motions, such breaks must be accounted for in some secondary process, such as allowing a reset of the coordinates with no change in the long-term velocity. At some level, position jumps can in many cases be ignored since the secular velocity will be impacted only minimally. However, setting the appropriate level at which to take action is inherently subjective and must be measured against the noise in individual point measurements, which is affected by the overall RF stability.

Discontinuities can occur for many reasons and often the cause is unknown. With GPS, changes in observing equipment are the most common cause. Even updates of receiver firmware can have an impact. In principle, if the IGS station logs are kept current the effects on station position can be tracked, at least to some extent. In other cases, natural causes such as earthquakes can shift stations. These processes are not necessarily abrupt and the post-event motions can be non-linear.

The mechanics of tracking all such changes, especially at RF stations, and taking appropriate actions in the data analysis and combination is tedious and mostly manual at this stage. There is no standardized record of all such events except for the changes tabulated in station logs, most of which do not correspond to position changes. Individual Analysis Centers usually make their own decisions as to how and when to introduce discontinuities. This approach is quickly becoming unwieldy and prone to adding further errors into the IGS RF.

Another complication of the weekly IGS RF combinations is that the temporal evolution is clearly non-linear. Each weekly realization differs from the long-term combination by more than a simple translation of the geocenter. Local site displacements, especially in the vertical, have long since been demonstrated due to effects such as atmospheric pressure loading. Since geophysical processes usually possess more power in the longest wavelength scales (or lowest spherical harmonic degree), the report by Blewitt et al. (2001) of global deformational modes at annual periods is apparently consistent with the observed local behavior. This could account for the geographically correlated variations in non-linear site motions described in a number of studies. On the other hand, large-scale distortions could also be artifacts of the data analysis, at least to some extent. Defects in orbit modeling are an obvious candidate for such effects. Indeed, the dispersion in RF results among IGS Analysis Centers using different orbit modeling strategies, which generally show different levels of geographically correlated residuals, argues for a significant component of analysis error in the weekly RF results. It remains to be demonstrated how significant these processing effects are compared to the geophysical forcings.

5 General Requirements for RF Stations

Below are some general considerations for selecting IGS RF stations; more detailed criteria are given in the Appendix. Of course, additional, non-RF stations are also needed in the tracking network to fulfill other important objectives. For instance, co-locations at timing laboratories are useful for time transfer operations even if they are not suitable as IGS RF stations.

5.1 Numbers of Sites

If we accept that the typical scatter in repeated GPS measurements of a station's local coordinates is roughly 4.5 mm in the horizontal components and 10 mm in the vertical using 24 hours of observational data, then it would require about 100 globally well distributed stations to achieve an average frame to the ~1-mm level each day (neglecting geographically correlated errors). The vertical errors set the more challenging limit and these are generally correlated even over very large regions. If we allow a further 50% margin for interruptions in data availability and other unavoidable disruptions, then the goal for the IGS RF network is about 150 global stations, or nearly half of the currently active network. Fortunately, about 80% of the IGS stations are monumented with permanent physical markers.

5.2 Global Distribution

Ideally the stations forming the IGS RF should be evenly distributed over the Earth's surface. Historically this has been most difficult to achieve over the oceans and in lesser developed land areas. If the goal is ~150 reference stations, then the average spacing between them would be about 1840 km (or 2260 km for 100 RF stations). New IGS stations to fill gaps are needed especially in the Pacific region and the Southern Hemisphere.

5.3 Regional Stability

For this application it is essential that the long-term motion of each reference station be a simple function of time, preferably linear. Therefore plate boundary zones, active volcanic terrains, and other regions of large-scale, non-linear deformation are to be avoided whenever possible. It is appropriate and necessary to locate IGS stations in such areas for a variety of reasons, but these are usually not suitable as RF stations. Motions that are secular and can in principle be determined, such as post-glacial rebound, should not exclude a site from consideration.

5.4 Local Installation Stability

Likewise, the highest feasible stability is sought for the GPS installation with respect to its local setting. It is essential that the GPS antenna be anchored to an external physical monument of utmost stability and that the eccentricity be constant and accurately known. It is also important to establish a high-accuracy local geodetic control network to monitor motions of the primary GPS station. In order to distinguish very local monument displacements from larger-scale effects, the control network should include permanent markers covering a range of distances from ~10-100 m out to at least 10 km. The nearby reference markers can also serve to re-establish the primary station in the event it is destroyed or becomes unusable. The local network must be resurveyed regularly to be useful and should include any co-located space geodetic systems that may exist nearby. Discontinuing use of the primary GPS monument in favor of another is to be done only in extreme circumstances, and requires prior announcement and submission of overlapping data sets starting one year in advance.

