THE INTERNATIONAL GPS SERVICE FOR GEODYNAMICS (IGS): THE STORY

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ABSTRACT

The primary goal of the *International GPS Service for Geodynamics (IGS)* is to provide highly accurate *orbits, earth rotation parameters, and station coordinates* derived from observations of the Global Positioning System (GPS) to the geodynamics community, which currently demand the highest accuracy. A further goal is the extension of the IERS Terrestrial Reference Frame (ITRF) for the purpose of global accessibility. The data of the permanent IGS network consisting of about 80 stations are transmitted on a daily basis to regional and global data centers from where they are retrieved by the IGS Analysis Centers.

Today the IGS produces a *combined orbit* based on the contributions of seven Analysis Centers in addition to the orbit- and earth rotation- series of the individual IGS Analysis Centers. The IGS orbit is available about two weeks after the observations, its accuracy is of the order of 10 cm. The IGS orbits together with the IGS station coordinates and the GPS measurements in the IGS network give the user community a direct access to the ITRF.

The paper gives an overview of the development of the IGS through 1995. The present structure is discussed, the accuracy and the reliability of the products will be mentioned, current developments and future plans will be presented.

DEVELOPMENT OF THE IGS

According to (Mueller, 1993), the primary motivation in planning the IGS was the recognition in 1989 that the most demanding users of the GPS satellites, the geophysical community, were purchasing receivers in exceedingly large numbers and using them as more or less black boxes, using software packages which they did not completely understand, mainly for relative positioning. The observations as well as the subsequent data analyses were not based on common standards; thus the geodynamic interpretation of the results could not be trusted. The other motivation was the generation of precise ephemerides for the satellites together with by-products such as earth orientation parameters and GPS clock information.

Table 1: Chronicle of Events 1989-1991

Date	Event
Aug 89-Feb 90	IAG General Meeting in Edinburgh. Initial Plans developed by I.I. Mueller, G. Mader, W.G. Melbourne, B. Minster, and R.E. Neilan
16-Mar-90	IAG Executive Committee Meeting in Paris decides to establish a Working Group to explore the feasibility of an IGS under IAG auspices. I.I. Mueller was elected as chairman.
25-Apr-90	The Working Group is redesignated as *The IAG Planning Committee for the IGS* in Paris
02-Sep-90	Planning Committee Meeting in Ottawa Preparation of the Call for Participation (CFP)
01-Feb-91	CFP mailed. Letters of Intent due 1 April 1991
01-Apr-91	CFP Attachments mailed to those whose letters of intent were received
01-May-91	Proposals due
24-Jun-91	Proposals evaluated and accepted in Columbus, Ohio
17-Aug-91	Planning Committee reorganized and renamed as IGS Campaign Oversight Committee (OSC) at the 20th IUGG General Assembly in Vienna
24-Oct-91	First IGS Campaign Oversight Committee Meeting in Greenbelt, MD. Preparation of the 1992 IGS Test Campaign scheduled for 21 June - 23 September 1992 and for a two weeks intensive campaign called Epoch 92

These ideas were first discussed in 1989 at the IAG General Meeting in Edinburgh (Neilan, Melbourne and Mader, 1990) and led soon thereafter to a Working Group (later redesignated as the *IAG Planning Committee for the IGS*) with Ivan I. Mueller, then President of the IAG, as chairman. After several meetings the *Call for Participation* was issued by this group on 1 February 1991. More than 100 scientific organizations and governmental survey institutions announced their participation either as an observatory (part of the IGS network), as an analysis center, or as a data center. The Jet Propulsion Laboratory (JPL) volunteered to serve as the Central Bureau, and The Ohio State University as the Analysis Center Coordinator. At the 20th General Assembly of the IUGG in Vienna, August 1991 the IAG Planning Committee was restructured and renamed as *IGS Campaign Oversight Committee*. This committee started organizing the 1992 events, namely the *1992 IGS Test Campaign* and *Epoch'92*. Two IGS Workshops (the first at the Goddard Space Flight Center in October 1991, the second in Columbus, Ohio in March 1992) were necessary to organize the 1992 activities. The essential events of this first phase of the IGS development are summarized in Table 1.

