33. The International GNSS Service

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The International global navigation satellite system (GNSS) Service (IGS) is an organization devoted to the generation of high-precision GNSS data and products; a service that benefits science and society. It is a voluntary federation of over 200 self-funding agencies, universities, and research institutions in more than 100 countries. Established in 1992 and formally launched on 1st January 1994, the IGS has delivered an uninterrupted time series of products that are utilized by a broad spectrum of users. IGS products have evolved over time, including the provision of GNSS data for constellations other than GPS, and the addition of real-time GNSS data and products.

This chapter provides an overview of the IGS, including a brief history and details of the current organization and its key components. The various products offered by the IGS are described and an outlook of future activities is given.

33.1 Mission and Organization

33.1.1 Mission

The stated mission of the IGS is as follows [33.1]:

> *The International GNSS Service provides, on an openly available basis, the highest-quality GNSS data, products, and services in support of the terrestrial reference frame; Earth observation and research; Positioning, Navigation and Timing (PNT); and other applications that benefit the scientific community and society.*

The IGS promotes a culture of shared expertise to encourage global best practice for developing and delivering GNSS data and products worldwide. This collaborative approach encourages input from a diverse user community to strengthen uptake and promote innovation. The IGS has a strong interface with providers of GNSS equipment and services, and the owners of GNSS themselves. Drawing on a global research community, the IGS ensures that new technologies and systems can be integrated into its routine products. To support best practice among the global user community, the IGS also develops and publicly releases standards, guidelines, and conventions relating to the collection and use of GNSS data and products.

The IGS is a key element of the Global Geodetic Observing System (GGOS [33.2]) and fulfils three essential roles. The first is to provide the global linkage between the other elements of the global geodetic observing network, namely Satellite Laser Ranging (SLR) systems, Very Long Baseline Interferometry (VLBI)

Table 33.1 Key dates and milestones for the IGS

Date	Event
Aug 1989	First ideas for an International GPS Service were presented at the IAG General Meeting in Edinburgh
Jun 1992	Start of 1992 IGS Test Campaign (ended 23 Sep 1992)
Aug 1993	IAG Approval for IGS at IAG Scientific Meeting in Beijing.
Jan 1994	Start of official IGS
May 2000	Selective Availability removed from GPS
Mar 2001	GLONASS Service Pilot Project commenced
Mar 2001	TIGA (GPS Tide Gauge Benchmark Monitoring) project established
Apr 2003	Ionosphere maps (IONEX) etc. became official IGS product
May 2003	First operational combined GPS/GLONASS analysis products released
Mar 2005	IGS renamed as International GNSS Service
Dec 2005	International Committee on GNSS created by the UN office of Outer Space Affairs
Aug 2011	Multi-GNSS Experiment (MGEX) Call for Participation
Jul 2013	Real-Time Pilot Project commenced

telescopes, and Doppler Orbitography and Radio positioning Integrated by Satellite (DORIS) ground beacons. These links are fundamental to generating the International Terrestrial Reference Frame (ITRF) [33.3]. Given the high cost of establishing and maintaining SLR and VLBI facilities, and the fact that direct colocation of SLR, VLBI, and DORIS is not always viable, IGS products provide a cost-effective means of geometrically linking these other observing techniques. The second role is to densify and improve the geometric distribution of the global geodetic network, allowing accurate modeling of satellite orbits and clocks, atmospheric behavior, and Earth processes like neo-tectonics. The final role is to provide the user segment with access to the ITRF, which is increasingly important as both the accuracy of publicly accessible GNSS positioning improves and the consequent need to better understand the relationship between the ITRF and national datums emerges.

There are numerous benefits for an organization or station operator to support the IGS, including increased accuracy of the reference frame in the organization's region of interest; simpler and more accurate connections to the reference frame; increased accuracy of global positioning products, such as satellite orbit and clock products; and more accurate determination of transformations between realizations of the reference frame in that region and the respective national datum.

The adoption of a United Nations General Assembly Resolution in 2015 supporting the Global Geodetic Reference Frame is in many ways recognition of the role the IGS plays in supporting society and more specifically the UN Sustainable Development Goals [33.4].

The IGS strives to maintain an international federation with committed contributions from its members. It does this by providing effective leadership, management, and governance. While the value proposition for participation in the IGS varies for different contributors, its data and products are largely driven by user needs. IGS governance encourages an inclusive culture, and particular attention is given to outreach across regions and countries with lower than expected participation levels. The IGS also provides support and leadership to a multitude of other science programs. Considerable attention is paid to providing advocacy for the IGS into the Group on Earth Observations (GEO); the Global Earth Observation System of Systems (GEOSS); the Committee on Earth Observation Satellites (CEOS); and a variety of United Nations committees.

A comprehensive history of the IGS can be found in [33.5] and Table 33.1 lists key dates and milestones since the IGS was first conceived.

33.1.2 Structure

An overview of the IGS organization as of 2015 is provided in Fig. 33.1. Key elements include:

- The *Governing Board (GB)* that oversees the IGS activities establishes its policies and decides on the establishment of new activities and products.
- The *Central Bureau (CB)* that performs the overall coordination and day-to-day management of IGS activities.
- The *IGS Network* of globally distributed monitoring stations that provide continuous observations of all GNSS constellations.
- The *Analysis Centers (ACs)* that generate quality controlled products such as precise orbit and clock solutions, tropospheric and ionosphere maps, and station position estimates from GNSS observations.
- The *Data Centers (DCs)* that make all data and products available to the community.
- Various *Working Groups (WGs)* that provide technical guidance and expertise in specific fields to advance the product generation and to establish new data and processing standards.

The tasks of each organizational element are further described in Sect. 33.2.

