Univ.-Prof. Dr.-Ing. Prof. h.c. Günter Seeber anlässlich seines 65. Geburtstages
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Revolution in Geodesy, Navigation, and Surveying

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Preamble

This article is written in honor of Günter Seeber, a protagonist and outstanding expert of satellite geodesy. Many, if not most, tasks in surveying and navigation are today solved (at least partially) with the methods of this comparatively young branch of science. The generation of geodesists and fundamental astronomers, whose professional career happened to coincide with the pioneer times of the space age are privileged from my perspective. This generation could witness and – to some extent – coin the rapid development associated in their profession. Günter Seeber undoubtedly contributed greatly to the rapid development of positioning and navigation in the second part of the 20th century. His admirable treatise of satellite geodesy, Seeber (1993), has inspired generations of young geodesists.

Summary

In this article we try to put the development of geodesy, surveying and navigation in a broad context. We analyze in particular the impact of satellite geodesy or, more generally, of space geodesy, on modern positioning and navigation, which in turn has considerable impact on the development of our modern society.

The first part deals with the development in the pre-space age. The review reminds us that geodesy and surveying always were intimately related through their tools and methods.
The second part deals with the revolution of our science and professions initiated by the space age. In essence a new branch of science, that of space geodesy, was born. It became, e.g., possible to define and maintain global terrestrial reference frames with cm-accuracy and to monitor Earth rotation with sub-mas-accuracy (mas = milliarcsecond) and very high (daily or higher) time resolution.

The third part is devoted to the civil use of Global Navigation Satellite Systems (GNSS), which had a deep impact on geodesy, navigation, and surveying. The International GNSS Service (IGS), working under the auspices of IAG, was of particular importance. Its development and achievements are reviewed in some detail.

1 Fundamental Astronomy, Navigation, Geodesy and Surveying

The introduction to Peter Apian's *Geographia* from 1533 in Figure 1 nicely illustrates that *surveying, geodesy, positioning, navigation* and *astronomy* in the "glorious old times" in essence meant measuring angles – the scale was eventually introduced by one (or few) known distance(s) between two sites (as indicated by the symbolic measurement rod in the center of the wood-cut).

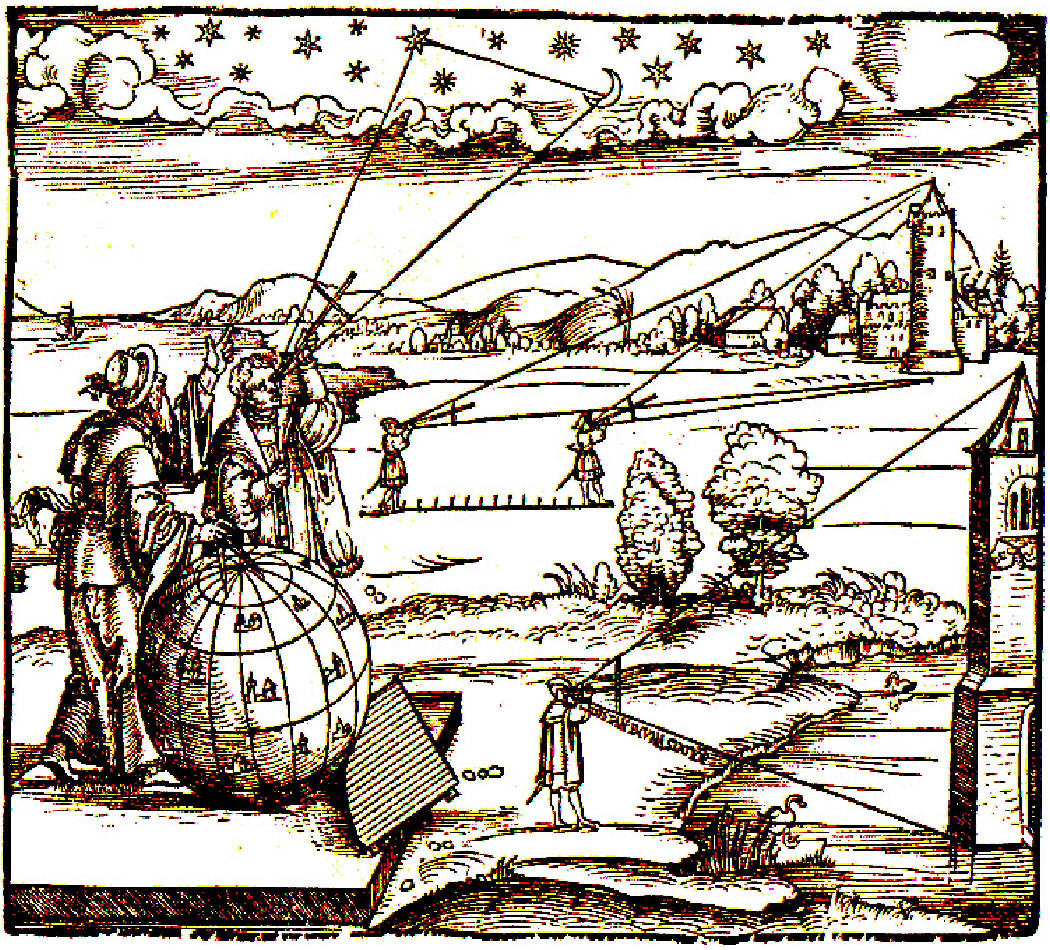

Figure 1: Peter Apian's Geographia

Figure 1 also indicates that relative local and absolute positioning was performed with the same instruments, the so-called cross-staffs, in Apian's days. *Global* positioning simply meant the determination of the observer's *geographical latitude* and *longitude* relative to an arbitrarily selected reference site (first several, then the Greenwich site, were used for this purpose).

The latitude of a site could be established "easily" by determining the elevation (at the observer's location) of the Earth's rotation axis, approximately given by the polar star.
In principle, longitude determination was simple, as well: One merely had to determine the *time difference* (derived either by observing the Sun (local solar time) or the stars (sidereal time)) between the unknown site and Greenwich. The problem resided in the realization of Greenwich time at the unknown observing site in the pre-telecommunications era.

One astronomical solution to this problem, also illustrated in Figure 1, consisted of measuring the so-called *lunar distances* (angles between bright stars and the Moon). With increasing accuracy of the (prediction of the) lunar orbit, the angular distances between the Moon and the stars could be accurately predicted and tabulated in astronomical and nautical almanacs using Greenwich local time as argument. For navigation on sea the method became obsolete with the development of marine chronometers, which were capable of transporting accurately Greenwich time in vessels over time spans of weeks. Figure 2 shows the first chronometer developed by the ingenious British watchmaker J. Harrison (1693-1776).

