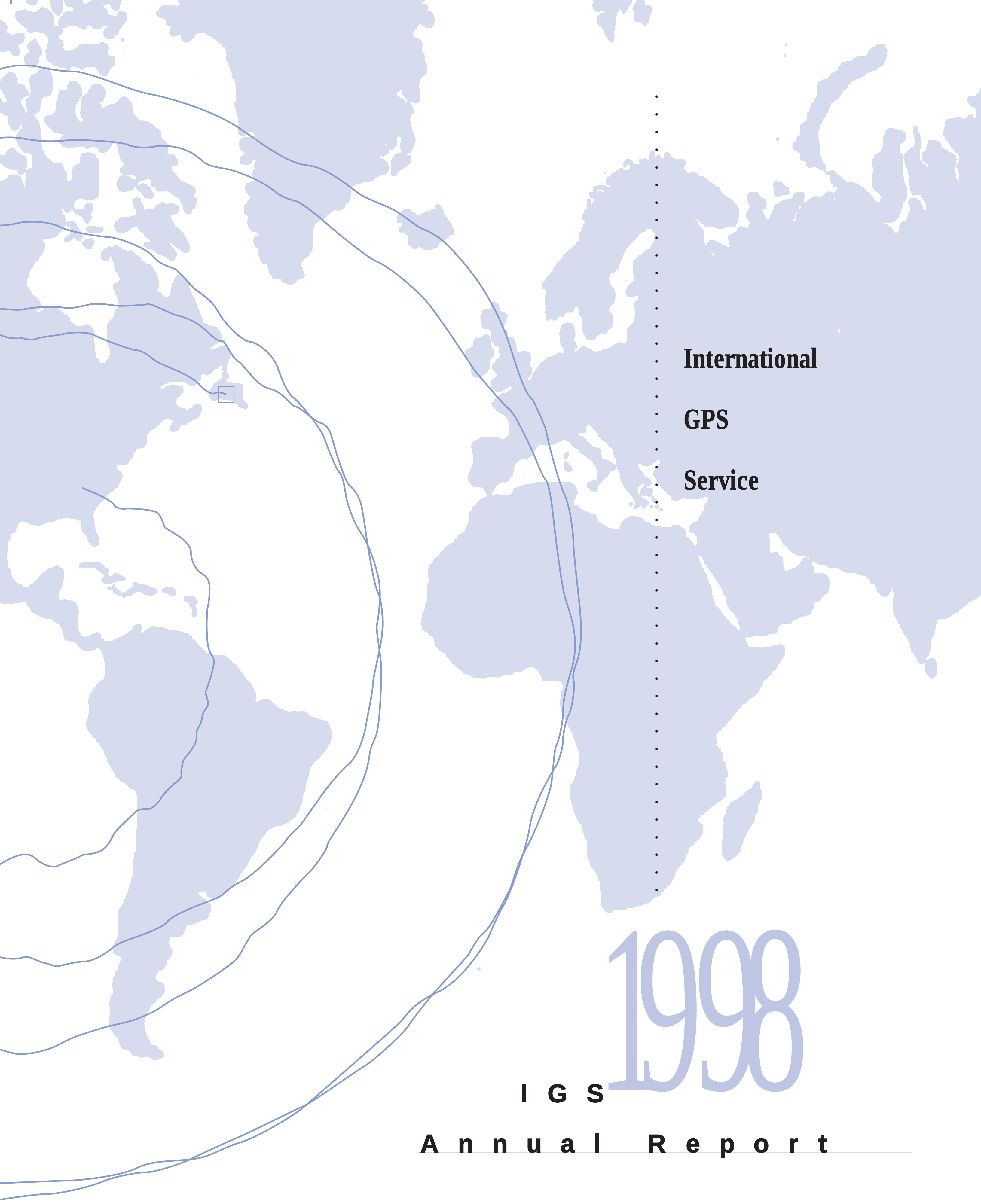

International GPS Service

IGS 1998

Annual Report

Introduction

IGS ANNUAL REPORT

Christoph Reigber

Chair, IGS Governing Board, 1999

GeoForschungsZentrum, Potsdam, Germany

In current discourse regarding scientific services in the geodetic and geophysical communities, one service is preeminent — the International GPS Service (IGS). This service started in 1992 with a pilot project in a multination, multiagency effort to improve the Global Positioning System (GPS) orbit quality, GPS ground station positions and velocities, and Earth-orientation information. IGS has become so successful in this short time span of seven years that it now serves as a model for the creation or renewal of other services within the International Association of Geodesy (IAG). In addition to the efficient GPS technology used and the truly active engagement of so many institutions worldwide in the operation of the service, a number of significant factors have been crucial to the IGS success story. Fundamental are the clear organizational structure and task description of the service as laid down in the Terms of Reference. Continuous efforts have been made to improve the service's functions and products by establishing and running pilot projects and working groups. To a very large extent, the IGS success has benefited from the strong leadership, high scientific competence, farsighted consideration of new developments, and tireless activities devoted to the service by the past chair of the Governing Board, Gerhard Beutler; the past Analysis Center Coordinator, Jan Kouba; the director of the Central Bureau, Ruth Neilan; and their staffs.

From my perspective as the new chair of the Governing Board, the model bequeathed by my predecessor and the resulting IGS achievements imply a strong obligation to devote a considerable amount of time to ensure a successful continuation of the functions and duties of the service. Yet simultaneously, even more time and reflection may be required to meet the challenges the IGS may encounter and to take advantage of new opportunities. We are presently on the threshold of an era of transformative and intensive use of ground- and space-based GPS observation and information systems in the pursuit of resolution of certain fundamental problems — in studies of global and regional dynamics of Earth and global climate processes, in numerical weather forecasting, and in the emerging field of space weather monitoring. The continuous densification and upgrade of the GPS network; the explosive expansion of dense regional networks; and the schedule of forthcoming low-Earth orbiting (LEO) missions with GPS precision orbit determination, limb sounding, and surface reflection instrumentation on board indicate that at the beginning of the millennium, adequate ground-observing systems and as many as five LEO missions will be usable for wide applications in geodesy, geodynamics, and in the atmospheric and ionospheric sciences.

Possibilities for improvements of IGS products or services should be observed closely and investigated thoroughly. Besides the already existing opportunity of adding observations from the Russian Global Navigation Satellite System (GLONASS) to the GPS data analysis, the further development of GPS with Block IIF satellites will add new frequencies and additional observables from 2003 at the latest, enabling the IGS to improve the quality of its products and to shorten the time for product generation and distribution. Another opportunity to improve the IGS products in the midterm could be the development of the European satellite navigation system termed Galileo. When it is completed — expected for the 2007 time frame — another full constellation of navigation satellites on GPS-like orbits and with GPS/GLONASS–compatible signals will become available and could add a significant level of improvement in robustness and quality compared with today's solutions. It is important for the IGS to begin preparations now for the operational use of the new GPS ground- and space-based observing systems, to follow closely new developments, to identify new customer demands for IGS services and products, and to prepare to meet their requirements.

TENTH IGS GOVERNING BOARD MEETING, SAN FRANCISCO, 10 DECEMBER 1998

Left to right, front row: Angelyn Moore, Gerhard Beutler, Ruth Neilan, Christoph Reigber. Second row: Bjorn Engen, Mike Bevis, Yehuda Bock. Third row: Ivan Mueller, Carey Noll, Bill Melbourne. Fourth row: Jan Kouba, Geoff Blewitt, Claude Boucher. Fifth row: John Dow, Robert Serafin. Absent: John Manning.

Contributing Agencies of the IGS

Alfred Wegener Institute, Germany (AWI)

Astronomical Institute, University of Bern, Switzerland (AIUB)

Astronomical Latitude Observatory, Poland (ALO)

Australian Survey and Land Information Group, Australia (AUSLIG)

Bundesamt für Kartographie und Geodæsie, Germany (BKG)

Bundesamt für Landestopographie (Federal Topography), Switzerland (BfL)

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)

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)

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)

European Space Agency, Germany (ESA)
European Space Operations Center, Germany (ESOC)

Finnish Geodetic Institute, Finland (FGI)

FOMI Satellite Geodetic Observatory, Hungary (FOMI)

Geodetic Observatory Pecny, Czech Republic (GOPE)

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 (ISRO)

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 Geological and Nuclear Sciences, New Zealand (IGNS)

Instituto Brasileiro de Geografia de Estatistica, Brazil (IBGE)

Instituto Nacional de Pesquisas Espaciais, Brazil (INPE)

International Deployment of Accelerometers/ Incorporated Research Institutions for Seismology (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)

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, USA (NCAR)

National Geophysical Research Institute, Hyderabad, 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 (NRCan)

Observatoire Royal de Belgium (ROB)

Olsztyn University of Agriculture and Technology, Poland (OUAT)

Onsala Space Observatory, Sweden (OSO)

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

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

Proudman Oceanographic Laboratory, UK (POL)

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

Royal Greenwich Observatory, UK (RGO)

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

Scripps Institution of Oceanography, USA (SIO)

Shanghai Astronomical Observatory, China (SAO)

Southern California Integrated GPS Network, USA (SCIGN)

Statens Kartverk, Norwegian Mapping Authority, Norway (SK)

United States Naval Observatory, USA (USNO)

University Consortium for Atmospheric Research (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 Newcastle on Tyne, United Kingdom (NCL)

University of Padova, Italy (UPAD)

Warsaw University of Technology, Poland (WUT)

Western Pacific Integrated Network of GPS, Japan (WING)

Wuhan Technical University, China (WTU)

Governing Board

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

Former Members	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

* Members' current term is four years.

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

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

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1998

The IGS in 1998— An Executive Summary

Gerhard Beutler

Astronomical Institute, University of Bern, Switzerland

Past Chair, IGS Governing Board

A Year of Tradition and Transition

The International GPS Service (IGS), which supports geodetic and geophysical research activities, truly provides a service to its users. The access statistics of the IGS Data Centers prove that the IGS products are widely used by a heterogeneous and steadily growing community.

For the Governing Board, it is very encouraging to observe that, among many other groups, the European Reference Frame (EUREF) subcommission of the International Association of Geodesy (IAG) and the Sistema de Referencia Geocéntrico para América del Sur (SIRGAS) are working very independently and successfully with IGS products to establish and maintain regional reference frames in Europe and South America, respectively. There are indications that such examples will be followed in other parts of the world for the establishment of a global homogeneous reference frame.

It is thus fair to state that the IGS is a successful service. Its success is based on the timely availability, superb quality, reliability, and robustness of IGS products. The classic IGS products, GPS satellite orbits and clocks, Earth orientation parameters, and length of day, are available for every single day since 21 June 1992, the first day of the "1992 IGS Test Campaign."

As of 1 January 1999, IGS stands for International GPS Service, and no longer for International GPS Service for Geodynamics. This new understanding of our acronym indicates that the IGS network and its products are used more and more in other than geodetic or geodynamical disciplines of science, such as atmospheric sciences and accurate time and frequency transfer.

This expansion of the IGS does not mean, however, that the classical IGS contributions to space geodesy are viewed as less important by the Governing Board and the IGS components. The Analysis Coordinator's report proves that in 1998 the IGS Analysis Centers not only maintained, but again improved, the quality of these products. The year 1998 thus was a year of preserving the traditional characteristics of IGS products: timeliness, accuracy, reliability, and robustness.

For the IGS, the year 1998 was also a year of transition:

- On the Governing Board, Mike Bevis (University of Hawaii) and Robert Serafin (National Center for Atmospheric Research) replaced Bob Schutz (Center for Space Research) and Gerald L. Mader (National Oceanic and Atmospheric Administration/National Geodetic Survey) on 1 January 1998.

- For the position of Analysis Coordinator, Tim Springer (Astronomical Institute, University of Bern) succeeded Jan Kouba (Natural Resources Canada) on 1 January 1999.
- For the Chair of the IGS Governing Board, Christoph Reigber (GeoForschungsZentrum Potsdam) succeeded Gerhard Beutler (Astronomical Institute, University of Bern) on 1 January 1999.

Quite a few restructuring processes took place or were invoked within the IGS in 1998.

In a service, such transitions have to be planned carefully and performed in a way to avoid disturbances of operations. The Analysis Coordinator's report discusses the transition of IGS analysis coordination (this Annual Report); the last section of this report refers to the transition in the Chair of the Governing Board.

Apart from these transitions, quite a few restructuring processes took place or were invoked within the IGS in 1998. The following IGS components were considerably modified in 1998:

- The IGS Central Bureau was reorganized in response to recommendations of the 1997 IGS Retreat. In particular, we note that Angelyn Moore became Ruth Neilan's deputy as Director of the Central Bureau (for more information, see the Central Bureau and Network Coordinator's reports in this Annual Report).
- IGS working groups were set up and a new charter for IGS working groups and pilot projects was developed and accepted by the Board (see below).
- The IGS Governing Board invited the leaders of IGS pilot projects and working groups to become nonvoting members of the Governing Board.

These changes are essential for the future development of the IGS. They required a modification of the Terms of Reference by the end of 1998. The latest version of the Terms may be found on the IGS Web site on the Internet at <http://igscb.jpl.nasa.gov>.

