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A new look at planet Earth: Satellite geodesy and geosciences

INTRODUCTION

Yes! The Earth is also a planet! In the recent past, looking back at the long list of scientific space missions launched by space agencies, you have the impression that neither any celestial body, nor astronomical or geophysical theme has not been covered. But looking more carefully, you soon realize that something is missing … the Earth!

It is not the case that space is ignoring the Earth; indeed, huge programs are devoted to Earth observations, but they are designed as if there was no need for a scientific study of our planet, itself.

This equivocation is not just a semantic one. It seems that the Moon or other planets in the solar system deserve more attention than the Earth. As an example, the Magellan mission made a complete mapping of the surface of Venus which took five years with a SAR instrument (Synthetic Aperture Radar); several years before such an instrument could have very usefully flown around the Earth.

Now, there is a new appeal for understanding the Earth, and the situation has changed drastically. The Chernobyl accident caused a strong public reaction and created a widespread feeling that the atmosphere knows no borders. The recent large-scale ocean-atmosphere movements, like the ENSO (El Niño), widely discussed on by TV channels, contributes to public awareness.

The scientific community was perfectly aware of the lack of knowledge of the Earth as a planet and recognised that the main problem was the poor quality of observations. The need for a global perspective was such that a dedicated planetary program was undertaken and implemented in 1957–1958; the objective of this IGY (International Geophysical Year) was to collect as many geophysical measurements as possible from world-wide well distributed sites. Although successful in some fields it also showed the limits of this approach over the long term. As a coincidence, the first SPUTNIK satellite was launched in October 1957 and the government of USSR claimed officially that it had to be considered as a contribution to IGY, not a bad vision indeed.

The space agencies recently reconsidered their programs and made the knowledge of the Earth a top priority. ESA (European Space Agency) started a new program called "Earth Living Planet" while NASA (National Aeronautics and Space Administration) started a huge program devoted explicitly to Earth sciences. To be even more explicit, they named it "Destination Earth"; this movement was world-wide. Today the space agencies try to optimise their participation in a common endeavour through such ad hoc committees as CEOS (Committee on Earth Observation Satellites).

After 35 years of satellite geodesy and oceanography, our objective is to show that in spite of the absence of dedicated important programs in Earth physics from space, there was a de facto strategy. It began at the time when the necessity to undertake the study of the Earth became apparent and has produced significant results, as well as developed both tools and a living and multi-disciplinary community ready to go. We will show this development that through a historical overview of activities over the past 35 years, presenting the different phases and major turns in Earth-space science.

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François Barlier and Michel Lefebvre, The Century of Space Science, 1–29

1. FROM GEODESY TO SATELLITE GEODESY BEFORE 1957

Geodesy is one of the oldest disciplines in the IUGG (International Union of Geodesy and Geophysics) and has its roots in the early stages of civilization. When you live somewhere, the first thing to do is to know where you are, what is your local environment like, then to share your views with your neighbours, extend your perspective from local to regional and finally to planetary scales.

The Chamber's dictionary gives the following definition of geodesy: "it measures the Earth and its parts on a larger scale". The etymology from Greek tells us that geodesy comes from GE, the Earth and DAIEIN to share. Indeed what we have now to share is the EARTH.

When Sputnik was launched in October 4, 1957, geodesy was confined to improving the accuracy of measurements as well as increasing the resolution of the grid of networks. A high level of expertise existed and was exercised in specialized geodetic institutes, most of them sponsored by governments. The links with equivalent bodies working on military objectives have been varied but on average were well established, such that the release of data and results was often prevented. Concerning the shape of the Earth and its gravity field, numbers will give some ideas of the status. At the level of the continental formations, there were some efforts to get homogeneous sets of parameters representing at best the results obtained by triangulation and by astrogeodesy on the shape of the Earth and to get coherent geodetic systems like the NAD datum (North American Datum) or the EUR 50 datum (European datum). The relative accuracy, at least for the horizontal components, was acceptable inside a given system and when close to the main fundamental networks was of the order of 10^{-5} or 10^{-6} (1 meter over 1000 kilometers). However, it was uncertain in the limits of networks when no closure was available (as an example the south of Spain relative to EUR 50). The precision of vertical angle measurements was also limited by the atmospheric refraction.

