International GPS Service 2000: Life without SA

Ruth E. Neilan, Angelyn Moore *(IGS Central Bureau, Jet Propulsion Laboratory California Institute of Technology)*
Tim Springer *(University of Bern, Switzerland)*
Jan Kouba *(Natural Resources of Canada)*
Jim Ray *(US Naval Observatory, USA)*
Christoph Reigber *(GeoForschungsZentrum, Germany)*

Institute of Navigation GPS 2000
Salt Lake City, Utah
September 19-22, 2000

BIOGRAPHIES

Ms. Ruth E. Neilan is the Director of the Central Bureau of the International GPS Service. The Central Bureau is funded by NASA at Caltech's Jet Propulsion Laboratory (JPL) in Pasadena, CA and is responsible for the daily coordination of the IGS.

Dr. Angelyn Moore serves as the Deputy Director of the IGS Central Bureau and as IGS Network Coordinator, is responsible for all network operations.

Prof. Tim Springer serves as the Analysis Center Coordinator for the IGS at the Astronomical Institute, University of Bern from January 1999 through December 2000.

Dr. Jan Kouba currently advises the IGS Central Bureau on analysis and user issues. Recently retired from the Natural Resources of Canada, he was the Analysis Center Coordinator of the IGS from 1993 until 1998.

Dr. Jim Ray co-chairs a project on 'Precise Time and Frequency Transfer', a joint effort between the IGS and the Bureau International des Poids et Mesures (BIPM).

Prof. Dr. Christoph Reigber is the chairman of the IGS Governing Board and Director of Division 1 at the GeoForschungsZentrum, Kinematics and Dynamics of the Earth in Potsdam, Germany.

ABSTRACT

Over the last eight years the International GPS Service (IGS) has produced GPS data and products at the highest level of precision available. Today, IGS orbit determination of the GPS satellites is consistently at the 5 centimeter level, 3d-wrms[1], with sub-centimeter station positioning globally. How does the removal of Selective Availability (SA) affect and enhance the IGS processes and products? This paper will provide the status of IGS products and applications, contrasting before and after the removal of SA. Future directions of the IGS rely on the evolving infrastructure and expertise of IGS, which support an increasing number of activities. These activities include a project for precise time transfer dependent on GPS; support for low Earth orbiting satellites (LEOs) carrying on-board GPS flight receivers; a pilot service for tracking the Russian GLONASS satellites; analyses of ground-based GPS atmospheric parameters; global monitoring and mapping of the ionosphere; and continued extension of a dense homogenous reference frame through GPS.

INTRODUCTION

Within hours of the 'removal' of selective availability on May 2, 2000, the plot shown in Figure 1 was made available by the IGS Analysis Center Coordinator. The figure depicts the dramatic improvement in the clock performance for GPS satellites. While many users benefit from the removal of SA, particularly real-time and navigation applications, there is some benefit to precision users of the GPS as we will describe.

This paper will first provide an overview and current status of the IGS, enhancements realized in 2000, and then describe the impact of the removal of SA on IGS products, processes and applications. We will conclude by summarizing the potential for precise point positioning using IGS products with SA off.

---

[1] Three dimensional weighted root mean square error.