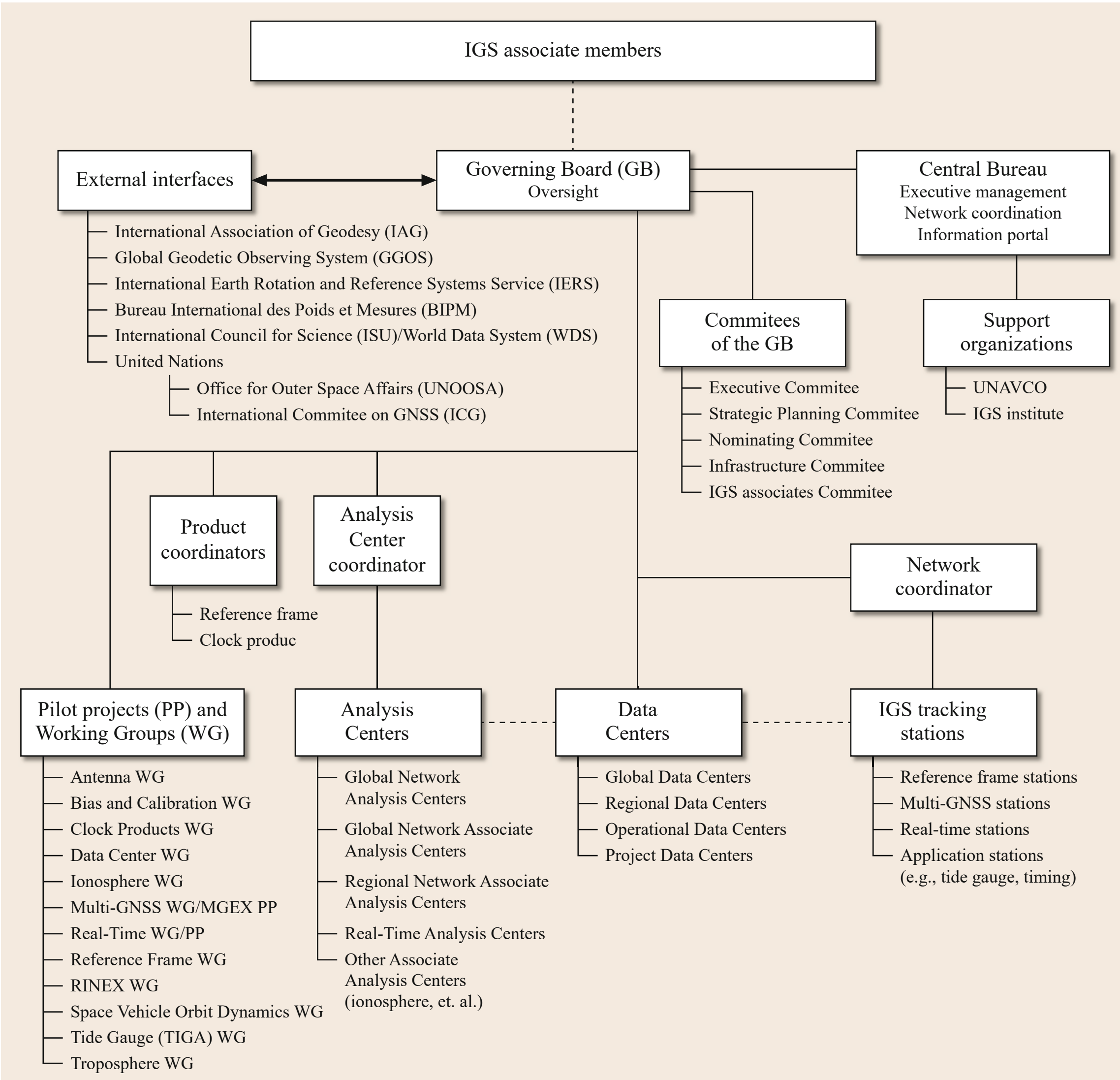

Fig. 33.1 Organizational structure of the IGS

33.2 Components

Key components of the IGS were identified in Fig. 33.1. This section provides a brief summary of the roles and responsibilities associated with each of these components. Further details are provided in the IGS Terms of Reference [33.1].

33.2.1 IGS Governing Board and Executive Committee

The Governing Board (GB) is the international body that sets policy for the IGS and exercises broad oversight of all IGS functions and components. It controls the general activities of the IGS and implements restructuring if needed to increase the organization's efficiency and reliability for integrating and making full use of all available GNSS technologies.

The GB has an Executive Committee (EC) with specific responsibilities that allow it to act on behalf of the GB outside formal GB meetings.

33.2.2 IGS Central Bureau

The Central Bureau (CB) coordinates the day-to-day operations of the IGS. It is the executive arm of the

IGS GB with responsibilities for coordinating general aspects of IGS network operations; promoting compliance to IGS standards; monitoring network operations and providing quality assurance of data; maintaining documentation; organizing meetings and workshops; and coordinating development and publishing of IGS reports. The performance of the CB is formally reviewed by the GB at least every 5 years to ensure it is capable of fulfilling its long-term coordination role.

33.2.3 IGS Network

The foundation of the IGS is a global network of over 450 permanent and continuously operating stations of geodetic quality, which track signals from GPS. Increasingly signals from GLONASS, Galileo, BeiDou, QZSS, and several Space-Based Augmentation Systems (SBAS) are also tracked. To ensure continuous tracking of high-accuracy GNSS data, stations in the IGS network are developed to a minimum set of physical and operational standards defined by the *IGS Site Guidelines* [33.6]. For example, IGS infrastructure must be physically stable to support long-term operation of the IGS network, and any changes to a station's configuration should be carefully planned and documented to minimize discontinuities in the station's position time-series. Minimum scheduling requirements are also implemented to ensure that data from each station is transmitted as rapidly as possible to global and regional DCs for archiving and analysis.

Station locations in the global IGS tracking network are illustrated in Fig. 33.2.

33.2.4 Analysis Centers

ACs receive and process tracking data from one or more DCs for the purpose of producing IGS products. ACs are recognized by the GB as those groups which commit to deliver some or all of the core IGS products (Sect. 33.3), within a specified time period, using designated IGS standards and conventions. Core products typically include satellite ephemerides, Earth rotation parameters, station coordinates, and clock information. The products are produced in Ultra-rapid, Rapid, Final, and Reprocessed versions for each AC.

Associate ACs (AACs) are a second category of AC that produce specialized products, including ionospheric information, tropospheric parameters, or station coordinates and velocities for global or regional subnetworks. Regional Network Associate Analysis Centers (RNAACs) and Global Network Associate Analysis Centers (GNAACs) are currently recognized by the GB. The functions of AACs continue to evolve as new capabilities and products emerge within the IGS.

Finally, the Analysis Center Coordinator (ACC) is responsible for combining products from each AC into a single set of orbit and clock products, which are the official IGS products made available to users through the Global DCs. The ACC monitors and assists the activities of ACs to ensure IGS objectives and standards for quality control, performance evaluation, and analysis are carried out. The ACC is a voting member of the IGS GB and interacts regularly with the CB and International Earth Rotation and Reference Systems Service (IERS). The responsibilities for the ACC typically rotate around the ACs with appointments and terms specified by the GB.

33.2.5 Data Centers (DCs)

The *Charter for IGS DCs* [33.7] defines three categories – Operational, Regional, and Global DCs – each of which builds redundancy into the IGS network. DCs are approved by the GB based on recommendations of the DCWG, and a demonstrated commitment to IGS principles and standards.

Operational DCs are in direct contact with IGS tracking sites. Their tasks include station monitoring,

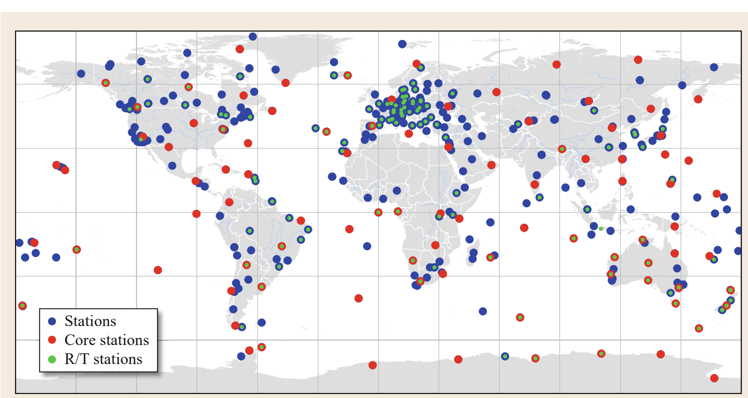

Fig. 33.2 Sites in the global IGS tracking network. Out of an overall set of about 470 stations available in Oct. 2015, the 90 core stations marked in *red* are used to establish the IGb08 reference frame. *Green dots* indicate stations with real-time data transmission capability

data validation, data formatting and exchange (e.g., RINEX), data compression, local archiving of GNSS data, and the electronic transmission of data to Regional and Global DCs [33.8]. Download schedules and data continuity requirements are specified in the IGS Site Guidelines for Operational DCs.

Regional DCs collect tracking data in the required exchange format from several Operational Centers and/or stations. They maintain a local archive of this data, provide on-line access to the data, and transmit the data from a subset of their sites (minimally, the IGS reference frame stations) to Global DCs. The stations managed by Regional DCs can be those of an individual agency or those located across a specific geographic region (Europe, Australia, etc.).

Global DCs are the main interfaces to the ACs and general user community. They receive, retrieve, archive, and provide online access to tracking data from Operational and Regional DCs. They are responsible for archiving and backing up IGS data and products, and exchanging data between other DCs to balance data holdings across the IGS network. At a minimum, Global DCs must archive GNSS data that has been sampled at 30 s intervals from IGS reference frame sites. As of 2015, the IGS comprises four global DCs hosted by institutions in the United States, France, and Korea:

- Crustal Dynamics Data Information System (CDDIS [33.9])
- Institut National de l'Information Géographique et Forestière (IGN)
- Scripps Institution of Oceanography (SIO)
- Korean Astronomy and Space Science Institute (KASI).

Routine quality control is encouraged by all DCs to validate data prior to transmission.

33.2.6 Working Groups

The IGS has a number of working groups that focus on different aspects of product generation. These WGs also support IGS pilot projects (Sect. 33.4) to investigate future GNSS developments that could lead to the generation of new IGS products.