The knowledge of the relationships between the origin of these systems and the center of mass of the Earth was poor, such that the absolute positions of the stations were maybe in error up to several hundred meters. No data were available over the oceans that are over 70% of the Earth surface. Over the continents, the data were sparse in many areas. Moreover, the networks were measured by discrete campaigns at different times with different instruments by different teams. Despite the high quality of the actors, there were some intrinsic limitations. The users had no other way than asking to their national geodetic institutes to make the geodetic links; the advantage was to have them made by professionals and well controlled. But the lack of a unified system was still a problem. Even in the 1960s the position of the same radar antenna given by 2 institutes from neighbouring countries differed in several cases by an amount larger than the internal error; it was simply coming from the use of different reference systems. The above comments do not aim at making any assessment of classical geodesy but rather at putting emphasis on the limitations of classical geodetic systems at the scale of the Earth. Now, satellite is there but how to use it at the best?

2. TRANSITION EXPLORATORY PHASE 1957–1970

2.1 The geometrical optical phase: A too obvious approach

First of all, how to observe? At first, the favoured method of observation was optical. Observatories had or developed big cameras and made photographs of artificial satellites lightened by the Sun, the spatial reference being provided by the surrounding stars. The first obvious idea was to use a satellite as a target, high enough to make intercontinental links that seem the most obviously missing element in geodesy and to have access to the 3D dimension. Everybody was enthusiastic; nobody realised that a satellite indeed ignores national boundaries: we remember the shock of some authorities, military or otherwise, when scientists published the co-ordinates of Malvern (UK) and Nice (FR), breaking for ever the long tradition to keep such data and positions secret.

The geometrical approach was limited by the magnitude of the satellite. A first solution was to launch some dedicated satellites shaped like balloons with a large diameter, about 25 meters, such as the ECHO 1 and 2 satellites (Note: it was the common approach used in a telecommunication experiment, the expectation being to use the satellite as a reflector for electromagnetic waves) The visual magnitude of ECHO satellites was around, 1, so that they were accessible to many small existing cameras, allowing the increase in the number of stations within the nets to link.

The two ECHO satellites were so bright that it was possible for anybody to watch them visually with the naked eye, and to follow their motion across the stars. It was attractive enough to drive the newspapers to publish the times that these "New Stars", passed over head.

Several million people watched and acquired a personal physical feeling for the existence of satellites and became aware that we were entering the space age. The visual observations were not just curiosities; networks of amateurs observed with some optical instruments and provided the directions, elevation and azimuth to some centers using these observations, especially from very low altitude satellites. The result was the first models of the Earth's gravity field and of the upper atmosphere density.

Several geodetic institutes were thus able, through intensive campaigns, to make geodetic intercontinental links. One on the most successful campaign was the geodetic connection between Europe and Africa.

Going beyond, a more optimized dedicated program was undertaken; PAGEOS, a better designed and more stable balloon satellite was put in orbit at a higher altitude. The existing BC – 4 cameras from the US Coast and Geodetic Survey were deployed in networks occupying 40 sites well distributed around the Earth; the geocentric positions of the 40 stations were published and were considered by this time as making one of the first homogeneous global Earth reference systems. It was in fact a dead-end and it is interesting to understand why. First the accuracy was not good enough. The best result obtained for the positioning was at the 10–15 meters level, but there is also a major disadvantage; this new reference system was not accessible to the common user.

2.2 The space geodetic scheme

The general principles of satellite geodesy may be depicted with an elementary diagram, the **GSM** scheme (Figure 1).

G is the center of mass of the Earth,
S is the position of a tracking station,
M is the position of the moving satellite.

At any time **GM = GS + SM:**

SM corresponds to the observation. It may be the measurement of range, range rate, directions whatever.
GS corresponds to the position of the tracking station. It is an unknown to be determined and it must be referred to a unified homogeneous Earth reference system.
GS moves (due to tides, tectonic motions, and local effects). The terrestrial reference frame, the position of the axis of rotation as well as the speed of rotation (the parameters of the Earth rotation) vary over time.
GM characterises the motion of the satellite.

The unknowns are:

– the initial conditions (position and velocity of the satellite) at a reference time.
– the acting forces on the satellite (gravity field of the Earth, solid and ocean tides, air drag, direct and reflected solar radiation pressure ...).