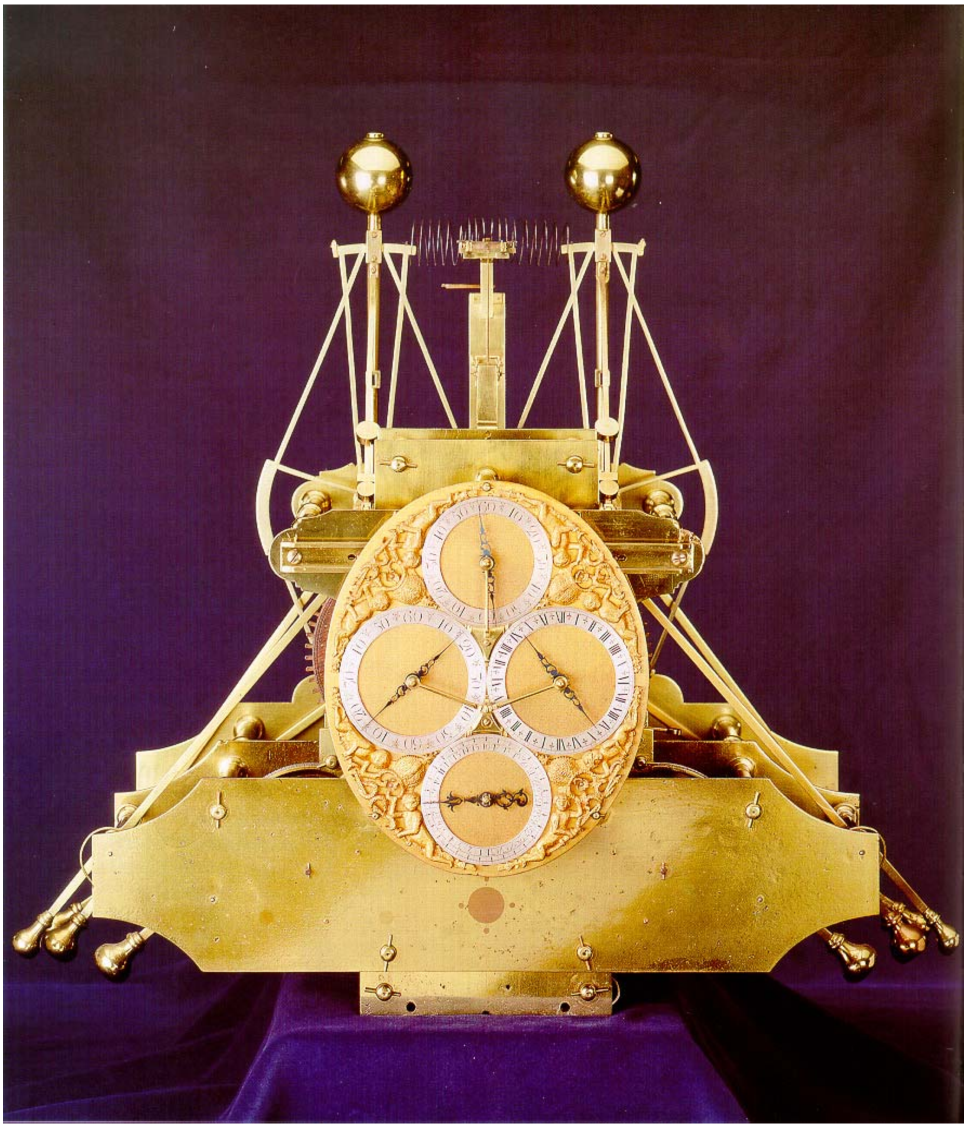

Figure 2: Harrison I, First marine chronometer

The *principles* of precise positioning and navigation remained in essence the same since Apian's times till well into the second half of the 20th century. The development of instruments and of the achieved accuracy was, however, dramatic: the cross-staff was replaced by increasingly more sophisticated optical devices, telescopes in particular. More precise star catalogues (fundamental catalogues) were produced and the fine art of predicting the motion of the Moon and the planets was refined in celestial mechanics. Eminent astronomers, mathematicians, and physicists, from L. Euler (1707-1783), P.S. de Laplace (1749-1827), to S. Newcomb (1835-1909), were steadily improving the quality of ephemerides. Highly precise pendulum clocks and marine chronometers allowed it eventually to time-tag the observations with millisecond accuracy.

The relationships between pure science on the one hand and precise positioning and navigation on the other, but also between geodesy and surveying, were truly remarkable: the discipline of *fundamental astronomy* emerged from this interaction between theory and application. In fundamental astronomy one defines and realizes the global terrestrial and the celestial reference systems *including* the transformation between the systems. The terrestrial reference system was realized by the geographical coordinates of a network of astronomical observatories. An accuracy of about 100 meters was sufficient for the purpose.
Until quite recently the celestial reference system was realized through fundamental catalogues of stars. The establishment of the transformation between the two systems implies the monitoring of Earth rotation in the inertial space and on the Earth's surface. Figure 3 illustrates the motion of the Earth's rotation axis in space.

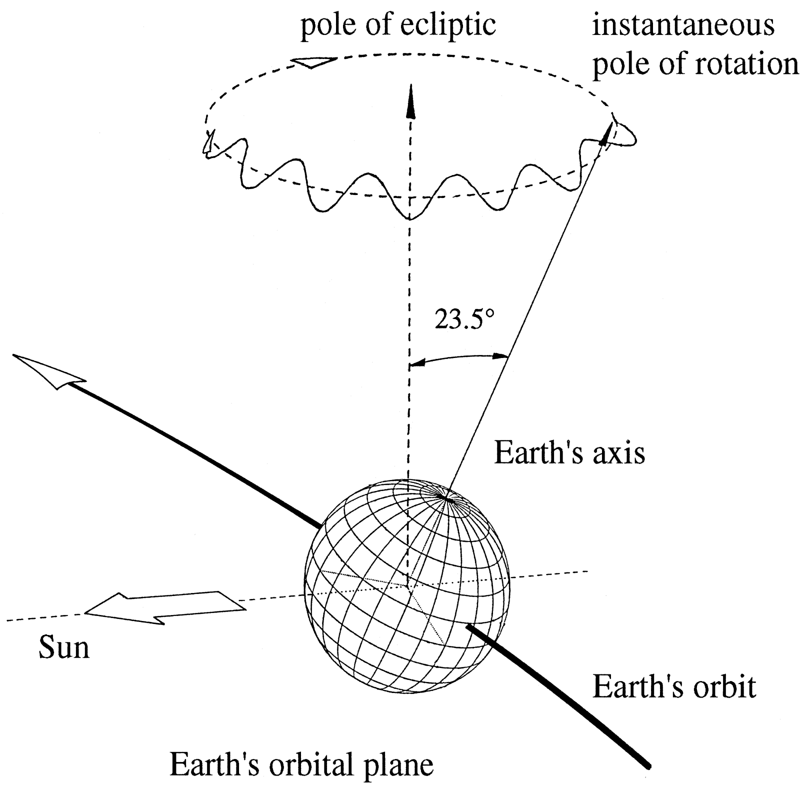

Figure 3: The Earth's rotation axis in inertial space

It is well known that the rotation axis approximately moves on a straight cone inclined by 23.5^o w.r.t. the pole of the ecliptic, an effect known as precession, which was already discovered in the Greek era (and usually attributed to the great Greek astronomer Hipparchus). This motion is not fully regular, but shows short-period variations, which is why the astronomers make the distinction between precession and nutation. A study of ancient solar eclipses revealed eventually that the length of day is slowly (by about 2 ms per century) growing. The Earth axis also moves on the Earth's surface, an effect known as polar motion. This and other discoveries related to Earth rotation made in the era of optical astronomy are summarized in Table 1.