The 1992 IGS Test Campaign, scheduled from 21 June to 23 September 1992, focused on the routine determination of high accuracy orbits and ERPs; it was to serve as the proof of concept for the future IGS. Epoch'92 on the other hand was scheduled as a two-week campaign in the middle of the three-month IGS Campaign for the purpose of serving as a first extension of the relatively sparse IGS Core Network analyzed on a daily basis by the IGS Analysis Centers. More background information about this early phase of IGS may be found in (Mueller, 1993), (Mueller and Beutler, 1992).

Two events prior to the 1992 IGS Test Campaign have to be mentioned: (1) the *communications test*, organized by Peter Morgan, Australia, demonstrated that data transmission using the scientific Internet facility had sufficient capacity for the daily data transfer from the IGS stations to the Regional, Operational and Global Data Centers then to the Analysis Centers. (2) The establishment of the *IGS Mailbox* and the *IGS Report* series based on e-mail proved to be very important as information resources and as a tool to insure a close cooperation between the IGS participants. This e-mail service, initially located at the University of Bern, was transferred to the Central Bureau (JPL) by the 1st of January 1994.

The 1992 IGS Campaign started as scheduled on 21 June 1992. About two weeks later the first results of the IGS Analysis Centers started to flow into the IGS Global Data Centers, which made these results available to the user community. The ERP series were regularly analyzed by the IERS Central Bureau and by the IERS Rapid Service Sub-bureau.

Data collection and transmission as well as data analysis continued on a *best effort basis* after the official end of the 1992 IGS Test Campaign on 23 September, 1992. At the third IGS Campaign Oversight Committee meeting on October 15, 1992 at Goddard Space Flight Center (Table 2) it was decided to formally establish the IGS Pilot Service to bridge the gap between the 1992 IGS Test Campaign and the start of the official service. Since 1 November 1992 the orbits of the individual processing centers were regularly compared by the IGS Analysis Center Coordinator (Goad, 1993). An overview of the 1992 IGS events may be found in the Proceedings of the 1993 IGS Workshop (Brockmann and Beutler, 1993).

Two Workshops, the Analysis Center Workshop in Ottawa (Kouba, 1993) and the Network Operations Workshop in Silver Spring, MD, and the first Governing Board (GB) Meeting (also in Silver Spring) took place in October 1993. One important outcome of IGS meetings in October 1993 was the decision to produce an official IGS orbit. This responsibility was given to the IGS Analysis Center Coordinator, who, according to the Terms of Reference must be an analysis centers' representative.

Table 2: Chronicle of Events 1992-1993

Date	Event
17-Mar-92	2nd IGS O S C Meeting at OSU,Columbus,Ohio
04-May-92	Communication Tests
21-May-92	IGS e-mailbox installed
21-Jun-92	Start of IGS Test Campaign
01-Jul-92	First results, about 2 weeks after begin of campaign
27-Jul-92	Start of Epoch-92 (2 weeks)
23-Sep-92	official end of campaign, NOT of data collection, processing
15-Oct-92	3rd IGS O S C Meeting at GSFC,Greenbelt MD
01-Nov-92	Start of IGS PILOT Service Start of routine orbit comparisons by IGS Analysis Center Coordinator
24-Mar-93	1993 IGS Workshop and 4th IGS O S C Meeting at the University of Bern
27-May-93	5th IGS O S C Meeting, AGU, Baltimore MD
09-Aug-93	IAG-Symposium in Beijing. Approval of the Service by the IAG
12-Oct-93	Analysis Center Workshop, Ottawa
18-Oct-93	Network Operations Workshop and 1st IGS Governing Board Meeting in Silver Spring MD
08-Dec-93	GB Business Meeting in San Francisco

In view of the success of the 1992 IGS Test Campaign and of the IGS Pilot Service the IGS Campaign Oversight Committee at its 4th Meeting in March 1993 in Bern decided to take the necessary steps towards the establishment of the official IGS on 1 January 1994. In particular the Terms of Reference for this new service were written (IGS Colleague Directory, 1994), the organizations active in the 1992 IGS campaigns were asked to confirm their participation in the future service, and last but not least the IAG approval for the establishment of the IGS for 1 January 1994 was requested. It was encouraging that most of the key organizations confirmed their participation in the official service: the Central Bureau stayed at JPL, the three Global Data Centers and all but one Analysis Centers continued contributing to the IGS. In view of this encouraging development it was gratifying that the preliminary IAG approval (to be confirmed at the 21st IUGG General Assembly in Boulder, 1995) was given in August 1993.

