COORDINATION OF IGS ANALYSIS CENTERS

J.Kouba[1], G. Beutler[2] and R. Neilan[3]

[1] Geodetic Survey Div, NRCan, Canada, K1A 0E9; (currently visiting scientist at Astronomical Institute, University of Berne); e-mail: kouba@geod.emr.ca
[2] Astronomical Institute, University of Berne, Switzerland; e-mail: beutler@ubeclu.unibe.ch
[3] IGS Central Bureau, JPL, CALTech, USA; e-mal: ruth.neilan@jpl.nasa.gov

ABSTRACT

The International GPS Service (IGS) evolved from a pilot project during 1992 and 1993 into a full Service of IAG on January 1, 1994. IGS relies on voluntary contributions of more than 70 research and government agencies. It is organized along constituent components of continuously operating GPS stations, Data Centers, Analysis Centers and a Central Bureau. For IGS, the International Governing Board provides the cognizant authority under regularly updated Terms of Reference as a charter. A unique feature of IGS is that the IGS Analysis Center coordination and official product generation are external to the IGS Central Bureau. The Analysis Centers (ACs) play an important role within the IGS, addressing ever-increasing demands for new products and improved precision to support changing and new GPS applications. The ACs contribute significantly to the current and future directions of IGS, which was demonstrated most recently at an IGS retreat held in December 1997.

AC coordination and adherence to the common processing standards are important and necessary for the success of IGS and its products, though freedom to innovate and new research approaches are equally essential and encouraged. Format development, model standardization, processing documentation, e-mail discussions as well as annual AC workshops have become an integral part of the IGS AC coordination. However, by far the most significant impact has been through the IGS product combinations. The effective AC solution comparisons, feedback, free exchange of research ideas and results, often connected with IGS product combinations, have resulted almost in an order of magnitude precision improvements of AC solutions and IGS products since 1994. This experience, though it may be specific and unique to the GPS technique, could be useful and applicable to SLR and the new International SLR/LLR Service.

