IGS
Annual Report

1997

International

GPS

Service

The IGS 1997 Technical Reports volume is the companion to this IGS 1997 Annual Report. The Technical Reports volume is available from the IGS Central Bureau upon request and is also accessible at the IGS World Wide Web site.

The Central Bureau Information System can be accessed using the World Wide Web (WWW) or via anonymous File Transfer Protocol (FTP) —

• WWW — http://igscb.jpl.nasa.gov

• FTP — igscb.jpl.nasa.gov (or 128.149.70.171)

Use the directory /igscb. See README.TXT for online help, and TREE.TXT and IGSCB.DIR for directory and file information.

On the Cover: The GPS receivers — one is shown at upper right in a ground installation — detect, decode, and process signals from the Global Positioning System satellites. Also shown is an artist's concept of a GPS Block IIF satellite (courtesy of Boeing Reusable Space Systems).

Introduction

The United States' Global Positioning System **(GPS)** constellation of satellites plays a major role in regional and global studies of Earth. In the face of continued growth and diversification of GPS applications, the worldwide scientific community has made an effort to promote international standards for GPS data acquisition and analysis, and to deploy and operate a common, comprehensive **global tracking** system.

As part of this effort, the International GPS Service for Geodynamics (IGS) was established by the International Association of Geodesy (**IAG**) in 1993 and began formal operation in January 1994. The IGS, with a multinational membership of organizations and agencies, provides GPS orbits, tracking data, and other data products in support of geodetic and geophysical research. In particular, since January 1994, the IGS has made available to its **user community** the IGS official orbit, based on **contributions** from the seven current IGS Analysis Centers. The IGS also supports a variety of governmental and commercial activities and develops international GPS data standards and specifications.

Highly accurate and reliable data and data products supplied by the IGS meet the demands of a **wide range** of applications and experimentation. They can be accessed on the Internet through the Information System maintained by the IGS Central Bureau, which is **sponsored** by the National Aeronautics and Space Administration (NASA) and managed for NASA by the Jet Propulsion Laboratory (JPL) of the California Institute of Technology. In 1996, the IGS became a member of the Federation of Astronomical and Geophysical Data Analysis Services (FAGS).

IGS ANNUAL REPORT

Contributing Agencies of the IGS

Astronomical Institute, University of Bern, Switzerland

Astronomical Latitude Observatory, Poland

Australian Survey and Land Information Group, Australia

Bundesamt für Landestopographie (Federal Topography), Switzerland

Bundesamt für Kartographie und Geodaesie, Germany

Center for Space Research, University of Texas, USA

Centre National d'Études Spatiales, France

Centro de Estudios Espaciales, Chile

Centro de Investigación Científica y de Educación Superior de Ensenada, Mexico

Chinese Academy of Sciences, China

Crustal Dynamics Data Information System, NASA Goddard Space Flight Center, USA

CSIR Centre for Mathematical Modeling and Computer Simulation, India

Delft University of Technology, Netherlands

Deutsches Zentrum für Luft- und Raumfahrt e.V., Germany

Earthquake Research Institute, University of Tokyo, Japan

East-Siberian Research Institute for Physicotechnical and Radioengineering Measurements, Russia

European Space Agency

European Space Operations Center, Germany

Finnish Geodetic Institute, Finland

FOMI Satellite Geodetic Observatory, Hungary

Geodetic Observatory Pecny, Czech Republic

Geodetic Survey Division, NRCan, Canada

GeoForschungsZentrum, Potsdam, Germany

Geographical Survey Institute, Japan

Geophysical Institute, University of Alaska, USA

Geosciences Research and Development Laboratory, National Oceanic and Atmospheric Administration, USA

Goddard Space Flight Center, National Aeronautics and Space Administration, USA

Hartebeesthoek Radio Astronomy Observatory, South Africa

Incorporated Research Institutions for Seismology, USA

Institut Cartografic de Catalunya, Spain

Institut Géographique National, France

Institute for Metrology of Time and Space, GP VNIIFTRI, Russia

Institute for Space and Astronautic Science, Japan

Institute for Space Research Observatory, Austria

Institute of Applied Astronomy, Russia

Institute of Astronomy, Russian Academy of Sciences, Russia

Institute of Earth Sciences, Academia Sinica, Taiwan

Institute of Geological and Nuclear Sciences, New Zealand

Instituto Brasileiro de Geografia de Estatistica, Brazil

Instituto Nacional de Pesquisas Espaciais, Brazil

International Deployment of Accelerometers/ IRIS, Scripps Institution of Oceanography, USA

Italian Space Agency, Italy

Jet Propulsion Laboratory, California Institute of Technology, USA

Korean Astronomy Observatory, Korea

Kort & Matrikelstyrelsen, National Survey and Cadastre, Denmark

Land Information New Zealand

Massachusetts Institute of Technology, USA

National Aeronautics and Space Administration, USA

National Bureau of Surveying and Mapping, China

National Geophysical Research Institute, India

National Imagery and Mapping Agency, USA

National Institute in Geosciences, Mining and Chemistry (INGEOMINAS), Colombia

National Oceanic and Atmospheric Administration, USA

Natural Resources of Canada (NRCan)

Observatoire Royal de Belgium, Belgium

Olsztyn University of Agriculture and Technology, Poland

Onsala Space Observatory, Sweden

Pacific Geoscience Center, Geological Survey of Canada, NRCan, Canada

Paris Observatory, International Earth Rotation Service, France

Proudman Oceanographic Laboratory, UK

Real Instituto y Observatorio de la Armada, Spain

Royal Greenwich Observatory, UK

Scripps Institution of Oceanography, USA

Shanghai Astronomical Observatory, China

Southern California Integrated GPS Network, USA

Statens Kartverk, Norwegian Mapping Authority, Norway

United States Naval Observatory, USA

University Federal de Parana, Brazil

University Navstar Consortium, USA

University of Bonn, Germany

University of Colorado at Boulder, USA

University of Newcastle on Tyne, UK

University of Padova, Italy

Warsaw University of Technology, Poland

Western Pacific Integrated Network of GPS, Japan

Wuhan Technical University, China

Governing Board

Member	Institution and Country	Functions	Term*
Gerhard Beutler	University of Bern, Switzerland	Chair,† Appointed (IAG)	1996–1999
Mike Bevis	University of Hawaii, USA	Appointed (IGS)	1998–2001
Geoffrey Blewitt	University of Newcastle upon Tyne, UK	Analysis Center Representative	1998–2001
Yehuda Bock	Scripps Institution of Oceanography, USA	Analysis Center Representative	1996–1999
Claude Boucher	Institut Géographique National, International Terrestrial Reference Frame, France	International Earth Rotation Service (IERS) Representative	—
John Dow	European Space Operations Center, Germany	Network Representative	1996–1999
Bjorn Engen	Statens Kartverk, Norway	Network Representative	1998–2001
Jan Kouba	Natural Resources Canada	Analysis Center Coordinator,‡ Analysis Center Representative	1996–1999
John Manning	Australian Survey and Land Information Group	Appointed (IGS)	1996–1999
Bill Melbourne	Jet Propulsion Laboratory, USA	IGS Representative to IERS	—
Ivan Mueller	Ohio State University, USA	International Association of Geodesy Representative	1996–1999
Ruth Neilan	Jet Propulsion Laboratory, USA	Central Bureau Director	—
Carey Noll	NASA Goddard Space Flight Center, USA	Data Center Representative	1998–2001
David Pugh	Southhampton Oceanography Center, UK	Federation of Astronomical and Geophysical Data Analysis Services Representative	—
Christoph Reigber	GeoForschungsZentrum Potsdam, Germany	Appointed (IGS)	1996–1999
Robert Serafin	National Center for Atmospheric Research, USA	Appointed (IGS)	1998–2001

Former Members and Institutions		Service
Martine Feissel	International Earth Rotation Service, France	1994–1995
Teruyuki Kato	Earthquake Research Institute, University of Tokyo, Japan	1994–1995
Gerry Mader	Geosciences Research and Development Laboratory, National Oceanic and Atmospheric Administration, USA	1994–1997
Bob Schutz	Center for Space Research, University of Texas–Austin, USA	1994–1997

* Members' current term is four years, unless noted with a dash due to the individual's position.

† Term as Chair is extended through the end of 1998; term on Board may continue.

‡ Analysis Center Coordinator duties will transfer to Tim Springer, University of Bern, Switzerland, beginning 1999.

1997

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The IGS in 1997— An Executive Summary

Gerhard Beutler

Astronomical Institute, University of Bern, Switzerland

Chair, IGS Governing Board

Development of the IGS as an IAG — and as a FAGS — Service

In 1997, the International Global Positioning System (GPS) Service for Geodynamics (IGS) concluded its first four-year period as an official service of the International Association of Geodesy (IAG). Four years constitutes the "fundamental period" within the IGS: Governing Board Members, Chairpersons, Analysis Coordinators, etc., are elected or assigned for four-year periods. It was thus only natural to take this completion of the first four-year period of the official IGS operations as an opportunity to critically review IGS operations in the past and to draw important conclusions for the future of the IGS. Let us briefly review the IGS events in order to fully appreciate the 1997 events.

The IAG General Meeting in August 1989 in Edinburgh, UK, is usually considered to be the starting point for the IGS. The IGS Planning Committee was created shortly thereafter, and the IGS Call for Participation was sent out in February 1991. At the International Union of Geodesy and Geophysics (IUGG) XX General Assembly in Vienna, Austria, in August 1991, the IGS Planning Committee was reorganized and renamed the IGS Campaign Oversight Committee. This Oversight Committee organized the 1992 IGS Test Campaign, scheduled from 21 June to 23 September. For more information concerning this early phase of the IGS, refer to Mueller, 1992, and Beutler, 1992.

The 1992 operations were considered so successful that data collection, processing, and product dissemination continued without interruption after 23 September 1992, first on a "best-effort basis" and then, starting 1 November 1992, as the IGS Pilot Service. During this pilot phase in 1993, the IGS Terms of Reference (see, e.g., Zumberge et al., 1997) were written and the IGS structure (Network, Data Centers, Analysis Centers, Governing Board, IGS Associates) was established. On 1 January 1994, the IGS was established as an official service of IAG.

The IGS became a recognized service of the Federation of Astronomical and Geophysical Data Analysis Services (FAGS) in 1996. The development of the IGS was thus really breathtaking from the administrative point of view. That the development was extremely rapid from the technical point of view as well may be concluded from the *IGS*

Annual Report for 1994, 1995, and 1996. For a review of the IGS operational activities, refer to Beutler et al., 1996 and to Neilan et al., 1997.

IGS Events in 1997

The essential IGS-related events in 1997 are summarized in Table 1. It should be emphasized that this table gives only a partial impression of the IGS activities. The IGS is represented by its Central Bureau through numerous presentations, splinter sessions, etc., at all major conferences where high-accuracy applications of the GPS technique are discussed.

Table 1. Important IGS-Related Events

12 March 97	1997 IGS Analysis Center Workshop
15 March 97	Business Meeting of the Governing Board
17 March 97	IGS Sea-Level Workshop
5 September 97	7th IGS Governing Board Meeting
16 September 97	10th International Technical Meeting of the Institute of Navigation (ION GPS-97)
11 December 97	8th IGS Governing Board Meeting
12 December 97	1997 IGS Retreat

The first three events took place in spring 1997 at the Jet Propulsion Laboratory (JPL) in Pasadena, California. Detailed reports concerning the first two events may be found in IGS Mail Message No. 1569. (IGS Mail and Reports are cataloged in the Central Bureau Information System and can be accessed at <http://igscb.jpl.nasa.gov>.)

IGS Analysis Workshops always give important clues concerning the future of the IGS. Space-borne GPS applications and a possible IGS involvement in this domain were the focal point of the 1997 IGS Analysis Center workshop. The interest of many IGS participants in such activities was sufficient to justify the creation of the IGS Low-Earth Orbiter (LEO) Working Group, with Michael Watkins of JPL as Chairman, at the Business Meeting of the Governing Board on 15 March. The report of the LEO Working Group is included in this *Annual Report*. A possible involvement of the IGS in tracking the Russian Global Navigation Satellite System (GLONASS) satellites was a topic at the workshop as well.

The main purpose of the IGS Sea-Level Workshop (17–18 March) was to set up an interface with the Global Sea-Level Observing System (GLOSS) community for the establishment of a systematic permanent tide-gauge survey using the GPS. This workshop was jointly organized by the Permanent Service for Mean Sea Level and the IGS. That the workshop's goal could be reached can be concluded from a detailed report in IGS Mail Message No. 1592. The workshop proceedings are available through the Central Bureau (Neilan et al., 1998).