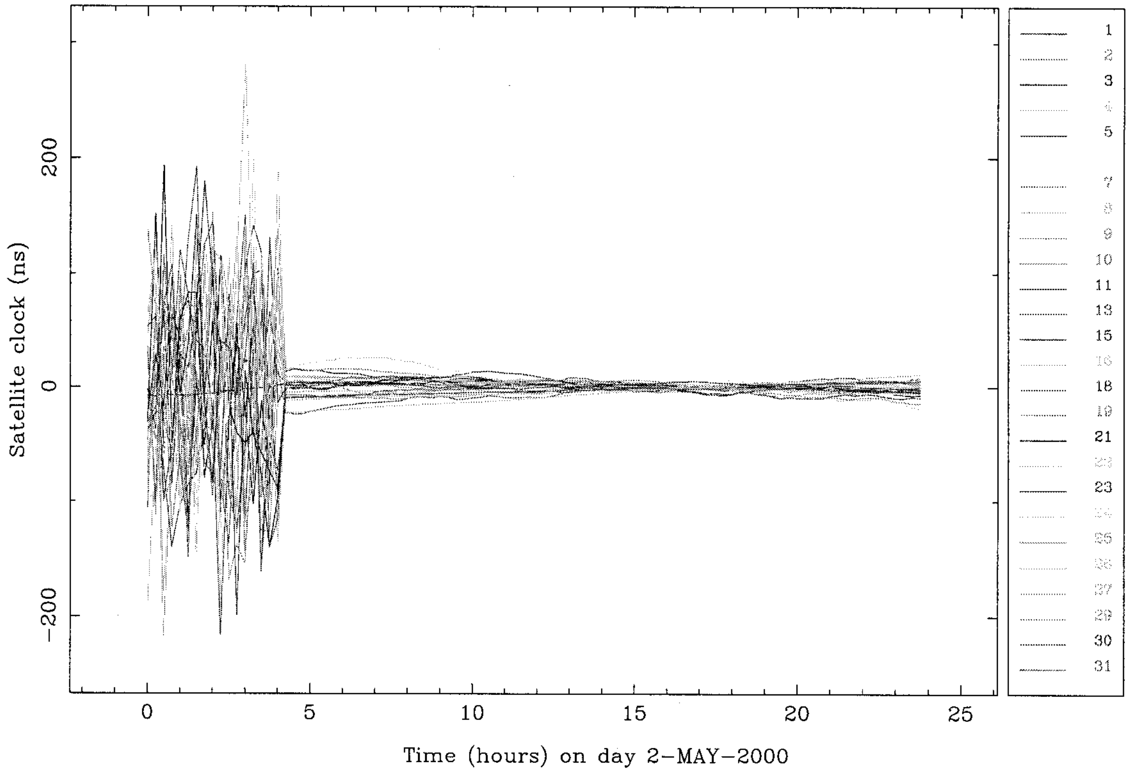

Figure 1. SA Off! May 2 GPS Week 1060, Day 2 at about 04:00 UTC

OVERVIEW AND STATUS

The mission of the International GPS Service is *"to provide a service to support geodetic and geophysical research activities through GPS data and data products'* as described in the 'IGS Terms of Reference'[1]. But why dose such an organization exist – why IGS?

One of the key factors in the formation of IGS is that all geodynamics and geodetic organizations realized the potential of GPS by early 90's. A motivating goal was driven by a science requirement "to achieve the capability for millimeter level accuracy in both horizontal and vertical positioning ... with low-cost, routine deployment, anywhere in the world", a recommendation stemming from workshops in Erice, Sicily (1988) and Coolfont, West Virginia (1989) [2].

At the same time, these organizations began to realize that not one agency could nor should assume the capital investment & recurring costs to support the required infrastructure to realize such an objective. The solution was to join with key international partners to outline the cooperation, establish standards, define roles, responsibilities and a governance structure, and form a federation largely driven by science.

The results are evident in the successful implementation and operation of the robust international GPS tracking system supporting scientific research, engineering and related applications. A defining principle of the IGS is the word *service*, and the commitment to ensure that users have access to the GPS data and data products developed within the IGS. The IGS is recognized globally as an organization that strongly advocates an open data policy.

Today the IGS has grown to include more than 100 contributing organizations. The IGS is an approved service of the International Association of Geodesy since 1994 and is recognized as a member of the Federation of Astronomical and Geophysical Data Analysis Services (FAGS). The International Union of Geodesy and Geophysics (IUGG) and the International Council of Scientific Unions (ICSU) recognize IGS.

ENAHNCED OPERATION OF THE IGS 2000

The IGS has developed a continually evolving system to make high-quality GPS data, products and information accessible as quickly as possible. A cartoon diagram of the IGS organization is shown in Figure 2, giving the reader a quick look at the relations within the IGS. For more detailed information on the goals, organization and responsibilities of the IGS and its components, refer to the IGS Terms of Reference [1].

The foundation of the IGS is the tracking network (Figure 3) of over 200 permanent geodetic GPS receivers that produce data on a continuous basis, including a subset of over 50 stations (Figure 4) that submit hourly data to one of the IGS data centers. All data files are in the RINEX (Receiver Independent Exchange) Format.

A key development in the IGS occurred on March 5, 2000, GPS week 1052, when the production of a new combined orbit called the 'IGS Ultra Rapid' began. In June 1999 at the IGS Analysis Center workshop in San Diego, CA, it was decided to take advantage of the hourly files available from the IGS network. This Ultra Orbit is a notable shift from using 24-hour data files and daily processing, to implementing sub-daily analyses. The main reason for the generation of the Ultra products is in response to requirements for both timeliness and accuracy for near-real time atmospheric and ionospheric monitoring. Such a scheme may facilitate the rapid inclusion of GPS information into weather forecasting algorithms and numerical weather prediction [3]. The IGU products will contain 48 hours worth of orbits. The first 24 hours contain a "real" orbit, i.e., an orbit based on actual observations. The second 24 hours contain a predicted orbit. However, the orbit should be continuous at the boundary between the real and predicted part The average age of the IGS predicts are thus reduced from 36 hours to 9 hours. This product became an official IGS product on November 6, 2000 [4], after a lengthy period of quality verification. The quality of the IGU orbits IGS Ultra rapid orbits are estimated to be at the 20cm level, much better than the ~70 cm accuracy of the current IGS predicted, and clearly an order of magnitude better than the Broadcast ephemeris. This is a very significant achievement and it is expected to improve even further as more IGS stations start submitting hourly RINEX files.