The current WGs are briefly summarized below along with their goals and objectives:

- *Antenna Working Group (AWG)* – To increase the accuracy and consistency of IGS products the AWG coordinates research on GNSS receiver and satellite antenna phase center determination, and manages official IGS antenna files and their formats.
- *Bias and Calibration Working Group (BCWG)* – Different GNSS observables are subject to different satellite biases that can degrade the IGS products. The BCWG coordinates research for retrieving and monitoring GNSS biases, and develops rules for handling these biases.
- *Clock Products Working Group (CPWG)* – The CPWG is responsible for aligning the combined IGS products to a highly precise timescale traceable to the world standard; Coordinated Universal Time (UTC).
- *Data Center Working Group (DCWG)* – The DCWG works to improve the provision of data and products from the Operational, Regional, and Global DCs, and recommends new DCs to the GB.
- *Ionosphere Working Group (IWG)* – The IWG produces global ionosphere maps of Ionosphere Vertical Total Electron Content (TEC). A major task of IWG is to make available global ionosphere maps from the TEC maps produced independently by Ionosphere Associate Analysis Centers (IAACs) within the IGS.
- *Multi-GNSS Working Group (MGWG)* – The MGWG supports the MGEX Project by facilitating estimation of intersystem biases and comparing the performance of multi-GNSS equipment and processing software. The MGEX Project was established to track, collate, and analyze all available GNSS signals including those from BeiDou, Galileo, and QZSS in addition to GPS and GLONASS satellites.
- *Reference Frame Working Group (RFWG)* – The RFWG combines solutions from the IGS ACs to form the IGS station positions and velocity products, and Earth rotation parameters for inclusion in the IGS realization of ITRF.
- *Real-Time Working Group (RTWG)* – The RTWG supports the development and integration of real-time technologies, standards, and infrastructure to produce high-accuracy IGS products in real time. The RTWG operates the IGS Real-Time Service (RTS) to support Precise Point Positioning (PPP) at global scales, in real time.
- *RINEX Working Group (RINEX-WG)* – The RINEX-WG jointly manages the RINEX format with the Radio Technical Commission for Maritime services-Special Committee 104 (RTCM-SC104). RINEX has been widely adopted as an industry standard for archiving and exchanging GNSS observations, and newer versions support multiple GNSS constellations.
- *Space Vehicle Orbit Dynamics Working Group (SVODWG)* – The SVODWG brings together IGS groups working on orbit dynamics and attitude

modelling of spacecraft. This work includes the development of force and attitude models for new GNSS constellations to fully exploit all new signals with the highest possible accuracy.

- *Tide Gauge (TIGA) Working Group* – TIGA is a pilot study for establishing a service to analyze GPS data from stations at or near tide gauges in the IGS network to support accurate measurement of sea-level change across the globe.
- *Troposphere Working Group (TWG)* – The TWG supports development of the IGS troposphere products by combining troposphere solutions from individual ACs to improve the accuracy of PPP solutions.

Information on the WG charters and membership can be found at [33.10]. WG chairs report to the IGS GB on a regular basis.

33.3 IGS Products

The primary objective of the IGS is to provide the reference GNSS products and observations for a wide variety of scientific and engineering users involving GNSS. To fulfil this role, the IGS produces a number of fundamental products such as:

- GNSS orbits and clocks
- Earth orientation parameters and station coordinates
- Ionosphere and troposphere parameters and
- Systematic bias estimates.

These high-quality products are used to support scientific applications such as the realization of the ITRF, monitoring the deformation of the solid Earth due to ocean tides and hydrology, and monitoring of sea-level change and associated climate change events. Increasingly the products are also used for sounding the atmosphere and producing ionospheric and tropospheric maps. Lastly, the IGS products are used extensively to support precise positioning applications for industry and society.

33.3.1 Orbits and Clocks

In order for a user to achieve precise positioning (Chap. 25), knowledge of the orbits and clocks of the GNSS satellites is fundamental. The positioning accuracy is directly affected by errors in the satellite orbits and clocks. Relatively low accuracy orbit and clock information are transmitted through the GNSS navigation messages. Other more precise orbits and clock information are provided by the IGS and its individual ACs. An indicative list of the IGS orbit and clock products, together with their latency and availability, is provided in Tables 33.2 and 33.3.

Table 33.2 Accuracy, latency, continuity, availability, and sampling intervals for IGS orbit and clock products relating to GPS satellite orbits and satellite (sat) and station (stn) clocks as of 2013 (after [33.11, 12]). For definition of latency, continuity, and availability see [33.11]

GPS satellite ephemerides Satellite and station clocks		Sample interval	Accuracy	Latency	Continuity	Availability (%)
Broadcast (for comparison)	Orbits Sat. clocks	–	$\approx$ 100 cm $\approx$ 5 ns RMS, 2.5 ns σ	Real time	Continuous	99.99
Ultra-rapid (predicted half)	Orbits Sat. clocks	15 min	$\approx$ 5 cm $\approx$ 3 ns RMS, $\approx$ 1.5 ns σ	Predicted	4× daily, at 3 h, 9 h, 15 h, 21 h UTC	95
Ultra-rapid (observed half)	Orbits Sat. clocks	15 min	$\approx$ 3 cm $\approx$ 150 ps RMS, $\approx$ 50 ps σ	3–9 h	4× daily, at 3 h, 9 h, 15 h, 21 h UTC	
Rapid	Orbits, Sat. & stn. clocks	15 min 5 min	$\approx$ 2.5 cm $\approx$ 75 ps RMS, $\approx$ 25 ps σ	17–41 h	daily, at 17 h UTC	95
Final	Orbits, Sat. & stn. clocks	15 min 30 s (Sat) 5 min (Stn)	$\approx$ 2 cm 75 ps RMS, 20 ps σ	12–18 d	weekly, Thursday	99
Real-time	Orbits Sat. clocks	5–60 s	$\approx$ 5 cm 300 ps RMS, 120 ps σ	25 s 5 s	Continuous	95

Table 33.3 Accuracy, latency, continuity, availability, and sampling intervals for IGS orbit and clock products relating to GLONASS satellite ephemerides as of 2013 (after [33.11, 12])

GLONASS satellite orbits	Sample interval	Accuracy	Latency	Continuity	Availability (%)
Final	15 min	≈ 3 cm	12–18 d	Weekly, every Thursday	99

The IGS continuously monitors the performance of its products through its ACC. The ACC is in charge of monitoring the performance of the orbits and clocks by comparing the final products against each individual AC product. An example of this comparison is illustrated in Fig. 33.3 where each individual AC orbit is compared to the IGS final orbits via three-dimensional (3-D) differences.

33.3.2 Earth Orientation and Site Coordinates

The Earth Orientation Parameters (EOPs) are another product derived from the complex computations performed by the IGS (Table 33.4). EOPs specify the motion of the Earth's rotation pole and its irregularities through time. These parameters provide the connection or tie of the International Celestial Reference Frame (ICRF) to the ITRF and the IGS Terrestrial Reference Frame, known as the IGb. They consist of:

- The Universal Time (UT), which is the time of the Earth clock
- The length-of-day (LOD), which describes any excess in the revolution time
- The polar motion, which describes the varying position of the Earth's pole through coordinates x and y of the Celestial Ephemeris Pole (CEP) relative to the IERS reference pole
- The polar motion rate, which represents the velocity of the polar coordinates and how they vary through time.

The physical meaning of the individual parameters is further discussed in Chap. 2 of this Handbook and the IERS Conventions [33.14].