The 7th IGS Governing Board meeting took place in Rio de Janeiro, Brazil, on Friday, 5 September 1997, during the Scientific Assembly of the IAG from 3–9 September 1997. A detailed report may be found in IGS Mail Message No. 1683. Let us briefly address four key issues:

- It was decided to initiate the establishment of an IGS/Bureau International des Poids et Mesures (BIPM) pilot project for the full exploitation of the IGS for time and frequency transfer. James Ray and Dennis McCarthy, both from the US Naval Observatory, were asked to act on behalf of the IGS in the discussions with BIPM Director Claudine Thomas and the timing community in general.

- The establishment of a GLONASS Working Group was addressed. It became clear that this issue was experimental in nature and that the microwave subcommission of the Commission on the Coordination of Space Techniques for Geodesy and Geodynamics (CSTG), with Pascal Willis as chairman, should coordinate the activities in close cooperation with the IGS and with the Institute of Navigation (ION). (CSTG is Commission VIII of IAG and Subcommission B.2 of COSPAR, the Committee for Space Research.) The report of the working group may be found in this *Annual Report*, as well.
- The third key issue concerned the Analysis Coordinator. Jan Kouba, the IGS Coordinator since late 1993, informed the IGS Governing Board that he would no longer be available as coordinator starting 1 January 1999, due to his early retirement from the Geodetic Survey Division, Natural Resources Canada (NRCan). It was thus necessary to invoke the procedure for the selection of a new Analysis Coordinator. It was decided that the new coordinator should be elected at the 8th Governing Board meeting in San Francisco, California, in order to allow for a smooth transition. According to the IGS Terms of Reference, the coordinator must be associated with one of the Analysis Centers. Therefore the Analysis Centers were asked to submit proposals until the end of November 1997.
- The fourth key issue was the decision to organize an IGS Retreat in December 1997 (see next section).

A special session of the 1997 Scientific Assembly of IAG was devoted to IAG-sponsored scientific services. Ruth Neilan, Director of the IGS Central Bureau, presented the IGS in this session. The IAG publishes a special volume containing the information about all IAG services.

ION GPS-97 was held in Kansas City, Kansas, in September 1997. It is worth mentioning that the IGS Chair was asked to take part in the opening Plenary Session, which consisted of a panel discussion entitled “The Civil and Military Issues Facing GPS and GNSS [Global Navigation Satellite System]” (McDonald, 1997). In the same proceedings, one also finds the latest update of the recent IGS activities (Neilan et al., 1997).

The first part of the 8th IGS Governing Board meeting took place in San Francisco, California, on Thursday, 11 December 1997 (attached to the American Geophysical Union fall meeting). The second part was held on Sunday, 14 December during the IGS Retreat in Napa Valley, California. A detailed report about the 8th IGS Governing Board Meeting may be found in IGS Mail Message No. 1763. Here are a few highlights:

- Thanks to the work performed by both the IGS and the BIPM representatives, the IGS/BIPM Project to Study Accurate Time and Frequency Comparisons using GPS Phase and Code Measurements could be officially established, with James Ray from the United States Naval Observatory and Claudine Thomas from BIPM as co-chairpersons. A report concerning their activities may also be found in this *Annual Report*.
- Three Governing Board positions were up for election by the end of 1997. The Terms of Reference allow for a second four-year term. The Chair was pleased to congratulate Geoffrey Blewitt (University of Newcastle, UK), Bjorn Engen (Statens Kartverk, Norway), and Carey E. Noll (NASA Goddard Space Flight Center, USA) for their reelections.

In 1994, the IGS was established as an official service of the International Association of Geodesy.

- Two new Governing Board Members were appointed by the board based on a recommendation from the Central Bureau. The candidates were presented in the first part of the meeting, the election took place at the second part in Napa Valley. The Board decided that Robert J. Serafin of the National Center for Atmospheric Research (NCAR) and Michael Bevis of the University of Hawaii would succeed Robert E. Schutz (University of Texas) and Gerald L. Mader (National Geodetic Survey [NGS]). With these appointments, the Governing Board underlines the importance of atmospheric research using both ground- and space-based applications of the GPS. The Chair thanked Drs. Schutz and Mader for their important contributions as Governing Board Members.
- One proposal, from the Center for Orbit Determination in Europe (CODE) Analysis Center, was received to fill the position of the IGS Analysis Coordinator. CODE proposed that Tim Springer (University of Bern) should succeed Jan Kouba on 1 January 1999 for a period of four years. The proposal, which received the full support of all IGS Analysis Centers, was discussed and accepted by the Governing Board. The Board gratefully acknowledged that NRCan continues to act as the IGS Analysis Coordinating Center until the end of the year 1998.

The 1997 IGS Retreat

The IGS Retreat was scheduled from Friday, 12 December (afternoon) through Sunday, 14 December (morning) in Napa Valley, California. It was organized by Ivan I. Mueller and the IGS Central Bureau. There are no published proceedings of the 1997 IGS retreat, but Prof. Mueller prepared recommendations and action items emerging from the retreat.

These recommendations and action items were first presented to the IGS Governing Board at the Business Meeting attached to the 1998 IGS Analysis Center Workshop. They were also made available to all workshop participants in Darmstadt and they are included in the proceedings of this workshop. Decisions will be made at the 9th IGS Governing Board Meeting in May 1998 in Boston.

The IGS Retreat, its recommendations and action items, and the Governing Board decisions emerging from them are presented in the proper context in the *1997 Technical Report*s.

ACKNOWLEDGMENTS

We should keep in mind that the IGS is based on a voluntary collaboration of a large number of scientific and survey institutions. It is worth pointing out that the contributing organizations are not funded by the IGS, but have to raise funds for their IGS-related activities. An organization like the IGS thus only works properly if all contributing institutions are convinced of the IGS mission and its performance, and if the benefit from IGS activities justifies the investments.

The other pillar of the IGS success is the personal engagement of many individuals devoting a fair amount of their time to the IGS. I was not aware of the large number of enthusiasts willing to cooperate on a voluntary basis for the benefit for the scientific community before I became involved in the IGS. I am convinced that most IGS associates share these feelings. On behalf of the IGS Governing Board I would like to cordially thank all institutions and individuals devoting time and funds to make the IGS so successful.

Overview of the IGS and the Central Bureau

Four Years of Growth and Achievement

The end of 1997 marks a "rite of passage" for the IGS — the first four-year period devoted to nurturing this fledgling scientific service based on the Global Positioning System (GPS). The past four years have resulted in solidifying this now-well-known international activity and reinforcing its importance for scientific and research applications. During this time period, the IGS has become the fundamental supporting infrastructure for numerous geodetic, geophysical, and geodynamical applications that depend on the utilization of GPS technology. The IGS also advocates standards and specifications for achieving excellence in precision-use aspects of GPS from network operations through GPS analysis and applications, so that users worldwide can make use of the wealth of data and products afforded by the IGS.

Ruth E. Neilan

Jet Propulsion Laboratory, California Institute of Technology, USA

Director, IGS Central Bureau

How It Works

The GPS was developed by the United States for joint military and civilian use in navigation, timing, and ranging, primarily in the single-user mode or absolute positioning. Precise applications of GPS for civilian use depend on differential or relative-positioning techniques, including determination of the precise orbits of the GPS satellite constellation. In 1996, under US Presidential directive, the GPS system was guaranteed as a dual-use system, ensuring continued civilian access. Civilian use of the GPS has increased dramatically over the last 10 years, and it is recognized that these applications are only possible through the investment, operations, and enhancements made by the US government.

The organization of the IGS is shown in Figure 1. The GPS stations in the IGS global network are permanently installed to operate continuously, receiving and recording the L-band, dual-frequency signals transmitted by the GPS satellites. The map of the IGS network of tracking stations can be seen in Figure 2. The station data are accessed by Operational Data Centers through various communication schemes, currently through Internet, telephone, INMARSAT, radio modem, and V-SAT. The Operational Data Centers operate subnetworks, oftentimes in a specific regional area. These Operational Centers monitor, validate, and format the GPS data according to standards, then forward the data sets to the Regional or Global Data Centers. Additional details on the IGS data system can be found in the "IGS Data Center Report" by Carey E. Noll, in

Figure 1 (opposite). The IGS organization.

this *Annual Report*, as well as in previous *IGS Annual Reports*. The IGS Analysis Centers retrieve the data sets from the Global Data Centers and each Analysis Center produces GPS ephemerides, station coordinates, Earth rotation parameters, etc. These products are then sent to the Analysis Center Coordinator who uses an orbit combination technique to produce the official IGS orbits (predicted orbits are available daily, the rapid orbit is also available on a daily basis for the previous day, and the final orbit is available with a delay of approximately 8 to 10 days and is based on weekly fits). The Analysis Center Coordinator article ("Analysis Activities," by Jan Kouba, this volume) outlines the process and products that are the core of the IGS. The generated products are sent from the Analysis Centers and the Coordinator to the Global Data Centers and to the Central Bureau Information System (CBIS) for access by users as well as for archiving.

The Central Bureau is responsible for the overall coordination and management of the IGS service and is located at the Jet Propulsion Laboratory in Pasadena, California, operated for NASA by the California Institute of Technology. The International Governing Board is the oversight body that actively makes decisions determining the activities and directions of the IGS. The report of 1997 activities is summarized in "The IGS in 1997 — An Executive Summary" (this volume) by the current Chair of the Governing Board, Prof. Gerhard Beutler.

It is quite clear that the strength of the IGS is directly due to the many participating individuals and their sponsoring agencies. The achievement of the IGS is something that each can lay claim to and it is the recognition that through mutual cooperation much greater benefit is realized by all.

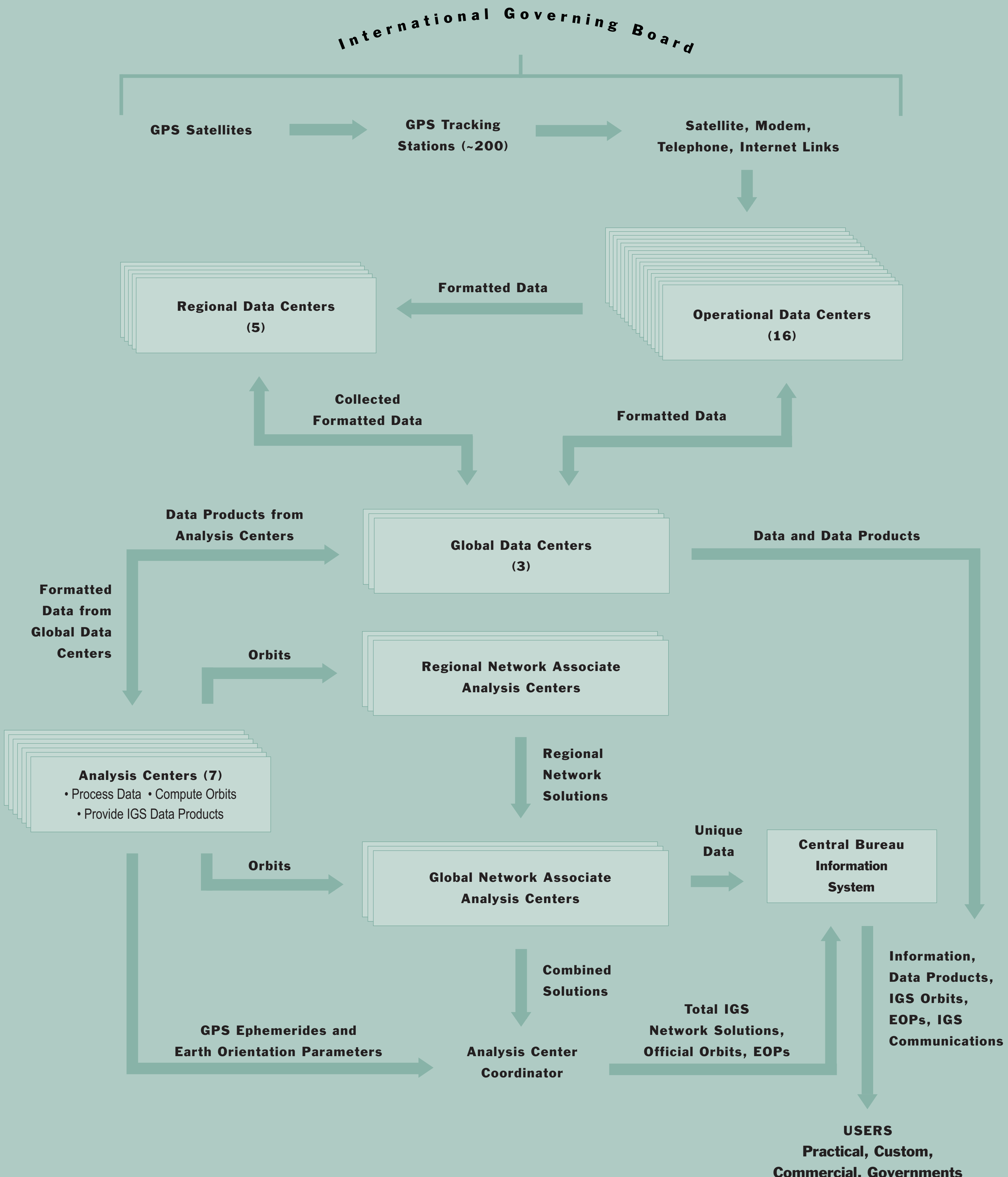
Network Status Update

The IGS network consists of precision, geodetic, dual-frequency GPS stations that observe the GPS satellites on a continuous 24-hour basis. These globally distributed stations are funded, implemented, and operated by one of the IGS participating agencies (see the list at the beginning of this *Annual Report*). At the end of 1997, nearly 200 stations were listed as part of the IGS network, an increase of nearly 70 stations registering with the IGS in 1997. Currently, the data files from each station span a 24-hour period, although the IGS is planning hourly data retrievals in the future. A Network Workshop is planned in November 1998 to address the current and future operations of the network and the many new requirements that affect these operations. It is recognized that there are increasing demands on the infrastructure, and it is in the best interests of all to keep the infrastructure technically current and operationally robust.

