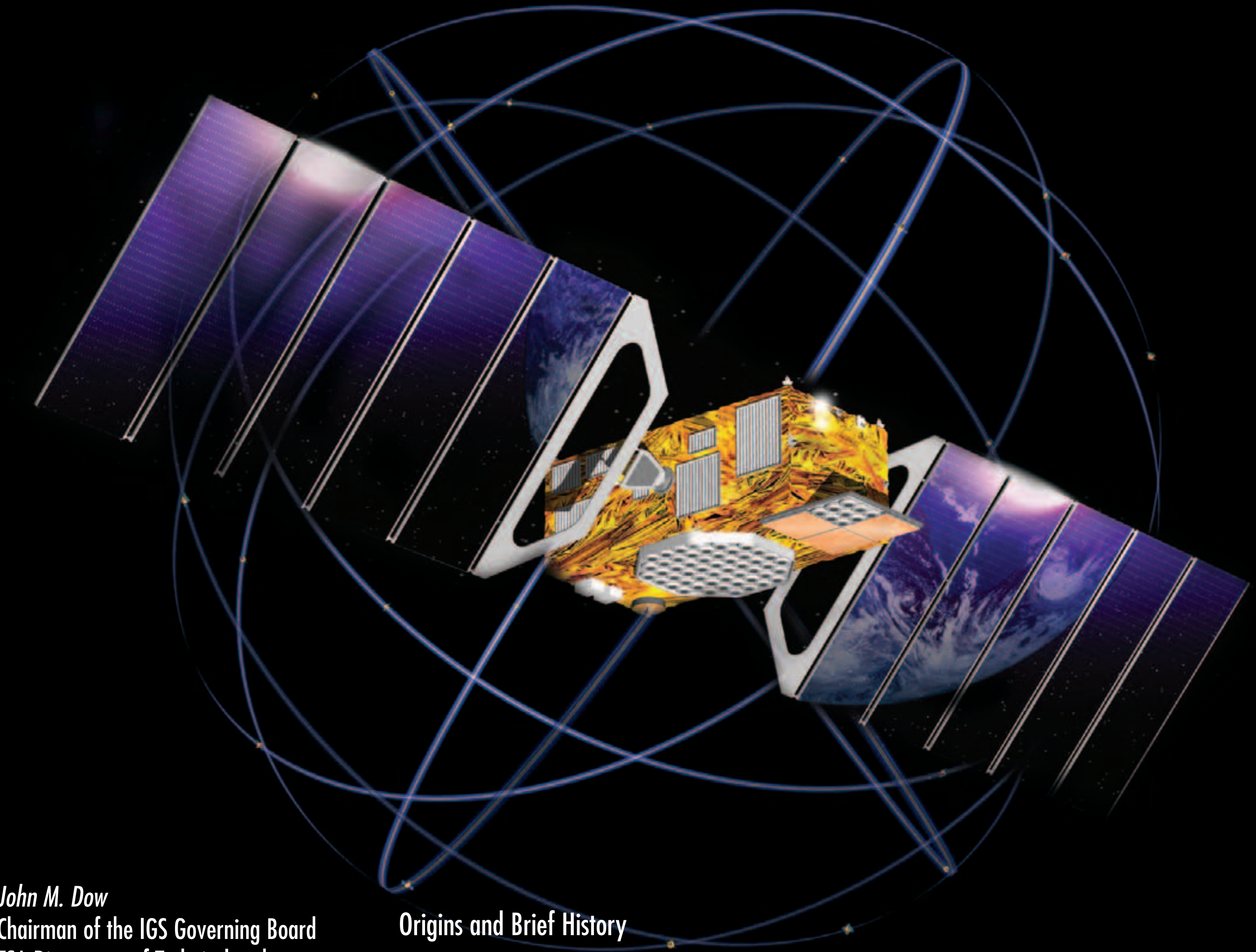
IGS The International GPS Service – for Leading-Edge Space Missions



John M. Dow
Chairman of the IGS Governing Board
ESA Directorate of Technical and Operational Support, ESOC, Darmstadt, Germany

Origins and Brief History

Global Navigation Satellite Systems (GNSS) are gradually becoming part of our daily lives. Their uses for aircraft navigation and more and more in our private cars are especially well-known. The general concept involves measuring distances from the user to several satellites and thereby obtaining an almost instantaneous determination of one's current position. The user systems are passive in that only the satellites transmit signals, and are based on the time differences between the transmission and reception of the signals. Two essential elements of the system are therefore a highly stable oscillator in the user receiver and an algorithm that determines the offset between the GNSS system time and the user's clock, as well as his or her position.

