The International Association of Geodesy (IAG) - More than 130 Years of International Cooperation -

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1. *Introduction*

Geodesy is the science of determining the size and figure of the earth, and its external gravity field (see *Torge* 1991). This definition includes the orientation of the earth in space, and temporal variations of the earth's orientation, its surface and its gravity field. Obviously, geodesy therefore is part of the geosciences, providing significant boundary conditions for modelling the earth's body and its dynamics, including the oceans and the atmosphere. On the other hand, geodesy has strong relations to surveying and cartography, to navigation and engineering. Consequently, geodesy can trace back its roots several thousands of years. We mention the highly developped cadastral and engineering surveys in Mesopotamia and Egypt, and astronomical positioning at mapping the territories of the large antique empires. The proper geodetic problem was attacked by arc measurements which aimed at determining the diameter of the earth, after the sphere was adopted as a reasonable model of the earth. Well documented is the meridian arc measurement of Eratosthenes (276 - 195 B.C.). With the distance between Aswan and Cairo known from Egyptian cadastral surveys, and the corresponding central angle of the earth determined by observations to the sun, he found the earth's diameter with an error of only 2 %. Several other arc measurements followed in the classical Greek, Chinese, Arabian and European civilizations but a more pronounced international collaboration started only in the 18th century.

In the sequel, we mainly follow *Torge* (1993, using partly the English translation given by *Reilly* 1994). We first summarize the development of international cooperation in geodesy, from the 18th century until the present, concentrating on the different stages which the International Association of Geodesy passed through since its beginnings in 1862. Three examples then demonstrate which strategies and programs have been developped by the international organisations in order to attack and solve in an iterative manner the problem areas of "Geodetic Reference Systems", "Gravity Reference Systems", and "Geoid Determination".

2. *International collaboration in geodesy: the precursors*

In the seventeenth century the ellipsoidal form of the Earth had been postulated on the basis of the physically-defined models of Newton and Huygens; astronomical observations and pendulum measurements in various latitudes supported this assumption (for an historical introduction see *Torge* 1991). What was lacking was a geometric proof that the curvature of the Earth's surface was latitude-dependent, and here again the method of measuring an arc of meridian offered itself. Measurement of the meridian arc at different latitudes demanded international agreements and coordinated programmes to carry out the local observations, which was a field of collaboration for the various scientific academies that were at that time coming into being. As an outstanding example, we can point to the Academy of Sciences of Paris (founded in 1666) which sponsored the arc-measurement in Peru (1735-1744; Bouguer, La Condamine, Godin) and in Lapland (1736-37; Maupertuis, Clairaut et al.), which yielded both the geometric flattening of the poles, and the major semidiameter of the Earth-ellipsoid. Agreements between France and Spain, in the one case, and Sweden and Russia, in the other, were a necessary preliminary. Pendulum measurements, which following Clairaut's Theorem could equally yield the geometric flattening, were undertaken along with the arc measurements, and also on extensive maritime expeditions by English, French and Russian navigators in the first decades of the nineteenth century.

A further example of an important international operation was the Hanoverian arc-measurement of Carl Friedrich Gauss (1821-1825). This continued the Danish arc-measurement southward, joining up with the Dutch and the Hessian triangulation networks, and thereby with the French arc measurement, leading Gauss to hope that "...perhaps it is not an unrealisable prospect, that one day all the astronomical observatories of Europe could be connected together by trigonometric means ...".