Table 1: Discoveries related to Earth rotation in the optical era of fundamental astronomy

Year	**Discoverer**	**Effect**
300 B.C	Hipparchus	Precession in longitude (50.4”/y)
1728 A.D.	J. Bradley	Nutation (18.6 years period, amplitudes of 17.2” and 9.2” in ecliptical longitude and obliquity, respectively)
1765 A.D.	L. Euler	Prediction of polar motion (with a period 300 days)
1798 A.D.	P.S. Laplace	Deceleration of Earth rotation (length of day)
1891 A.D.	S.C. Chandler	Polar motion, Chandler period of 430 days and Annual Period

So far we have only mentioned the determination of geometrical quantities, namely of

- the terrestrial reference systems,
- the celestial reference system, and
- the transformation between the two systems (i.e. the monitoring of Earth rotation).

These quantities are the relevant *objects of desire* in fundamental astronomy and navigation. The determination of the Earth’s gravity field is a task of equal importance in geodesy *and* in surveying. The importance of the gravity field becomes immediately clear, if we recall the products derived from or associated with it, namely

- the determination of the gravity potential from which the quasi-geoid (or the geoid at the oceans) may be derived,
- the determination of potential differences from levelling and gravity, which are converted to orthometric or normal heights and associated with a local or regional height datum, and
- the determination of deflections of the vertical, used to correct measurements referring to the plumb-line.

In the pre-space era gravity field determination uniquely had to be based on *in situ* measurements on (or near) the surface of the Earth. Gravimeters, measuring the absolute value of gravity or of gravity differences, were developed.

Other instruments, such as zenith cameras were developed, which allow the determination of the plumb-line (the vertical), from which deflections of the vertical may be computed.
Gravimeters and zenith cameras are examples of terrestrial tools to determine the Earth’s gravity field. These in situ measurements are well suited for modeling the local or regional properties of the Earth’s gravity field. However, the global properties of the gravity field can only be modeled using a global data distribution, which today is achieved through satellite gravity missions, see section 2.1.

This brief review of the methods and achievements of fundamental astronomy, navigation, surveying and geodesy reveals that all disciplines were in essence based on the same instruments in the pre-space-age era. This overview had the focus on positioning, navigation, and fundamental astronomy and therefore is far from complete. Let me mention that the entire field of photogrammetry, modeling e.g., the projection of the sky (or of a satellite image acquired by a remote sensing satellite) onto a photographic plate, is of highest interest to geodesy, as well. For more details concerning the development of navigation and positioning the reader is referred to Beutler (2003).

2 The Revolution of Geodesy and Surveying in the 20th Century

2.1 The Advent of the Space Age, Satellite Geodesy, and Space Geodesy

The *space age* was initiated by the launch of the first artificial satellite, Sputnik I, on October 4 of the International Geophysical Year 1957. With the launch of artificial satellites it became possible to use these objects *either* to study the size and figure of the Earth from space *or* to observe them as targets from the surface of the Earth. The use of artificial satellites for geodetic purposes led to the development of *satellite geodesy*.

The second essential development in space geodesy in the second half of the 20th century is that of the *Very Long Baseline Interferometry* (VLBI) technique as a new tool to realize an extraordinarily accurate and stable inertial (celestial) reference system. The replacement of the fundamental star catalogues by a catalogue of Quasars for the definition of the celestial reference frame (surprisingly accepted by both, the IUGG and the IAU in the 1990s) was an epochal event (which passed, however, almost unnoted by the larger scientific community). Satellite geodesy and VLBI together often are referred to as space geodetic methods or techniques.

Today, space geodetic techniques are the primary tools to study size, figure and deformation of the Earth, and its motion as a finite body in the inertial reference system. Space geodetic techniques thus are fundamental for geodesy, geodetic astronomy, and geodynamics.
The development of space geodesy took place in overlapping *periods*. All, except the last of these periods, are mainly of scientific interest. The last one, the GNSS period, has had (and will continue to have) a much greater impact. It should be viewed as the replacement of classical navigation and positioning (which, according to Section 1 is based on the observation of astrometric positions of natural celestial objects) by measurements of microwave signals emitted by artificial satellites. Let us now briefly review the periods of space geodesy:

- **Optical period.** Optical (astrometric) observations were made of the first generation of artificial Earth satellites, like Sputnik 2 and Explorer 1. The balloon satellites Echo 1 and 2 and PAGEOS (passive geodetic satellite), which could even be seen "by the naked eye", were observed by a worldwide dedicated tracking network. These satellites were (supposedly) spherical, consisted of layers of aluminized mylar foil, and, thanks to their brightness, their tracks could easily be photographed against the star background. Even better suited, although more difficult to track, were smaller satellites like Geos 1 (Explorer 29) and Geos 2 (Explorer 36) equipped with flash lamps.
  Fascinating results came out of this first phase of satellite geodesy. The geodetic datums on different continents could be related to the geocenter and thus to each other with an accuracy of about 5 meters. First reliable coefficients of the gravity field (spherical harmonic expansion up to degree and order of about 12-15) were also derived.
  The astrometric technique, when applied to artificial satellites in the 1960s and 1970s, had serious disadvantages. The observation was day time- and weather-dependent; the star catalogues were not of sufficiently high quality and the processing time (time between observation and availability of results) was of the order of a few weeks in the best case. The optical technique therefore no longer played a significant role in space geodesy after about 1975. Remote sensing satellites, like LANDSAT and SPOT, producing images of the Earth's surface, might also be mentioned in this category. These satellites were, however, only of marginal benefit for the determination of the Earth's gravity field or of a highly accurate global terrestrial reference frame.

- **Doppler period.** The U.S. Navy Navigation Satellite System (NNSS), also called the TRANSIT system, had a significant impact on the development of space geodesy. It proved that a system based on the measurement of the Doppler shift of signals generated by stable oscillators on board the satellites could be used for positioning with a remarkable accuracy (0.1-0.5 m relative, about 1 m absolute). The satellites transmitted information on two carrier frequencies (400 MHz and 150 MHz) near the microwave band. The two frequencies allowed for a compensation of ionospheric refraction. Rather small receivers connected to omni-directional antennas made the technique well suited to establish regional and global geodetic networks. Observation periods of a few days were required to obtain the above stated accuracy. The NNSS satellites were in polar, almost circular, orbits about 1100 km above the Earth's surface. The Doppler technique is weather-independent. The Transit system was shut down as a positioning system in December 1996 (see Kouba 1983, for details).