A key element of the new Service is the Governing Board (GB) consisting of 15 members (current membership in (IGS Colleague Directory)). Another key element is the interface between the IGS and the IERS both being IAG services with many common interests. In practice the IERS relies on the IGS for all GPS operations, the IGS in turn relies on the IERS for the continuous maintenance of the terrestrial reference frame.

Table 3 contains the essential events since the start of the official IGS on January 1, 1994. It was of greatest importance that the Central Bureau Information System (CBIS) (Liu et al, 1994) and the combined IGS orbit (Beutler, Kouba, Springer, 1995) became available with the start of the new service.

The densification of the ITRF through regional GPS analyses was a key issue in 1994. The guidelines for such a densification were defined at the IGS Workshop in December 1994. The topic will continue to be in the center of IGS activities in 1995 and in the years to come.

Table 3: Chronicle of Events 1994- mid 1995

Date	Event
01-Jan-94	Start of official IGS Production of Combined IGS Orbit Central Bureau Information System (CBIS) established
21-Mar-94	Combined Workshop IERS/IGS in Paris (1 week)
25-Mar-94	2nd IGS Governing Board Meeting
30-Nov-94	IGS Workshop Densification of the ITRF through regional GPS Analyses in Pasadena
06-Dec-94	3rd IGS Governing Board Meeting in San Francisco
15-May-95	IGS Workshop on special Special Topics and New Directions in Potsdam
06-Jul-95	4th IGS Governing Board Meeting in Boulder

STRUCTURE AND PERFORMANCE OF THE IGS IN 1995

The IGS consists of a *network* of permanent high-accuracy GPS tracking receivers, a set of operational, regional, and global *data centers*, currently seven *Analysis Centers*, the *Analysis Center Coordinator*, the *IGS Central Bureau*, and the IGS Governing Board (IGS Colleague Directory).

The network was considerably growing since the 1992 IGS Test Campaign. Figure 1 shows the current permanent IGS tracking network, where the distinction is made between fully operational and planned or future sites. Even today the network is far from ideal : we still have the problem that the regions of the former USSR, of China, India and of the Southern hemisphere are underrepresented; but the situation is *much better today* than in 1992. It should be mentioned that all operational sites in Figure 1 are connected with high performance data links. Usually the scientific Internet facility is used, sometimes satellite data links had to be established (e.g. from Kitab to Potsdam by the GFZ).

Figure 1: IGS Permanent Tracking Network in 1995

Table 4: Analysis Centers (A), Global Data Centers (D), Analysis Center Coordinator (C), Central Bureau (B) of the IGS

Abbreviation	Institution	Participating
CODE (A)	at Astr. Institute, Bern, Switzerland joint venture of AIUB, IfAG, IGN, and Swiss Federal Office of Topography	since 21 June 1992
NRCan(A)	Natural Resources, Canada (former EMR)	since September 1992
ESOC (A)	European Space Agency, Germany	since 21 June 1992
GFZ (A)	Geoforschungszentrum, Germany	since 21 June 1992
JPL (A)	Jet Propulsion Laboratory, USA	since 21 June 1992
NOAA (A)	Natl. Oceanic and Atmosph. Adm. USA	since March 1993
SIO (A)	Scripps Inst. of Oceanography, USA	since 21 June 1992
UTX (A)	University of Texas at Austin,USA	21 June to 23 Sep 1992
CDDIS(D)	Goddard Space Flight Center, USA	since 21 June 1992
IGN (D)	Institut Geographique National, France	since August 1992
SIO (D)	Scripps Institution of Oceanography USA	since 21 June 1992
OSU (C)	Ohio State University	21 June 92 - Dec 1993
NRCan(C)	Natural Resources, Canada (former EMR)	since January 1994
JPL (B)	Jet Propulsion Laboratory, USA	since 21 June 1992

Table 4 lists the IGS Analysis Centers (A), the Global Data Centers, the current IGS Analysis Coordinating Center (C), and the IGS Central Bureau (B). Table 4 documents the remarkable stability of the essential IGS components. Let us keep in mind that the primary task of the IGS Analysis Center Coordinator (C) is the *production of the combined IGS orbit* based on the contributions of the currently seven IGS Analysis Centers. The Central Bureau coordinates all IGS activities, it is also responsible for the interface with the IERS. The *Central Bureau Information System (CBIS)* introduced in the previous section is accessible through Internet from all over the world.

