GEODYNAMICS: TRACKING SATELLITES TO MONITOR GLOBAL CHANGE

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The Global Positioning System is fast becoming indispensable for geodynamic investigations. The International GPS Geodynamics Service (IGS), a new worldwide Navstar satellite tracking service, proved its worth in recent trials, providing a rich data set with which to begin a study of global change. IGS marks a new era of international cooperation in the determination of precise ephemerides and earth rotation parameters.

The majority of GPS uses are associated with surveying and navigation, but the near completion of the GPS satellite constellation and the maturity of mathematical modeling and data communication networks have ushered in an important new application for GPS: permanent arrays to monitor geodynamic processes. GPS is an effective tool for monitoring global changes over time, which is the key to understanding long-term effects. Applications include measuring crustal deformation, postglacial rebound, volcanic uplift, and coseismic and postseismic activity. Geodynamic investigations that rely on GPS data require precise knowledge of the Navstar satellite orbits. Only an international GPS tracking service can defray the costs and provide the necessary data, expertise, and large parameter estimation processes.

Of all GPS applications, geodesy and geodynamics demand the most accurate modeling of the GPS observables. Relative positioning accuracies of one centimeter (horizontal) and a few centimeters (vertical) over 1,000 kilometers can be achieved if the GPS satellite orbits are properly modeled. Two recent global and regional GPS experiments (First GPS Experiment for International Earth Rotation Service and Geodynamics Experiment "GIG '91") clearly demonstrated the value of GPS in geodesy and geodynamic applications. Indeed, compared to two well-established space techniques, very long baseline interferometry (VLBI) and satellite laser ranging, GPS promises to cost-effectively provide the highest spatial density of precise positions and the highest temporal resolution of the Earth's pole.

The Jet Propulsion Laboratory (JPL) and the Scripps Institution of Oceanography (SIO) jointly operate the Permanent Geodetic and Geodynamics Array (PGGA) in southern California, a prototype of this new application. The Cooperative International GPS Network (CIGNET) and NASA's Fiducial Laboratories for International Natural Science Network (FLINN) provide tracking data to PGGA to be reduced for precise orbit determinations.

IGS TO THE RESCUE

The idea for a global tracking service was first put forward at the 1989 International Association of Geodesy (IAG) General Assembly in Edinburgh, Scotland, by Ruth Neilan, Gerald Mader, and William Melbourne. That initial suggestion has since been nurtured into the International GPS Geodynamics Service (IGS).

IGS Goals. IGS has two main goals. Its primary long-term goal is to offer the scientific community GPS orbits accurate enough for performing regional and local GPS analysis. The products should enable consistent results for regional or smaller-scale networks that are measured only periodically: typical accuracies are one part in 10^8 and as low as a few parts in 10^9. Its secondary goal is to provide daily precise earth rotation information. The precision levels already achieved by various analysis groups exceed one milliarcsecond per day for polar motion and 0.1 millisecond for length-of-day estimates. As IGS matures, it will provide the user community with information concerning the ionosphere and status of the individual GPS satellites.

These goals are service-oriented; that is, IGS hopes to provide these precise products on a daily basis. The delay in making these products available ranges from five days to two weeks, depending on the timeliness and cutoffs applied to the delivery of the global tracking data. IGS uses numerous processes and communication paths to transfer a full raw data set from the station receivers to the processing centers, and then it requires at least a few days to transform the data set into a refined product available to users.

Development of IGS. In January 1990, IAG president Ivan Mueller invited Neilan, Mader, Melbourne, and Bernard Minster to submit a formal proposal for a permanent international GPS service. During its March 1990 meeting, the IAG executive committee considered the proposal and established a planning group, chaired by Mueller, to further study the concept. The planning group had three goals:

- formulate an organizational structure and present a detailed campaign plan to the 20th General Assembly of International Union of Geodesy and Geophysics (IUGG) in Vienna in August 1991
- organize an observational campaign for 1992, the International Space Year, and
- present a proposal to IAG at the end of the campaign.