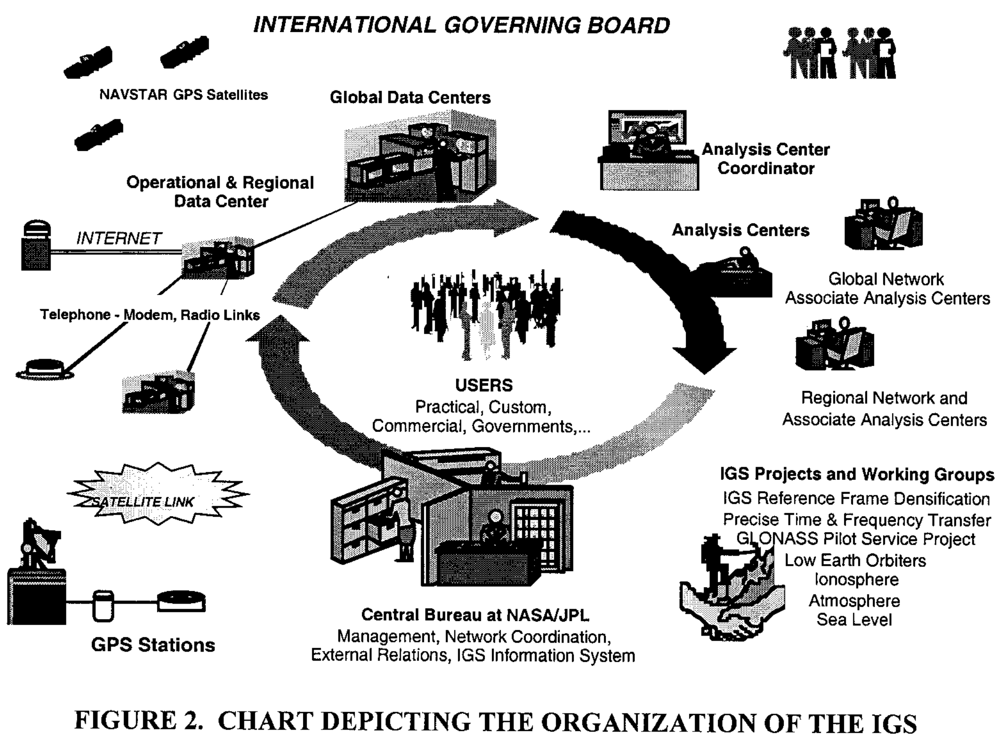

FIGURE 2. CHART DEPICTING THE ORGANIZATION OF THE IGS

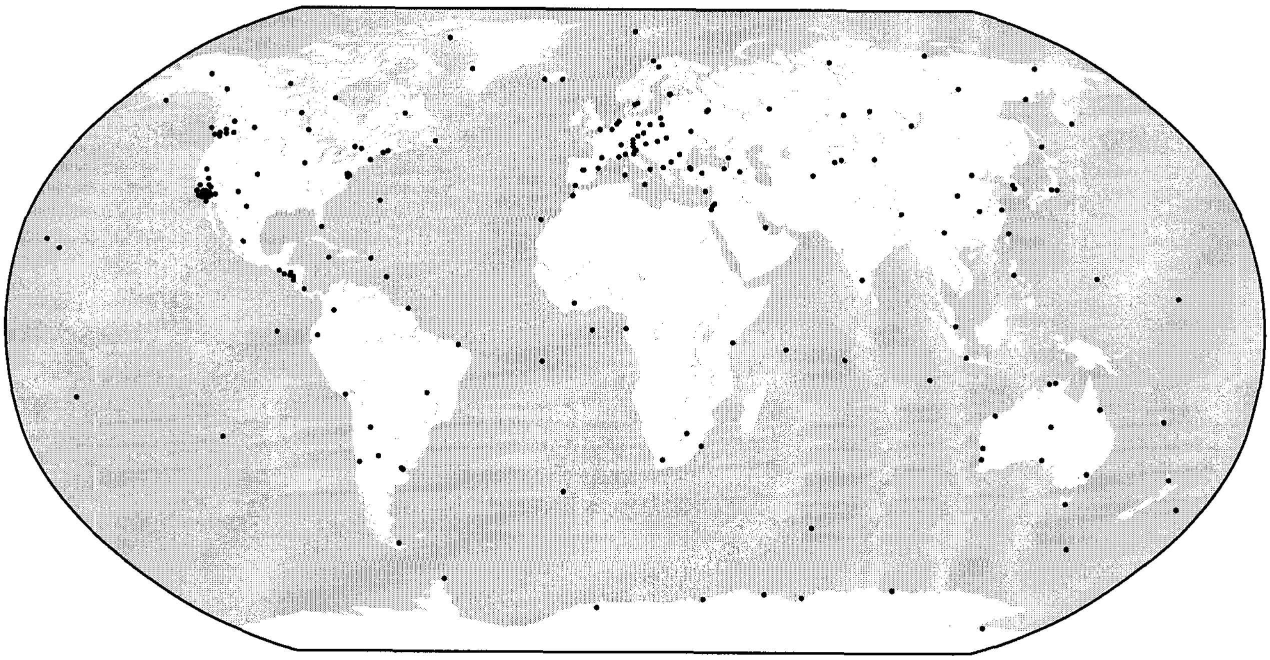

FIGURE 3. THE GLOBAL GPS TRACKING NETWORK OF THE INTERNATIONAL GPS SERVICE 2000

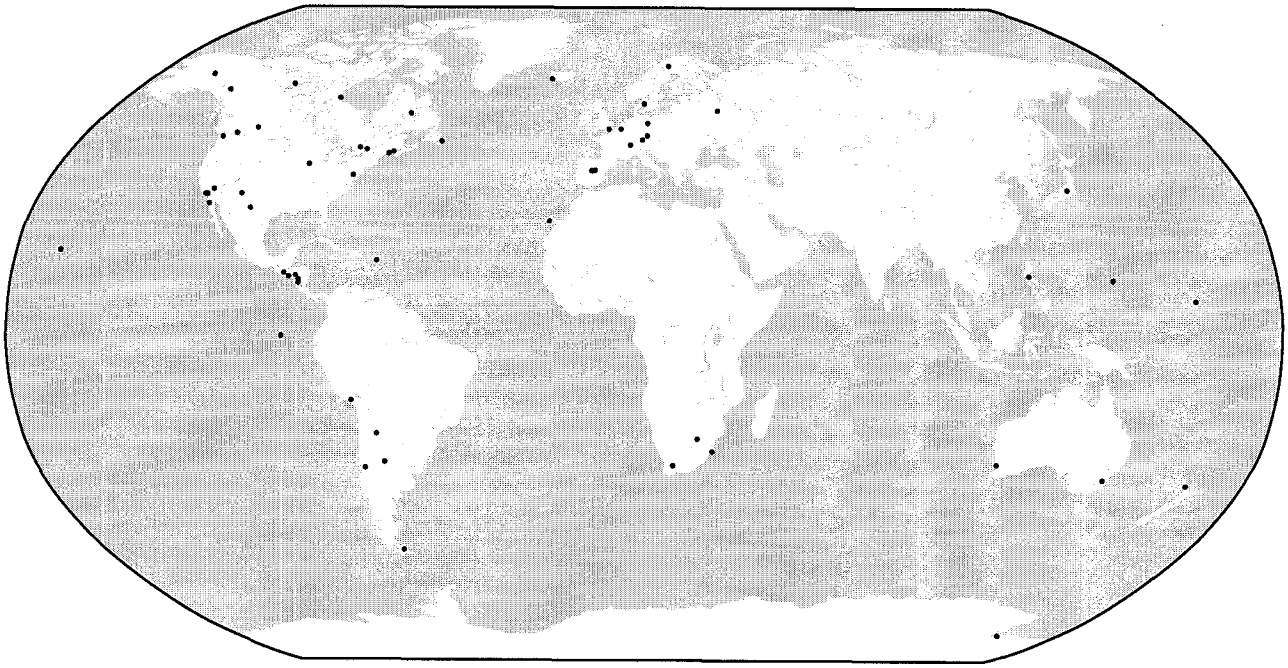

FIGURE 4. SUBNETWORK OF THE IGS PROVIDING HOURLY DATA FILES

Optimizing the global distribution or IGS stations, whether for the hourly data files or daily files, remains challenging, particularly within Africa, Asia and the oceanic areas. The primary obstacle to realizing a better geographic distribution in these areas is the availability of reliable, and cost effective communications for data retrieval and remote station operation and support. The IAG and IGS are jointly working to support an initiative for the establishment of an continental reference system for Africa beginning in 2001, which will hopefully enable additional space geodetic stations at least within Africa. A key goal is to ensure appropriate technology transfer and support for necessary expertise in such countries in order to sustain the GPS geodetic technology for the foreseeable future.