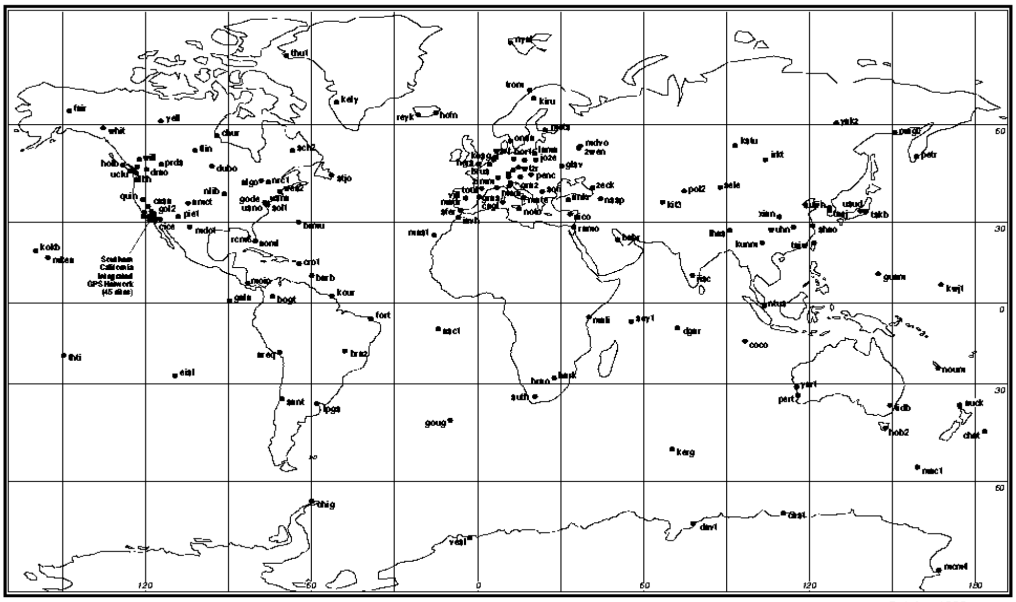
INTRODUCTION

The International GPS Service for Geodynamics, recently renamed the International GPS Service (IGS), evolved from a three month campaign starting in June, 1992, followed by a pilot project till the end of 1993. IGS has officially started as an International Association of Geodesy (IAG) Service on January 1, 1994. Since 1996 IGS is a member of the Federation of Astronomical and Geophysical Data Analysis Services (FAGS). The primary goal of IGS is to support a wide range of scientific and practical GPS applications, including the most precise ones, such as global and national terrestrial reference realizations, geodynamics, Earth rotation monitoring, etc. This is accomplished by continuously making available, in a timely manner, high quality GPS tracking data and the associated solution products, such as the so called 'core' products, consisting of precise GPS satellite orbits, clock corrections, Earth rotation parameters (ERP) and the corresponding station coordinate solutions. The IGS solution products should be consistent and must conform to the international conventions. Consequently, from the beginning, IGS has been closely aligned to and coordinated with the International Earth Rotation Service (IERS), through adopting largely the same analysis standards (IERS conventions), mutual representations at the respective directing/governing boards as well as regular submissions of IGS results to IERS. Such close links and cooperation between the IGS and the IERS are also firmly imbedded in the IGS Terms of Reference.

The Russian GLONASS system is similar to GPS, yet differing in some important aspects, thus it could be quite complementary to GPS for both scientific and practical applications. For example, a combination of GPS and GLONASS improves satellite coverage, geometry and it should result in solutions that are better than with standalone GPS or GLONASS. Furthermore, unlike GPS (where only two satellites have a small laser reflector), all GLONASS satellites are equipped with large laser reflectors allowing easy and precise SLR observations, thus providing a direct link between the SLR and GPS/GLONASS techniques. GLONASS satellites have orbits that are also sufficiently lower than the GPS orbits so that they do not suffer from the deep, 2:1 resonance with Earth rotation; thus GLONASS can significantly enhance GPS solutions and orbit improvement studies. For these reasons and since there is a considerable expertise connected with the initiation and operation of IGS, it is only logical that IGS would take part in GLONASS observations, monitoring and applications. A general consensus seems to be developing that the IGS should incorporate, take part in, or actively cooperate with a GLONASS service. This is why IGS is also cosponsoring the International GLONASS Experiment (IGEX). The IGEX campaign has started on 18 October 1998, and will continue at least for three months. It is a joint project of the Commission on the Coordination of Space Techniques for Geodesy and Geodynamics (CSTG), the IGS, the IERS, and the Institute of Navigation (ION). See the web site: *http://lareg.ensg.ign.fr/IGEX* for more detail information on IGEX.

IGS ORGANIZATION

IGS is a world-wide co-operative effort of many (more than 70) agencies, operating continuously about 200 permanent GPS stations (Fig. 1) that conform to the IGS station guidelines and standards. GPS data, the associated information and solutions are continuously made available through several Regional and Global Data Centers located on several continents (see Table 1), to provide redundancy and optimize communication/ data flow. In order to facilitate also solution redundancy and enhance product reliability, the GPS tracking station data is continuously analyzed and processed by seven IGS Analysis Centers (ACs) that produce the core global products of orbit/clock/ERP and station solutions. Additionally, there is a number of Associate Analysis Centers (AAC) specialized in certain products or solutions. For example, the Global Network AACs and Regional Network AACs produce weekly global and regional station solutions in SINEX format; Tropospheric and Ionospheric AACs are producing tropospheric and ionospheric solution products, etc. The existence of IGS AACs allows flexibility and gives IGS the potential to accommodate future applications of IGS data and products. Table 2 shows the IGS ACs and some of the IGS AACs.



October 1998

Figure 1. IGS Continuous Tracking Station Network as of October 1998.

Table 1. IGS Regional and Global Data Centers

Regional Data Centers	
AUSLIG	Australian Land Information Group, Australia
BKG	Bundesampt für Kartographie und Geodæsie, Germany
GODC	GRD/NOAA Operational Data Center, NOAA, USA
JPL	Jet Propulsion Laboratory, USA
NRCan	Natural Resources Canada, Canada
IGS Global Data Centers	
CDDIS	Crustal Dynamics Data Information System, NASA GSFC, USA
IGN	Institut Geographique National, France
SIO	Scripps Institution of Oceanography, USA

The IGS AC Coordinator (ACC) is also an important component of the formal IGS organization structure because GPS global analyses are rather complex and require considerable cooperation and coordination amongst IGS Analysis Centers. This is so in particular, when the production of official (combined) IGS products is required. The IGS core product combination, specified in the IGS Terms of Reference, is another important function of ACC. The first author served as the ACC for the first five years of IGS, since January 1999 Tim Springer of CODE AC has taken over the IGS Analysis Coordination. For more on the analysis coordination and related developments see the next section as well as the ACC contributions in the 1994-1997 IGS Annual Reports (*http://igscb.jpl.nasa.gov/overview/pubs.html*).