The planning group co-opted a wide range of volunteers, and in February 1991 the IGS planning group solicited proposals for data-collecting observatories, data centers, analysis centers, and a central bureau. Since issuing that call for participation, IGS has received about 150 responses — far more than it expected and a direct measure of the need for and importance of the IGS concept. The original call for participation was based on two different networks:

■ a core network of about 30 globally distributed high-quality sites with continuous, daily data transmission to data centers. The network would use data for the determination of orbits and earth rotation parameters.

■ a fiducial network with 100–200 stations to serve as a first densification of the core network. These stations are called fiducial in the sense that they are tied to the global network and the resulting reference frame and coordinate system. If a denser scientific network is planned for some area, investigators can occupy the fiducial station as part of their network and thus tie smaller networks to the international network. This "standardization" can make intercomparisons of results and use of other people's data much easier. This network would be periodically equipped with high-precision geodetic GPS receivers (about one to two weeks every two years). Data flow and data management are too costly to maintain the network continuously at this time.

IUGG — The Next Step. Many IGS-related activities took place during IUGG's 20th general assembly. The original planning group reorganized into the IGS Campaign Oversight Committee (see Table 1), and IUGG adopted Resolution No. 5, which is regarded as the IGS charter. The oversight committee, through working groups, investigated standards for data acquisition, communications, standards for GPS data exchange, analysis center coordination, reference frame issues, and the Epoch '92 Campaign. Of all these activities, the committee's main goal was to organize Campaign '92.

CAMPAIGN '92 — THE FIRST LOOK

Campaign '92 was a comprehensive evaluation of IGS conducted from June 22 to September 22, 1992. The evaluation focused on the transfer of data among data centers and processing centers, processing of the core station data, and finally the shipment of results from the processing centers back to the data centers for dissemination. In addition, the Epoch '92 Campaign experiment took place during this time.

The fundamental design of Campaign '92 was a core network of about 30 globally distributed observing stations (see Figure 1) that used P-code receivers to gather observation data. Figure 2 shows how IGS analyzes and distributes observation data.

Table 2 shows the nominal core sites used in Campaign '92. Some stations use dual-frequency non–P-code instruments and serve as regional backups or as network enhancement at the discretion of the processing centers. Analysis coordinators designated 18 of the sites as important for intercomparison studies. Processing centers included at least 10 such sites in their analyses. The standard for data acquisition is dual-frequency (both L1 and L2) precision P-code receivers producing C/A- and P-code pseudoranges and carrier phases. Processing centers are free to disseminate the data. Prior to the campaign, IGS successfully conducted a full communication test starting at the instruments and concluding at the processing centers to ensure that recording data every 30 seconds was a manageable rate for the existing electronic communication networks. The Receiver Independent Exchange Format (RINEX) was chosen for exchange. The RINEX files were

Table 1. IGS Campaign Oversight Committee

Position	Name	Institution	Country
IGS Chair	G. Beutler	Astronomical Institute, University of Bern	Switzerland
	Y. Bock	IGPP/Scripps Institution of Oceanography	USA
	L. Boloh	CNES	France
IERS — ITRF Coordinator	C. Boucher	IGN	France
	M. Campos	Universidad Federal do Parana	Brazil
Epoch '92 Regional Coordinator	J. Chen	National Bureau Surveying and Mapping	China
Epoch '92 Regional Coordinator	D. Delikaraoglou	EMR, Canadian Geodetic Survey	Canada
	J. Dow	European Space Agency, ESOC	Germany
IGS Vice-Chair	J. Engeln	NASA	USA
Epoch '92 Regional Coordinator	B. Engen	Norwegian Mapping Authority	Norway
	P. Fell	Naval Surface Weapons Center	USA
	M. Fubara	Rivers State University	Nigeria
IGS Analysis Coordinator	C. Goad	Ohio State University	USA
Data Formats Coordinator	W. Gurtner	Astronomical Institute, University of Bern	Switzerland
	T. Kato	Tokyo University	Japan
	G. Mader	NOAA NGS	USA
Epoch '92 Regional Coordinator	J. Manning	Australian Land Information Group	Australia
IERS GPS Coordinator	W. Melbourne	Jet Propulsion Laboratory	USA
Science Advisor Epoch '92	B. Minster	IGPP/ Scripps Institution of Oceanography	USA
Data Flow Coordinator	P. Morgan	University of Canberra	Australia
IAG Representative	I.I. Mueller	Ohio State University	USA
IGS Central Bureau	R.E. Neilan	Jet Propulsion Laboratory	USA
	W. Schluter	IfAG	Germany
President, CSTG	B. Schutz	University of Texas–Austin	USA
	B. Roth	Defense Mapping Agency	USA
Epoch '92 Regional Coordinator	S. Tatevian	Institute for Astronomy	Russia
	H. Tsuji	Geodetic Survey Institute	Japan
	V. Velikov	Institute of Applied Astronomy	USA