- **SLR and LLR period.** SLR stands for Satellite Laser Ranging, LLR for Lunar Laser Ranging. The laser technique, developed in the 1950s, may be used to generate high energetic short light pulses. These pulses are sent out by a conventional astronomical telescope, travel to the satellite (or Moon), are reflected by special corner cubes on the satellite (or Moon) back to the telescope. The travel time of the laser pulse from the telescope to the satellite (or Moon) and back to the telescope is measured and corresponds (after multiplication with the speed of light) to twice the distance between satellite and telescope at the time the light pulse is reflected by the satellite. Today's SLR technique is capable of determining the distance between observatories and satellites with an accuracy of few millimeters and with a high repetition rate (up to a few Hz). SLR techniques may be used for every satellite equipped with corner cubes. The unique and most valuable contributions of SLR lie in the determination of the Earth's (variable) gravity field, in the determination of the geocenter, and in calibrating geodetic microwave techniques. LLR measures distances between an observatory and the reflectors deployed on the Moon by the Apollo space missions and the Russian Lunokhod missions. The technique is, e.g., capable of measuring directly the secular increase of the Earth-Moon distance (3.8 cm per year). Also, LLR is well suited for evaluating gravitational theories.

- **VLBI period.** Very Long Baseline Interferometry (VLBI) is the only non-satellite geodetic technique contributing to the International Earth Rotation Service (IERS). Its unique and fundamental contribution to geodesy and astronomy is the realization of the celestial reference system and the maintenance of the long-term stability of the transformation between the celestial and terrestrial reference frames. The ICRS (International Celestial Reference System) is defined and maintained by the (recently renamed) International Earth Rotation and Reference Systems Service (IERS). It was adopted by the IAU and the IUGG as the primary celestial reference system, replacing its optical predecessors based on fundamental star catalogues. The observation and analysis aspects are today coordinated by the IVS, the International VLBI Service for Astrometry and Geodesy.

- **Altimetry missions.** Altimetry missions, based on the radar technique, significantly improved our knowledge of the sea surface topography, of ocean currents, of tidal motions of the oceans, etc. There is a long list of altimetry missions including, e.g., GEOS-3, SEASAT, ERS-1 and -2, Envisat, etc. The TOPEX/Poseidon (TOPography EXperiment for ocean circulation) mission was the first mission which was specially designed to study the ocean currents. For space geodesy the TOPEX/Poseidon mission was a kind of *rosetta* *stone* mission, because its orbit was determined using three independent systems (the French DORIS system, SLR tracking, and the GPS). TOPEX/Poseidon was neither the first, nor will it be the last altimetry mission (actually, its successor Jason is already in orbit). Missions like CRYOSAT (a planned three-year ESA radar altimetry mission to determine variations in the thickness of the Earth's continental ice sheets) and ICESAT (NASA's mission for measuring the ice sheet mass balance, cloud, and aerosol heights, etc.) will significantly improve our knowledge of the Earth's ice sheets.

- **SAR and InSAR missions.** Satellite missions based on the *Synthetic Aperture Radar* technique and interferometric SAR (InSAR) have the proven potential to revolutionize deformation monitoring and measurements. As opposed to the conventional positioning techniques, SAR and InSAR give deformation information for extended areas (up to a few hundred km). In this sense the SAR techniques and photogrammetry are closely related.

- **Gravity space missions.** For geodesy and geodynamics the CHAMP (Challenging Mini-Satellite Payload for Geophysical Research and Application) mission, the GRACE (Gravity Recovery and Climate Experiment) mission, and the upcoming European GOCE (Gravity field and Ocean Current Explorer) mission are particularly fascinating. It is expected that our knowledge of the Earth's gravity field (thanks to the use of spaceborne GPS receivers, accelerometers, and gradiometers) will significantly grow. Gravity missions are of central importance for altimetry, because a precise geoid is required to refer the sea surface topography to an equipotential surface.

- **GNSS period.** GNSS stands for Global Navigation Satellite System. The current generation of GNSS may be viewed as the successor of the Doppler systems. The systems are based on coherent microwave signals (in the L-band) emitted by the satellites in (at least) two carrier frequencies. *Simultaneity* of measurement of the signals emitted by several satellites and recorded by a receiver allow for instantaneous positioning. The GPS (Global Positioning System) is the best known GNSS and, on top of that, the best known space geodetic technique today. The system has an impact on science *and* society as a whole, reaching far beyond space geodesy. GPS revolutionized surveying, timing, pedestrian, car, marine and aircraft navigation. Many millions of receivers are in use today. Spaceborne applications of the GPS have a deep impact on geodesy and atmospheric sciences. Other systems, like the Russion GLONASS and the planned European Galileo system (when/if fully deployed) will have a similar impact in future. The impact of GNSS on geodesy and on IAG was so significant, that this aspect will be dealt with separately in section 3.

The overview in this section was based on an article on space geodesy prepared by the author for the Encyclopedia of Astronomy (Murdin 2001).

2.2 Evolution of IAG in the Space Age

In geodesy, as in other branches of science, one has to distinguish between the scientific questions asked and the tools used to answer them. Many questions asked today in geodesy are still the same as, or closely related to, those asked in the 19th century.
The technical developments related to the space age, the development of powerful computers (note that in the "good old days" computers were human beings (!) in fundamental astronomy), and the development of communication allow it to tackle many more questions of, and to find much more detailed answers to, classical problems. One aspect, however, will never change in geodesy: Geodetic problems only can be successfully addressed through inter-

national collaboration. The discussion of the development of the IERS will underscore this statement. The Bureau Gravimetrique International (BGI), systematically collecting and archiving gravity(-related) information in a worldwide basis is another excellent example of international collaboration in geodesy.

It is a noble duty of an international association to focus the interests of its community on the relevant scientific questions using the state-of-the-art techniques. The IAG has made the attempt to cope with this challenge ever since its creation in 1864. This is true in particular in the space age – no trivial problem in view of the dramatic evolution of the geodetic tools in the second half of the 20^{th} century. For more information concerning the history of the IAG the reader is referred to Beutler et al. (2004a, 2004b).

Let us have a closer look at *Earth rotation* in this section. The example nicely demonstrates how the IAG works. There are quite a few topics in geodesy which only can be explored successfully, if a particular effect is regularly monitored. Sea level variations (on all time scales) and Earth rotation are two excellent examples. In such cases IAG tends to hand over the “routine work” to a *scientific service* in order to ensure the long-term availability of the raw measurements and the derived products.