The classical type of GNSS is the US Global Positioning System (GPS), which has been developed and refined over the past 30 years and was declared fully operational in 1995. The system consists of at least 24 satellites orbiting in six evenly distributed planes inclined at 55 degrees to the Earth's equator, at about 20 000 km altitude. There are currently 27 usable GPS satellites in orbit. A similar Russian system (GLONASS) briefly achieved an operational constellation of 24 spacecraft in the mid-1990s, but at present only 10 are active.

After a number of years of preparatory studies, Europe is now well on the way to developing its own system, Galileo, joint funded initially by the European Union and ESA and later, it is planned, by private investment. Galileo will comprise 30 satellites in three inclined orbital planes, a few thousand kilometres higher than the GPS and GLONASS satellites in order to minimise the number of correction manoeuvres needed during the system's 20-year lifetime.

During the 1980's, as the first GPS satellites went into orbit, it became clear that the system had great potential for scientific applications requiring positioning accuracies much beyond those specified by the system owner (the US Department of Defense). At a meeting held in 1989 during the Assembly of the International Association of Geodesy (IAG) in Edinburgh (UK), it was proposed to set up a network of GPS receivers for this purpose. In 1991 a Campaign Organising Committee was appointed by the IAG and, following a Call for Proposals, 45 agencies and institutions joined forces to carry out a three-month test campaign, from June to August 1992, involving tracking the GPS satellites from about 30 stations, centralising the data rapidly through the (then just emerging) Internet for processing. With a few weeks' time lag, the analysis centres began to produce orbital solutions for the whole constellation which were about two orders of magnitude more accurate than the orbital data broadcast to users by the satellites themselves.

This campaign was such a success that the participants decided to continue operations without interruption. The 'International GPS Service for Geodynamics (IGS)' was officially launched as an IAG service in January 1994. The name clearly indicated the scope of the new service, which in particular was supporting research on plate motions and earthquake movements. A central task was to maintain an accurate Terrestrial Reference Frame, through determinations of Earth orientation parameters (rotation and polar motion) and a grid of globally distributed ground reference points. As the service developed, more and more applications were investigated, and in 1998 the name was shortened to 'International GPS Service'.

ESA, at its European Space Operations Centre (ESOC) establishment in Darmstadt, has been actively involved in the IGS from the outset, as a station operator and operational data centre (currently running GPS at 8 sites world-wide) and as an analysis centre, and has played an active role in a number of Working Groups and on the international Governing Board.

The GPS equipment at ESA's New Norcia ground station in Western Australia

Organisation and Available Products

The IGS routinely provides:
– high-quality orbits for all GPS satellites: accuracy is better than 5 cm, while real-time predictions are better than 25 cm at any time (the satellites broadcast orbits with accuracies of ca. 3 m)
– satellite and ground receiver clock correction with sub-nanosecond accuracy
– Earth orientation parameters (rotation, polar motion)
– tracking-site coordinates and velocities in the International Terrestrial Reference Frame, currently ITRF 2000
– pseudo-range and phase measurements, in daily and/or hourly files.

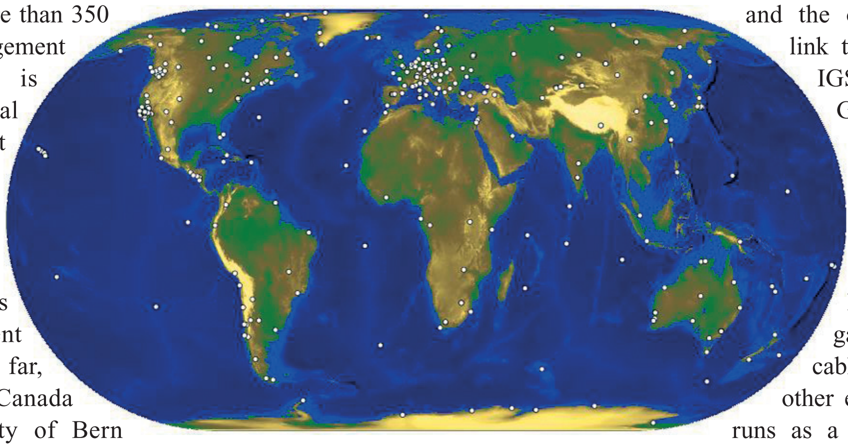
Over 200 institutions in more than 75 countries now participate in the IGS, providing data from more than 350 sites. Day-to-day management of the operations is conducted by a Central Bureau, located at the Jet Propulsion Laboratory in Pasadena (USA) and by the Analysis Centre Coordinator (ACC). The ACC function rotates between the different Analysis Centres: so far, Natural Resources Canada (Ottawa), the University of Bern (Switzerland), and (currently) the GeoForschungsZentrum Potsdam (Germany) have performed this task.