compressed using the Lempel-Ziv algorithm to reduce network connection times. Navigation and status files broadcast by the satellites were concatenated and sorted at the network data center level to aid data flow and provide a uniform source of information.

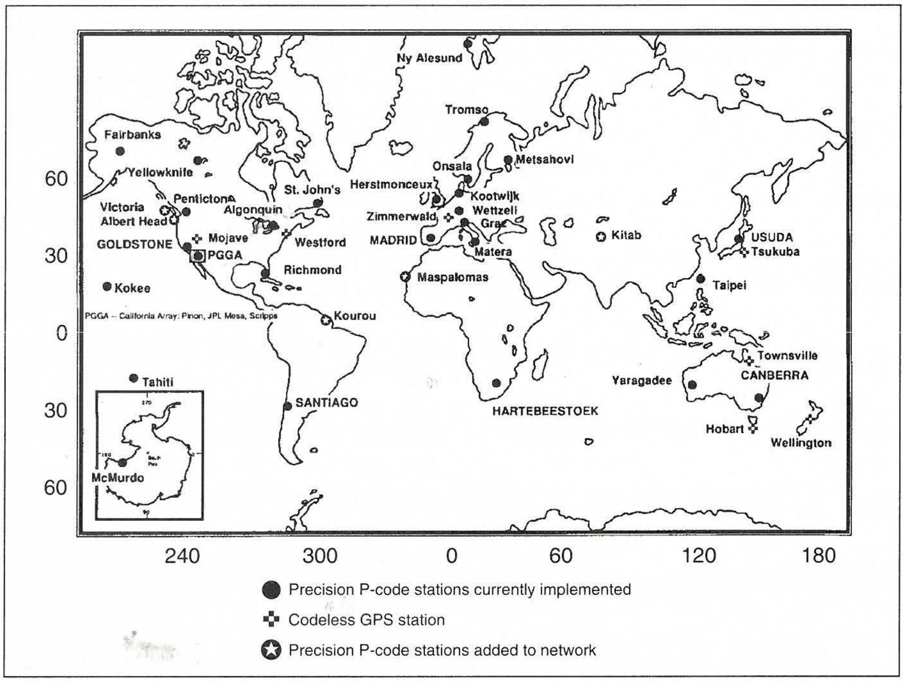
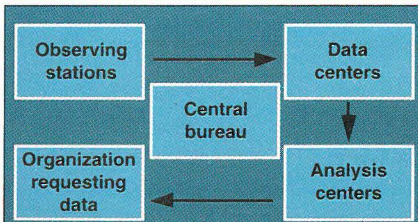


Figure 1. International GPS and Geodynamics Service operational tracking network.

EPOCH '92 CAMPAIGN

Epoch '92 was a classic campaign-oriented GPS experiment conducted from July 25 to August 8. About 100 observation stations served as fiducial sites. Each station was tied to a regional data center for data flow and archiving purposes and to a processing center or an associate processing center to ensure that the data were adequately analyzed and reported. Data from these fiducial sites are expected to flow to the regional data centers after the completion of Campaign '92 because a 90-day delay is permitted due to physical media transfers. Many receivers were operated in remote areas worldwide. Uploading, formatting, and cataloging data from many different receivers and countries is an enormous task; electronic transfer is generally impossible from these locations.