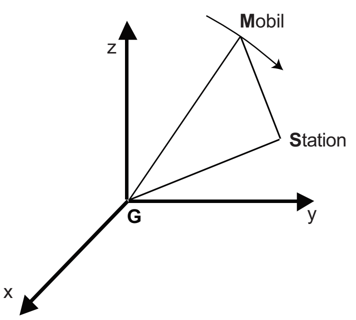

Figure 1 A simplified scheme for geodesy.

So the **GSM** game is easy to explain. Knowing the functions relating quantities (the measurements) to some parameters considered as unknowns, you have to compare your observation with a value computed by marking a first guess about the unknowns. In a linearized approach, you have to compute the partial derivatives of the observation relative to the unknowns. Then you have to minimize the differences between all computed and observed values using statistical assumptions and an algorithm of adjustment. The problem is in fact not linear, so you need to process by using iterations. Among the unknowns, there are possible systematic biases in your system or errors in the physics of your model. You expect to converge on accurate and reliable values.

In the dynamical approach, the motion of the satellite is an important component in many respects. Firstly, it is the natural way to scan any part of the planet. This sampling can be optimized using the orbital parameters that can be adjusted accordingly. Secondly, the perturbations of the satellite motion provide the determination of the acting forces and in priority the gravity field of the Earth. Conversely, a perfect knowledge of the forces provide a powerful constraint on the orbit determination. Then the accurate knowledge of the position and velocity of the satellite in a well-controlled reference system allows us to have the benefit of other measurements performed by onboard instruments; such as, for instance, those provided by radar altimeters in oceanography.

2.3 First look at observing technique candidates

2.3.1 Photographic observations

Photographic observations were the only precise material available for a while; nowadays, these types of observations are no longer used (except for specific applications, such the observation of space debris); but it is still interesting to examine all the efforts made.

Photographic Observations

The photography of satellites with respect to stars was the first type of precise measurements of the angular positions of satellites.

The procedure requires a capability of observing even satellites with faint magnitudes. The only way was to integrate enough light by a longer time of exposure, that means to use cameras able to track the satellite during its pass. The fully optimized system was the American network of Baker-Nunn cameras that were modified by adding an extra degree of freedom. It was successful and a world-wide network was

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implemented. There was a large effort in automation not only to observe but also to measure the films and provide in a few weeks better right ascensions and declinations of the satellite, the reference being provided by the surrounding stars.

These photographic observations were the core of the first global determination of the gravity field (see Standard Earth below). The accuracy was limited to about 2 arc seconds, that is to say around 10 to 20 meters.

In parallel, other countries were developing their own systems, like the AFU 75 camera in USSR (aperture of 20 cm and focal length of 75 cm), the tracking camera ANTARES at the Nice Observatory, the HEWITT camera at the Malvern Observatory and the ZEISS camera in Germany.

For the purpose of developing the geometrical space geodesy with satellites like ECHO or PAGEOS, many smaller cameras were used: as examples the Wild BC4 camera of the Coast and Geodetic Survey in USA (aperture 11.7 cm, focal length 30.5 cm), the IGN camera in France (aperture 10 cm, focal length 30 cm). Schmidt Telescopes were also successfully used for observing flashing satellites (ANNA – 1B, GEOS-A and -B satellites launched by the USA) or for observing laser returns on the satellites and obtaining the 3 components of the station-to-satellite vector. But nowadays, all these techniques are generally abandoned, taking into account the progress realized with the laser techniques and the radio techniques. However, they played a major role in the beginning and old photographic data continued to be used in gravity field modeling to ensure a good decorrelation between the different harmonics.

2.3.2 Satellite laser ranging

Laser technology is able to emit highly concentrated phased optical energy in very narrow beams. This capability was used in transmitting energy from the ground towards the satellite equipped with corner cubes that reflect the light back in the same direction. The returned energy is detected and the time elapsed between emission and reception, after some corrections, provides the range. The first satellite equipped by the USA with laser corner cubes was BEB (1964). There was a competition to get first returns. The Goddard Space Flight Center (GSFC) team in the USA got the first ones in December 1964. The French CNRS team (Centre National de la Recherche Scientifique) at Verrières-le-Buisson obtained the first pass at the Haute Provence Observatory in January 1965. They only presented the first orbit computed with laser observations at the COSPAR meeting in Buenos-Aires in spring 1965. The claimed precision from the rms (root mean square) of the measurements was of about 1.0–1.5 meters.

Today, laser ranging is the most accurate technique, and it is still open to many improvements. One of the advantages is that the onboard equipment is light, cheap, has an infinite lifetime and does not consume any energy.