IGS Events in 1998

The essential IGS-related events are summarized in Table 1. Two workshops took place in 1998: the 1998 Analysis Center Workshop (9–11 February in Darmstadt, Germany) and the 1998 Network Workshop (2–5 November in Annapolis, Maryland). Brief reports about both events may be found in IGS Mail messages nos. 1806 and 2086. The proceedings of both workshops are also available at the Web site or through the Central Bureau (see Appendix B, IGS Publications). It is remarkable that the proceedings of the Darmstadt workshop were available with a delay of only about three months. The 1998 IGS Workshops were very inspiring to the attendants and to the wider IGS community. Many improvements were initiated at these workshops (e.g., acceptance of a new IGS realization of the International Terrestrial Reference Frame [ITRF] at the Darmstadt workshop), and many plans were developed (e.g., creation of an IGS subnetwork with hourly data download at the Annapolis workshop).

In 1998 there were two official IGS Governing Board meetings (numbers 9 and 10) and two business meetings (attached to the Darmstadt workshop and to the IAG Section II Symposium in Munich).

The central issues of the 9th Governing Board Meeting in Boston were:

- Definition of action items emerging from the 1997 IGS retreat.

Table 1. Important IGS-Related Events in 1998

9 February 98	1998 IGS Analysis Center Workshop
12 February 98	Business meeting of the Governing Board
28 May 98	9th IGS Governing Board Meeting in Boston
16 July 98	Committee for Space Research (COSPAR) Symposium with interdisciplinary lecture on IGS
4 October 98	Business Meeting of the Governing Board
5 October 98	Integrated Global Geodetic Observing System (IGGOS) Symposium in Munich
18 October 98	Start of IGEX-98, the first Global Navigation Satellite System (GLONASS) tracking and analysis experiment
2 November 98	IGS Network and Data Center Workshop in Annapolis, Maryland
6 December 98	10th IGS Governing Board Meeting in San Francisco

- Definition of the IGS policy for the establishment of IGS projects and working groups.
- The creation of the IGS Ionosphere Working Group with Joachim Feltens (European Space Agency/European Space Operations Center) as Chair.
- Status of the joint IGS/Bureau International des Poids et Mesures (BIPM) Precise Time and Time Transfer Project, co-chaired by Jim Ray (IGS) and Claudine Thomas (BIPM).

Many action items emerged from the discussion of the 1997 IGS retreat. It was clear that, among other changes, the IGS Terms of Reference would need to be revised. As always, Ivan I. Mueller, the Board's (and the geodetic world's) specialist on Terms of Reference, was responsible for coordinating and preparing these changes. It is quite an achievement that the new terms were accepted by the Board by the end of 1998.

The Board accepted the document "IGS policy for the Establishment of IGS Projects and Working Groups," which gives these IGS entities many more responsibilities and much more independence than in the past. Refer to IGS Mail message no. 1916 for more information concerning the 8th Governing Board Meeting.

The central issues of the 10th IGS Governing Board Meeting were:

- The IGS Densification Project and creation of an IGS Reference Frame Coordinating Center at the Geodetic Survey Division of Natural Resources Canada, with Remi Ferland as coordinator.
- Establishment of the IGS Troposphere Working Group with Gerd Gendt as Chair.
- Acceptance of the revised IGS Terms of Reference.

And, last but not least:

- Election of the new IGS Governing Board Chair.

The changes in the Terms of Reference were substantial and may be summarized as follows:

- The IGS Central Bureau is the executive arm of the IGS Governing Board.
- The IGS working groups and pilot projects are clearly defined.
- IGS working group and pilot project Chairs become nonvoting members of the IGS Governing Board.
- The method for becoming an IGS Analysis Center is defined.
- Review processes for essential IGS Components are defined.

Refer to IGS Mail message no. 2106 for more information concerning the 10th IGS Governing Board meeting.

The IGS Chair was invited to give a 1-hour interdisciplinary lecture on the topic “The IGS: An Interdisciplinary Service in Support of Earth and Atmosphere Sciences.” The associated article (Beutler et al., 1999) made the authors, and hopefully the readers of the article, aware of all the fascinating aspects of the IGS and of all the science that it enables.

The IGS Governing Board has recognized that GPS is not the only “game in town” — to be more precise, not the only microwave satellite system of interest for high-accuracy applications. The French Doppler Orbitography and Radio-positioning Integrated by Satellite (DORIS), the German Precise Range and Range Rate Equipment (PRARE), and the Russian GLONASS have to be considered as well. As a matter of fact, the Russian GLONASS is such a close relative of GPS that it was only natural for the IGS to contribute in a significant way to the International GLONASS Experiment 1998 (IGEX-98), the first global tracking and analysis experiment for GLONASS. The experiment was led by CSTG — International Coordination of Space Techniques for Geodesy and Geodynamics, a joint endeavor of Commission VIII of IAG and Subcommission B2 of COSPAR — with Pascal Willis of Institut Géographique National, France, as Chair, and set up in close cooperation with the IGS, the Institute of Navigation (ION), and the International Earth Rotation Service (IERS). The IGS Governing Board views the IGEX-98 as an IGS pilot project. IGEX was made possible by the network and data center infrastructure of the IGS.

It will be interesting to observe how the relationship between the IGS and the IGEX-98 develops in 1999. The next milestone will be the IGEX Workshop in Nashville in September 1999. The IGEX mail server has detailed information at <http://lareg.ensg.ign.fr>, or refer to the Institute of Navigation Web site at <http://www.ion.org/workgroup.html>.

Transition of Governing Board Chair

The nomination procedure for the new IGS Chair was invoked in fall 1998. The search generated a short list of very valuable candidates. An open and frank discussion at the 10th Governing Board meeting on 6 December 1998 in San Francisco, including all candidates and all IGS Governing Board Members, revealed that Prof. Christoph Reigber from the GeoForschungsZentrum (GFZ), Potsdam, Germany, would be the ideal candidate, in particular in view of GFZ’s long-term contributions to the IGS and deep involvement in upcoming low-Earth orbiter (LEO) space missions:

Challenging Mini-Satellite Payload for Geophysical Research and Application (CHAMP), Gravity Recovery and Climate Experiment (GRACE), and Gravity Field and Ocean Current Explorer (GOCE).

In consideration of these facts, it is not surprising that Prof. Christoph Reigber from GFZ in Potsdam was unanimously elected as the new Chairman of the IGS Governing Board for 1999–2002.

Let me conclude this summary with a few personal comments. I was elected Chair of the IGS Campaign Oversight Committee (1991–1993) and eventually became the first Chairperson of the IGS Governing Board (1993–1998). I am proud to have contributed to the development of the IGS, and in particular, it was an honor for me to have served as Chair of two IGS governing bodies.

ACKNOWLEDGMENTS

I would like to thank my colleagues from the Governing Board and all my friends from all IGS components for their help and gentle guidance. I hope, and I am truly convinced, that our new Chair, Christoph Reigber, will develop the same deep affection for these colleagues and find as much satisfaction in his challenging new position as I did. Good luck!

Central Bureau Report 1998

Ruth E. Neilan

Jet Propulsion Laboratory, California Institute of Technology, USA

Director, IGS Central Bureau

A Season of Change and Opportunity

The year 1998 was a year of significant change within the structure of the IGS that was accommodated with little impact to the levels of service provided by the organization. As noted by Prof. Beutler above, the official name of the IGS has been changed, new Terms of Reference were adopted in December 1998, the IGS Analysis Coordination shifted from Natural Resources Canada under the direction of Dr. Jan Kouba to the University of Bern, Switzerland under Dr. Tim Springer. Policies were adopted to incorporate working groups and pilot projects into the IGS, and the heads of these groups have been added to the IGS Governing Board.

This year also marks the end of Gerhard Beutler's term of office as the Chairman of the IGS Governing Board. He is succeeded by Prof. Christoph Reigber, who became the new chair by acclamation of the Board in December.

Change spread quickly to the Central Bureau as we implemented a considerable reorganization. This was in part a response to the recommendations stemming from the Napa Valley Retreat of December 1997:

- "that at least two persons should be given full-time responsibility within the Central Bureau. One of these should be the Director, the other may be the Network Coordinator," and
- that "the IGS Global Network needs overall enhancement."

These recommendations set the direction of change at the Central Bureau throughout 1998 by underscoring the necessity of a more defined Central Bureau and staff to manage varied aspects of the service with increased emphasis on the rapidly expanding GPS tracking network and extensive IGS infrastructure. A summary report on the Napa Valley Retreat and final recommendations for all IGS components can be found in the IGS 1997 Technical Reports.

A very positive outcome of internal restructuring at the Jet Propulsion Laboratory was the ability to create within the Central Bureau the new position of Deputy Director/Network Coordinator for the IGS. Dr. Angelyn Moore was appointed to this position in October and is actively engaging with the IGS components, particularly the Infrastructure Committee and the Analysis Coordinator, to address critical issues of the network system. Responsibilities of a Network Coordinator or "Network Engineer" have been discussed since the inception of the IGS, and it is refreshing to see this role and position finally realized (the report from the IGS Network Coordinator follows). Nonetheless, the Central Bureau sustained significant changeovers in personnel and positions due to the reorganization, which were professionally and personally challenging (see IGS 1998 Technical Reports).

The increasing focus on network issues throughout 1997 similarly resulted in a further recommendation from the Napa retreat stating "the Governing Board should consider organizing an IGS Network Workshop to have an open discussion on network/station issues and to develop a direct interaction between the Governing Board and the stations, upon which rest all IGS activities."

The Central Bureau organized a meeting in April in order to initiate planning for this workshop. Carey Noll, the manager of the Crustal Dynamics Data Information System (CDDIS) IGS Global Data Center at NASA Goddard Space Flight Center, proposed to host the workshop, and the meeting was jointly convened between the Central Bureau and the CDDIS. All who attended the Network Workshop in Annapolis in November 1998 considered it a great success. Both the technical content and the social atmosphere contributed to a refocusing on critical infrastructure issues and a strengthening of the IGS network community. This workshop generated additional recommendations and actions to be approved by the Governing Board in 1999. Proceedings from this workshop are currently on the Central Bureau Information System at the Web site <http://igscb.jpl.nasa.gov> and available from the Central Bureau.

Future Directions and Influences

GPS users and applications strongly influence the directions of the IGS, and one of the most visible impacts will certainly be the IGS response in support of low-Earth Orbiter (LEO) missions beginning in 1999 and spanning at least the next decade. Requirements of over a dozen missions, each carrying GPS onboard flight receiver(s), necessitate near-real-time GPS data and IGS products to generate various additional products in support of mission objectives. A key mission objective for a number of the missions, such as the Challenging Mini-Satellite Payload for Geophysical Research and Application (CHAMP), Argentina's Satélite de Aplicaciones Científicas (SAC-C), the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC), etc., are radio-occultation measurements (Melbourne et al., 1994) derived from GPS that are tailored nominally every 3 hours for use as input observations to numerical weather models and forecasting. This demands that IGS take a major evolutionary leap this year as the entire system moves toward subdaily network operations and analysis processes. Since its inception, the IGS has been operating on a system of daily data files and daily production of orbits. It is envisioned that data and orbit products will be available within hours as we collectively upgrade the IGS. There are a number of applications and projects that will benefit greatly from this stepping up of IGS.

The next decade will also see modernization of the GPS satellite system, solidifying its realization and recognition as a truly dual-use system employed worldwide for many applications, some yet to be imagined. Civil users will benefit from the implementation of a C/A code on the L2 frequency by 2003, and future Block IIF GPS satellites will implement a third civil frequency at 1176 MHz by 2005, according to current plans (Divis, 1999b). Recommendations were recently made by the European Commission to develop and implement a Global Navigation Satellite System (GNSS) called Galileo, which may be both complementary and competitive with the GPS. Utilizing the space segments to their fullest will require additional considerations by the IGS in the future (Divis, 1999a). A demonstration of the extensibility and flexibility of the IGS was the successful international Global Navigation Satellite System (GLONASS) tracking experiment — the International GLONASS Experiment (IGEX) (see the IGEX-98 report by Pascal Willis and Jim Slater, this Annual Report).

In summary, the future appears full of potential to take advantage of new technologies by building on the very solid foundation of the IGS and the international community of participants.

Central Bureau Activities in 1998

The Central Bureau is responsible for the overall coordination and management of the IGS service, and, as stated in the Terms of Reference adopted in December 1998, is the executive arm of the IGS Governing Board. The Central Bureau is located at the Jet Propulsion Laboratory, which is operated for the National Aeronautics and Space Administration (NASA) by the California Institute of Technology. The International Governing Board is the oversight body that actively makes decisions that determine the activities and directions of the IGS.

The Central Bureau Information System was completely redesigned and implemented in September 1998. This was one of the first sites on the World Wide Web designed in 1993 by Werner Gurtner from the University of Bern, Switzerland. The new system was declared operational and presented at the Network Systems workshop in November. The responses to date have been very positive, and it is proving to be a valuable resource for IGS users and information seekers. Plans are progressing to have a full active backup of the system and better mirroring of the site at other global locations to increase the ease of access by users on different continents.

The IGS Annual Report Series in 1997 is also considered a successful change. The revised format was proposed in order to migrate to a two-volume series — the first is the IGS Annual Report with a very wide distribution (the first in the new, two-color format was the 1997 Annual Report), and the second, an in-depth technical report primarily of interest to internal IGS participants. Both are available on the CBIS.

In the latter part of 1998, the Central Bureau was actively involved in organizing the Low-Earth Orbiter workshop held March 1999 at GeoForschungsZentrum, Potsdam, Germany. The workshop was convened by Prof. Christoph Reigber, Dr. Bill Melbourne, and Prof. Gerhard Beutler (see the report by Mike Watkins, this Annual Report).

Activities and accomplishments of the Central Bureau within the area of the IGS network are included in the report of the Network Coordinator in this volume.

