IGS

International

GPS

Service

Annual Report 1999

The IGS 1999 Technical Reports volume is the companion to this IGS 1999 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 (WWW) site, known as the IGS Central Bureau Information System (CBIS).

The CBIS can be accessed using the WWW or via anonymous File Transfer Protocol (FTP) —

- *WWW — http://igscb.jpl.nasa.gov*
- *FTP — ftp://igscb.jpl.nasa.gov (See pub/IGSCB.DIR for directory and file information.)*

For the IGS Mail archive, please see —

- *http://igscb.jpl.nasa.gov/mail/mailindex.html*

The United States' Global Positioning System (GPS) constellation of satellites plays a major role in regional and global studies of Earth. Data products of the International GPS Service (IGS) may be accessed on the Internet through the Central Bureau, 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.

IGS

International

GPS

Service

Annual Report 1999

Introduction

This 1999 Annual Report of the International GPS Service serves as the executive summary of key annual activities for this thriving global organization. This year proved to be an exciting one due to anticipated roll-overs of “Y2K” and in the GPS week system; adoption of the new reference frame (ITRF97) in August; and completion of the International GLONASS experiment (IGEX) that included the GLONASS tracking network into IGS processing. IGEX resulted in the first precise transformation between GLONASS (Russian) and GPS (United States) satellite navigation systems. This experiment validates IGS as highly extensible to other Global Navigation Satellite Systems (GNSS). During 1999, the IGS was actively exploring and developing the structure for supporting low-Earth orbiter missions (LEOs) that carry onboard GPS receivers. This activity will be a significant endeavor in coming years and promises to bring about major enhancements for the IGS.

IGS Governing Board 1999

Tom Herring, Carey Noll, Angelyn Moore, Christoph Reigber, Ruth Neilan, Yehuda Bock, Bob Serafin, Ivan Mueller, Bill Melbourne, Gerhard Beutler, Bjorn Engen, John Dow, Jim Ray, Jan Kouba, Gerd Gendt, Mike Watkins, Tim Springer, Jim Zumberge, Remi Ferland. Missing: John Manning, Claude Boucher.

The IGS mission is to support geodetic and geophysical research activities, measurements and global change studies through GPS data and products. The IGS has extensive global resources based on a nearly 225-station GPS network that contributes significantly to the maintenance and extension of the International Terrestrial Reference Frame (ITRF). The IGS, through its Analysis Centers, collectively produces the most precise GPS orbit products available anywhere. The IGS as an organization leverages the resources of nearly 90 very active contributing organizations and fosters the evolution of many GPS applications through projects and working groups. IGS is a recognized scientific service of the International Association of Geodesy (IAG) and a member of the Federation of Astronomical and Geophysical Data Services (FAGS).

For more detailed information on the activities of the IGS, please refer to the companion volume, the 1999 IGS Technical Reports.

1999 Contributing Organizations of the IGS

Alfred Wegener Institute, Germany (AWI)

Astronomical Institute, University of Bern, Switzerland (AIUB)

Australian Survey and Land Information Group, Australia (AUSLIG)

Bakosurtanal, Indonesia (BAKO)

Bundesamt für Kartographie und Geodäsie, Germany (BKG)

Bureau International des Poids et Mesures, France (BIPM)

Center for Space Research, University of Texas at Austin, USA (CSR)

Centre National de Études Spatiales, France (CNES)

Centro de Estudios Espaciales, Chile (CEE)

Centro de Investigación Científica y de Educación Superior de Ensenada, Mexico (CICESE)

Chinese Academy of Sciences, China (CAS)

Chinese Academy of Sciences, Kunming Astronomical Observatory, China (KAO-CAS)

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

CSIR Centre for Mathematical Modeling and Computer Simulation, India (CMMACS)

Delft University of Technology, Netherlands (DUT)

Department of Land, New Caledonia (DITTT)

Deutsche Forschungsanstalt für Luft- und Raumfahrt e.V., Germany (DLR/DFD)

Earthquake Research Institute, University of Tokyo, Japan (ERI)

East-Siberian Research Institute for Physicotechnical and Radiotechnical Measurements, Russia (VS NIIFTRI)

Electromagnetic Field Expedition (Bishkek, Kyrgyzstan) of the Institute of High Temperatures, RAS (IVTAN)

European Space Agency, Germany (ESA)

European Space Operations Center, Germany (ESOC)

Finnish Geodetic Institute, Finland (FGI)

FOMI Satellite Geodetic Observatory, Hungary (FOMI)

Geodetic Survey Division, NRCan, Canada (GSD)

GeoForschungsZentrum Potsdam, Germany (GFZ)

Geographical Survey Institute, Japan (GSI)

Geophysical Institute, University of Alaska, USA (GIUA)

Geosciences Research and Development Laboratory, National Oceanic and Atmospheric Administration, USA (GRDL)

Goddard Space Flight Center, National Aeronautics and Space Administration, USA (GSFC)

Hartebeesthoek Radio Astronomy Observatory, South Africa (HRAO)

Incorporated Research Institutions for Seismology, USA (IRIS)

Institut Cartografic de Catalunya, Spain (ICC)

Institut Géographique National, France (IGN)

Institute for Metrology of Time and Space, GP VNIIFTRI, Russia (IMVP)

Institute for Space and Astronautic Science, Japan (ISAS)

Institute for Space Research Observatory, Austria (GRAZ)

Institute of Applied Astronomy, Russia (IAA)

Institute of Astronomy, Russian Academy of Sciences, Russia (INASAN)

Institute of Earth Sciences, Academia Sinica, Taiwan (IESAS)

Institute of Geodesy and Geodetical Astronomy, Warsaw University of Technology, Poland (IGGA-WUT)

Institute of Geological and Nuclear Sciences, New Zealand (IGNS)

Instituto Brasileiro de Geografia de Estatistica, Brazil (IBGE)

Instituto Nacional de Estadistica Geografia e Informatica, Mexico (INEGI)

Instituto Nacional de Invetigaciones Geologico Mineras, Colombia (INGEOMINAS)

Instituto Nacional de Pesquisas Espaciais, Brazil (INPE)

International Deployment of Accelerometers / IRIS, Scripps Institution of Oceanography, USA (IDA)

Italian Space Agency, Italy (ASI)

Jet Propulsion Laboratory, California Institute of Technology, USA (JPL)

Korean Astronomy Observatory, Korea (KAO)

Kort & Matrikelstyrelsen, National Survey and Cadastre, Denmark (KMS)

Land Information New Zealand (LINZ)

Main Astronomical Observatory of the Ukrainian National Academy, Ukraine (MAO)

Manila Observatory, Philippines (MO)

Massachusetts Institute of Technology, USA (MIT)

National Aeronautics and Space Administration, USA (NASA)

National Bureau of Surveying and Mapping, China (NBSM)

National Center for Atmospheric Research, UCAR, USA (NCAR)

National Geophysical Research Institute, India (NGRI)

National Imagery and Mapping Agency, USA (NIMA)

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

National Oceanic and Atmospheric Administration, USA (NOAA)

Natural Resources of Canada, Canada (NRCan)

Observatoire Royal de Belgium, Belgium (ROB)

Olsztyn University of Agriculture and Technology, Poland (OUAT)

Onsala Space Observatory, Sweden (OSO)

Pacific Geoscience Center, Geological Survey of Canada, NRCan, Canada (PGC)

Paris Observatory, International Earth Rotation Service, France (IERS)

Proudman Oceanographic Laboratory, UK (POL)

Real Instituto y Observatorio de la Armada, Spain (ROA)

Research Institute of Geodesy, Geodetic Observatory Pecny, Czech Republic (RIG)

Royal Greenwich Observatory, UK (RGO)

Royal Jordanian Geographic Center (RJGC)

Russian Academy of Sciences (RAS)

Russian Data Archive and Analysis Center, Russia (RDAAC)

School of Ocean and Earth Science and Technology, University of Hawaii, USA (SOEST)

Scripps Institution of Oceanography, USA (SIO)

Scripps Orbit and Permanent Array Center, SIO, USA (SOPAC)

Shanghai Astronomical Observatory, China (SAO)

Southern California Integrated GPS Network, USA (SCIGN)

Space Research Center of the Astrogeodynamical Observatory, Poland (SRC-PAS)

Statens Kartverk, Norwegian Mapping Authority, Norway (SK)

Survey of Israel (SOI)

Swiss Federal Office of Topography, Switzerland (L+T)

Technical University Munich (TUM)

United States Naval Observatory, USA (USNO)

University Consortium for Atmospheric Research, USA (UCAR)

University Federal de Parana, Brazil (UFPR)

University Navstar Consortium, USA (UNAVCO)

University of Bonn, Germany (UB)

University of Colorado at Boulder, USA (CU)

University of Nevada, USA (UNR)

University of Newcastle on Tyne, UK (NCL)

University of Padova, Italy (UPAD)

Western Pacific Integrated Network of GPS, Japan (WING)

Wuhan Technical University, China (WTU)

Governing Board

Member	Institution and Country	Functions	Term*
Christoph Reigber	GeoForschungsZentrum Potsdam, Germany	Chair, Appointed (IGS)	1999–2002
Gerhard Beutler	University of Bern, Switzerland	Appointed (IAG)	—
Mike Bevis	University of Hawaii, USA	Appointed (IGS)	1998–2001
Geoff 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, ITRF, France	IERS Representative to IGS	—
John Dow	ESA/European Space Operations Center, Germany	Network Representative	1996–1999
Bjorn Engen	Statens Kartverk, Norway	Network Representative	1998–2001
Joachim Feltens	ESA/European Space Operations Center, Germany	Ionosphere Working Group Chair	1999–2000
Remi Ferland	Natural Resources Canada	IGS Reference Frame Coordinator	1999–2000
Gerd Gendt	GeoForschungsZentrum Potsdam Germany	Troposphere Working Group Chair	1999–2000
Jan Kouba	Natural Resources Canada	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	IAG Representative	1996–1999
Ruth Neilan	Jet Propulsion Laboratory, USA	Director of IGS Central Bureau	—
Carey Noll	NASA Goddard Space Flight Center, USA	Data Center Representative	1998–2001
Jim Ray	U. S. Naval Observatory, USA	Precise Time Transfer Project Chair	1999–2000
Tim Springer	University of Bern, Switzerland	Analysis Center Coordinator	1999–2000
Robert Serafin	National Center for Atmospheric Research, USA	Appointed (IGS)	1998–2001
Michael Watkins	Jet Propulsion Laboratory, USA	Low-Earth Orbiter Working Group Chair	1999–2000
Pascal Willis	Institut Géographique National, France	International GLONASS Experiment CSTG/IGS Chair	1999–2000

Former Member	Institution and Country	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
David Pugh	Southhampton Oceanography Center, UK	1996–1998
Bob Schutz	Center for Space Research, University of Texas–Austin, USA	1994–1997

* Current terms are four years for elected members and two years for working group or project chairs. Terms are from 1 January–31 December.

1999

Contents

Perspectives on the IGS Governing Board '99

Christoph Reigber

GeoForschungsZentrum Potsdam, Germany

Chair, IGS Governing Board, 1999

The International GPS Service clearly remains unique in supporting numerous geodetic and geophysical research and engineering activities. The IGS is recognized for providing the best GPS products, from the orbits and clocks of the GPS satellites, to station positions and velocities of the tracking network — the IGS continues to evolve and improve as a premier scientific service.

The IGS products are widely used to support many activities and various applications that continue to emerge. IGS is foremost in providing the GPS-based reference frame on a global basis, a strong and essential contribution to the International Terrestrial Reference Frame (ITRF).

It is therefore a great honor to be elected Chair of the IGS Governing Board and to have served the first year of my term during 1999 — a time of transition for the IGS and the Governing Board. During my tenure, measures will be taken to sustain and advance the achievements of my predecessor in this position, Prof. Gerhard Beutler of the University of Bern in Switzerland, who served as Chair of the Governing Board from 1993 through 1998.

Transitions of the Board

Changes within the Board were expected from the start of this year. By the end of 1999, new dynamics developed for the IGS and the Board that will reach into the year 2000 and beyond. Four members of the Governing Board retired from their positions in December 1999, each of whom had been members of the Board since the inception of the IGS. The collective talents of these individuals greatly helped to shape the organization. They are:

- Dr. Yehuda Bock, Scripps Institution of Oceanography
- Dr. Jan Kouba, Analysis Center Coordinator of the IGS (1993–1998), Natural Resources of Canada
- Dr. Bill Melbourne, Jet Propulsion Laboratory
- Prof. Emeritus Ivan Mueller, Ohio State University

Retiring members of the Governing Board. Left to right: Bill Melbourne, Yuhuda Bock, Ivan Mueller, Jan Kouba.

'99

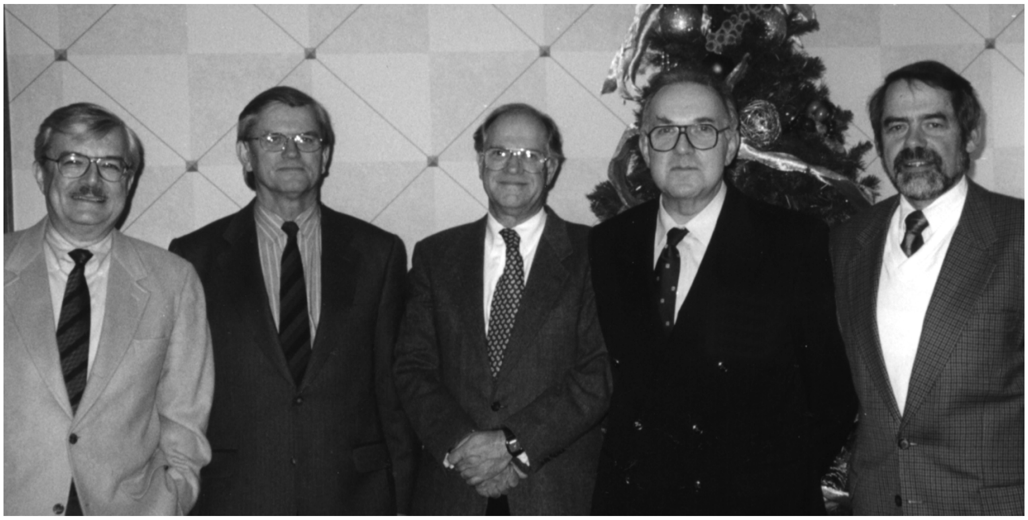
These gentlemen were celebrated in December during the AGU with an Honors Reception organized by the Central Bureau to provide a venue to recognize their considerable contributions to the IGS. Remarkably, all of these individuals have served on the Governing Board since the IGS was officially established, and all were members of the IGS Oversight Committee from 1991–1993, overseeing the successful IGS Pilot Project in 1992. Special recognition is certainly due to Ivan Mueller and Bill Melbourne for their part in creating the vision of what has become the IGS — through initiating the IGS Planning Committee a decade ago in 1989.