The IGS Central Bureau (CB) is hosted by Jet Propulsion Laboratory (JPL), with Ruth Neilan as Director. It provides the necessary logistical and operational support, including coordination and monitoring of IGS network operations; compliance to the IGS standards; publication and distribution of reports and the IGS Mail; organization of meetings, workshops and pilot projects, etc. Most of station information, IGS products, publications and the IGS Mail are made available at the IGS CB Archives (*http://igscb.jpl.nasa.gov*).

Table 2. Analysis Centers and Associate Analysis Centers of IGS

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IGS Analysis Centers (ACs)
COD       Center for Orbit Determination in Europe, AIUB, Switzerland
EMR       Natural Resources Canada, Canada
ESA       European Space Operations Center, ESA, Germany
GFZ       GeoForschungsZentrum, Germany
JPL       Jet Propulsion Laboratory, USA
NGS       National Oceanic and Atmospheric Administration / NGS, USA
SIO       Scripps Institution of Oceanography, USA

Rapid Service Associate Analysis Centers (RSAACs)
USN       U.S. Navy observatory, USA

Global Network Associate Analysis Centers (GNAACs)
NCL       University of Newcastle-upon-Tyne, UK
JPL       FLINN Analysis Center Jet Propulsion Laboratory, USA
MIT       Massachusetts Institute of Technology, USA

Some of the IGS Regional Network Associate Analysis Centers (RNAACs)
GSI       Geographical Survey Institute of Japan
GIA       Geophysical Institute of the University of Alaska, USA
EUR       EUREF - IAG Commission X - Subcommission for Europe
          (includes 11 European RNAAC solutions)
SIR       SIRGAS, Deutsches Geodätisches Forschungsinstitut, Germany
OSO       Onsala Space Observatory, Sweden
PGC       Pacific Geosciences Center  Canada
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The international IGS Governing Board (GB) consists of 15 members representing all the above IGS components, while maintaining balanced international representation. It provides control over all IGS activities, including the formulation and approval of the IGS Term of Reference (ToR). The GB members elect a Chairperson of the GB who is the official representative of the IGS. Gerhard Beutler has been the first IGS GB Chair and Christoph Reigber of GFZ has succeeded him on January 1, 1999. The GB initiated a retreat held in December 1997 in Napa Valley, Cal. which resulted in considerable enhancements and broadening of the IGS Terms of Reference (Mueller, 1998). The new ToR now include regular reviews of most IGS components, including the ACs, DCs and the CB. Also, the new ToR now contain the IGS policy on the IGS Working Groups and Pilot Projects, a charter for ACs and AACs. A similar charter for DCs is in preparation. Accurate and up to date ToR proved to be essential for IGS in order to cope with ever increasing demands and new applications.

IGS ANALYSIS CENTER COORDINATION

Coordination of IGS global analyses is essential for the IGS product generation and improvements. As a minimum the IGS/AC solution products must conform to international standards such as the IERS 96 Conventions (McCarthy, 1996). The IGS/AC solution products must be in standardized formats containing specified parameters at specified sampling and must be submitted within specified delays. Since there was no predecessor to IGS, all these aspects had to be developed and some of them took considerable effort and discussions amongst all ACs. Though, following the example set by the IERS and its predecessors, innovation analysis approaches have been and are encouraged by IGS. All ACs are required to provide standard documentation of their processing approaches and they are also required to keep them up to date. The standard AC processing documentation (so called the 'action' files) is made available at the IGS CB Archives (*http://igscb.jpl.nasa.gov/center/analysis/center.acn*). However, the timely updates of the action files has been only partly successful.

Development of standardize formats took a considerable effort. Though some formats and data naming conventions predated the official IGS and could be readily adopted, such as the SP3 satellite orbit format (Remondi, 1989), the RINEX (Receiver Independent Exchange). However, completely new formats and templates, such as the ERP format (*ftp://igscb.jpl.nasa.gov/igscb/data/format/erp.txt*), the SINEX (Software Independent Exchange) format and the action file form had to be developed.