External Meeting Participation and Support During 1998

The Central Bureau participated in or supported the following meetings and workshops by representing the IGS through presentations, exhibits, or participation in working groups:

- Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) Science Workshop, Taipei, Taiwan (February).
- Newcastle Workshop on “GPS in the Middle East,” Newcastle, United Kingdom, (March).
- European Geophysical Society Annual Meeting, Nice, France (May).
- Asian Pacific Space Geodesy Project Meeting, Tahiti (May).
- IGS/Bureau International des Poids et Measures (BIPM) Meeting on Precise Time Transfer Joint Project, Paris, France (May).
- Meetings with Geographical Survey Institute and University of Tokyo, Japan (June).
- Meetings with Shanghai Observatory and Kunming Observatory, Chinese Academy of Sciences, China (June).
- Organizational support of the first IGS tutorial at the annual meeting of the “Working Group of European Geoscientists for the Establishment of Networks for Earth Science Research” (WEGENER), Honefoss, Norway (June).
- Sea Level in the Western Pacific Meeting, organized by the Permanent Service for Mean Sea Level, hosted by the Institute of Earth Sciences, Academia Sinica, Taipei, Taiwan (July).
- Western Pacific Geophysical Union Meeting, Taipei, Taiwan (July).
- Institute of Navigation, Nashville, Tennessee, USA (September)
- International Earth Rotation Service meeting, Potsdam, Germany (October).
- Towards an Integrated Global Geodetic Observing System, International Association of Geodesy, Section II Symposium, Munich, Germany (October).
- Precise Time and Time Interval Meeting participation, IGS/BIPM pilot project meeting, Reston, Virginia, USA (December).
- American Geophysical Union meeting, San Francisco California, USA (December).

Publications of the IGS Central Bureau in 1998

IGS 1997 Annual Report
IGS 1997 Technical Reports
IGS 1997 Directory
Resource Sheets

All IGS publications are available electronically at the CBIS at <http://igscb.jpl.nasa.gov/overview/pubs.html> or through the Central Bureau.

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Network Activities

The IGS global network of precise GPS tracking stations is critically depended upon by every other component of the IGS. A review of IGS Mail messages summarizing Governing Board meetings in late 1997 and 1998 shows that the Board and 1997 IGS Retreat attendees recognized that "the global IGS Network should be enhanced in the overall sense," and recommended that a Network Coordinator be appointed. By 28 September 1998, the IGS Central Bureau had created and filled a Deputy Director position, which also carries the Network Coordination duty.

Immediately it was clear that the need for network coordination was both real and challenging. On the one hand, analysts had issues, which were from their perspectives quite long-standing, such as inconsistencies in site parameters between those reported in stations' daily data file headers and those found in IGS logs of station configuration. Meanwhile, site operators produced requests for clarification of the guidelines under which their stations should be operated. Both items were exacerbated by the quick movement of the IGS into a wide array of multipurpose projects, increasing the complexity of site instrumentation and operation. It was apparent that these suggested a singular need for careful consideration of the network as a whole in view of analysis requirements as well as practical implementation matters.

The Network Workshop held in November 1998 was a productive gathering of participants representing all components of the IGS to discuss Network needs and functions. Recommendations and action items — available at the Central Bureau Information System at <http://igscb.jpl.nasa.gov> — which became early priorities for the Network Coordination task include:

- Functional classification of sites into application networks and generation of instrumentation and operation guidelines appropriate to the various applications.
- Moderation of a dialogue regarding station-naming guidelines, and the broader issue of the relationship of regional or alternate sites to the IGS Network.

- Quality control of information contained in site logs and data headers.
- Improvement of communication and sense of community in the Network component.

Activities to these ends by the end of 1998 included:

- Identification of the necessity of updating the IGS list of antenna and receiver-naming conventions to accommodate equipment newer than the existing list.
- Improvement of existing code identifying site log/Receiver-Independent Exchange (RINEX) header inconsistencies, and two rounds of e-mail to Operational Data Centers requesting correction. Good response eliminated most inconsistencies not due to use of equipment too new for the approved list.
- Procurement of a new computer to act as the Central Bureau Information System, which will allow more interactive functions and better communication to all IGS components.
- Preliminary formulation of recommendations for the relationship of regional arrays and alternate sites at established locations to the IGS.

The IGS tracking network itself (see Figure 1) continued to expand in 1998 with the addition of 14 new stations. Significantly adding to the global coverage of the IGS network are GOUG (Gough Island, South Atlantic), PETP (Petropavlosk–Kamchatka, Russian Federation), and TIXI (Tixi, Russian Federation), which are classified as IGS Global Stations (see Figure 2)

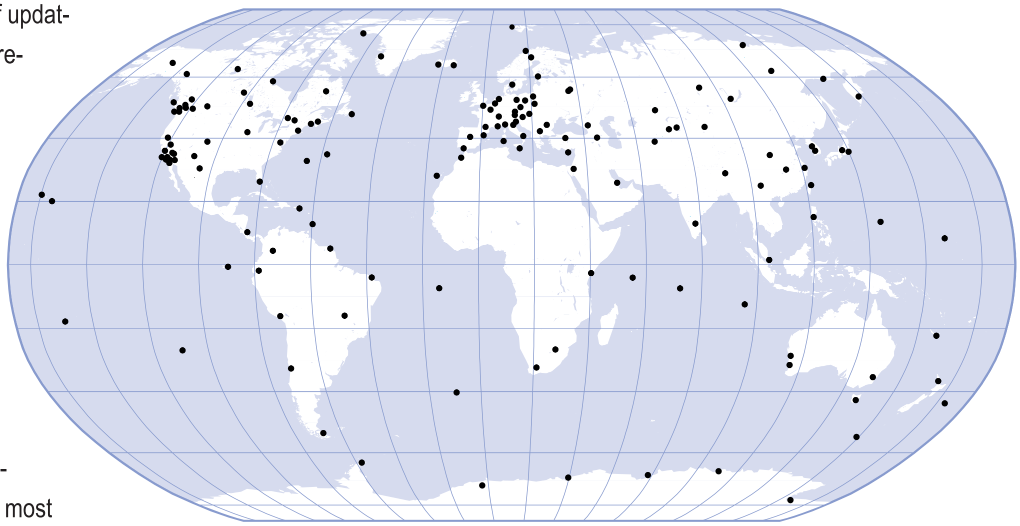

Figure 1. The IGS tracking network.

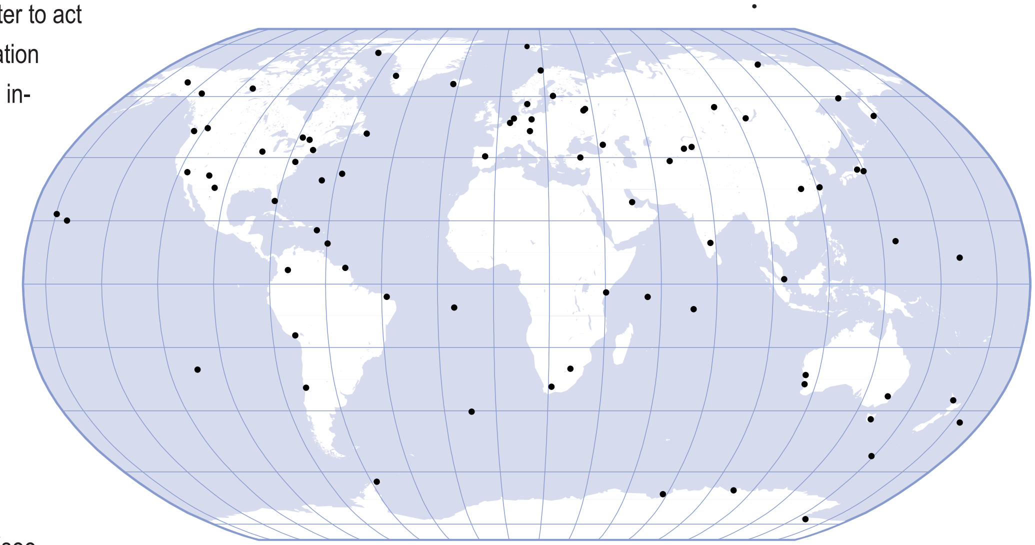

Figure 2. IGS global stations.

because they are regularly analyzed by three Analysis Centers on more than one continent.

Network coordination in 1999 will entail continuation of the previous years' activities as well as the others required to bring to fruition the recommendations of the 1998 Network Workshop. Doubtless, in a network consisting of approximately 200 sites and 75 agencies, new issues will emerge; the foundation laid by increasing the efforts expended on coordination in late 1998 and 1999 will allow the network to more flexibly adapt to future demands and applications.

analysis Activities

Jan Kouba

Geodetic Survey of Canada, Geomatics Canada, Natural Resources Canada

IGS Analysis Center Coordinator, 1996–1999

Analysis Center Research and Solution Improvement

During 1998, all IGS Analysis Centers continued their concentrated efforts in research as well as in maintaining and improving the solution precision, reliability, and timeliness. Most Analysis Centers have succeeded in improving or at least maintaining their solution precision and quality. This is clearly seen from Figure 1, showing the weighted orbit rms (WRMS) of the final Analysis Center solutions with respect to the IGS final orbit combinations during 1998. Several Analysis Center solutions are already approaching an unbelievable 3-centimeter orbit precision level! The figure is also indicative of the final IGS/Analysis Center GPS orbit accuracy as it is implied from the IGS quality control, i.e., 7-day arc orbit fitting and precise navigation positioning with fixed orbits and clocks, performed daily during the IGS final combinations of orbits, clocks, and Earth rotation parameters (ERPs). For more details, see the Analysis Coordinator Report (IGS 1998 Technical Reports).

This is further supported, subject only to a small yet unexplained scale bias, by comparisons with satellite laser ranging (SLR) observations to the GPS satellites PRN 5 and 6, both equipped with SLR reflectors (e.g., see Springer and Gurtner, 1998). Also shown in Figure 1 are the IGS rapid (IGR) combined orbits that were produced within a delay of 22 hours and often based only on a subset of station data available for the final orbit solutions. The significant improvement of the IGR precision is clearly seen after GPS Wk 0947 (1 March 1998), when a new and more precise International Terrestrial Reference Frame (ITRF) realization based on 47 ITRF96 station positions was introduced for IGR and all Analysis Center/IGS solutions. A similar quality and precision performance could also be observed for Analysis Center clock, ERP, and station coordinate solutions (see IGS 1998 Technical Reports for more details).

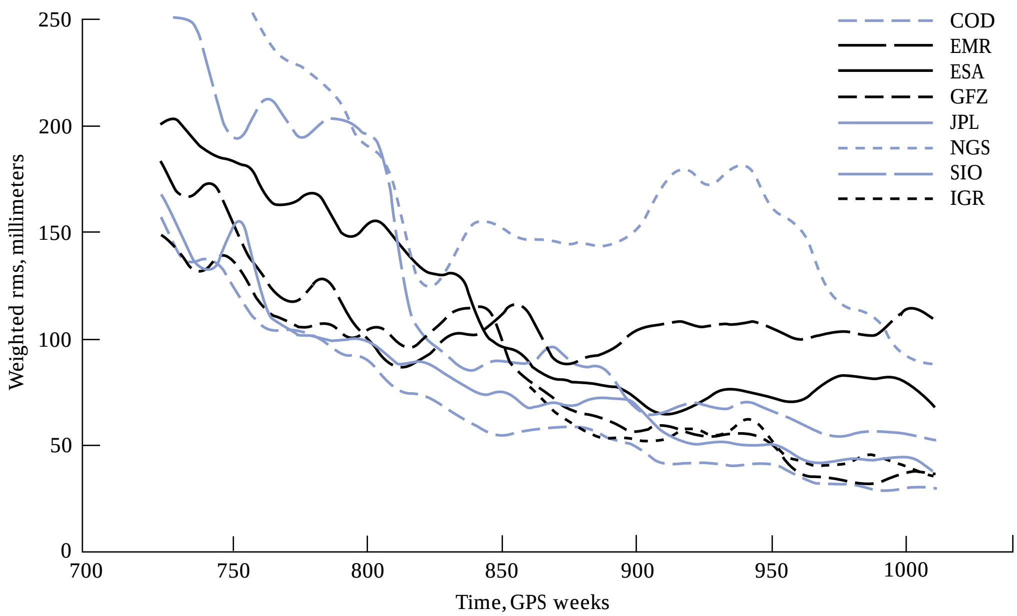

Figure 1. Individual final Analysis Center and IGS rapid orbit solutions compared to IGS final orbit combinations showing steady improvement since November 1993, GPS week 723. The year 1998 corresponds to GPS weeks 938 to 990.

During 1998, in addition to the satellite antenna offset problem, Analysis Center research concentrated again on the chronic weakness of GPS modeling, i.e., the radiation pressure effects on the GPS satellites. As recommended by the February 1998 Darmstadt Analysis Center Workshop, the latest radiation pressure models (Bar-Sever et al., 1998; Springer et al., 1999) from both the Jet Propulsion Laboratory (JPL) and Center for Orbit Determination in Europe (CODE) were made available to all Analysis Centers for testing. Subsequently, some Analysis Centers have implemented one of the two radiation pressure models. Furthermore, CODE, GeoForschungs-Zentrum Potsdam (GFZ), and JPL Analysis Centers, puzzled by the results and uncharacteristic behavior of the new PRN 13 (the first of the new Block IIR GPS satellites), investigated and tried to solve for the individual satellite antenna offsets. Despite the geometrically weak solutions, satellite antenna offsets of all satellites, except for the new PRN 13, have agreed with the nominal (Block II) satellite radial antenna offset within a few decimeters. Station and orbit global solutions were found to be quite insensitive to changes of satellite antenna offsets. However, the clock solutions fully reflected, or compensated for, different satellite antenna offsets used. The antenna offset solution of the new Block IIR, PRN 13 satellite tended to be close to 0 meter and it differed from the rest of the GPS satellites (as well as its nominal value) by almost 1.5 meters. The corresponding PRN 13 satellite clock solutions were offset from the clock solutions based on the nominal satellite antenna offset by almost 5 nanoseconds. This is why Analysis Centers have agreed to use a nominal (conventional) set of satellite antenna offsets for all Analysis Center and IGS clock solutions (see the following section on the IGS combined products).