It was noted that the recent past presidents of the IAG Commission on Space Techniques for Geodesy were all present at this meeting. CSTG has always supported the development of the IGS as a key activity of the IAG, and all recent presidents have played a significant role in this regard.

Realizing these changes were imminent, preparations for Board elections began in mid-1999 with the electing body, the IGS Associate Membership, being approved at the Board meeting during the IUGG in Birmingham, England, July 1999. These elections were managed by Ivan Mueller with support from the Central Bureau. The results of the election were:

- Dr. John Dow, European Space Agency/European Space Operations Center (ESA/ESOC), was re-elected as Network Representative.
- Prof. Markus Rothacher, Technical University of Munich, was elected as a new Analysis Representative.
- Dr. Jim Zumberge, Jet Propulsion Laboratory, was elected as a new Analysis Representative.

For the IGS appointed positions, the IGS Central Bureau recommended the reappointment of John Manning, Australian Surveying and Land Information Group, and also recommended the appointment of Dr. Carine Bruyninx from Royal Observatory of Belgium as the IGS representative to the International Earth Rotation Service (IERS) Directing Board in accordance with the the new structure of the IERS. Both were unanimously accepted by the Board. Gerhard Beutler will remain on the Board as one of two designated representatives of the International Association of Geod-



Past presidents of the IAG's Commission on Space Techniques for Geodesy (CSTG). Left to right: Ivan Mueller, Chris Reighber, Bob Schutz, Gerhard Beutler, Herman Drewes (current president).

esy (IAG) due to his position as Vice President of IAG, and Prof. Tom Herring, Massachusetts Institute of Technology, will serve as the second representative of the IAG. Dr. Claude Boucher, Institut Géographique National, will continue to serve on the IGS Board as a representative of the IERS.

Key Events of 1999

LEO WORKSHOP

One of the first events that set the direction of the IGS was a joint workshop of the International GPS Service, GeoForschungsZentrum Potsdam, and the Jet Propulsion Laboratory. It was titled "Workshop on Low-Earth Orbiter Missions: Developing and Integrating Ground and Space Systems for GPS Applications," and was held 9–11 March at GeoForschungsZentrum Potsdam, Germany. The IGS LEO Working Group was key in organizing the workshop; the 1999 IGS Technical Reports provides a section devoted to the workshop and some of the papers. This was the first international workshop focusing on end-to-end systems and science aspects for supporting an array of forthcoming LEO missions over the next decade.

Discussions within the IGS and among the mission representatives resulted in the consensus to convene this workshop. The broad objective was to determine the relative interest, roles, and responsibilities of each interested and contributing party. It is widely recognized that the IGS can play an essential role in the ground support aspects of LEOs — such a recommendation has been made by the IGS LEO Working Group. The ground network, a subset of the IGS tracking network, is being planned to provide high-rate, low-latency data for integration with the flight data for atmospheric occultation objectives. Precise orbit determination as performed by the IGS Analysis Centers may actually benefit from an array of LEOs that serve as observing stations in space. This synergistic opportunity can signal the next enhancement of successful international cooperation for multipurpose GPS applications.

The workshop goal is to bring together interested principals in these endeavors and attempt to derive plausible multimission support plans and roles, a starting point for the next decade.

GPS99 afforded a dynamic venue for exploring new GPS developments and applications.

ANALYSIS CENTER WORKSHOP AND BOARD MEETING

All Analysis Center workshops are pivotal events for the IGS. The 1999 Analysis Center workshop, "Real-Time Applications and Long-Term Accuracy," was convened by Tim Springer and Yehuda Bock at Scripps Institution of Oceanography in La Jolla, California, 8–10 June. A very good summary of this meeting can be found in the IGS Mail archive as well as in the 1999 IGS Technical Reports section devoted to this workshop. A Governing Board meeting was held in conjunction with the workshop and resulted in an important step for the IGS — the creation of a new position, the IGS Reference Frame Coordinator. The Board designated Dr. Remi Ferland of Natural Resources Canada to assume the role of providing the coordination of GPS reference frame realization within the IGS and establishing stronger interfaces with the ITRF.

INTERNATIONAL SYMPOSIUM ON GPS

The International Symposium on GPS 1999 was held in Tsukuba, Japan, in October and afforded a dynamic venue for exploring new GPS developments and applications. (There is a separate report about the symposium by Teruyuki Kato of the Earthquake Research Institute, University of Tokyo, elsewhere in this Annual Report.) Representatives from the Asian nations as well as the broad international community attended the symposium, which was organized with the joint endorsement of the IAG, the IGS, and the Asian Pacific Space Geodynamics Project (APSG), with significant interest, participation, and support by IGS. This was the first formal presentation of the newly developed IGS tutorial. More details may be found in the report of the Central Bureau by Ruth Neilan elsewhere in this Annual Report.

DECEMBER BOARD MEETING

The year ended with the meeting in December as mentioned above, culminating with many changes and new opportunities for the IGS. Decisions made at the December meeting initiated a strategic planning process for the IGS in 2000 to explore where energies and resources would be best directed over the next five years. It was also decided to release a broad Call for Participation in the IGS LEO Project. The consensus of the Board is that this activity will affect every component of the IGS and become the next major initiative of the IGS. With the launch of the Challenging Mini-Satellite Payload for Geophysical Research and Application (CHAMP) and the Satelite de Aplicaciones Cientificas–C (SAC-C) LEO missions scheduled for the year 2000, the annual report series for next year should prove interesting.

Summary

The year 1999 closed quietly despite the possibility of difficulties envisioned in conjunction with "Y2K." The IGS continues to move forward and to be an exciting and worthy endeavor that offers a true international association attracting dedicated participation worldwide.

Acknowledgments

I would like to thank the members of the Governing Board and the Central Bureau for their support during my first year as Chair of the IGS, and look forward to the next years working together. I am very grateful to the IGS network and station operators, the Data Centers, the Analysis Centers, and Associate Analysis Centers for maintaining the high standards of the IGS while pursuing the new initiatives. These are the essential elements of the IGS — without these, the IGS would not exist.

Central Bureau Report

Ruth E. Neilan

Jet Propulsion Laboratory, California Institute of Technology, USA

Director, IGS Central Bureau

This was a year of continued growth for the IGS as new activities and applications provided exciting exploration and developments in many areas. These include IGS plans in support of low-Earth orbiter (LEO) missions, incorporation of data from the Russian satellite navigation system (GLONASS) into the IGS processing streams, and establishing an official position for an IGS Reference Frame Coordinator. While these activities were being pursued within the IGS community, the IGS Central Bureau was still busy completing the restructuring process started in 1998 and keeping up with the ever-increasing responsibilities of the office.

One of the first duties of the Central Bureau in 1999 was to support a smooth transition in the Governing Board leadership. Prof. Christoph Reigber from GeoForschungsZentrum Potsdam, Germany, began his first year as Chair, succeeding Prof. Gerhard Beutler from the University of Bern in Switzerland who resigned as IGS Chair after serving since 1993. Prof. Beutler remains on the IGS Governing Board in his capacity as Vice President of the International Association of Geodesy (IAG), one of two representatives from IAG to the IGS Board.

In addition to designated responsibilities, the Central Bureau notes three areas of attention this year:

- Improving coordination, reliability and functioning of the IGS network.
- Development of an IGS tutorial for expanding outreach to users and promoting broader use and acceptance of IGS data and products.
- Preparing for the Governing Board elections in December 1999, where significant changes in representation were anticipated.

The enhanced and proper functioning of the IGS network was a very hot topic at the beginning of 1999. This was also the first year that the IGS could realize tremendous benefit from a designated Network Coordinator enabled through the restructuring of the IGS Central Bureau. This position was assumed by Dr. Angelyn Moore, jointly appointed as the Deputy Director of the Central Bureau. It is evident that this was an excellent decision — the continued expansion of IGS stations and pressures on the Analysis Centers to deliver highest quality products in less time demand coordinated robust and reliable network operations. The quality of IGS products can only be achieved if all contributors to the infrastructure observe established conventions and standards. At the conclusion of 1999, many discrepancies were resolved owing to Angelyn's keen attention to detail and advocation of compliance to IGS standards. Significant progress in this area is summarized in the Network Activities report by Angelyn Moore in this Annual Report and referenced in the companion volume, IGS Technical Reports.

One key accomplishment coordinated by the Central Bureau was the formal development of an IGS tutorial for the venue of the International Symposium on GPS 1999 held in Tsukuba, Japan (see Teruyuki Kato's account in this Annual Report). This four-hour tutorial covers aspects from the basics of GPS, the organization of the IGS, the network and data center descriptions, IGS product quality and availability, reference frame details, and user issues. The Central Bureau was fortunate to have the assistance of Dr. Jan Kouba, former Analysis Center Coordinator (1993–1998) of Natural Resources Canada (NRCan); Carey Noll, Manager of the Crustal Dynamics Data Information System (CDDIS) at NASA Goddard Space Flight Center, an IGS Global Data Center; and Remi Ferland, IGS Reference Frame Coordinator, also at NRCan. Able assistance was provided from other Governing Board members Mike Bevis, University of Hawaii; Tim Springer, IGS Analysis Center Coordinator, University of Bern; and Markus Rothacher, Technical University of Munich. This tutorial is now updated and expanded as necessary and is available from the IGS Central Bureau Information System (CBIS) as a Postscript or PowerPoint document. This is a first step towards greater outreach to users; we anticipate a web-based/CD interactive tutorial development over the next few years and an improved user interface, depending on available resources.

PUBLICATIONS

- IGS 1998 Annual Report
- IGS 1998 Technical Report
- IGS Network Workshop Proceedings
- IGS Directory 1999

1 9 9 9

International Symposium on GPS 1999

The International Symposium on GPS held in Tsukuba, Japan, in October was convened by multiple sponsors — the Commission on Space Techniques for Geodesy (CSTG), the International Association of Geodesy (IAG), and the IGS. Former IGS Governing Board member Prof. Teruyuki Kato of the Earthquake Research Institute of Japan was the Secretariat of the Conference for the Local Organizing Committee. This was an excellent venue providing a great opportunity to meet with colleagues from all over the world, and especially from neighboring Asian countries. The IGS commends the organizers of this symposium for its great success. For more details on the symposium, see Prof. Kato's account in this Annual Report. Session summaries are available at *http://wwwsoc.nacsis.ac.jp/geod-soc/gpssymp/index.html*.

Central Bureau Outreach for IGS

In April, Angelyn Moore represented the IGS at the AIAA International workshop, "International Space Cooperation: Solving Global Problems," in Bermuda. Over 80 experts from around the world were invited to participate in this workshop, which was divided into five working groups, with the IGS joining a working group on Global Navigation Satellite Systems (GNSS): Fostering International Cooperation and Benefits to Worldwide Users. This working group generated a number of recommendations and findings based on the satellite navigation systems and the role of international cooperation in current and future GNSS systems — very timely, given the potential synergies between the GPS and the proposed Galileo system.

The final report is available from the AIAA at *http://www.aiaa.org*. This workshop was a preparatory activity for the UNISPACE III Conference, a United Nations–convened conference on "Space Benefits for Humanity in the Twenty-First Century."

Low-Earth Orbiter Workshop

Early in 1999, the Central Bureau was deeply involved in the organization of the workshop on "Low-Earth Orbiter Missions: Developing and Integrating Ground and Space Systems for GPS Applications," held in Potsdam, Germany, 9–11 March, at the GeoForschungsZentrum (GFZ). The workshop was jointly organized by IGS, GFZ, and JPL, bringing together GPS experts, mission representatives, and the science community intent on the application of LEO GPS flight instruments to provide data for precise orbit determination (POD), atmospheric occultation, gravity, and ionospheric studies. It is evident from the attendance and the lively discussions that there is a positive synergy and great potential benefit between IGS and the LEO missions. There are more than a dozen such LEO missions over the next decade that will carry onboard GPS receivers, which can all potentially benefit from a common ground-based GPS/GNSS infrastructure. See the IGS Technical Reports for 1999 for more detailed information on the workshop.

IGEX-98

The International GLONASS Experiment 1998 (IGEX-98) successfully concluded the experimental phase on 19 April 1999. This was a unique experiment that demonstrated the IGS flexibility to incorporate and process other satellite navigation system data in a precise and meaningful manner. This was the first time that GLONASS orbits were computed at the 20- to 50-cm level, and a valid reference system transformation between the Russian PZ-90 systems, WGS 84, and the ITRF was achieved. In September, a workshop was convened by Jim Slater and Carey Noll in conjunction with and jointly sponsored by the Institute of Navigation (ION) at its annual GPS meeting (GPS99) in Nashville, Tennessee. The proceedings are available at the IGS website or through the Central Bureau. Based on the success of the project, a proposal was presented to the IGS Governing Board in December to continue the experiment as a pilot service within the IGS. Named the International GLONASS Service Pilot Project (IGLOS-PP), the proposal was approved by the Governing Board following some modifications. The project is chaired by Jim Slater of the National Imagery and Mapping Agency (NIMA), whose IGEX report can be found in this Annual Report.

Of Note

The IGS supported an experiment during the total eclipse of the Sun on 11 August 1999. High-rate GPS data were collected at a number of sites, mostly a selected subset of the IGS network and regional stations within the eclipse-affected area of Europe. This was largely organized by the Ionospheric Working Group, chaired by Joachim Feltens of ESA/ESOC. Data are archived at the CDDIS.

Workshops, External Meetings, and Activities Supported by the Central Bureau

- IGS LEO Workshop — "Low-Earth Orbiter Missions: Developing and Integrating Ground and Space Systems for GPS Applications," 9–11 March, GeoForschungsZentrum, Potsdam, Germany.

IGS99 was a great opportunity to meet with colleagues from all over the world.