Site Coordinates

Site positions and velocities (Table 33.5) for the IGS stations are generated by the analysis centers on a weekly basis. The individual solutions are provided

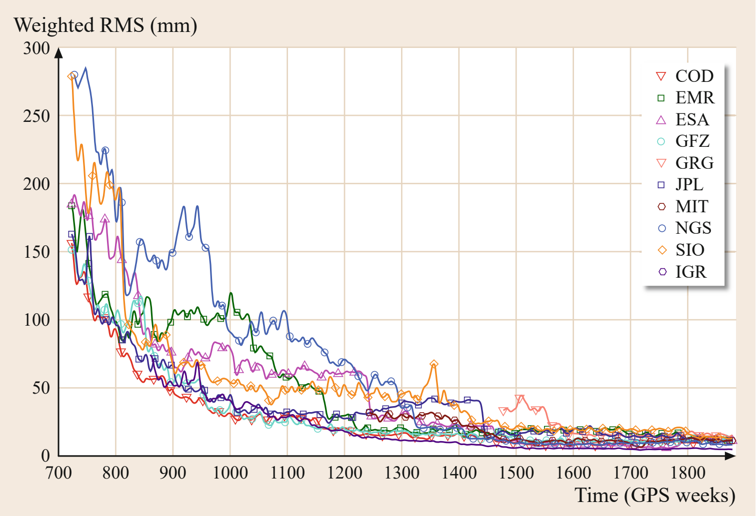

Fig. 33.3 Weighted RMS (mm) of the individual AC orbit solutions with respect to the IGS Final orbits for the period 1994 to Dec. 2015 (smoothed). Individual Analysis Centers are identified by their three-letter acronyms (COD: Center for Orbit Determination in Europe, Switzerland; EMR: Natural Resources Canada; ESA: European Space Agency; GFZ: GeoForschungsZentrum Potsdam, Germany; GRG: Groupe de Recherche de Géodésie Spatiale – Centre National d'Etudes Spatiales (CNES) and Collecte Localisation Satellites (CLS); JPL: Jet Propulsion Laboratory, USA; MIT: Massachusetts Institute of Technology, USA; NGS: National Geodetic Survey, National Oceanic and Atmospheric Administration (NOAA), USA; SIO: Scripps Institute of Oceanography, USA [33.13]). Image courtesy of Geoscience Australia and MIT

Table 33.4 IGS Earth orientation products (after [33.11, 12])

Earth rotation parameters		Sample interval	Accuracy	Latency	Continuity	Availability (%)
Ultra-rapid (predicted half)	Polar motion Polar motion rate Length-of-day	Daily integrations at 0 h, 6 h, 12 h, 18 h UTC	$\approx 200\,\mu$as $\approx 300\,\mu$as/d $\approx 50\,\mu$s	Real time	4× daily, at 3 h, 9 h, 15 h, 21 h UTC	99
Ultra-rapid (observed half)	Polar motion Polar motion rate Length-of-day	Daily integrations at 0 h, 6 h, 12 h, 18 h UTC	$\approx 50\,\mu$as $\approx 250\,\mu$as/d $\approx 10\,\mu$s	3–9 h	4× daily, at 3 h, 9 h, 15 h, 21 h UTC	99
Rapid	Polar motion Polar motion rate Length-of-day	Daily integrations at 12 h UTC	$\approx 40\,\mu$as $\approx 200\,\mu$as/d $\approx 10\,\mu$s	17–41 h	Daily, at 17h UTC	99
Final	Polar motion Polar motion rate Length-of-day	Daily integrations at 12 h UTC	$\approx 30\,\mu$as $\approx 150\,\mu$as/d $\approx 10\,\mu$s	11–17 d	Weekly, Wednesday	99

Note 1: $100\,\mu$as = 3.1 mm and $10\,\mu$s = 4.6 mm of equatorial rotation at the Earth's surface.
Note 2: The IGS uses VLBI from IERS Bulletin A to partially calibrate for LOD biases over a 21-day sliding window, but residual time-correlated LOD errors remain.

Table 33.5 IGS station coordinate products (after [33.11, 12])

Geocentric coordinates of IGS tracking stations (> 250 sites)		Sample interval	Accuracy	Latency	Continuity	Availability (%)
Final positions	Horizontal Vertical	Weekly	3 mm 6 mm	11–17 d	Weekly, Wednesday	99
Final velocities	Horizontal Vertical	Weekly	2 mm/yr 3 mm/yr	11–17 d	Weekly, Wednesday	99

in the Solution Independent Exchange (SINEX) format (Annex A.2.3), which facilitates combinations of different ACs but also of GNSS-derived solutions with other space-geodetic techniques.

Through its GNSS network and processing the IGS contributes to, extends, and densifies the ITRF. The ITRF provides an accurate and consistent frame, or datum, for referencing positions at different times and in different locations around the world. The IGS realization of ITRF, which extends the number of stations significantly, makes the reference frame easily accessible.

The IGS network shown in Fig. 33.2 includes a well-distributed subset (the *reference frame stations* indicated in red) called the IGb08 core network. This subnetwork is recommended for comparison or alignment of global solutions to the IGb08 reference frame, in order to mitigate the aliasing of station nonlinear motions into transformation parameters (network effect). It is used for the alignment of the IGS weekly combined solutions to IGb08.

IGS reference frame stations are the highest-quality GNSS stations in the world. This quality directly impacts the level of accuracy that can be achieved by using the ITRF. Requirements for stations include: a high-quality monument on stable crustal bedrock with excellent sky visibility; a long observing history; high-quality, consistent, continuous, and complete raw data; minimal changes to equipment and its surroundings; and a commitment to keep the station operating for as long as possible. Full requirements are detailed in the IGS Site Guidelines [33.6]. These site requirements are stringent in order to ensure reliable measurements uniformly across the global network in support of projects such as sea-level change, which occurs at the millimeter level. Limitations in a reference frame negatively impact the accuracy of numerous scientific and positioning applications, especially in the region immediately surrounding the station.

33.3.3 Atmospheric Parameters

Other IGS products are developed by AACs in relation with WGs and pilot projects. These products include Zenith Troposphere Delay (ZTD; also known as Zenith Path Delay, ZPD) parameters and ionospheric vertical total electron content (VTEC) maps, which have application in climate and atmospheric research (Chaps. 38 and 39). A summary of the IGS atmospheric products is given in Table 33.6.

Troposphere

The ZTD products are generated from the IGS ACs through the processing of ground-based GNSS

Table 33.6 IGS atmospheric products (after [33.11, 12])

Atmospheric parameters	Sample interval	Accuracy	Latency	Continuity	Availability (%)
IGS final tropospheric delay (ZTD and gradients)	5 min	$\approx$ 4 mm for ZTD	$\approx$ 3 weeks	Daily	99
Ionosphere TEC grid	2 h, $5° \times 2.5°$ (lon./lat.)	2–8 TECU	$\approx$ 11 d	Weekly	99
Rapid ionosphere TEC grid	2 h, $5° \times 2.5°$ (lon./lat.)	2–9 TECU	< 24 h	Daily	95

data [33.15, 16]. For the extraction of the ZTD and its horizontal gradients, observations of the surface pressure and temperature at the GNSS sites are needed. In order to produce these ZTD products, the IGS ACs need to use all of the aforementioned products as known parameters, that is orbits, clocks, and EOPs.

Ionosphere

The ionosphere products, which comprise a set of VTEC maps [33.17], are also a product of a GNSS processing strategy using orbits, clocks, and EOPs, which are derived from dual frequency observations. Another by-product of this is the estimates of the differential code biases (DCBs) (discussed in the following section). These ionosphere products are available from the rapid solutions with a latency of less than 24 hours, a final solution with a latency of approximately 11 days, and a predicted solution available both 1 and 2 days prior. Ionosphere products are provided in IONEX (Ionosphere Exchange) format (Annex A.2.4).

33.3.4 Biases

All GNSS observations are biased and contain unknown quantities characterized as systematic errors. The IGS, through the Bias and Calibration Working Group (BCWG), coordinates the production, research, and monitoring of these biases. The BCWG is responsible for defining the rules and procedures, which dictate the consistent handling and processing of these biases in an inhomogeneous GNSS environment.

The current set of IGS bias estimates comprises DCBs for GPS and GLONASS signals on the L1 and L2 frequencies:

- L1 P(Y)- or P-code minus L1 C/A-code biases (termed *P1-C1* in accord with the heritage two-letter RINEX 2 observation designations) for the GPS and GLONASS constellation for a moving 30-day combination (considering the bias estimates of the latest 30 daily solutions).
- L2 P(Y)- or P-code minus L2C or L2 C/A-code biases (termed *P2-C2*) for the GPS and GLONASS constellations for a moving 30-day combination.
- P1-P2 bias values for GPS and GLONASS as a by-product of the ionospheric analysis as monthly values.