1998 IGS Combined Products

The IGS final, combined solutions of orbits, clocks, ERP, and station positions de facto facilitate the IGS realization of ITRF. Figure 2 shows a polar motion plot from CODE (Beutler et al., 1999). The currently operational product combinations of orbits, clocks, and ERP are made available within 11 days for the final (IGS) products, within 22 hours (since December 1998, within 17 hours) for the IGS rapid (IGR) combinations and in real time for the IGS predicted (IGP) combinations. After July 1998, as recommended by the Darmstadt Analysis Center workshop and in preparation for the new IGS realization of ITRF (Kouba et al., 1998; see the report of the IGS Reference Coordinator in this Annual Report), all the Analysis Center orbit, clock, ERP, and station position final solutions are consistent and based on minimum (rotational) constraints only. Furthermore, at the same workshop it was recommended that all orbit solutions, including the marginal ones, be included in all the Analysis Center and IGS products with the correspondingly (low) orbit weights in the SP3 format header. This is why it is essential that all users of IGS orbit products take into account the IGS orbit weights included in the SP3 format headers.

Because the satellite clock solutions fully reflect the adopted (fixed) satellite (radial) antenna offsets, all Analysis Centers agreed, as a temporary measure until better values are obtained or determined, to adopt the following set of satellite offsets for all Analysis Center and IGS satellite clock solutions:

Block II & IIa
dx = 0.279 meter; dy = 0.000 meter;
dz = 1.023 meters

Block IIR
dx = 0.000 meter; dy = 0.000 meter;
dz = 0.000 meter

Note that the Analysis Centers are free to use any value of satellite antenna offsets they consider the best for their orbit solutions, as orbit solutions are largely insensitive to any change of satellite antenna offsets. Station coordinate solutions are also largely unaffected by differences in

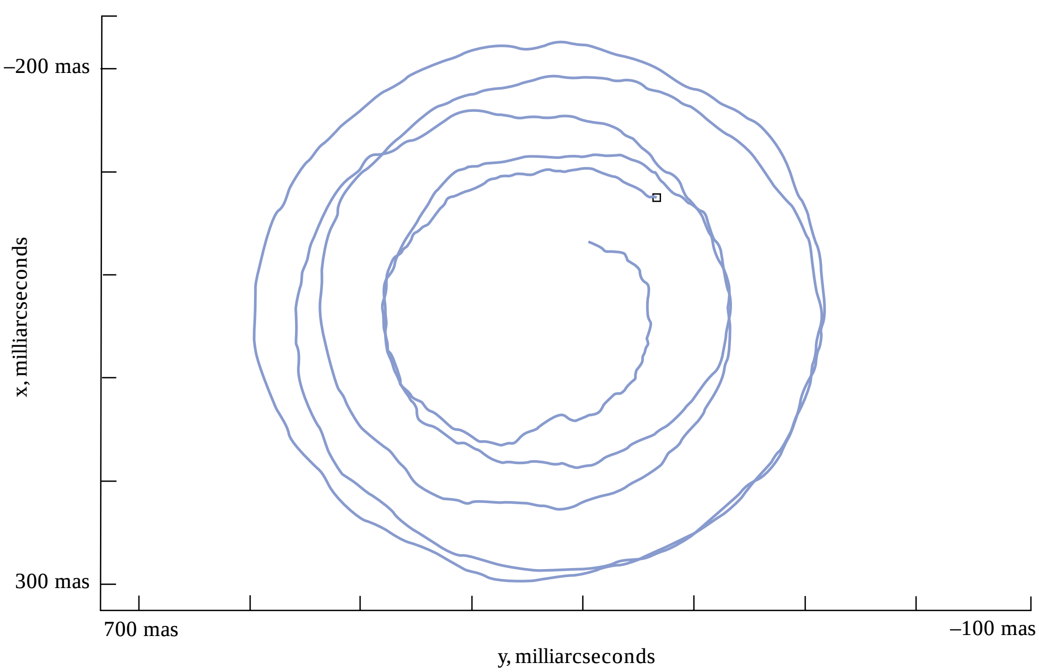

Figure 2.
Polar motion plot from June 1993 to June 1999, courtesy of CODE Analysis Center.

satellite antenna offsets (this is not the case for station antenna offsets that map directly into both station coordinate and clock solutions!). Additionally, the most demanding users of IGS clock solutions need to address the compatibility and consistency with the IGS clock solutions. Namely, all the IGS combined clock solutions (like the clock corrections broadcast in the navigation message) are corrected for the periodical relativistic correction:

$$-2(\mathbf{X} \cdot \mathbf{V})/c$$

where **X** and **V** are the inertial satellite state and velocity vectors and c is the speed of light. Also, no satellite L1/L2 (group) calibration delay should be applied when using IGS clock products. Furthermore, the IGS clock corrections are consistent with C1-P1 pseudorange, satellite-specific biases, which is a result of the observable type produced by the current (1999) receiver hardware that is used by the vast majority of stations of the IGS network. This observable type (bias) may have to be specifically formed for modern receivers in order to achieve the highest precision and consistency with the IGS combined clock products.

IGS ITRF Realization During 1998

Up to 28 February 1998 (GPS Wk 0946), all the IGS and Analysis Center solutions, and the IGS ITRF realization, were based on the ITRF94 positions and velocities of the same 13 stations that were also used for previous IGS ITRF realizations. Since Wk 0947 (1 March 1998), all the IGS products are nominally in ITRF96 and are based on up to 47 ITRF96 station positions and velocities (ftp://igscb.jpl.nasa/gov//igscb/station/coord/ITRF96_IGS_RS47.SNX.Z). Comparisons of the IGS final polar motion (PM) with independent PM series and analyses of the IGS orbit orientations (i.e., shifts of the daily mean positions at test stations Williams Lake, British Columbia (WILL), Brussels, Belgium (BRUS), and Usuda, Japan (USUD) indicated that the 1 March shift of the IGS final PM–y series is about half of the expected value of 0.2 milliarcsecond (IGS Mail message no. 2105). The remaining rotations (R2 = PM–x and R3), as well as the scale changes, were found to be in good agreement with the expected values, as estimated from the 13 ITRF94 and ITRF96 station positions (see IGS Mail message no. 1838). So, for the highest-accuracy applications — and in particular when one desires to remove the apparent discontinuities of the derived series involving the IGS final products (orbits, ERP) on 1 March 1998 — the transformation shown in Table 1 is recommended. For more information, see IGS Mail message no. 2105. For more information on the past IGS realizations of ITRF, including estimated transformations, see IGS Mail message no. 1838.

Analysis Center Coordinator Transition

Tim Springer of the CODE Analysis Center, University of Bern, Switzerland, has been appointed the new Analysis Center Coordinator of IGS beginning 1 January 1999. This significant change concluded the first five years of IGS Analysis Center coordination and successful generation of IGS combined products; it also necessitated a timely transfer of all IGS orbit/clock and ERP combinations from Natural Resources Canada (NRCan) to the CODE Analysis Center. The smooth and seamless transition occurred on 17 December 1998, well ahead of schedule. The ease of this transition is a tribute to the dedication of two IGS Analysis Center colleagues — Yves Mireault of NRCan and Tim Springer. Yves Mireault, who single-handedly was producing IGS combined orbits for most of the past five years, has prepared and documented the vast suite of

Table 1. (IGS(ITRF94)–IGS(ITRF96); epoch 1998.16 (1 March 1998, Wk 0947, MJD 50873): confirmed by independent ERP series and IGS final orbit precise point navigation (the transformation parameters are consistent with International Earth Rotation Service conventions).

	Translations			Scale	Rotations		
IGS Orbits/EOP	**T1(cm)**	**T2(cm)**	**T3(cm)**	**D(ppb) PM–y**	**R1(mas) PM–x**	**R2(mas) (–dUT)**	**R3(mas)**
Parameter	0.0	0.1	–0.1	0.4	0.10	0.01	0.22
Sigma	0.3	0.3	0.3	0.4	0.05	0.05	0.10
Rates per year	–0.02	0.09	–0.02	0.07	0.02	–0.001	–0.001
Sigma	0.06	0.06	0.06	0.09	0.03	0.02	0.03

EOP = Earth orientation parameter
cm = centimeter
ppb = parts per billion
mas = milliarcsecond
PM = polar motion
UT = Universal Time

combination software and scripts for this transfer. Tim Springer, who visited NRCan in the summer of 1998, has managed to transfer and implement the IGS combination system on CODE computer systems with significant help from Yves Mireault, who visited the CODE Analysis Center in October 1998. The author has also spent almost half a year as a visiting scientist at the Astronomical Institute of University, Bern/CODE, to aid this transfer process. This is a major achievement, which should not be overlooked due to its seamless implementation. Both colleagues should be congratulated for a job well done!

ACKNOWLEDGMENTS

In conclusion, a few parting words of thanks and appreciation are due to all Analysis Center colleagues for their help and cooperation. It was a great pleasure of mine to be associated with such a vigorous and friendly, yet competitive group. It only remains to thank you all and to wish you well for all the future challenges and surprises IGS may hold for you in the future years. Lastly, I wish for our new Coordinator, Tim, all the best. I hope that he and CODE Analysis Center find as much pleasure and rewards with the new duty as the author and NRCan did!

IGS Data Center Report

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Background

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

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

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

The IGS Global Data Centers are ideally the principal GPS data source for the IGS Analysis Centers and the general user community. These online data are employed by the IGS Analysis Centers to create a range of products, which are then transmitted to the CBIS and Global Data Centers for public access and use. The GPS observation data available through the Global Data Centers consists of observation, navigation, and sometimes meteorological files, all in RINEX format. Global Data Centers are tasked to provide an online archive of at least 100 days of GPS data in the common data format, including, at minimum, the data from all global IGS sites. The Global Data Centers are also required to provide an online archive of derived products, generated by the IGS Analysis Centers and Associate Analysis Centers. These data centers equalize holdings of global sites and derived products on a daily basis, at minimum. The three Global Data Centers provide the IGS with a level of redundancy, thus eliminating a single point of failure should a data center become unavailable, since users can continue to reliably access data on a daily basis from one of the other two data centers. Furthermore, three centers reduce the network traffic that could occur in a single geographical location. Figure 1 shows the data flow from the GPS stations to the Analysis Centers and user community.

Highlights for 1998 and Plans for 1999 General

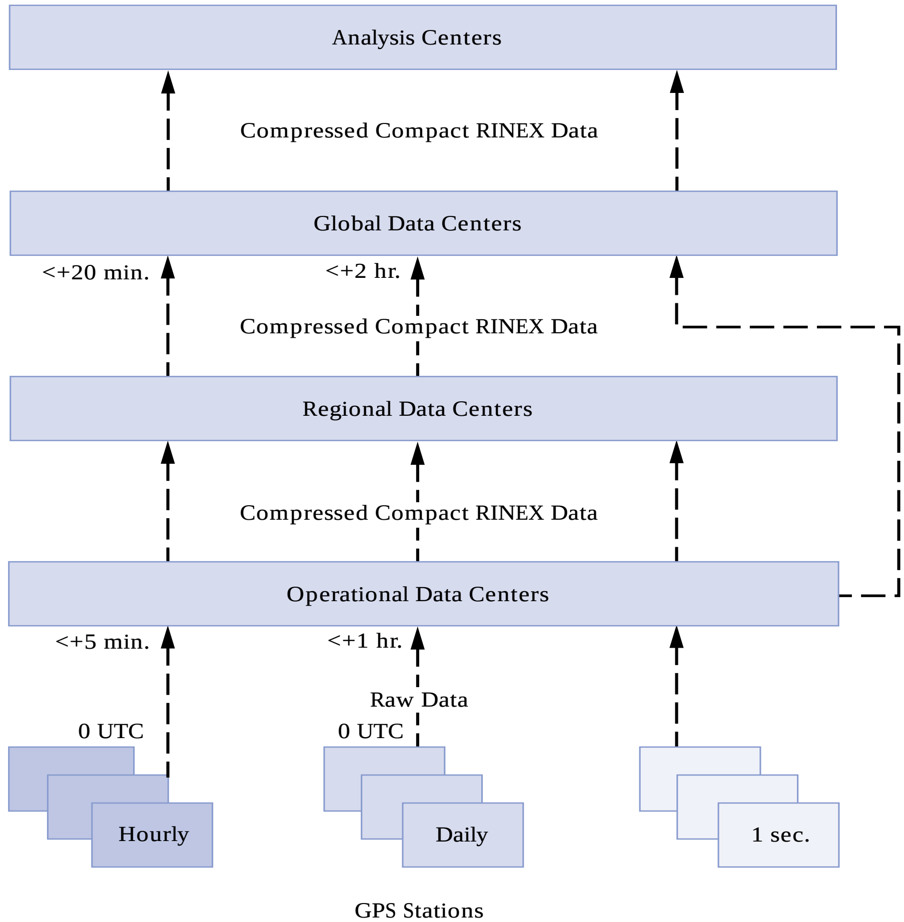
In November 1998, NASA Goddard Space Flight Center, through the Crustal Dynamics Data Information System (CDDIS) — an IGS Global Data Center — in conjunction with the IGS Central Bureau, hosted the IGS Network Systems Workshop for three and one half days in Annapolis, Maryland. The goals of the workshop focused on developing a closer community and strengthening communications within the IGS infrastructure, improving the performance of the network as well as developing a shared vision of the future network, and preparing a proceedings targeted along the lines of an “IGS Network Operations Plan” that would document the network operations of the IGS and future plans. The workshop provided a venue for the various network components of the IGS to meet and discuss current configurations, problems and their resolutions, how to incorporate the many future requirements into the existing infrastructure, and what new technologies are available that could be incorporated into various levels of the service. The proceedings were completed in April 1999 and are available via the IGS Web site and in limited hard copy distribution.