By far, the most difficult and complex task was the development of the SINEX format. This format was first proposed in March 1996 by the SINEX working group led by G. Blewitt and after considerable discussions amongst all ACs it was adopted by IGS in July 1996 (*http://igscb.jpl.nasa.gov/igscb/data/format/sinex.txt*). The SINEX format attempts to preserve station and ERP solutions in a complete manner, including the occupancy, hardware and solution information as well as both a priori and a posteriori variance-covariance matrices. It is structured in a form of specific ASCII blocks, which should make it also adaptable to other space techniques (e.g., SLR). It contains sufficient information for removal of the a priori information (e.g., datum and/or parameter constraints) thus allowing the reconstruction of the original (usually nearly singular) solutions. In the fall of 1996, the responsibility for the SINEX development and maintenance was transferred to the Project on Coordination and Combination of Space Geodetic Analysis (chaired by T. Herring of MIT). The SINEX format has been also adopted by IERS for ITRF submissions as well as for the IERS time series pilot project (*http://lareg.ensg.ign.fr/ITRSTS/appeldoffre.html*). Despite of a sustain effort, and the capability of SINEX, the effort of documenting and standardizing the AC station solutions has been only partially successful. Station information, such as antenna type and offset problems/conflicts have not been fully eliminated. Such conflicts are largely responsible why, at this time, there still is not an official IGS station combined product. Recently, however, the IGS CB established a convenient and 'official' SINEX template (IGS.SNX-*ftp://igscb.jpl.nasa.gov/igscb/station/general/igs.snx*) with station, antenna, receiver and occupancy SINEX blocks that are consistent with RINEX and station log files. This should greatly aid with resolving the SINEX header conflicts, since all ACs are required to use this IGS.SNX template for the generation of all SINEX files. For applications not requiring variance-covariance matrices and in order to facilitate efficient communication, all the AC SINEX files are also made available at DCs in the so called the short SINEX format version (*.SSC). The SSC format is identical to the regular SINEX, only the variance-covariance matrix blocks are omitted. Subsequently variants of the SINEX format were adopted for IGS tropospheric and the future clock products (see *http://maia.usno.navy.mil/gpst.html* for the new clock format and information on the IGS/BIPM Time pilot Project).

AC workshops, with theme position papers prepared and distributed prior to the workshops, proved to be important not only for IGS ACs, and the IGS product generation, but also for the whole IGS. Such AC workshops were limited to about 30 invited participants representing ACs, DCs and other components of IGS. The 1997 Napa Valley retreat has confirmed that, in fact, IGS was well prepared to meet new challenges. This is so, likely thanks to the past AC workshops. Usually, the AC workshops have resulted in significant changes, new products, new deadlines, new reference frame realization, etc. All these changes always have created more work and new challenges for the Acs, in addition to their continuous improvements and research. Table 3 lists some of the AC workshops and some of the main changes/actions that resulted from them. Regular AC beer/wine Dinners, usually held during the AC workshops, also proved to be very useful and often helped to resolved 'delicate' issues. They were also useful to build a consensus amongst ACs, in particular during the initial years of the IGS operation. Such AC Dinners were a nice alternative to rather frequent e-mail discussions amongst ACs.

Table 3: Some of the IGS AC workshops and the main AC actions and changes initiated or resulting from the workshops

AC Workshop	Changes/Actions/dates of Implementation
OTTAWA (Oct 93)	IGS orbit/clock product combinations (Jan 1/94)
POTSDAM(May 95)	IGS Rapid orbit combinations directly in ITRF rather than Bull A ERP alignment (Jun 95)
SILVER SPRING(Mar 96)	The June 30/96 'Great Divide' includes: Sub-daily PM, PM rates, both IGS Rapid (22h) & IGS Final (11 days) orbit combinations directly in ITRF, IGS Prediction (IGP) combinations, ITRF94, IGS Rapid & Final combined ERP products, etc.
DARMSTADT(Feb 98)	ITRF96 (Mar 1/98), Tropospheric combined product; new clock & ERP (version 2) formats, new IGS Rapid deadline (17h), initiation of the new realization of ITRF (July-Dec 98), etc.

