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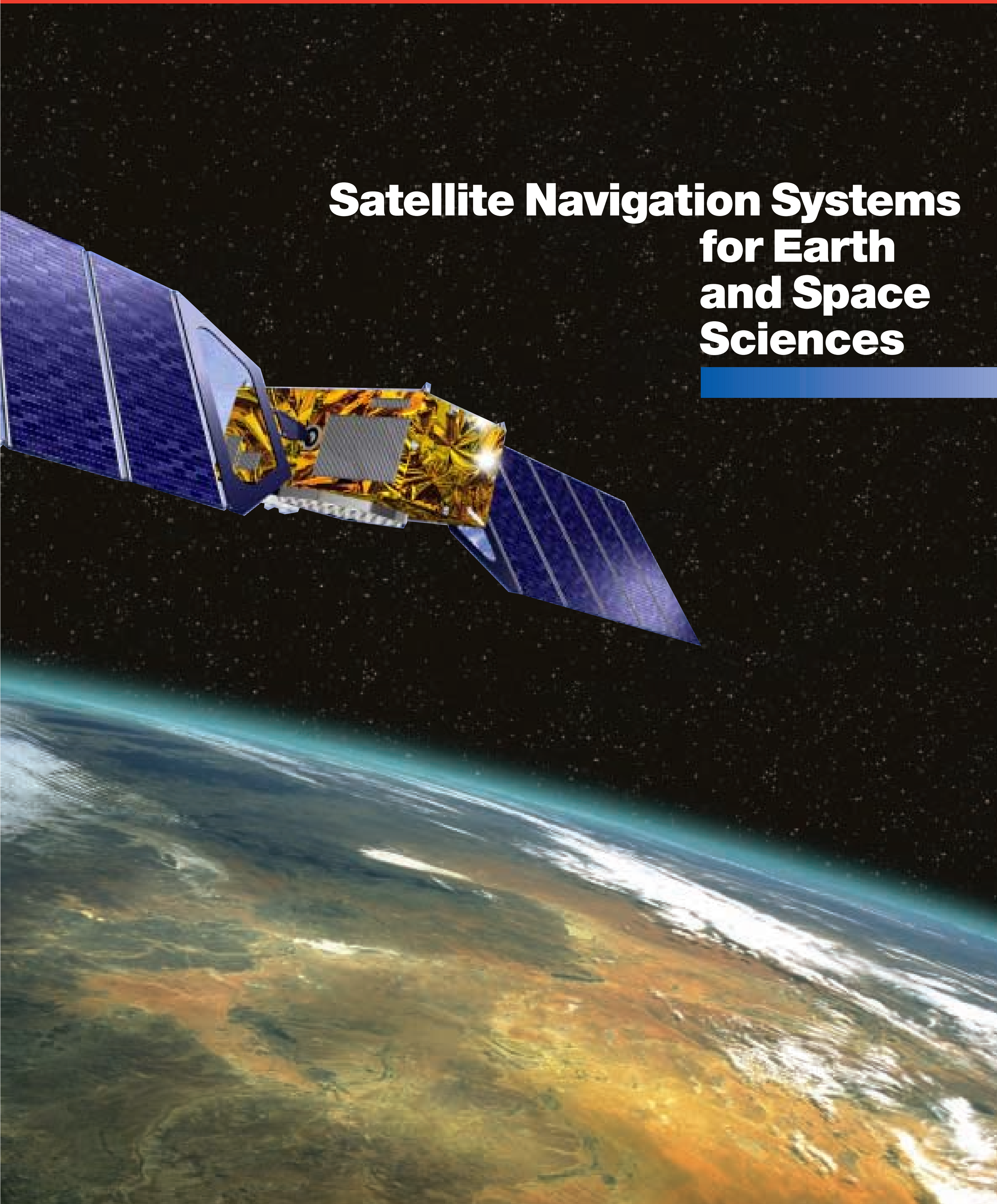
Satellite Navigation Systems for Earth and Space Sciences



Editorial

It was in 1915 when the German scientist Alfred Wegener published the "The Origin of Continents and Oceans" outlining the concept of continental drift for the first time. According to this theory, all the continents on Earth had formed from one single mass about 300 million years ago, called Pangaea. Later on, Pangaea had split, and its pieces had been moving away from each other ever since. Where such continental plates collide, mountain ranges may be pushed up, like for example the Alps that are the collision product of the African and the Eurasian plate.

Initially, Wegener's theory was strongly contested not least because he did not provide convincing explanations for the mechanics allowing for the movement of the continents through the oceans (as it was seen at that time). Today we know that below the continental plates there is a hot liquid zone, the asthenosphere, on which the continents float. The plates are separated by ridges, where fresh magma spills out from the asthenosphere providing the thrust to the continental plates moving them apart thereby.

In the meantime such different scientific branches as geology, palaeontology, botany and zoology have provided ample proof in support of Wegener's theory. Even space technology has contributed by the direct measurement of the continental drift. As an example, the drift velocity between America and Europe has been determined to be in the order of 2.5 centimetres/year.

Global satellite navigation systems are based on a constellation of Earth orbiting spacecraft emitting signals with precise orbital and time data. Suitable receiver equipment combines the signals from at least four spacecraft yielding the time and the three space coordinates. The US Global Positioning System (GPS) for instance consists of 24 spacecraft orbiting the Earth in six different planes. The Russian Glonass system as well as the planned European Galileo system are based on the same concepts.

Of course, the GPS originally was not conceived as a scientific tool but much more as a sophisticated military infrastructure for the fulfilment of navigational tasks. It was only after its commissioning that its scientific value became apparent. The continental drift velocities measurement is just one of a number of fascinating scientific applications of global navigation systems to which the present issue of Spatium is devoted. We are greatly indebted to Prof. Gerhard Beutler, Astronomical Institute, University of Berne for his kind permission to publish herewith a revised version of his exciting lecture of November 12, 2002 for the members of our association.

Hansjörg Schlaepfer
Zürich, June 2003

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Front Cover: The Galileo navigation satellite in an artist's view (credit: European Space Agency ESA)

Satellite Navigation Systems for Earth and Space Sciences *)

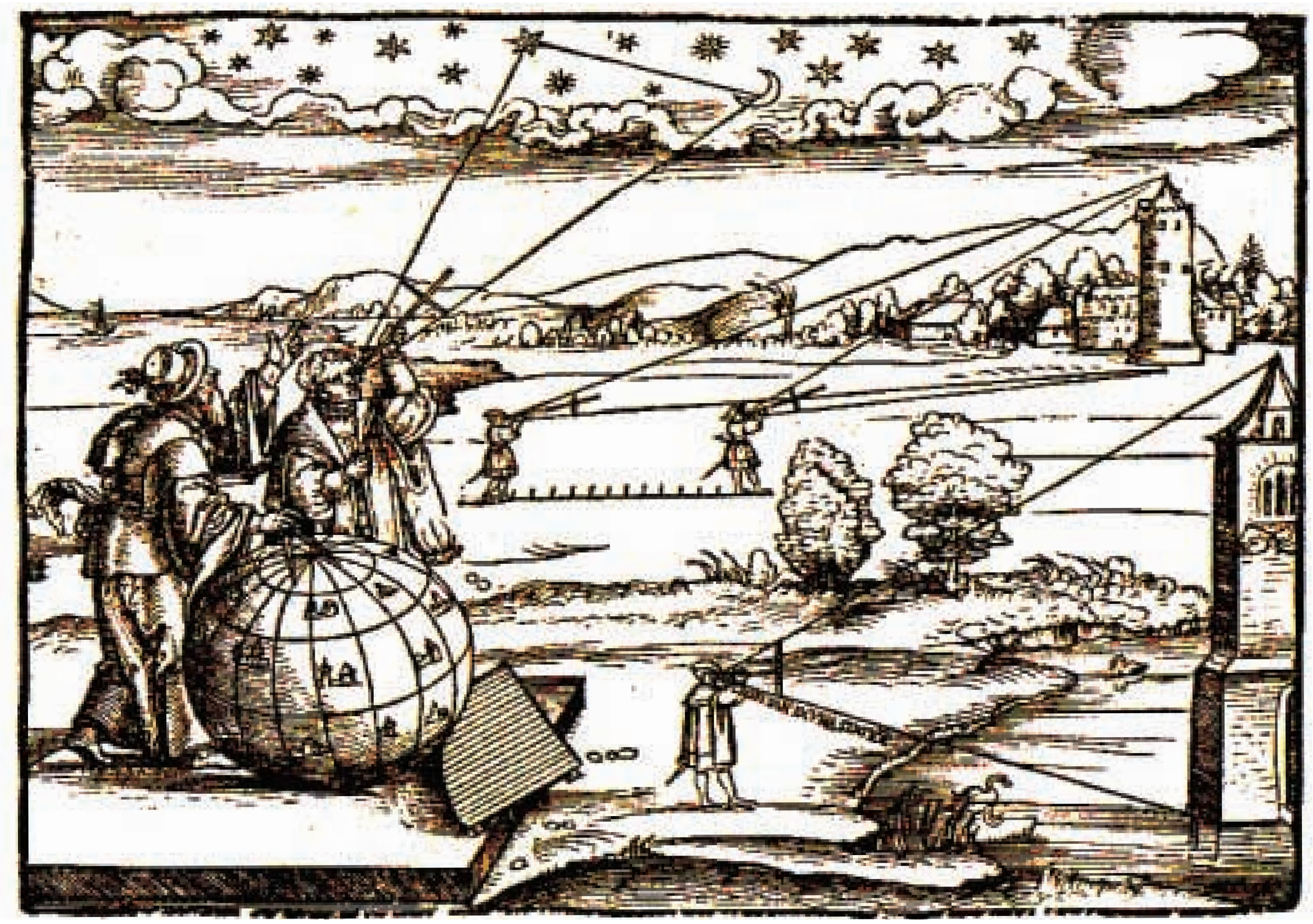
Gerhard Beutler, Astronomical Institute, University of Bern

Navigation and Science in the Past and Today

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

Figure 1
Geographia by Peter Apian, dated 1533.