An IAG service is created, if measurements and products are well defined, regularly generated, and of importance for a large user community. The IERS, e.g., is the IAG service dealing with all aspects of Earth rotation, the definition and maintenance of the global terrestrial and the celestial reference frames, and with monitoring the transformation between the two reference systems. The IERS is a multi-technique service.

The roots of the IERS go back to the year 1899 when the *ILS*, the International Latitude Service, was founded by the IAG. Polar motion was derived from latitude observations performed at (initially) six observatories (Mizusawa (Japan), Tschardjui (former USSR), Cagliari (Italy), Gaithersburg (USA), Cincinnati (USA), Ukiah (USA)). The Central Bureau of the ILS was initially located at the Geodetic Institute of Potsdam (Director F. R. Helmert, responsible C.T. Albrecht), then moved to Japan (Mizusawa) in 1922 with H. Kimura as director, then to Italy in 1935, to go back to Japan in 1962 with S. Yumi as director.

With the reorganization of the international scientific associations after the first world war, in particular with the creation of the IAU and the IUGG, the ILS became a service working under the auspices of these two large international unions. The IAG, now an Association of IUGG, was *de facto* responsible for the ILS - together with the IAU. A fundamental review of the polar motion work took place in the 1950s and it was decided to considerably expand this work. The *IPMS*, the *International Polar Motion Service*, was to succeed the ILS with a broader mandate. The IPMS became a service which would

- advance the study of all problems related to the motion of the pole,
- collect the observations, which can be utilized for the determination of this motion,
- calculate the coordinates of the pole, and
- distribute the data required, and publish the initial data and obtained results.

This mandate is close to the mandate of the IERS. It is interesting to note, however, that the celestial and terrestrial reference frames, *implicitly needed* for the work of the IPMS, were *not explicitly mentioned* in the above list, because the celestial frame could be taken from astronomy (fundamental catalogues) and the terrestrial frame from geodesy with sufficient accuracy.

It was *not* the IPMS first embracing the new space techniques. This mandate was then given to an IAU/IUGG joint working group in 1978. This working group initiated and conducted the project MERIT (Monitoring Earth Rotation and Intercomparison of Techniques of observation and analysis). All candidate techniques, in particular optical astrometry, Doppler tracking, SLR, LLR, and VLBI, were invited to demonstrate their capabilities for Earth rotation monitoring. Based on the MERIT experiences and on recommendations made by the project team, the IAU and IUGG decided to set up the IERS (International Earth Rotation and Reference Systems Service), which started operations on January 1, 1988. The mandate of the IERS is to

- define and maintain the International Celestial Reference Frame (ICRF),
- define and maintain the International Terrestrial Reference Frame (ITRF),
- monitor the Earth rotation parameters, and
- define the standards, constants, models, etc., required for Earth rotation work.

VLBI, SLR, and LLR were the techniques originally considered by the IERS. It was undoubtedly a wise decision to set up the IERS as a multi-technique service. From our perspective it would have been preferable to also have included astrometry, because this would have added an independent technique to determine UT1. (Also, the “transfer problem” of the celestial reference frame from the microwave to the optical domain would have been solved, or at least initiated, in this way.)

Figure 4 gives an impression of the achievements of the three IAG services monitoring polar motion (the “only” product of the ILS, one of the products of the IPMS and the IERS). Obviously the advances were dramatic, at least in terms of accuracy. It is, however, important to point out that in all cases one and the same aspect was studied with the state-of-the-art tools of their respective eras.

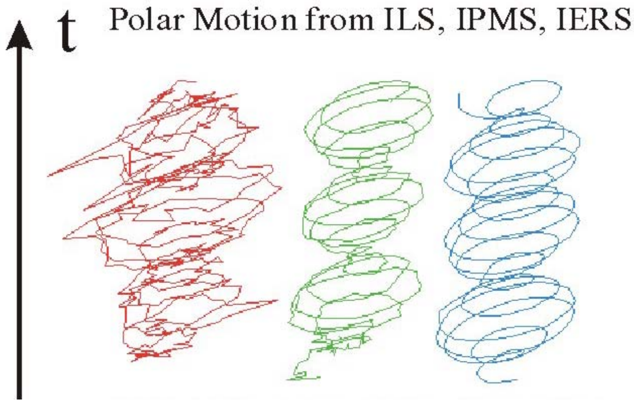

Figure 4: Polar Motion as determined by the ILS, the IPMS, and the IERS

3 The Impact of GNSS on Geodesy, Surveying and other Earth Sciences

In Section 2.1 it was said that the impact of the development of GNSS, and of the GPS in particular, on science *and* society is deep and long lasting. The impact of these systems on geodesy, surveying, and the Earth sciences is intimately linked to yet another IAG service, called the *International GPS Service for Geodynamics (IGS)*, later shortened to *International GPS Service*, then generalized to *International GNSS Service.*

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 other motivation was the generation of precise ephemerides for the satellites together with by-products such as Earth orientation parameters and GPS clock information.*

These ideas were discussed in 1989 at the IAG General Meeting in Edinburgh and led soon thereafter to the establishment of a Working Group, later re-designated as the *IAG Planning Committee for the IGS*, with Ivan I. Mueller as chairman. The *Call for Participation* was issued on February 1, 1991. More than 100 scientific organizations and governmental survey institutions announced their participation. At the 20th General Assembly of the IUGG in Vienna in 1991 the IAG Planning Committee was restructured and renamed as the *IGS Campaign Oversight Committee*. The author was asked to chair the committee and accepted the honour. The committee started organizing the *1992 IGS Test Campaign* and *Epoch'92*. The essential events of this first phase of the IGS development are summarized in Table 2.

Table 2: IGS of Events 1989-1991

Date	**Event**
August 1989	IAG Scientific Assembly in Edinburgh. Plans by Mueller, Mader, Melbourne, Minster, and Neilan
February 1991	Call for Participation mailed. Letters of Intent due 1 April 1991
August 1991	Planning Committee reorganized and renamed as *IGS Campaign Oversight Committee* at the 20th IUGG General Assembly in Vienna
October 1991	First IGS Campaign Oversight Committee Meeting in Greenbelt

The *1992 IGS Test Campaign*, scheduled to last from 21 June to 23 September 1992, focused on the *routine determination* of high accuracy orbits and Earth Rotation Parameters (ERPs). It was to serve as the *proof of concept* for the future IGS.

Epoch'92 was scheduled as a two-week campaign in the middle of the 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.