IGS Data

Consistent with past years, the number of stations archived by the IGS data centers increased by approximately 15 percent in 1998. Nearly 200 sites filed completed site logs with the CBIS. On a daily basis during the past year, nearly 350 stations were archived at Scripps Institution of Oceanography (SIO), supporting both the IGS and other regional/global research activities; over 160 at CDDIS, supporting both IGS and NASA activities; and over 100 at Institut Géographique National (IGN). The data centers experienced increased user activity as well during 1998; the

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

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



CDDIS, for example, saw over 7K GPS data and product files per day (nearly 5 gigabytes) downloaded from their new UNIX computer system toward the end of 1998.

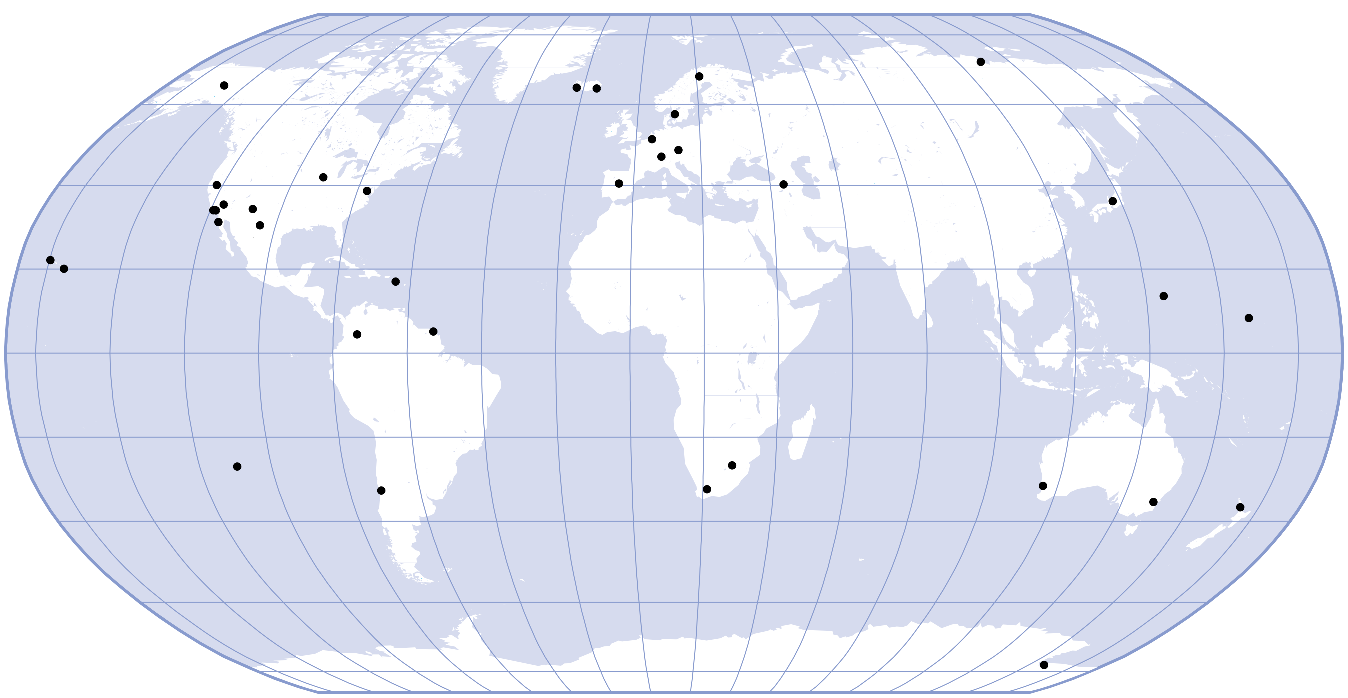
The Hatanaka compression scheme was adopted in 1998 to save data transmission time by reducing typical daily files to 200 kilobytes (as compared to 500 kilobytes for typical Unix-compressed RINEX files) and is now considered the operational method for transmitting data within the IGS itself. All data centers used this software to create smaller data files for exchange with other data centers and Analysis Centers. However, as a service to the general user community, many data centers continue to provide data in both compressed RINEX format and compressed, compact RINEX.

IGS data centers began the routine and rapid transmission and archive of hourly, 30-second data during 1998. The rationale for an hourly tracking network was presented at the Silver Spring Workshop in 1996 by JPL, which has been operating an hourly subnetwork since August 1996. These data were typically available to users within 25 minutes after the hour. By late 1998, data from over 30 sites have been collected by the Jet Propulsion Laboratory (JPL), European Space Agency Space Operations Center (ESOC), and Bundesamt für Kartographie und Geodæsie (BKG), and transmitted to and archived at the IGS Global Data Centers. These hourly files are archived in compressed, compact RINEX format and are retained at the Global Data Centers for 3 days. No additional validation is performed on these data after arrival at the CDDIS 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 hourly RINEX network.

On average, the latency of the data arrival at the Global Data Centers improved during 1998. Approximately 40 percent of the daily data files arrived at the Global Data Centers within one hour, 65 percent within 3 hours, and 75 percent within 6 hours. As usual, efforts to reduce both daily and hourly time delays, particularly for global IGS stations, will continue during 1999.

The IGS was a co-sponsor of 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

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



The Governing Board recommended that the combined zenith path delay estimates become an IGS product.

GLONASS data and products. Although IGEX-98 was scheduled for completion in mid-April 1999, this activity will continue indefinitely, perhaps becoming a permanent component of the IGS itself.

In 1999, the data centers will begin to see 1-second data transmitted in hourly files. These data, from a 20- to 30-station subnetwork of IGS sites, will be primarily utilized in support of low-Earth orbiter (LEO) missions such as 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 data format, probably binary, will be developed in the near term. Plans are to have these data available at IGS data centers in files containing hourly data only. IGS data centers may also become involved in the archival of GPS flight data for some of these LEO missions.

IGS Products

The IGS Analysis Coordinator began generating two new products in early 1998 — accumulated IGR (rapid orbit) and IGS (final orbit) Earth orientation parameter (EOP) files on a daily and weekly basis, respectively. The files, igs96p02.erp (to be used with IGS rapid orbits) and igs95p02.erp (to be used with IGS final orbits) are available through the Global Data Centers and the CBIS. Also in 1998, the IGS Analysis Center Coordinator activities transitioned from Jan Kouba at Natural Resources Canada to Tim Springer at Astronomical Institute of the University of Bern (AIUB). Following this move, both the rapid and predicted products were made available to the user community sooner, at 17:00 UTC and 23:30 UTC, respectively.

At the February 1998 IGS Analysis Workshop in Darmstadt, Germany, the IGS Governing Board recommended that the pilot phase of the experiment on the combination of troposphere estimates be considered complete and that the combined zenith path delay (ZPD) estimates generated by GeoForschungsZentrum (GFZ) become an IGS product. Using a sampling rate of 2 hours, the ZPD estimates generated by the IGS Analysis Centers are combined by GFZ to form weekly ZPD files for nearly 150 IGS sites. The troposphere products are now available at all IGS Global Data Centers.

Also at the 1998 IGS Analysis Workshop, it was decided to start a coordinated, routine processing and a combination of IGS ionosphere products. The IGS Ionosphere Working Group was formally established by the IGS Governing Board at its meeting in May. An official format for the exchange of ionosphere maps, called IONEX, was developed and approved thereafter for exchange of these data. In mid-1998, five IGS Analysis Centers began supplying daily, global ionosphere maps of total electron content (TEC) in the form of IONEX files. These products are available from the IGS Global Data Centers. A (daily) IONEX file includes 12 2-hour snapshots of the global TEC.

At the 1999 LEO Workshop, it was recommended that the IGS Analysis Centers develop new rapid analysis products, including orbits, clocks, EOP, and predictions; furthermore, 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 the summer of 1999.

Table 1 lists the data centers currently supporting the IGS; information on contacting data centers is available through the IGS Web site at <http://igscb.jpl.nasa.gov>.

Table 1. Data Centers Supporting the IGS in 1998

Operational Data Centers	
ASI	Italian Space Agency
AUSLIG	Australian Surveying and Land Information Group
AWI	Alfred Wegener Institute for Polar and Marine Research, Germany
CNES	Centre National d'Études Spatiales, France
DUT	Delft University of Technology, The Netherlands
ESOC	European Space Agency (ESA) Space Operations Center, Germany
GFZ	GeoForschungsZentrum Potsdam, Germany
GSI	Geographical Survey Institute, Japan
ISR	Institute for Space Research, Austria
JPL	Jet Propulsion Laboratory, California Institute ofTechnology, USA
KAO	Korean Astronomical Observatory
NGI	National Geography Institute, Korea
NIMA	National Imagery and Mapping Agency, Department of Defense, USA
NMA	Norwegian Mapping Authority
NOAA	National Oceanic and Atmospheric Administration, USA
NRCan	Natural Resources Canada
RDAAC	Russian Data Analysis and Archive Center
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 Geodæsie, Germany
JPL	Jet Propulsion Laboratory, California Institute of Technology, USA
NOAA	National Oceanic and Atmospheric Administration, USA
NRCan	Natural Resources 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

The International Terrestrial Reference Frame

Claude Boucher

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 IERS Central Bureau 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 determination of Earth's rotation.

The ITRF Section of the IERS Central Bureau (ITFS) cooperates closely with the different IGS participants (Central Bureau, Analysis Centers, and tracking stations) for ITRF station coordinates and analysis of solutions provided by IGS Analysis Centers, as well as site information and local ties of collocation sites. For more information, visit the ITRF Web site at <http://lareg.ensg.ign.fr/ITRF>.

ITRF and IGS Relationship

Since the beginning of the IGS preliminary test activities in 1992, the IGS Analysis Centers have used ITRF coordinates for some subset of stations in their orbit computations. The combined IGS ephemerides are expressed in ITRF 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, and ITRF96 starting on 1 March 1998.

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, which are included in the ITRF combinations. IGS also provides very efficient methods to densify the ITRF network: one can now obtain millimetric positions directly expressed in ITRS by processing suitable GPS data with IGS products.

ITRF97

The ITRF97 solution has been achieved by simultaneous combination of positions and velocities using full variance/covariance matrices of the individual solutions provided by the IERS/IGS Analysis Centers. A weighting scheme, based on the analysis and estimation of the variance components using the Helmert method, was developed and used in the generation of ITRF97. Figure 1 illustrates the data used in the ITRF97

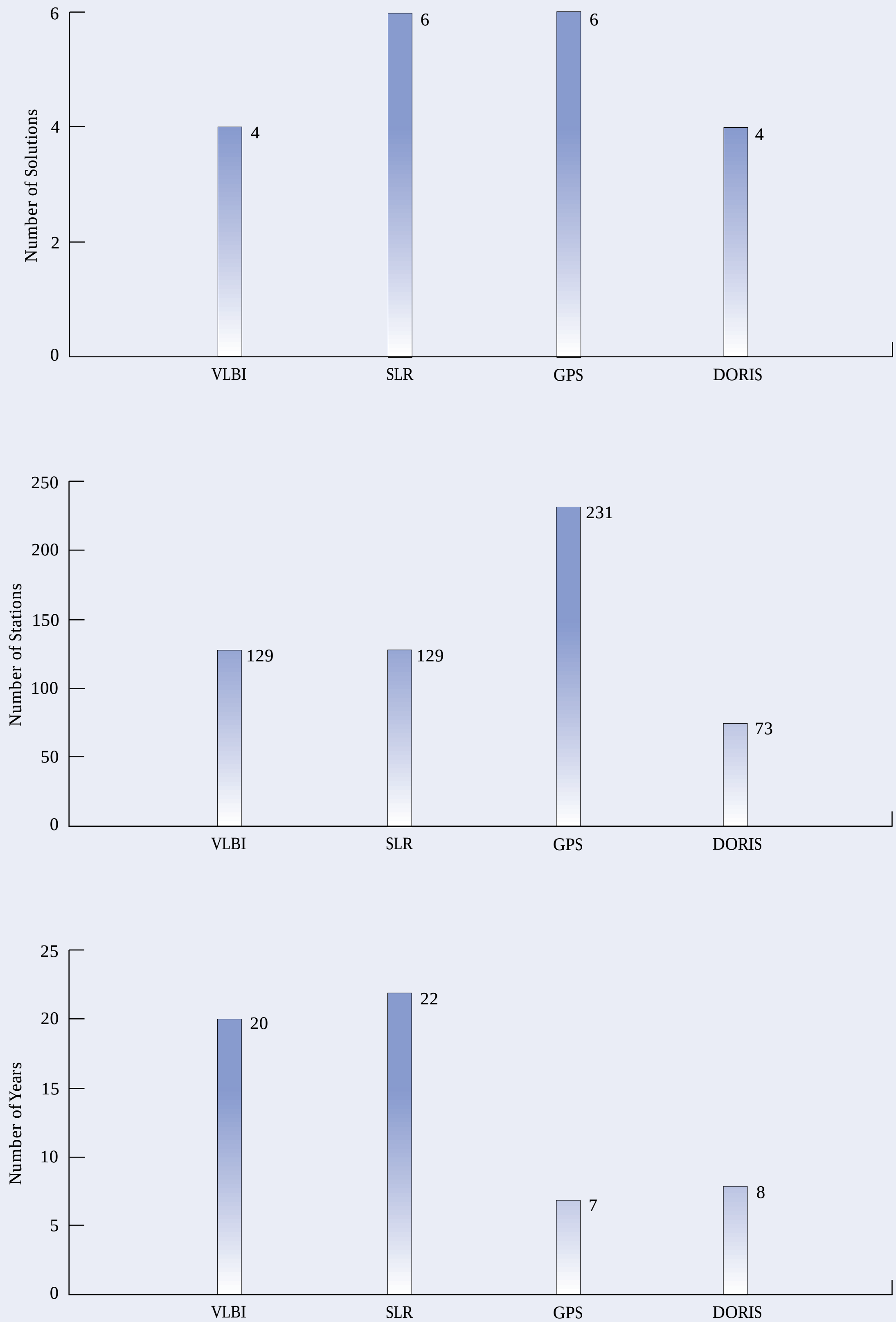


Figure 1. Data used in the ITRF97 combination.