- Civil GPS Service Interface Committee (CGSIC), 15–18 March, Washington, D.C., USA.
- “International Space Cooperation: Solving Global Problems,” 12–15 April, American Institute of Aeronautics and Astronautics, Bermuda.
- European Geophysical Society, 19–23 April, The Hague, Netherlands.
- Global Sea Level Observing System Meeting (GLOSS GE6), Intergovernmental Oceanographic Commission (IOC), United Nations Educational, Scientific, and Cultural Organization (UNESCO) and Project, 10–13 May, Toulouse, France.
- IGS Analysis Center Workshop — “Real-Time Applications and Long-Term Accuracy,” 8–10 June, Scripps Institution of Oceanography, La Jolla, California, USA.
- XXII General Assembly, International Union of Geodesy and Geophysics (IUGG), 19–30 July, University of Birmingham, UK.
- International GLONASS Experiment 1998 (IGEX-98), Concluding Workshop, 13–14 September, Institute of Navigation, GPS ’99, Nashville, Tennessee, USA.
- US–China GPS Workshop, 29–30 September, National Science Foundation, U.S. Geological Survey, Palm Springs, California, USA.
- International Symposium on GPS, “Application to Earth Sciences and Interaction with Other Space Geodetic Techniques GPS ’99,” 18–22 October, Tsukuba, Japan.
- American Geophysical Union Fall Meeting, December, San Francisco, California.

The IGS Network: Meeting the Challenges of 1999

Angelyn W. Moore

Jet Propulsion Laboratory, California Institute of Technology, USA

IGS Network Coordinator and Deputy Director, IGS Central Bureau

A major focus for the IGS network of precise GPS tracking stations in 1999 was the integrity of tracking station metadata, such as receivers and antennae installed over the history of the site, as recorded in the official IGS site logs. Necessary information such as standardized equipment naming conventions was updated at the Central Bureau with the help of a team including IGS Operational Data Centers and GPS equipment manufacturers. The system for detecting format errors and inconsistencies between site logs and data file headers was vastly improved and took on the automatic task of e-mailing site operators with any problems found. Furthermore, the format-scanning software enabled a new system for the automatic e-mail submission of logs, and a facility for operators to check site log format compliance on a test basis prior to submission. These tools, along with considerable operator effort, reduced the number of metadata discrepancies from well over 120 to 7 over the course of calendar 1999.

The year 1999 may be considered the "year of rollovers," perhaps especially for the GPS community, which experienced a GPS week 1000 rollover, a GPS week 1024 rollover, and of course preparations for the well-publicized Y2K rollover. In retrospect, these were readily handled in terms of the IGS network with software changes where necessary, and diligent attention by many IGS operators and analysts around the times of the rollovers. Rollover testing on the GPS satellites themselves resulted in undesirable effects in some IGS network receivers, and the IGS community quickly determined the extent and resolution by way of the IGS Mail e-mail list.

The approaching solar maximum presented another network technical difficulty, which was addressed by several IGS components. The effect was first reported in late 1998 when sites with certain older receivers situated near the equator began to exhibit degraded tracking performance around local noon. Through 1999, as ionospheric activity continued to increase, this situation worsened to include mid-latitude sites. Communication

The network of GPS stations continued to grow in number and function through 1999.

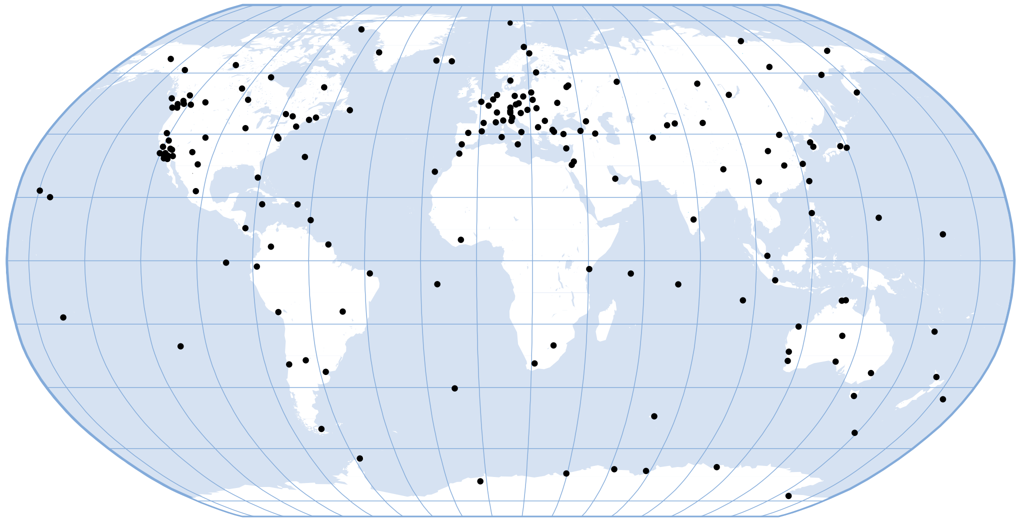


Figure 1. The IGS tracking network at the end of 1999.

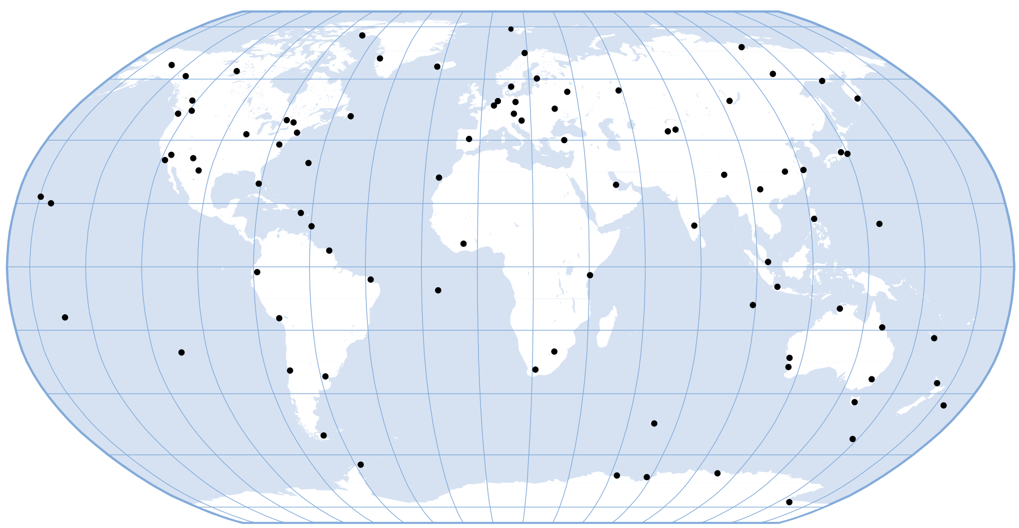


Figure 2. IGS global stations at the end of 1999.

and cooperation within the network and analysis components allowed evaluation of the extent of the problem and identification of equipment upgrades or software workarounds that would restore acceptable data acquisition.

Growth of the IGS Network

The network of GPS stations continued to grow both in number and in function through 1999 — the network at the end of 1999 is depicted in Figure 1. In total, 28 stations were added, including both new installations and previously existing sites that became IGS stations by submitting a site log to the IGS Central Bureau. The new group includes 11 southern hemisphere sites, and some that are favorably situated in regions where IGS coverage has been historically low, such as YKRO (Yamoussoukro, Cote D'Ivoire) and ARTU (Arti, Russian Federation). Six of the new stations enjoy sufficient worldwide popularity among Analysis Centers as of this writing to earn the IGS "Global" site label, which denotes sites regularly analyzed by at least one Analysis Center, including at least one on a different continent. The set of IGS Global sites is shown in Figure 2.

The IGS hourly subnetwork, still voluntary in 1999, grew to nearly 50 sites, benefiting developments such as the new IGS ultrarapid orbit, as well as other near real-time applications, and readying the IGS for the upcoming low-latency needs of the Low-Earth Orbiter project (see Figure 2 in the IGS Data Center Report by Carey Noll in this Annual Report).

Beyond the Successes of 1999

The advances in increasing and especially easily maintaining station metadata integrity not only aid IGS analysts and users, but also free the Central Bureau and Operational Data Centers to pursue other improvements in coming years. There is increasing interest in pinpointing patterns of usage of IGS station data; easy determination of which working groups and pilot projects make use of a particular site is a common request warranting attention from the network coordination element. Rapid advancements in applications requiring low-latency network operations will continue to demand insightful communication within the network in order to meet the need for collective network development and improvement.

The voluntary IGS hourly sub-network grew to nearly 50 sites.

Tim Springer

Astronomical Institute,

University of Bern, Switzerland

Analysis Center Coordinator

Analysis Activities

Low-Earth orbiter missions have the potential to fundamentally change the IGS as we know it today.

Introduction

Two key activities in 1999, from an IGS Analysis point of view, were the LEO (low-Earth orbiter) workshop and the 1999 Analysis Center workshop. The LEO workshop was held in Potsdam in March 1999. Although there are currently no operational LEO satellites that are equipped with a (usable) GPS receiver, a relatively large number of missions are planned in which LEO satellites will carry one (or more) GPS receivers. In general, the GPS applications for LEO satellites can be divided into two groups: precise orbit determination (POD) and atmospheric sounding. Both types of LEO missions require rapid (if not real-time), accurate orbits for the GPS satellites. In addition, the atmospheric sounding missions will also require a very high data rate (few-second sampling) from a GPS ground receiver network. Clearly, LEO missions have the potential to fundamentally change the IGS as we know it today. It is therefore necessary that the IGS take an active role in this field if it does not want to lose its position as the service that delivers the reference system for all GPS applications.

The 1999 IGS Analysis Center workshop took place in June 1999 at the Scripps Institution of Oceanography in La Jolla, California. A summary of the workshop may be found in IGS Mail message no. 2359. The workshop dealt with two major topics — real- and near-real-time products and applications, and long-term stability and accuracy of the GPS reference frame. The position paper “Moving IGS Products Towards Real-Time” by Gerd Gendt, Peng Fang, and Jim Zumberge proposed the generation of both more rapid and more frequent IGS products for (near-) real-time usage. These products, which will be delivered every 12 hours (two times per day), will contain a 48-hour orbit arc from which 24 hours are real orbit estimates and 24 hours are orbit predictions. The latency of this product is 3 hours. The first Analysis Center ultrarapid products were provided by GFZ by the end of October 1999. The generation of a combined “ultrarapid” product started in March 2000 based on contributions from up to five different Analysis Centers.

Change of Terrestrial Reference Frame (ITRF97)

As discussed and agreed upon during the Analysis Center workshop, the IGS changed its realization of the International Terrestrial Reference Frame by switching from the ITRF96 to the ITRF97 on 1 August 1999 (GPS week 1021). At the same time, the set of reference stations was slightly enhanced from 47 to 51 sites. The main change was the inclusion of a few sites for which the accuracy was insufficient in the ITRF96, but which are well determined in the ITRF97. A Software-Independent Exchange (SINEX) file containing the necessary information about these 51 reference stations may be found at the IGS Central Bureau website.

Although the ITRF96 and ITRF97 frames are nominally aligned globally in all 7 Helmert transformation components and their rates, comparison of the IGS subset of reference sites shows significant differences between the ITRF96 and ITRF97 realizations. The expected differences between the IGS products based on the ITRF96 and ITRF97 reference frames are given in Table 1. More information about this ITRF change may be found in IGS Mail message no. 2432.

Current IGS and AC Product Quality

Despite the still rapidly increasing processing load due to more stations, additional products (ultrarapid), and shortening submission delays, the Analysis Centers managed again to improve and/or maintain their solution precision, timeliness, and reliability. The quality improvement of the IGS products since 1994 is demonstrated in Figure 1, which shows the weighted orbit RMS for the final Analysis Center solutions with respect to the combined IGS final orbit products. Several Analysis Centers and also the IGS rapid orbit products have reached the 3–4 centimeter orbit precision level. Similar levels of accuracy are indicated by the IGS 7-day arc orbit analysis and by comparisons with satellite laser ranging observations of the GPS satellites PRN 5 and 6. The enormous efforts and the resulting improvements of the Analysis Center global solutions are also shown in Table 2, where the yearly averages of weighted orbit RMS values are shown for all Analysis Centers and the IGS rapid orbit.

The Analysis Centers improved and/or maintained their solution precision, timeliness, and reliability.

The primary objective of the IGS is to provide a reference system for a wide variety of GPS applications. To fulfill this role, the IGS produces a large number of different combined products, which constitute the practical realization of the

Table 1. Transformation from IGS (ITRF96) to IGS (ITRF97) at Epoch 1-AUG-1999. The IERS convention for the transformation parameters was followed. The equivalent changes in polar motion (PM), in the sense (ITRF97–ITRF96) may be obtained using PMx = RY and PMy = RX.

