The International GPS Service:
A Global Resource for GPS Applications and Research

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BIOGRAPHIES

Ruth **E.** *Neilan* is the Director of the IGS Central Bureau, fancied by NASA at Caltech's Jet Propulsion Laboratory (JPL) in Pasadena, CA. She received her M.S. in Civil and Environmental Engineering from the University of Wisconsin-Madison in 1986 and has been involved in the coordination and establishment of the GPS Global Network since 1987.

James F. Zumberge serves the IGS as a member of its Central Bureau and as a member of one of seven IGS Analysis Centers. He received his Ph.D. in physics from Caltech in 198 I, and joined the Satellite Geodesy and Geodynamics Group at JPL in 1990

Gerhard Beutler currently serves as the chairman of the IGS and is the Director of the Astronomical Institute of the University of Bern.. He received his Ph.D. in astronomy from the University of Bern, Switzerland. The development of algorithms to process observations of the GPS eventually led to the development of the Bernese GPS Software Package and to the operat ion of the CODE analysis center of the IGS.

Jan Kouba has acted as the Analysis Center Coordinator of the IGS since 1993 through the sponsorship of the Geodetic Division of the Natural Resources of Canada. He received his DrSc. in satellite geodesy from the Czech Academy of Sciences, Prague, CR in 1993.

ABSTRACT

Since June, 1992, the international GPS Service has been coordinating a global civilian GPS infrastructure in order to support numerous GPS appl i cat ions and research activities. A key aspect of the IGS is the reliability and quality of the analysis products that have been made available over the past five years through the IGS Analysis Centers and the Analysis Center Coordinator. On a daily basis these IGS centers produce precise satellite orbits, Earth orientation parameters, satellite and receiver clocks, atmospheric and ionospheric data.

Recent improvements in the IGS include production of predicted (50 cm rms) and rapid orbit products (1(1 cm rms), generation of an official IGS Earth orientation parameters (cop) series, combined site-specific tropospheric est i mates for determining precipitable water vapor, and ionospheric delay estimates from the IGS network. A key project of the IGS is the Densification Project of the international Terrestrial Reference Frame (ITRF) through GPS. On a regular basis station coordinates and velocities of global and regional stations are produced in this precise, truly global reference frame. Additionally, the IGS is now considering its role in supporting upcoming Low Earth Orbiting missions; its potential contribution to long term monitoring of sea level heights and altimeter calibration through the GPS; and extending the IGS in frastructure to support observations and analysis of GLONASS system.

1N'I'KO1)UCTION

The primary mission of the International GPS Service as staled in the organization's Terms of Reference is "*to provide a service to support, th rough GPS data products, geodetic and geophysical research activities. Cognizant of the immense growth in GPS applications the secondary objective of the IGS is to support a broad spectrum of operational activities performed by governmental or selected commercial organ izations. The service also develops the necessary standards/specifica tions and encou rages in ternational adherence to its con ventions.* " The IGS *Terms of Reference* [I] describes in broad terms the goals and organization of the IGS.

The IGS was formally recognized in 1993 by the International Association of Geodesy (IAG), and began routine operations on January 1, 1994. A description of the development and evolution of the IGS can be found in a number of publications, with detailed documentation contained in the IGS Annual Report Series published by the Central Bureau [2, 3, 4]. This series contains the yearly contributions from all components of service and demonstrates that the key to success of the IGS through the last seven years has been the broad of the international geodynamics and geodetic communities and their sponsoring organizations.

The IGS collects, archives, and distributes GPS observation data sets of sufficient accuracy to satisfy the objectives of a wide range of applications and experimentation. These data sets are used by the IGS to generate data products mentioned above which are made available to interested users through Internet access.

In particular the accuracies of IGS products are sufficient for the improvement and extension of the International Terrestrial Reference Frame (ITRF), the monitoring of solid Earth deformations, the monitoring of Earth rotation and variations in the liquid Earth (sea level, ice-sheets, etc.), for scientific satellite orbit determinations, ionosphere monitoring, and recovery of precipitable water vapor measurements.

To accomplish its mission, the IGS has a number of components: an international network of over 140 continuously operating dual-frequency GPS stations (Figure 1), more than a dozen regional and operational data centers, three global data centers, seven analysis centers and a number of associate or regional analysis centers. The Central Bureau for the service is located at the Jet Propulsion Laboratory, which maintains the Central Bureau Information Service (CBIS at http://igscb.jpl.nasa.gov/) and ensures access to IGS products and information. An international Governing Board oversees all aspects of the IGS. 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) since 1996.