OFFICIAL PRODUCTS OF THE IGS

The IGS Analysis Coordinator is responsible for producing the official IGS orbits, based on the combination of orbits from the analysis centers of the IGS, shown in Table 1. There are currently three types of orbits, based on accuracy and time to access. The predicted orbits, as described above, are available in real-time at the ~20 cm level as compared to the Broadcast ephemeris accuracy of ~2 to 4 meters. Rapid and Final IGS orbits are available within 17 hours and 10 day delays, respectively and are estimated to be better than 10 cm. Because of consistency checks, the combined IGS orbits are largely free of systematic errors that occasionally remain in results from individual AC's.

Table 2 lists the precision and timeliness of IGS orbits, clocks, Earth rotation parameters (erp's), and station locations are shown in Table 3 [5]. The improvement of the Final IGS orbits since 1994 can be seen in Figure 4, which compares each centers orbits to the IGS Final orbit. Figure 5 shows the performance of the Ultra Rapid Orbits (the new IGS Predicts as of November 2000) compared to the daily IGS Rapid orbits.

The estimates of Earth orientation and station coordinates from the AC's are coordinated with the International Terrestrial Reference Frame (ITRF), part of the International Earth Rotation Service (IERS). Through the IGS, GPS-derived station locations are contributing more and more to the ITRF since the IGS currently provides the ITRF with the coordinates of the globally distributed network sites that comprise dense regional GPS networks. Since June 1999, the IGS designated the Natural Resources of Canada as the 'IGS Reference Frame Coordinator' which is responsible for the combination of the GPS station positions with the IGS [6].

TABLE 1. IGS ANALYSIS CENTERS AND THEIR PRODUCT ABBREVIATIONS

Astronomical Institute University of Bern - COD	Switzerland
European Space Agency - ESA	Germany
GeoForschungsZentrum - GFZ	Germany
Jet Propulsion Laboratory - JPL	USA
National Oceanic and Atmospheric Administration - NGS	USA
Natural Resources, Canada - EMR	Canada
Scripps Institution of Oceanography – SIO	USA
US Naval Observatory-USNO	USA
Associate Analysis Center	

TABLE 2. IGS COMBINED PRODUCT PRECISION AND TIMELINESS, SANS SA

Product	Availability	Accuracy
GPS Satellite Orbits and Clocks		
Ephemerides		
Predicted	Real Time	20 cm
Rapid	17 hours	10 cm
Final	10 days	5 cm
Clocks		
Predicted	Real Time	30 ns
Rapid	17 hours	0.5 ns
Final	10 days	0.3 ns
IGS Station Locations (Combined)		Position & Velocity
Weekly Solutions	2-4 weeks	3 - 5 mm 3mm/yr
Earth Rotation Parameters		
Polar Motion		
Rapid	17 hours	0.2 mas
Final	10 days	0.1 mas
Polar Motion Rates		
Rapid	17 hours	0.4 mas/day
Final	10 days	0.2 mas/day
UT1-UTC		
Rapid	17 hours	100 μs
Final	10 12 days	50 μs
Length of Day		
Rapid	1 -2 days	60 μs /day
Final	10 - 12 days	30 μs /day
Derived Parameters		
Tropospheric Zenith Path Delay	< 4 weeks	4 mm
Ionospheric Grid TEC	<4 weeks	2 TECU ~0.2m