	TX mm	TY mm	TZ mm	RX mas	RY mas	RZ mas	D ppb
Offset	0.3	0.5	–14.7	0.159	–0.263	–0.060	1.430
+/–	2.1	2.1	2.1	0.090	0.098	0.088	0.31
	dTX mm/y	**dTY mm/y**	**dTZ mm/y**	**dRX mas/y**	**dRY mas/y**	**dRZ mas/y**	**dD ppb/y**
Drift	–0.7	0.1	–1.9	0.013	–0.015	0.003	0.192
+/–	0.3	0.3	0.3	0.011	0.012	0.011	0.043

D = scale
dD = scale rate of change
dR = rotation rate of change
dT = translation rate of change
mas = milliarcsecond
mm = millimeter
PM = polar motion
ppb = parts per billion
T = translation
R = rotation

Table 2. Yearly Average Weighted Orbit RMS (cm) Differences of the Analysis Center and IGS Rapid (IGR) Orbit Solutions with Respect to the IGS Final Orbits

Year	COD	EMR	ESA	GFZ	JPL	NGS	SIO	IGR
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
1997	4	10	7	6	6	16	7	5
1998	4	10	7	4	5	14	6	5
1999	3	10	7	3	4	9	5	4

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
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
IGR = IGS Rapid

Table 3. Quality of the IGS Reference Frame Products at the Start of 2000

Products:	Predicted	Rapid	Final
Delay:	Real-Time	17 hours	11 days
Orbit	50.0 cm	10.0 cm	5.0 cm
Clock	150.0 ns	0.5 ns	0.3 ns
Pole	—	0.2 mas	0.1 mas
LOD	—	30.0 sec/day	20.0 sec/day
Stations	—	—	5.0 mm
Troposphere	—	—	4.0 mm ZPD
Geocenter	—	—	30.0 mm
Terrestrial Scale	—	—	2.0 ppb

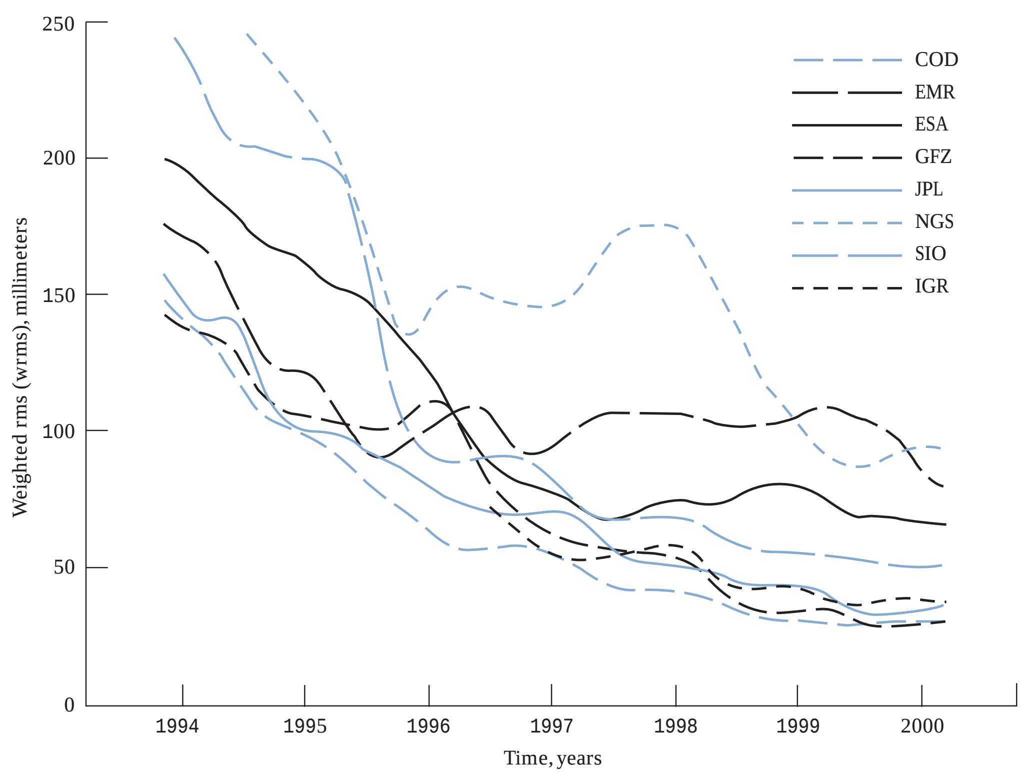


Figure 1. Weighted orbit RMS (cm) of the Analysis Center and IGS rapid (IGR) orbit solutions with respect to the IGS final orbits. The weekly WRMS values from the orbit combination summaries were smoothed for plotting purposes, using a sliding 10-week window.

IGS reference system. Table 3 gives an overview of the estimated quality of these different IGS reference frame products at the start of 2000.

Outlook

As mentioned earlier, a new, ultrarapid IGS combined product will become available in the near future. This product will be available for real-time usage, like the IGS predicted orbits, but the quality should be significantly better because the average age of the predictions is reduced from 36 to 18 hours. In the months to come, the quality and the reliability of the IGS ultrarapid (IGU) orbits will be assessed against the IGS predicted (IGP) and IGS rapid (IGR) products. When it reaches a satisfactory level (which could be sooner than we think), the IGU products will replace the IGP and IGR products.

A second, nearly completed, change is the new clock combination which is based on the Receiver-Independent Exchange (RINEX) clock format. This new clock combination will provide the normal combined satellite clocks in the orbit (SP3) format and it will also provide both satellite and station clocks in the RINEX clock format. These clock products will have a sampling rate of 5 minutes as compared with the current 15 minutes. Some Analysis Centers even provide higher sampled clock products, e.g., JPL provides clocks with a sampling rate of 30 seconds. This new clock combination is currently (March 2000) running in a test mode and preliminary results are being made available.

The plans for the new and improved IGS reference frame realization, as proposed during the 1997 Analysis Center workshop by Jan Kouba, were finalized in March 2000. Starting with GPS week 1050, the weekly IGS reference frame realization, as generated at NRCan by Remi Ferland, has become official — see IGS Mail message no. 2740 for more details. In this new IGS reference frame realization, the combined orbits are made consistent with the combined IGS reference frame SINEX solution by using both the transformation parameters and the combined Earth-rotation parameters (ERPs) stemming from the SINEX combination.

IGS Data Center Report

Carey E. Noll

NASA Goddard Space Flight Center, USA

Manager, Crustal Dynamics Data Information System, IGS Global Data Center

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 maintaining a level of redundancy allowing for security of the data holdings.

Operational Data Centers (ODCs) are responsible for the direct interface to the GPS receiver, connecting to the remote site hourly or daily and downloading and archiving the raw receiver data. The quality of these data are validated and are then translated from raw receiver format to a common format (RINEX) and compressed. Both the daily observation and navigation files (and meteorological data, if available) are then transmitted to a Regional or Global Data Center, ideally within an hour following the end of the observation day. For hourly data, files are transmitted from the Operational Data Center within 5 minutes of the end of the hour.

Regional Data Centers (RDCs) 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 collect daily data from several Operational Data Centers before transmitting them to the Global Data Centers. Typically, data not used for global analyses are archived and available for on-line access at the RDC level. IGS Regional Data Centers have been established in several areas, including Europe and Australia.

The IGS Global Data Centers (GDCs) are ideally the principal GPS data source for the IGS Analysis Centers and the user community in general. These online data are utilized by the IGS Analysis

The IGS began to see an emphasis on near-real-time activities that will continue in the coming year.

Centers to create a range of products, which are then transmitted to the Global Data Centers for public use. The GPS data available through the Global Data Centers consist of observation, navigation, and meteorological files, all in RINEX format. GDCs are tasked to provide an online archive of at least 100 days of daily GPS data files in the common data format, including, at a minimum, the data from all global IGS sites. The GDCs also provide an archive of hourly data files for at least 3 days. Furthermore, the GDCs are required to provide an online archive of derived products, generated by the IGS Analysis Centers, Associate Analysis Centers, and analysis coordinators. These data centers equalize holdings of global sites and derived products on a daily basis (at minimum). The three GDCs 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 (or hourly) 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 lists the data centers currently supporting the IGS; contact information for these data centers is available through the IGS Central Bureau website. Figure 1 shows the data flow from the GPS station to the Analysis Centers and the user community.

Highlights for 1999 and Plans for 2000

GENERAL

In 1999, the IGS began to see an emphasis on near-real-time activities that will continue in the coming year. Timeliness of the hourly data product was a growing concern, causing all levels of service within the IGS to review existing methods of data transmission and develop new processing capabilities to ensure data would be available to users within a few minutes. During 2000, with the start of rapid product production by the IGS Analysis Centers, data centers will be further challenged to ensure the timely delivery of both data and products to the user community.

The IGS infrastructure experienced two major outages in 1999 due to a computer system failure at the Crustal Dynamics Data Information System (CDDIS) Global Data Center. During August and late December, the CDDIS computer facility was down for several weeks because of various hardware and software problems. Since many sources of both GPS data and products deliver their files to the CDDIS, delays in data availability were felt throughout the IGS system. These problems have further emphasized the need for the IGS to develop and test backup data flow paths for all major components of the service. These problems and possible solutions will be further discussed at the next IGS Network workshop, to be held in July 2000 in Oslo, Norway.

IGS DATA

Consistent with past years, the number of stations archived by the IGS data centers increased by several percent in 1999. Over 225 sites staged completed site logs with the IGS Central Bureau Information System (CBIS). On a daily basis during the past year, over 575 stations were archived at Scripps Institute of Oceanography (SIO), supporting both the IGS and other global research activities; over 160 at CDDIS, supporting both the IGS and NASA activities; and over 100 at Institut Géographique National (IGN). The data centers experienced increased user activity as well during 1999; the CDDIS, for example, saw over nearly 60 gigabytes of GPS data and product files per month downloaded from their system in 1999.

IGS data centers continued the routine archive of hourly, 30-second data during 1999. These data were typically available to users within 15 minutes

Table 1. Data Centers Supporting the IGS in 1999

Operational Data Centers	
ASI	Italian Space Agency
AUSLIG	Australian Surveying and Land Information Group
AWI	Alfred Wegener Institute for Polar and Marine Research, Germany
BKG	Bundesamt für Kartographie und Geodäsie, Germany
CNES	Centre National d'Études Spatiales, France
DGFI	Deutsches Geodätisches Forschungsinstitut, Germany
DSN	Deep Space Network (National Aeronautics and Space Administration), USA
DUT	Delft University of Technology, The Netherlands
ESOC	European Space Agency, Space Operations Center, Germany
GFZ	GeoForschungsZentrum, 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, USA
NMA	Norwegian Mapping Authority
NOAA	National Oceanic and Atmospheric Administration, USA
NRCan	Natural Resources of Canada
RDAAC	Regional GPS Data Acquisition and Analysis Center on Northern Eurasia, Russia
SIO	Scripps Institution of Oceanography, USA
UNAVCO	University NAVSTAR Consortium, USA
USGS	United States Geological Survey

Regional Data Centers	
AUSLIG	Australian Surveying and Land Information Group
BKG	Bundesamt für Kartographie und Geodäsie, Germany
JPL	Jet Propulsion Laboratory, California Institute of Technology, USA
NOAA	National Oceanic and Atmospheric Administration, 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, USA

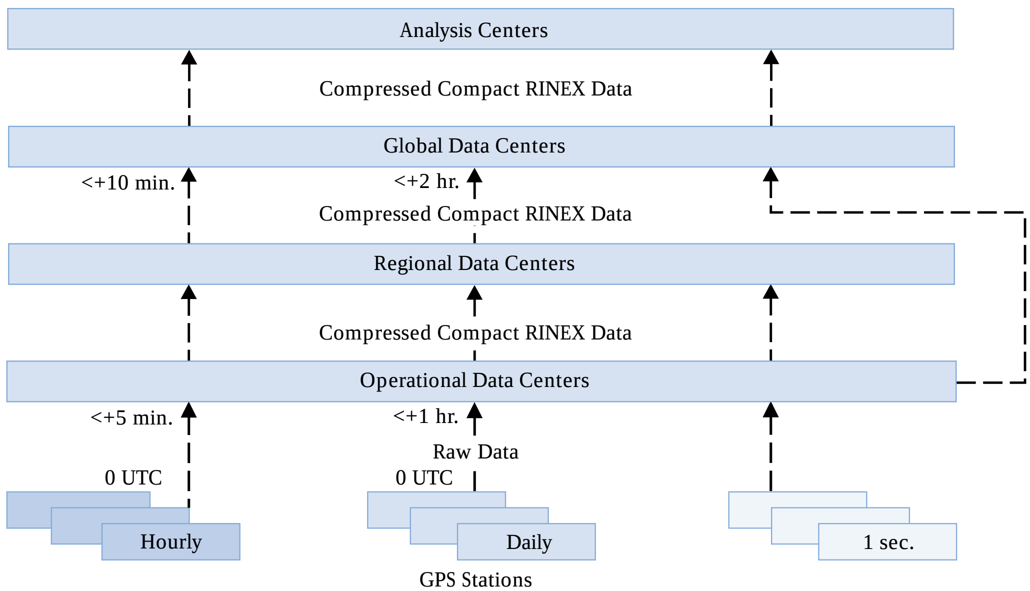


Figure 1. Internal IGS data flow from the GPS stations to the Analysis Centers.

after the hour. By late 1999, data from over 45 sites were collected by the Jet Propulsion Laboratory (JPL), European Space Operations Center (ESOC), Natural Resources Canada (NRCan), and Bundesamt für Kartographie und Geodäsie (BKG), and transmitted to and archived at the IGS Global Data Centers. These hourly files are archived in compressed, compact RINEX format and retained at the GDCs for 3 days. No validation or checking of data quality is performed on these data in order to provide the files in the most timely fashion to the user community. The daily observation and navigation files, containing 24 hours of data, are then transmitted through "normal" channels and archived indefinitely at the data centers. Figure 2 shows the network of GPS stations providing hourly RINEX data.

On average, the latency of the data arrival at the Global Data Centers improved during 1999. Over 50 percent of the daily data files arrived at the global data centers within 3 hours and about 75 percent arrived within 6 hours. The timeliness of the hourly data improved greatly as the year drew to a close, with data from many sites available within 10 minutes after the end of the previous hour. As usual, efforts to reduce the time delay of both daily and hourly data, particularly for global IGS stations, will continue during the coming months.

The IGS co-sponsored a new activity to establish an international campaign for Global Navigation Satellite System (GLONASS) observations during late 1998 and early 1999. The main purpose of the International GLONASS Experiment (IGEX-98) was to conduct the first global GLONASS observation campaign for geodetic and geodynamics applications. Several of the existing IGS data centers proposed to participate in IGEX-98, thereby increasing the diversity of their archives with the addition of GLONASS data and products. Although the IGEX-98 campaign officially ended in mid-April 1999, the flow of data and products continues on a best-effort basis. The IGS Governing Board approved the follow-on program, the International GLONASS Service–Pilot Project (IGLOS-PP) in early 2000. During the coming months, the IGS and the IGLOS Pilot Project committee will investigate how to incorporate both GLONASS data and products into the existing IGS data flow.

In 2000, the data centers will begin to see 1-second RINEX data transmitted in hourly files. These data, from a 20- to 30-station subnetwork of IGS sites, will be utilized primarily in support of low-Earth orbiter (LEO) missions such as the Challenging Mini-Satellite Payload for Geophysical Research and Application (CHAMP) and Gravity Recovery and Climate Experiment (GRACE). Because of the volume of the 1-second data files, a new, more efficient binary data format will be utilized. Plans are to make these data available at IGS data centers in files containing hourly data only. Selected IGS data centers will become involved in the archiving of GPS flight data for some of these LEO missions as well.

IGS Products

The IGS data centers continued to archive a wide range of IGS products during 1999. These products include the weekly, standard orbit, clock, and Earth-rotation parameters (ERPs) from the seven IGS Analysis Centers and the combined product from the IGS Analysis Coordinator. The accumulated IGR (rapid orbit) and IGP (predicted orbit) products were distributed and archived on a daily basis as well. IGS station coordinate and reference frame solutions were routinely provided by seven IGS Associate Analysis Centers as well as a combined solution by the IGS Reference Frame Coordinator. The IGS troposphere product, in the form of combined zenith path delay (ZPD) estimates for over 150 sites were generated by GeoForschungsZentrum (GFZ) and archived on a weekly basis at the Global Data Centers. Individual ionosphere maps of total electron content (TEC) were derived on a daily basis by five IGS Associate Analysis Centers and were also archived at the Global Data Centers. A daily file of these data in IONEX format includes 12 2-hour snapshots of the TEC and optional corresponding RMS information.