Current Working Groups and Pilot Projects

Following is the current list of IGS projects and working groups; more information can be found in later sections of this *Annual Report*.

- Commission on the Coordination of Space Techniques for Geodesy and Geodynamics (CSTG)/IGS Working Group on the Russian Global Navigation Satellite System (GLONASS) (organizing the International GLONASS Experiment, IGEX-98)
  Chair: Pascal Willis, IGN, France
- IGS/Bureau International des Poids et Mesures (BIPM) Pilot Project on Time Transfer
  Co-Chairs: Jim Ray, USNO, USA;
  Claudine Thomas, BIPM, France
- IGS Troposphere Pilot Project
  Chair: Gerd Gendt, GFZ, Germany
- IGS Low-Earth Orbit (LEO) Working Group
  Chair: Mike Watkins, JPL, USA


International Governing Board
GPS Satellites
GPS Tracking
Stations (~200)
Satellite, Modem,
Telephone, Internet Links
Formatted Data
Regional Data Centers
(5)
Operational Data Centers
(16)
Collected
Formatted Data
Formatted Data
Data Products from
Analysis Centers
Global Data Centers
(3)
Data and Data Products
Formatted
Data from
Global Data
Centers
Orbits
Regional Network Associate
Analysis Centers
Analysis Centers (7)
• Process Data • Compute Orbits
• Provide IGS Data Products
Regional
Network
Solutions
Unique
Data
Central Bureau
Information
System
Orbits
Global Network Associate
Analysis Centers
Combined
Solutions
Information,
Data Products,
IGS Orbits,
EOPs, IGS
Communications
Total IGS
Network Solutions,
Official Orbits, EOPs
GPS Ephemerides and
Earth Orientation Parameters
Analysis Center
Coordinator
USERS
Practical, Custom,
Commercial, Governments

It is quite clear that the strength of the IGS is due to the many participating individuals and their sponsoring agencies.

- IGS Ionosphere Working Group
  Chair: J. Feltens, ESA/ESOC, Germany (nominated May 1998)
- IGS Pilot Project on the Densification of the International Terrestrial Reference Frame (ITRF) using GPS
  Chair: Geoff Blewitt, U. of Newcastle on Tyne, UK
- IGS Infrastructure Committee
  Chair: Yehuda Bock, SIO, USA

IGS Central Bureau Activities in 1997

The IGS Terms of Reference, the relations by which the IGS is governed (i.e., bylaws) were established at the beginning of the service in 1994. These terms state that the "Central Bureau of the International GPS Service is responsible for the overall coordination and management of the Service." In order to fulfill this role, the Central Bureau has been actively engaged in the many activities of the IGS. Given the current scope of IGS activities, the ongoing fundamental processes, and the new projects and directions of related GPS applications, the personnel of the Central Bureau must have a number of different talents to collectively perform the necessary tasks for coordinating with the various components of the service.

The Central Bureau is in the process of reorganizing the office based on the recommendations from the Napa Retreat in December 1997. One of the most noticeable results will be a nearly full-time Director and a full-time position of a Deputy Director. These staffing allocations are appropriate given the necessity of the Central Bureau to assume more of the daily coordination of the IGS, especially with regard to the robust performance of the ~200 station network, and to assume the role of the executive arm of the Governing Board. In the first year or two of IGS operations, the contributing agencies were all working to achieve their objectives as part of the IGS, in the spirit of the IGS mission statement. During this period, it took time to develop and solidify the working relationships internal to the IGS. Today, we are increasingly aware that additional effort is warranted in two areas — sustaining the fundamental IGS and providing interface to users, both internal and external. The status and key activities of the Central Bureau in 1997 are noted here:

- Upgrade design and implementation of the Central Bureau Information System.
- 55,000 to 65,000 file transfers or accesses per month on the CBIS, noting that the CBIS does not archive data, but information and products only. Data are archived and accessible from the IGS Regional and Global Data Centers.
- Workshops hosted at JPL, Pasadena, California
  — 1997 IGS Analysis Center Workshop
  — Workshop on Methods for Monitoring Sea Level and Altimeter Calibration, a Joint IGS and Permanent Service for Mean Sea Level (PSMSL) activity
- Presentations
  — Scientific Assembly of the International Association of Geodesy (IAG), Rio de Janeiro, Brazil, September 1997
  — First United States–Argentina Joint Conference on Space Science and Technology for Society, Buenos Aires, September 1997
- Meetings of the IGS organized by the Central Bureau in 1997
  — Business Meeting of the Governing Board, March 15, Pasadena, California
  — 7th Governing Board Meeting, September 5, Rio de Janeiro, Brazil
  — 8th Governing Board Meeting, December 11, San Francisco, California
  — IGS Retreat, December 12–14, Napa, California

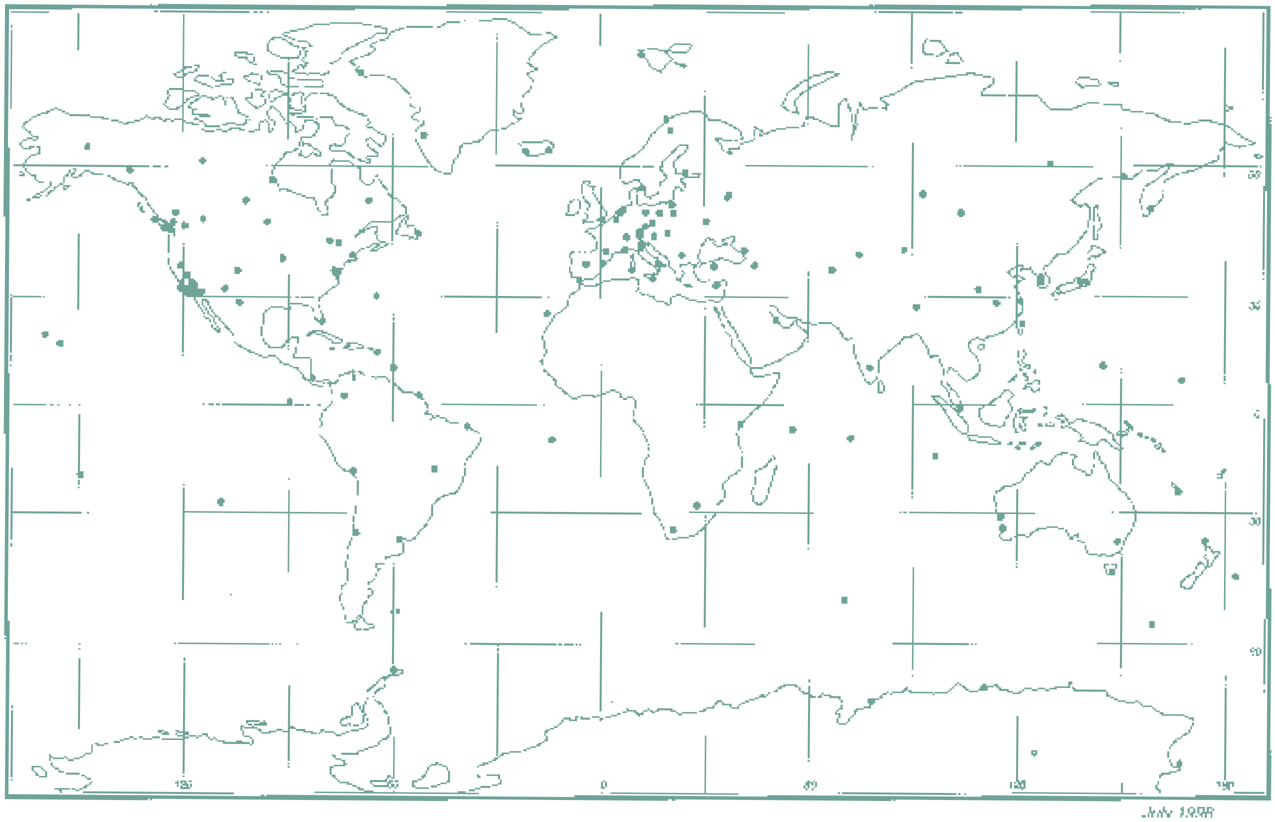


Figure 2. The IGS tracking station global network.

The Central Bureau also managed a record number of IGS exhibits this year in order to promote information on the IGS. These exhibits included a computer slide show, backdrop information, publications for pickup or order, and people stationed at the booth to answer questions. Exhibits for 1997 were organized at the following meetings:

- Spring American Geophysical Union (AGU) Meeting, Baltimore, Maryland
- International Association for the Physical Sciences of the Ocean (IAPSO), Melbourne, Australia
- International Association of Geodesy (IAG), Rio de Janeiro, Brazil
- Institute of Navigation (ION) GPS Annual Technical Meeting, Kansas City, Missouri
- Geological Society of America (GSA), Salt Lake City, Utah
- December AGU Meeting, San Francisco, California

The Central Bureau was responsible for these IGS publications in 1997:

- *IGS 1996 Annual Report*
- *IGS Directory*, 1997
- The IGS brochure "International GPS Service: Monitoring Global Change by Satellite Tracking," published in English (JPL 400-701) and Spanish (JPL 400-702)
- IGS Resource Packets, updated quarterly

This *IGS 1997 Annual Report* and the companion volume, the *1997 Annual Technical Reports*, are available in hard-copy and electronic versions.

Analysis Activities

Jan Kouba

Geodetic Survey of Canada, Geomatics Canada, Natural Resources Canada

IGS Analysis Center Coordinator

Role of the Analysis Centers

The IGS Analysis Centers play a key role within the IGS and in particular in the IGS global reference system realization, maintenance, and easy accessibility for all IGS users. Here the IGS reference system is used in a broad sense, encompassing calibrations and standards for tropospheric, ionospheric, and other GPS-based applications in addition to the traditional reference system with embedded reference frames (such as the International Terrestrial Reference Frame [ITRF]), GPS tracking data, and the adopted conventions. The maintenance and realization of an easily accessible IGS reference system is best accomplished through precise and timely global solutions that are continuously generated by the IGS Analysis Centers and submitted to the IGS for combinations into IGS official products. In particular, the IGS GPS Orbit/Earth orientation parameter (EOP), station positions, and satellite clock products are fundamental in nature as they imply an easily accessible ITRF reference frame.

Throughout 1997, the Analysis Centers have continued to exert significant effort despite the ever-increasing processing load due to more stations, additional products, and shortening submission delays. For example, on 20 April 1997, the IGS rapid-solution deadline was shortened by 2 hours (to 22:00 UTC) to make IGS Rapid (IGR) orbits available to the Analysis Centers participating in the new IGS combined orbit-prediction product. All but one of the Analysis Centers are taking part in the IGS orbit predictions (IGPs) that were officially introduced on 2 March 1997. Additionally, since the summer of 1997, all Analysis Centers have been submitting their tropospheric zenith path delay (ZPD) solutions to Gerd Gendt of GeoForschungsZentrum, who developed the ZPD combined product (officially made available since

March 1998). All Analysis Centers (including the US Naval Observatory, which only participates in IGR) have demonstrated solid reliability despite persisting delivery and data problems at some crucial stations.