3. *The international scientific organisations*

In April 1861, the Prussian General Johann Jacob Baeyer, a collaborator of Bessel in the East Prussian arc measurement (1831-1836), submitted to the Prussian War Ministry a document "On the size and figure of the Earth: a memorandum on the establishment of a Central European arc measurement, along with a sketch map", which he dedicated to the memory of Alexander von Humboldt. The aim of the proposal was to connect the numerous astronomical observatories to be found in Central Europe by the existing and planned triangulation networks, thereby to determine the regional and local curvature anomalies (i.e. the deflections of the vertical, and thus the relative structure of the geoid). This scientific project entailed international collaboration in surveying and in the collection and evaluation of the data, as well as for the analysis of the results. In the same year, the Prussian King ordered Baeyer's plan to put into effect. In 1862 an inaugural conference took place in Berlin, and by the end of 1862 fifteen European states had affirmed their participation in this organisation. This was the start of an organized international collaboration in geodesy and the International Association of Geodesy counts the foundation of this "Mitteleuropäische Gradmessung" (Central European Arc Measurement) as its origin (see *Levallois* 1980, *Mueller* 1990, and *Torge* 1994, with an extensive reference list). In 1864 the first General Conference of the "Mitteleuropäische Gradmessung" took place, and fixed both the organisational structure (Central Bureau, Permanent Commission, General Conferences at three-yearly intervals) and the research programme (e.g. "Systematic investigation of local deflections at all principal triangulation points", "Determination of the intensity of gravity", "Standardisation of units of measurement"). It is notable that this was a scientific organisation built around a gathering of governmental delegates; the resolutions of the General Conference had an advisory character, and were usually enthusiastically adopted. The Central Bureau began its work in 1866 with Baeyer as President; in 1867 followed its expansion as the "Europäische Gradmessung", and in 1870 the Prussian Geodetic Institute was established and entrusted with the operation of Central Bureau.

After Baeyer's death in 1885, Friedrich Robert Helmert became in 1886 Director of the Geodetic Institute and of the Central Bureau. Particularly notable is the 8th General Conference, where the scope was extended to the "Internationale Erdmessung" (Association Internationale de Géodésie), the organisation overhauled, and the scientific programme essentially broadened. Arc measurements remained the fundamental means of earth-measurement, but other objectives were added. Along with the prosecution of programmes, there was increasing emphasis on the discussion of fundamental scientific problems and the development of methods. We cite from the report of the Central Bureau 1899 the following areas of scientific work :

"1. Continuation of the calculations for the European system of deflections of the vertical;

2. Derivation of the movement of the Earth's axis within the Earth's body, from the results of the voluntary cooperation of the astronomical observatories;

3. Preparations for the International Polar Motion Service;

4. Absolute pendulum measurements;

5. Connection of the national gravity fundamental stations by relative pendulum measurements; collection of relative pendulum results."

In 1916 the last intergovernmental agreement for the "Internationale Erdmessung" lapsed and was not renewed. With this, and with Helmert's death in 1917, ended a fruitful period of international cooperation, although several neutral states continued some of the programmes, and the Prussian Geodetic Institute continued to function as the Central Bureau.

From 1919, international science organized itself in many areas, but now in a "non-governmental" form. An International Research Council (from 1931 the International Council of Scientific Unions - ICSU) united under its aegis a number of scientific unions, amongst them being the International Union for Geodesy and Geophysics (IUGG). Geodesy set up here its own section, known since 1932 as the International Association of Geodesy (IAG), as the successor to the "Internationale Erdmessung". The objectives of the IAG were further widened to embrace the whole field of geodesy. The statutes give these in a quite general form (see "The Geodesist's Handbook", Bulletin Géodesique 66(2), 1992):

"2. The Objectives of the Association are

a) to promote the study of all scientific problems of geodesy and encourage geodetic research;

b) to promote and coordinate international cooperation in this field, and promote geodetic activities in developing countries;

c) to provide, on an international basis, for discussion and publication of the results of the studies, researches and works indicated in paragraphs a) and b) above."

The work of the IAG is pursued through the existing structure of the Association, and at the quadrennial General Assemblies. The Association is subdivided into five Sections:

Section I:	*Positioning*
Section II:	*Advanced Spac Technology*
Section III :	*Determination of the Gravity Field*
Section IV :	*General Theory and Methodology*
Section V :	*Geodynamics*

Within the framework of the Sections are included Commissions, Special Commissions, Special Study Groups, and International Services for specialised functions; examples are given below.