IGS delegated the planning, organization, realization, and processing of Epoch '92 and other future Epoch campaigns to regional coordinators, led by Minster as the scientific adviser. The regions included North and South America; Europe and Africa; Australia/Asia, Southeast Asia, and Antarctica; China; and Russia. The tentative list of stations for Epoch '92 demonstrated that large regions of the Earth's surface are not yet ade-



Observation Stations throughout the world gather P-code data of satellite observables.

Data Centers perform three basic functions. *Operational data centers* operate and provide quality control of observation sites; *regional data centers* handle regional data, especially for global densification; and *network data centers* relay global data to the analysis centers and provide archive functions.

Analysis Centers analyze the core and/or fiducial network data and derive information such as GPS ephemerides, earth rotation, reference frame, and site coordinates. *Processing centers* focus on the global analysis of data collected mainly by the core network; *associate processing centers* analyze specific times and/or data sets; and *evaluation centers* assess overall quality and performance.

Central Bureau coordinates and manages the service. Major responsibilities include liaison with external organizations, product distribution, and information dissemination.

Figure 2. Flow of IGS data.

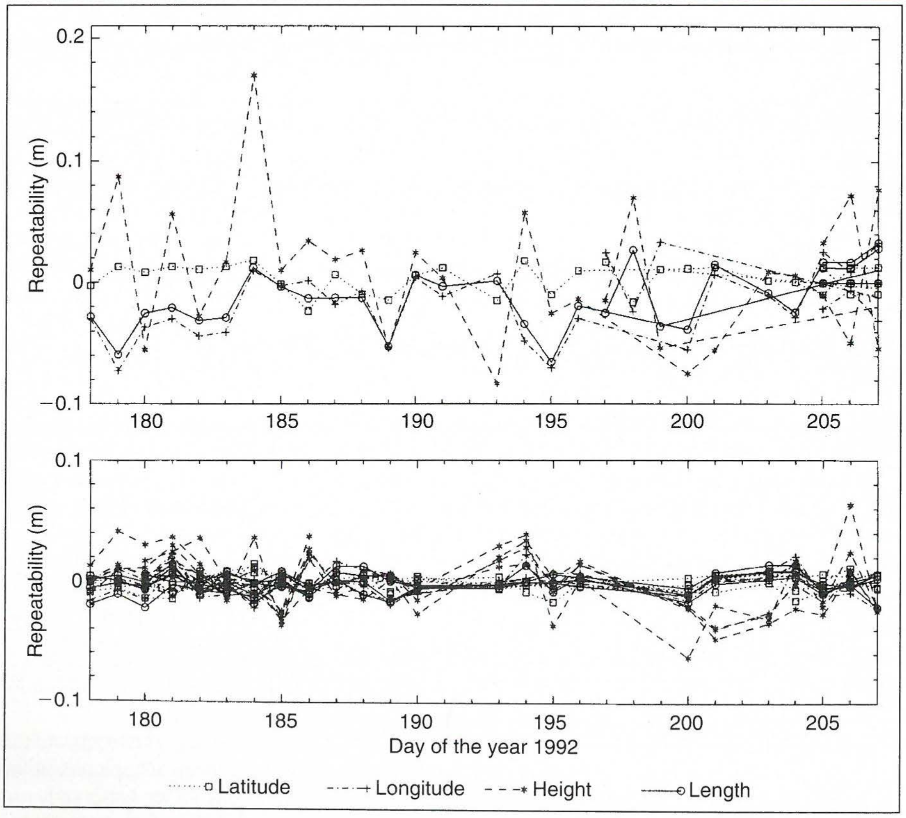


Figure 3. Baseline Wettzell Zimmerwald (470 kilmeters) broadcast ephemerides compared to IGS ephemerides.

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quately covered for truly global reference frame control. The final list of stations occupied will be available by the end of 1992.

Results. The analysis centers provided detailed analyses of the results of the individual processing centers. The accompanying figures demonstrate that IGS product quality met IGS's high expectations.

Figures 3a and 3b show the baseline repeatabilities in latitude, longitude, height, and length obtained when processing the daily 24-hour observation files from Wettzell, Germany, and Zimmerwald, Switzerland, using broadcast orbits in Figure 3a and using the IGS orbits (produced by the processing centers of Table 2) in Figure 3b.