These biases are generated by two methods: the indirect and direct method. In the indirect estimation process the biases are generated as estimable parameters in the clock determination process. In the direct process, the biases are generated directly from the differences of the observations of the different signals.

In the face of GPS and GLONASS modernization programs and upcoming GNSS, like the European Galileo and the Chinese BeiDou, an increasing number of types of biases are expected [33.18]. Some of the future biases products that the IGS will have to produce in the context of multi-GNSS multifrequency signals are:

- Transition to RINEX 3.xx compatible bias types and designations (e.g., C1W-C1C, C2W-C2S, C1W-C2W, etc.)
- Biases for particular linear combinations such as wide-lane biases (WLB), ionosphere-free biases (LCB), narrow-lane biases (NLB)
- GLONASS interfrequency code biases
- GLONASS differential code-phase biases for ambiguity resolution
- Uncalibrated phase delays (UPD) relevant to undifferenced integer fixing for precise point positioning
- GPS quarter-cycle phase offset issues (specifically between L2W and L2C)
- Differentials code biases for new signals and constellations
- Absolute or observable code bias values, being consistent with respect to each DCB set and with respect to the signals currently used for the clock offset determination.

The generation of multi-GNSS DCB products has been initiated in the frame of the IGS multi-GNSS Experiment (MGEX; Sect. 33.4.2), where prototype DCB products covering new signals and constellations are made available by selected analysis centers since 2014 [33.19].

33.4 Pilot Projects and Experiments

Throughout its history, the IGS has organized various campaigns, experiments, and pilot projects to actively support emerging GNSS developments and to prepare for the generation of new IGS products. Past examples include the International GLONASS Experiment [33.20] and the subsequent International GLONASS Service (IGLOS) pilot project [33.21], which laid the foundation for today's IGS GLONASS products. Another example is the GPS Tide Gauge Benchmark Monitoring (TIGA) project, which applies precise GPS results to monitor vertical motion of tide gauges. The TIGA pilot project became the TIGA Working Group in 2010. More recent activities include the IGS RTS and the Multi-GNSS Experiment (MGEX), which are discussed in this section.

33.4.1 Real-Time

Launched in April 2013, the IGS RTS generates GNSS products in real time to support Precise Point Positioning (PPP; Chap. 25) at global scales. It makes use of raw data which are continuously streamed from a subset of high-quality GNSS receivers in the global IGS network. The RTS products consist of GNSS satellite orbit and clock corrections. Data and products from the RTS provide real-time access to the global reference frame. The RTS is a public service made openly available to users that hold a free subscription.

Prior to launching the RTS, access to the global reference frame using IGS products has been *ex post factor* or *after-the-fact*. The RTS makes these products available with little or no latency to support PPP in real time. This enables scientific, educational, and commercial applications at worldwide scales, including geophysical hazard detection and warnings, conventional and space weather forecasting, time synchronization, and performance monitoring of GNSS constellations [33.22].

The RTS is built on the network of tracking stations, DCs and Real-Time Analysis Centers (RTACs) that underpin the global IGS network. Planning for the RTS has been underway since 2002, with careful attention given to network design and management, algorithm development, product generation, and defining real-time protocols and standards for accessing data and products. Support is provided by over 120 station operators, multiple DCs, and 10 RTACs around the world.

A brief outline of the RTS network and its data and products is provided below. Up-to-date information on the network status, product types, and performances as well as user access is provided through the IGS RTS website [33.23].

RTS Network

The RTS is built on the global IGS infrastructure that functions as a world standard for high-precision GNSS data and products. Contributions to the IGS are made on a collaborative and best-efforts basis, meaning the RTS including all data and products is offered without a service guarantee. However, it is these global contributions that build redundancy into the RTS and its products. The global RTS architecture ensures that a reliable flow of data and products is available without interruption.

The RTS comprises over 120 globally distributed GNSS stations maintained by a wide variety of local and region IGS operators. These stations deliver 1 Hz data to real-time DCs within the IGS network, with typical latencies of 3 s or less. The distribution of real-time tracking stations within the overall IGS network is illustrated in Fig. 33.2.

Network redundancy and a global distribution of stations are needed to provide full coverage and a reliable flow of real-time data. Coverage is challenging in some areas, particularly in regions of vast open ocean. Additional contributions to the network are encouraged where possible, however new stations in the RTS network must adhere to a minimum set of infrastructure standards and IGS best practices for real-time operations. Examples of these best practices are provided in [33.24] and illustrated in Fig. 33.4:

- Real-time data should be transmitted to a minimum of two separate real-time DCs.
- Stations that contribute to the realization of the IGS reference frame should be operated in real time to

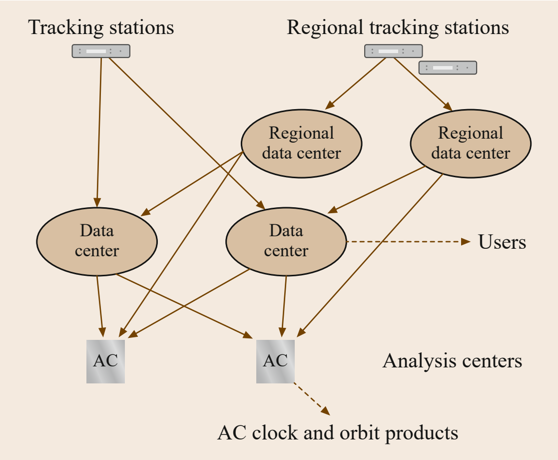

Fig. 33.4 Real-time data is streamed to multiple DCs and ACs to build redundancy into the RTS (after [33.24])

guarantee reliable alignment of the real-time products to a stable reference frame.
- RTACs are encouraged to ingest data from two or more global data centers.

Individual correction products are produced within each RTAC once the real-time data streams have been received from each DC. The final orbit and clock correction products delivered from the RTS are actually a combination of the individual RTAC correction products, producing a more reliable and stable set of products than any single RTAC product alone.

This highly redundant design is made possible through the contribution of 10 RTACs within the RTS. Operational responsibility for producing the official combination products lies with the IGS RTAC Coordinator (RTACC), which is currently contributed by European Sapce Agency (ESA/ESOC) in Darmstadt, Germany. Figure 33.5 illustrates the RTS architecture for combining and distributing RTAC solutions via multiple DCs worldwide.

To support ongoing development and management of the RTS, the IGS RTWG addresses issues pertaining to infrastructure management and data analysis. The activities of the RTWG consist of planning, designing, and implementing next stages for the RTS, including development of multi-GNSS correction products and associated standards, along with outreach to new IGS participants and users of the RTS. This work is guided by the broader IGS strategy to enhance standards and best practices for GNSS infrastructure management and data availability to benefit the global user community.

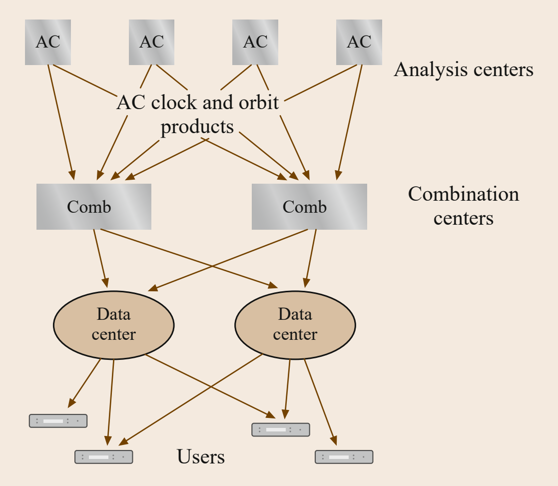

Fig. 33.5 Orbit and clock corrections produced by each AC in the RTS are combined to deliver a more reliable and stable correction product to users (after [33.24])

RTS Data and Products

To support global interoperability and integration of GNSS technologies and systems, the IGS develops and maintains standards and formats for disseminating GNSS data and products. IGS joined the Radio Technical Commission for Maritime Services Special Committee 104 (RTCM-SC104) in 2008 and adopted the RTCM-3 format for GPS and GLONASS observation messages shortly after. In Fig. 33.4, for example, the real-time GNSS data streams flowing from IGS tracking stations to the RTACs, via each DC, are formatted in the latest version RTCM-3 (most recently v3.2 [33.25]). Annex A.1.3 of this Handbook also describes the new RTCM3 Multi-Signal Message (MSM) format being developed to handle all GNSS constellations, signals, and observation types as part of the IGS Multi-GNSS Experiment (MGEX). Prototype MSM data streams are already being tested through the MGEX project and receiver manufacturers have started to release firmware supporting MSM [33.26].