First Laser Returns, A Hunting Party

During the winter of 1964, we had the good luck to be involved in the first attempts to get some returns from BEB just to help R. and M. Bivas in charge of this experiment at the Haute Provence Observatory.

It was like a hunting party. At this time, the game was to view the satellite with binoculars, in a position as low as possible on the horizon, the best situation to get your prey in case of non-accurate predictions. So the game was to watch and, as soon as the satellite was in view, to transmit orally useful information to the Bivas. They were seated in an old turret that they manoeuvred around two axes to maintain the instrument in the direction of the satellite. In the meantime, they shot with the laser transmitter. The overall system was heating, requesting some cooling. The subsequent leakage of oil was evaporated with Mrs Bivas's hairdryer!

When you participate in such a venture, you become more respectful of the data, though without falling into exotic comments such as made by a newsman: shooting at a laser target is equivalent to firing at the eye of a bee flying around with a speed of 10 kilometers per second.

Thanks to celestial mechanics it was not as hard!

2.3.3 Radio frequency tracking data: the TRANSIT system

During the 60s, some radio-electric systems were developed and research undertaken to better understand the different components in order to identify the key points for the design of permanent and weather independent accurate system of tracking.

The TRANSIT system was developed very early by the US Navy to provide an improved navigation system for their fleet. The core was a one way Doppler downlink mode. In such a system, the transmitter is onboard the satellite, the receiver on the ground in tracking stations where the Doppler effect is measured and dated in the station time scale. The system is global.

The three main components are:

- a network of tracking stations well distributed around the Earth (TRANET network),
- a fleet of orbiting satellites, the TRANSIT satellites, with enough redundancy to provide a global coverage,
- a main operating center that collects the Doppler measurements from the ground stations, computes orbits and enters these coded orbits onboard the satellites.

In 1966, CNES (The French Space Agency), launched a small satellite named Diapason with a USO (ultra stable quartz oscillator) onboard to test accurate one-way Doppler downlink measurements. In 1967, two other satellites, named DIADEME 1 and 2, equipped with USO and laser reflectors were launched. The data from DIADEME were used in 1968 to make a pilot experiment with three ground stations equipped with laser tracking systems and Doppler receivers.

Notice that the Doppler measurements differ from the laser ones in that the former can only measure the relative speed ("range rate") between satellite and station, not the distance ("range") itself.

2.4 Dynamical approach and first zonal harmonics

At the surface of the Earth as well as in its environment, where the satellites revolve the value of the gravity, considerably varies. For representing such variations in space, the geodesists chose mathematical functions. They expanded the potential function of the gravity field with mathematical functions called spherical harmonics. They distinguished the functions only depending on latitude called zonal harmonics (characterised by a degree) and the others depending also on longitude called tesseral harmonics (characterised by a degree and an order). Determining the Earth gravity field is equivalent to determine the numerical values of the coefficients placed before each harmonic. Low degree coefficients describe long wavelengths, higher degrees increasingly shorter scales. Since gravity is the strongest force controlling the orbit of a satellite, one uses the best existent gravity model to predict the orbit, then the differences of the observed orbit are mapped back to changes in the gravity coefficients. The altitude effect is easily taken into account.

In space geodesy, the almost immediate result was the determination of the first coefficients of the zonal harmonics. The value of the first coefficient can be easily interpreted in terms of the position of the center of mass with respect to the crust. This position has been corrected by more than 100 meters. The value of the second coefficient (C_{20} or J_2) characterising the dynamic flattening of the Earth was computed with an accuracy 10 times better that the previous accepted value from classical geodesy. The value of the third coefficient (C_{30} or J_3), representing the gravity field asymmetry between the 2 hemispheres, was not known at all but was later discovered (the "pear" shape of the Earth!).

Several determinations were made, inter-compared and some initial attempts at geophysical interpretation published… In fact, It was rather easy; the amplitudes of the perturbations in the trajectory were comparatively quite large, up to several degrees/day on the ascending node (it defines the angular position of the orbital plane) and on the argument of perigee (the point of the orbit where the distance to the Earth center is minimal). But beyond these results, this dynamical approach provided the 2 objectives that one had in mind: tracking station and satellite positions using the gravity field.