The IGS has a solid structure that provides support for science and engineering. The infrastructure for maintenance and control of the GPS global reference frame is nearing completion. Figure I shows the stations of the IGS Network as of July 1997; a number 01 future stations arc still being planned to optimize the global distribution, 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 direction that many scientists and agencies arc heading is the implementation of dense or regional GPS arrays, often coupled with other instrumentation. Tbc link between these localized arrays and the IGS is primarily in the hierarchy of reference frame and global data products. A pilot project for the Regional Densification of the ITRF has been ongoing since 1995, and is successfully demonstrating the unique capability afforded by this technique to position any GPS network station within a homogenous reference frame at the 3 to 5 mm level. This is possible through distributed processing, the combination of the regional network analysis solutions, and the solid infrastructure of the global network [5].

Similarly, some of the IGS components have been working with the Sea level community of the Permanent Service for Mcaa Sea Level (PSMSL) and the Global Ocean Observing System, to develop the GPS methodology and mechanisms for long term monitoring of tide gauge beach marks and for altimeter calibration of spaceborne altimeter missions, such as the TOPEX/Poseidon and the upcoming JASON.

OPERATION OF THE IGS

The IGS has developed a worldwide system — comprising satellite tracking stations, Data Centers, and Analysis Centers — to make high-quality GPS data, data products and information accessible as quickly as possible.

Each IGS silt of the global network has a high-precision dual-frequency P-code receiver which records measurements at 30-sec intervals. The Operational Data Centers ('Table l), which are in direct contact with the tracking sites, collect the raw receiver data and format them according to a common standard, using a data format called Receiver Independent Exchange (RINEX). The formatted data are then forwarded to the Regional or Global Data Centers (Table l). To reduce electronic network traffic, the Regional Data Centers collect data from several Operational Data Centers before transmitting them to the Global Data Centers. Data not used for global analyses arc archived and available for on-line access at the Regional Data Centers.

The Global Data Centers archive and provide on-line access to tracking data aad data products. The on-line data arc employed by the Analysis Centers to create a range of products, which are then transmitted to the Global Data

Centers and Central Bureau Information System (CBIS) for public use.

TABLE 1. IGS DATA CENTERS

Operational and Regional	
Australian Land Information Group	Australia
Centre National d'Etudes Spatiales	France
Delft University of Technology	Netherlands
European Space Operations Center	Germany
GeoForschungZentrum	Germany
Geographical Survey Institute	Japan
Geosciences Research Lab /NOAA	USA
Institut für Angewandte Geodäsie	Germany
Institute for Space Research	Austria
Itali an Space Agency	Italy
Jet Propulsion Laboratory	USA
Korean Astronomical Observatory	Korea
National Imaging and Mapping Agency	USA
Natural Resources of Canada	Canada
Scripps 1 nstitution of Oceanography	USA
Norwegian Mapping Authority	Norway
University NAVSTAR Consortium	USA
Global	
NASA/Goddard Space Flight Center	USA
Institut Géographique National	France
Scripps Institution of Oceanography	USA

There are currently seven IGS Analysis Centers (AC's) ('1'able 2) that routinely analyze all or a subset of the data from the IGS global network. AC's compute precise GPS ephemerides and Earth orientation parameters. Results arc posted daily for the rapid and predicted products, and within two weeks for the final products. Annual Coordinate solutions arc given

The IGS Analysis Coordinator is responsible for producing the official IGS orbits, based on the combination of orbits from the separate AC'S [7]. There arc currently three types of orbits, based on accuracy and time 10 access. Predicted orbits are available in real-lime at the -50 cm level as compared to the Broadcast ephemeris accuracy of -2 to 5 meters. The Rapid and Final IGS orbits are available with 1-2 and 10-12 day delays, respectively, and arc estimated to be at or below the 10 cm orbit rms level. Because of consistency checks, the combined IGS orhits arc largely free of some systematic errors that occasionally remain in results from individual AC'S, Agreement among AC'S in GPS satellite ephemerides is generally at the level of less than 10 cm. It is estimated that the absolute accuracy of the IGS orbits is *at least* one order of magnitude better than the broadcast ephemeris, even when anti-spoofing is in effect.