The basic products are classified according to their latency (time elapsed since the last measurement data included in the solution). At present, IGS 'Final' orbit and clock products are available within 11 days, 'Rapid' products within 17 hours, and 'Ultra-rapid' products within 3 hours. The latter are currently generated twice per day and include 24 hours of prediction, thus ensuring the availability of real-time orbit and clock products. No restrictions have been placed on user access to products.

Examples of the use of IGS products in place of GPS broadcast messages include 'precise point positioning' using GPS data from a user receiver and IGS orbit and clock solutions with centimetre accuracy, provided a few modelled corrections are taken into account (mainly tides and antenna offsets).

Special Projects of the IGS

Over the years a number of special activities have developed within the IGS. These have generally been organised in the form of Working Groups or Pilot Projects. In some cases they are of a fundamental nature (e.g. timing or reference frame) affecting all the basic products, in others they may be considered to be 'nuisance parameters' that need to be modelled or estimated within the basic algorithms (e.g. atmospheric products - troposphere and ionosphere).



The IGS global tracking network in 2003

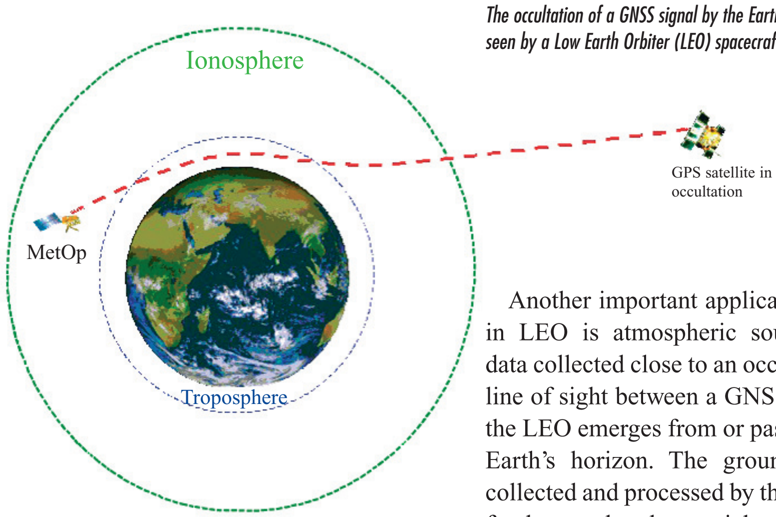
Reference Frame
The IGS Reference Frame (RF) Coordinator has responsibility for the coordination of IGS inputs to the International Terrestrial Reference Frame (ITRF). The ITRF is maintained by the International Earth Rotation and Reference Frame Service (IERS – name slightly modified since January 2003). GPS plays a major role in the ITRF, due to the large number of well-distributed, very well determined sites which it contributes (typical accuracies are 3 mm horizontally and 6 mm vertically, worldwide). The RF Coordinator is assisted by a Working Group consisting of representatives of the Analysis Centres and the IERS. The principal inputs from the Analysis Centres are weekly updates for the station positions and velocities and the Earth-orientation parameters, in a format known as SINEX (Software/Solution Independent Exchange Format), which includes information on the accuracy of the parameters determined (covariance matrix).