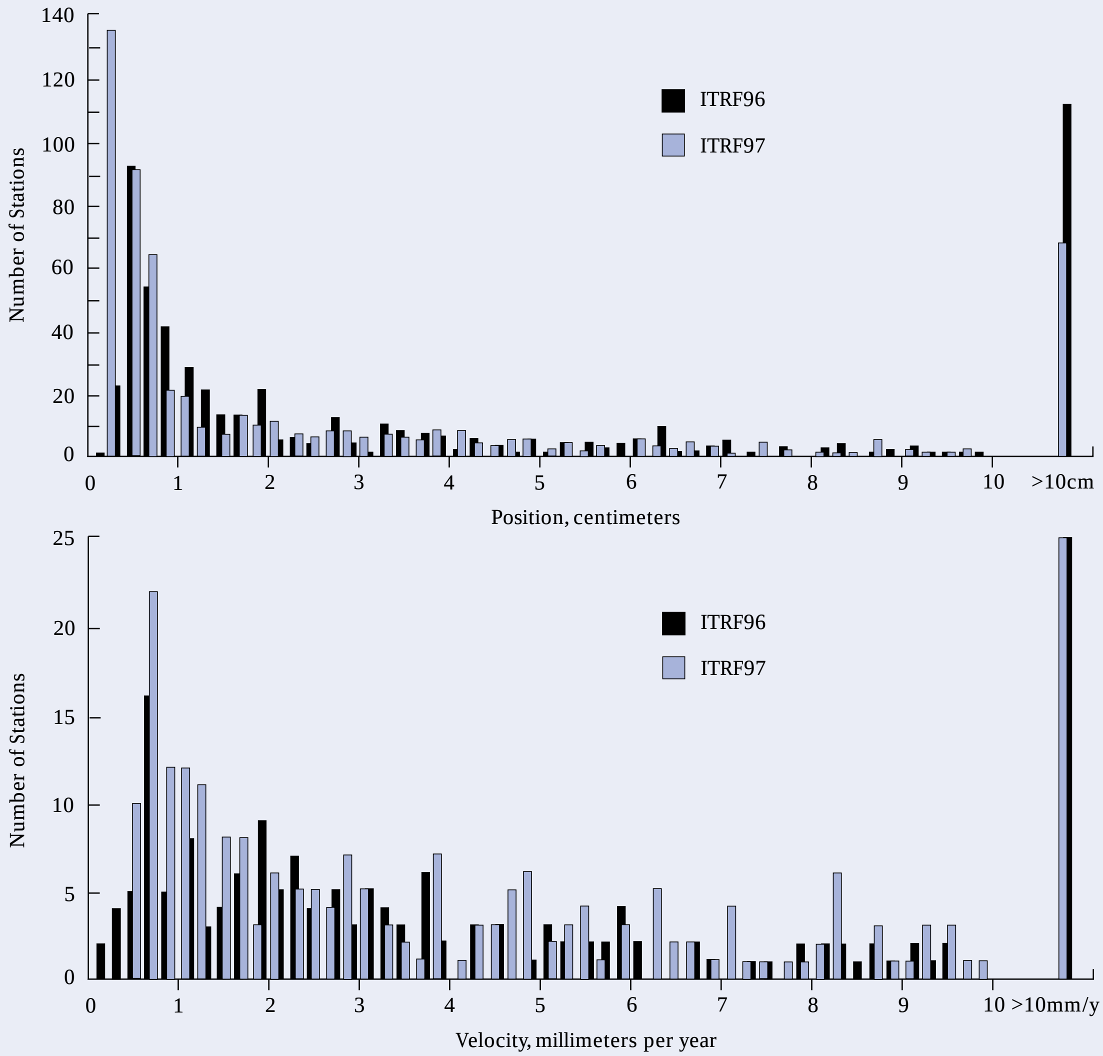


Figure 2. Position (cm, at epoch 1997.0) and velocity (mm/y).

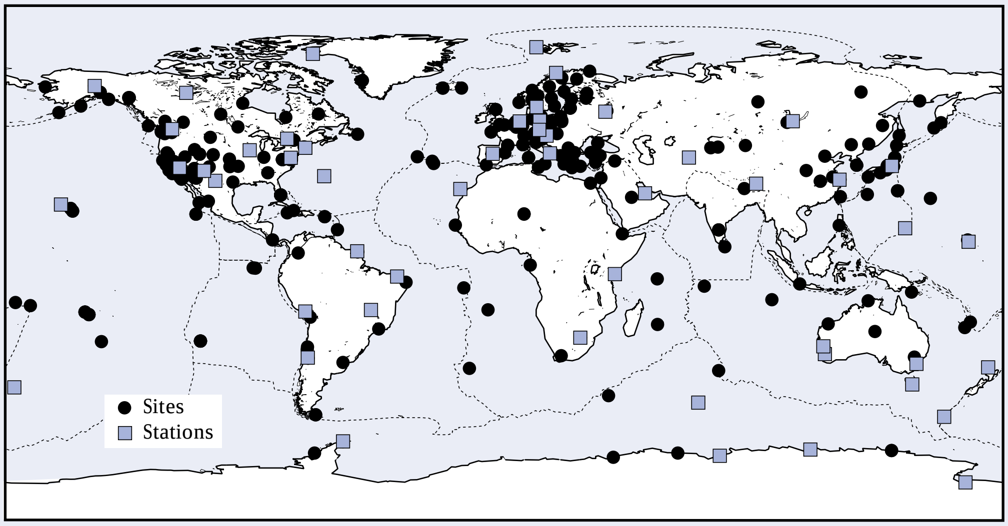


Figure 3. ITRF97 Sites (circle) and the 52 IGS reference stations (square).

solution. This figure shows the significant contribution of IGS/GPS solutions.

The reference frame fixation (origin, scale, orientation, and time evolution) is achieved in such a way that ITRF97 is in the same reference system as ITRF96. The position and velocity spherical errors plotted in Figure 2 demonstrate an improvement of ITRF97 with respect to ITRF96.

All the ITRF97-related files are available via the Internet at <http://lareg.ensg.ign.fr/ITRF/ITRF97>.

ITRF97 and the IGS Reference Stations

Starting on 1 March 1998, IGS uses 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 ITFS has performed a specific quality analysis based on ITRF96 position and velocity residuals. The analysis was repeated in the light of the ITRF97 results concerning 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. Figure 3 shows the coverage of the ITRF97 sites, underlying the 52 IGS reference stations.

IGS Reference Frame Pilot Project

Remi Ferland

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The importance of a global, accurate, and readily accessible network of stations in a common robust reference frame was recognized early on by the IGS participants and was addressed at the December 1994 IGS workshop on the densification of the International Reference Frame through regional networks (the Proceedings of the 1994 workshop are available from the Central Bureau). The IGS International Terrestrial Reference Frame (ITRF) densification pilot project was initiated at the end of 1995 with the combination of weekly Analysis Centers station coordinates solutions by the Global Network Associate Analysis Centers (GNAACs).

The three GNAACs — Jet Propulsion Laboratory (JPL), Massachusetts Institute of Technology (MIT), and University of Newcastle, United Kingdom (NCL) have since been producing weekly station coordinate solutions, ensuring needed redundancy. The need to generate a unique IGS station coordinate product was recognized, and the improvement of the consistency between the different IGS products was also expressed. While combining the station coordinates, it is possible to add the Earth rotation parameters (ERPs) in the combination, thus ensuring the consistency of those two products. The creation of a Reference Frame Working Group tasked to address those issues was recommended during the 1998 Darmstadt IGS Workshop and approved at the December Governing Board Meeting in San Francisco. The charter of the newly formed working group is currently being circulated to potential members.

A preliminary cumulative solution using the GNAAC weekly solutions was generated and submitted to the International Earth Rotation Service (IERS) in July 1998 and an improved solution was submitted in the fall, with results presented at the

Potsdam IERS technical meeting. Analysis done by IERS indicates that the horizontal position and velocity weighted root mean square (WRMS) were respectively 2.1 millimeters and 2.8 millimeters per year. Natural Resources Canada (NRCan) weekly comparisons reveal the following data:

The residuals root mean square (rms) error (north, east, up) in millimeters for each of the GNAACs with respect to the cumulative solution are (3.6, 4.3, 9.8) for JPL, (3.3, 4.1, 9.7) for MIT and (3.3, 3.8, 9.5) for NCL. This and other comparisons confirm the good consistency between the GNAAC weekly submissions.

Estimation of the weekly geocenter showed an apparent annual period with amplitude of about 2 centimeters in the Z component observed in the weekly combined GNAAC solutions. Weekly coordinate residuals and geocenter variations indicate a gradual but steady repeatability improvement. This was also noticed in the formal sigma of the geocenter estimation.

A first attempt at producing simultaneous coordinates and ERP combinations for GPS weeks 964 to 971 with Earth orientation parameters (EOPs) from NRCan, GeoForschungsZentrum (GFZ), and JPL was compared to the final IGS ERP combination. The average difference and standard deviation of that comparison for X–pole, Y–pole, and length of day (LOD) are:

X–pole	–0.03 milliarcsecond, ± 0.04 milliarcsecond
Y–pole	–0.06 milliarcsecond, ± 0.07 milliarcsecond
LOD	0.000 millisecond, ± 0.011 millisecond

These results indicate no significant differences between the current final IGS ERP and proposed station coordinates and the ERP combination procedure.

Over the last few months, significant effort went into developing, upgrading, and automating the software required to combine and report the results. The report content is based to a large extent on the suggestions made by a small group of potential working group members. The weekly products currently generated (preliminary submissions should start by June 1999) include a report, weekly station coordinates with ERP, and cumulative station coordinates and velocities combination along with residuals. As of week 1003, six Analysis Centers include daily ERPs in their weekly Software-Independent Exchange (SINEX) submission and one GNAAC includes the EOPs in its combination. A weekly station coordinates and ERP combination was obtained between GPS weeks 978 and 1000 from the Analysis Centers. A comparison of these ERPs with the final IGS ERPs produced average differences and standard deviation of:

X–pole	0.06 milliarcsecond, ± 0.04 milliarcsecond
Y–pole	–0.06 milliarcsecond, ± 0.06 milliarcsecond
X–pole	–0.04 milliarcsecond rate per year, ± 0.09 milliarcsecond per year
Y–pole	–0.05 milliarcsecond rate per year, ± 0.11 milliarcsecond per year
LOD	0.000 milliarcsecond per year, ± 0.013 milliarcsecond per year

These results again confirm the agreement with the final IGS ERP estimates.

The estimated station coordinates and velocities from the cumulative solution up to week 0999 were compared with the newly available ITRF97 for the 47 reference frame stations, resulting in the following coordinate differences RMS at epoch 1999.0:

North, east and up components — 2.3, 2.4 and 8.1 millimeters

Corresponding velocity components — 1.4, 1.6, 4.9 millimeters per year

When compared with the IERS WRMS above, this indicates that six more months of data have significantly improved the quality of the velocity estimation.

The IGS/BIPM Pilot Project to Study Accurate Time and Frequency Comparisons using GPS Phase and Code Measurements are sponsored jointly with the Bureau International des Poids et Mesures (BIPM). A working group was formed in spring 1998, and first met at BIPM in June. The central goal is to investigate and develop operational strategies to exploit GPS measurements for improved availability of accurate time and frequency comparisons worldwide. This will become especially significant for maintaining the international UTC timescale as a new generation of frequency standards emerges.