2.5 Two major turns: The Standard Earth and the Williamstown Meeting

2.5.1. The Standard Earth

Following these preliminary studies, the first big step was when a first Earth model, the so-called Standard Earth (SE), was initiated in the mid-60s by the Smithsonian Astrophysical Observatory (SAO) at Cambridge, Massachusetts. The SE was a set of spherical harmonics coefficients depicting the gravity field and consistent station coordinates. There were a lot of new things. It was managed as a project with a clear global objective.

All the requirements were identified and actions were taken:

– for getting photographic observations from modified Baker Nunn cameras,
– for having a plan to select the satellites to track in order to have a maximized diversity of orbits,
– for deploying the network of these cameras to optimize the sampling,
– for developing analytical theories to describe the satellite motion and the statistical scheme for data assimilation with the recovery of unknowns,
– for creating and maintaining a unique atomic time scale, AS,
– for performing in parallel a model of atmospheric densities to filter the air drag.

This project was a full success. The Standard Earth I (SE I) was published and widely distributed during the COSPAR meeting in 1967. It was followed later by the SE II published by M. Gaposchkin and K. Lambeck in the Journal of Geophysical Research in 1971. This was the first civilian very significant project. The first solution provided co-ordinates of about 25 tracking stations and a gravity field to the degree and order 15. It was made in close co-operation with people coming from different countries; many of them were lucky enough to share the spirit of co-operation, the brain storming and hard work during summertime. SE was not an end but a basis for the future and had a strong impact on the future program.

2.5.2 The meeting in Williamstown – A vision

The expertise being acquired, it was time to express some views. A workshop was convened by NASA in July 1969, and was devoted to "Earth and Ocean Application Physics". W. Kaula chaired it. The main idea was, starting from existing technology, to present some initial results and emerging new objectives in order to set up a strategy with clear priorities expressed in terms of projects. The executive summary is one of the best visions in our discipline. It had a decisive

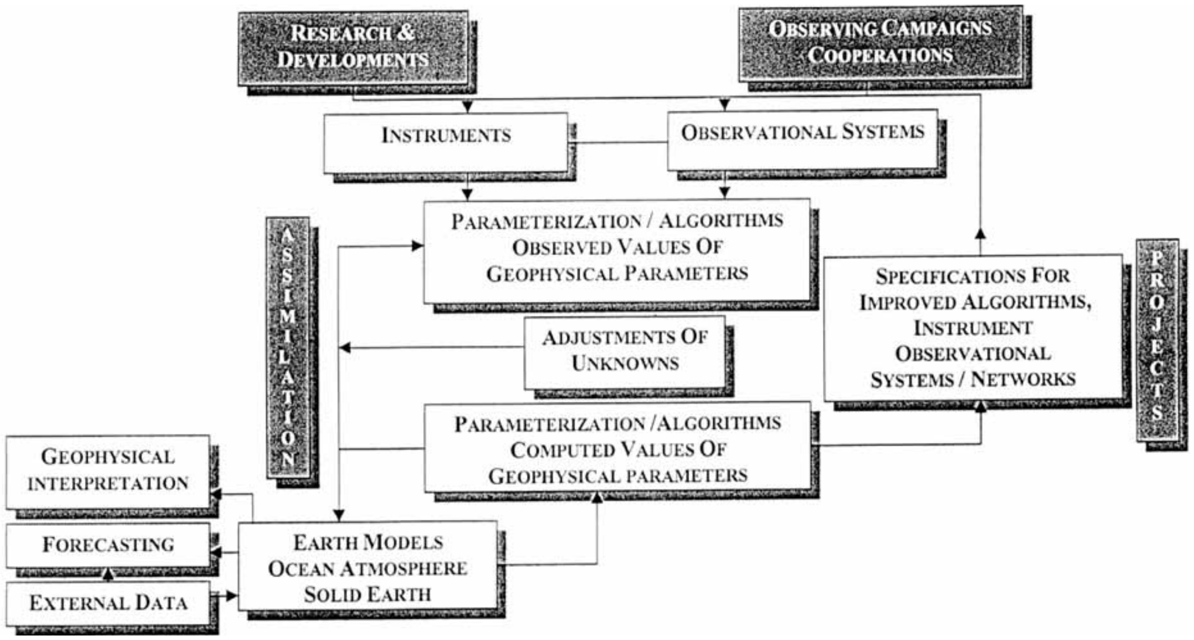

Figure 2 Lundquist's chart. (NASA document, 1969.)

impact at least on the 80 participants and is still considered as a foundation.