Two weeks after the start of the IGS Test Campaign on June 21, 1992 the first results of the IGS Analysis Centers started to flow into the IGS Global Data Centers, which in turn 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. When approaching the scheduled end of the IGS Test Campaign it became apparent that the campaign was a great, somewhat unexpected success and that it would be most harmful to stop or interrupt the IGS data collection and analysis activities. Therefore, data collection and transmission, as well as

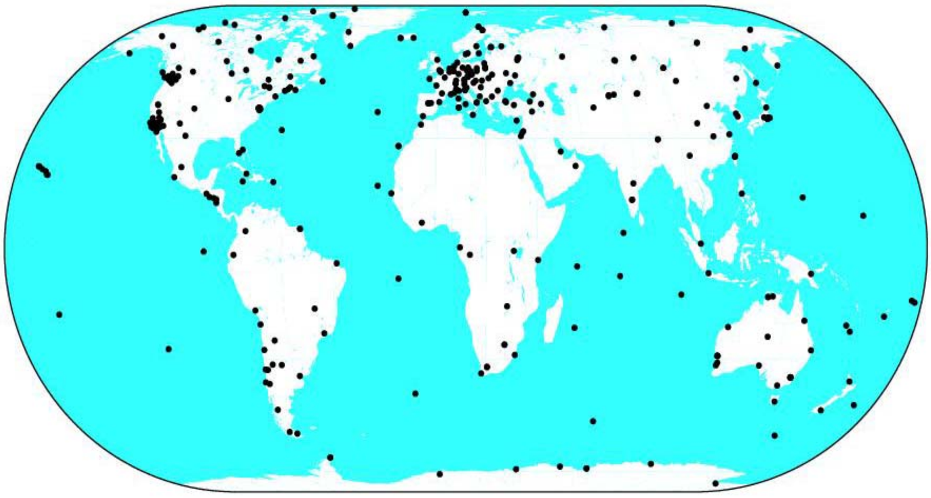

Figure 5: IGS Tracking Network in 2004

data analysis, continued on a *best effort basis* after the official end of the 1992 IGS Test Campaign on 23 September, 1992. As a consequence, the Oversight Committee decided to formally establish the *IGS Pilot Service* to bridge the gap between the 1992 IGS Test Campaign and the start of an official service. At the 1993 IGS Workshop in Bern, devoted to the evaluation of the 1992 IGS Test Campaign and of Epoch'92, "everybody" was confident that the IGS community was ready to start with an official service in the near future.

Table 3: IGS events 1991-1993

Date	**Event**
June 21, 1992	Start of IGS Test Campaign 1992
July 1992	First results!
July 27, 1992	Start of Epoch'92 campaign, lasting for two weeks
Sept 23, 1992	Official end of the campaign, continuation on best effort basis
November 1992	Start of IGS Pilot Service
March 1993	1st IGS Workshop in Bern, IGS Terms of Reference drafted
August 1993	IAG Approval for IGS at IAG Scientific Meeting in Beijing
October 1993	IGS Analysis Center Workshop in Ottawa
October 1993	IGS Network Operations Workshop in Silver Spring

The IGS started its operations as an official IAG Service on January 1, 1994. The official IGS products, orbits, ERPs, and the satellite clock corrections, were based on the contributions of individual IGS Analysis Centers. So-called *final* and *rapid* products were defined and delivered. From the technical point of view the IGS Analysis Center Coordinator was responsible for regularly generating the IGS products in a timely manner. Since January 1, 1994 (as a matter of fact already since June 21, 1992) this task was performed without failure and with increasing accuracy. This was possible because

- the IGS network grew steadily and was extremely reliable (see Figure 5),
- the data transmission, based on the Internet, was always available and reliable,
- the IGS concept of hierarchical Data Centers worked very well,
- the IGS Analysis Centers performed their analyses in a timely fashion, and
- the orbit, ERP, and satellite clock comparison, and the combination strategies documented by Beutler et al. (1995) proved to be reliable and robust.

It was felt as a necessity that the user community should be able to access reliable, robust and *unique* IGS products of the highest quality within the announced time limits *in addition to* the products of the individual Analysis Centers. The consistency of the IGS "combined" products is difficult to establish, because they are based (at least partly) on the same observations used by the Analysis Centers. They are used to estimate a common subset of parameters in addition to center-specific parameters.

Figure 6 documents the development of the consistency of the individual solutions of IGS Analysis Centers (mean error per satellite coordinate) since 1993. The figure illustrates that today the consistency level of the IGS final products is of the order of 1-3 cm. (The picture was taken from the current Analysis Center Coordinator's home page – http://www.gfz-potsdam.de/pb1/igsacc/index_igsacc.html.)