Research and Improvements

Despite the effort needed to sustain continuous operation, most Analysis Centers have managed to increase the number of stations processed, to implement the new International Earth Rotation Service IERS96 Conventions, and to do significant research in their quest to further improve solutions. The Analysis Center research concentrated on the two main weaknesses of the GPS technique — radiation pressure and tropospheric refraction modeling. The radiation pressure effects can be mitigated by introducing stochastic orbit velocity, or radiation pressure impulses, at least once per revolution (e.g., Rothacher et al., 1997a). Additionally, improved deterministic models can better utilize the Sun–satellite geometry and result in much-improved a priori information (as well as orbit predictions) and consequently may eliminate the need for the above stochastic impulse parameters, thus increasing the reliability and robustness of the Analysis Center global solutions (Springer et al., 1998a). The introduction and estimation of tropospheric delay gradients by some Analysis Centers further improved results, in particular for station heights (Bar-Sever, 1997; Rothacher et al., 1997b). The great effort and the resulting improvements in the Analysis Center global solutions are seen for most centers in Table 1, where the yearly averages of weighted orbit rms values are shown for all Analysis Centers. Shown are the new IGR orbit, introduced only on 30 June 1996 with delays of less than 24 hours, together with all Analysis Centers orbits for the first quarter of 1998.

The solid improvements are clearly visible for most Analysis Centers. The IGR performance is truly remarkable when we consider the short production delay of only 22 hours, which often causes significant lack of data, and thus often only a small subset of the data available is used for the final Analysis Center solutions. Furthermore, some Analysis Centers use completely different processing and station selections in their rapid solutions. The remaining Analysis Center solutions (EOP/clocks and station coordinates) show similar improvements as the one seen in Table 1. For more details on Analysis Center solutions and improvements, see the *1997 Technical Reports*.

Combined Products

In addition to the above Analysis Center improvements that are essential for improved precision, considerable effort was made during 1997 to improve precision, consistency, and robustness of the IGS combined products. The IGS Combined Prediction (IGP), Length of Day/Universal Time (LOD/UT) combination, and recently, satellite clock combination and evaluation, have received the most attention. IGP outlier detection and reliable orbit precision estimation presented the most difficult challenge that required and still requires a considerable development time. The current IGP outlier detection and orbit precision (in SP3 format headers) are based on the comparisons with IGR, which are performed daily as a part of IGR combinations, but almost two days later. Clearly, more rapid and partial daily orbit solutions would considerably enhance the IGP reliability and consistency. The IGS LOD/UT combinations and subsequent improvements also proved to be difficult due to LOD/UT biases that are inherently present in all satellite solutions, and in particular the GPS global solutions.

Table 1. Analysis Center and IGR Weighted Orbit rms (cm) with Respect to the IGS Final Orbits, During Years 1994.0–1998.25

Year	COD	EMR	ESA	GFZ	JPL	NGS	SIO	IGR	Remarks
1994	11	14	17	12	14	32	21	—	
1995	8	10	14	10	9	17	16	—	
1996	6	10	9	9	7	15	8	6	IGR second half only
1997	4	10	7	6	6	16	7	5	
1998	4	11	7	6	5	17	7	6	First quarter only

COD = Center for Orbit Determination in Europe, University of Bern, Switzerland

EMR = Geodetic Resources Division, Natural Resources Canada, Ottawa, Canada

ESA = European Space Operations Center, European Space Agency, Darmstadt, Germany

GFZ = GeoForschungsZentrum, Potsdam, Germany

IGR = IGS Rapid

JPL = Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA

NGS = National Oceanic and Atmospheric Administration/National Geodetic Survey, Silver Spring, Maryland, USA

SIO = Scripps Institution of Oceanography, University of California, San Diego, California, USA

The current Analysis Center LOD alignment and weighting are based on comparisons with the IERS Bulletin A during three weeks ending five days before the last nonpredicted Bulletin A daily value. Since this alignment scheme was adopted for the IGR in June 1997 and the use of Analysis Center weighting according to the alignment LOD rms was introduced in December 1997, the combined LOD and the integrated IGR UT precisions have improved. The current (1998) IGR UT precision is about 0.100 milliseconds. Table 2 shows the IGS and IGR comparisons with the IERS Bulletin A during 1997.

In order to facilitate a continuous monitoring of orbit rotation/EOP consistency, tables with EOP combination statistics — in a format analogous to the orbit transformation tables — have been included in both IGS Final and Rapid summary reports since August 1997. For more information on the orbit rotation/EOP consistency and Analysis Center solution performance, see the Analysis Center Coordinator Report in the *1997 Technical Reports*.

Table 2. Comparisons of IGS Rapid and IGS Final Combined Earth Orbital Parameter with the IERS Bulletin A for 1997

	IGS Final				IGS Rapid			
	PM x	PM y	LOD	UT	PM x	PM y	LOD	UT
	mas	mas	ms	ms	mas	mas	ms	ms
Mean	0.28	0.15	0.001	0.015	0.40	0.26	–0.004	0.043
Sigma	0.07	0.07	0.026	0.044	0.24	0.27	0.034	0.203

PM = polar motion; mas = milliarcsecond; ms = millisecond

Clock combinations with proper weighting are quite difficult due to possible discontinuities, lack of sufficiently accurate ground truth, and smaller combination redundancy (only five of the seven Analysis Centers are solving for satellite clocks). Currently adopted Analysis Center clock alignments are done with respect to a chosen Analysis Center clock solution previously aligned to broadcast satellite clocks. Analysis Center clock weights are computed from absolute values of Analysis Center deviations from an arithmetic mean.

While the current IGS combined clock alignment is at the same quality as the previous alignments to non-SA (selective availability) satellites only, the new Analysis Center clock weighting has improved the IGS combined clock products (Springer et al., 1998b). The residual rms is approaching the 0.1–0.2-nanosecond level for the best Analysis Centers. To facilitate a more efficient evaluation of clock/orbit precision and consistency, in March 1998 the pseudorange point navigation in the IGS summary reports was replaced with GPS Inferred Positioning System/Orbit Analysis and Simulation Software (GIPSY II/OASIS) precise-point navigation, utilizing phase data at 15-minute intervals with the IGS and Analysis Center orbits/clocks held fixed. Table 3 summarizes the navigation rms compiled from recent IGS and IGR summary reports.

Table 3 not only demonstrates a high precision and consistency of both IGS and IGR combined orbit/clock products that is comparable to the best Analysis Center solutions, but also indicates the usefulness and impact of the IGS combined products on both static and navigation solutions. With the IGS orbits/clocks fixed, static and navigation positioning with precision of only a few centimeters should be possible anywhere in the world without the need for any base station data. Note that the current IGS SP3 clock sampling of 15 minutes and SA limits navigation to 15-minute intervals only. For higher sampling, more frequent IGS clocks (with at least 30-second sampling) are needed to allow precise interpolation of the SA clock effects.

Considerable effort was made in 1997 to improve precision, consistency, and robustness of IGS combined products.

Table 3. GIPSY II /OASIS Precise Navigation rms (cm) Compiled from Recent IGS Final (IGS) and Rapid (IGR) Combination Summary Reports (GPS Wks 0948-0951)

Station	IGS			IGR		
	N	E	H	N	E	H
BRUS	4	5	7	4	4	7
USUD	4	5	9	4	6	10
WILL	4	4	7	4	3	8

BRUS = Brussels, Belgium **USUD = Usuda, Japan** **WILL = Williams Lake, Canada**

Reference Frame Realization

From the beginning, the IGS ITRF reference frame realization has been accomplished by simply fixing, constraining, or aligning IGS/Analysis Center solutions to the adopted ITRF coordinates (i.e., ITRF94 since 30 June 1996) of the same 13 stations — ALGO (Algonquin Park, Ontario, Canada); FAIR (Fairbanks, Alaska, USA); GOLD (Goldstone, California, USA); HART (Hartebeesthoek, South Africa); KOKB (Kokee Park, Hawaii, USA); KOSG (Kootwijk, The Netherlands); MADR (Robledo, Spain); SANT (Santiago, Chile); TIDB (Tidbinbilla, Australia); TROM (Tromsoe, Norway); WETT (Wettzell, Germany); YAR1 (Yaragadee, Australia); and YELL (Yellowknife, NW Territory, Canada).

All the 13 stations have, or have had, multitechnique (in most cases, very long baseline interferometry) collocations. Clearly, a much larger number of ITRF stations and more consistent set of ITRF station positions were needed, since the reference-frame errors introduced by missing or malfunctioning ITRF stations could easily exceed the rms errors shown in Tables 1 and 2. A search for a new and much larger set of ITRF stations was initiated in March 1997 during the Analysis Center Workshop held at JPL. The discussions continued by e-mail until August 1997, when a more definitive set of 52 reference frame stations was identified and agreed upon by all Analysis Centers. All 52 stations survived rigorous tests and criteria of GPS data and solution quality, consistency, and timeliness.

Unlike for the 13 ITRF station selection, good multitechnique and ITRF coordinates, though important, were no longer considered essential because there were a sufficient number of multitechnique stations remaining in the station set. Subsequently, the ITRF96 positions and velocities of the 52 new reference-frame stations were carefully examined by all Analysis Centers in cooperation with the ITRF Section of IERS, which resulted in a definitive, highly consistent subset of 47 ITRF96 stations. On 1 March 1998 (GPS Wk 0947), this new 47 ITRF96 station set was adopted for all IGS solutions, including the IGS combined products. The ITRF Section of IERS kindly made the new ITRF96 set of

47 station positions and velocities, in Software-Independent Exchange (SINEX) format, available to IGS. It can be obtained at the IGS Central Bureau archives at <ftp://igscb.jpl.nasa/gov//igscb/station/coord/ITRF96_IGS_RS47.SNX.Z>.

Since both ITRF94 and ITRF96 are supposed to be nominally the same, only very small changes (~0.2 milliarcsecond/0.5 part per billion) are expected between ITRF94/96 on 1 March 1998 (see IGS Mail Message No. 1838 for more details and ITRF94/96 transformation). For more information on the ITRF96 station selection and the future plans for a new and improved IGS ITRF realization, see Kouba et al., 1998.

ACKNOWLEDGMENTS

The cooperation and assistance of all IGS Analysis Center colleagues is gratefully acknowledged. The reliability and timeliness of the IGS combined products are solely due to the diligence and hard work of Yves Mireault of NRCan who has been responsible for IGS combined product generation since 1995.

IGS Data Center Report

Background

The IGS collects, archives, and distributes GPS observation data sets of sufficient accuracy to meet the objectives of a wide range of scientific and engineering applications and studies. During the IGS design phases, it was realized that a distributed data flow and archive scheme would be vital to the success of the IGS. Thus, the IGS has established a hierarchy of data centers to distribute data from the network of tracking stations: Operational, Regional, and Global Data Centers. This scheme provides efficient access and storage of GPS data, thus reducing traffic on the Internet, as well as a level of redundancy allowing for security of the data holdings.

Operational Data Centers are responsible for the direct interface to the GPS receiver, connecting to the remote site daily and downloading and archiving the raw receiver data. Data quality is validated by checking the number of observations, number of observed satellites, date, and time of the first and last record in the file. The data are then translated from raw receiver format to a common format (Receiver-Independent Exchange [RINEX]) and compressed. Both the observation and navigation files (and sometimes meteorological data) are then transmitted to a Regional or Global Data Center, ideally within an hour following the end of the observation day.

Regional Data Centers gather data from various Operational Data Centers and maintain an archive for users interested in stations of a particular region. Furthermore, to reduce electronic network traffic, the Regional Data Centers are used to collect data from several Operational Data Centers before transmitting the data to the Global Data Centers. Typically data not used for global analyses are archived and available for online access at the Regional Data Centers. IGS Regional Data Centers have been established in several areas, including Europe and Australia.

The IGS Global Data Centers are ideally the principal GPS data source for the IGS Analysis Centers and the general user community. These online data are employed by the IGS Analysis Centers to create a range of products, which are then transmitted to the Global Data Centers for public use. The GPS observation data available through the Global Data Centers consist of observation, navigation, and sometimes meteorological files, all in RINEX format. Global Data Centers are tasked to provide an online archive of at least 100 days of GPS data in the common data format, including, at a minimum, the data from all global IGS sites. The Global Data Centers are also required to provide an online archive of derived products, generated by the IGS Analysis Centers and Associate Analysis Centers. These data centers equalize holdings of global sites and derived products on a daily basis (at minimum). The three Global Data Centers provide the IGS with a level of redundancy, thus preventing a single point of failure should a data center become unavailable. Users can continue to reliably access data on a daily basis from one of the other two data centers. Furthermore, three centers reduce the network traffic that could occur to a single geographical location. Table 1 comprises a list of the data centers currently supporting the IGS; information on how to contact these data centers is available on line through the Central Bureau Information System (CBIS) at <http://igscb.jpl.nasa.gov>.