C. Lundquist, who was the manager of the Standard Earth and a driver in Williamstown, constructed a flow chart that seems very simple, but clearly put forward the relationships between the various tasks. This end-to-end strategy with an iterative process appeared as the key to success. We will use extensively an imitation of this chart to analyse the evolution (Figure 2).

Based upon the conclusions of Williamstown we wrote in 1970, a report called "Propositions à long terme en géodynamique". Our proposal was to-study "all that can be determined from accurate measurements of range, range rate, directions between ground stations and satellites, or between satellites". It concerns the study of the Earth and the Moon as elastic-viscous bodies; large motions of fluid envelopes like oceans, atmosphere or ice caps have to be considered. This proposal was criticized as being technical and not scientific. But 30 years later, it is recognized that it was a good approach. If we would like to have a more noble definition we could rename it the "Metrology of the Earth".

In conclusion, Williamstown was an opening and it is interesting that the program was aiming beyond scientific and technical objectives. It reveals a confidence in facing the challenge confronting scientists and humanity. This meeting was definitely a change of vision. The rationale was simple; there was enough scientific expertise to new possible applications of Earth and Ocean Physics. One of the major new outputs was the emergence of the radar altimetry as a new type of measurement and of a clear objective. It made a major contribution to understanding the Earth and its environment.

3. THE PREPARATORY PHASE 1970–1980

The flow chart described above provides a basis for the implementation of projects to be developed. The main difficulty is to maintain not only a high level of expertise in developing each component but also to maintain a high level of communication between the different teams. This requires a new way of involving scientists, and it is a major concern when the project is realized in an international cooperation in taking the existing cultural differences into account.

3.1 Observing systems and Pilot experiments

3.1.1 Laser upgrading

First laser returns obtained from BEB then from D1C and D1D gave the impetus to put laser corner cubes on other satellites BEC, GEOS A, GEOS B, GEOS C. In parallel, several countries started building their own laser stations and, after testing, were ready to participate. The success of "Standard Earth" led to further improvements using more accurate laser data. That implied co-ordination of laser stations and the use of a larger diversity of satellites. In 1970, there was no satellite with inclination lower than 40°.

Therefore the CNES proposed to use a test launch of a new version of the DIAMANT launcher to put in orbit a flight model of the EOLE Spacecraft equipped with corner cubes; this so-called PEOLE satellite had an orbital inclination of 15°. CNES proposed to take this opportunity to co-ordinate an international program dedicated to the laser ranging use (adding optical direction measurements from cameras), that is a large observation campaign from the whole laser network to track 8 satellites. This program called ISAGEX, which was managed by G. Brachet, was quite successful. After 18 months, ISAGEX provided a unique new data set to undertake a new generation of gravity field models. (SE II and SE III at SAO, GEM series (Goddard Earth Model) at GSFC (Goddard Space, Flight Center) and GRIM series (GRgs/IMunich at Toulouse and Munich).

After ISAGEX, there were major improvements concerning the laser stations. They acquired the capabilities to make daylight measurements and to fire automatically at the satellites using an ephemeris, which could be improved locally. These developments were so promising that, in the 1970s, the idea came to have dedicated satellites fully optimized for laser tracking.

Two such satellites were launched:

- STARLETTE (CNES, 1975) in a low altitude orbit so as to be sensitive to gravity field and its temporal variations and even to the solid Earth and ocean tides,
- LAGEOS (NASA, 1976) in a very high altitude orbit to be as insensitive as possible to the gravity field and to the air drag effects, thus being a stable target to determine the Earth rotation motions and geocentric reference frames (i.e. in using the orbit of LAGEOS as a reference).

These two first dedicated satellites (followed later by similar satellites: STELLA (CNES), LAGEOS 2 (NASA and Italian Space Agency, ASI), AJISAI (Japan), ETALON (USSR), GFZ-1 (Germany)) were very useful, each having different but complementary characteristics. They all had a heavy weight in the gravity field solutions. As expected, LAGEOS was extremely useful in determining the polar motion and the rotation of the Earth. As expected, STARLETTE was also sensitive to the tidal potential and allowed researchers to determine the tidal potential parameters. Despite the limitations in coverage due to weather conditions and anisotropy of the laser network, the laser technique continued to be used and was upgraded again and again. One of the main interests of this kind of satellite is their lifetime: 1 million years for LAGEOS? 10000 years for STARLETTE? The Lifetime is an important factor for detecting and for determining long periodic perturbations. As an example, remember that the prime period of the nutation and associated tide is 18.6 years and the post-glacial rebound is of secular type. The latter is the main origin of the secular variation of the geodynamic flattening of the Earth.