A thorough discussion of the quality of IGS products as available today would require much more space than is available in this short report. We confine ourselves to a few remarks concerning the orbit quality and refer to other articles in the same volume for a more detailed discussion of the quality of clocks (Mireault et al, 1995) and earth rotation and orientation parameter (McCarthy, 1995). The quality of the annual coordinate solutions stemming from IGS Analysis Centers is e.g. documented in the first IGS Annual Report (Zumberge et al, 1995a).

Figure 2 gives an impression of the consistency of the orbits stemming from different IGS processing agencies. We can see the rms per satellite coordinate of the fit of individual solutions with respect to the IGS Combined Orbit as it is computed for every day by the IGS Analysis Center Coordinator (Table 4, weekly averages are given in Figure 2). Clearly the best four contributions show an rms-consistency per satellite coordinate of about 10 cm. We also see a clear trend of all processing centers to the same level of accuracy. This fact makes the orbit combination relatively unproblematic, and the detection of occasional outliers relatively easy. In consequence the IGS combined orbit is not only a very accurate, but also a very *robust and reliable* product (the principles of IGS orbit combination are given in (Beutler, Kouba, Springer, 1993)).

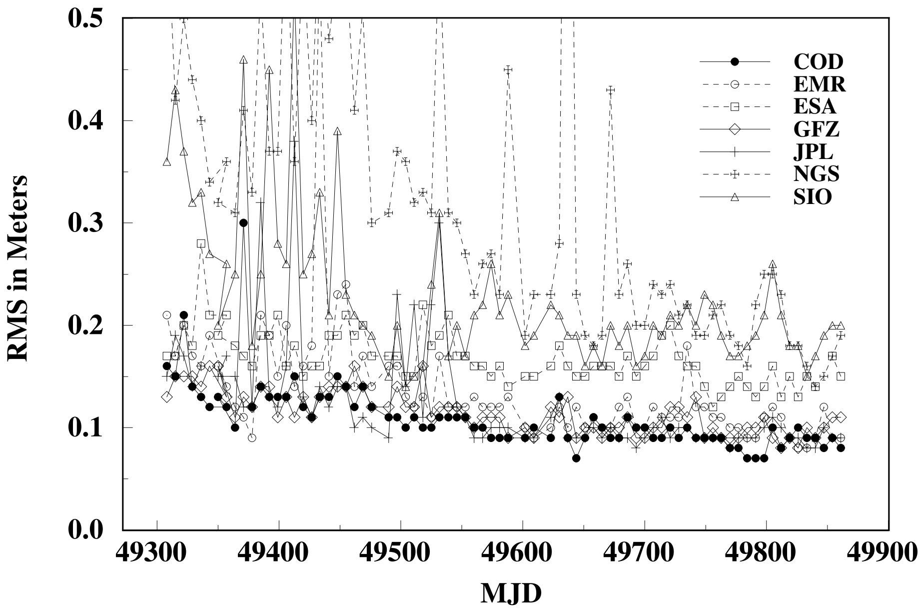

Figure 2: Orbit Quality from IGS Orbit Combination November 1993 - May 1995 (Weighted RMS, Weekly Averages)

This high level of consistency is also reflected by the other IGS products. We believe that today the precision of the individual IGS polar motion series are of the order of 0.2 - 0.5 mas for diurnal estimates (these are the accuracies attributed to the individual IGS series by the IERS), that the length of day estimates (daily means) are of the order of 0.03 msec/day), and that the precisions of the IGS coordinates are about centimeter in annual coordinate solutions (sub-centimeter values in horizontal coordinates, 1-2 cm in height). With increasing length of the IGS time series the velocity estimates for the IGS tracking network are becoming more and more reliable, too.

RECENT, CURRENT AND FUTURE DEVELOPMENTS WITHIN THE IGS

Let us discuss some results of the latest two IGS Workshops, namely the *IGS Workshop Densification of the ITRF through regional GPS Analyses in Pasadena* and the *IGS Workshop on special Special Topics and New Directions in Potsdam.*

The first attempt to densify the relatively sparse permanent IGS tracking network in Figure 1 to a network of relatively uniform density (spacings of 1000 - 2000 km are aimed at) was *the 1992 IGS Epoch Campaign* (Table 2). A large number of sites was observed during the two weeks and processed afterwards, some of the networks measured (e.g. the French DORIS network) even showed a rather nice global distribution. Due to several reasons the overall result was *not* satisfactory, however. Therefore it was decided to devote a three-days Workshop to the topic of densifying the IGS network.