4. *Geodetic Reference Systems*

In geodesy, two distinct reference systems are to be noted:

1. a space-fixed (quasi) inertial system (Conventional Inertial System CIS);
2. an Earth-fixed terrestrial system (Conventional Terrestrial System CTS).

Both systems share the Earth's centre of gravity (Geocentre) as an origin, and the Earth's rotational axis as a coordinate axis. The reciprocal connection is through precession and nutation, as well as Earth-rotation (polar motion and time). The IAG has from the beginning collaborated closely with Astronomy on the questions of reference systems and the determination of the Earth's rotation.

The classical solution used the fixed stars for the realisation of the CIS. This space-fixed system was achieved using the coordinates and proper motions determined by astronomy, as well as precession and nutation. The terrestrial system was then fixed by the vertical deflections (astronomical latitude and longitude) of fundamental points, and oriented by astronomical azimuth. In practice, the many national survey systems established in this century, differ between themselves, and from the Geocentre, by 100 to 1000 m, while the parallelism of the rotation axis, and the reference meridian, is determinable to the accuracy of geodetic astronomy (0.01_, or 1 ms). The question of the reciprocal relationships between these individual systems, and the creation of a global system, cannot be solved in the absence of global measurements methods.

The "Internationale Erdmessung" placed great value on the definition and establishment of the Earth-rotation parameters, and therewith the coordinate axes of the terrestrial reference system. In 1898 the 12th General Conference decided to set up the International Polar Motion Service (IPMS). The Bureau International de l'Heure (BIH) was established in 1913, and with the Greenwich meridian a common worldwide reference x-axis in the equatorial plane was fixed. The z-axis was defined by the mean polar axis 1900.0 to 1906.0 (Conventional International Origin). IPMS and BIH worked without significant interruption until 1987, when IUGG decided, in cooperation with the International Astronomical Union, to incorporate them into the International Earth Rotation Service (IERS). This service exclusively employs modern space methods (Very Long Baseline Interferometry, Satellite Laser Ranging, Lunar Laser Ranging), which allow to monitor polar motion and rotation time with an accuracy of ± 0.001 _ and ± 0.1 ms and a resolution of one day, or better. The CIS is now realized by extragalactic radio sources, in connection with a limited number of fixed stars. By including the satellites' orbits into the models, geocentric station coordinates can be determined now with cm-accuracy, thus realizing the CIS.

At the 20th General Assembly in Vienna in 1991, the IUGG defined anew the Conventional Terrestrial Reference System (CTRS), with consideration of relativistic effects and of earth deformation, and in accordance with the corresponding IAU resolution adopted at Buenos Aires in 1991:

"1. CTRS to be defined from a geocentric non-rotating system by a spatial rotation leading to a quasi-Cartesian system,

2. the geocentric non-rotating system to be identical to the Geocentric Reference System (GRS) as defined in the IAU resolutions,

3. the coordinate time of the CTRS as well as the GRS to be the Geocentric Coordinate Time (TCE),

4. the origin of the system to be the geocentre of the Earth's masses including oceans and atmosphere, and

5. the system to have no global residual rotation with respect to horizontal motions at the Earth's surface."

The IERS now provides yearly values for these newly-defined reference systems: the Terrestrial Reference Frame (ITRF) and the Celestial Reference Frame (ICRF). They include the coordinates of the radio sources used and of the terrestrial stations (more than 100) participating at the Service, as well as the parameters of Earth rotation. For geodynamic investigations the IAG has set up an "International GPS Geodynamic Service (IGS)" based on the Global Positioning System (GPS), and operational from 01.01.1994. This service already now significantly contributes to the IERS, densifying this net and extending it over the whole globe. Regional reference systems are now under construction by GPS measurements and tied to a certain epoch of the ITRS. For Europe a corresponding "European Terrestrial Reference System" has been established in 1989, in close cooperation between IAG and the national survey agencies, and a similar enterprise has been initiated for South America, with a continental GPS campaign scheduled for 1995.