Timing Products
A very successful Time Transfer Pilot Project was operated from 1999 to 2002 by the IGS in conjunction with the Bureau International des Poids et Mesures (BIPM), Paris. The latter is responsible for the definition and maintenance of the UTC and TAI time scales, which provide the basis for civil time worldwide. GPS has long provided an important link between national time laboratories and BIPM, and the objective was to better link the laboratories with the IGS references (ITRF and GPS system time, both as realised by IGS). Important aspects were those of setting up GPS receivers close to the hydrogen masers of the laboratories, and investigating critical variations in cables due to thermal and other effects. This project now runs as a Working Group with a Coordinator, whose main task is to establish and make available an IGS time scale with more stability than is available from the satellites themselves, taking advantage of the presence of very stable hydrogen masers in the IGS ground network.

Low Earth Orbiters
GNSS receivers carried on spacecraft in Low Earth Orbit (LEO orbits have heights varying from just a few hundred to a few thousand kilometres) are very effective tools for rapidly and accurately determining the spacecraft's orbit. Due to the large number of satellites in the GNSS constellation, the coverage is redundant and continuous, so that it almost becomes possible to determine the orbit in a kinematic (geometric) way, minimising the

dependence on dynamic models of the motion.

The number of satellites in orbit with high-quality, two-frequency receivers has grown rapidly since mid-2000 with the launches of CHAMP, Jason-1, GRACE, Icesat and others. The ESA GOCE (Gravity Field and Steady-State Ocean Circulation Explorer) and the ESA/Eumetsat MetOp-1 spacecraft will join this group by 2006. Very impressive advances are already being made by processing of the GPS and other data from CHAMP and GRACE (CHAMP has accelerometer data, GRACE has very precise inter-satellite range-difference measurements between the two GRACE spacecraft). These efforts are leading to the best models currently available for the Earth's gravity field.

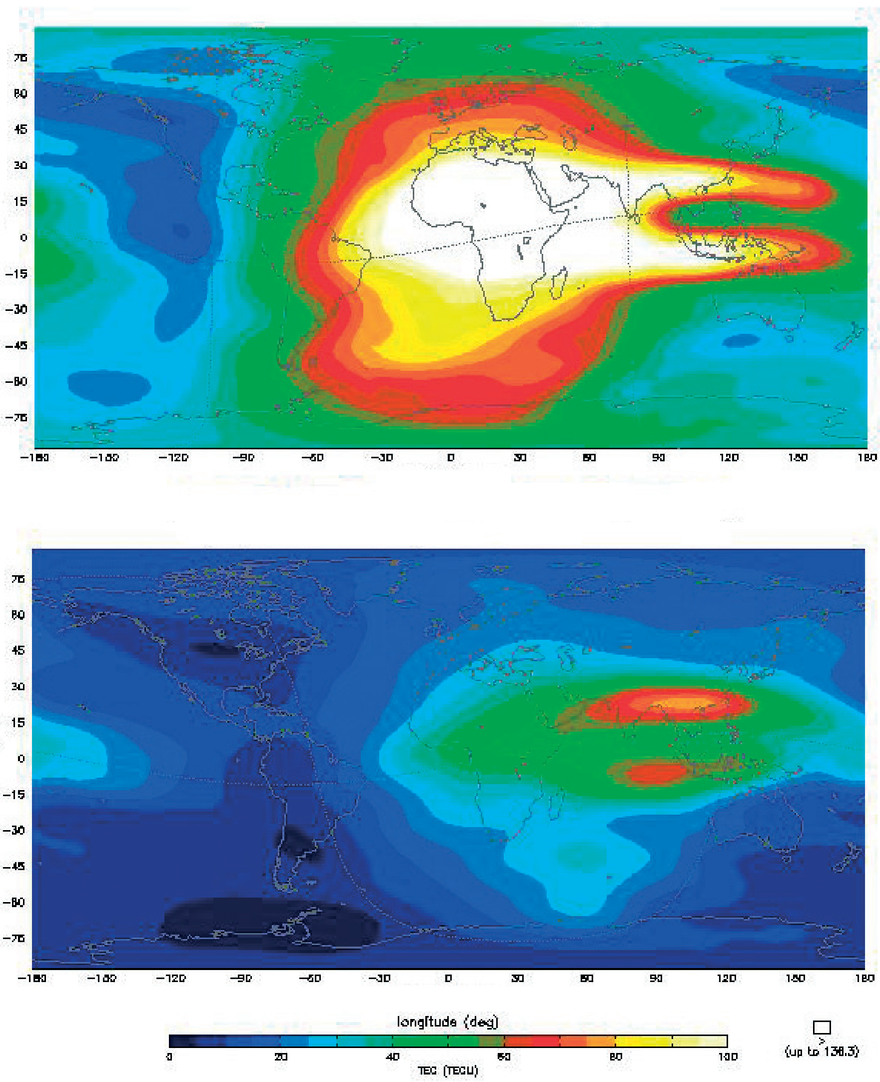


The occultation of a GNSS signal by the Earth's atmosphere as seen by a Low Earth Orbiter (LEO) spacecraft