Figure 1 also shows that relative local and absolute positioning was performed with the same instruments, the so-called cross-staffs, in Apian's days. Global positioning meant the determination of the observer's *geographical latitude* and *longitude* (relative to an arbitrarily selected site – first Paris, then Greenwich was used for this purpose). The latitude of an observing site was easily established by determining the elevation (at the observer's location) of the Earth's rotation axis, approximately represented by the polar star. In principle, longitude determination was simple, as well: One merely had to determine the *time difference* (derived either from the Sun [local solar time] or from the stars [sidereal time]) between the unknown site and Greenwich. The problem resided in the realisation of Greenwich time at the observing site in the pre-telecommunication era. One astronomical solution to this problem, 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 with Greenwich local



*) Pro ISSI lecture, Bern, 12th November 2002

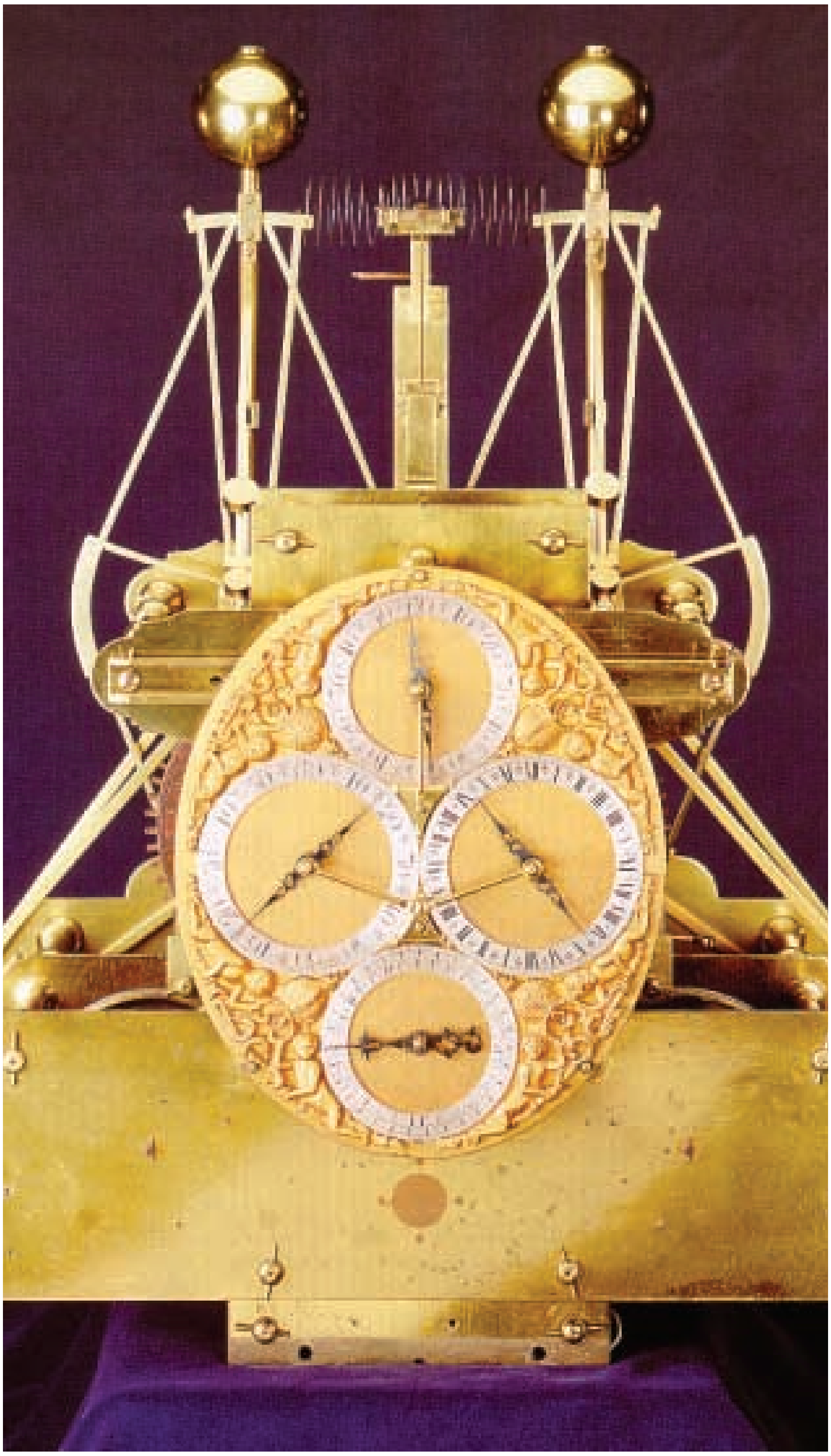


Figure 2
Harrison I, first marine Chronometer (credit: D. Sobel und W.J.H. Andrewes: Längengrad, Berlin Velag 1999).

time as argument. Lunar distances were used for centuries for precise positioning. For navigation on sea the method became eventually 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).

The *principles* of precise global positioning and precise navigation remained in essence the same from Apian's times till well into the second half of the 20th century. The development of the accuracy was dramatic: The cross-staff was replaced by increasingly more sophisticated optical telescopes. More precise star catalogues (fundamental catalogues) were produced and the art of predicting the motion of planets was developed in analytical celestial mechanics. A long list of 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 ephemerides. Highly precise pendulum clocks and marine chronometers allowed it eventually to time-tag the observations in the millisecond accuracy range.
The relationship between science on one hand and precise positioning and navigation on the other hand were truly remarkable: The discipline of *fundamental astronomy* emerged from this interaction between theory and application. In fundamental astronomy one defines and realises the global terres-

trial and the celestial reference systems *including* the transformation between the systems. The terrestrial system was realised by the geographical coordinates of a network of astronomical observatories. Until quite recently the celestial reference system was realised through fundamental catalogues of stars. Celestial mechanics, so to speak the fine art of accurately describing the motion of celestial bodies in the celestial reference systems, is also part of fundamental astronomy.

The establishment of the transformation between the two systems implies the monitoring of Earth rotation in inertial space. **Figure 3** illustrates that the rotation axis of the Earth moves in inertial space.

It is well known that the rotation axis approximately moves on a straight cone inclined by 23.5° 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 Hipparchos). 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 was slowly (by about 2 msec 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 summarised in **Table 1**.

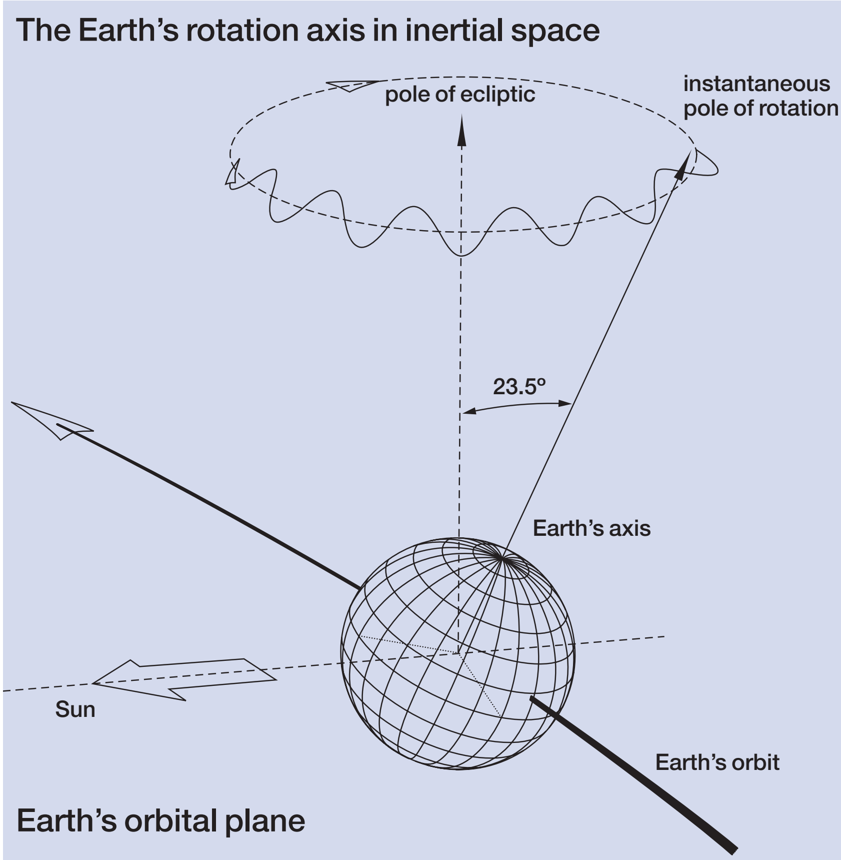


Figure 3
Precession and Nutation.