The question of the reference system is closely bound up with that of a standard Earth model. Such an Earth model should approximate both the Earth's surface (geometric parameters) and its gravity field (physical parameters) by the simplest possible mathematical formulations. Consistent Earth-models were established by the IAG General Assemblies of 1924/1930 and 1967; the currently recommended "Geodetic Reference System" (GRS80) was adopted at the 17th General Assembly in Canberra in 1979:

"The International Union of Geodesy and Geophysics, recognizing that the Geodetic Reference System 1967 adopted at the XIV General Assembly of IUGG, Lucerne, 1967, no longer represents the size, shape and gravity field of the Earth to the accuracy adequate for many geodetic, geophysical, astronomical and hydrographic applications and considering that more appropriate values are now available, recommends

"a) that the Geodetic Reference System 1967 be replaced by a new Geodetic Reference System 1980, also based on the theory of the geocentric equipotential ellipsoid, defined by the following conventional constants:

1. equatorial radius of the earth:
$a = 6\,378\,137$ m,

2. geocentric gravitational constant of the Earth (including the atmosphere):
$GM = 3\,986\,005 \cdot 10^8$ m^3 s^{-2},

3. dynamical form factor of the Earth, excluding the permanent tidal deformation:
$J_2 = 108\,263 \cdot 10^{-8}$,

4. angular velocity of the Earth
$\omega = 7\,292\,115 \cdot 10^{-11}$ rad s^{-1},

b) that the same computational formulas, adopted at the XV General Assembly of IUGG in Moscow 1971 and published by the IAG, be used as for Geodetic Reference System 1967, and

c) that the minor axis of the reference ellipsoid, defined above, be parallel to the direction defined by the Conventional International Origin, and that the primary meridian be parallel to the zero meridian of the BIH adopted longitudes".

The GRS80 has been widely introduced in science and practice. In view of the increasing use of GPS positioning, it should be noted that the ellipsoidal parameters of GPS-system WGS84 are identical with the corresponding values of GRS80 (except for one unit in the ninth place in the value for the flattening).

5. *Gravity reference systems*

The performance of gravity measurements with simple physical pendulums, with wire pendulums, and (after 1817) with reversible pendulums, was restricted to several arc-measuring campaigns and other expeditions, and the results showed the dependence of gravity on latitude, height, and mass anomalies. The "Mitteleuropäische Gradmessung" from the beginning put gravity intensity measurements on its programme, and later, the "Internationale Erdmessung" undertook the organisation of measuring campaigns and the establishment of national fundamental gravity stations; regular reports were issued on the collected gravity values (approximately 2500 values by 1912).

The problem of the combination of very onerous but inaccurate absolute gravity values with the more accurate gravity differences led to the adoption of a strategy of establishing a global gravity standard by connection with relative measurements to the most accurate possible absolute station. In 1900 the "Vienna Gravity System" was adopted by IAG, but already in 1894, on Helmert's suggestion, preparations for a new determination of absolute gravity at the Geodetic Institute in Potsdam started. The basic investigations and numerous series of measurements were brought to a conclusion in 1906 with the publication by Kühnen and Furtwängler of the adjusted gravity value at the pendulum pillar (standard error of ± 30 μms^{-2}).

The "Potsdam Gravity System" thus established by IAG was a great success. It served well into the 1960's as a reference for national gravity networks, for regional gravimetric surveys, and for the numerous gravimetric measurements in applied geophysics. Later evaluations of the Potsdam Gravity System, and new absolute gravity measurements in the 1930's, showed that the adopted Potsdam gravity value was too large by about 100 to 200 μms^{-2}. The national networks connected by relative measurements to Potsdam, themselves exhibited additional errors of a similar magnitude. In the second half of the twentieth century, metrology and geodesy could no longer tolerate such errors in the gravity standard. New absolute gravity measurements, and the experience of Woollard, Morelli and others that relative gravity measurements could yield useful results even over great distances, opened up the possibility that a better gravity standard could be established. The IAG tackled this problem through its