The IGS realizations of ITRF have also required considerable coordination and effort on the part of the ACs. C. Boucher and Z. Altamimi of the ITRF Section of IERS extended considerable help and cooperation to IGS. The first three ITRF realizations, ITRF92 (from Jan 2/94), ITRF93 (from Jan 1/95) and ITRF94 (from June 30/96) were accomplished by fixing or constraining the ITRF positions and velocities of a carefully selected set of 13 stations with multitechnique collocations. The latest realization of ITRF96, which was adopted on March 1, 1998, utilizes much larger set of 47 ITRF96 stations. This station coordinate/velocity set was selected after careful analyses and discussions amongst all the IGS ACs during 1997 and 1998 and it was found to be consistent at a few mm precision level (Kouba at al., 1998; Altamimi, 1998). The 47 ITRF96 SSC/SSV official set is available (in the short SINEX format), from the IGS CB Archives: *ftp://igscb.jpl.nasa/gov/igscb/station/coord/ITRF96_IGS_RS47.SSC*. Since July 1998, in preparation for the new IGS realization of ITRF, all AC Final solution submissions are based on minimum constraints that in turn are based on the above 47 ITRF96 station set. However, the AC Rapid Solutions, currently submitted within a 16 h delay, still employ constraining or fixing large subsets of the 47 ITRF96 station set. The new ITRF realization, recommended by the Darmstadt position paper #3 (Kouba et al., 1998), is to be based on the new IGS combined station/ERP SINEX product. The IGS SINEX product is to be based on a combination of GNAAC SINEX solutions for station positions, velocities and ERP, properly attached to the official (i.e., ITRF96) reference frame.

All ACs have been extending a great effort to sustain continuous global analyses, while still managing significant research activities. The great improvements made by most ACs is seen in Figure 2, the best ACs are now approaching an orbit rms of only about 3 cm and a clock rms (not shown) of about 1 ns. The IGS Rapid combination (IGR) is also shown in the Figure 2. It is remarkable that this IGR product, which is regularly produced within less than 24h, shows reliability and precision comparable to the best Final AC solutions, in particular after March 1998 (GPS Week 0947) when ITRF96 has been adopted by IGS.

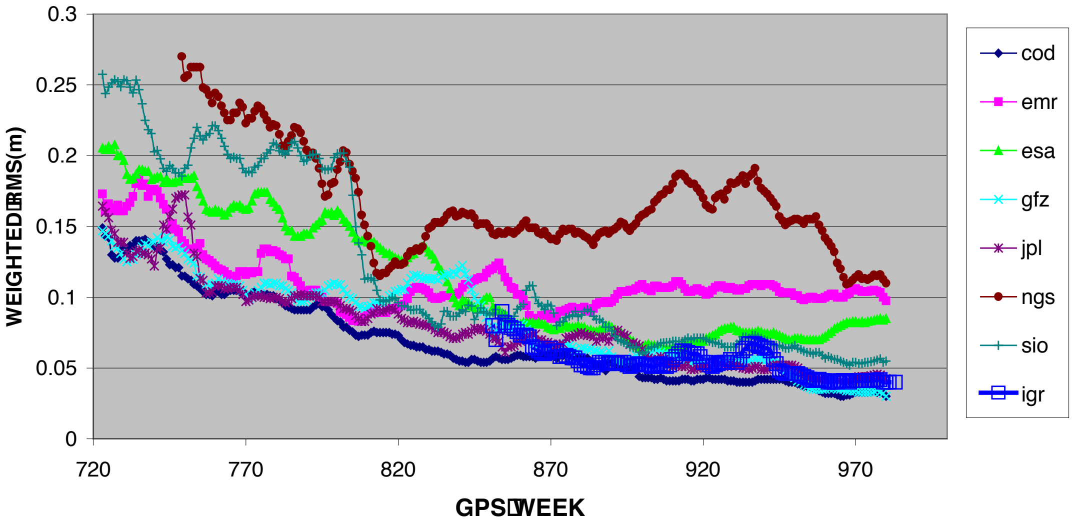

Figure 2. Weighted Orbit RMS with respect to the IGS Final Orbit Combinations, starting on November 14, 1993 (GPS Week 0723).