5.5 Instrumentation Stability

Because changes in the GPS instrumentation can affect the apparent position of the station, any configuration change should be made only under the most stringent conditions to ensure no discontinuity. Equipment changes should be: 1) made only when absolutely necessary; 2) thoroughly tested beforehand in a parallel, non-interfering operation; 3) announced in advance.

5.6 Long-term Commitment

Long-term institutional commitment is of the utmost importance. National geodetic agencies are ideally suited to this task, especially where their contributions to the IGS RF also provide backbone links to national or regional datums. These groups also possess the geodetic expertise needed for secure stable monumentation and local network control. However, other groups, especially those representing governmental or similar long-term interests, should also be encouraged to participate.

The extra commitment and effort put forth in operating a RF station must be formally recognized and publicized by the IGS. By necessity, the IGS Analysis Centers will generally prefer to process data from these stations.

6 Summary and Recommendations

During its first decade of service, the IGS and collaborating groups have made huge strides in advancing a modern, space geodesy-based RF that is both highly accurate and readily accessible. However, the progress since 1998-2000 has stalled and not kept pace with general improvements in GPS data analysis. This threatens to limit the potential usefulness of IGS products in fully addressing the most demanding geophysical, scientific, and societal applications. Fortunately, certain improvements are clear and can be implemented in straightforward, if not always easy, ways. Some basic steps are suggested here.

6.1 Near-term RF Upgrades

Immediate benefits can be obtained by updating the *ad hoc* strategy of Kouba et al. (1998) with increased numbers and improved geometry of RF stations from the current network. The IGS Reference Frame Working Group should recommend such changes to the Analysis Centers at the earliest opportunity. As many as 100 RF stations seems feasible at present, though the global distribution may not be greatly improved in the near future.

The next most important task is to develop better procedures to track and handle apparent station discontinuities. This must be closely coordinated with the Analysis Centers, IERS, other techniques, and the user community.

6.2 Develop Guidelines for RF Stations

Also in the near-term, the IGS should adopt accepted standards for the installation and operation of RF stations specifically. In recent years there has been a growing erosion of the awareness of RF requirements as many of the original leaders in space geodesy retire. One important objective is to reinstill the level of care and concern evident in the early IGS.

The RF specifications and guidelines should then be strictly enforced once RF stations are officially designated. The Appendix tabulates many criteria that should be considered.

6.3 Designate and Recognize RF Stations

In the longer term, the current *ad hoc* process used by the Analysis Centers to pick RF stations from the available network is inadequate. The most serious shortcoming now is the lack of commitment by the chosen stations to meet the necessary RF standards. Many station operators may not even be aware of the needs. A fully informed collaborative approach is required, building upon the mutual consent of data analysts and station operators.

Certainly any future IGS RF must evolve from the current IGS00/54 framework, preferably in well controlled stages. Many stations, though, need to improve their performance or stability. Evidence of long-term committed support should be requested for all RF stations. And concerted efforts are needed to fill the remaining gaps in global coverage, especially in the Pacific region.

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

6.4 Develp Quality Assessment System

Any RF strategy will be only as effective as the quality actually attained. Therefore, it is vital that mechanisms be established to continuously monitor and report RF station performance. The monitoring tools must be automated, but most corrective actions will probably require manual interventions. The proper lines of communication must be reliable and effective.

Most of the elements of this system are already in place, thanks to the IGS Network Coordinator.

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

6.5 Improve User Interfaces

One of the weakest aspects of IGS service generally is in its interface to the broader user community. Many of the procedures, methods, and standards are poorly or incompletely documented. This applies particularly to the RF. The current expert system severely limits its greater utility, while creating large risks of mistakes or misunderstandings among non-specialists.

This can viewed in part as a need for better educational outreach. One approach to improve the situation would be to invite collaborations with outside groups or even commercial services to provide value-added user interfaces.

6.6 Develop Long-Range RF Strategy

In the longer-term, the IGS needs a new vision of how best to maintain and improve its RF. The goals outlined by Kouba *et al.* (1998) have been accomplished. That approach can (and should) be extended in the near-term by increasing the number of RF stations. However, an expanded view is needed to really advance the state-of-the-art in major ways.

6.7 Proactive Leadership

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

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Appendix. Specific Criteria for IGS RF Stations

Below are detailed specifications proposed for IGS RF stations, drawn mostly from prior reports. While it will often not be feasible to satisfy all the conditions, it is nonetheless necessary to establish specific criteria and to aim to satisfy at least the most important of these. Some stations may be accepted as "RF candidates" until certain aspects are satisfied, such as having a sufficient observing history.