Highlights for 1997 and Plans for 1998

IGS DATA

The number of stations archived by the IGS data centers increased by approximately 20 percent in 1997. On a daily basis during the past year, nearly 300 stations were archived at Scripps Institution of Oceanography (SIO), supporting both the IGS and southern California research activities; over 140 at Crustal Dynamics Data Information System (CDDIS), supporting both the IGS and NASA activities; and over 100 at Institut Géographique National (IGN). Both SIO and CDDIS experienced usage figures of several hundred users downloading 2K to 3K files per day from their archives (approximately 1 to 2 gigabytes per day).

The latency of the data arrival at the Global Data Centers improved during 1997. On average, 50 percent of the data arrived at the Global Data Centers within 6 hours. Several Operational Data Centers (e.g., Natural Resources Canada [NRCan] and NOAA's Geosciences Research Laboratory Operational Data Center) significantly improved their turnaround time, providing the RINEX data to the Global Data Centers within 1 to 2 hours of the end of the Universal Time Coordinated (UTC) day. Efforts to reduce the time delay, particularly for global IGS stations, will continue during 1998.

The IGS is a cosponsor of a new activity to establish an international campaign for the Russian Global Navigation Satellite System (GLONASS) observations during the fall of 1998. The main purpose of the International GLONASS Experiment — IGEX-98 — is to conduct the first global GLONASS observation campaign for geodetic and geodynamics applications and to evaluate the results in an international workshop in 1999. Many of the existing IGS data centers will propose to participate in IGEX-98, thereby increasing the diversity of their archives with the addition of GLONASS data and products.

A second enhancement to the Global Data Center archives will be the inclusion of hourly data received in a rapid fashion. These data are primarily utilized by scientists involved in atmospheric research. Plans are for a subset of the global network (20 to 30 stations) to provide RINEX data through the IGS data flow in hourly files. At the end of the 24-hour period, the daily file would be generated and archived as usual. It is envisioned that these hourly files need only be retained at the Global Data Centers for a few days to a few weeks.

HATANAKA COMPRESSION

During 1997, a new RINEX compression procedure, developed by Yuki Hatanaka of Geographi-

Table 1. Data Centers Supporting the IGS

Operational Data Centers	
ASI	Italian Space Agency
AUSLIG	Australian Land Information Group
CNES	Centre National d'Études Spatiales, France
DSN	Deep Space Network, NASA, USA
DUT	Delft University of Technology, The Netherlands
ESOC	European Space Agency (ESA) Space Operations Center, Germany
GFZ	GeoForschungsZentrum, Potsdam, Germany
GSI	Geographical Survey Institute, Japan
ISR	Institute for Space Research, Austria
JPL	Jet Propulsion Laboratory, California Institute of Technology, USA
KAO	Korean Astronomical Observatory
NGI	National Geography Institute, Korea
NIMA	National Imagery and Mapping Agency (formerly DMA), Department of Defense, USA
NOAA	National Oceanic and Atmospheric Administration, USA
NRCan	Natural Resources of Canada
SIO	Scripps Institution of Oceanography, University of California, San Diego, USA
SK	Statens Kartverk, Norwegian Mapping Authority, Norway
Regional Data Centers	
AUSLIG	Australian Land Information Group
BKG	Bundesamt fuer Kartographie und Geodaesie (formerly IfAG), Germany
JPL	Jet Propulsion Laboratory, California Institute of Technology, USA
NOAA/GODC	National Oceanic and Atmospheric Administration/Geosciences Laboratory Operational Data Center, USA
NRCan	Natural Resources of Canada
Global Data Centers	
CDDIS	Crustal Dynamics Data Information System, NASA Goddard Space Flight Center, USA
IGN	Institut Géographique National, France
SIO	Scripps Institution of Oceanography, University of California, San Diego, USA

cal Survey Institute (GSI) was tested within the IGS community in the hopes of adopting it as a new standard for distribution of the GPS observation data. This compression is performed in two steps: first, the RINEX observation file is compacted using the new software (an ASCII to ASCII compression); second, the compact RINEX observation file is compressed using standard UNIX compression (ASCII to binary format). The original RINEX observation file is compressed by a factor of 8 using this software combined with UNIX compression, as compared to a factor of about 2.9 with UNIX compression alone. By the end of 1997, many of the Operational Data Centers and Regional Data Centers were using this compression software in their processing and data transmission procedures. The Global Data Centers started archiving data in this format, in addition to the previous, UNIX-compressed-only files. Software to decompress and un-compact the files is available through the CBIS. Plans for 1998 include operational use of this data format within the IGS community, both for exchange of data between the data centers themselves and with the Analysis Centers.

IGS PRODUCTS

Starting with GPS week 0895, the IGS Analysis Coordinator began the operational generation of IGS combined orbit predictions. The predicted-orbit files (orbit, Earth rotation parameter [ERP], and summary) are available at the Global Data Centers ideally 30 minutes prior to the start of the day of the orbit. This new data set is now available from all IGS Global Data Centers as well as from the CBIS.

At the December 1996 IGS Workshop in Pasadena, California, the Analysis Center representatives discussed the generation of a "short" SINEX file containing site information but no matrices. This product could be produced either by the Analysis Centers themselves or by the Global Data Centers. A conversion program was written by Gerd Gendt of GeoForschungsZentrum (GFZ) and has been utilized at the Global Data Centers to convert historic as well as incoming SINEX files into these "new" products, denoted with an extension of SSC.

Since January 1997, the IGS has conducted a pilot experiment, headed by Gerd Gendt at GFZ, on the combination of troposphere estimates. Using a sampling rate of 2 hours, the zenith path delay (ZPD) estimates generated by the IGS Analysis Centers were combined by GFZ to form weekly ZPD files for approximately 100 IGS sites. At the February 1998 IGS Workshop in Darmstadt, Germany, the IGS Governing Board recommended that the pilot phase of this experiment be terminated and that these ZPD estimates become an official product of the IGS. The combination is performed by GFZ on a weekly basis. The troposphere products will be available at all IGS Global Data Centers. Future plans include conversion of the ZPD values into precipitable water vapor — ideally when a sufficient number of collocated GPS-meteorological instruments are available in the IGS network. Users can convert ZPD into precipitable water vapor by utilizing existing meteorological files as well as interpolation within global or regional meteorological fields.

The IGS Analysis Coordinator will soon supply users with two new products: accumulated IGR (rapid orbit) and IGS (final orbit) ERP files on a daily and weekly basis, respectively. The files, <igs96p02.erp> (to be used with IGS rapid orbits) and <igs95p02.erp> (to be used with IGS final orbits) will be available through the CBIS and the Global Data Centers.

The Global Data Centers are ideally the principal GPS data source for the IGS Analysis Centers and the user community.

The International Terrestrial Reference Frame

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Following its Terms of Reference, IGS works in close cooperation with the International Earth Rotation Service (IERS). The IERS Central Bureau is operated jointly by Institut Géographique National (IGN), which is in charge of the primary realization of the International Terrestrial Reference System (ITRS) through the International Terrestrial Reference Frame (ITRF), and the Paris Observatory, which is in charge of the International Celestial Reference Frame (ICRF) and the determination of Earth's rotation.

The ITRF Section of the IERS Central Bureau (ITFS) cooperates very closely with the different IGS participants (Central Bureau, Analysis Centers, and tracking stations) for ITRF station coordinates and analysis of solutions provided by IGS Analysis Centers, as well as site information and local ties of collocation sites.

For more information, visit the ITRF Web site at <http://lareg.ensg.ign.fr/ITRF>.

ITRF and IGS Relationship

Since the beginning of the IGS preliminary test activities in 1992, the IGS Analysis Centers have used ITRF coordinates for some subset of stations in their orbit computations. Moreover, the combined IGS ephemerides are expressed in ITRS because the coordinates used by the IGS are based on ITRF91 from the beginning until the end of 1993, ITRF92 during 1994, ITRF93 during 1995 until mid-1996, ITRF94 since mid-1996 until the end of February 1998, and ITRF96 starting on 1 March 1998.

IGS also supports the continuous improvement of the ITRF by contributing to the extension of the ITRF network, providing new collocations or by improving position accuracy. The IGS Analysis Centers contribute greatly to ITRF by providing IGS/GPS solutions, which are included in the ITRF combinations. Figure 1 shows data obtained through various techniques that were used in the ITRF96 combination.

Therefore, IGS provides very efficient methods to densify the ITRF network — one can now obtain millimetric positions directly expressed in ITRS by processing suitable GPS data together with IGS products.

ITRF96

The ITRF96 solution has been achieved by simultaneous combination of positions and velocities using full variance/covariance matrices of the individual solutions provided by the IERS and IGS Analysis Centers. Moreover, a rigorous weighting scheme, based on the analysis and estimation of the variance components using the Helmert method, has been developed and used in the generation of ITRF96.

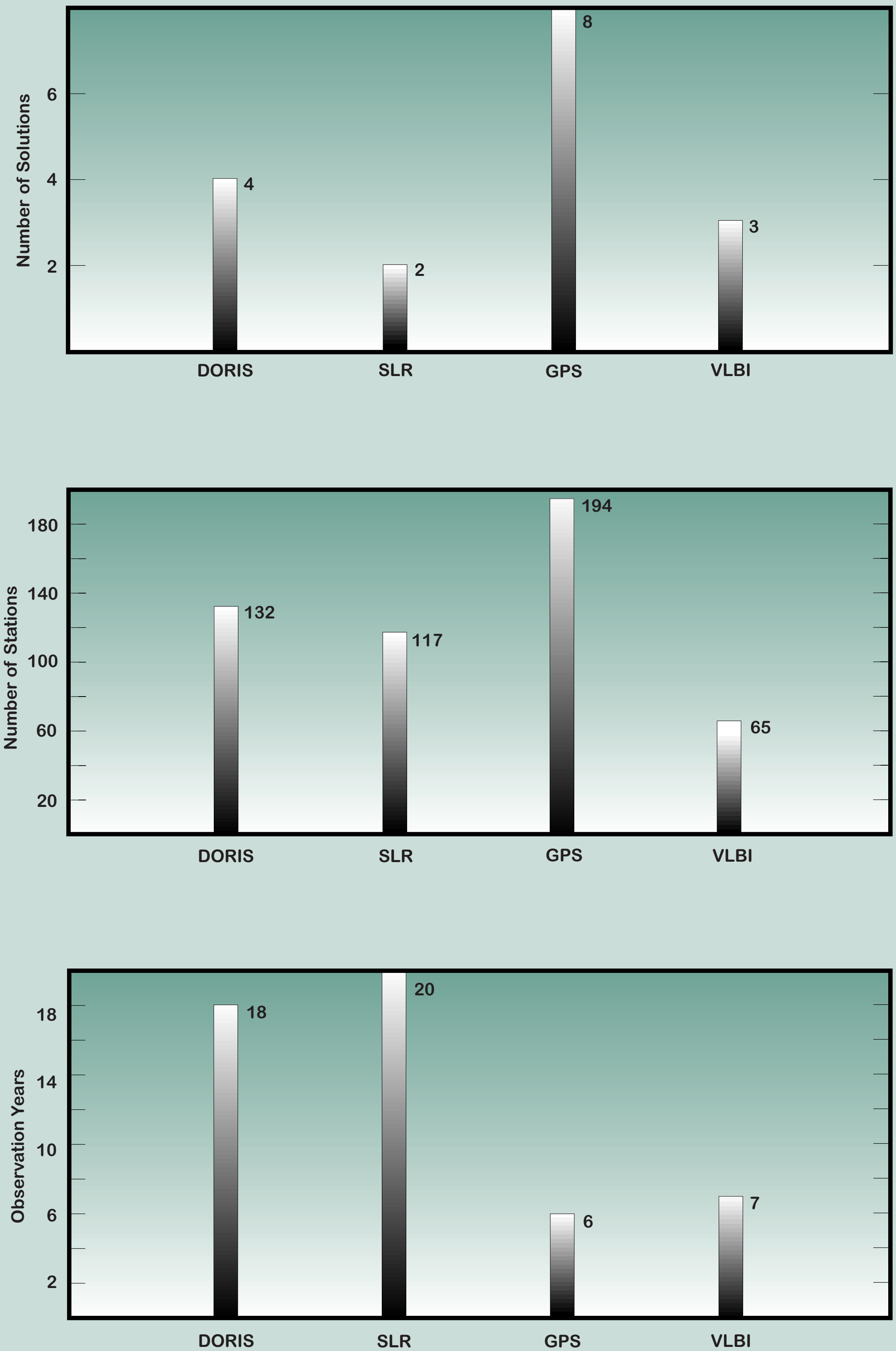


Figure 1. Data used in the ITRF96 combination.

Figure 2.
Position (cm, at epoch 1993.0) and velocity (mm/y) spherical errors.