IGS/BIPM Time and Frequency Project

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The respective roles of the IGS and BIPM are complementary and mutually beneficial. Activities generally fall into the following areas:

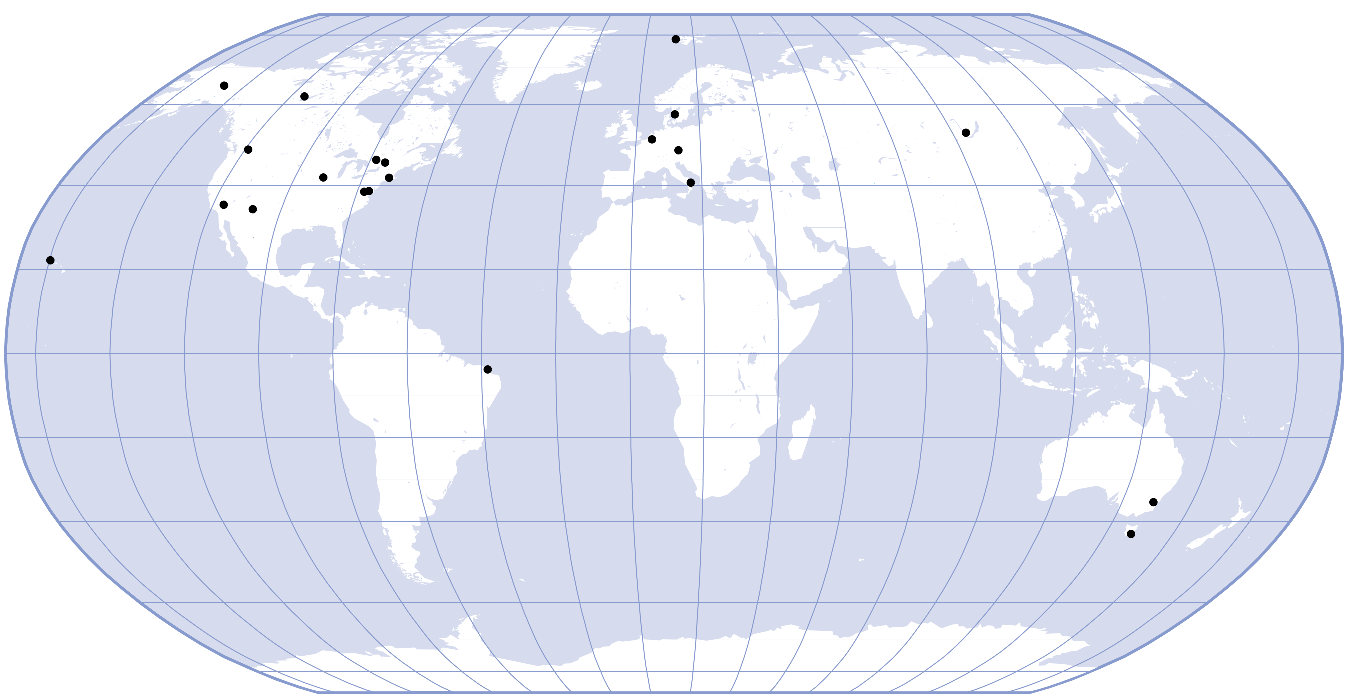
- Deployment of GPS receivers — The IGS network currently consists of about 200 permanent, continuously operating stations that are globally distributed. Figure 1 shows a map of the fiducial clock network. Of these, external frequency standards are used at approximately 30 with H-masers, approximately 20 with cesium clocks, and approximately 20 with rubidium clocks; the remainder use internal crystal oscillators. Figure 2 shows a comparison of time differences between sites, and Table 1 lists the 11 IGS stations currently located at timing laboratories.
- GPS data analysis — Of the IGS Analysis Centers, all but two already provide satellite clock estimates. A plan has been adopted to expand the IGS products during 1999 to include combined receiver clocks. To improve the timescale alignment and weighting of Analysis Center solutions, a set of “fiducial clock” sites was adopted, most of which are equipped with H-maser frequency standards.
- Instrumental delays — Efforts are underway to develop techniques for measuring the calibration biases which 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

Table 1. IGS Stations Located at BIPM Timing Laboratories

IGS	Time Lab	GPS Receiver	Frequency Standard	Site City
AMC2	AMC*	AOA TR with ACT	H-maser	Colorado Springs, CO, USA
BOR1	AOS	AOA TurboRogue	Cesium	Borowiec, Poland
BRUS	ORB	AOA TurboRogue	H-maser	Brussels, Belgium
GRAZ	TUG*	AOA TurboRogue	Cesium	Graz, Austria
MDVO	IMVP	Trimble 4000SSE	H-maser	Mendeleevo, Russia
NRC1	NRC*	AOA TurboRogue	H-maser	Ottawa, Canada
PENC	SGO	Trimble 4000SSE	Rubidium	Penc, Hungary
SFER	ROA	Trimble 4000SSI	Cesium	San Fernando, Spain
TOUL	TA(F)	AOA TurboRogue	Cesium	Toulouse, France
USNO	USNO*	AOA TurboRogue	H-maser	Washington, DC, USA
WTZR	BKG	AOA TurboRogue	H-maser	Wettzell, Germany

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

Figure 1. The fiducial clock network.



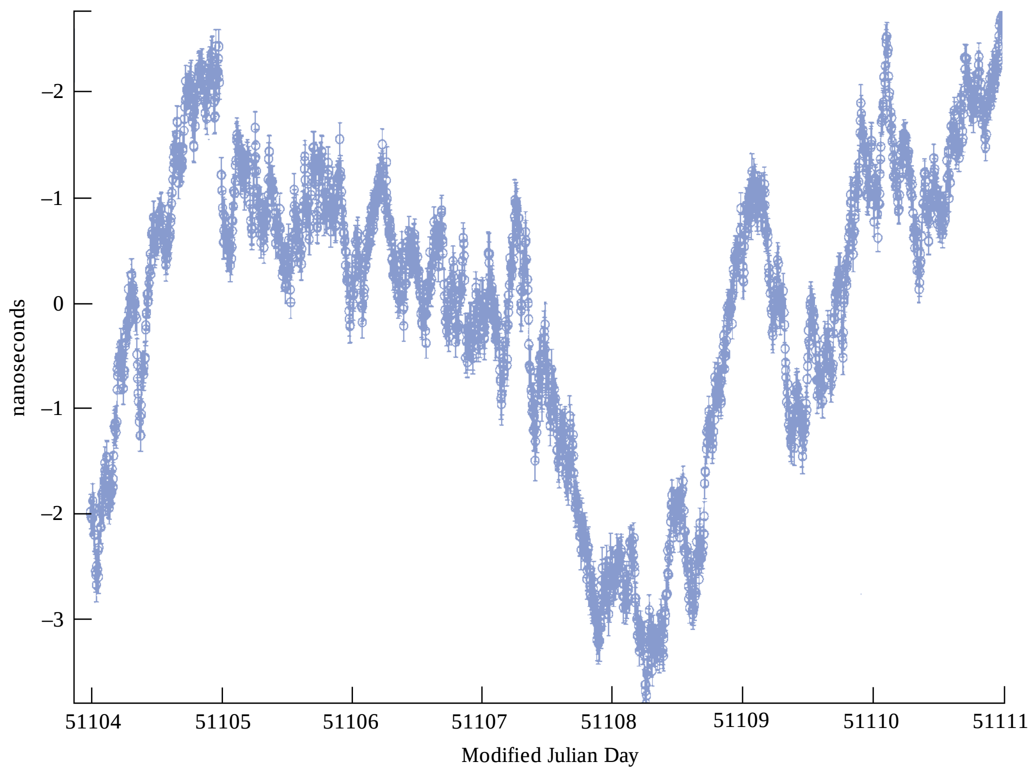


Figure 2. A comparison of GPS-based time differences between GRAZ (Graz, Austria), using a cesium clock, and USNO (Washington, DC), using an H-maser, for GPS week 0980. The modified Julian day corresponds to GPS week 980: the calendar week of 18–24 October, 1998. (Removed slope: –0.106346 E–07 seconds/day)

clock products. This effort is the foremost technical challenge facing the pilot project.

- Comparison experiments — So far, only a few controlled experiments have been conducted to compare geodetic timing results with simultaneous, independent techniques. However, high-quality frequency comparisons already appear entirely feasible provided that reasonable care is taken to minimize environmentally induced variations.

For further information, please refer to this Web site: <http://maia.usno.navy.mil/ gpst.html>.

A Combined IGS Ionosphere Product

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The IGS Ionosphere Working Group

The IGS Ionosphere Working Group was formally established by the IGS Governing Board at its meeting of 28 May 1998, in Boston. The working group's most important short-term goal is the routine provision of global ionosphere total electron count (TEC) maps plus GPS satellite differential code biases (DCBs) with a delay of some days. The working group's medium- and long-term goals are the development of more sophisticated ionosphere models, as well as models of regional and local extent, with near-real-time and real-time availability. The final target is the establishment of an independent IGS ionosphere model.

Pilot Phase

The working group started with its pilot phase in June 1998. Pilot-phase activities commenced with the routine delivery of TEC maps and GPS satellite DCBs in Ionospheric Map Exchange (IONEX) format files (Schaer, Gurtner, and Feltens, 1997) by the Ionosphere Associate Analysis Centers (IAACs) to the IGS Global Data Center located at the Crustal Dynamics Data Information System (CDDIS). Currently, five IAACs are delivering their IONEX files routinely to CDDIS:

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

Every 24 hours, each IAAC delivers an IONEX file containing 12 TEC maps, i.e., TEC information is provided with a time resolution of 2 hours, and the header includes a daily set of GPS satellite DCBs. The working group's main goal is now to find a scheme with which these individual IAAC TEC maps can be combined into common IGS TEC maps with the same time coverage and time resolution.

Comparisons

The European Space Agency/European Space Operations Center (ESA/ESOC) is the working group's designated Ionosphere Associate Combination Center (IACC). Based on a proposal for a future comparison/combination algorithm (worked out by J.Feltens), and some improvements to this proposal that came from S.Schaer (CODE), B.Wilson (JPL), and J. Feltens, a new Fortran77 program called "CMPCMB" was coded by J. Feltens from scratch to do this task (J. Feltens, 1998).

However, the comparison/combination algorithm is based on a pure statistical approach using weighted means (Schaer, Gurtner, and Feltens, 1997). On the other hand, the approaches used by the distinct IAACs to model the ionosphere are very different. In order to achieve a real combination scheme, the existing comparison/combination algorithm must be improved, and its current version must be considered as preliminary. Using the existing version, the IACC at ESA/ESOC started with a routine (preliminary) comparison of IONEX TEC maps from day 98295 (22 October 1998) forward. At the moment, these comparison results are circulated within the Ionosphere Working Group.

Validations

As stated above, ionosphere modeling at the different IAACs is based on very different conceptions, which is also reflected in the comparison results. The working group has thus decided that before combined products will be given to the outside world, extensive validations must be made in order to calibrate the distinct IAAC ionosphere models with respect to each other and to assess their real quality in order to be able to assign objective weights to each IAAC model. The working group is now concerned with the preparations of these validations. In addition to the satellite DCBs, the receiver DCBs will be exchanged, with the aim of finding explanations for the discrepancies that can be seen in the TEC levels. The International Reference Ionosphere (IRI) will be used for checking the mathematical adaptability of the distinct IAAC ionosphere models, with validations with ionosphere data anticipated from independent (non-GPS) sources, e.g., ionosonde and TOPEX/Poseidon.

Future Tasks

The first results of comparisons will be presented to the IGS community at the next IGS workshop. If a final comparison/combination algorithm has been agreed upon by then, combined IGS ionosphere products could be made publicly available later in the year.

Another important item to discuss is the reduction of the time deadline for ionosphere products delivery. The ionosphere is a very rapidly changing medium, and the intent of the working group should be to provide actual ionosphere models in short time frames.

Status of the IGS Troposphere Working Group

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Combined tropospheric estimates for more than 80 sites are provided by three or more Analysis Centers,

Zenith Path Delay Estimate Now an Official Product

The IGS combined tropospheric estimates are an official product since 1998, after the successful performance of the Pilot Experiment in 1997. The product is the weighted mean estimate for the zenith path delay (ZPD) in the neutral atmosphere. The number of sites involved has steadily grown and is now about 150. For the majority of sites, time series of two years with a sampling rate of 2 hours are available now. The IGS Analysis Centers derive the estimates during or after their computation of the IGS Final Products, so the ZPD product is available with a delay of three to four weeks. Figure 1 shows the IGS stations with tropospheric estimates.

Estimates for more than 80 sites are provided by three or more Analysis Centers. For these sites, reasonable estimates of internal consistency can be obtained. The standard deviation for most of the sites is at the level of 2–5 millimeters ZPD, corresponding to < 1 millimeter in the precipitable water vapor (PWV). The scattering of the bias from site to site is about 3 millimeters ZPD. For sites in the equatorial region, where some severe problems with the higher ionospheric activities occur, the scattering is much higher but in most cases below the 2-millimeter level in PWV.