TABLE 2, IGS ANALYSIS CENTERS ANI) THEIR PRODUCT AI)1{RI1VIATIONS

Astronomical Institute University of Bern - CO1)	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 1 nstitution of Oceanography SIO	USA

PRODUCTS OF THE IGS

The approximate accuracies of IGS orbits, clocks, Earth orientation, and station locations are shown in Table 3 [6, 7]. Estimates of Earth orientation and station coordinates from the AC'S arc coordinated with the International Earth Rotation Service (IERS) in Paris [8]. Through the IGS, Cil'S-derived station locations arc contributing more and more to the I'I'RF since the IGS currently provides the ITRF with the coordinates of the globally distributed network and sites that comprise dense regional GPS networks.

BENEFITS TO USERS

The IGS has been in formal operation for nearly four years, and detailed analysis strategies that exploit the qualities of its data and products continue to be developed.

High quality RINEX tracking data from the global tracking network, predicted and post-processed GPS ephemerides that are more accurate than the broadcast orbits by at least an order of magnitude, and precisely - determined locations of dozens (and eventually hundreds or more) of silts distributed over the entire globe, all provide benefits 10 users.

Geodynamics investigators who use GPS in local regions 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 data from his own network with maximum accuracy and minimum computational burden. Furthermore, the results will be in a well-clcfirlcclglob:ll reference frame.

W ith the prol i feration of GPS receivers throughout the world, including dense regional networks in many areas, the IGS is keenly interested io extending the ITRF. That is, the IGS seeks the determination of a 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 hy global IGS stations (those sites that are regularly used by Analysis Centers in determination of precise orbits and Earth orientation). To achieve this goal, an infrastructure of Associate Analysis C-enters is being implemented, and

TABLE 3. APPROXIMATE ACCURACIES OF IGS PRODUCTS

Product	Availability	Accuracy
GPS Satellites		
Ephemerides		
Predicted	Real Time	50 cm
Rapid	1 - 2 days	10 cm
Final	10 - 12 days	5 cm
Clocks		
Predicted	Real Time	150 ns
Rapid	1 - 2 days	0.5 ns
Final	10 - 12 days	0.3 ns
IGS Station Locations		
Weekly Solutions	4 Weeks	3 - 5 mm
Earth Orientation		
Pole		
Rapid	1-2 days	().2 mas
Final	10- I 2 days	0. I mas
Pole Rates		
Rapid	1 -2 days	0.4 mas/day
Final	10 - 12 days	0.2 mas/day
Rapid	I -2 days	300" ms
Final	10 - I 2 days	50 ms
Length D11)(IS		
Rapid	I -2 days	60 ms /day
Final	10 - 12 days	30 Ills /day

analysis techniques arc being developed that can successfully cope with the enormous volume Of data that is involved [3,4,5].

In the future, the IGS infrastructure will become a val uable asset for sup port of new' ground-based applications and will also contribute to space-hascd missions in which highly accurate flight aod ground differential techniq ues are req uired. The IGS has the potential to support the following multidisciplinary application as:

- Monitoring ground-based water-vapor distributions on global and regional scales for global climate studies and enhanced weather forecasting.

- Monitoring sca level through maintenance of tide gauge benchmark positions and velocities.

- Performing precise orbit determination of space-based remote-sensing systems such as radar altimeters and synthetic aperture **radars.**

- Supporting **limb** soundings from space-basccl radio occultation systems for recovery of ionospheric and atmospheric parameters and for monitoring global climate Change.

- Supporting recovery of geopotential data from Space systems.

- Disseminating rca-lime GPS satellite orbits, clocks, and integrity information for w'ide-area differential GPS navigation applications.

- Monitoring global ionosphere electron density and ionic-cur rent distribution using tomography and modeling techniques.

- Supporting ground-based gravimetry programs through collocations of gravimeters and GPS instruments.

- incorporating Russian Global Navigation Satellite System (GLONASS) data into the IGS network; performing orbit determination and station positioning for GLONASS users.

- Supporting seismic-hazards programs through maintenance of the global geodetic reference network.

- Providing ionosphere- ind uced group delay corrections lospacc-based radar systems.

CENTRAL BUREAU INFORMATION SYSTEM

The IGS CBIS, accessible on the Internet, provides both IGS member organizations and the public with a gateway to all the IGS global data and data product holdings, as wel l as a wealth of related information, This system contains summarized global GPS orbit and tracking data files, which are updated daily; these lilts indicate the sources and dates of observations and how to access the complete data sets through the on-l inc archi ves of the Global Data Centers. Also available are summarized IGS products and how to access the complete prod ucts electronically. in addition, the information System contains data on the current status of GPS, the IGS tracking stations and Data Centers, and the IGS Analysis Centers. So ftware developed for data compression and decompression schemes used in IGS data exchange is available on line for 1)0S, UNIX, and VMS platforms; you can also obtain information on file formats. The IGS electronic mail (e-mail) service is also provided through the Information System: IGS messages, reports, and address lists arc archived and accessible.