Today, by using a spherical target, more homogeneous laser beams, and, most important, a new rapid and precise system of detection, it is possible to have laser echoes with only a few photons, thus providing a unique and proven accuracy. Moreover the laser observations are less sensitive to propagation delay errors due to the atmosphere than radioelectric measurements are therefore, the laser is used as a reference to calibrate the other systems and as a back up to continue to observe a spacecraft when it is no more transmitting, as happened to ERS 1 and GEOSAT FOLLOW ON.

Story of STARLETTE

STARLETTE is a success story, which illustrates how fast a decision was sometimes taken in the 70s and then how drastically the situation changed later.

There was a queue in the cafeteria of the CNES at Bretigny (1972). The queue was long enough to allow JC Husson, in charge of Earth and planetary programs, to inform us that a test of a new version of the Diamant Rocket was to be made but there was no payload and no money to do it.

The project to build a small satellite optimized for laser tracking came back in to our minds. At the end of the queue, we had the orbital parameters and first draft of the scientific mission. After lunch a telex was mailed to SAO (Smithsonian Astrophysical Observatory) in Cambridge (USA). Their reply was enthusiastically positive and wise, and came back the same day. The complete dossier was ready in a few weeks and approved in a few months. Indeed the feasibility was confirmed, especially the core built with no radioactive Uranium by a mechanical department of CEA (the French Nuclear Agency). STARLETTE, only equipped with laser corner cubes, was successfully launched in 1975. To the big surprise of engineers asking for formats of telemetry, no format and even no telemetry were foreseen. Their comments were that a satellite with no telemetry is not really a satellite but a piece of "debris". We may recognise that, after the successful launch, we had some concerns because we got no returns at all until we realized that we were tracking the third stage of the Diamant launcher.

STARLETTE was supposed to be both a perfect target for laser ranging and a perfect proof mass (physical realization of point M with mass m) and the laser observations were extensively performed and used as a core of gravity field improvements. STARLETTE has been tracked for more than 25 years now and will remain in the program for decades; it allowed us to determine perturbations like tidal potential over long periodic terms like those connected to the nutation.

The last bit of trouble concerned administration which has to take account of any objects put in orbit. The case was applied to STARLETTE and it was difficult to explain that it is a "passive" satellite but we expect to track it for decades if not centuries to study the "dynamics" of the Earth. STARLETTE is not alone, the sister satellite STELLA was launched as a passenger of SPOT3.

3.1.2 Other laser ranging applications: the Moon and time synchronisation

A new application of the laser ranging was its successful extension to the Moon. NASA put three panels of laser reflectors, on the landing sites of Apollo 11, 14 and 15. Two French panels were put on the Soviet vehicles Lunakhod. Today, only a few stations are able to get returns, but that is enough to measure the Earth-Moon distance with a one centimeter accuracy level. The lunar laser range root mean square deduced from a very precise trajectory is of about few centimeters for the last years (a result obtained at the JPL (Jet Propulsion Laboratory), the Côte d'Azur and the Paris Observatories). From these data, it is possible to determine the exact rate at which the Moon recedes from the Earth. This measurement is one of the ways to estimate the dissipation of energy within the Earth-Moon system. Several important results have been obtained concerning, for example, the properties of the Moon's rotation around itself, the Equivalence Principle, which was checked with a greater precision and the internal constitution of the Moon (Dickey *et al*. 1994, Samain *et al*. 1998).

Another application is the time synchronisation. The satellite laser ranging is also used to perform very accurate time synchronisation at intercontinental scales in combining ranges obtained by several stations from round trip measurements. It is necessary to determine the time differences of arrival of laser pulses emitted by the ground stations and detected by an optical sensor onboard a dedicated satellite. That was indeed realized by ESA on a geostationary telecommunication satellite (the Italian satellite SIRIO 2 with the LASSO package proposed by J. Gaignebet and M. Lefebvre in 1972 (Veillet *et al*. 1992) In the future, it could be possible to get this synchronisation with an accuracy of about a few tens of picoseconds (T2L2/PHARAO/ ACES experiment to be put onboard the International Space station in 2004).