Year	*Discoverer*	*Effect*
300 B.C	*Hipparchos*	*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*

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

The Global Positioning System (GPS)

Sputnik-I, launched on October 4 of the International Geophysical Year 1957, did broadcast a (relatively) stable radio-frequency f. The relative Doppler shift $\Delta f/f$ of such signals is proportional to the radial component v of the relative velocity between satellite and receiver, i.e., $\Delta f/f = v/c$, where c is the speed of light. Actually, this relationship is only the non-relativistic approximation of the more elaborate relativistic expression.

The Doppler shift of radio signals emitted by satellites may be easily measured by standard radio equipment. As the orbital velocity of a low Earth orbiter (LEO) is rather big (about 7 km/sec), the radial velocity is expected to vary roughly between the limits ±5 km/s. One may therefore expect to reconstruct rather accurately the orbit of the satellite using the Doppler shift of the signal, as measured by a few receivers located at known positions on the surface of the Earth. If, on the other hand, the orbit is assumed known, the measurement of the Doppler shifted signal recorded at an unknown location may be used to determine its position on the Earth. The first generation of navigation satellite systems, e.g., the NNSS (U.S. Navy Navigation Satellite System) was based on these simple principles. The advantages over optical navigation were considerable: the observations were weather-independent and available in digital form from the outset. The system worked remarkably well. Using the observations of one pass of one satellite over a receiver (duration about 5–10 minutes), the (two-dimensional) position of the observer could be established with an accuracy of a few ten meters. Apart from the limited precision the most serious disadvantage of the system had to be seen in the limitations of the system for high-speed navigation (the necessity to collect observations over several minutes ruled out the use of the NNSS for air- or space borne applications).

The second-generation satellite navigation systems cured this problem. They are based on

- the measurement of the propagation times of radio signals between the satellites and the observer and on
- the simultaneous observation of several satellites.

Neglecting propagation delays caused by the atmosphere and assuming that all clocks (those of satellites and receivers) are synchronised, the known numerical value of the speed of light c allows it to calculate (from the signal travelling time) the distance ρ between the satellite S at signal emission time and the receiver R at signal reception time. The receiver R thus must lie on a sphere with centre S and radius ρ. If three satellites are observed simultaneously, the receiver's position is obtained by intersecting three spheres with known centres and radii. (One may remember from school that in general two solutions emerge from the intersection process, but one easily recognises that one solution – lying far above the Earth's surface – may be ruled out). As one wishes to use rather cheap oscillators in the receivers, one cannot assume that the receiver clock error is zero (or known a priori), but that it has to be estimated together with the three coordinates of the receiver. The unknown position of R may thus be found by intersecting three hyperboloids with foci (S_1, S_2), (S_1, S_3), (S_1, S_4), and the corresponding differences of the semi-major axes $(\rho_1 - \rho_2)$, $(\rho_1, -\rho_3)$, $(\rho_1 - \rho_4)$. If a satellite system shall be used for positioning and navigation in this sense, one therefore has to make sure that at any time and for any location of the receiver R on the Earth's surface at least four navigation satellites are above the observer's horizon. This implies that the navigation satellites are rather high above the Earth's surface, that the inclinations of

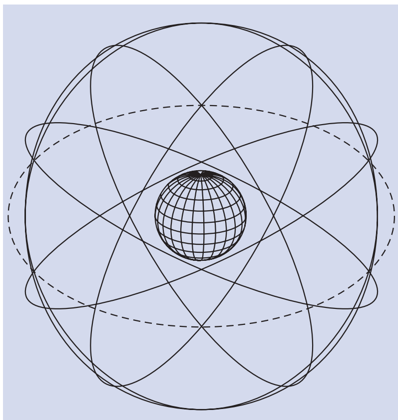


Figure 4
GPS constellation

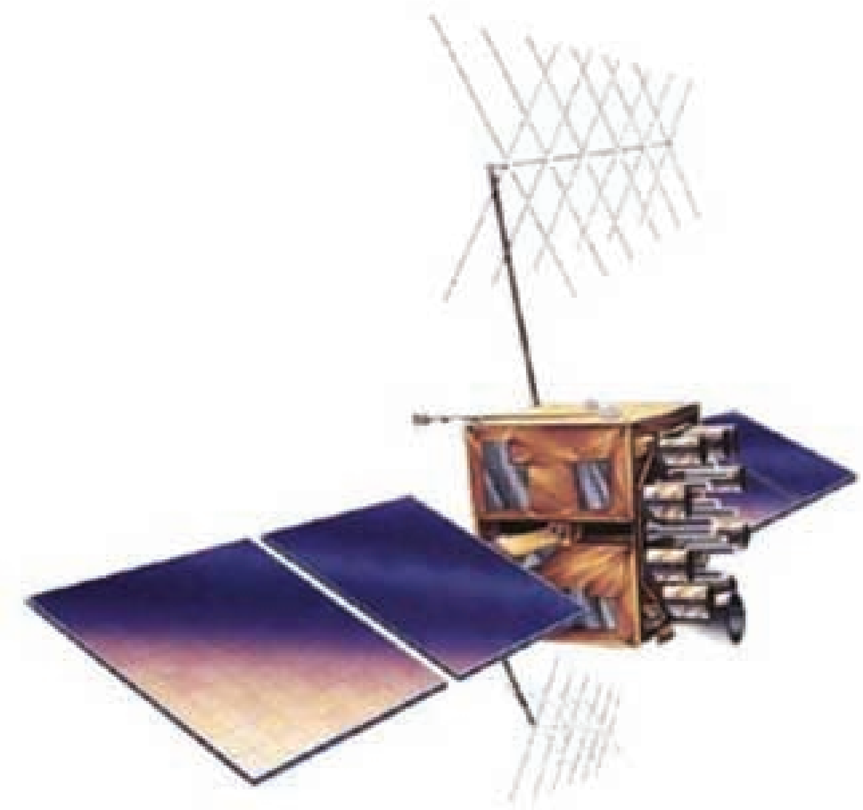


Figure 5
GPS IIR spacecraft (credit USAF).

their orbital planes w.r.t. to the equatorial plane are rather big, and that the satellites are well separated (equally spaced) in the orbital planes.

The best known of these second generation satellite systems is the fully deployed U.S. Global Positioning System (GPS). **Figure 4** illustrates the GPS configuration as seen from a latitude of 35° from outside the actual configuration. The constellation consists of six orbital planes, each inclined by 55° w.r.t. the equator and separated by 60o in it. The satellite orbits themselves are almost circular with radii of about 26.500 km – giving rise to revolution periods of half a sidereal day. There are (at least) four satellites, well separated from each other, in each orbital plane.
The satellites transmit information on two L-band wavelengths, L1 and L2, with wavelengths of $\lambda_1 = 19$ cm, $\lambda_2 = 24$ cm. **Figure 5** shows a GPS satellite. Obviously, the antenna array always has to point towards the centre of the Earth. The solar panels axes have to be perpendicular to the line Sun–satellite at any time. The attitude emerging from these requirements is actively maintained using momentum wheels within the satellite's body.

Alternative systems are the Russian GLONASS (Global Navigation Satellite System) or the European GALILEO system, to be deployed by the European Space Agency (ESA) in the first decade of the third millennium. All systems are based on the same principles.

In order to fully appreciate the results presented subsequently we have to inspect the actual observables of second-generation navigation satellite systems in more detail. The signal transmitted by satellite S at time t^S (satellite clock reading) contains this transmission epoch. This information may be used by the receiver R to compute the so-called pseudorange p using the reading of the receiver clock at signal reception time t_R:

$$p = c\,(t_R - t^S) \qquad \mathbf{1}$$

In the "best possible of fundamental-astronomical worlds" p would just be equal to the geometric distance ρ. Because neither the satellite nor the receiver clocks are exactly synchronised with atomic time, because the signal has to travel through the Earth's atmosphere, and because of the measurement error the actual relationship between the pseudorange and the distance ρ reads as

$$p = \rho + c\Delta t_R - c\Delta t^S + \Delta\rho_T + \Delta\rho_I(\lambda) + \varepsilon \qquad \mathbf{2}$$

where ρ is the distance between satellite S and receiver R, Δt_R the receiver clock error, Δt^S the satellite clock error, $\Delta\rho_T$ the propagation delay due to the electrically neutral atmosphere, $\Delta\rho_I$ the delay due to the ionosphere (caused by the free electrons in layers between 200 km and 1200 km height), and ε the measurement error. For the code measurements the error ε is of the order of a few decimetres allowing for real time positioning with about one meter accuracy. For scientific purposes the phase-derived pseudorange p' is extensively used. The receiver R generates this observation by counting the incoming carrier waves (integers plus fraction part) and by multiplying the result by the speed of light c. This observable is related to the geometrical and atmospheric quantities by

$$p' = \rho + c\Delta t_R - c\Delta t^S + \Delta\rho_T - \Delta\rho_I(\lambda) + N\lambda + \varepsilon' \quad \mathbf{3}$$

Obviously, the code- and phase-derived pseudoranges are intimately related. The key difference resides in the fact that the phase measurement error ε' is very small, of the order of few millimetres, whereas the code-derived measurement error ε is about a factor of 100 larger. This positive aspect is somewhat counterbalanced by the term $N\lambda$, the initial phase ambiguity term, which is unfortunately unknown. The parameter N, known to be integer, has to be estimated as a real-valued parameter. Under special conditions it is possible a posteriori to assign the correct integer number to the estimated real-valued unknown. Note that the ionospheric signal delay in **equation 2** is replaced by a phase advance in **equation 3**.