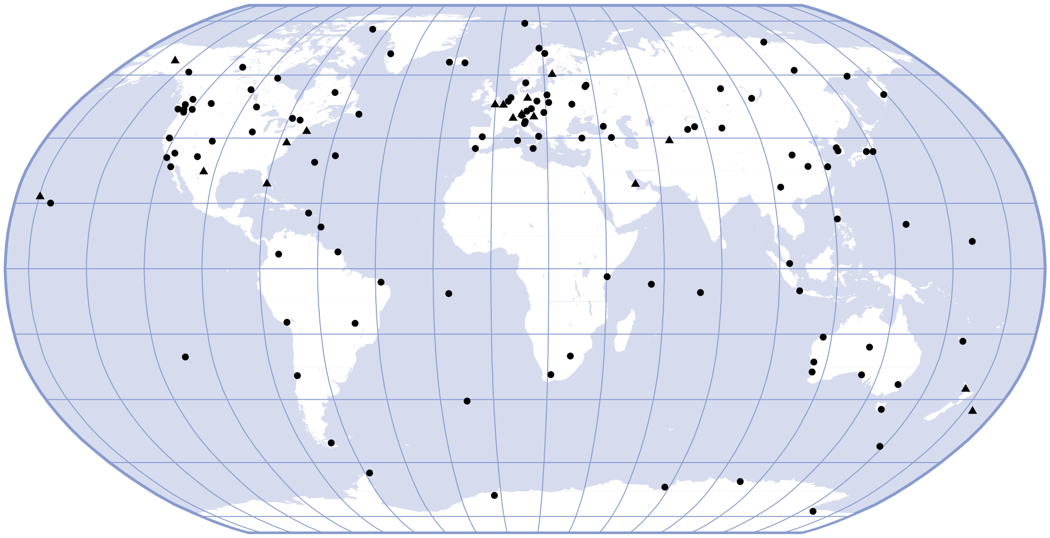

Figure 1. IGS stations with tropospheric estimates. Triangles indicate sites with meteorological sensors.

Site solutions delivered by only one Analysis Center are also contained in the product, sampled and transformed into the troposphere format. Most of those sites are located in denser parts of the network, where all sites have nearly the same accuracy and therefore the quality can be deduced from neighboring sites.

In addition to the ZPD product, Receiver-Independent Exchange (RINEX) meteorological files are offered for conversion. Despite the fact that IGS has encouraged its members to add suitable meteorological packages to the IGS tracking stations, very little progress has been made during the last two years. At the moment, 30 sites are equipped with meteorological packages. Unfortunately, for some of the sites the data quality is not good enough. There are too many data gaps, so that often no meaningful series of water vapor can be compiled. The most critical sensor is the pressure sensor. Unless highly accurate and rather expensive sensors are used, significant temperature dependence may occur. In those cases, the recommendation is to separate the pressure sensor and use an indoor place instead. To support the decision as to where future meteorology packages should be installed, IGS will maintain a list of high-priority candidate sites (for example, equatorial regions may be especially interesting).

The number of projects and activities involving near-real-time monitoring of water vapor using ground-based GPS instruments is steadily increasing. IGS may not be involved in such near-real-time activities directly. However, IGS can support regional activities of this kind by making available hourly RINEX data within the global tracking network and by generating predicted orbits. The presently available predictions based on daily data batches must be predicted over 48 hours, and are, for a number of satellites, often not the quality needed. Based on the hourly downloads, IGS will be able to generate predictions more frequently and the shortened prediction interval will lead to significant improvements. Within the IGS during 1999, the development in this new direction will be discussed and technologies will be developed.

IGEX-98

International GLONASS Experiment

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Context

GLONASS is the Russian Global Navigation Satellite System, whose technology and principles are very close to GPS. Several manufacturers already market dual GPS/GLONASS receivers for navigation or geodetic applications, taking full advantage of the extended number of available satellites from the combined systems. Future systems, such as the GNSS-1 project in Europe for aviation, plan to use GPS and GLONASS signals.

Scientific Objectives

The major goals of the IGEX-98 campaign are to investigate scientific uses of the GLONASS satellites for geodetic and geophysical applications and to try to solve the interoperability issues of the GPS and GLONASS systems. The simultaneous use of GLONASS and GPS measurements and navigation data requires that the two systems be represented in common reference frames for time and coordinates. A related objective is to produce precise GLONASS orbits so that the other goals can be realized.

Campaign Organization

In early 1998, the IGEX-98 Steering Committee was formed; it issued an international call for participation in order to set up this observation campaign (observation sites, data centers, and analysis centers). The IGEX-98 Steering Committee members are G. Beutler, W. Gurtner, G. Hein, R. Neilan, C. Noll, J. Slater, R. Weber, and P. Willis. More than 60 groups answered the call for participation, ultimately resulting in a global network of approximately 65 stations (receivers), mostly collocated with IGS stations, in 25 countries. The tracking campaign began on 20 October 1998, and, although originally scheduled for three months, was extended to 19 April 1999 to take advantage of the 31 December 1998 launch of three new GLONASS satellites and to compensate for delays in the start of operations of some of the network stations. Figure 1 shows the IGEX network.

Web sites were set up at the Institut Géographique National (http://lareg.ensg.ign.fr/IGEX) and the Institute of Navigation (http://www.ion.org/workgroup.html) to provide information about the experiment, including station lists, station logs, organizational contacts, and data requirements. An IGEX mail facility was created to enable rapid and efficient communication among the participants and other interested individuals.

Five organizations have been performing orbital computations and analyses — University of Bern, Switzerland; Bundesampt für Kartographie und Geodæsie (BKG), Germany; European Space Operations Center (ESOC), Germany; Geo-ForschungsZentrum Potsdam (GFZ), Germany; and National Environment Research Council (NERC), UK. Observations and precise orbits are archived at two global data centers at the Institut Géographique National (IGN), France, and NASA Goddard Space Flight Center, US, which may be accessed by anyone wishing to procure the data. Regional data centers — for example, in Australia and Germany — have also been archiving data.

The IGEX-98 Steering Committee also requested and received increased satellite laser ranging (SLR) observations of the GLONASS satellites by the SLR observatories of the newly formed International Laser Ranging Service. Nine satellites were tracked by 33 observatories in 14 countries during the campaign.

Preliminary Results

Precise GLONASS orbits, consistent at the submeter level, have been obtained by the four analysis groups in Switzerland and Germany and have been compared to the SLR-derived orbits and measurements to evaluate their accuracy. Geodetic results were also obtained showing daily repeatabilities of several millimeters for regional baselines. However, there are still scientific problems under investigation, among them an unknown bias common to both GPS and GLONASS when compared to the SLR measurements, and ways to combine GPS/GLONASS geodetic solutions. The timing community has used the precise orbits in conjunction with dual-frequency GLONASS P-code observations to transfer time with uncertainties of 2 nanoseconds compared to about 10 nanoseconds using the broadcast orbits.

Owing to the success of the experiment, there are already plans to maintain the global tracking program in 1999 after the official end of the IGEX-98 campaign. An international workshop is being organized in the US in Nashville on 13–14 September 1999 to allow participants to present their results and exchange experiences.

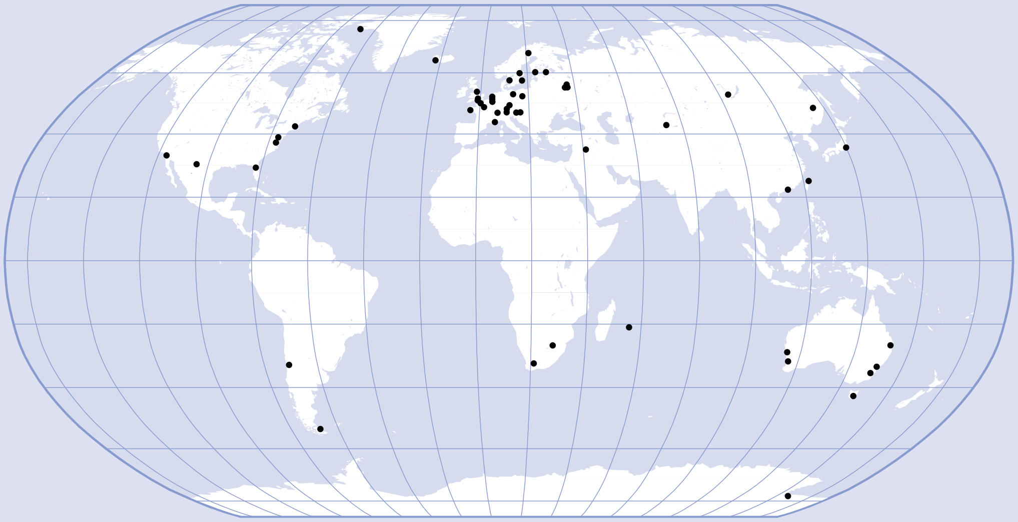

Figure 1. The IGEX network.

Low-Earth Orbiters

Several key developments have reaffirmed the place for IGS involvement in LEO data and analysis products.

Michael Watkins

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Support for Low-Earth orbit (LEO) missions continues to be recognized as a very important up-and-coming activity for various components of the IGS. Although the definition and onset of an IGS LEO Pilot Project was affected by delays in initial spacecraft launches past the end of 1998, several key developments have reaffirmed the place for IGS involvement in LEO data and analysis products. As suggested in the 1997 LEO Working Group report, Jet Propulsion Laboratory (JPL) and GeoForschungZentrum Potsdam (GFZ) continue to progress toward a high-data-rate, low-latency subnetwork primarily targeted at supporting the upcoming Challenging Mini-Satellite Payload for Geophysical Research and Application (CHAMP) mission; however, the ground network architecture and requirements for many of the upcoming LEO missions are identical. This CHAMP network (see Figure 1) is presumed to be the forerunner of a general IGS LEO network for multimission support.

Data are not yet routinely collected at sampling rates appropriate for LEO activities (generally assumed to be 1-second intervals), but low-latency operations began to be tested with hourly deliveries of 30-second data to IGS Global Data Centers in July 1998 (see the IGS Data Center Report in this volume). Initial participation from JPL and the Crustal Deformation Data Information System soon spread to other Global Data Centers (Institut Géographique National [IGN]) and Operational Data Centers (European Space Operations Center [ESOC]; Bundesampt für Kartographie und Geodæsie [BKG]). This is a very promising activity in terms of a future IGS LEO application network of low-latency tracking stations.

The IGS Governing Board addressed the high expectations of the LEO Working Group at its 10th meeting in December 1998 (reference IGS Mail message no. 2106), noting that Prof. Christoph Reigber would be in an excellent position as the Board's new Chair to meet the challenges of LEO projects in the IGS. Also noted by the Board was substantial planning by the LEO Working Group for an IGS/JPL/GFZ Workshop on Low-Earth Orbiters that was held in Potsdam in March 1999.

At the time of this writing, the LEO Workshop can be considered a great success in addressing topics such as mission overviews, ground data and product systems, user interfaces, and science applications. The workshop generated plans and recommendations for IGS LEO activities in 1999 and beyond. The key recommendations focus on the following:

- Establishing a standardized subnetwork of the IGS specifically in support of LEO requirements.
- Developing ultrarapid analysis products by shifting to subdaily operations and processing within the IGS.
- Developing an efficient format for the 1-hertz ground data (otherwise, these files would be a factor of 30 larger than the current file size).
- Planning a call for participation in a three- to six-month pilot project to investigate the use of LEO GPS flight data for IGS precise orbit determination.

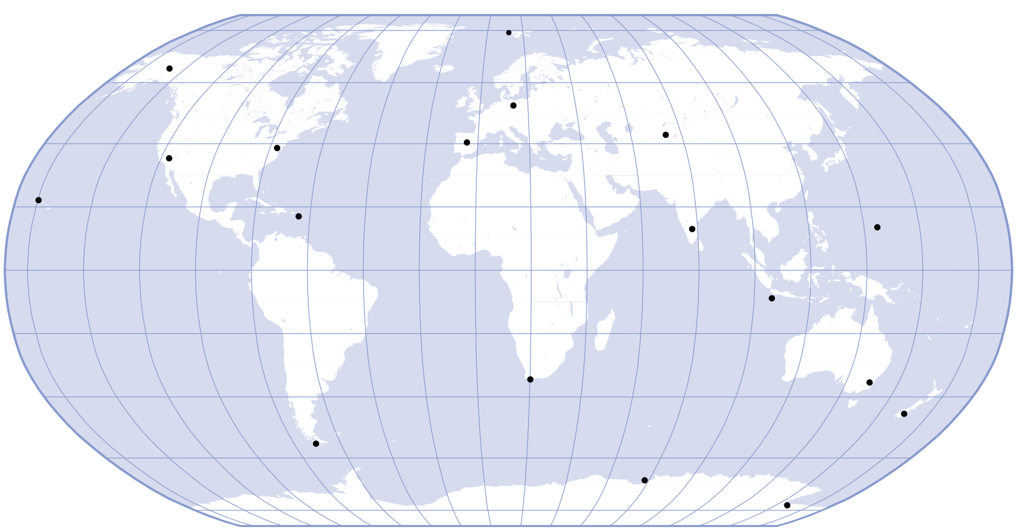

Figure 1. Preliminary subnetwork of high-rate stations to support LEO applications.

The Use of GPS at Tide Gauge Sites

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Director, Permanent Service for Mean Sea Level

Vertical land movements are an important signal in sea-level records as measured at tide gauges. Over the past few years, considerable developments have taken place with the GPS and other advanced geodetic techniques for monitoring rates of vertical land movements. Arrangements have been put in place for the Permanent Service for Mean Sea Level (PSMSL) to work closely with the IGS, another Federation of Astronomical and Geophysical Data Analysis Services (FAGS) entity, in order to provide time series of vertical land movements alongside the tide gauge sea-level time series. This will thereby provide a decoupling of land and real sea-level changes within the relative sea-level tide gauge records. An important joint workshop addressing this topic was held 17–18 March 1997 (Neilan, 1998).

The workshop delegated a technical committee chaired by Dr. Mike Bevis of the University of Hawaii to address many of the remaining technical issues connected with operating GPS receivers at gauge sites, as well as to consider the practical implications of GPS stations as satellite altimeter calibration sites. A follow-up workshop was held in Toulouse during 10–11 May 1999, one of the main objectives of which was the production of a report on “How to Operate GPS at Gauges.”

Appendix a

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Appendix b

IGS Publications

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

IGS WORKSHOP PROCEEDINGS

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.

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