Table 2. Campaign '92 core network stations used by processing centers

	Station	CSR	GFZ	CODE	ESOC	JPL	SIO	Total Number Processed
1	Wettzell*	✗	✗	✗	✗	✗	✗	6
2	Tromso*	✗	✗	✗	✗	✗	✗	6
3	Algonquin*	✗	✗	✗	✗	✗	✗	6
4	Yaragadee*	✗	✗	✗	✗	✗	✗	6
5	Canberra*	✗	✗	✗	✗	✗	✗	6
6	Usuda*	✗	✗	✗	✗	✗	✗	6
7	Yellowknife		✗	✗	✗	✗	✗	5
8	Hartebeestoeck*	✗	✗		✗	✗		4
9	Kokee*	✗	✗	✗		✗	✗	5
10	Tahiti*	✗	✗		✗	✗		4
11	Santiago*	✗	✗		✗	✗	✗	5
12	Madrid	✗		✗	✗	✗	✗	5
13	Goldstone	✗	✗	✗		✗	✗	5
14	Fairbanks*	✗	✗		✗	✗	✗	5
15	McMurdo*	✗	✗		✗	✗	✗	5
16	Herstmonceux*	✗			✗	✗	✗	4
17	Ny Alesund		✗		✗	✗	✗	4
18	Richmond*			✗	✗	✗	✗	4
19	Matera*			✗	✗	✗		3
20	Kootwijk				✗	✗	✗	3
21	Tai Pei*	✗		✗	✗	✗		4
22	Penticton*			✗		✗	✗	3
23	*Wellington*			✗			✗	2
24	*Hobart*			✗			✗	2
25	*Townsville*						✗	1
26	Onsala					✗	✗	2
27	Pinon Flat*					✗	✗	2
28	Metsahovi					✗		1
29	*Mojave*							
30	*Tsukuba*							
31	JPL					✗		1
32	Maspalomas					✗		1
33	Kourou							
34	Kitab							
35	Alberthead					✗		1
36	*Westford*							
37	Scripps							
38	*Zimmerwald*							
39	Graz							
40	St. John's							
	Total # Stations	16	15	16	19	28	23	

CSR: Center for Space Research, University of Texas at Austin
GFZ: Geoforschungszentrum
CODE: Center for Orbit Determination in Europe
ESA/ESOC: European Space Agency, Operations Center
JPL: Jet Propulsion Laboratory
SIO: IGPP/Scripps Institute of Oceanography
* designated as important for intercomparison studies
Italics: stations use dual-frequency non–P-code instruments and serve as regional backups or at the discretion of the processing centers for network enhancement