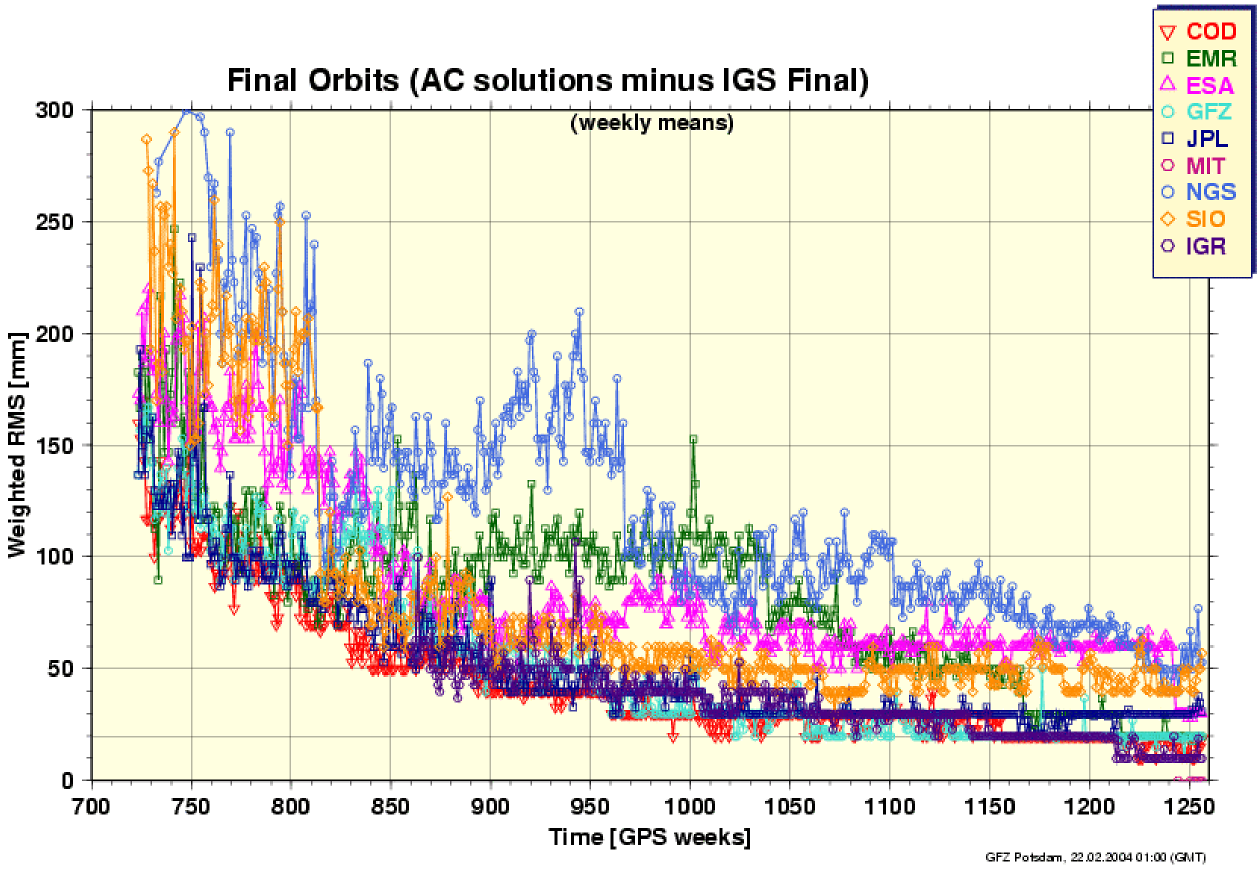

Figure 6: Consistency of IGS individual solutions

The IGS network is undoubtedly the densest space geodesy network of tracking stations, and therefore makes a very strong contribution to the ITRF. Similar statements can be made about the IGS ERPs: with their sub-milliarcsecond accuracy and their (at least) daily resolution of polar motion, the IGS significantly contributes to the monitoring of the ERPs.

What was said so far about the development of the IGS since 1993 could be characterized by the olympic logo "*altius, citius, fortius*". The IGS development had, however, yet another component: the IGS developed into a *multi-disciplinary service* by extracting the maximum information from the permanent IGS tracking activities. Today, the IGS should therefore be viewed as an *Interdisciplinary Service in support of Earth Sciences*, see Beutler et al. (1999). The IGS workshops, taking place at a frequency of 1-2 per year, were extremely important in this context. They are listed, together with other important IGS events, in Table 4.

Table 4: Important IGS events 1994-present

Date	Event
January 1994	Start of official service on January 1
November 1994	Workshop on the *Densification of the ITRF* at JPL, Pasadena
May 1995	IGS Workshop on *Special Topics and New Directions* at GFZ in Potsdam
March 1996	IGS Analysis Center Workshop in Silver Spring, USA
March 1997	IGS Analysis Center Workshop at JPL in Pasadena
February 1998	IGS Analysis Center Workshop at ESOC in Darmstadt
March 1999	LEO Workshop, Potsdam, Germany
June 1999	Analysis Center Workshop, La Jolla, California
July 2000	IGS Network Workshop
September 2000	IGS Analysis Center Workshop at USNO
December 2000	IGS Strategic Planning Meeting
February 2001	LEO Workshop
March 2001	Glonass Service Pilot Project
April 2002	Ottawa Workshop: Towards Real-time
April 2003	Ionosphere maps (IONEX) etc. official IGS product
May 2003	First operational combined GPS/GLONASS analysis products
March 2004	IGS Analysis Center Workshop and 10 Years Symposium
March 2005	IGS renamed as International GNSS Service

Whenever a new aspect was studied within the IGS, a Working Group was created. The charter of these working groups went far beyond the original IGS charter, which focused on the core products: GPS orbits, clock corrections, ERPs, station coordinates and velocities. The IGS extended its activities in particular into the following domains:

- atmospheric research,
- determination of LEO orbits,
- time and frequency transfer using the GPS code and phase observables,
- exploitation of the Russian GLONASS,
- tide gauge projects, and
- development in the direction of a GNSS service.

Let us illustrate the interdisciplinarity of the IGS with an example stemming from Fall 2003, when there was exceptionally high solar activity. This high level of solar activity induced in turn a very high level of ionization in the Earth's ionosphere, which was recorded by the IGS network. At the CODE (Center for Orbit Determination in Europe) homepage (URL http://www.aiub.unibe.ch/igs.html) one may find a "movie" of the maps of the exceptionally high ionospheric activity in the same time frame. Figure 7 shows the maximum Total Electron Content observed in October 2003.

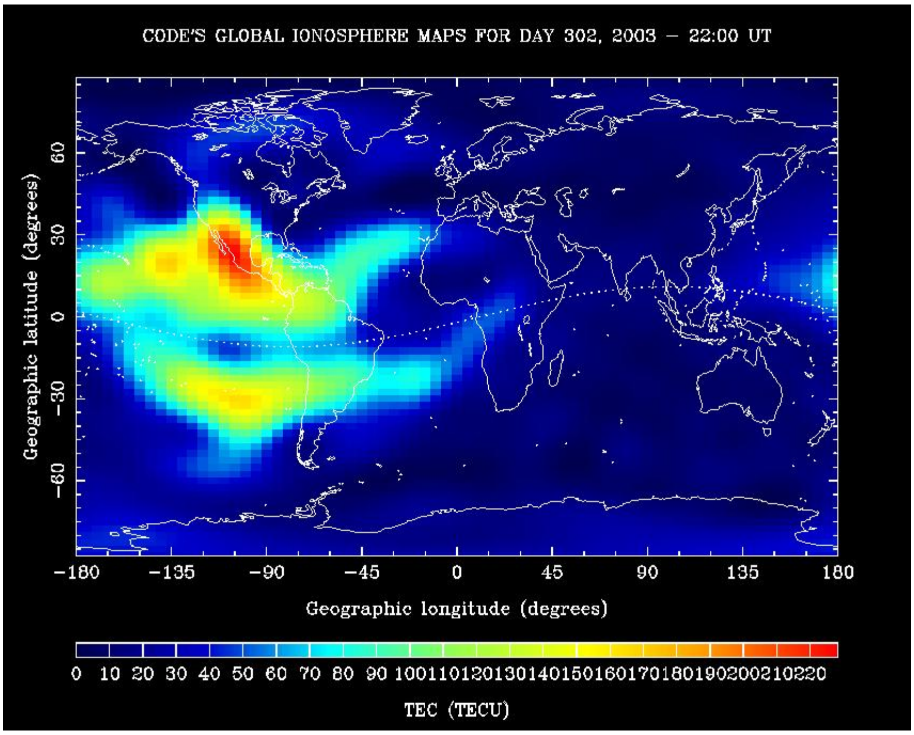

Figure 7: Maximum Total Electron Content observed on October 29, 2003 by the IGS Network

The new IAG Structure and the GGOS

The IGS, together with the IERS, pioneered the development of modern services within the IAG, probably even in the entire field of Earth sciences. Their example was followed by the IVS (International VLBI Service for Geodesy and Astrometry) and the ILRS (International Laser Ranging Service). These space geodetic services, together with the services related, e.g., to the determination of the Earth's gravity field, are of fundamental importance in modern geodesy, and in the wider field of Earth sciences. They are part of a precious global geodetic infrastructure.

The development of space geodesy has had a significant impact on the new structure of the IAG in the 1999-2003 time frame. In the new structure, the four new IAG Commissions, established in 2003, *and* the IAG Services are elements on the "same level" (Beutler et al. 2004a, 2004b). Three service representatives are members of the IAG Executive Committee in order to facilitate the creation of the proper interfaces between the IAG Commissions and Services.