Another important application of GNSS in LEO is atmospheric sounding, using data collected close to an occultation as the line of sight between a GNSS satellite and the LEO emerges from or passes below the Earth's horizon. The ground-based data collected and processed by the IGS provide fundamental and essential support to these LEO missions. The LEO Pilot Project (coordinated by ESOC) focuses the efforts of interested analysis centres on improved data processing for these orbiting receivers.

Atmosphere

Due to the multi-frequency nature of GNSS (at least two frequencies are needed in order to remove large measurement errors, which would otherwise be caused during propagation of the signals through the Earth's ionosphere), a well-distributed network of GNSS stations allows global mapping of the distribution of free electrons in the ionosphere with unprecedented spatial and temporal resolution. (In effect, each two-frequency measurement of pseudo-range or phase from every ground station, or LEO satellite, to every GNSS satellite provides a measure of the electron density, integrated along the line of sight). Five IGS Associate Analysis Centres produce global ionospheric maps with resolutions of 2.5 deg in latitude, 5 deg in longitude and 2 hours in time. The delay in delivery is currently about 5 days, but efforts are being made to reduce this. Regional solutions can be generated much faster. Heightened solar activity is being observed by the IGS through its effects on the Earth's atmosphere.



IGS Global Ionospheric Maps for high and medium solar activity, generated by combining the inputs from five Associate Analysis Centres

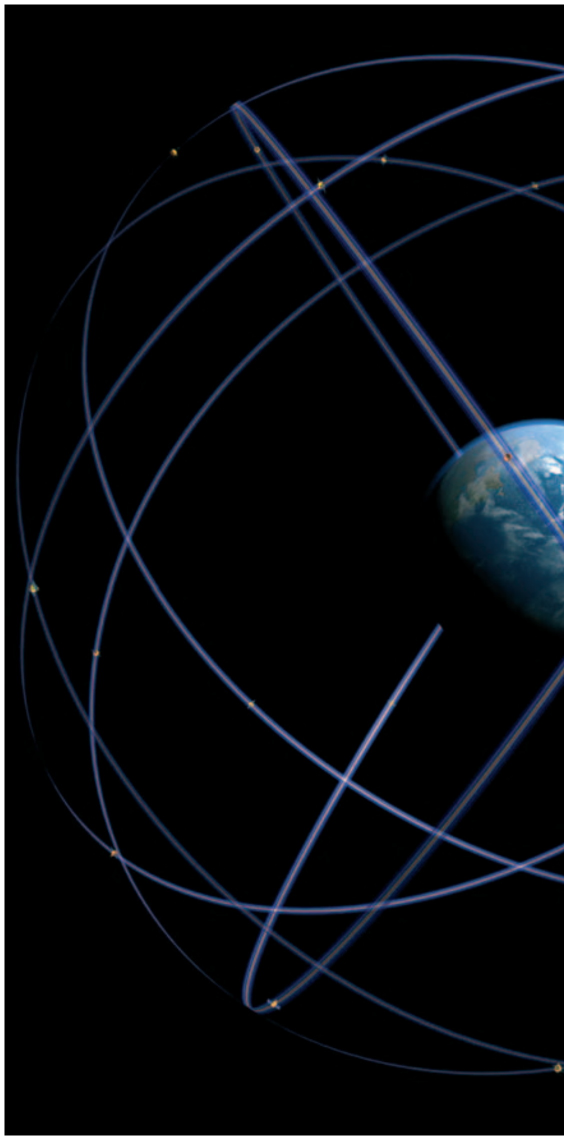
The magnitude of the tropospheric delay at each station, normalised to the zenith direction, is determined routinely by all IGS Analysis Centres and a combined product is generated by the Troposphere WG Coordinator. The physical parameter involved is the humidity content of the air in the lowest few kilometres of the atmosphere. Of course, unlike the case of the ionosphere, only isolated point values can be provided by GNSS, or at best regional maps where particularly dense station networks are located (e.g. Europe, Southern California). These values are being assimilated by meteorological institutes into both their weather forecasting (IGS ultra-rapid prediction values) and climate studies (values based on IGS final products).