International Gravity Commission (IGC) set up in 1951. A new world-wide gravity net, and extensive gravity calibration lines, were planned and measured, and in 1968 the free-fall apparatus of Faller became available as a transportable absolute gravity measuring device. The adjustment of a global network of absolute and relative gravity measurements (pendulum and spring-gravimeter) finally yielded the International Gravity Standardization Net 1971 (IGSN71) that was adopted at the 15th General Assembly of IUGG in Moscow as the new gravity standard. The mean accuracy of $\pm$ 1μms^{-2} (and better) of IGSN71 suffices for most users in physics, geodesy, geophysics, and navigation. The IGSN71 has also quickly ensured that gravimetric surveys can be correspondingly transformed, and new networks either connected, or based upon new absolute measurements, with an improvement of from a half to one order of magnitude (and can thus be declared to be compatible with IGSN71).

Transportable absolute gravimeters, which now permit an accuracy in the range of $\pm$0.03 to 0.1 μms^{-2}, make possible the use of gravimetry to study global geodynamic processes. The IAG has taken up this issue with the proposal for the establishment and regular measurement of the global International Absolute Gravity Basestation Network (IAGBN). Of 36 stations, chosen mainly from geodynamic considerations, more than two-thirds have now been set up and measured at least once.

6. *Geoid determination*

The geoid is defined as that equipotential surface of the Earth's gravity field that most closely coincides with mean sea level. Already introduced in 1828 by C.F. Gauss as the "geometric surface of the Earth", it was involved during the nineteenth century in investigations of the nature and computation of this surface. However, because of the lack of global data there was no question of applying spherical harmonic expansions for modelling the geoid. For regional modelling, the integral formula of Stokes (1849) was available, which even so presupposed gravity anomalies over the whole Earth. It was therefore of great significance that Helmert in 1880/1884 showed, with "astronomical levelling", how local and continental geoid sections could be computed by path-integration of the deflections of the vertical. From a synthetic evaluation of the influences of continental land-masses, Helmert concluded that the values of geoidal undulations were likely to lie within a range of 400 m; but by taking into account plausible isostatic compensation, the actual geoidal variation was likely to be within $\pm$ 27 m. From a later consideration of gravity anomalies he derived a range of $\pm$ 50 m.

Both the "Mitteleuropäische Gradmessung" and the "International Erdmessung" gave special importance to the determination of the geoid, particularly in relation to the investigation of the curvature anomalies (the field of deflections of the vertical) and of the best-fitting ellipsoid; and the geological-geophysical information in the form of the geoid was early recognized. Later, an IAG "Geoid Section" concerned itself from 1948 with the compution of a European Geoid. As a result we had from 1954 onwards the famous Bomford Geoid in progressively updated versions (the last in 1978 revised by Levallois and Monge). The collection and evaluation of deflections of the vertical in Europe continued into the 1980s under an IAG Special Study Group led by Biradi.

The gravimetric geoid computations by Stokes' method needed better gravity surveys of the Earth, and a central bank of data and their reduction to a common system. This was begun by the "Internationale Erdmessung", with regular publications of results. From the 1920s the number of gravity observations grew rapidly, at first by the submarine pendulum measurements of Vening Meinesz, and from the 1930s with the introduction of elastic-spring gravimeters in geophysics. An "International Gravity Survey Project" was proposed to IAG by de Graaf Hunter in 1936, with the object of the gravimetric determination of the geoid, and in the same year the IAG founded the International Isostatic Institute in Helsinki. Here Heiskanen began a global collection and reduction of gravity values, continued later in Columbus, Ohio, and leading to the publication of the gravimetric "Columbus Geoid" in 1957. Along with the establishment in 1951 of the new International Gravity Commission (IGC) there was also set up the Bureau Gravimétrique International (now domiciled in Toulouse), whose principal task is the systematic collection, preparation and dissemination of global gravity data.