The term "best possible of fundamental-astronomical worlds" was coined to characterise a world, in which clock corrections and atmosphere delays do not exist. The following results will show that this label is not really justified when interested in other than geometrical aspects. The clock- and atmosphere-related "nuisance" terms are, as a matter of fact, exploited to synchronise clocks worldwide and to describe the Earth's atmosphere. The limited space allows us only to present one of these aspects (the derivation of ionosphere models from a worldwide net of GPS receivers). All the other results are related to the term ρ, the distance between satellite and receiver. The satellite orbits, the positions (and tectonic motions) of the observing sites, and the Earth rotation parameters are derived from ρ.

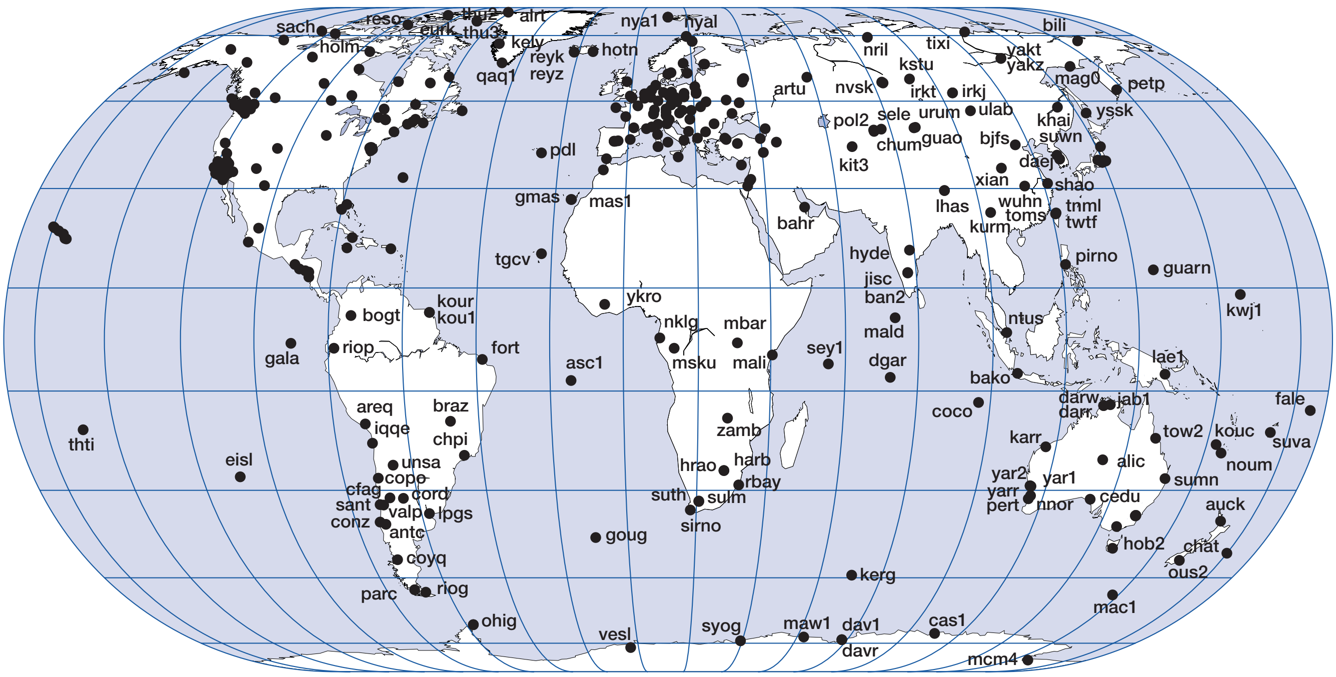


Figure 6
The IGS network in March 2003 (credit: IGS Central Bureau; JPL; Pasadena, California.

The International GPS Service (IGS) and the Code Analysis Centre

The International GPS Service (IGS) was created in 1991. It became fully operational, after a pilot phase of about two years, on January 1, 1994. The IGS is based on a voluntary collaboration of scientific and academic organisations in the fields of geodesy, space science, and fundamental astronomy. Big research organisations like NASA, JPL, ESA, etc. contribute as well as National Geodetic Survey institutions, and universities. The IGS deployed and maintains a network of more than 200 globally distributed permanent GPS sites. **Figure 6**, taken from the IGS homepage, gives an impression of the network.

The IGS network reflects to some extent the fact that the IGS is a voluntary collaboration: The station distribution is far from homogeneous, but one can also see that there are only few "empty" areas left today. Each IGS station tracks each GPS satellite in view. At least once per 30 seconds all available code and phase measurements on the two frequencies are stored – giving rise to 2 x 8640 measurement epochs per day. At least on a daily turnaround cycle the raw data are sent (via internet or telephone modems) to regional and global data centres, from where they can be retrieved by the wider scientific community, but also (perhaps more importantly) by the IGS Analysis Centres to generate the IGS products. There are currently seven IGS Analysis Centres (three in the USA, one in Canada, two in Germany (where the one at ESA should be considered as multi-national) and one, called CODE, situated at the University of Bern. CODE is a joint venture of the University of Bern's Astronomical Institute (AIUB) with the Swiss *Bundesamt für Landestopographie* (Swisstopo), the German *Bundesamt für Kartographie und Geodäsie* (BKG) and the French *Institut Géographique National* (IGN). The work of the IGS Analysis Centres (AC) is truly remarkable. Every day, a table of geocentric orbital positions is generated by each of the AC's for each active GPS satellite with a spacing allowing it to reconstruct the satellites' positions and velocities with cm-precision for any time argument within the day. These satellite orbits originally were the primary IGS product. They are a big relief for research and production organisations using the GPS for high-accuracy surveys. It is, e.g., worth mentioning that since 1991 the Swiss first order geodetic survey is uniquely based on GPS and on the IGS products. A similar development was observed in most other countries worldwide.

The IGS Analysis Coordinator is first comparing, then combining the orbits of all IGS Analysis Centres into one official IGS orbit. The work of the individual centres is rated by the root mean square error per satellite position (actually per geocentric coordinate) w.r.t. this official, so called final orbit, available about one week after real

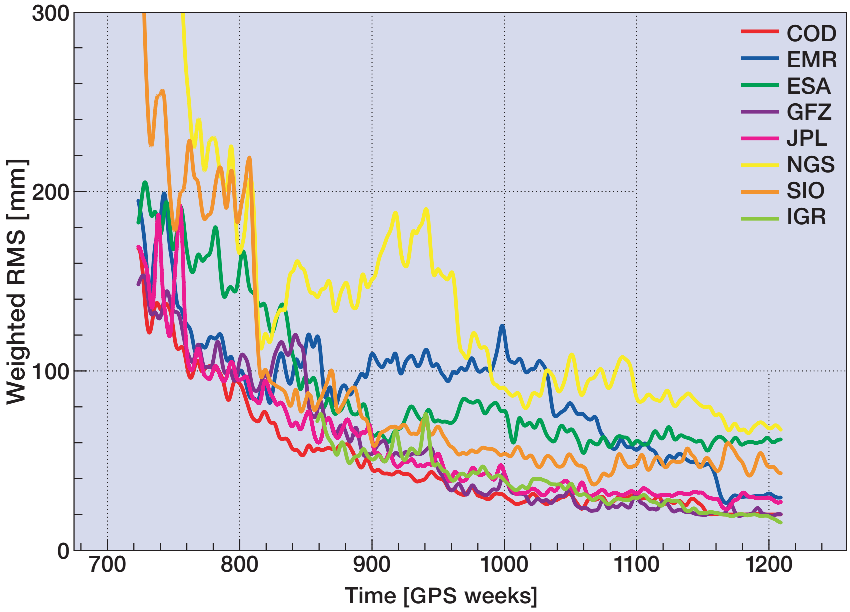


Figure 7
RMS-error per satellite coordinate for IGS-AC-orbits.

time. **Figure 7** shows these root mean square errors for each centre since 1994 to March 2003. The consistency of the best contributions is today of the order 2–3 cm. Not without pride we note that the CODE-contribution (red curve) always was among the best since the advent of the IGS. (Note that the green curve labelled "IGR" characterises the combined IGS rapid solution, which is already available within one day after "real time".) Elementary geometric considerations show that this orbit accuracy of few cm is sufficient for millimetre precision positioning on the Earth or in Earth-near space (e.g., for LEO's). It is a remarkable IGS achievement that the GPS orbits may be considered virtually "error-free" for most applications.

Scientific Applications

In 1991 it was the intention to base the IGS orbit determination on the Earth rotation parameters calculated by the (at that point in time) well established space techniques VLBI (Very Long Baseline Interferometry) and Satellite Laser Ranging (SLR). It turned out that the required information was not available in due time for IGS orbit production. This is why each IGS Analysis Centre has to solve for the daily position (and velocity) of the Earth rotation pole. **Figure 8** shows the daily estimates of polar motion by the CODE Analysis Centre since 1993. Note that the units are arc seconds, implying that the daily estimates of the Earth's rotation axis are accurate to about 2–3 mm.