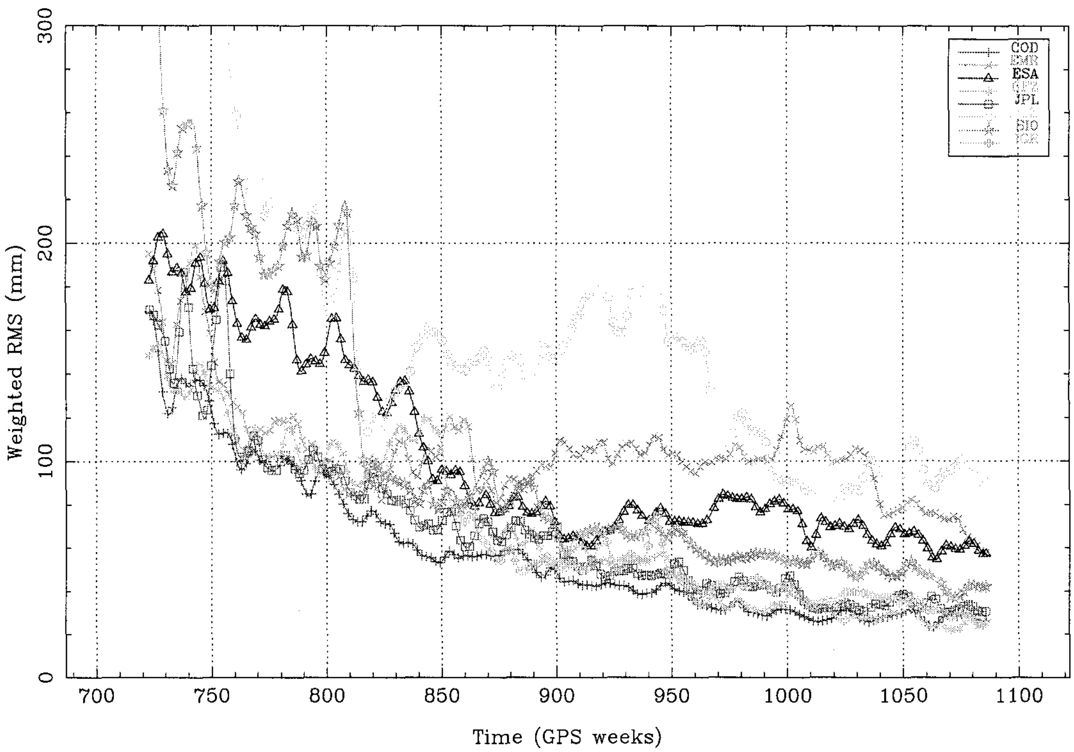

FIGURE 5. IGS FINAL ORBIT PERFORMANCE SINCE 1994

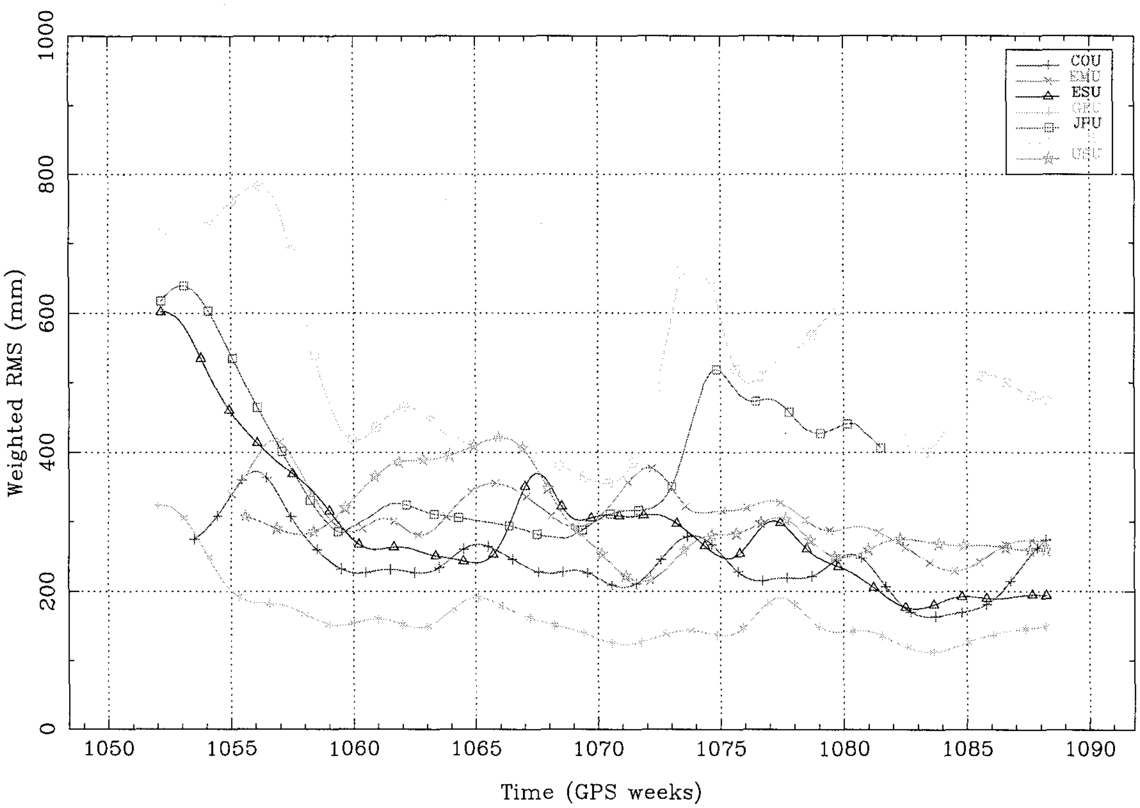

FIGURE 6. COMPARISON OF THE IGS ULTRA ORBIT AND PREDICTION COMPARED TO THE IGS DAILY RAPID ORBIT

IGS APPLICATIONS AND PROJECTS

The IGS has become increasingly involved in supporting GPS oriented applications such as shown in the lower right corner of Figure 2. The working groups and pilot projects dependent on the infrastructure afforded by the IGS help to keep the IGS vital, and view the IGS as a valuable asset, if not a global utility.