At the 1999 LEO workshop, it was recommended that the IGS Analysis Centers develop a new rapid analysis products, including orbits, clocks, EOP, and predictions. It was further recommended that these products should be made available to users through the IGS data centers with a latency of less than 3 hours. Plans are to begin a pilot project for this activity in 2000.

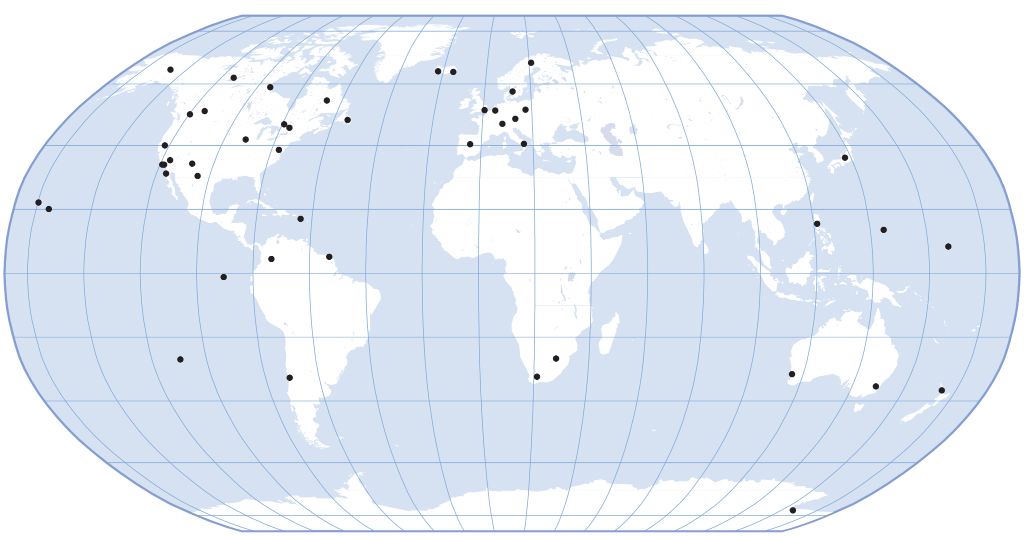


Figure 2. Subnetwork distribution of IGS stations delivering hourly RINEX data files.

The International Terrestrial Reference Frame

Zuheir Altamimi

Institut Géographique National, France

ITRF Section, International Earth Rotation Service

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

IGS supports the continuous improvement of the ITRF by contributing to the extension of the ITRF network.

The ITRF Section of the IERS Central Bureau (ITFS) cooperates very closely with the different IGS participants (Central Bureau, Analysis Centers, 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, see *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 April 1998; ITRF96 starting on 1 March 1998; and ITRF97 since 1 August 1999.

IGS 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 that are included in the ITRF combinations.

IGS also provides a very efficient method to densify the ITRF network: one can now obtain millimetric positions directly expressed in ITRS by processing suitable GPS data together with IGS products.

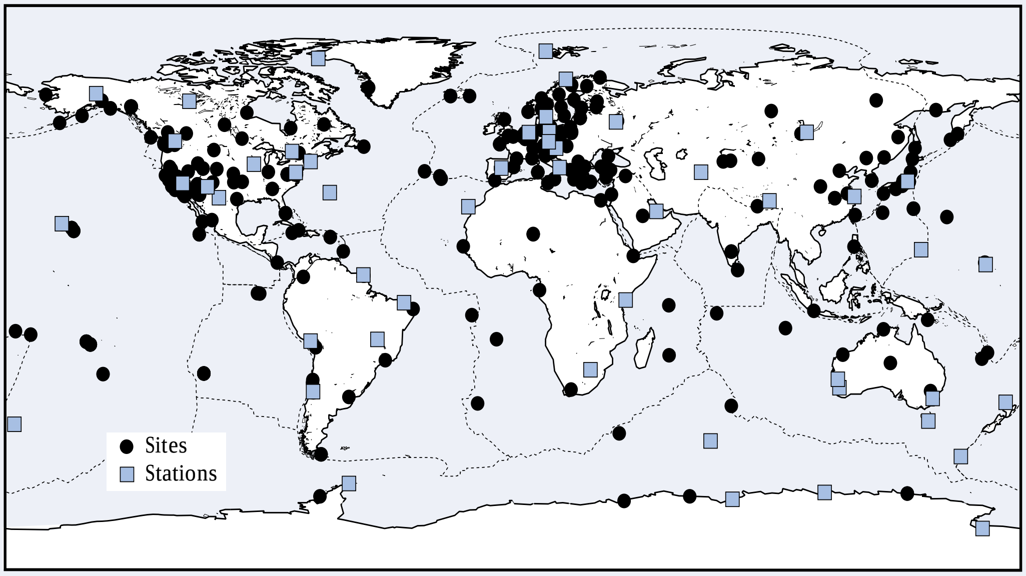
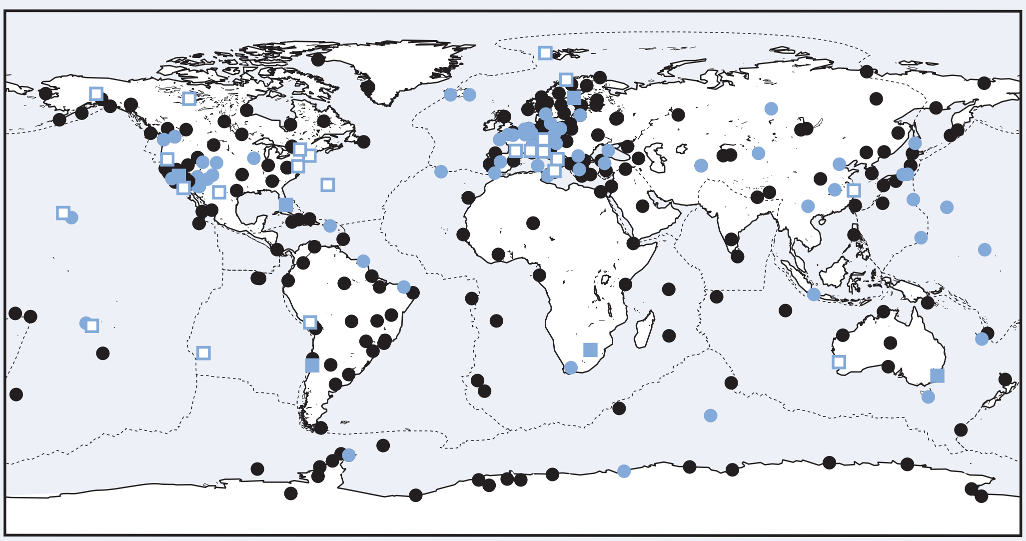


Figure 1. ITRF97 sites (circle) include the 52 IGS reference stations (square).



● any single technique (GPS, VLBI, SLR, DORIS)
● 64 collocations (any two of the techniques at one location)
□ 24 collocations (any three)
■ 6 collocations (all four)

Figure 2. ITRF2000 sites and collocated techniques.

One of the year 2000 major trends of the IERS is the establishment of the ITRF2000.

ITRF and the IGS Reference Stations

Starting on 1 March 1998, the IGS began using ITRF96 positions and velocities of a set of 47 reference stations. The IGS selection of these stations is the result of criteria tests including primarily the quality of their ITRF96 coordinates. For this latter criterion, the ITRS has performed a specific quality analysis based on ITRF96 position and velocity residuals. The analysis was repeated in light of the ITRF97 results upon the original 52 stations proposed by the IGS Analysis Centers. The main result of this quality analysis is that the ITRF97 position quality (at 97.0 epoch) is better than 1 centimeter for 47 stations and better than 2 centimeters for the remaining 5 stations. Moreover, the velocity quality is better than 5 millimeters per year for 37 stations, and better than 10 millimeters per year for the remaining 13 stations. The 52 selected ITRF97 reference stations have been used by IGS since 1 August 1999.

Figure 1 shows the coverage of the ITRF97 sites underlying the 52 IGS reference stations.

ITRF2000

One of the year 2000 major trends of the Earth IERS is the establishment of the ITRF2000. This global reference is to be considered as a standard solution for a wide user community (geodesy, geophysics, astronomy, etc.). The ITRF2000 comprises on the one hand primary core stations observed by very long baseline interferometry (VLBI), LLR, GPS, SLR, and DORIS techniques and, on the other hand, significant extension provided by regional GPS networks for densifications as well as other useful geodetic markers tied to the space geodetic ones. The current ITRF2000 network is illustrated in Figure 2. It is expected that the ITRF2000 will be published at the end of year 2000 or in early 2001.

KEY AREAS

International Symposium on GPS

Teruyuki Kato

Earthquake Research Institute, University of Tokyo, Japan

Former Member, IGS Governing Board

The International Symposium on GPS 1999 (GPS99) — "Application to Earth Sciences and Interaction with Other Space Geodetic Techniques" — was held 18–22 October at the Tsukuba International Congress Center, Tsukuba, Japan. The symposium was convened under the auspices of the National Committee of Geodesy, Science Council of Japan, and other domestic organizations as well as IGS and CSTG (Commission VIII in Section II of IAG and Commission B.2 of COSPAR). The symposium was, in part, jointly held with the Third International Meeting of the Asia-Pacific Geodynamics Program (APSG). In light of the recent expansion of applications of GPS technologies to vast areas of Earth sciences, 14 sessions were organized (shown in Table 1).

In addition to the scientific sessions, a plenary session of APSG was held. The symposium aimed at not only exchanging recent results and ideas among advanced researchers but also assisting those who were beginners in using GPS science. It was expected that there would be many attendees from developing countries, so three tutorial sessions were organized, one of which was arranged by the IGS Central Bureau. A number of experienced scientists presented lectures and panel discussions for GPS beginners. These tutorial sessions were all very well attended. Recent developing GPS research fields were also highlighted, such as GPS meteorology, tectonics in Asia and the western Pacific, kinematic applications, etc. A series of large, devastating earthquakes in Turkey, Taiwan, Greece, and California impelled the symposium Local Organizing Committee (LOC) to set up an urgent poster session in the symposium.

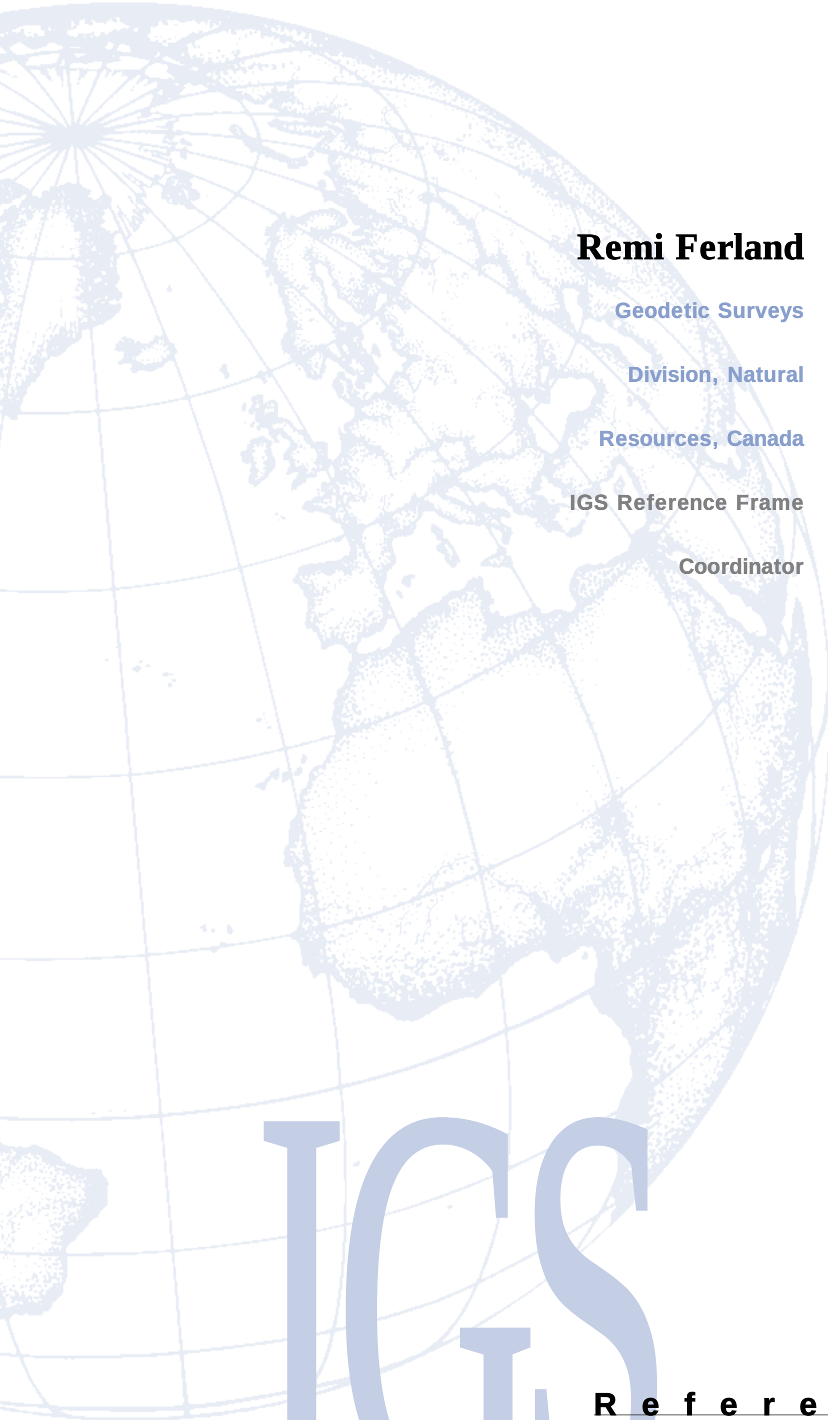
Table 1. GPS99 Sessions

No.	Title	Convened By
1	Permanent GPS Arrays, Current and Future	• Yehuda Bock and Yuki Hatanaka
2	GPS Meteorology: Atmospheric Sensing with Ground and Space-Based GPS Receivers	• Bill Kuo, Mike Bevis, Yoaz Bar-Sever, Randolph Ware, Nobutaka Mannoji, and Toshitaka Tsuda
3	A New View of the Tectonic Deformations in the Pacific and Asia Using Space Geodetic Techniques (Joint session with the Asia Pacific Space Geodynamics Program [APSG])	• Shui-Beih Yu, Jeff Freymueller, Takao Tabei and Minoru Kasahara
4	Determination and Interpretation of Global and Regional Plate Motions Deduced from Space Geodetic Techniques	• Kristine Larson and Kosuke Heki
5	Combination of Space Geodetic Techniques for Global Dynamics and Reference Frames	• Thomas Herring, Zuheir Altamimi, Shigeru Matsuzaka, and Yukio Takahashi
6	Space and Terrestrial Techniques for Advanced Crustal Deformation Research	• Will Prescott, Frank Webb, Seiichi Shimada, and Takeshi Matsushima
7	Application of GPS for Monitoring Earth's Environmental and Global Sea Level Change	• Erik Ivins and Yoshiaki Tamura
8	Application of GPS for Ionospheric Research and Impact of Solar Maximum for GPS Measurements	• Richard Langley and Akinori Saito
9	Modeling of the Crustal Process Based on GPS Measurements	• Paul Segall, Manabu Hashimoto, and Takeshi Sagiya
10	Theory and Methodology of GPS and Other Space Techniques	• Peter Teunissen and Peiliang Xu
11	Kinematic Application of GPS Technology to Earth Sciences	• Oscar Colombo and Tetsuichiro Yabuki
12	Issues of Data Quality Management and Hardware/Software Technological Problems in GPS	• James Davis, Peng Fang, and Akio Yasuda
13	GPS for Gravity Field and Geoid Determination	• Rene Forsberg and Yoichi Fukuda
14	Innovative Developments in GPS Geodesy in Support of the Earth Sciences	• Chris Rizos and Shigeru Nakao