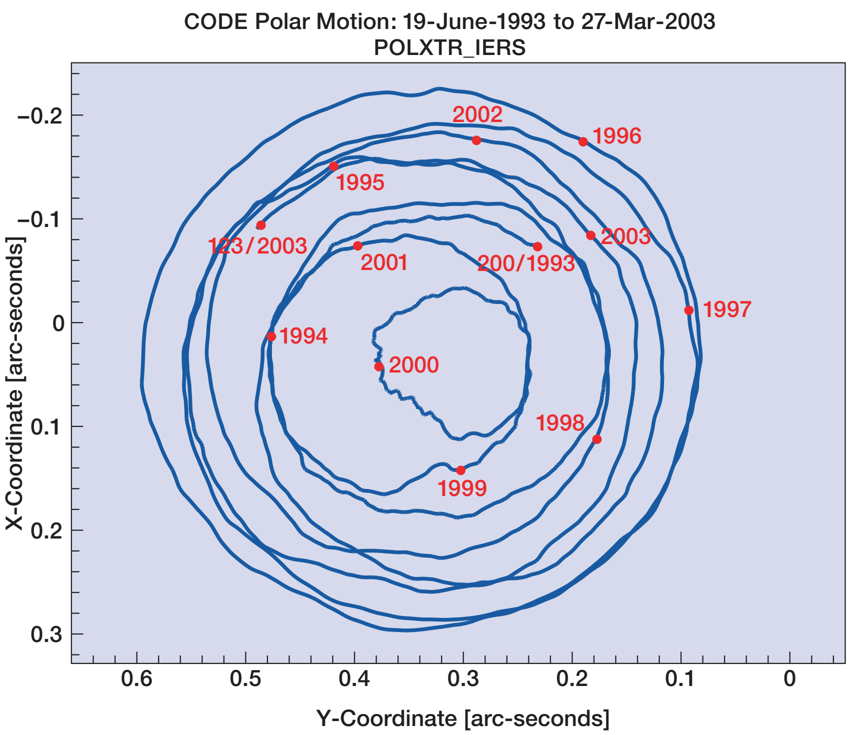


Figure 8
Daily estimates of polar motion by CODE since 1993.

Polar Motion

One arc second corresponds to about 30 m on the Earth's surface. The motion of the pole between 1993 and 2003 thus roughly takes place within a circle of about 7 m centred roughly at the endpoint of the Earth's axis of the maximum moment of inertia. Bigger excursions may occur occasionally. A spectral analysis of polar motion reveals two dominating periods, one of 430 days (amplitude of about 0.17″), the so-called Chandler period, and one of one year (amplitude of about 0.08″). The Chandler period is related to the motion of a solid (not completely rigid) body. The period may be derived from the numerical values of the Earth's principal moments of inertia and from the elastic properties of the Earth. The annual period originates from the interaction between the solid Earth and the atmosphere (and oceans).

The superposition of the Chandler and annual periods results in a beat period of about six years letting the pole move on a ("bad") circle with a radius varying between 2 m and 8 m. Many short-period variations show up in **Figure 8**. Most of them are related to the exchange of angular momentum between atmosphere and solid Earth.

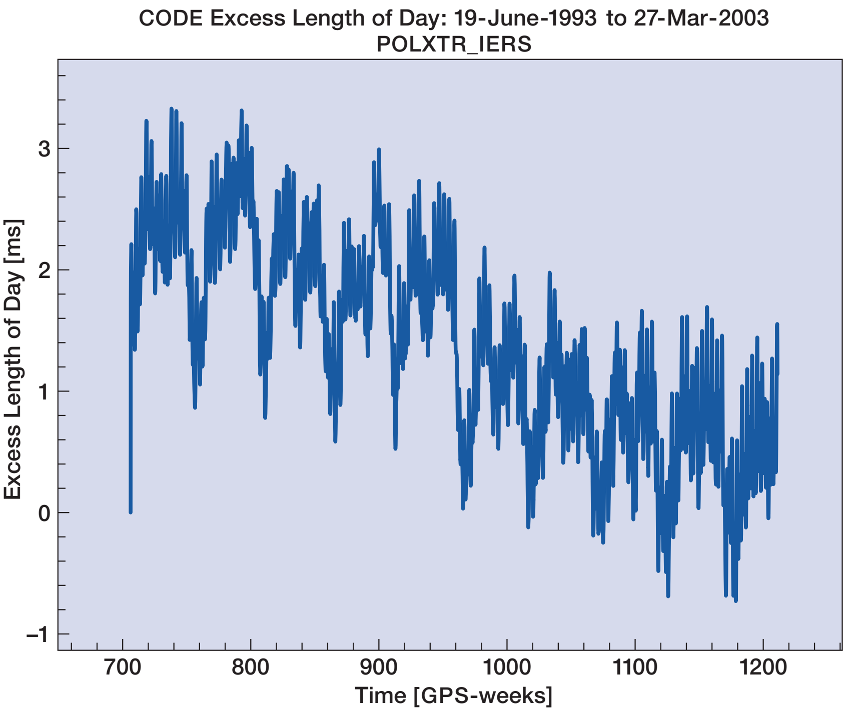


Figure 9
Length of day variations 1993–2003.

Length of Day

In inertial space (i.e., w.r.t. the stars) the Earth rotates once about its axis in a sideral day, corresponding to about 23 h 56 m of atomic time. **Figure 9**, emerging from the daily estimates of the CODE AC, shows that the actual length of day is "far" from constant. Short period variations (e.g., of two weeks) are easily explained by the tidal deformation of the Earth due to the Moon (the tidal displacement causes a varying polar moment of inertia, which in turn leads to a varying angular velocity of Earth rotation). Observe that the bimonthly changes in the length of day (lod) are small (amplitude well below the millisecond), but that they are easily detected in this global analysis. The annual variations with amplitudes of about one millisecond are more interesting.

The phenomenon is explained by comparing the polar component of the solid Earth's angular momentum (which may be derived from the length of day variations) with the so-called atmospheric angular momentum (which is derived from the global meteorological networks, registering pressure, temperature, and wind profiles).

Figures 10a and **10b** compare the relative polar (axial) angular momenta of the solid Earth (red line) and of the Earth's atmosphere. The "true" angular momentum of the solid Earth was used in the case of **Figure 10a**, whereas a low-order polynomial was removed from this time series in **Figure 10b**. The

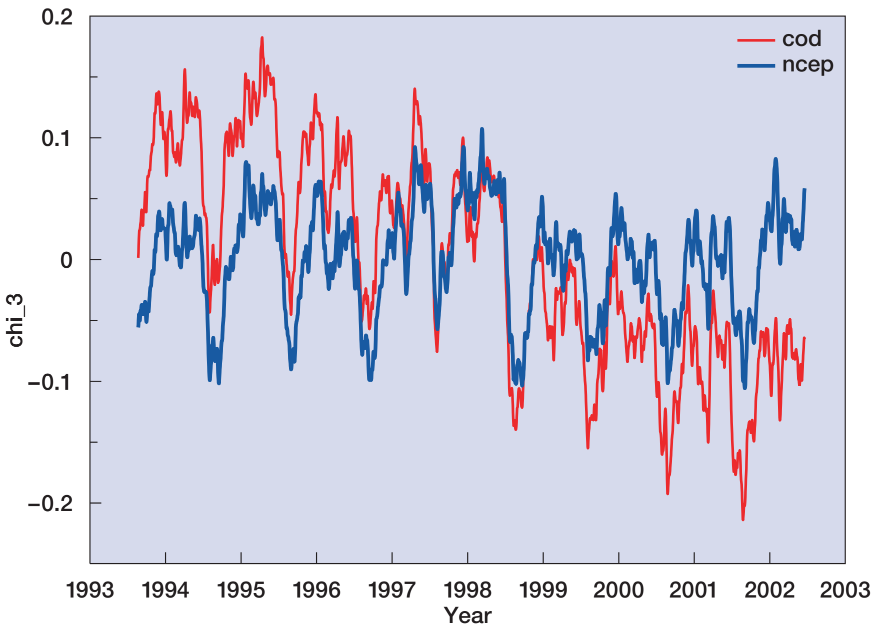


Figure 10a
Polar angular momenta solid Earth and athmosphere.

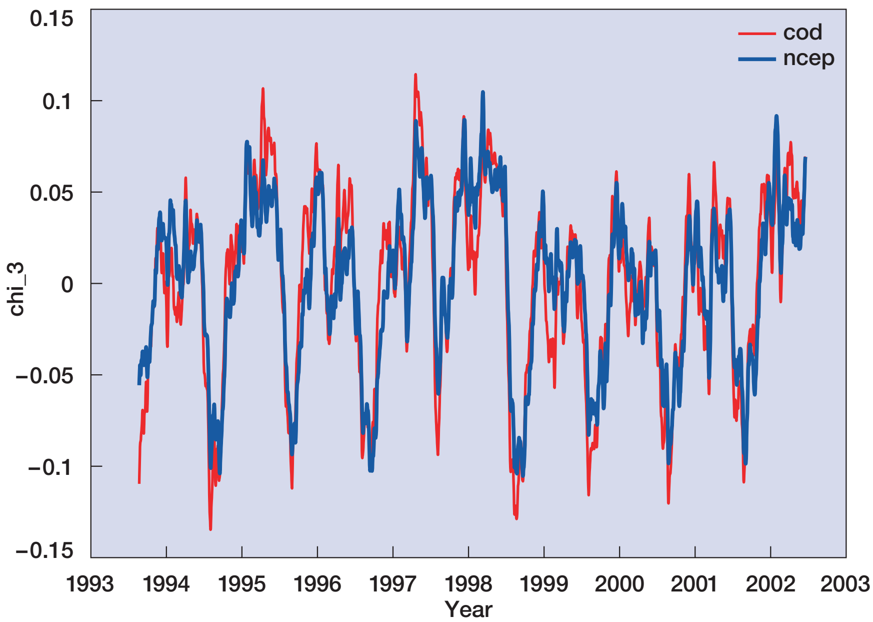


Figure 10b
Polar angular momenta solid Earth (trend removed) and athmosphere.

correlation of the two curves – which are completely independent – is striking in both cases. In **Figure 10b** the correlation coefficient is r = 0.98, implying that the polar component of the system (solid Earth plus atmosphere) is almost perfectly conserved – at least when considering variations with periods of one year or smaller.