The IGS has also adopted the RTCM-State Space Representation (RTCM-SSR [33.27]) format for disseminating real-time orbit and clock correction messages. RTCM-SSR currently supports GPS and GLONASS constellations. These orbit and clock corrections are expressed within the International Terrestrial Reference Frame 2008 (ITRF08) and are designed to enable real-time PPP. The combined resolution of the RTCM-SSR corrections supports millimeter-accuracy corrections, and these corrections are broadcast over the Internet using the Network Transport of RTCM by Internet Protocol (NTRIP, [33.28]). NTRIP is an RTCM standard for disseminating and receiving RTCM-SSR messages.

Official IGS products from the RTS service are described in the IGS Strategic Plan 2013-2016 and briefly summarized in Table 33.7. Aside from orbit and clock corrections, the RTS also provides real-time access to broadcast ephemeris through the two data streams described below:

- RTCM3EPH: Broadcast ephemeris data for GPS, GLONASS, and Galileo satellites. This data stream is derived from receivers in the real-time IGS global network and encoded in RTCM-3 messages. The complete set of messages is repeated every 5 s.
- RTCM3EPH01: A GPS-only broadcast ephemeris stream also derived from the real-time IGS global network and encoded in RTCM Version 3 messages with a 5 s repetition rate.

Along with the state-space correction messages, these broadcast ephemeris can be used to reconstruct

Table 33.7 Content description of the RTS Product Streams (IGS, 2015b). APC: Antenna Phase Center; CoM: Center-of-Mass (not part of current RTCM-SSR standard). The figures in brackets next to each RTCM message ID denote the message sample interval in seconds

Stream name	Description	Ref. point	RTCM messages	Provider/Sol. ID	Bandwidth (kbits/s)	Combination center
IGS01	Orbit/Clock correction, single-epoch combination	APC	1059 (5), 1060 (5)	258/1	1.8	ESA/ESOC
IGC01	Orbit/Clock correction, single-epoch combination	CoM	1059 (5), 1060 (5)	258/9	1.8	ESA/ESOC
IGS02	Orbit/Clock correction, Kalman filter combination	APC	1057 (60), 1058 (10), 1059 (10)	258/2	0.6	BKG
IGS03	Orbit/Clock correction, Kalman filter combination	APC	1057 (60), 1058(10), 1059(10), 1063(60), 1064(10), 1065(10)	258/3	0.8	BKG

RTCM message types:

1057 GPS orbit corrections to Broadcast Ephemeris
1063 GLONASS orbit corrections to Broadcast Ephemeris
1058 GPS clock corrections to Broadcast Ephemeris
1064 GLONASS clock corrections to Broadcast Ephemeris
1059 GPS code biases
1065 GLONASS code biases
1060 Combined orbit and clock corrections to GPS Broadcast Ephemeris.

the precise orbit and clock information for use in real time or near-real-time PPP applications.

Standard IGS data and products are traditionally made available to users after-the-fact once a sufficient period of GNSS observation and processing has been undertaken to accurately model satellite orbits and clocks. The latency of these corrections ranges from hours to days to weeks depending on the final accuracy requirement. For example, *Final* orbit and clock products provide the highest accuracy and are delivered with a latency of 12–18 days. By contrast, the current RTS architecture enables real-time orbit and clocks products for GPS to be produced with an average latency of 25 s. The final accuracy of the RTS products is less than that of the Final IGS products, but sufficient enough to support real-time PPP. The accuracy, latency, continuity, and availability of all IGS orbit and clock products are compared in Table 33.2 above for the year 2013. Up-to-date performance monitoring results of the real-time products are provided at the IGS RTS website [33.23] on a routine basis.

33.4.2 Multi-GNSS

Today there are many GNSS signals available from multiple satellite navigation systems in addition to the well-known US Global Positioning System (Table 33.8). Other global systems include the Russian Global'naya Navigatsionnaya Sputnikovaya Sistema (GLONASS), the Chinese BeiDou Navigation Satellite System (BDS), and Europe's Galileo. In addition to the global systems, there also exist regional systems such as the Japanese Quasi-Zenith Satellite System (QZSS) and the Indian Regional Navigation Satellite System (IRNSS/NavIC) as well as various Satellite-Based Augmentation Systems. This multi-GNSS environment offers various advantages to the users:

- Increased signal availability, even in undesirable environments (such as urban canyons)
- Increased number of frequency bands to improve robustness against interference
- Superior continuity of service and reduced dependency on a single system
- Efficiency gains due to faster ambiguity resolution
- Better reliability and redundancy, which enhances outlier detection
- Improvements in accuracy of position estimates.

The IGS Multi-GNSS Working Group (MGWG) was formed by the IGS in recognition of the rapidly evolving GNSS landscape to explore and promote the use of new constellations and navigation signals. The core activity of the MGWG is the Multi-GNSS Experiment (MGEX), which aims to build up a network of sensor stations, characterize the space segment and user equipment, develop theory and data-processing tools, and generate data products for the emerging satellite systems. The MGWG works closely with other IGS entities, such as the Data Center Working Group, the

Table 33.8 Global and regional satellite system deployment status and transmitted signals as of Oct. 2016. Brackets denote satellites not yet declared operational

System	Type	Signals	Satellites
GPS	IIR	L1 C/A, L1/L2 P(Y)	12
	IIR-M	+L2C	7
	IIF	+L5	12
GLONASS	M	L1/L2 C/A + P	23
	M+	+L3	1
	K1	+L3	1+(1)
BeiDou-2	GEO	B1, B2, B3	5+(1)
	IGSO	B1, B2, B3	6
	MEO	B1, B2, B3	3
BeiDou-3	IGSO	B1, L1, B2, E5a/b/ab	(2)
	MEO	B1, L1, B2, E5a/b/ab	(3)
Galileo	IOV	E1, E6, E5a/b/ab	3+(1)
	FOC	E1, E6, E5a/b/ab	6+(4)
QZSS	IGSO	L1 C/A, L1C, L1 SAIF, L2C, E6 LEX, L5	1
IRNSS/NavIC	IGSO	L5, S	4
	GEO	L5, S	3

Antenna Working Group, and the Infrastructure Committee to achieve these goals.

The Multi-GNSS EXperiment was launched in February 2012. It was initially targeted at the global tracking of new and modernized GNSS signals as well as the build-up of analysis center capabilities to process such data and to generate associated multi-GNSS products. Within a couple of years, most of these goals have been reached and the IGS can offer its user a global network with multi-GNSS tracking capabilities supported by the corresponding data centers, analysis centers, and prototype products [33.26].

MGEX Network

Starting from a handful of individual stations available in early 2012, the MGEX network has grown to almost 130 sensor stations providing global/regional coverage of GPS, GLONASS, BeiDou, Galileo, and QZSS in late 2015. Figure 33.6 illustrates the location of stations offering tracking of at least one of the new constellations in addition to GPS or GLONASS.