In total, there were 366 participants from 39 countries (190 from Japan and 176 from other countries) of all continents around the world, and more than 300 presentations (oral and poster). This symposium thus became “the largest GPS geodesy conference of 1999, and one of the biggest such events ever held in the Asian region,” according to Dr. Chris Rizos (personal communication). The papers read in the symposium were published as two volumes of Earth, Planets and Space, a refereed English journal published by the Japanese Earth Science Societies, edited by Kosuke Heki and seven other co-editors. These volumes, which include more than 80 articles, were bound for a hard covered book and distributed to participants.

The symposium emphasized that the interdisciplinary approach of space geodesy is extremely useful and valuable in a variety of fields in the Earth sciences. The Global Positioning System may play a central role in this kind of application in the coming decades. IGS or IAG may be responsible for tracking new trends and creating new areas of study for Earth science through gathering together researchers in related areas and assisting new participants with potential capabilities. The symposium’s Local Organizing Committee (chairman, Torao Tanaka; secretary, Teruyuki Kato) hopes that IGS/IAG continues to make efforts to promote events of this kind involving various fields of GPS-related research around the world.

The GPS99 home page gives more information on the symposium and includes information about the sessions —
http://wwwsoc.nacsis.ac.jp/geod-soc/gpssymp/



IGS Reference Frame Pilot Project

Remi Ferland

Geodetic Surveys Division, Natural Resources, Canada

IGS Reference Frame Coordinator

The need to generate unique IGS station coordinates and velocities, Earth-rotation parameters (ERPs), and geocenter estimates was recognized as early as 1994 by the IGS members. The Reference Frame Working Group (RFWG) was organized to address this need. Starting with GPS week 1000 (7 March 1999), the first weekly preliminary Software-Independent Exchange (SINEX) combinations were produced. The Analysis Centers' weekly SINEX solutions are used in the combinations. The Global Network Associate Analysis Centers' (GNAAC) weekly combinations are used to control the quality of the results. Following several improvements proposed by the RFWG members, it was agreed to officially start generating products. With the IGS Governing Board approval, the SINEX products became official starting with GPS week 1050 (20 February 2000).

The orbit products are aligned by the IGS Analysis Center Coordinator at the Center for Orbit Determination in Europe (CODE) to the weekly SINEX cumulative combinations, thus ensuring product consistency. This requires that the SINEX combination be available at the time of the final orbit combinations, which is now produced 12–13 days after the end of each week.

The IGS realization of ITRF97 has been implemented starting with GPS week 1021 (1 August 1999). It consists of 51 high-quality, well-distributed global reference frame (RF) stations. It replaces the IGS realization of ITRF96, which utilized 47 RF stations. Table 1 shows the estimated transformation parameters between the two ITRF realizations IGS ITRF96 to IGS ITRF97.

per year in the north, east, and up directions. The comparison of the ITRF97 RF stations with NUVEL-1A plate-motion model shows an RMS of 3.1 millimeters per year, 4.1 millimeters per year, and 3.8 millimeters per year in north, east, and up respectively. These results indicate some improvement in the horizontal velocity with the adoption of the IGS realization of ITRF97.

The cumulative solution contains 4 years of weekly solutions. Between GPS week 0837 and 0977 (21 January 1996–3 October 1998), the GNAAC solutions were used. Since then, the Analysis Center SINEX solutions have been used to update the cumulative SINEX combined solution. Using the cumulative solution for the GPS week 1046 (23 January 2000), a new set of the

Table 1. Estimated Transformation Parameters Based on the 46 Common Stations Between the Two ITRF Realizations IGS ITRF96 to IGS ITRF97 at the 1 August 1999 Epoch (Sigmas in Brackets)

TX, mm	TY, mm	TZ, mm	RX, 0.01 mas	RY, 0.01 mas	RZ, 0.01 mas	D, ppb
0.3 (2.1)	0.5 (2.1)	–14.7 (2.1)	15.9 (9.0)	–26.3 (9.8)	–6.0 (8.8)	1.43 (0.31)
			Rates, per year			
–0.7 (0.3)	0.1 (0.3)	–1.9 (0.3)	1.3 (1.1)	–1.5 (1.2)	0.3 (1.1)	0.19 (0.04)

D = scale
mas = milliarcseconds
mm = millimeters
ppb = parts per billion
R = rotation
T = translation

Additional stations in the South Pacific/Antarctic regions have improved the RF station global coverage. The root mean square (RMS) of the transformation residuals between the two IGS realizations of ITRF, at the reference epoch (1 January 1997), are 1.7 millimeters, 2.0 millimeters, 4.3 millimeters, and 1.4 millimeters per year, 2.3 millimeters per year, and 3.2 millimeters

IGS coordinates and velocities for the RF stations was proposed for the IGS realization of ITRF97. Comparisons with ITRF97 at the epoch of the cumulative solution (1 January 1998) show RMS position and velocity differences at 0.9 millimeter, 0.8 millimeter, and 3.6 millimeters, and 1.0 millimeter per year, 1.2 millimeters per year, and 4.3 millimeters per year in north, east, and

There is continuous improvement of station coordinates and velocities, ERPs, and geocenter products.

up components. When both solutions are propagated to 1 January 2000, the RMS position differences become 2.8 millimeters, 3.5 millimeters, and 11.2 millimeters.

The comparisons between the IGS and the ITRF solutions are optimistic since the ITRF solution for the stations considered here is, to a large extent, based on earlier Analysis Center cumulative solutions. A somewhat more independent estimate can be obtained by comparing the estimated velocities with the NUVEL-1A plate-motion model. After removal of the stations influenced by local effects, the RMS velocity differences are 2.3 millimeters per year, 2.5 millimeters per year, and 3.7 millimeters per year in north, east, and up.

Between 1 August 1999, and 26 January 2000, the mean difference between the polar motion (PM) combination produced by the official orbit combination and the SINEX combination was consistent at the 0.009-milliarcsecond and 0.030-milliarcsecond level in x and y components, with a standard deviation of the mean of about 0.003 milliarcsecond for each component. This shows that there is a small average bias. Daily variations of the differences have a standard deviation of about 0.04 milliarcsecond. Comparisons with Bulletin A show a mean difference of –0.027 milliarcsecond and –0.260 milliarcsecond in the x and y components, respectively, with a standard deviation of the mean differences of about 0.005 milliarcsecond. The standard deviation of the daily variations is at the 0.06-milliarcsecond level.

The weekly apparent geocenter position is also combined from the Analysis Center weekly combinations. Since GPS week 0978 (4 October 1998), the average weekly geocenter estimates with respect to ITRF97 are 2.3 millimeters (x), 4.8 millimeters (y), and –15.2 millimeters (z), with standard deviations of 6.8 millimeters, 9.2 millimeters, and 14.4 millimeters, respectively.

The ongoing active participation by the group members is contributing to the continuous improvement of the station coordinates and velocities, ERPs, and geocenter products.

Jim R. Ray

United States Naval Observatory, USA

Earth Orientation Department

IGS/BIPM Time and Frequency Project

The IGS/BIPM Pilot Project to Study Accurate Time and Frequency Comparisons Using GPS Phase and Code Measurements is sponsored jointly with the Bureau International des Poids et Mesures (BIPM). The project has been under way since early 1998. Its central goal is to investigate and develop operational strategies to exploit GPS measurements for improved availability of accurate time and frequency comparisons worldwide.

The respective roles of the IGS and BIPM are complementary and mutually beneficial. The IGS brings a global GPS tracking network; standards for continuously operating geodetic, dual-frequency receivers; an efficient data delivery system; and state-of-the-art data analysis groups, methods, and products. The BIPM and the timing laboratories contribute expertise in high-accuracy metrological standards and measurements, timing calibration methods, algorithms for maintaining stable time scales, and formation and dissemination of UTC.

Our foremost technical challenge is the effort to measure calibration biases that relate internal receiver clocks to external time standards.

Activities generally fall into the following areas:

- Deployment of GPS receivers — The IGS network currently consists of about 200 globally distributed, permanent, continuously operating stations. Of these, external frequency standards are used at approximately 30 with H-masers, approximately 20 with cesium clocks, and approximately 20 with rubidium clocks; the remainder use internal crystal oscillators. Table 1 lists the IGS stations currently located at timing laboratories.

- GPS data analysis — Of the IGS Analysis Centers, all but two provide satellite and station clock estimates. The IGS is expanding its official products to include combined receiver clocks, in addition to combined satellite clocks.

- Instrumental delays — Efforts are under way to develop techniques to measure the calibration biases that relate internal receiver clocks to external time standards. When available for IGS stations located at timing laboratories, traceability to UTC can be established for IGS clock products. This effort is the foremost technical challenge facing the Pilot Project.

- Comparison experiments — Several controlled experiments are being conducted to compare geodetic timing results with simultaneous, independent techniques. However, high-quality frequency comparisons are already feasible provided that reasonable care is taken to minimize environmentally induced variations.

Table 1. IGS Stations Located at BIPM Timing Laboratories in 1999

IGS Site	Time Lab	GPS Receiver	Frequency Standard	City
AMC2	AMC*	AOA SNR-12 ACT	H-maser	Colorado Springs, CO, USA
BOR1	AOS	AOA TurboRogue	Cesium	Borowiec, Poland
BRUS	ORB	AOA SNR-12 ACT	H-maser	Brussels, Belgium
GRAZ	TUG*	AOA TurboRogue	Cesium	Graz, Austria
MDVO	IMVP	Trimble 4000SSE	H-maser	Mendeleevo, Russia
NRC1	NRC*	AOA SNR-12 ACT	H-maser	Ottawa, Canada
OBER	DLR	AOA SNR-8000 ACT	Rubidium	Oberpfaffenhofen, Germany
PENC	SGO	Trimble 4000SSE	Rubidium	Penc, Hungary
ROAH	ROA	AOA TTR4-P	Cesium	San Fernando, Spain
SFER	ROA	Trimble 4000SSI	Cesium	San Fernando, Spain
TOUL	CNES	AOA TurboRogue	Cesium	Toulouse, France
USNO	USNO*	AOA SNR-12 ACT	H-maser	Washington, DC, USA
WTZR	IFAG	AOA SNR-8000 ACT	H-maser	Wettzell, Germany

***Participates in two-way satellite time transfer operations.**

Activities of the IGS Ionosphere Working Group

Joachim Feltens

European Space Agency

European Space Operations Center, Germany

Stefan Schaer

Astronomical Institute

University of Bern, Switzerland

The IGS Ionosphere Working Group (Iono_WG) has been active since June 1998. The working group's most important short-term goal is the routine provision of global ionosphere total electron content maps plus GPS spacecraft differential code biases with a delay of some days. The major medium- and long-term tasks are the development of more sophisticated ionosphere models and the establishment of a near-real-time service. The final target is the establishment of an independent IGS ionosphere model.

We plan to validate the different methods used by the IAACs with the aim of achieving an objective combination scheme.

Five Ionosphere Associate Analysis Centers (IAACs) contribute with their products to the Iono_WG activities:

- CODE — Center for Orbit Determination in Europe, Astronomical Institute, University of Bern, Switzerland
- ESOC — European Space Operations Center, Darmstadt, Germany
- JPL — Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, USA
- NRCan — National Resources Canada, Ottawa, Ontario, Canada
- UPC — Polytechnical University of Catalonia, Barcelona, Spain

Routine Activities

DAILY IONOSPHERIC TEC INFORMATION

Each IAAC delivers an Ionospheric Map Exchange (IONEX) file (Schaer et al., 1997) every 24 hours, with 12 total electron count (TEC) maps containing global TEC information at 2-hour time resolution and a daily set of GPS satellite differential code biases (DCBs) in its header.

WEEKLY COMPARISONS

Each Tuesday, the TEC maps from the IAACs are compared for all days of the week before. These comparisons are done at ESA/ESOC. A weekly comparison summary is e-mailed to the working group members. Additionally, the daily summaries, the daily IONEX files with the mean TEC maps and GPS satellite DCBs, and daily TEC and DCB difference files with respect to the mean for each IAAC, and also plots of these maps, are made available via ESOC's FTP account. The algorithm used in the comparison program is described in Feltens, 1999.

For the northern hemisphere, the deviations of the different ionospheric maps from the IGS mean are, under normal conditions, 5 TEC units or less. At the equator and for the southern hemisphere, the situation is more problematic because of gaps in the station coverage at these latitudes. The agreement of the DCB sets is normally better than 0.3 nanosecond, and sometimes 0.5 nanosecond. Any DCB set showing differences of 1 nanosecond or more with respect to the IGS mean is excluded from the comparison. Figure 1 was computed by Stefan Schaer at CODE and shows the development of the mean TEC since the beginning of 1995. A clear increase of the TEC, closely related to increasing solar activity, can be seen in this figure.