The projects and working groups of the IGS are:

- *Reference Frame Densification* - Focused on the extension and maintenance of a robust, homogeneous reference frame defined by positions and velocities of hundreds to thousands of sites, with the same qualities of redundancy, consistency, and precision that are currently realized by global IGS stations (3-5mm position, 3mm/yr velocities).
- *Precise Time and Time Transfer* - Developing operational strategies to exploit GPS measurements for improved accurate time and frequency comparisons worldwide in a rapid manner. A joint project between the IGS and the BIPM.
- *Low Earth Orbiter Project (LEO)* - Supporting generation of (near) real-time GPS precise orbit determination (POD), clocks, and integrity information for scientific satellite missions and applications (gravity, atmospheric occultation, ionospheric tomography, etc.)
- *International GLONASS Service Pilot Project* IGLOS-PP- Integrating Russian Global Navigation Satellite System (GLONASS) data into the IGS processes; performing orbit determination and station positioning, making products available for GLONASS users.[7]
- *Tropospheric Working Group* - Monitoring ground-based water-vapor distributions on global and regional scales for global climate studies and enhanced weather forecasting.
- *Ionospheric Working Group* - Monitoring global ionosphere electron density and ionic-current distribution using tomography and modeling techniques. Providing ionosphere-induced group delay and developing ionospheric grid maps.
- *Sea Level Monitoring Initiative* - Monitoring sea level through maintenance of tide gauge benchmark positions and velocities using GPS and linked to the IGS reference system. Supporting calibration of altimeter missions via GPS (e.g., TOPEX/Poseidon, JASON, etc.)

LIFE WITH AND WITHOUT SA

Selective Availability, the intentional dithering of the satellite clocks, has really no impact on the classic IGS products and applications. The majority of IGS applications traditionally need products for post processing. However, the removal of SA benefits precision products supporting real-time applications, and this regard, benefits the approach of two of the projects – the Precise Time Transfer Project and the Low Earth Orbiter Project.

When the IGS began to provide users with an official predicted ephemeris in March 1997 there was little hope of implementing a predicted clock due to SA. The IGS was unable to predict the corresponding satellite clocks and therefore limited to the level of SA in this regard, at about the 150 ns level, certainly not sufficient for real-time precision applications. The individual IGS clock solutions achieve sub-nanosecond accuracy in processing of the data and an IGS combined clock was initiated in early 2000. This has been recently replaced with a new clock combination scheme on November 6, 2000 [7]. The next step is an IGS combined predicted clock, an experimental process implemented by USNO in July 2000 [8]. In this manner it should be possible to produce the IGS predicted satellite clocks at the few nanosecond in real time. This requires hourly to real-time data and analysis, and the ability to handle the variations of the SV transmitters [9].

SA affected the LEO project mainly in the need for high rate ground data to remove the effect of SA on the flight receiver data for atmospheric occultation. The current observation of a ground-tracking receiver is 30-seconds and was considered sufficient for the POD of the satellite. However, compensation for SA to support the atmospheric occultation applications of the flight receiver required a global subset of the IGS network to operate at the 1-second rate, a factor of 30 increase over current data and communications measures. This is a significant impact to communication links, data centers and analysis.

PRECISE POINT POSITIONING WITHOUT SA

.The removal of SA is expected to have a significant impact on precise point navigation or positioning within the IGS. Precise point positioning (PPP) [9] is a method for checking the integrity of the IGS products. By using IGS classic products fixed and performing a point positioning solution, comparisons can be made at the centimeter level for the absolute positioning of a single station. Table 3 shows typical PPP results with IGS orbit and clocks held fixed [10]. Without SA it should now be possible to interpolate the IGS satellite clocks, currently sampled at 5-minute intervals, at or below the 20 cm precision level. Consequently, it should now be possible to do precise navigation at any interval or by fixing IGS orbits and clocks. The navigation precision of better than 10 cm with IGS products fixed is being demonstrated daily and weekly in the summary reports of the IGS Rapid (IGR) and Final combinations.