ITRF96

ITRF94

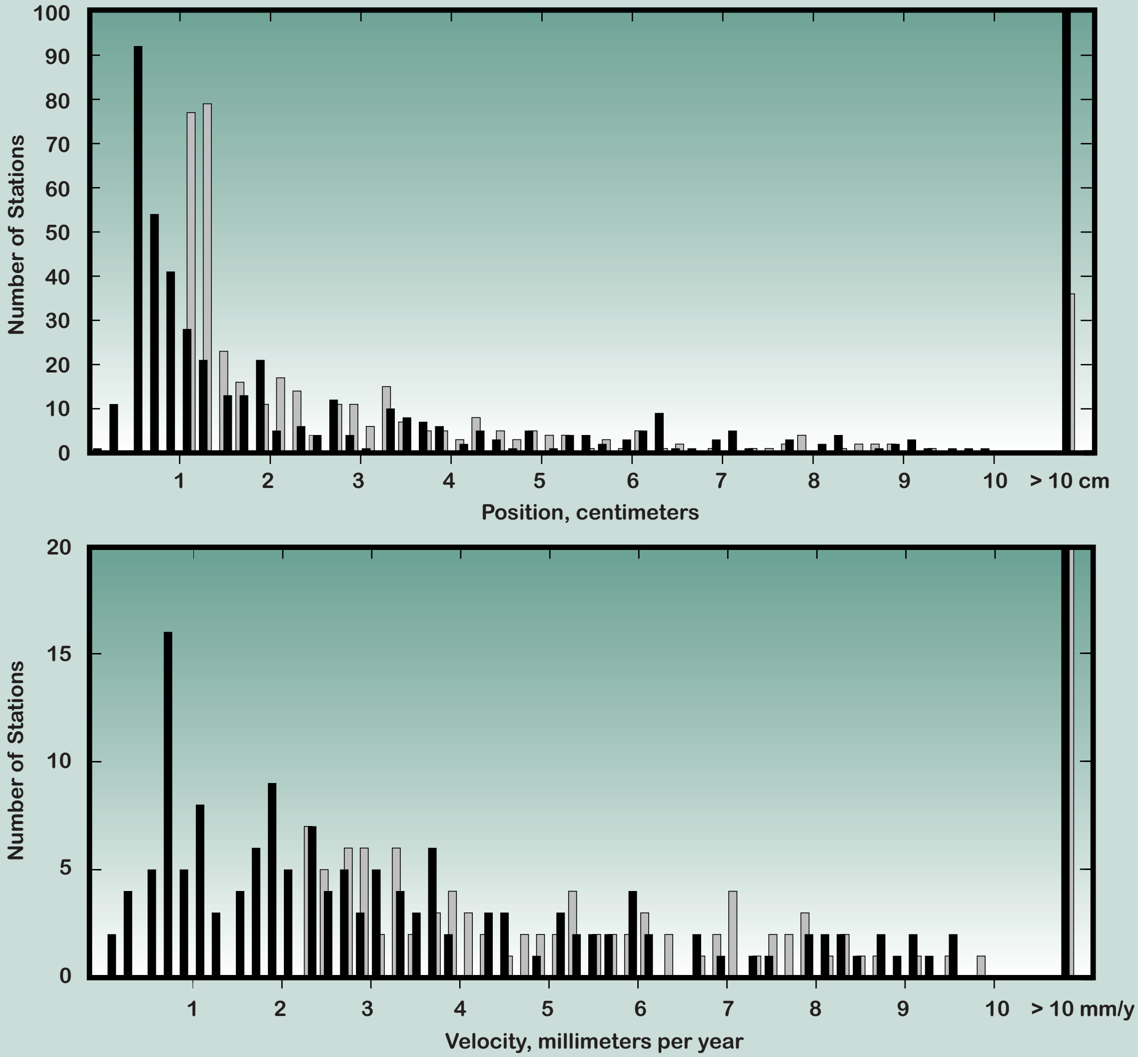
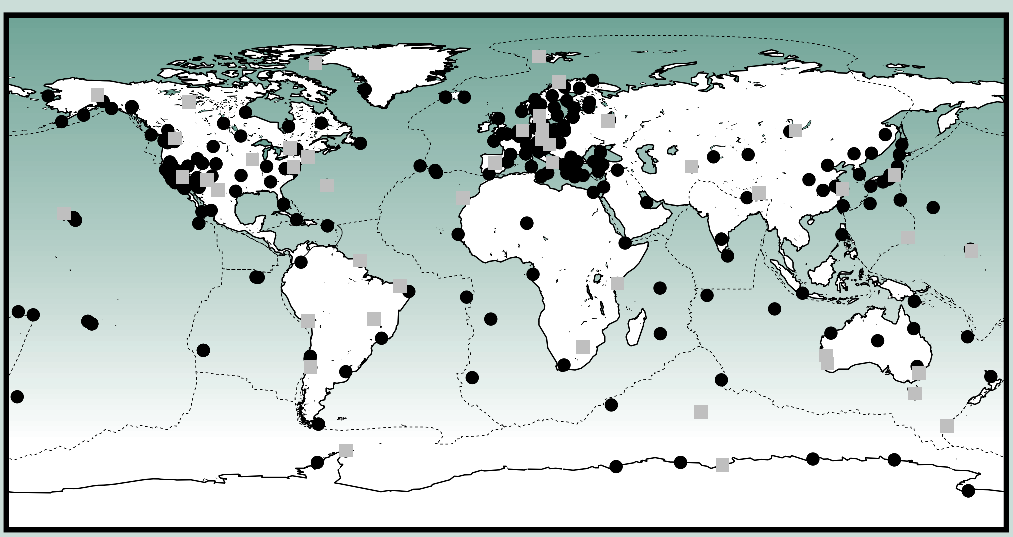


Figure 3.
ITRF96 sites and IGS reference stations.

Sites

Stations



The reference frame fixation (origin, scale, orientation, and time evolution) is achieved in such a way that ITRF96 is in the same reference system as ITRF94.

The position and velocity spherical errors plotted in Figure 2 demonstrate an improvement of ITRF96 with respect to ITRF94. Forty percent of ITRF96 stations have position uncertainty below 1 centimeter, and 30 percent have velocity uncertainty below 3 millimeters per year.

All the ITRF96-related files are available via the Internet at the site <http://lareg.ensg.ign.fr/ITRF/itrf96.html>.

ITRF96 and the IGS Reference Stations

Starting 1 March 1998, IGS uses ITRF96 positions and velocities of a set of 47 reference stations. Figure 3 shows the coverage of the 290 sites of ITRF96, underlying the 47 IGS reference stations.

The IGS selection of these stations is the result of criteria tests including primarily the quality of their ITRF96 coordinates. For this criterion, the ITFS has performed a specific quality analysis based on ITRF96 position and velocity residuals. The main result of this quality analysis is that the position quality (at 97.0 epoch) is better than 1 centimeter for 38 stations and better than 2 centimeters for the remaining 9 stations. Moreover, the velocity quality is better than 5 millimeters per year for 25 stations, and better than 10 millimeters per year for the remaining 22 stations.

IGS Densification Program

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The Distributed-Processing Approach

The IGS officially commenced operations in January 1994, by which time approximately 40 to 50 IGS stations had become operational. The expanding global network of high-precision GPS receivers was seen to present an opportunity to produce a reference frame that is dense, of a reasonably homogeneous quality, of few-millimeter accuracy on a global scale, readily accessible to GPS users, and ideal for monitoring variations in Earth's shape and for providing kinematic boundary conditions for regional and local geodetic studies.

Distributed processing was developed as a method that could be carried out as a natural extension to the existing operations of the IGS.

The challenge was to be able to analyze cohesively the data from an ever-increasing number of receivers, such that near-optimal solutions could be produced. Although ideally all data should be analyzed simultaneously to produce a single solution, in practice this is computationally prohibitive.

This led to the distributed-processing approach, which, at the algorithm level, partitions the problem into manageable segments, and, at the organizational level, delegates responsibility to Associate Analysis Centers who would naturally have an interest in the quality of the solutions. Another characteristic of this approach is a level of redundancy, such that a meaningful quality assessment can be made by other, independent groups. Distributed processing was developed as a method that could be carried out as a natural extension to the existing operations of the IGS.

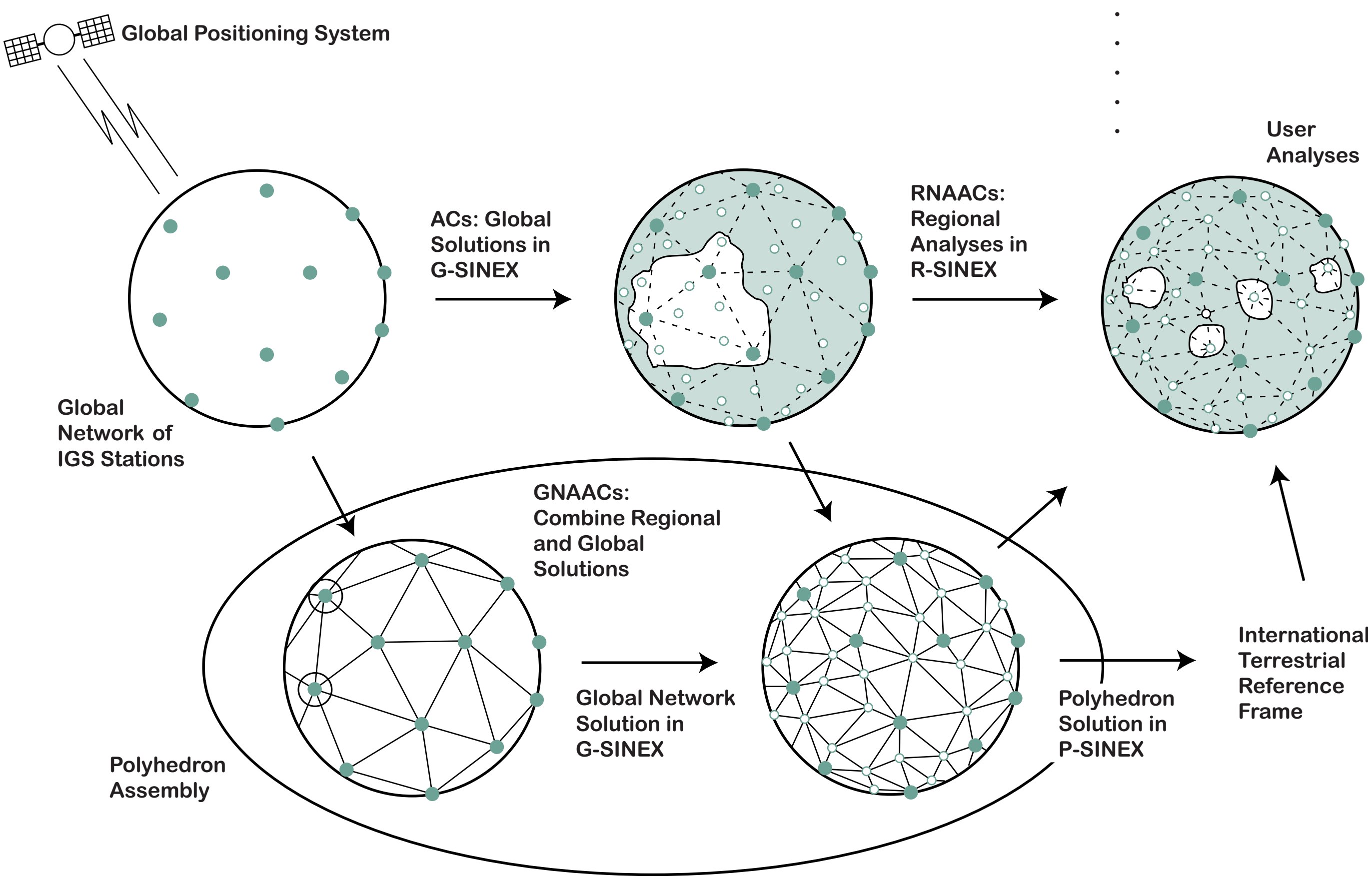
The Polyhedron Solution

Following a planning workshop at JPL in December 1994, a pilot program was initiated in September 1995 to test these ideas. Global Network Associate Analysis Centers (GNAACs) were set up at Newcastle University, Massachusetts Institute of Technology, and JPL. A format was developed for the exchange of coordinate solutions, covariance matrices, and site information (Software-Independent Exchange [SINEX] format). Initially these GNAACs combined solutions for global network station coordinates provided every week by the seven Analysis Centers, producing a single unified SINEX file. Approximately one year later, Regional Network Associate Analysis Centers (RNAACs) began submitting regional GPS solutions, computed using weekly published IGS orbit solutions. These solutions were then assimilated by the GNAACs into the unified global solution — known as the IGS polyhedron solution.