With the availability of global gravity field parameters, derived from the analysis of satellite orbits, and the computation of high-order geopotential models, geodesy, geophysics and oceanography can benefit from improved determination and interpretation of the geoid. The regional accuracy requirements of operational GPS positioning are in the 1 to 10 cm range over distances from a few km out to 1000 km and more. The geoid can then serve for the reduction of GPS heights to orthometric heights, and thus render GPS useful for heigt determination. The IAG has responded to these needs by setting up the International Geoid Commission (1987) and the International Geoid Service (1991). Again Europe serves as a test area for these high-precision geoid calculations. An IAG Subcommission for the European geoid was set up in 1990, and the Institute für Erdmessung (IfE), University of Hannover, Germany, was asked to serve as the corresponding computing center. The gravimetric geoid solution uses high-resolution global models, local point gravity data, and digital terrain models for the high frequency geoid part. A final result will be available 1995 at the IUGG General Assembly in Boulder, Colorado.

7. *Conclusion*

We have shown how geodesy after several 1000 years of development, over the last 130 years pursued solutions to geodetic problems through targeted programmes organized within the framework of international scientific collaboration. The initial phase of this organized cooperation (1862-1885) was dominated by the President of IAG, Johann Jacob Baeyer. The following phase of the "Internationale Erdmessung" (1886-1916) was essentially determined by Friedrich Robert Helmert in his role as Director of both the Prussian Geodetic Institute and of the IAG Central Bureau. The examples of the definition and realisation of geodetic reference systems, of the introduction of a gravity reference system, and of the determination of the geoid, show how progress dependent on the development of theory, methods and techniques has continued to the present day, particularly through the sponsorship and coordination of the International Association of Geodesy. Solutions emanating from scientific geodesy have been and are of practical importance for a multiplicity of users. Amongst these are numbered, outside the obvious astronomy and land surveys, also engineering surveys, hydrography and navigation, geophysics including oceanography, and finally - because of the accuracy attainable on global, regional and local scales - all the disciplines concerned with recent geodynamic processes. The IAG has taken account of these interdisciplinary aspects in revising its organisational structures at its most recent General Assembly in Vienna in 1991. Among others new Special Commissions have been established for "Applications of Geodesy to Engineering", "Marine Positioning", "Mathematical and Physical Foundation of Geodesy", and "Fundamental Constants". New Special Study Groups deal with "Kinematic Global Positioning System", "Combined use of gravimetry and stress-strain measurement techniques", "Global geodynamic variations", and "Geodetic research toward the reduction of natural hazards". Future directions of IAG activities are already clearly visible, they will in many cases require a stronger collaboration with other geosciences, but also with the engineering and geoinformatics disciplines, represented in the International Union of Surveys and Mapping. Developping countries have much more to be involved in IAG activities, and a number of measurements has been taken already in that direction. From the scientific point of view the most important statement is that geodesy can now contribute fundamentally to the understanding of the kinematics and dynamics of the Earth, at global, regional and local scale.

References

Levallois, J.J.: The history of the International Association of Geodesy. Bulletin Géodesique 54, 249-313, 1980.

Mueller, I.I.: 125 Years of International Cooperation in Geodesy. IAG Symp. Proceed 102, 421-432, Springer Verlag, New York etc. 1990.

Torge, W.: Geodesy. 2nd edition, Walter de Gruyter, Berlin-New York 1991.

Torge, W.: Von der mitteleuropäischen Gradmessung zur Internationalen Assoziation für Geodäsie. Z.f.Vermessungswesen 118, 595-605,1993. English translation (partly) by W.I. Reilly, Newsletter New Zealand Geophysical SocietyInc., No. 38, July 1994, 43-52.

Torge, W.: Die Geodäsie im Übergang zur international organisierten Wissenschaft -Zum 200. Geburtstag von Johann Jacob Baeyer. Z.f.Vermessungswesen 119, 513-522, 1994.