Regional GPS networks can include data from one or more nearby IGS stations, fix the site coordinates from such stations to their ITRF values, and fix GPS satellite positions to their IGS-determined values. By doing so the investigator can reduce their network data with maximum accuracy and minimum computational burden. Furthermore, the results will be in the well-defined global reference frame of the

TABLE 2. IGS CONSISTENCY EVALUATION USING PRECISE POINT POSITIONING (PPP)

Analysis Center	# SV Clk Epochs	BRUS ϕ	BRUS λ	BRUS h	TOW2 ϕ	TOW2 λ	TOW2 h	WILL ϕ	WILL λ	WILL h
cod	2659	3	4	7	5	6	8	2	3	4
emr	2554	3	3	6	2	3	8	2	3	4
esa	2372	6	4	9	2	2	5	2	3	4
gfz	2663	2	2	7	2	2	6	1	2	3
igc	2688	2	2	6	2	2	6	2	3	3
igr	2688	3	3	7	3	3	5	2	2	5
igs	2688	2	2	6	2	2	6	1	2	3
jpl	2576	3	3	7	2	1	5	2	3	4

This table shows the comparison of PPP results IGS stations Brussels, Belgium (BRUS), Cape Ferguson, Australia (TOW2), and Williams Lake, Canada. (WILL) using the orbits of the respective IGS Analysis Centers. The number of available satellite clock epochs on that day is included and the values listed are the rms in centimeters for absolute station position in latitude ϕ, longitude λ, and height, h. This data is from GPS week: 1076, day: 0, MJD: 51776.0

SUMMARY

SA off is a tremendous benefit for real-time and near real-time applications, greatly simplifying analysis and system design. The IGS Predicted orbits are now at the level of ~20 cm and combined predicted clock should be realized in the next year to less than a few nanoseconds.

A single user fixing IGS predicted orbits and clocks and applying appropriate precise point positioning methods should achieve decimeter level positioning results anywhere.

CENTRAL BUREAU INFORMATION SYSTEM

The IGS Central Bureau Information Service (CBIS) provides IGS member organizations and the public with a gateway to all the IGS global data and data product holdings, as well as a wealth of related information. The IGS electronic mail (e-mail) service is also provided through the Information System, where IGS messages, reports, and address lists are archived and accessible. The CBIS is at http://igscb.jpl.nasa.gov.

ACKNOWLEDGMENTS

The work described in this paper was carried out in part by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The authors would like to thank all participants of the IGS for their continuing contributions. These cooperative efforts have enabled the IGS to realize a successful and productive international operation.

REFERENCES

[1] IGS Governing Board, *International GPS Service: Terms of Reference (revised June 1999)*, in International GPS Service 1999 Technical Report, IGS Central Bureau, Jet Propulsion Laboratory, Pasadena CA, 2000. Also see: *http://igscb.jpl.nasa.gov/organization/bylaws.html*

[2] Committee on Geodesy, Board of Earth Sciences and Resources, National Research Council, 'Geodesy in the Year 2000', National Academy Press, Washington, D.C., 1990.

[3] Springer, T., U. Hugentobler *'IGS Ultra Rapid Products for (near) Real-time Applications'* Proceedings of the IGS Network Workshop, Oslo, Norway, July 2000. To be published by Physics and Chemistry of the Earth, 2001.

[4] Springer, T., IGS Mail Message #3088, IGS Ultra Rapid Products, November 3, 2000, ref.: *http://igscb.jpl.nasa.gov/mail/igsmail/2000*

[5] Kouba, J., *'Overview of the Organization and Resources of the International GPS Service-Products and Applications Section'*, Users Forum, Capetown, South Africa, March 2000. IGS Central Bureau, Jet Propulsion Laboratory, Pasadena CA, updated June 2000.

[6] Ferland, R. *'IGS Reference Frame Pilot Project'* in International GPS Service 1999 Technical Report, November 2000, IGS Central Bureau, Jet Propulsion Laboratory, Pasadena CA, 2000.

[7] Springer, T., IGS Mail Message #3087, New IGS Clock Combination, November 3, 2000, see:. *http://igscb.jpl.nasa.gov/mail/igsmail/2000*

[8] Ray, J., IGS Mail Message #2962, USNO Ultra-rapid clock predictions, July 31, 2000, see:. *http://igscb.jpl.nasa.gov/mail/igsmail/2000*

[9] Zumberge, J., G. Gendt, *'The Demise of Selective Availability and the Implications for the International GPS Service Network,'*. Proceedings of the IGS Network Workshop, Oslo, Norway, July 2000. To be published by Physics and Chemistry of the Earth, 2001.

[9] Zumberge, J.F., M.B. Heflin, D.C. Jefferson, M.M. Watkins, F.H.Webb, *'Precise Point Positioning for the Efficient and Robust Analysis of GPS Data from Large Networks'*, Journal of Geophysical Research, Vol.102, No B3, p.5005, 1997

[10] Kouba, J., IGS Mail Message #2824, IGS Orbit/Clock navigation & Sat. Clock Interpolations with no SA, May 5, 2000, ref.: *http://igscb.jpl.nasa.gov/mail/igsmail/2000*