The MGEX network contains a diverse assortment of receiver and antenna equipment with five basic receiver types and eight main antenna types. All of the user equipment in the MGEX network is recognized and characterized by the IGS in the equipment description file. Many of the stations contain multiple receivers connected to the same antenna, known as a *zero-baseline* setup, which provides a basis for cross-validation of equipment performance. Some of the sites also contain multiple stations for short baseline comparison experiments. The variety of equipment used in the tracking network is both an asset as well as a challenge. The diversity of deployed receivers and antennas poses a challenge for consistent data processing, but allows a greater understanding of the types of data received and how the assessment of navigation signals is to proceed. The cross comparison of different receivers can contribute directly to design improvement by receiver manufacturers.

During the initial deployment of the MGEX network, relaxed site requirements were imposed on new station contributions and the network was essentially operated independently and in parallel to the legacy IGS tracking network for GPS and GLONASS to avoid any adverse impact on the standard IGS product generation. With the ongoing modernization of the legacy stations and the improved quality of new MGEX contributions, the vast majority of MGEX stations could ultimately be integrated into the standard IGS network in the course of 2015. Users can now take advantage of a single network of stations meeting the high-quality standards imposed by the IGS site guidelines. While only a subset of all IGS stations is presently multi-GNSS capable, the fraction of such stations is expected to grow continuously over time in the years to come.

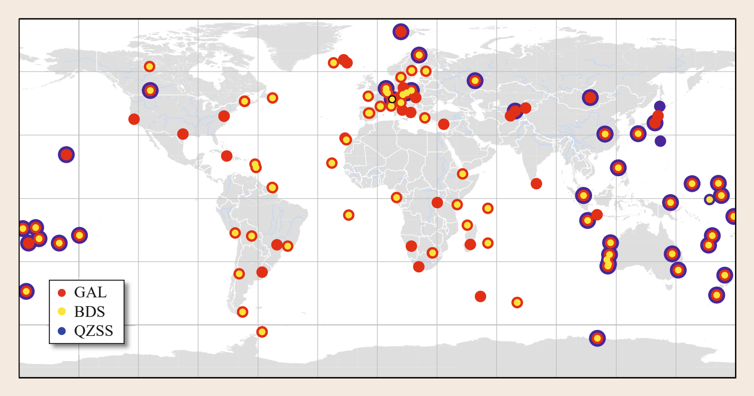

Fig. 33.6 MGEX network of stations (Oct. 2015)

Table 33.9 MGEX analysis centers generating precise multi-GNSS orbit and clock products on a routine basis (Oct. 2016)

Institution	Constellations
CNES/CLS, France [33.30]	GPS + GLO + GAL
CODE, Switzerland [33.31]	GPS + GLO + BDS + GAL + QZS
GFZ, Germany [33.32, 33]	GPS + GLO + BDS + GAL + QZS
JAXA, Japan	GPS + QZS
TUM, Germany [33.34]	GAL + QZS
Wuhan Univ., China [33.35]	GPS + GLO + BDS + GAL + QZS

All IGS multi-GNSS stations provide offline observation files in RINEX3 format [33.29], which supports all required observation types and constellations. Data archives are hosted by established IGS DCs including NASA's Crustal Dynamics Data Information System (CDDIS) in the United States, the French National Geographic Institute (IGN), and the German Federal Office for Cartography and Geodesy (BKG) Daily RINEX3 files with observation rates of 30 s are made available for all multi-GNSS stations and a subset of stations also delivers high-rate data files with 1 Hz observation data.

Next to the offline data, roughly 60% of all multi-GNSS stations also provide their data as real-time data streams. Where needed, manufacturer-specific data formats are encoded in the RTCM3 Multiple-Signal-Message (MSM) format once received from the individual sites and transferred to a dedicated MGEX NTRIP caster hosted by BKG in Frankfurt. The dedicated caster provides an experimental platform on which the new MSM format can be tested and facilitates user software adaptation.

MGEX Products

The data collected by the MGEX network provide the basis for the generation of precise orbit and clock products for the new constellations. As of late 2015, six analysis centers contribute such products to the MGEX project on a regular basis (Table 33.9). While early products were often confined to individual GNSSs, a growing number of ACs have lately moved to generating five-constellation products with a common underlying time and reference frame. Except for the Indian Regional Navigation Satellite System, the MGEX products thus cover all legacy and emerging navigation systems. Addition of IRNSS is foreseen, once an adequate number of monitoring stations with dual-frequency IRNSS tracking capability becomes available within the IGS.

Clock products were initially confined to 5 min or 15 min but have later been made available with sampling intervals of down to 30 s. Furthermore, various ACs also provide associated data such as Earth orientation parameters, intersystem biases, or estimated station coordinates along with their orbit and clock products.

Other than for GPS and GLONASS, no combination process has yet been implemented within the IGS for precise orbit and clock products of the new constellations, but cross-comparison of different ACs as well as satellite laser ranging can serve to assess the precision or accuracy of the various products. For Galileo, a performance at the 10–20 cm level (3-D rms orbit consistency and differences w.r.t. SLR observations) has been demonstrated in [33.36] for the 2013–2014 time frame. Further improvements are expected through better characterization of the spacecraft and respective refinements of radiation pressure models or antenna phase center variations. A performance at the few dm-level is also achieved for BeiDou MEO and IGSO satellite, whereas the orbit consistency for geostationary satellites is limited to a few meters [33.37]. The degraded GEO orbit determination accuracy reflects the adverse impact of a near-static viewing geometry, which does not enable a reliable determination of the along-track position from one-way pseudorange and carrier-phase observations.

Even though the accuracy of the multi-GNSS products lags behind the performance of the standard IGS products for GPS and GLONASS, they pave the way for a full exploitation of new signals and constellations in navigation, surveying, geodesy, and remote sensing.

Special products provided in the frame of MGEX include combined multi-GNSS broadcast ephemeris data as well as multi-GNSS DCBs. The combined broadcast ephemeris data have initially served as a substitute for constellations not yet covered by the precise orbit and clock products, but are of continued interest because of their lower latency and the access to GNSS-specific system time scales.

An understanding of DCB is a prerequisite for processing multiconstellation code observations, which are essential in many navigation applications. They are also essential for many nonnavigation applications such as time transfer and ionospheric analysis for correction of pseudorange differences. The need for comprehensive DCB analysis is increasing as the rate of signals offered by new and modernized satellite systems rises. Prototype DCB products generated by the German Aerospace Center (DLR) and the Chinese Academy of Science (CAS) are available through MGEX at the CDDIS and IGN product archives. GPS, GLONASS, Galileo, and BeiDou DCBs are derived from pseudorange differences corrected for ionosphere path delays [33.19] and are provided in a preliminary version of the Bias SINEX format, which is currently under development within the

IGS and will serve as the new standard for the exchange of phase and code bias information.

For real-time users, early services include a combined multi-GNSS broadcast ephemeris stream (including GPS, GLONASS, Galileo, BeiDou, QZSS, and SBAS) prepared by BKG as well as Galileo orbit and clock corrections generated by the CNES/ILS analysis center.

For further information about MGEX, including news, constellation status, network and station information, data holdings, real-time data, and products, users are referred to the IGS MGEX website [33.38]. In the long run, it is planned to integrate all MGEX products into the regular IGS processing to offer a reliable and high-performance multi-GNSS service to the GNSS community.

33.5 Outlook

The IGS continues to evolve into a truly multi-GNSS service. It is expected that the new constellations of positioning satellites will be fully operational by 2020. This has driven the IGS to commence a strategic review of its activities, products, and services. While it is clear that the IGS has a role to play in producing products for all constellations (orbits and clocks), it is not so clear which combinations of signals will be utilized for the products that are nonconstellation-specific including the reference frame and atmospheric products. A considerable body of research is currently being undertaken to establish evidence to support such decisions.

As the uptake of GNSS as a public utility continues, an emerging need to understand the accuracy and integrity of all positioning satellites, including their system differences, is becoming evident. The use of GNSS now extends well beyond the military and science applications, including many industrial and Location Based Services (LBS) applications. The IGS has been cooperating with Working Group A of the International Committee on Global Navigation Satellite Systems (ICG) to develop a common understanding of the requirement for system monitoring through the International GNSS Monitoring and Assessment (IGMA) subgroup.