- <u>Geographic criteria</u>:

  - appropriate distance to nearest neighboring RF station (on average, ~1800 km)
  - relatable to regional/national geodetic network, if one exists
  - clear horizon with minimal obscurations above 5 degrees elevation

- stability of local surroundings (buildings, trees, no new constructions planned, etc)
- free of nearby reflective surfaces (fences, walls, etc) and other sources of signal multipath
- free of excessive radio frequency interference
- free of excessive natural or man-made surface vibrations from ocean waves or heavy vehicular traffic

● Geologic/tectonic criteria:

- on a stable regional crustal block, away from active faults or other sources of deformation, subsidence, etc
- on firm, stable material, preferably basement outcrop
- certainly not located on soil that might slump, slide, heave, or vary in elevation because of subsurface liquid variations

● Monumentation criteria:

- permanent physical monument required; antenna reference points (ARPs) not rigidly related to a close physical marker are not acceptable for RF stations
- monument isolated from unstable surface material and extending into stable subsurface formation
- monument of ultra-stable design
- ancillary monuments must be provided for local geodetic control, reference, azimuth, and especially for recovery in the event that the primary monument is destroyed
- a minimum of three footprint monuments are recommended to be located 10 to 15 km away to aid in delineating between local, regional, and large-scale ground motions
- monuments on building rooftops are to be avoided where possible; if unavoidable, the building should be as low as possible and its structure highly rigid
- discontinuation of primary monument to be done only in extreme circumstances, requiring prior announcement and submission of overlapping data sets starting one year in advance
- <igscb.jpl.nasa.gov/network/monumentation.html> provides additional information and advice

● Surveying criteria:

- GPS antenna phase center eccentricity to primary marker (a permanent, ultra-stable ground monument) known to ~1 mm accuracy
- conventional three-dimensional ground surveys with 1 to 3 mm accuracy should be used to relate all site monuments to the primary station, preferably at least every two years
- the RF station should be tied into the first-order control network of the host country, if such exists
- survey measurements, field notes, and reduced results should be preserved and be made publicly accessible
- all survey data should be rigorously and globally adjusted and the results be made available in SINEX format, including full variance-covariance information

● Operational and logistic criteria:

- operated by an institution, preferably a government agency, with a long-term commitment and geodetic expertise
- permanent, continuous operation
- site not likely to be abandoned or overtaken by other uses
- associated operational data center responsible for data flow and metadata reliability
- personnel available to effect maintenance and repairs, as needed
- reliable data transfer, preferably by Internet, and equipped with ample, reliable power
- physical site security

● GNSS instrumentation criteria:

- high-quality, dual-frequency GPS receiver system for current installation
- consistently high-quality raw data, with high yields, low multipath, and low cycle slips
- anticipate upgrades to observe new GNSS signals (but with close attention to avoiding position discontinuities)
- support for GLONASS observations is desirable, but not required
- avoid all unnecessary changes in the GNSS instrumentation; when unavoidable, any configuration change must ensure no position discontinuity by thorough testing beforehand in a parallel, non-interfering operation and must be announced in advance
- only one receiver at each RF station can be designated for official IGS use, which should be determined on the basis of highest quality and RF suitability
- high-quality meteorological sensors for temperature, barometeric pressure, and humidity are highly desirable
- high-quality external frequency standards are highly desirable but not required
- <igscb.jpl.nasa.gov/network/guide_igs.html> provides further information

● Co-location criteria:

- nearby installations of other space geodetic systems (SLR, VLBI, and DORIS) are highly desirable
- other geophysical systems — such as absolute or superconducting gravimeters, Earth tide gravimeters, seismometers, strain meters, ocean tide gauges — are also desirable and will enhance the value of the station for multi-disciplinary studies
- other scientific systems which rely on accurate positioning, such as timing labs, are also recommended where appropriate

- <u>Metadata criteria</u>:

  - reliable, current site log information is critical for the proper analysis of the data
  - RINEX data file headers must be current, accurate, and consistent with the IGS site log information
  - the station operator must ensure that these conditions are rigorously satisfied
  - planned equipment changes must be announced in advance via IGS Mail and must always be reflected in updated RINEX headers and site logs within 1 business day

- <u>Analysis criteria</u>:

  - for useful coordinates and velocities, sufficient observing history is needed (usually >2 years)
  - new stations can be accepted as "RF candidates"
  - adequate stability and performance must be demonstrated