IGS COMBINED PRODUCTS

Perhaps the most significant impact on the IGS AC precision and reliability has been realized due to regular comparisons and timely feedback connected with the IGS orbit/clock and ERP combinations. Strictly speaking, it is illegal to combine (adjust) solutions that are largely based on the same observational data. However, the IGS experience during the first five years has shown that such 'illegal' combinations, in fact, tend to be more precise, reliable and robust than the individual AC solutions. This is perhaps due to the fact that GPS global analyses are complex and the differences amongst AC solutions tend to behave randomly even when using the same or compatible approaches and/or software. However, such orbit combinations, even when based on largely same data still satisfy equations of motion (Beutler et al., 1995) and still give a realistic correlation matrix.

Depending on precision and availability, there are three distinct IGS orbit/clock and ERP combined products, namely the IGS Final products, available within 11 days, the IGS Rapid (IGR) products currently available with a delay of only 17 hours and the IGS Predicted (IGP) orbit combinations available in real time. The most accurate and definitive are the IGS Final orbit/clock/ERP combinations; they are based on the Final AC solutions. All the seven ACs (see Table) are required to submit weekly, as a minimum, their Final orbit/ERP as well as the corresponding station SINEX solutions, within 11 days. The seven Final AC orbit/ERP solutions and five AC Final clock solutions (all but NGS and SIO) are used weekly in the IGS Final combinations. Note that the AC clock solutions (according to the AC/AAC Charter) are recommended but not mandatory for those ACs that utilize double differenced GPS observations. Furthermore, since July 98, all AC Final orbit/ERP/clock solutions are internally consistent and based on minimum (ITRF96 rotational) constraints only.

The IGR orbit/ERP/clock combinations, which are currently (January 1999) produced within 17 h of the last observation, utilize eight orbit/ERP (the 7 AC, plus USNO) and five AC clock solutions (COD, NGS, SIO do not submit rapid clock solutions). The AC Rapid solutions are typically based on less station data and usually include a number of constrained or fixed ITRF96 station positions. No AC Rapid SINEX station solutions are required and submitted to IGS. The IGS Predicted orbit combinations use six AC predictions of 24 to 48 hours (NGS does not participate in IGP), that are usually based on the fit of the four preceding AC or IGR daily orbit solutions. IGP use the IERS Bull A ERP predictions, and are produced about one hour before the start of the current day so that they are available to IGS users for real time applications.

Table 4. Current IGS Combined Solution Products

Product	Avail.	interval	Precision	
Orbits&clocks			*orbits*	*clocks*
Predicted	Real-time	15 min	50 cm	150 ns
Rapid	17 h	15 min	10 cm	.5 ns
Final	11 d	15 min	5 cm	.3 ns
IGS Station Positions (not an official IGS product yet)				
Weekly sol.	2-4 weeks	7 days	3-5 mm	
Earth Orientation			*param.*	*rate/LOD*
Rapid PM	17 h	1 d	.2 mas	.4 mas/d
Final PM	11 d	1 d	.1 mas	.2 mas/d
Rapid UT /LOD	17 h	1 d	.30 ms	.06 ms/d
Final UT /LOD	11 d	1 d	.05 ms	.03 ms/d
Tropo ZPD	*2-4 weeks*	*2 hours*	*4 mm*	

Broadly speaking, the IGS combined products can be viewed as a reference system with the associated imbedded reference frames. Such a reference system should be consistent, precise and reliable. Since July 1998 there have been a concentrated effort by all ACs to produce and maintain consistencies amongst various AC solutions and submissions. The current list of IGS combined products; their precision, delays and sampling are listed in the Table 4.

CONCLUSIONS

AC coordination, AC discussions/cooperation, and the IGS product combinations have resulted in unprecedented improvements of precision and reliability of the AC and IGS combined solutions. Regular AC workshops have initiated new products and changes that helped to set new directions and strategies for IGS. Likely, the extensive AC research effort and vision are the main reason why IGS appears to be well positioned to accommodate new demands and applications. Some of the above IGS experience and developments, such as IGS product combinations and feedback, ITRF realizations, formats as well as documentation of AC processing may be also applicable to the new SLR and VLBI Services.

To meet the future demands and to support GPS applications, a new ITRF realization and ERP combinations, consistent and based on a new IGS combined station product, will have to be implemented in near future. Also, to meet the challenging applications of Low Earth Orbiter (LEO) applications, the IGR products will have to be made available even sooner than now, within a few hours and with a more frequent clock sampling than the current 15 minute sampling of the IGS/IGR combined satellite clock corrections.

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