The IGS, together with all other space geodetic services, are part of our global geodetic infrastructure. The network of gravity sites, space geodetic missions (such as Lageos, CHAMP, GRACE, GOCE), and the network of geodetic analysis centers are part of this global infrastructure as well. This global infrastructure is, however, not secure in our times of reduced funding levels for science in general. These considerations were the motivation to create the GGOS project in the new IAG structure.

GGOS stands for *Global Geodetic Observing System*. *System* should be understood as the basis on which the future advances in geosciences can be built. By considering the Earth system as a whole (solid Earth, atmosphere, ocean, hydrosphere, ice, liquid core, etc.), by monitoring it by geodetic techniques and by studying it from the geodetic point of view, the geodetic community does provide a powerful tool to the global geosciences community. GGOS is based on the existing IAG Services. GGOS seeks to provide a framework for existing, or future, services and to ensure their long-term stability. New entities will be established only if there is a stringent requirement to do so. GGOS shall be recognized by partners outside the IAG, e.g., by UNESCO, ICSU (International Council of Science), IGOS (the United Nations' Integrated Global Observing Strategy), governments, inter-government organizations, WCRP (World Climate Research Program), IGBP (International Geosphere Biosphere Program), etc., as geodesy's most important contribution to the Earth sciences.

GGOS must promote its master product(s) and the related sub-products. GGOS must promote research in geodesy, provide standards and enforce quality management (validation, calibration, at the one-ppb level or better) either by a new GGOS entity or by delegating this task to one or several of the existing services. The initial structure established for the GGOS definition phase between 2003 and 2005 was simple and compatible with the existing IAG Services. The key elements of this initial GGOS structure were:

- the GGOS Project Board as the central oversight entity,
- a few well defined working groups,
- the relevant IAG Services.

In its final form GGOS intends to provide

- geometric products (e.g., the global terrestrial reference frame),
- gravity products (e.g., the Earth's stationary and time varying gravity field), and
- the transformation between the "Earth-fixed" and inertial reference frame (the Earth rotation parameters),

in one and the same consistent reference system. The consistency of the geometrical and gravitational GGOS products at the 1 ppb or better level are of central importance. Prof. Christopher Reigber of the GeoForschungsZentrum (GFZ), Potsdam, was chairing the GGOS in its definition phase 2003-2005. His successor, Prof. Markus Rothacher, also took over the responsibility to chair the GGOS project for the implementation phase having started after the IAG Scientific Assembly 2005 in Cairns, Australia.

Epilogue

We reviewed the development of geodesy, positioning, and surveying since the middle ages. We saw that the measurement of angles was the only available observation technique till well into the 20th century. Remarkable discoveries (from the precession by Hipparchos to the prediction of polar motion by Leonhard Euler and the observational confirmation towards the end of the 19th century) were made in this long time period. The global gravity field could only be established to a very modest level; in essence only the dynamical flattening of the Earth was firmly established before the space age.

We then reviewed the development of satellite geodesy as a branch of space geodesy since 1957, the first year of the space age. Classical astronomical observations dominated the first period of this new age (the optical period). Impressive results were achieved. A first truly global terrestrial reference system (with an accuracy of few meters) was established, reliable estimates for a few dozen coefficients of the Earth's outer gravity field were determined.

With the ability to launch artificial satellites alternative observation techniques could be developed. The new techniques were all based on the establishment of distances by measuring the traveling times of electromagnetic signals between the satellites in space and the observers (on the surface of the Earth, on sea, in the atmosphere, or in the Earth-near space). Satellite and Lunar Laser Ranging (SLR and LLR) offered the technique of choice for determining the gravity field and the geocenter. The weather-independent Doppler satellite systems indicated the potential of microwave systems for positioning and navigation.

But only the deployment of the latest generation of GNSS, in particular of the GPS, the GLONASS, and the GALILEO system, enabled the successful transition from research to – at times even useful (!) – application. The use of microwave signals quasi-simultaneously emitted by a system of navigation satellites and quasi-simultaneously received by many, today probably millions of, cheap but accurate receivers, revolutionized geodesy, geodynamics, fundamental astronomy, surveying, and navigation on Earth and in the Earth-near space. It is a beautiful aspect of this development that the underlying physical principles are amazingly simple. One should, however, also be aware of the fact that the infrastructure needed to maintain the celestial and terrestrial reference frames (including the transformation between them) on the required accuracy level (sub-cm and sub-mas, respectively) is much heavier than in the pre-space age era. It is not a luxury, but rather a necessity, to maintain services of the type of the IGS for all the relevant observation techniques, and multi-observation-type services like the IERS in order to provide the metrological basis for science and application in the future.

This article, reviewing the development in our beautiful field of science, was written to honor Prof. Günter Seeber, who greatly contributed in many respects. His book on satellite geodesy, Seeber (2003), witnesses this statement. I would like to conclude by congratulating Günter Seeber personally and on behalf of IAG for his outstanding scientific career and oeuvre.

References

Beutler, G., J. Kouba, T. Springer (1995). Combining the Orbits of IGS Processing Centers, Bulletin Géodésique, Vol. 69, No. 4, pp. 200—222.

Beutler, G. (1996). The International GPS Service for Geodynamics: The Story. IAG Symposium No 115, pp. 3-13, Springer Verlag.

Beutler, G., M. Rothacher, S. Schaer, T. A. Springer, J. Kouba, R. E. Neilan (1999). The International GPS Service (IGS): An Interdisciplinary Service in Support of Earth Sciences. Advances of Space Research, Vol. 23, pp. 631—653.

Beutler, G. (2003). Satellite Navigation Systems for Earth and Space Sciences. Spatium, 10 (June 2003), International Space Science Institute (ISSI), Bern.

Beutler, G., H. Drewes, A. Verdun (2004a). The Integrated Global Geodetic Observing System (IGGOS) Viewed From the Perspective of History. Journal of Geodynamics, Vol. 40, pp. 414-431.

Beutler, G., H. Drewes, A. Verdun (2004b). The New Structure of the International Association of Geodesy (IAG) Viewed From the Perspective of History, Journal of Geodesy. Journal of Geodesy, Vol. 77, pp.566-575.

Kouba, J. (1983). A Review of Geodetic and Geodynamic Satellite Doppler Positioning, Rev. Geophys. Space Phys., Vol. 21, 27-40.

Murdin, P. (ed.) (2001). Encyclopedia of Astronomy and Astrophysics, Institute of Physics Publ., Bristol, Philadelphia.

Mueller, I.I. (1993). Planning an International Service using the Global Positioning System (GPS) for Geodynamic Applications. IAG Symposium No.109 on Permanent Satellite Tracking Networks for Geodesy and Geodynamics, Springer Verlag.

Seeber, G. (2003). Satellite Geodesy – foundations, methods, and applications. 2nd edition, Walter de Gruyter, Berlin and New York.