Lastly, through GGOS, it has become clear that SLR observations to GNSS satellites and GNSS observations on non-GNSS satellites like GRACE, have a strong role to play in improving our understanding of observational errors, and therefore improving the accuracy of IGS products. The IGS will continue to collaborate with other elements of the GGOS to integrate these observations into the product generation.

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References

33.1 International GNSS Service: *Terms of Reference* (IGS, Pasadena, 2014) http://kb.igs.org/hc/en-us

33.2 H.-P. Plag, M. Pearlman: *Global Geodetic Observing System: Meeting the Requirements of a Global Society on a Changing Planet in 2020* (Springer, Berlin 2009)

33.3 Z. Altamimi, X. Collilieux: IGS contribution to the ITRF, J. Geod. **83**(3/4), 375–383 (2009)

33.4 United Nations: A global geodetic reference frame for sustainable development, Resolution A/RES/69/266 adopted by the General Assembly on 26 Feb. 2015 (United Nations, New York 2015)

33.5 G. Beutler, A.W. Moore, I.I. Mueller: The International Global Navigation Satellite Systems Service (IGS): Development and achievements, J. Geod. **83**(3/4), 297–307 (2009)

33.6 IGS Central Bureau: *IGS Site Guidelines* (Infrastructure Committee, IGS Central Bureau, Pasadena 2015) http://kb.igs.org/hc/en-us

33.7 IGS: *Charter for IGS Data Centers – Definition of IGS Data Center Activities* (IGS, Pasadena 2010) http://kb.igs.org/hc/en-us

33.8 C. Noll, Y. Bock, H. Habrich, A. Moore: Development of data infrastructure to support scientific analysis for the International GNSS Service, J. Geod. **83**(3/4), 309–325 (2009)

33.9 C.E. Noll: The Crustal Dynamics Data Information System: A resource to support scientific analysis using space geodesy, Adv. Space Res. **45**(12), 1421–1440 (2010)

33.10 IGS: IGS Working Groups website, http://igs.org/wg

33.11 IGS: Strategic Plan 2013–2016 (IGS Central Bureau, Pasadena 2013) http://kb.igs.org/hc/en-us

33.12 IGS: IGS Products website, http://www.igs.org/products/

33.13 IGS: IGS Analysis Center Coordinator website http://acc.igs.org/

33.14 G. Petit, B. Luzum: *IERS Conventions (2010)*, IERS Technical Note No. 36 (Verlag des Bundesamts für Kartographie und Geodäsie, Frankfurt 2010)

33.15 S.H. Byun, Y.E. Bar-Sever: A new type of troposphere zenith path delay product of the international GNSS service, J. Geod. **83**(3/4), 1–7 (2009)

33.16 C. Hackman, G. Guerova, S. Byram, J. Dousa, U. Hugentobler: International GNSS Service (IGS) troposphere products and working group activities, FIG Work. Week 2015, Sofia (FIG, Copenhagen 2015) pp. 1–14

33.17 M. Hernández-Pajares, J.M. Juan, J. Sanz, R. Orus, A. Garcia-Rigo, J. Feltens, A. Komjathy, S.C. Schaer, A. Krankowski: The IGS VTEC maps: A reliable source of ionospheric information since 1998, J. Geod. **83**(3/4), 263–275 (2009)

33.18 S. Schaer: Biases and calibration working group technical report 2014. In: *IGS Technical Report*, ed. by Y. Jean, R. Dach (IGS Central Bureau, Pasadena 2014)

33.19 O. Montenbruck, A. Hauschild, P. Steigenberger: Differential code bias estimation using Multi-GNSS observations and global ionosphere maps, Navigation **61**(3), 191–201 (2014)

33.20 P. Willis, J. Slater, G. Beutler, W. Gurtner, C. Noll, R. Weber, R.E. Neilan, G. Hein: The IGEX-98-campaign: Highlights and perspective, Geod. Beyond 2000, Int. Assoc. Geod. Symp., Vol. 121, ed. by K.-P. Schwarz (Springer, Berlin 2000) pp. 22–25

33.21 R. Weber, J.A. Slater, E. Fragner, V. Glotov, H. Habrich, I. Romero, S. Schaer: Precise GLONASS orbit determination within the IGS/IGLOS pilot project, Adv. Space Res. **36**(3), 369–375 (2005)

33.22 IGS: *IGS Real-Time Service Fact Sheet* (IGS, Pasadena 2014) http://kb.igs.org/hc/en-us

33.23 IGS: IGS Real-Time Service website http://igs.org/rts

33.24 M. Caissy, L. Agrotis, G. Weber, M. Hernandez-Pajares, U. Hugentobler: Coming soon – The international GNSS real-time service, GPS World **23**(6), 52 (2012)

33.25 RTCM: RTCM Standard 10403.2 Differential GNSS Services, Version 3 with Ammendment 2, 7 Nov. 2013 (RTCM, Arlington 2013)

33.26 O. Montenbruck, P. Steigenberger, R. Khachikyan, G. Weber, R.B. Langley, L. Mervart, U. Hugentobler: IGS-MGEX: Preparing the ground for multi-constellation GNSS science, Inside GNSS **9**(1), 42–49 (2014)

33.27 M. Schmitz: RTCM state space representation messages, status and plans, PPP-RTK Open Stand. Symp., Frankfurt (BKG, Frankfurt am Main 2012) pp. 1–31

33.28 G. Weber, D. Dettmering, H. Gebhard, R. Kalafus: Networked transport of RTCM via internet protocol (Ntrip) – IP-streaming for real-time GNSS applications, Proc. ION GPS 2005, Long Beach (ION, Virginia 2005) pp. 2243–2247

33.29 IGS: RINEX – The Receiver Independent Exchange Format – Version 3.03 14 Jul. 2015 (IGS RINEX WG and RTCM-SC104, 2015)

33.30 S. Loyer, F. Perosanz, F. Mercier, H. Capdeville: MGEX activities at CNES-CLS Analysis Centre, IGS Workshop 2012, Olsztyn (IGS, Pasadena 2012)

33.31 L. Prange, R. Dach, S. Lutz, S. Schaer, A. Jäggi: The CODE MGEX orbit and clock solution. In: *IAG 150 Years, IAG Symposia*, International Association of Geodesy Symposia, Vol. 143, ed. by C. Rizos, P. Willis (Springer, Berlin, Heidelberg 2015) pp. 767–773

33.32 M. Uhlemann, G. Gendt, M. Ramatschi, Z. Deng: GFZ global multi-GNSS network and data processing results. In: *IAG 150 Years*, *IAG Symposia*, International Association of Geodesy Symposia, Vol. 143, ed. by C. Rizos, P. Willis (Springer, Berlin, Heidelberg 2015) pp. 673–679

33.33 Z. Deng, M. Ge, M. Uhlemann, Q. Zhao: Precise orbit determination of BeiDou Satellites at GFZ, IGS Workshop 2014, Pasadena (IGS, Pasadena 2014)

33.34 P. Steigenberger, A. Hauschild, O. Montenbruck, C. Rodriguez-Solano, U. Hugentobler: Orbit and clock determination of QZS-1 based on the CONGO network, Navigation **60**(1), 31–40 (2013)

33.35 J. Guo, X. Xu, Q. Zhao, J. Liu: Precise orbit determination for quad-constellation satellites at Wuhan University: Strategy, result validation, and comparison, J. Geod. **90**(2), 143–159 (2016)

33.36 P. Steigenberger, U. Hugentobler, S. Loyer, F. Perosanz, L. Prange, R. Dach, M. Uhlemann, G. Gendt, O. Montenbruck: Galileo orbit and clock quality of the IGS multi-GNSS experiment, Adv. Space Res. **55**(1), 269–281 (2015)

33.37 F. Guo, X. Li, X. Zhang, J. Wang: Assessment of precise orbit and clock products for Galileo, BeiDou, and QZSS from IGS Multi-GNSS Experiment (MGEX), GPS Solutions (2016), doi:10.1007/s10291-016-0523-3

33.38 IGS: IGS Multi-GNSS Experiment (MGEX) website http://igs.org/mgex