Obviously there are variations of longer period ("decadal" variations) in the polar angular momentum **(Figures 10a, 9a)**, which do not occur in the polar component of the atmospheric angular momentum. They are undoubtedly real. These variations are most interesting from the global geodynamics point of view. They may be explained by the fact that the IGS observing sites are attached to the Earth's crust, which is, however, not rigidly attached to the Earth's inner shells (in particular to the fluid outer and the rigid inner core of the Earth). It would be very nice to present pictures corresponding to **Figures 10a,b** proving the exchange of angular momentum with the inner layers, namely mantle, inner and outer core. Unfortunately there are no direct measurements of the angular momenta of these layers. This may be considered as a disadvantage. On the other hand, one has to acknowledge that the study of the decadal lod-variations **(Figure 9)** or of the corresponding angular momentum (red curve in **Figure 10a)** contains very valuable information concerning the rotational behaviour of the Earth's interior. Geodynamical Earth models must explain the long-term development in **Figure 10a**. With the polar motion time series of **Figure 8** it is possible to calculate the other two components (the equatorial components) of the solid Earth's angular momentum and to compare them with the corresponding atmospheric quantities, as well. The correlation between the two series is rather pronounced, but with correlation coefficients around r = 0.7 not nearly as high as in the case of the polar component.

Plate Motion Velocities

The Chandler period of 430 days (instead of 300 days) clearly indicates that the Earth is not rigid. This fact is also supported by **Figure 11** showing that the observing sites are not fixed. The figure is derived from weekly estimates of the coordinates of the tracking stations of the IGS network. It turns out that in the accuracy range achieved by the IGS analyses ([sub]cm accuracy for the daily estimates of the coordinates of the tracking sites) it is not possible to assume that the polyhedron of observing sites is rigid. One has to take the relative motion of the stations into account. **Figure 11** shows the "velocity" estimates for the stations processed daily by the CODE analysis centre (from a long series solutions). Other space-geodetic techniques are of course also capable of determining station velocities. The unique aspect of GPS analyses is the comparatively high density of observing sites. The velocities seem small at first sight. One is inclined to consider velocities of the order of 1–10 cm/year as irrelevant. Nothing could be more wrong: A velocity of 1 cm/year gives rise to a posi-

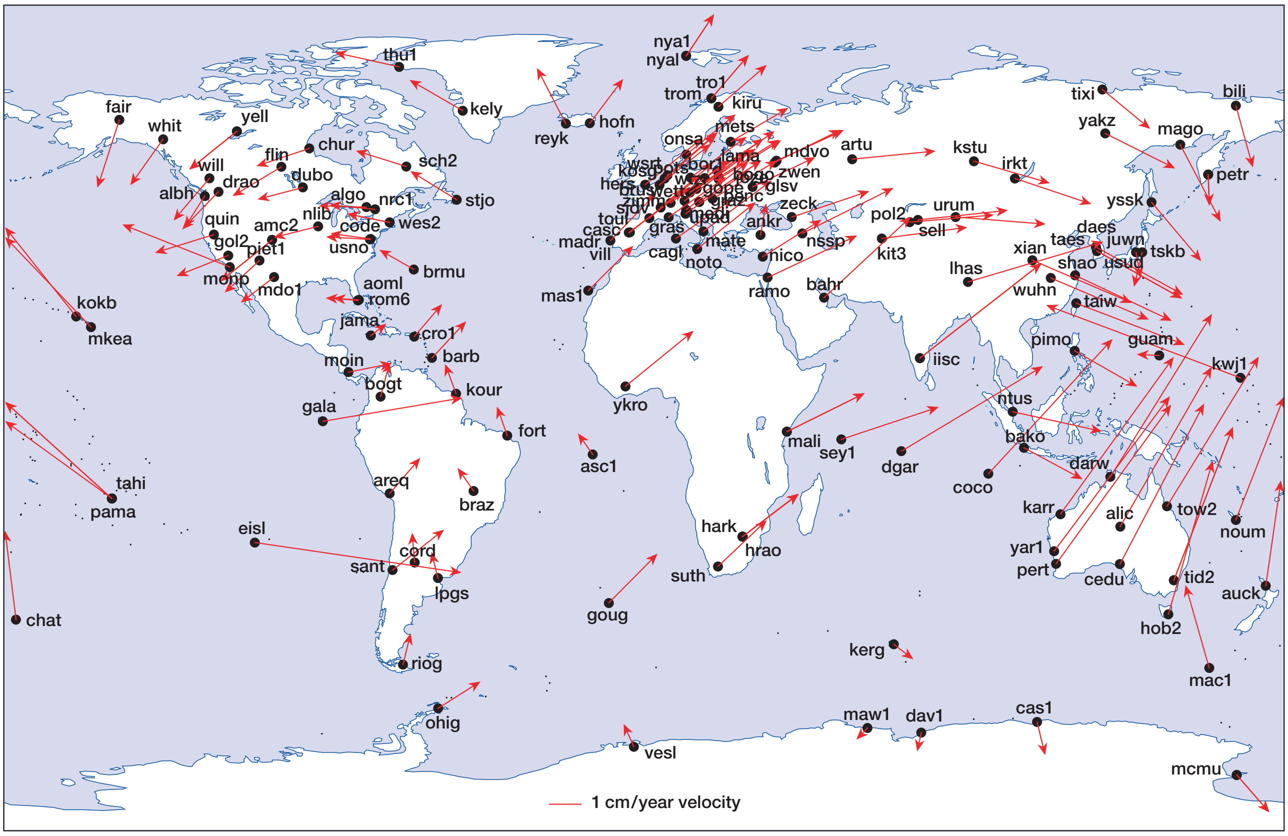


Figure 11
Station velocities estimated by CODE Analysis Center.

tion change of 1000 km in 100 million years! As a matter of fact, these velocities explain the "continental drift" postulated by Alfred Lothar Wegener (1880–1930) in 1915. At Wegener's epoch the continental drift, referred to more appropriately as plate motion, was pure speculation – today we are monitoring it in real time.

Electron Density in the Atmosphere

Let us continue our review of the scientific exploitation of the GPS by an example related to the atmosphere, the determination of the total number of electrons in the atmosphere. The information is extracted from the ionospheric refraction term $\Delta\rho_I(\lambda)$ in **equations 2, 3.** Whereas the results presented so far were obtained by analysing the so-called ionosphere-free linear combination of the L1- and L2-observables (which eliminate the wavelength-dependent ionospheric refraction term), the so-called geometry-free linear combination of the L1- and L2-observations is used for the purpose we have in mind now. This particular linear combination of observations is the plain difference of the **equations** of type **2** or **3** for the L1- and the L2-wavelengths. As all the other terms are wavelength *in*dependent, we obtain a direct observation of ionospheric refraction along the line of sight between observer and satellite by using this difference of observations. The result is proportional to the number of electrons contained in a straight cylinder between observer and satellite. Using the phase and code observations from the entire IGS network one may derive maps of the electron density (the simplest model assumes that all free electrons are contained in a layer in a given height H – usually set to H = 400 km). At CODE, such maps are produced with a time resolution of