Four position papers were presented at the *IGS Workshop Densification of the ITRF through regional GPS Analyses in Pasadena* (Zumberge and Liu, 1995b). The main conclusions may be summarized as follows:

- The densified IGS network should consist of about 200 globally well distributed sites. A maximum spacing should be specified.
- *Wherever possible permanent tracking should be established.*
- The densification should be realized in cooperation with other groups setting up permanent GPS networks (e.g. the Gloss group).
- Regional analyses will be performed by (new) IGS Associate Analysis Centers, called AAC Type-1 in this context. These will make extensive use of the global products (orbits, ITRF coordinates and velocities of sites well established in the global network). These AACs produce free network solutions on a weekly basis. The seven IGS Analysis Centers may play the role of AAC Type-2, too.
- The weekly free network solutions will be combined by special IGS analysis centers, called AAC Type-2 at present. These centers will analyse the results of the AAC Type-1 and prepare a weekly combined solution, giving all results in a consistent reference frame.
- A Pilot Phase involving *initially* only the seven IGS processing centers of the IGS as AAC Type-1 and *three AAC Type-2* will start on 1 September 1995 and will last for one calendar year. The three AAC Type-2 are:
  - Jet Propulsion Laboratory, Pasadena (J. Zumberge)
  - University of Newcastle (G. Blewitt)
  - Scripps Institution of Oceanography (Y. Bock)

  Later in the experiment a selected number of AAC Type-1 will join the Pilot Project.
- The ITRF section of the IERS will accompany the Pilot Project by analyzing the products of the AAC Type-2 on a monthly basis.

The topics at the *IGS Workshop on special Special Topics and New Directions in Potsdam* were quite different. The focus was on one hand on processing aspects (fascinating orbit modeling aspects and antenna problems were discussed) on the other hand on possible new products like the *ionosphere models*, the *station-specific precipitable water content values* with a high temporal resolution using the IGS network. Last but not least *commercial aspect* of the IGS activities were considered. For a more complete report we refer to (Beutler, 1995) and of course to the proceedings of this Workshop which are under preparation. Let us add a few remarks concerning the earth's atmosphere.

All IGS Analysis Centers have to model tropospheric refraction. It was shown that the consistency of estimates stemming from different IGS Analysis Centers is relatively high. It should thus be possible to extract on a routine basis the precipitable water content for the entire IGS network with a high temporal resolution (two hours or finer) – *provided high accuracy barometers are deployed in the IGS network.* Even if the IGS products are available "only" about two weeks after the observations, the results are still most valuable *for climatological studies.* Should the IGS decide to produce very rapid products in addition to what is available today, the same estimates might be used for weather prediction, a topic of highest interest to meteorologists (Bevis et al, 1992).

The motivation to produce GPS derived ionosphere models is manyfold: Local or regional models may be used to remove (reduce) biases in single frequency surveys; regional or global models may be used to calibrate e.g. altimeter measurements (ERS-1 is an example) or to calibrate radio signals from space vehicles in the planetary system; last but not least there are pure research projects (ionosphere maps, extraction of geomagnetic indices). At present we may *not* speak of a high degree of consistency of ionosphere models produced by different IGS Analysis Centers. This will be one aspect to focus on in the near future. The other, more important, aspect for the future development is to define an interface between the IGS and the ionosphere research community. What exactly is needed in ionospheric research, what kind of products should be made available ? The IGS definitely needs the help of the mentioned research community.

This report reflects (hopefully) the fact that the IGS is a most stimulating and rewarding adventure for all its participants. This GPS *service* makes essential contributions not only to geodesy an to regional and global geodynamics, but also to scientific areas like meteorology and ionosphere physics.

Undoubtedly the progress made since the XXth IUGG General Assembly in Vienna is far beyond any expectations. Only three years after the first plans the IGS, an IAG service in support of geodesy and geodynamics, became fully operational on January 1, 1994. In view of the complexity of this task such a rapid development is an achievement in itself. It was made possible through the experience, the expertise, and the pioneer spirit in the IGS Campaign Oversight Committee and its working groups. The IGS Oversight Committee was dissolved by the end of the 1993. We should acknowledge its important contribution to the creation of the IGS.

The first one and a half years of the official IGS service were extremely successful, too: the official IGS orbit has become the accepted standard for a highly accurate GPS orbit. The Central Bureau Information System (CBIS) developed into the reliable source of information about the IGS for a growing user community.

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