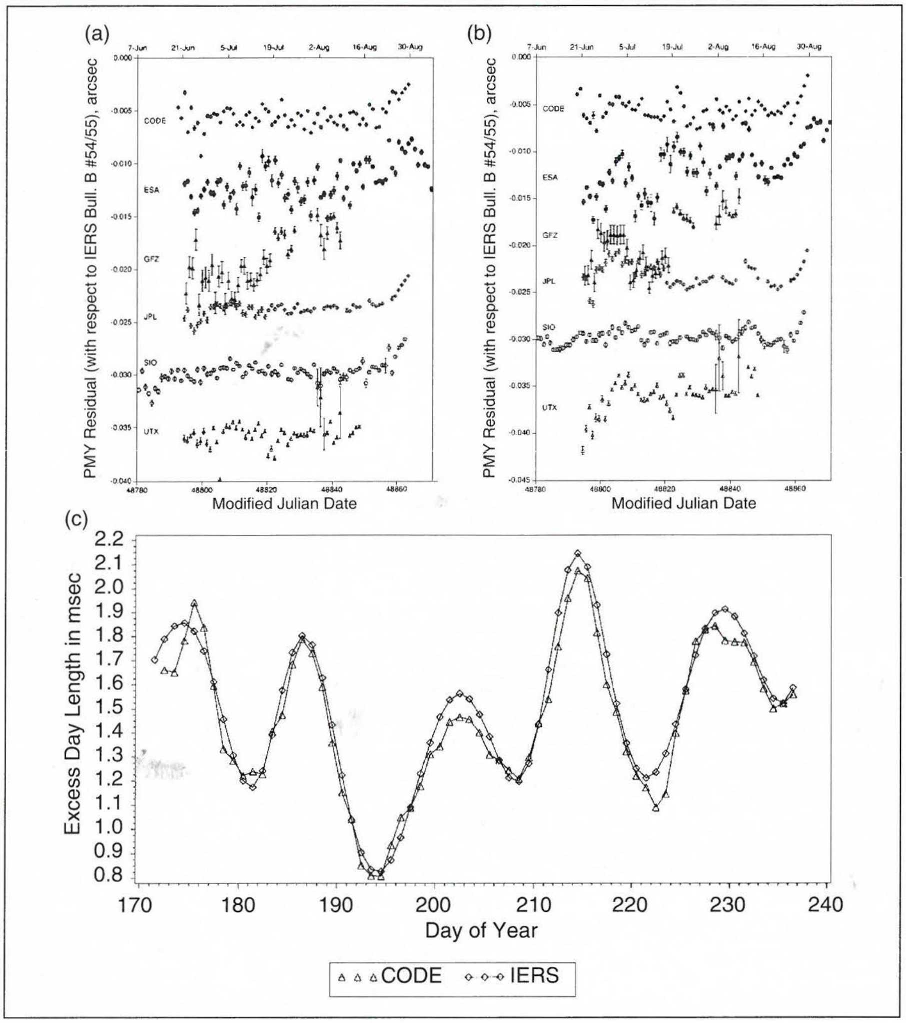

Figure 4. The difference between each center's estimate of the *x* and *y* positions of the pole and as determined by the International Earth Rotation Service. Figure 4c shows earth rotation parameters from the Center for Orbit Determination.

The length of the baseline is 470 kilometers, and none of the processing centers used the Zimmerwald data in the orbit-determination step because it would have skewed the results. A single software package processed the baseline (which demonstrates that one center is able to use the products of the other centers). Figure 3a shows that the Defense Mapping Agency was producing excellent broadcast orbits for the time span analyzed (June 21–July 23). The comparison of Figures 3a and 3b indicates that the IGS orbits are superior to the broadcast by about one order of magnitude. The difference between the broadcast and IGS orbits becomes even more apparent for longer baselines.

Figures 4a–4c demonstrate that GPS is indeed capable of estimating the earth rotation parameters with a high degree of accuracy. Plotted in Figures 4a and 4b is the difference between each center's estimate of the *x* and *y* position of the pole and that positions determined independently by the International Earth Rotation Service (IERS). This agreement of about 2 milliarcseconds is equivalent to about 6 centimeters in pole position and demonstrated that GPS is a useful tool for monitoring earth rotation parameters.

It is also impressive that though the computing software for each center is independent, processing centers agree so well with each other. (Each center's results are plotted with a separate, arbitrary origin for clarity so they do not overlap in the plot.) Figure 4c demonstrates similar agreement with IERS in determining universal time (UT1). All of the processing centers in Table 2 solve for earth rotation parameters as part of their service. These figures show that the IGS estimates of the *x* and *y* coordinates of the pole agree with those of IERS.

CONCLUSIONS

IGS marks a turning point in international cooperation in the use of GPS to determine precise ephemerides, earth rotation parameters, and ties to the terrestrial reference frame through collocation and station coordinates at a defined epoch. This coordinated effort has tested the daily limits of operational, data transfer, and computational structures. In addition, IGS is trying to densify global coverage and information with the fiducial stations used during the Epoch '92 experiment.

IGS requires the resources and cooperation of many organizations throughout the world. Some important examples are listed below:

- the European consortium's determination of regional orbits from observations at laser ranging and VLBI sites and the comparison of these orbits with globally determined orbits
- the Japanese permanent monitoring networks for earthquake research
- the PGGA array of JPL and SIO for regional deformation
- NASA's experiment to demonstrate GPS tracking of the low-earth-orbiting TOPEX/Poseidon Satellite
- the Norwegian SATREF Project.

Finally, Campaign '92 demonstrated the type of permanent international GPS service necessary for the near future and also provided us with a very rich and dense data set with which to begin a study of global change. ■

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