Real-Time

The trend in navigation and other applications of GNSS is towards real-time data delivery and processing. Many IGS stations changed some years ago from delivering daily data files to delivering hourly files, with typical latencies of a few minutes. With the new generation of LEO satellites carrying GPS receivers, near-real-time delivery with a higher sampling rate (in some cases one measurement epoch every second, instead of every 30 seconds) is being requested. This can be done in 15-minute batches or as a real-time data stream. The IGS agencies are establishing protocols and procedures for handling this.

Tide-Gauge Benchmark Monitoring Project (TIGA)

Tide-gauge measurements made at widely separated sites have traditionally been difficult to relate to each other. By locating a GPS system close to a tide gauge, the height of the reference point on the tide gauge can be determined in the ITRF, and global and regional changes in sea level can then be monitored more reliably. Local crustal movements affecting long-term tide-gauge records can also be better characterised. The main objective of the TIGA project is to assist in the establishment of a significant number of permanent GPS measurement facilities at tide-gauge sites, and to process multi-year data sets including all or many such sites. This is a globalisation of some local/regional campaigns made with GPS to support the early calibration of altimeter instruments, e.g. on ERS-1, Topex/Poseidon, Envisat and Jason-1.



The Galileo satellite constellation. The 30 satellites (27 operational plus three in-orbit spares) will orbit the Earth at an altitude of 24 000 km, in three equally spaced planes inclined at 56 degrees to the Equator

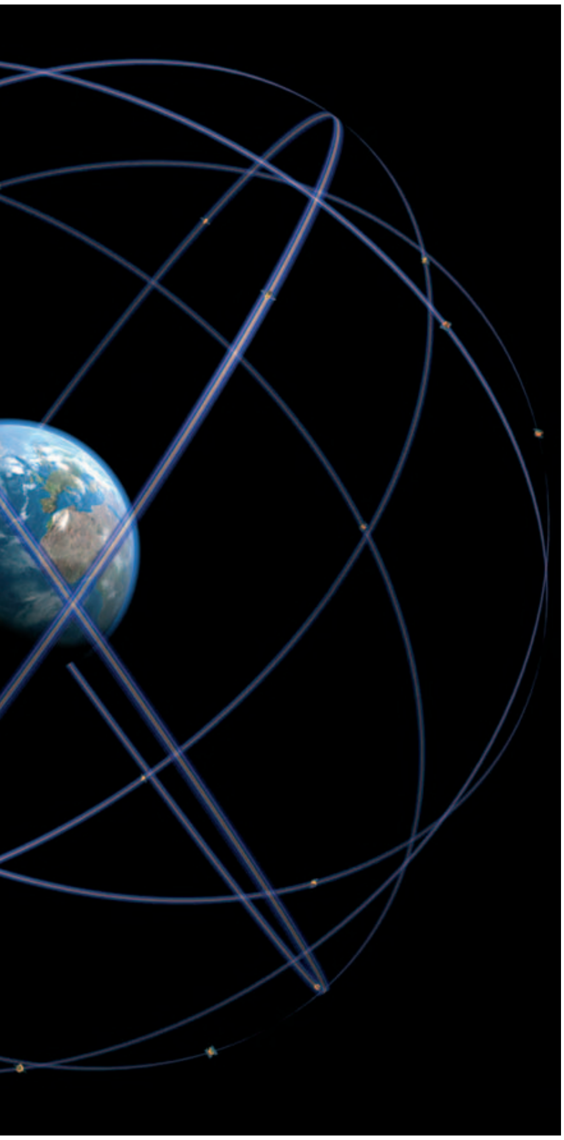
International GLONASS Service (IGLOS)

The International GLONASS Experiment IGEX was designed as a three-month test campaign by the IGS in 1998 to verify for the first time the feasibility of setting up a global network of GLONASS tracking receivers and processing the data for improved orbit, clock and ground position determination. IGLOS has evolved from this effort as a project within the IGS, and has been operational since 2000, unfortunately with a reduced space segment due to the long times between GLONASS replenishment launches. The standard IGS infrastructure (stations, data centres, analysis centres, data products) has been adapted in such a way that GLONASS data can be handled like GPS data. Currently, advances are being made at the IGLOS analysis centres to integrate GLONASS and GPS computations into a single process. This is exactly the approach that will be needed to support Galileo in-orbit validation for the first test satellites (Galileo System Test Bed V2) and the first operational satellites.