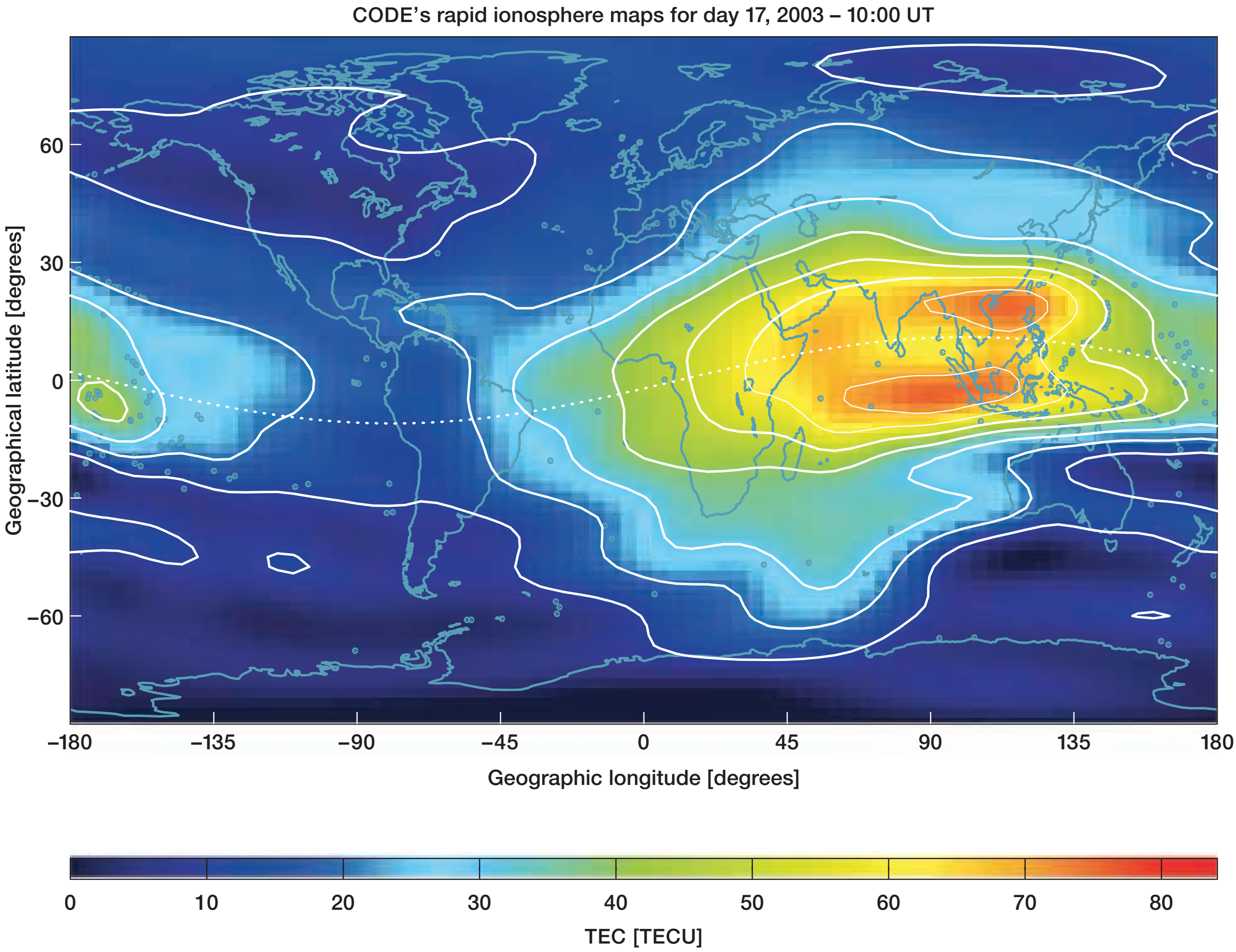


Figure 12
Map of total ionospheric content of electrons (1 TECU = 10^{16} electrons per m^3).

two hours. **Figure 12** shows one of these snapshots. The electron density is given in TECU's (Total Electron Content Units), 1 TECU corresponding to 10^{16} electrons per m^2.

Several mechanisms are responsible for producing free electrons in the Earth's atmosphere. The most important is related to the Sun's UV radiation ionising the molecules in the upper atmosphere. This is why the "spot" of maximum electron density closely follows the projection of the Sun onto the Earth's surface (subsolar point). The maximum is actually lagging behind the subsolar point by about two hours. In **Figure 12** we see a bifurcation of the ionosphere density along the geomagnetic equator (dotted line), an interesting aspect due to the Earth's magnetic field. Internally, the electron density is represented by a spherical harmonics series with about 250 terms. The zero-order term represents the mean electron density. **Figure 13** shows the development of this mean electron density, which may be inspected as a function of time.

This is a good example for solar-terrestrial relationships. A spectrum of the time series underlying **Figure 13** shows that the shortest period corresponds to the rotation

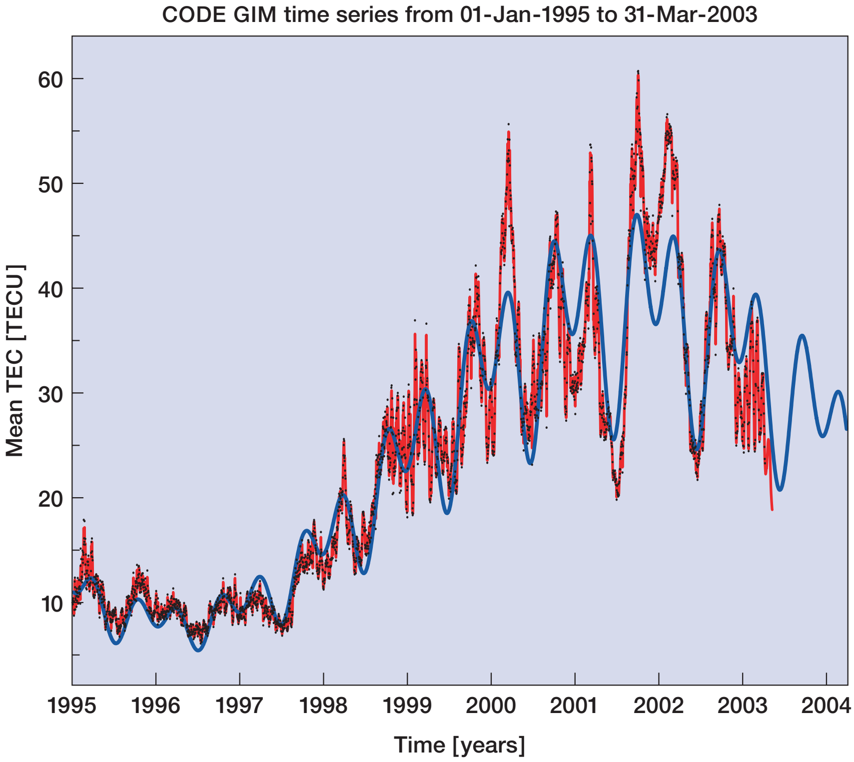


Figure 13
Mean TEC values 1995–2003.

period of the Sun (about 27 days), indicating that the UV radiation is related to the sunspots. Another prominent period is the annual period, which is due to the varying distance between Sun and Earth (because of the Earth's orbital eccentricity of $e = 0.016$). The longest period corresponds to the 11-year sunspot cycle. It should be pointed out that **Figure 13** probably represents the best history of the density of free electrons. Many more figures of this type might be generated by replacing the zero order term of the development of electron densities by the higher-order coefficients of the harmonic series underlying **Figure 12**.

Determination of the Earth's Gravity Field: Review and Outlook

It would have been fair and appropriate to discuss our knowledge of the Earth's gravity field in the introductory section together with the geometrical properties of the Earth. This was not done because our knowledge of the global aspects of the Earth's gravity field was very poor in the pre-space age: It was of course known that the Earth is, in good approximation, a sphere (meaning that the gravity field is that of a point mass). Thought experiments due to I. Newton and expeditions performed in the 18th century then revealed that the next better approximation for the shape of the Earth was that of a spheroid with a flattening of about $f={}^1/_{300}$ (giving rise to one second-order term of the gravity field, the so-called "dynamical flattening"). (Gravimeter measurements on the Earth's surface indicated that there were significant local and regional variations of the Earth's gravity field, but it was not possible to use these measurements to derive a consistent global gravity field of the Earth).

The analysis of the orbits of artificial Earth satellites, starting in the 1960s, greatly improved our knowledge of the Earth's gravity field. Instead of only two terms (the mass of the Earth and the dynamical flattening) a few thousand terms could be determined with reasonable accuracy in the first era of satellite geodesy. The two Lageos satellites (the acronym standing for Laser GEOdetic Satellite) were paramount for this task. The satellites were designed to minimise the impact of non-gravitational forces (the sphere of 70 cm diameter consists of Uranium) on the orbital motion and to optimise their observation by the Laser technique (Lageos II is shown in **Figure 14**).

Figure 15 shows University of Bern's 1 m telescope at Zimmerwald, which may be used as an optical telescope, but also as transmission and receiving device for Satellite Laser Ranging (SLR). The Laser technique is used to generate very short light pulses (few ten picoseconds). The measurement simply is the light travelling time of the Laser pulse from the observatory to the satellite and back. Due to the divergence of the Laser beam and due to the limited number of reflectors onboard the satellite **(Figure 14)** only few reflected photons may be detected in the observatory. The technique has outstanding properties: The accuracy is high (few picoseconds corresponding to about 1 cm in range) and the atmospheric effects may be modelled with highest accuracy (sub-cm) using only standard meteorological measurements at the sites. The technique has, however, also severe disadvantages: good weather is a precondition (the clouds in **Figure 15** would not allow it to track satellites). Moreover, a Laser observatory is rather bulky and expensive, which is why there exist only about thirty observatories today, which are globally coordinated by the International Laser Ranging Service (ILRS).

The sparseness of the Laser sites makes it therefore impossible to continuously track the orbit of a particular satellite. This situation is not at all ideal for the analysis of satellite orbits.

Figure 14
The Lageos satellite.

This circumstance was one of the key motivations to look for alternative space borne methods to determine the Earth's gravity field. All new methods rely on GPS to determine the orbit of the space vehicle(s) used to determine the Earth's gravity field and on the IGS products to model the GPS orbits and clocks. **Figure 16** shows an artist's view of the German research satellite CHAMP (ChAllenging Minisatellite Payload). Champ was launched in July 2000. It is, as the name implies, a multipurpose satellite, allowing atmospheric sounding, and the determination of the magnetic and the gravity fields. The gravity field is recovered from analysing the satellite's orbits using the GPS. This is possible because the satellite carries a space borne GPS receiver (JPL's blackjack receiver). CHAMP flies at rather low altitudes (from initially 450 km to 300 km at end of the mission in 2005). In view of the bulkiness of the satellite non-gravitational forces, residual air drag in particular, do seriously affect the orbit of the satellite – and therefore also the determination of the Earth's gravity field. CHAMP copes with this problem by so-called accelerometers, in essence a probe mass in the satellite's interior (shielded against non-gravitational forces). The displacement of this probe mass in the satellite-fixed reference frame may be used to "determine" the non-gravitational forces. This is, of course, only possible within certain limits given by the error spectrum of the accelerometers. It turns out that the separation of gravitational and

Figure 15
The Zimmerwald 1-m telescope.

non-gravitational forces is rather good for short periods and rather poor for the longer periods. It is in any case most encouraging to see that one month of CHAMP data gives better results for the short periodic part of the gravity field spectrum than about 40 years of Laser tracking! CHAMP marks the beginning of the new era of gravity field determination.