Improvement of the Comparison Scheme and Validations

The current comparison/combination algorithm is based on a pure statistical approach using weighted means. On the other hand, the methods used by the IAACs to model the ionosphere are very different. In order to achieve an objective combination scheme, the existing comparison/combination algorithm must be improved. The Ionosphere Working Group thus decided to make validations of the different models in order to define an objective weighting and an optimal comparison/combination scheme with which the individual TEC maps can be combined into one common IGS solution. Currently, the comparison results are circulated only to the working group members.

Several types of validation were proposed by the Ionosphere Working Group members (Feltens, 1999). In the meantime, validations were started with a method proposed by Pierre Heroux (Heroux, 1999), which is based on the computation of ground station DCB series by subtracting,

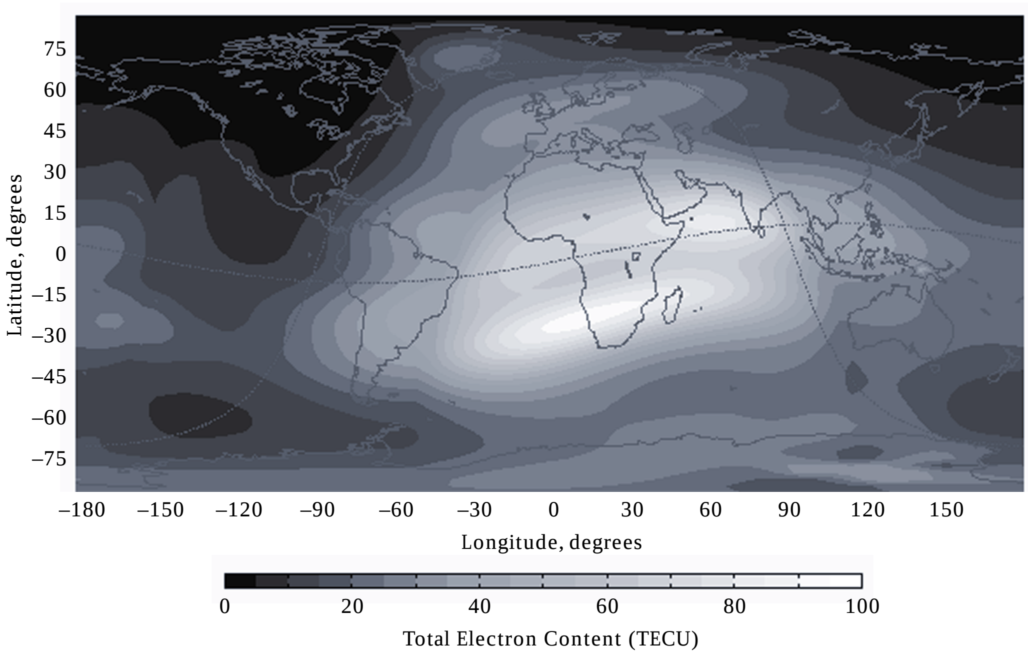


Figure 1. Development of mean total electron count since 1995 (computed at CODE). The full-color version is on the IGS Central Bureau website at — http://igscb.jpl.nasa.gov/projects/comb_ion.html

from observed TEC values, corresponding model TEC values and GPS satellite DCBs read from the IONEX files. The output is then given in the form of statistics generated from the ground stations' DCB series.

The software to run the validations with measured vertical TEC obtained from TOPEX altimeter data is ready. The method of using TOPEX data for validation was proposed by Brian Wilson of JPL. The software to run these validations was written by Joachim Feltens at ESA/ESOC. Routine access to the TOPEX data is being solved.

Special Activities

Initiated by a proposal from Norbert Jakowski from DLR Neustrelitz, Germany, a special GPS tracking campaign was organized by the Ionosphere Working Group during the total solar eclipse event on 11 August 1999. About 60 ground stations from the global IGS tracking network contributed to this campaign with high sampling rate tracking data (1 sec or 3 sec). These stations were located along the eclipse path from the east coast of North America over Europe to the Middle East. The high-rate data have been archived in RINEX files at the CDDIS and can be used for ionosphere analysis efforts (Feltens and Noll, 1999), with access via anonymous ftp to the host *cddisa.gsfc.nasa.gov* in the directory *gps/99eclipse*. First results obtained with GPS data from the eclipse day were published in Jakowski et al., 1999a and 1999b. IGS TEC maps of the Ionosphere Working Group for 11 August 1999 can also be found in Feltens and Schaer, 2000.

Under the heading "special activities," attention should also be drawn to the special issue of the Journal of Atmospheric and Solar-Terrestrial Physics, "GPS Applications to the Structure and Dynamics of the Earth's Oceans and Ionosphere: Measurement, Analysis, Instrument Calibration, and Related Technologies" (Vol. 61, No. 16, November 1999). This issue includes several papers co-authored by members of the Ionosphere Working Group.

Future Tasks

The Ionosphere Working Group intends to continue with validation activities so that we will soon be in a position to provide an IGS ionosphere product to users outside the IGS. The comparison/combination algorithm must be improved accordingly.

Another important aspect will be the reduction of the time deadline for ionosphere products delivery. The ionosphere is a very rapidly changing medium, and it must be the working group's intention to provide actual ionosphere information in short time frames — this is of special importance with regard to the solar maximum, which is approaching.

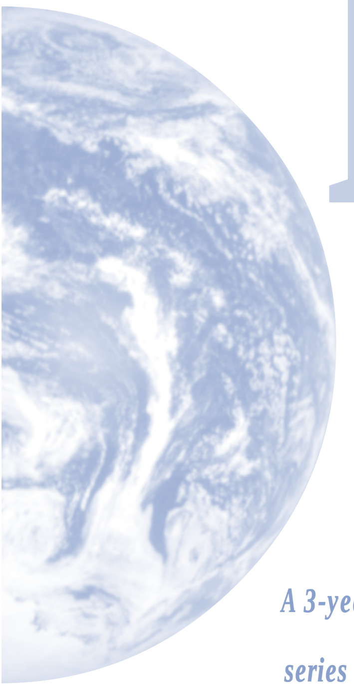
STATUS REPORT of the Tropospheric Working Group

Gerd Gendt

GeoForschungsZentrum

Potsdam,

Germany



A 3-year series of combined tropospheric product for 150 IGS sites is available.

The combined tropospheric product in the form of zenith neutral delay (ZND) was continued during 1999. Presently, a continuous series for 150 IGS sites spanning 3 years is available. The standards for the analysis are converging, so five Analysis Centers have implemented the Niell mapping function, and there is the tendency to use an elevation cut-off angle of 15 degrees. The quality of the product is of the level of 3 to 8 millimeters ZND, where a clear dependency on the latitude can be stated (Figure 1). The highest quality is reached within the denser networks in the northern hemisphere (30 to 60 degrees), and the lowest near the equator, which is caused by problems with some receivers' experience in the stronger ionosphere. Compared to the scattering, the biases are small, typically of the order of ±0.2 millimeter; however, systematic effects can be stated. The Center for Orbit Determination in Europe (CODE) and Scripps Institution of Oceanography (SIO) have different cut-off angles (weighted 10 degrees for CODE; 7 degrees for SIO) that clearly deviate from the other Analysis Centers (Figure 2).

Figure 1. Mean standard deviation for IGS sites used by three or more Analysis Centers, sorted by latitude (mean over 1999). Sites equipped with met sensors are indicated.

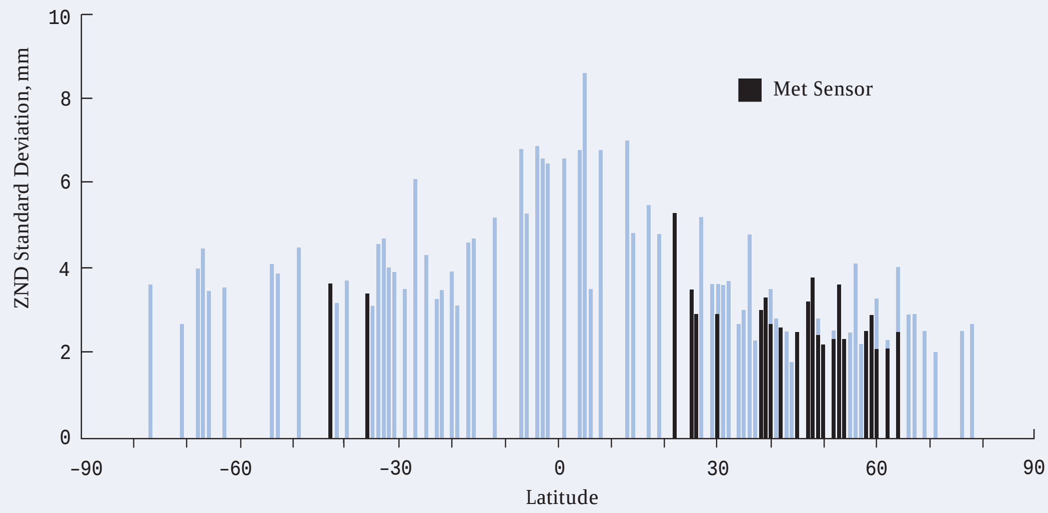
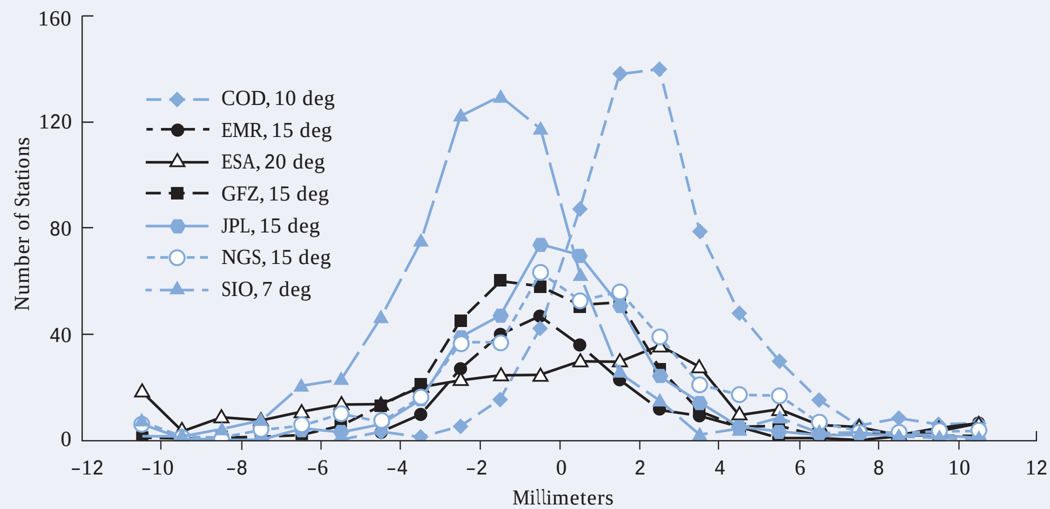


Figure 2. Differences in the ZND between the individual GPS estimates and the IGS combined product; histograms of biases for GPS weeks 999 to 1004 (cut-off angles are given in the legend).



A comparison with a collocated water vapor radiometer (WVR) was performed at the Potsdam site for an interval of more than 1 year. The five contributing Analysis Centers monitored the fluctuations in the water vapor with a high accuracy; the scattering was at the level of ±0.9 millimeter water vapor. All Analysis Centers had negative mean biases of about –1 millimeter (from –0.7 to –1.5 millimeters). The fluctuations in the bias were slightly larger (±–1 millimeter peak to peak), but quite uniform among the Analysis Centers, which implies common effects in GPS or varying biases in the WVR data.

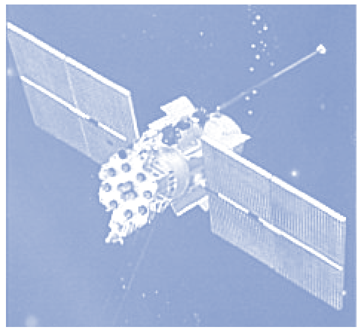
A still-existing, slowly improving problem is the small number of available met sensors. In total, 36 sites were equipped with sensors during 1999; the majority are located in the middle northern latitudes (Figure 1). Each day, typically about 10 sites were missing, so the usual number per day was about 25.

International GLONASS Experiment (IGEX-98)

James A. Slater

National Imagery and Mapping Agency, USA

During IGEX-98, a globally distributed GLONASS tracking network was established for the first time.



The International GLONASS Experiment (IGEX-98), which began in October 1998, ended as scheduled on 19 April 1999. Its purpose was to exploit the Russian GLONASS satellite system primarily as an enhancement to GPS for both scientific and navigation applications. Accordingly, the four sponsors of the experiment were the IGS, the Institute of Navigation (ION), the International Association of Geodesy (IAG), and the International Earth Rotation Service (IERS). Participants represented 25 countries and approximately 80 organizations.

The objectives of the experiment included —

- Establishment of a global network of GLONASS tracking stations collocated with GPS stations.
- Precise orbit determination.
- Evaluation of GLONASS receivers.
- Development of GLONASS applications software.
- Definition of reference frame relationships between the GPS WGS 84 frame, the GLONASS PZ-90 frame, and the International Terrestrial Reference Frame (ITRF).
- Time and time transfer applications.

A workshop, co-sponsored by IGS, ION, and NASA, was held in Nashville, Tennessee, on 13–14 September for the presentation and discussion of IGEX-98 results. More than 80 people attended. A downloadable version of the International GLONASS Experiment IGEX-98 Proceedings is available on the IGS Central Bureau Information System website.

Although IGEX-98 officially ended in April 1999, the success of the experiment prompted almost half of the tracking stations to continue their data-collection efforts, while three organizations continued to produce precise orbits during the remainder of 1999.

Major Accomplishments

A globally distributed GLONASS tracking network was established for the first time. More than 60 GLONASS tracking stations and 30 satellite laser ranging (SLR) observatories participated in the campaign. Three commercial manufacturers and one university produced dual-frequency GLONASS receivers, which were operated and given their most thorough testing and evaluation as a result of IGEX-98. All these receivers were designed to track both GLONASS and GPS satellites simultaneously, in a variety of configurations.