The pilot program has been viewed broadly as a success, demonstrating few-millimeter repeatability in weekly solutions for geocentric coordinates of not only the global stations, but also the regional stations. However, the actual process of densification (new GPS stations) is still less than adequate in many parts of the globe, particularly regions of Africa, Asia, and the oceans. The Densification Program essentially guarantees that new stations meeting IGS standards in such places can be consistently absorbed into future realizations of the reference frame. Furthermore, the Densification Program provides a natural way for science groups to participate in the IGS. It is important that not too much additional burden be placed on existing IGS components (in particular, the IGS Analysis Centers); therefore, participation as an RNAAC would be a natural way to extend the IGS community for the benefit of all.

Figure 1 shows the process: the Analysis Centers (ACs) analyze data from the global network and produce global solutions (orbits, station positions, velocities, etc.). These station solutions are reported in G-SINEX format — the GPS solution of the global reference frame using the IGS stations. Regional networks use the IGS products, the precise orbits, and some included stations' data to analyze the regional networks of interest. These solutions, in R-SINEX, are submitted to the GNAACs. The GNAACs combine the regional network solutions in R-SINEX with the global solutions in G-SINEX to produce a dense global network solution — reported in P-SINEX files, or the complete IGS polyhedron solution (P-SINEX for polyhedron). The processing is distributed in a coordinated, specific manner, and the densification of the network can be realized. More information can be found in Davies and Blewitt, 1997.

Figure 1. Schematic of the distributed-processing approach.



IGS/BIPM Time Transfer Project

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The goal is to develop strategies to exploit GPS measurements for improved availability of accurate time and frequency comparisons worldwide.

Using GPS Measurements for Time and Frequency

The IGS/BIPM Pilot Project to Study Accurate Time and Frequency Comparisons using GPS Phase and Code Measurements was authorized in December 1997 jointly by the International GPS Service for Geodynamics (IGS) and the Bureau International des Poids et Mesures (BIPM). A Call for Participation was issued shortly afterwards with responses due by 15 March 1998. The respondents will form a working group co-chaired by Claudine Thomas, BIPM, and Jim Ray, US Naval Observatory (USNO).

A number of groups have been working for several years to develop the capability of using geodetic GPS techniques for accurate time transfer. A variety of convincing demonstrations have already been performed showing the potential for determining clock differences at the level of a few hundred picoseconds. The current state of maturity of both the global tracking network and data analysis techniques now allows practical applications to be considered. The central goal of this pilot project is to investigate and develop operational strategies to exploit GPS measurements for improved availability of accurate time and frequency comparisons worldwide. This will become especially significant for maintaining the international Universal Time Coordinated (UTC) timescale as a new generation of frequency standards emerges.

Pilot Project Participation and Objectives

Investigators have been invited to participate in one or more of the following areas or to indicate others:

- Deployment of GPS receivers, including new receivers at timing laboratories and upgrading of existing tracking stations for better timing performance.
- GPS data analysis, including novel strategies for analyzing GPS phase and pseudorange observations from a large number of stations, consistent with other IGS products.
- Analysis of instrumental delays to relate GPS-derived clock estimates to external timing standards.
- Time transfer comparisons with simultaneous, independent techniques.

To accomplish the overall goal of improved global accessibility to accurate time and frequency using GPS, several specific objectives can be set:

- Accurate satellite clock estimates fully consistent with other IGS products, probably with 30-second resolution rather than the current 15-minute sampling.
- Accurate station clock estimates for as many IGS sites as possible, fully consistent with other IGS products, together with accurate monitor data to relate some of them to external timing standards.
- An accurate and stable reference ensemble timescale for use in IGS products to improve upon GPS time.

It is planned that the pilot project will run through the end of 1999 with an interim report near the end of 1998. By the year 2000, those aspects of this pilot project that are suitable for integration into the operational activities and official products of the IGS or BIPM should be under way. Information is exchanged via a Web site at the URL <http://maia.usno.navy.mil/gpst.html>.

Towards an IGS Combined Ionosphere Product

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New IONEX Format

For a long time, the IGS community has been aware of the fact that the worldwide IGS network offers a unique opportunity to extract information about the Earth's ionosphere. At the IGS Workshops held in Potsdam in May 1995 and in Silver Spring in March 1996, sessions were dedicated to ionospheric issues. For the latter workshop, total electron content (TEC) maps provided by Centre for Orbit Determination in Europe (CODE), Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), European Space Operations Center (ESOC), and University of New Brunswick (UNB) were compared, considering only regional (European) maps and the corresponding portion of global maps, respectively (Feltens et al., 1996). As a consequence of these TEC comparisons, an official format for the exchange of ionosphere maps, called IONEX, has been developed (Schaer et al., 1998) and approved by the IGS community. The IONEX format allows the storage of snapshots of the electron density (including associated rms information) referring to particular epochs and to a 2- or even 3-dimensional, Earth-fixed grid. IONEX is not a GPS-specific format. It is an interface to non-GPS users of IGS ionosphere products.

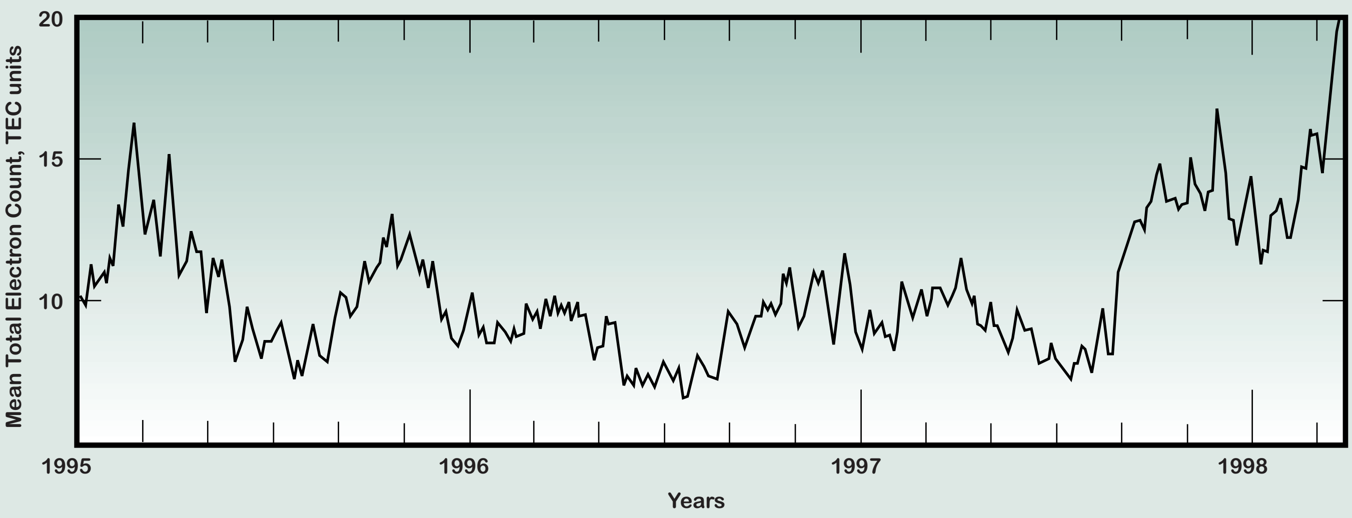
Monitoring for High Solar Activity

Several IGS Analysis Centers derive global ionosphere maps (GIMs) and, as a by-product of the TEC determination, differential code biases (DCBs) on a regular basis (or are close to doing so). At the 1998 IGS Analysis Center Workshop in Darmstadt, Germany, it was concluded that the IGS should monitor the ionosphere for (at least) the next period of high solar activity and study in particular the impact of the ionosphere on IGS core products (Feltens and Schaer, 1998). For that purpose, it was recommended to focus on two kinds of products: 2-hourly GIMs in 2-dimensional grid form and daily sets of DCBs for the satellites.

Figure 1 shows the evolution of the mean TEC during a period of low solar activity. The smoothed curve indicates (among other features) 27-day fluctuations caused by the Sun's rotation, and reveals that we have passed the recent ionospheric minimum in summer 1996 and are approaching the next maximum! The last solar maximum occurred in 1989; the next maximum solar activity is expected in 2000–2001 (occurring on an 11-year cycle).

The development of an IGS ionosphere model may be seen as a long-term goal. In order to accomplish these goals, an IGS Ionosphere Working Group shall be established in May 1998. The start of the pilot phase, where the IONEX files as produced by the individual Analysis Centers will be sent to the IGS Global Data Centers, may be expected for mid-1998. Finally, the provision of IGS combined ionosphere maps is planned.

Figure 1. Mean total electron count over 3.25 years, computed by CODE.



IGS Combination of Tropospheric Estimates

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A New IGS Product

Continuous and well-distributed measurements of water vapor are of great interest for numerical weather forecast, climate research, and atmospheric studies. Ground-based GPS receivers can provide continuous information on integrated water vapor at a site. Tropospheric parameters, in the form of zenith path delay (ZPD) corrections, are estimated by all IGS Analysis Centers in their routine daily work. With marginal additional effort, these estimates can be made available to form a new IGS product. For this it will be necessary that the GPS sites are equipped with meteorological sensors to have the data for the conversion of the ZPD estimates into integrated precipitable water vapor (PWV).

During a one-year pilot experiment starting in February 1997, the ZPD estimates of the IGS Analysis Centers were submitted to the combination center located at GeoForschungsZentrum (GFZ), Potsdam (POTS), for the computation of the IGS Tropospheric Product. All components involved in the combination have performed well and are timely. The product is a weekly file for each site. Weekly combination reports summarize some statistics on the differences of each Analysis Center to the IGS Mean.

Results of the Pilot Experiment

For more than 100 globally distributed sites, combined ZPD estimates are produced with a sampling rate of 2 hours. The ZPD product has high quality for all weeks. The consistency between the Analysis Centers and the IGS Mean is at the 4-millimeter level both for the bias and for the standard deviation. For sites in the equatorial region, the quality is not as good — by a factor of 1.5 to 2 worse. Even for sites with a larger bias, its repeatability is very high. The bias is highly correlated with the station height. For sites with fixed coordinates, the biases are very small, and the repeatability is at the 2-millimeter level. A lower elevation cutoff angle and the enlarged set of fixed sites would yield a smaller scattering in the daily station height solutions and thus may help to reduce the bias. The ZPD values must be converted into PWV using surface met data with high precision and reliability. Unfortunately, the number of instruments available now is not sufficient.

The GPS-derived PWV estimates can be compared with water vapor radiometer (WVR) measurements to get a measure for the absolute accuracy. A collocated WVR was available at POTS only. The agreement of the GPS results with the WVR is at the 1-millimeter PWV level (conversion factor PWV to ZPD is ~ 6.3). The standard deviation of the difference approaches 0.5 millimeter; the bias has a level of 1 millimeter and shows some long-periodic characteristics. To get better insight into the behavior of the bias, more collocated WVR should be made available. The pilot phase for the IGS Combined Tropospheric Product is finished and the combined ZPD estimates are an official product now. The conversion into precipitable water vapor will be postponed until a sufficient number of surface met packages are available. Currently, it is left to the customer to convert the ZPD by relying on the existing RINEX met files and on interpolation within global or regional meteorological fields. The product will be archived at the Global Data Centers and the Central Bureau Information System.

IGEX-98

International GLONASS Experiment

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Context

GLONASS is the Russian Global Navigation Satellite System. It is of interest to the IGS community for two main reasons: First, it is technologically very similar to the GPS system (even though there are some differences (different frequency for each satellite, no selective availability). Second, several projects already foresee combined uses of GPS and GLONASS — for example, the European Global Navigation Satellite System (GNNS)–1 project for aviation and rapid topographic GPS applications for surveyors. In both cases, the question of interoperability of the two systems is raised (including terrestrial reference frames and precise synchronization issues).

Scientific Objectives

Though the GLONASS system is not fully operational (only a limited number of satellites are presently available), it was felt that there was a need for a global GLONASS observation (called International GLONASS Experiment or IGEX-98) collocating the GLONASS receivers with permanent GPS sites of the IGS network.

The goal of this campaign is to investigate scientific uses of the GLONASS satellite for geodetic and geophysical applications and to try to solve the interoperability issues of the GPS and GLONASS systems. Precise GLONASS orbit estimation is a clear goal.

Report of Activity

In 1997, under the initiative of the International Association of Geodesy (IAG) subcommission for Precise Microwave Satellite Systems, a steering committee was formed that included the following individuals: Gerhard Beutler (Astronomical Institute, University of Bern [AIUB]), Werner Gurtner (AIUB), Guenter Hein (University FAF Munich [UdBM]), Ruth Neilan (IGS Central Bureau, Jet Propulsion Laboratory [JPL], California Institute of Technology), James Slater (National Imagery and Mapping Agency [NIMA]), and Pascal Willis (Institut Géographique National [IGN]; Chair). A first meeting was organized at the IAG Scientific Assembly (Rio de Janeiro, September 1997) and also at the American Geophysical Union meeting (San Francisco, December 1997), leading to an International Call for Participation that was agreed to by the IGS Governing Board and broadly distributed using IGS mail (see IGS Mail Message #1826).