You can access the IGS CBIS on the Internet in two ways:

- World Wide Web: http://igscb.jpl.nasa.gov/

Hypermedia client programs like Netscape Navigator and Microsoft Internet Explorer allow for easy navigation and lilt retrieval.

- Anonymous File Transfer Protocol (FTP): igscb.jpl.nasa.gov (or 128.149.70.17 |)

Use the directory /igscb. The files README.TXT, TREE.TXT, and IGSCB. DIR in the main directory provide orl-line help and cur-rent directory and file information.

To have your c-mail address added to one or more of the mail and report-distribution lists, contact the Central Bureau:

IGS Central B ureau
Jet Propulsion Laboratory, MS 238-540
4800 Oak Grove Drive
Pasadena, CA 91109 USA

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FAX: 8183936686

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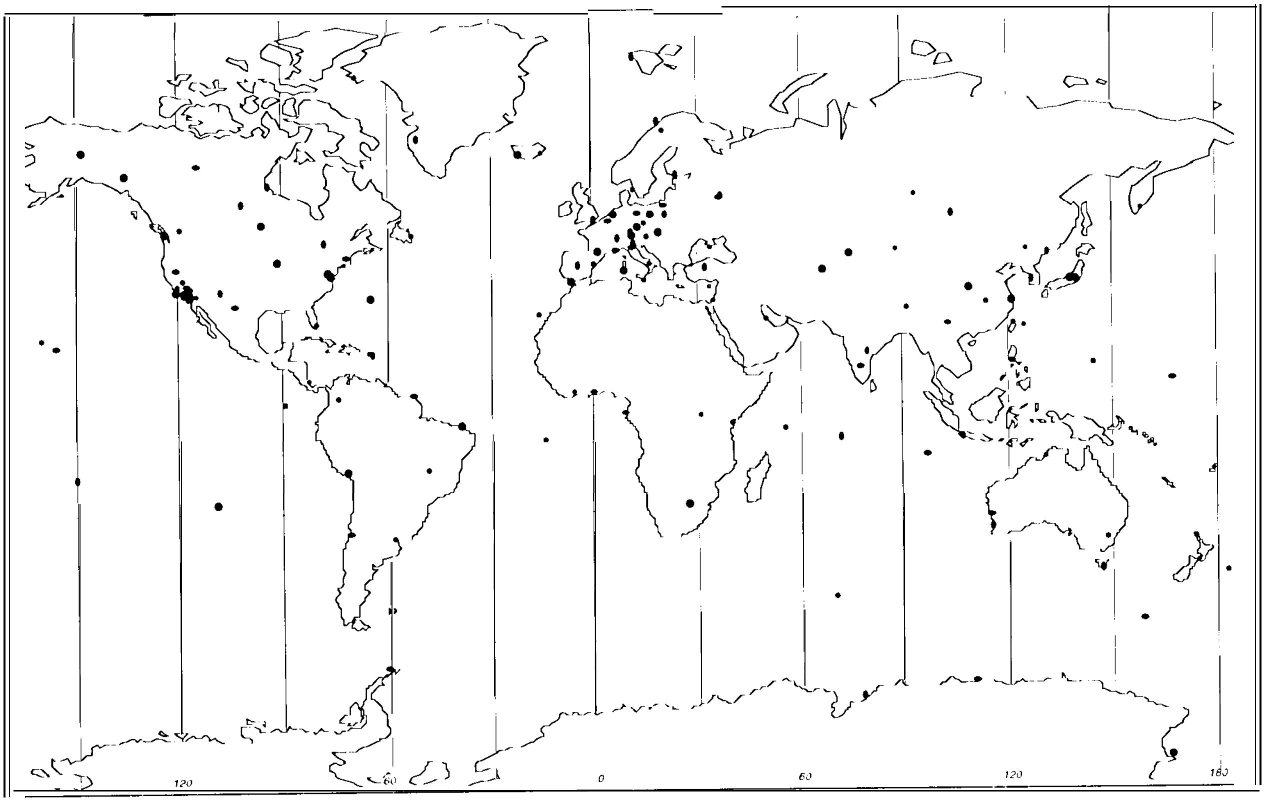

Figure 1. The GPS Tracking Network of the International GPS Service.