The two satellites GRACE A and GRACE B (see **Figure 17)** fly in the same orbit, separated by about 20 km. GRACE, launched in March 2002, stands for Gravity Recover And Climate Experiment. Obviously the two satellites are similar in shape to CHAMP. GRACE focuses on the time variability of the Earth's gravity field. For that purpose it determines the Earth's gravity field with a high time resolution allowing it, e.g., to study the seasonal water cycle (evaporation over oceans, precipitation over continents, ground water variability, flowing off into the oceans). It is amazing that such experiments can be performed by studying the Earth's gravity field! The orbits of GRACE A and B are reconstructed exactly like in the case of CHAMP by using the data of space borne GPS receivers. The orbit of GRACE A relative to GRACE B is, however, reconstructed with a so-called K-band link (distance measurements in the microwave range) between the two spacecraft. This K-band link establishes the distance between the two satellites with extreme precision. The measurements may be used to determine directly the second derivatives of the Earth's gravity potential. Both, the satellite orbit established by GPS and the K-band measurements, are used to reconstruct the Earth's gravity field. It is expected that the results will significantly improve our knowledge in a wide spectrum of Earth sciences.

The third of the new generation satellites to determine the Earth's gravity field is ESA's GOCE satellite, shown in **Figure 18** (GOCE standing for Gravity field and steady-state Ocean Circulation Experiment). As the name implies, GOCE is a combined mission to measure gravity and Ocean circulation. GOCE wants to establish the mean gravity field of the Earth with the highest possible accuracy and spatial resolution. When determining the gravity field associated with a mass distribution, one obtains, as a by-product, equipotential surfaces. The equipotential surface at sea level is called the geoide. The geoid to be determined by GOCE will be of greatest importance for the determination and monitoring of ocean circulation. For this purpose it is, in addition, necessary to determine the so-called sea surface topography using the measurements of altimeter satellites, reconstructing the sea surface using the radar echo technique. The difference between the geometrically established sea surface and the GOCE geoid gives the elevation of the sea surface over the geoid. Exactly as in the continents, the water in the oceans has to flow "mountains" to "valleys". It is indeed fascinating to see that sciences which were considered special disciplines for few experts are now developing into one multidisciplinary topic in Earth sciences.

Unfortunately we could only touch a few aspects related to this new era of gravity field determination. For more information we refer to the proceedings of the workshop *Earth Gravity Field from Space – From Sensors to Earth Sciences,* which was hosted by the ISSI in March 2002. The workshop brought together the leading experts in celestial mechanics, geodesy, Earth sciences, and in instrument manufacturing. The proceedings of the workshop underline the tremendous impact of this new sequence of space missions on a very broad field of science.

Figure 16
The CHAMP spacecraft launched in July 2000 (credit Astrium).

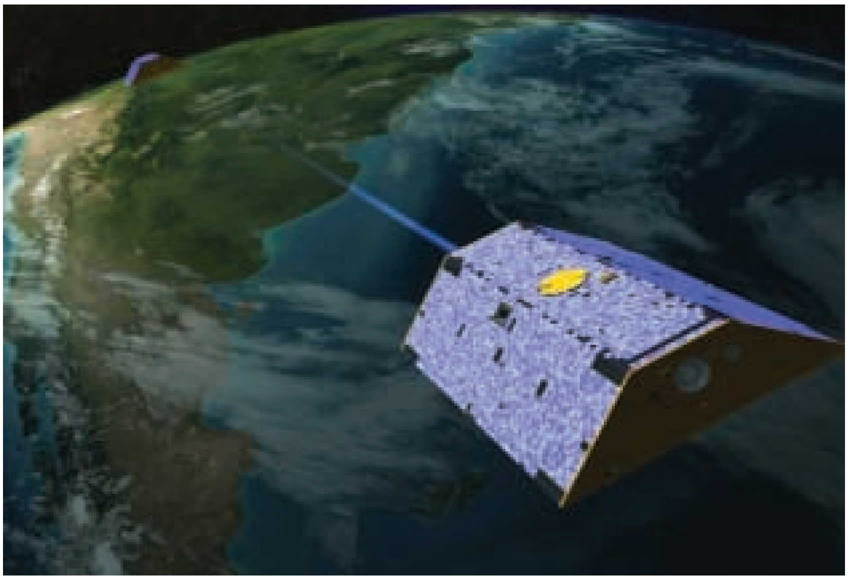


Figure 17
The pair of GRACE spacecraft launched in March 2002 (credit NASA).

Summary

Navigation and fundamental astronomy are intimately related since hundreds of years. Until about thirty years ago global navigation relied on measuring angles. Scientific discoveries include the phenomena of precession, nutation, secular deceleration of Earth rotation, and polar motion.

With the advent of the space age the astrometric observation of stars and planets was replaced by the measurement of distances (or distance differences) between observers and artificial satellites. As weather-and daytime-independence is an important aspect of navigation, the observation techniques were moreover moved from the optical to the microwave band of the electromagnetic spectrum. In view of the fact that the "old" methods were used for centuries, one can truly speak of a revolution in navigation, geodesy, and fundamental astronomy.

The scientific aspects emerging from the new navigation systems are co-ordinated by the International GPS Service (IGS). Polar motion, length of day, plate tectonics, and the Earth's ionosphere are monitored with unprecedented accuracy. The IGS products are also paramount for the success of gravity field determination with the new generation of gravity missions. The new era of gravity field determination will lead to a unification of geometric and gravitational aspects, truly bringing together the three pillars of modern geodesy and fundamental astronomy, namely (1) positioning and navigation, (2) Earth rotation, (3) gravity field determination.

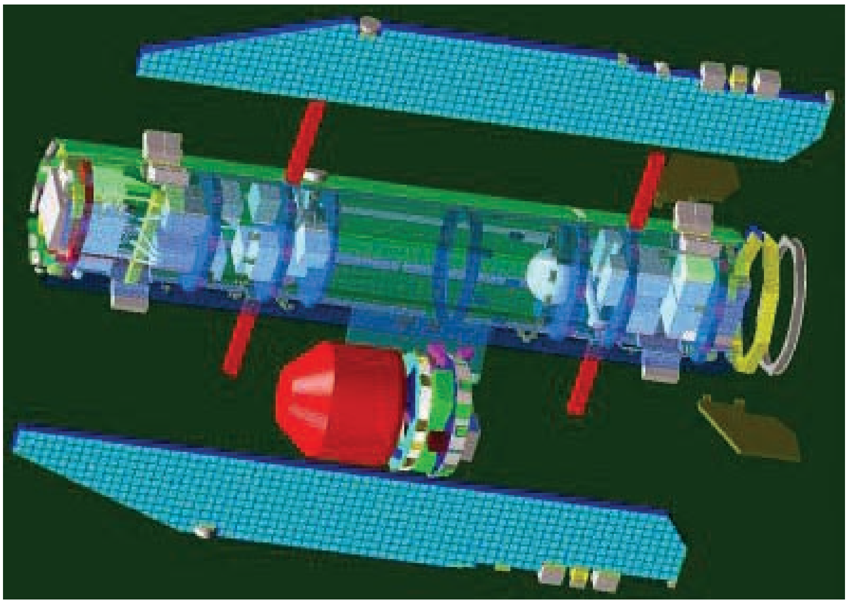


Figure 18
The GOCE spacecraft to be launched in 2006 (credit: ESA).

The author

Gerhard Beutler was borne in Kirchberg in the Canton Berne in 1946, where he visited the elementary school. After receipt of the type C maturity in 1964 he enrolled at the University of Berne in astronomy, physics and mathematics. These subjects turned out to be the ideal theoretical foundation when it came to exploring the scientific potential of navigation satellites when the U.S. Global Positioning System became operational.

In 1976 G. Beutler received the Ph.D. degree with a thesis on Integral Evaluation of Satellite Observations. The second thesis was devoted to the Solution of Parameter Estimation Problems in Celestial Mechanics and Satellite Geodesy. Later on, he held positions as research associate from 1983 until 1984 at the University of New Brunswick, Fredericton, Canada and from 1984 until 1991 at the University of Berne. During the latter period he was engaged in the development of the Bernese Global Positioning System Software, which is used today at about 150 research institutions worldwide. In 1991 he was elected Professor of Astronomy and Director of the Astronomical Institute of the University of Berne. His lectures cover such fields as celestial mechanics, Earth rotation, stellar dynamics and statistics, parameter estimation theory and digital filtering theory.

The main research interests of Gerhard Beutler are devoted to fundamental astronomy, celestial mechanics, global geodynamics and satellite-based positioning und navigation. He is a member of numerous national and international committees and working groups, as for example the Schweizerische Geodätische Kommission, the American Geophysical Union and the European Space Agency's Scientific Advisory Board on the European Navigation Satellite System Galileo. As of July 2003 he will serve as President of the International Association of Geodesy (IGS).

Based on his initiative the CODE Processing Centre of the International Geodetic Society was created. CODE today is a joint venture of the Astronomical Institute of the University of Berne, the Swiss Federal Office of Topography, the Institute for Applied Geodesy in Germany, and the Institut Géographique National in France.

Gerhard Beutler is a fervent supporter of the planned European navigation and positioning system Galileo, not only because this system would make more satellites available but also because its different orbit characteristics as compared to the US GPS system would provide the scientific user with an increased potential of positioning accuracy.

Gerhard Beutler lives with his family in Schüpfen in the Canton Berne. In his free time he likes biking through the wonderful landscapes of the Canton Berne, as well as playing tennis. Not without pride he counts himself to the world top league of the celestial mechanics tennis players.