The IGEX-98 campaign will start 20 September 1998, and will continue for at least three months. It is a joint project of the IAG and the Commission on the Coordination of Space Techniques for Geodesy and Geodynamics (CSTG), the IGS, and the Institute of Navigation (ION). Additional information can be found on line at the following Web site: <http://lareg.ensg.ign.fr/IGEX>.

Status of the IGS Working Group on Low-Earth Orbiters

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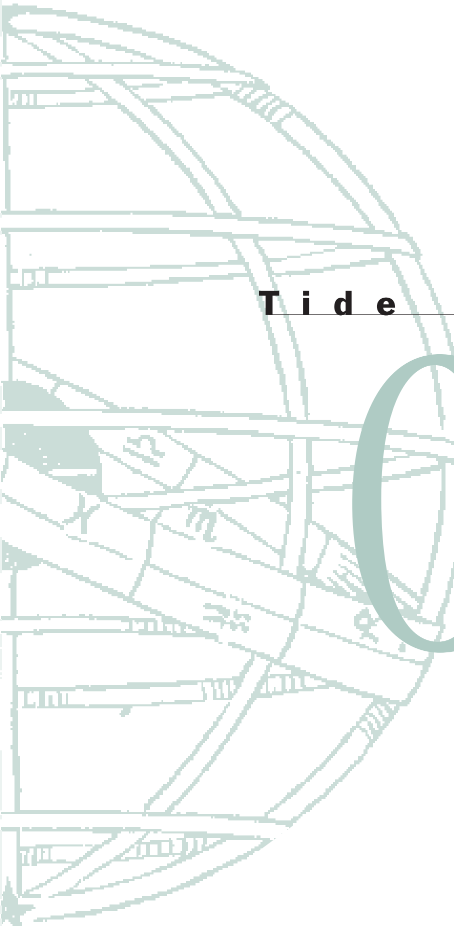
The Role of Low-Earth Orbiters in the IGS

Recognizing the compelling climate and geodetic science possible with, and the rapid growth of, satellites carrying precise, geodetic-quality GPS receivers, the IGS Governing Board created the Low-Earth Orbit (LEO) Working Group with the charter of exploring the role of LEOs in the IGS, and suggesting possible activities for the IGS and its components in the world of spaceborne GPS. The Working Group membership consists of John Dow (European Space Operations Center [ESOC]), Ruth Neilan (Jet Propulsion Laboratory [JPL], California Institute of Technology), Chris Reigber (GeoForschungsZentrum [GFZ]), Chris Rocken (University Corporation for Atmospheric Research [UCAR]), Bob Schutz (University of Texas), Michael Watkins (JPL; Chair), and Tom Yunck (JPL), all of whom have extensive experience with spaceborne GPS and applications.

Supporting LEO Missions

The committee, which has met in person and corresponded by e-mail, rapidly and unanimously understood and proposed that the IGS network component be capable of supporting LEO missions. This means the definition and operation of a robust, high-data-rate, low-latency subset of the global tracking network, whose development will be led by those IGS centers with strong ties to LEO missions — primarily JPL and GFZ at present.

The role of the analysis of LEO data as a core element of the IGS is still under discussion. Since there are clear potential benefits, but also additional complexity and analysis burden, a pilot project has been proposed and accepted by the LEO group. This pilot project will involve the analysis of data from spaceborne, geodetic-quality GPS receivers — tentatively identified as the GPS Met or TOPEX/Poseidon missions — and an assessment of the effects of the data on the traditional IGS analysis products (GPS ephemerides, clocks, Earth orientation, and troposphere), as well as an assessment of the additional computational and data center burden. We hope to attract new analysis centers with LEO expertise to join the other IGS Analysis Centers for this project, which we anticipate beginning in September/October 1998.



Tide Gauges, CGPS, and the IGS

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CGPS Station Installation at Tide Gauges

The space geodetic and sea-level communities have been discussing GPS positioning at tide gauges for many years. Oceanographers now seem on the verge of implementing continuous GPS (CGPS) stations at more than 20 globally distributed tide gauges for the purpose of calibrating satellite altimeters such as the instrument on TOPEX/Poseidon. This deployment could be complete in a year or so. It is possible that many dozens of additional tide gauges will be augmented with CGPS in the next five years. IGS is playing an advisory role in this effort, and may soon become involved operationally, as discussed at the December 1997 meeting in Napa Valley, California.

A technical committee is writing standards for installing CGPS stations at tide gauges. This committee resulted from the Permanent Service for Mean Sea Level (PSMSL)/IGS GPS Workshop at JPL in Pasadena, California, in March 1997. A second draft of the standards document will be available in the near future and will be distributed quite widely.

The most important insight that has developed during this process is that there are two distinct levels of positioning accuracy required, depending on the oceanographic application:

- Centimeter positioning. If the only purpose is using the CGPS stations to calibrate satellite altimeter measurements of sea level, then, according to the oceanographers, the geodetic accuracy required for

Several groups are proceeding with the construction of CGPS stations at tide gauges associated with sea-level studies.

vertical positioning accuracy is only 2–3 centimeters, although this must be obtained in 1 to 3 years.

- Millimeter positioning. If the purpose is to correct relative sea-level histories for vertical crustal motion, one needs to estimate vertical velocity at each site with an accuracy better than 1 millimeter per year (and hopefully much better than this) within a decade or so.

The second agenda — millimeter positioning — requires much more stringent CGPS installation and maintenance standards.

IGS Processing

Several groups are proceeding with the construction of CGPS stations at tide gauges associated with sea-level studies. For example, the University of Hawaii (UH) Sea-Level Center and the Pacific GPS Facility (also at UH) have installed a CGPS station at the Honolulu tide gauge, and plan to augment four other gauges with CGPS (two in the Pacific, one in the Atlantic, and one in the Indian Ocean). Other groups have started or will soon start similar efforts. The Honolulu data are available over the Internet on a same-day basis. Some of the other UH sites will not be online. This is probably typical of many new installations outside of Europe and North America. This may change as new low-Earth orbit (LEO) telecom systems appear and provide relatively low-cost telemetry links to remote locations. But for the next year or two we can expect to see quite a few off-line CGPS stations being installed at tide gauges.

The IGS must give serious consideration as to how this new global data set will be processed. Tide gauge (TG) CGPS stations are not well suited to the normal IGS orbit-analysis stream because many of these sites are quite unstable, and therefore unattractive on geodetic grounds, and in many cases the GPS data will not be made available until weeks or months after it is collected. The CGPS–TG data set needs one or more dedicated processing groups. Given the difficulty of eliminating systematic errors in the vertical, it would be advisable to ensure at least two to three independent analyses.

Workshop on the Use of GPS for Monitoring the Movement of Tide Gauge Bench Marks

A workshop on the use of GPS for monitoring the movement of tide gauge benchmarks, for application to long-term sea-level change studies and to satellite altimeter calibration, was held 17–18 March 1997 at JPL, Pasadena, California. The workshop was organized by the IGS and the Permanent Service for Mean Sea Level (PSMSL). One of the recommendations of the workshop was that a Technical Committee be formed to consider a range of technical issues that could not be discussed in detail at the workshop. This committee has approximately 10 members and is chaired by Dr. Michael Bevis, University of Hawaii, whose report is included here. The Technical Committee report and possibly a training manual stemming from the workshop and committee findings will be published as soon as possible. Workshop proceedings are available through PSMSL or the IGS Central Bureau.

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Director, Permanent

Service for Mean Sea Level

Sea-Level Workshop Objectives

The summary recommendations and requirements stemming from the 1997 Pasadena workshop target using the structure of the IGS and GPS to measure and understand the position and velocities of global tide gauge stations within the International Terrestrial Reference Frame (ITRF), with emphasis on the vertical velocities and accuracies at selected global locations. The workshop focused on how the techniques of GPS and tide gauges can be applied to:

- Studying the long-term changes in sea level through understanding the deformation of the solid earth, particularly the vertical motions, and how this affects the observations of the tide gauge records.
- Measuring the drift of the altimeter instruments for sea-surface height determination on missions like TOPEX/Poseidon, and several planned follow-on missions such as Jason, Geosat Follow-On (GFO), etc.
- Organizing those people and agencies involved in making such measurements, facilitating cooperation and soliciting sponsorship.

The summary recommendations from the workshop (see below) clearly identify the next steps that must be taken to in order to achieve these objectives.

Summary Recommendations

1. For the purpose of monitoring and understanding long-term changes in sea level, including the contribution of land motion to these changes, this group recommends that a science working group or groups be formed that interface with the IGS or are components of the IGS, at the Associate Analysis Center level (such as the Regional Network Analysis Centers), following all conventions established by the IGS Densification Project. (See this *Annual Report* for details.)

2. For the purpose of monitoring the drift of satellite altimeters, it is recommended that approximately 10 additional stations be incorporated into the IGS global analysis and data flow.

In order to realize these objectives, it is further recommended that:

3. The IGS, in cooperation with the International Earth Rotation Service (IERS), produce vertical velocity estimates to be updated annually in addition to a height time series derived from GPS, expressed in the International Terrestrial Reference Frame (ITRF).

4. A working group on the free exchange of data be formed that includes representation from the GPS and sea level communities, for the purpose of establishing necessary data links.

5. That science working groups that are established to address these developments ensure their representation under the umbrella of International Association for the Physical Sciences of the Ocean (IAPSO) and the International Association of Geodesy (IAG), including IGS, IERS, the IAG Subcommission on Sea Level and Ice Sheets, and the IAPSO Commission on Mean Sea Level and Tides.

6. A technical working group be constituted to set up recommended standards and specifications for operating GPS at tide gauge sites, in collaboration with the IGS working group on Site Specifications and Network Operations. This working group will consider, document, and make recommendations on the following types of tide gauge and site-specific information:
— Making measurements for precise ties (e.g., between the GPS, the tide gauge, the tide gauge benchmarks, the local reference networks, etc.)
— Data handling of the survey tie information
— Site stability aspects
— Monumentation techniques
— Collocation philosophy and observing methods (continuous measurement rationale)
— Absolute gravity measurements for complementary information on vertical coastal movements and mass redistribution
— Environmental parameters, meteorological sensors, ancillary measurements, etc.

Appendix a

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Appendix b

IGS Publications

The following publications, along with brochures, resource package, and the IGS Directory (printed annually), are available on request from the Central Bureau.

IGS WORKSHOP PROCEEDINGS

1998 Analysis Center Workshop, February 9–11, 1998, J.M. Dow (ESA), J. Kouba, (NRCan), T. Springer (AIUB), editors, ESA/ESOC, Darmstadt, Germany.

Workshop on Methods for Monitoring Sea Level: GPS and Tide Gauge Benchmark Monitoring and Altimeter Calibration, R.E. Neilan, P. VanScoy, P. Woodworth, editors, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, JPL Publication 97-017.

Proceedings of the IGS Analysis Center Workshop, Silver Spring, Maryland, USA, 19–21 March 1996, R.E. Neilan, P. Van Scoy, and J.F. Zumberge, editors, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, JPL Publication 96-023.

IGS Workshop Proceedings: Special Topics and New Directions, 15–18 May 1995, G. Gendt and G. Dick, editors, GeoForschungsZentrum, Potsdam, Germany.

IGS Workshop Proceedings: Densification of the IERS Terrestrial Reference Frame through Regional GPS Networks, 30 November–2 December 1994, J.F. Zumberge and R. Liu, editors, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA, JPL Publication 95-011.

IGS Workshop Proceedings: 1993 IGS Analysis Center Workshop, 12–14 October 1993, J. Kouba, editor, Geodetic Survey Division, Natural Resources Canada, Ottawa, Canada.

IGS Workshop Proceedings: 1993 IGS Workshop, 25–26 March 1993, G. Beutler and E. Brockmann, editors, Astronomical Institute, University of Bern, Switzerland.

IGS ANNUAL REPORTS

IGS 1996 Annual Report, J.F. Zumberge, D.E. Fulton, and R.E. Neilan, editors, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, JPL Publication 97-20.

IGS 1995 Annual Report, J.F. Zumberge, M.P. Urban, R. Liu, and R.E. Neilan, editors, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, JPL Publication 96-18.

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International GPS Service
for Geodynamics

International Association
of Geodesy
International Union of Geodesy
and Geophysics

Federation of Astronomical
and Geophysical Data
Analysis Services

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

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