Precise orbits were computed by 11 Analysis Centers using both the SLR and GLONASS receiver data, with resulting accuracies of 20–50 centimeters. A combined orbit was computed at the University of Technology, Vienna, from the individual solutions provided on a regular basis by a subset of the Analysis Centers (see the IGS 1999 Technical Reports, R. Weber and E. Fragner, on the IGEX Analysis). A number of different software packages that were designed for GPS observations were successfully modified to process GLONASS data and to compute precise orbits. A list of the Analysis Centers and their software (where known) is shown in Table 1. To accommodate the new GLONASS observations and orbits, the data and orbit exchange formats (RINEX and SP3) were expanded for the experiment.

The availability of independently computed orbits derived from the laser observations provided a measure of truth for orbit evaluations. Orbits computed from the SLR data by the United Kingdom SLR Facility (NERC), for example, had post-fit residual RMS values of about 6–10 centimeters. The University of Texas Center for Space Research (CSR) similarly computed RMS values of 3 centimeters for SLR normal point residuals over the campaign, although there was considerable week-to-week variation. The CSR noted RMS orbit differences in the radial, along-track, and cross-track directions of approximately 10 centimeters, 40 centimeters, and 45 centimeters when comparing their laser-based orbits with the receiver-based orbits of the other Analysis Centers. Comparisons of the Australian Surveying and Land Information Group (AUSLIG) SLR orbits and the Center for Orbit Determination in Europe (CODE) precise orbits produced similar values — 14 centimeters, 75 centimeters, and 51 centimeters.

Table 1. Analysis Centers that Produced Precise GLONASS Orbits During IGEX-98

Analysis Center	Software	Data Type
Bundesamt für Kartographie und Geodäsie (BKG)	Bernese	Phase
Center for Orbit Determination in Europe (CODE)	Bernese	Phase
European Space Agency/European Space Operations Center (ESA/ESOC)	BAHN	Phase/Code
GeoForschungsZentrum (GFZ)	EPOS.P	Phase
Jet Propulsion Laboratory (JPL)	GIPSY/OASIS	Phase/Code
University of Olsztyn, Poland	TOP	Phase/Code
University of Texas, Center for Space Research (CSR)	GIPSY/OASIS; UTOPIA	Phase; SLR
Australian Surveying and Land Information Group (AUSLIG)	MICROCOSM	SLR
United Kingdom SLR Facility (NERC)	SATAN	SLR
Russian Mission Control Center (MCC)/GEO-ZUP	—	SLR
University of Technology, Vienna	—	Combined

A new pilot project was initiated following the IGEX Workshop.

The availability of precise GLONASS orbits in the ITRF reference frame provided the means for several of the groups to compute transformations between the Russian PZ-90 reference frame and ITRF. CODE, BKG, and JPL all computed 7-parameter transformations between the broadcast PZ-90 orbits and their respective precise ITRF orbits. All found the rotation about the z-axis to be the most significant parameter. BKG also noted a time-dependence to the transformation parameters for x-, y-, and z-rotations and y-translation. An extensive study done by GEO-ZUP and the Mission Control Center in Russia shows this time dependence with longer term fluctuations that exceed one year, and attributes this to the way Earth orientation parameters are introduced into the operations GLONASS orbit-determination process by the GLONASS System Control Center (SCC). The GEO-ZUP work is based on comparisons of laser-based orbits with averaged post-processed GLONASS SCC ephemeris data and with broadcast orbits. The reported results show z-translation and z-rotation to be the most significant.

International GLONASS Service Pilot Project (IGLOS-PP)

After the IGEX Workshop, owing to the continued interest of the IGEX participants, a new pilot project was initiated under the auspices of the IGS. A charter was prepared by the Project Committee and approved provisionally by the IGS

Governing Board in December 1999. The general intent of the service is to facilitate the use of combined GLONASS and GPS observations for scientific and engineering applications, and to allow users to combine the systems as a prototype Global Navigation Satellite System (GNSS).

A Call for Participation will be issued in 2000 to enlist the participation of stations, Analysis Centers, and Data Centers. The plan calls for a pilot service to operate for a period of up to four years from 2000–2003. Every six months an assessment will be made as to the viability of the GLONASS constellation and whether or not the pilot service should be continued. For more details on this, see the IGS 1999 Technical Reports and International GLONASS Experiment IGEX-98 Proceedings.

Low-Earth Orbiters and the IGS

Michael Watkins

Jet Propulsion Laboratory, California Institute of Technology, USA

A Perspective of the IGS and LEO Missions

The IGS was extremely successful in organizing the resources of the international GPS community in the development of GPS science and applications. The pooling of resources led to an extremely efficient and rapid development of the IGS global network, the development of support centers for analysis and data archiving, and the rapid advancement of GPS science and applications. This was done because of the open nature of collaboration while maintaining friendly and supportive competition among the participants in the IGS. The development of a space network of orbiting GPS receivers is envisioned as an extension of the ground network while utilizing many of the resources that the IGS currently has in place.

It is clear that the IGS ground network will be an element for most uses of space-based GPS applications. Furthermore, several participants in the IGS are also key players in the development of space-based GPS applications. The IGS can then play a de facto key role. The stage is set for a significant role in the development of space-based GPS receiver applications. With the development of a significant role in the arena of orbiting space receivers, the IGS will serve the broader geoscience community as well as potentially provide services for commercial interests.

The operation of a space network of GPS receivers in service to the broader geoscience community will place special requirements upon the acquisition and distribution of data from the ground network, new requirements on the Analysis Centers, expanded capacity for the archiving centers (or creation of new ones), and a broader representation of scientific disciplines and agencies on the IGS Governing Board. These are the kind of questions being raised and issues being discussed within the IGS .

LEO Workshop

Owing to these IGS–LEO synergies, and as noted by Prof. Christoph Reigber, discussions within the IGS and within the mission agencies resulted in the consensus to convene a 3-day workshop devoted to LEOs in March. The obvious opportunities signal the next enhancement of successful international cooperation for multipurpose GPS applications. The main workshop goal was therefore to bring together these interested principals and attempt to derive plausible multimission support plans and roles — a starting point for the next decade.

The first day was devoted to goals of the workshop, mission overviews (future missions and mission overlap), science goals and objectives, and a requirements panel discussion.

The second day focused on the technical and engineering aspects and requirements such as the network systems, the flight data systems, integration of data and communications, and other mission support tasks and issues, and concluded with a discussion session.

The final day of the workshop was devoted to science applications and the user community, incorporating a range of participants from the varied science applications as well as the potential benefits to the orbit products. Products, external user access, interfaces and archives were discussed.

Following the workshop, on 12 March 1999, the LEO Working Group met to discuss plans and actions for the coming year. The meeting was open to interested people and was well attended. The group identified four key recommendations for proceeding:

- The standards for ground stations in the LEO subnetwork should be established and distributed. This is one of the true strengths of the IGS, setting an international standard and encouraging adherence.
- The IGS Analysis Centers should develop a new ultrarapid analysis product (orbit, clock, EOP, and predictions) with a latency of less than 3 hours. This was demonstrated through voluntary participation in a pilot project initiated in the summer. As reflected in the 1999 reports of the Analysis Center Coordinator, the IGS has moved quickly to realize this objective (in this Annual Report and the IGS 1999 Technical Reports, Section 7, Analysis Center Work-

The IGS will play an important role in the development of a network of orbiting GPS receivers.

shop). This is important because many growing applications of GPS data, both ground and flight, require analysis product latencies or prediction accuracies that could not be met with the "classic" 24-hour daily batch processing paradigm. Even now it is noted that several existing networks already provide data with near global coverage and less than 1-hour latency (see Carey Noll's report in this Annual Report).

- A new, efficient format should be developed for the 1-Hz ground data. Since the expected "high-rate" (1-Hz) data volume exceeds that of the standard IGS data product by a factor of 30, consideration should be given as to how to manage the data.
- A 3- to 6-month Pilot Project should be organized to use the GPS flight data from one of the upcoming flight missions for purposes of precise orbit determination of the LEO. This should include evaluating the effect on the IGS analysis products. Such a Pilot Project would require a comprehensive Call for Participation as many interfaces would be affected, and this is viewed as a key step for moving the IGS into the next decade.

Summary

By the end of 1999, the primary LEO science missions (CHAMP and SAC-C) experienced additional schedule changes resulting in successful launches in 2000. Late in 1999, and in anticipation of the future launches, the IGS developed a "Call for Participation in Support of Low-Earth Orbiting Missions" (see the following website: *http://igscb.jpl.nasa.gov/projects/leocfp.html*). More than 26 responses were received in early 2000, which indicates the great interest and planned participation in this project. The next few years hold much promise for this exciting area of LEO GPS applications.

Bibliography

Altamimi, Z., 1998, "IGS Reference Stations Classification Based on ITRF96 Residual Analysis," in J. M. Dow, J. Kouba, and T. Springer (editors), Proceedings of the IGS 1998 Analysis Center Workshop, Darmstadt, Germany, 9–11 February 1998.

Altamimi, Z., C. Boucher, and P. Sillard, 1999, "ITRF97 and Quality of IGS Reference Stations," Proceedings of the IGS 1999 Analysis Center Workshop, Scripps Institution of Oceanography, La Jolla, California, USA, 8–11 June 1999,

Boucher, C., Z. Altamimi, and P. Sillard, 1999, "The 1997 International Terrestrial Reference Frame (ITRF97)," IERS Technical Note 27, Observatoire de Paris, France.

Carrodeguas, J. and M. Gerard, editors, "Report of an AIAA, UN/OOSA,CEAS, CASI Workshop, April 1999, International Space Cooperation: Solving Global Problems," American Institute of Aeronautics and Astronautics, Reston, Virginia, 1999.

Feltens, J., 1999, "IGS Products for the Ionosphere — One Year of Iono_WG Activities," Proceedings of the 1999 IGS Analysis Center Workshop, Scripps Institution of Oceanography, La Jolla, California, 8–10 June 1999. See Section 7, IGS 1999 Technical Reports, Jet Propulsion Laboratory, California Institute of Technology, November 2000.

Feltens, J. and C. Noll (1999): "GPS Data Collected During August 1999 Solar Eclipse," CDDIS Bulletin, October issue.

Feltens, J. and S. Schaer, 2000, "1999 IGS Activities in the Area of the Ionosphere," IGS 1999 Technical Reports, IGS Central Bureau, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, November 2000.

Heroux, P., 1999, "NRCan Global Ionospheric Grid," Proceedings of the 1999 IGS Analysis Center Workshop, Scripps Institution of Oceanography, La Jolla, California, 8–10 June 1999. See Section 7, IGS 1999 Technical Reports, Jet Propulsion Laboratory, California Institute of Technology, November 2000.

Jakowski, N., S. Schlueter, S. Heise, and J. Feltens, 1999a, "Satellite Technology Glimpses Ionospheric Response to Solar Eclipse," EOS, Transactions, American Geophysical Union, Vol. 80, No. 51, 21 December 1999, pp. 621 ff.

Jakowski, N., S. Schlueter, S. Heise, and J. Feltens, 1999b, "Auswirkungen der Sonnenfinsternis vom 11. August 1999 auf die Ionosphaere," Allgemeine Vermessungs-Nachrichten (AVN), 11-12/1999, Wichmann Verlag, pp. 370-373.

Journal of Atmospheric and Solar-Terrestrial Physics (JASTP), Vol. 61, No. 16, November 1999 (special issue).

Schaer, S., W. Gurtner, and J. Feltens, 1997, "IONEX: The IONosphere Map EXchange Format Version 1," 25 February 1998, Proceedings of the 1998 IGS Analysis Centers Workshop, ESA/European Space Operations Centre, Darmstadt,Germany, 9–11 February 1998, pp. 233-247.

Slater, J., C. Noll, and K. Gowey, editors, Proceedings, International GLONASS Experiment, IGEX-98, IGS Workshop, 13–14 September 1999, Nashville, Tennessee, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, April 2000.

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

Proceedings of the International GLONASS Experiment (IGEX-98) Workshop, 13–14 September 1999, Nashville, Tennessee, USA, J. A. Slater, C. Noll,and K. Gowey, editors, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California.

Proceedings of the 1998 IGS Network Systems Workshop, 2–5 November 1998, Annapolis, Maryland, C. Noll, K. Gowey, and R. E. Neilan, editors, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, JPL Publication 99-10.

Proceedings of the 1998 Analysis Center Workshop, 9–11 February 1998, J. M. Dow, J. Kouba, and T. Springer, editors, European Space Agency/European Space Operations Center, Darmstadt, Germany.

Proceedings of the 1997 Workshop on Methods for Monitoring Sea Level, 17–18 March 1997, R. E. Neilan, P. A. Van Scoy, and P. L. Woodworth, editors, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, JPL Publication 97-17.

Proceedings of the 1996 IGS Analysis Center Workshop, 19–21 March 1996, Silver Spring, Maryland, R. E. Neilan, P. Van Scoy, and J. F. Zumberge, editors, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, JPL Publication 96-23.

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

Proceedings of the Workshop on 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, JPL Publication 95-11.

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

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

IGS ANNUAL REPORTS

IGS 1998 Annual Report (JPL 400-839) and 1998 Technical Reports (JPL Publication 00-002), IGS Central Bureau, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California.

IGS 1997 Annual Report, IGS Central Bureau, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, JPL 400-786.

IGS 1997 Technical Reports, I. Mueller, R. Neilan, and K. Gowey, editors, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, JPL Publication 99-10.

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.

IGS 1994 Annual Report, J. F. Zumberge, R. Liu, and R. E. Neilan, editors, Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, JPL Publication 95-18.

The directors of the Central Bureau of the International GPS Service, Ruth Neilan (Director, left) and Angelyn Moore (Deputy, right) beside a historical marker paying respects to Professor Helmert. Helmert is noted for many achievements, including the Helmert 7-parameter transformation, which is quite relevant to the IGS. The photo was taken at GeoForschungsZentrum–Telegrafenberg, Potsdam, Germany in March 1999.

Translation of the Inscription:

To the founder of mathematical and physical theories
of modern geodesy
Prof. Dr. Friedrich Robert Helmert
31 July, 1843 Freiberg
15 June, 1917 Potsdam
Director of the Geodetic Institute Potsdam 1886–1917
President of the International Geodetic Association*
Full Member of the Berlin Academy of Sciences
Professor at the University of Berlin

* *The Internationalen Erdmessung was the precursor to today's International Association of Geodesy.*

International GPS Service

International Association
of Geodesy
International Union of Geodesy
and Geophysics

Federation of Astronomical
and Geophysical Data
Services

National Aeronautics and
Space Administration

Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

JPL 400-978 07/01