Galileo/GNSS Working Group

The IGS has built up a reputation for providing the best available products for GPS applications, where the criteria for 'best' include timeliness and accuracy. Many of the concepts that are now standard in the GPS community have been developed within the IGS. GPS itself is being further developed, with the introduction of additional civil signals on the L2 (GPS Block IIR-M, from 2004) and L5 (GPS Block IIF, from about 2005) frequencies, while some studies have already been carried out for a next-generation GPS III, which would however not be fully operational before about 2015.

There is a strong interest in the IGS community in ensuring that the Galileo system is able to make a major contribution to scientific and other applications requiring very high positioning accuracy, as GPS has done. Inter-operability between GPS and Galileo is seen as a key requirement. While it is clear that IGS has had an exemplary function in some aspects of the early design and testing concepts for Galileo, notably in the Galileo System Test Bed GSTB V1, this community and its members, both European and non-



European, are well prepared to contribute their experience to the definition and validation of the Galileo system. A Galileo/GNSS Working Group was set up at the December 2002 Governing Board Meeting in San Francisco, with approved Terms of Reference that had been coordinated with ESA's Galileo project team.

Strategic Planning

The IGS is a self-governing, voluntary organisation with no central source of funding; it operates through the contributions of its component parts. Nevertheless, it has succeeded in carrying out long-term projects which no one of its members could have achieved alone. The IGS is directed by its international Governing Board, the composition of which is defined in the IGS Terms of Reference. Representatives of the IGS components (Analysis Centres, Data Centres, Networks) are elected by the IGS Associates, while representatives of related external bodies such as the IERS and IAG are appointed by those bodies. Working Group chairs are non-voting members of the Board. Following a significant preparatory effort, a two-day retreat of the Board in December 1999 resulted in a Strategic Plan for the years 2002-2007.

The IGS is committed to providing the highest-quality data and products as a standard for global navigation satellite systems in support of Earth-science research, multi-disciplinary applications and education. These activities aim to advance scientific understanding of the Earth-system components and their interactions, as well as to facilitate other applications benefiting society. As long-term goals the IGS aims to:

– provide GNSS data and products of the highest quality and reliability, making them openly and readily available to all user communities
– promote universal acceptance of IGS products and conventions as a World standard
– continuously innovate by attracting leading-edge expertise and pursuing challenging projects and ideas
– seek and implement new growth opportunities while responding to changing user needs
– sustain and nurture the IGS culture of collegiality, openness and cooperation
– maintain a voluntary organisation with effective leadership, governance and management.

Key areas of IGS activities in the next few years will be in the fields of GNSS on Low Earth Orbiters, real-time data availability and product generation, and new GNSS developments (Galileo; GPS IIR-M, GPS IIF, GPS III).

Outlook

The International GPS Service is about to celebrate - with a Workshop and Symposium to be held in Bern in March 2004 - its 10th Anniversary as an IAG service, though as I have explained the IGS as such is a few years older than this. The recently approved new IAG structure gives added status and roles to the services - others are the International Earth Rotation and Reference Frame Service (IERS), the International Laser Ranging Service (ILRS), the International VLBI Service (IVS) and the newly formed International Doris Service (IDS). The IAG's flagship project, the International Geodetic Global Observing System (IGGOS), will rely heavily on these services and on good collaboration between them.

The IGS has developed a great deal from the simple organisation that it was during the campaign of 1992, but the basic concept has been validated constantly over the years. A wide spectrum of projects and GNSS applications have been successfully integrated into its structure. Continuing improvement in the quality and reliability of the global network and data interfaces is critical to this success, as is the dedication of the data analysts. The IGS and its members continue to provide fundamental support to a range of scientific and applications space missions, and ESA's GOCE, MetOp and Galileo missions will benefit greatly from this.

Acknowledgment

The IGS operates through the combined efforts and enthusiasm of its more than 200 contributing organisations. Further information about the service and its products can be found on the IGS Central Bureau web site at:
http://igscb.jpl.nasa.gov.