Finally, note that new other applications from laser tracking emerge: the idea is to equip any launched bodies, including the stages of launchers put in orbit, with corner cubes allowing them to keep the orbital control of such objects in critical situations (CNES/ALOSI project).

3.1.3 Radio-frequency tracking modes: TRANSIT, ARGOS, PRARE

Three different modes have been realized with TRANSIT, EOLE, and ARGOS satellites:

– One way Doppler downlink mode: TRANSIT system.

The TRANSIT system was operational from 1970 until 2000. Although designed for navigation and military purposes, it was used for such civilian objectives as positioning. It was continuously upgraded so it was able to give, for the first time, independent values of polar motion and new international reference frames. This includes a lot of international or regional campaigns: EDOC, EROSDOC, WEDOC, RETDOC, MEDOC, ADOS, a dedicated campaign in the African continent… (proceedings on Doppler positioning at Austin 1979). The same system was used in support of the precise orbit determination of satellites equipped with radar altimeters, like GEOS 3 (1975), SEASAT (1978), then GEOSAT (1985).

– Double way range and range rate: EOLE and PRARE systems.

The two-way range and range-rate systems were used on the EOLE satellite. One of the objectives was to locate a fleet of balloons moving in the stratosphere. The signal emitted onboard went to a transponder put on the balloon and, after a change of frequency, went back to the satellite. The received signal was directly compared to the transmitted one and allowed the Doppler measurement. Several hundred balloons were successfully located from EOLE. It was so promising that, as early as 1968, an extension of this concept was proposed to be implemented on a satellite in high orbit. This so-called GEOLE project was studied in detail but finally not approved. A similar project named POPSAT was later proposed by Germany to ESA but also not approved. The studies confirmed the value of the concept that was used for the implementation of the German PRARE (Precise Range And Range Rate) tracking system, which was flown on ERS 1 and 2 satellites. The accuracy was as expected but the system requires a good signal-to-noise ratio, which means that antennas must be pointed at the ground stations; thus, the system is difficult to operate and can present some difficulties when installed in remote areas is required.

– One way Doppler and one way uplink mode: the ARGOS system.

The third operational system was ARGOS. It was designed at the urging of oceanographers wanting to measure the eddies on the surface of the ocean by using buoy motions. The EOLE system was too complicated and not adequate for completely unmanned and remote ground stations. Therefore, the design of ARGOS was to minimize the complexity of the ground stations. The tracking mode was a one way Doppler uplink transmitter from the buoy receiver to the satellite, which measures the Doppler effect. The time scale is unique and provided by the onboard clock. Data are collected onboard and retransmitted by telemetry to a main center. The system was operational as soon as 1978 and is still in use.

ARGOS: Biodiversity and New Users

A new class of users of ARGOS exists now: about 1700 animals of various species from whales to birds are permanently localized and their way of life recorded. Many lessons can be drawn from this new use of ARGOS: first the interest grows in a new scientific community to use new space systems. New ideas are proposed concerning biodiversity. Second, the biodiversity objective was considered in the beginning as being out of the specifications of ARGOS. It was wrong. Progress in small electronics allows us now to record permanently many biological parameters of animals and to transmit them later, thanks to ARGOS, alleviating the operational constraints.

There is no more need to educate the animals to stay on the surface when the satellite is passing over!

3.2 Altimetry emerging

Following the Williamstown's recommendations, a radar altimeter was placed in the space laboratory SKYLAB onboard a manned station (1973). It was switched-on by the astronauts and the first "around the world trip" was provided in real time. It demonstrated that there are bumps and hollows on the sea surface. The long wavelength features obtained in computing the geoid from the gravity field models were consistent with the amplitude of profiles. But at this time, it was amazing to see a lot of short wavelength details in whole coherence with tectonic features. This provided an extra impetus to get the decision for the launching of GEOS-3; the first satellite dedicated to satellite altimetry (the satellite orbits are not very sensitive to gravity features much shorter than the satellite height, but altimetry can see such scales on the sea surface).

However, the American Department of Defence (DOD) considered the altimetry as a very sensitive technique, and the overall experiment was classified. Indeed the altimetry provides deviations of the vertical as by-products, which can be useful for precisely launching rockets from the sea; at this time, these deviations were essential for cruise missiles as a part of the error in the initial conditions. Note that GEOS-3 had no onboard recorder, so the acquisition of telemetry was only possible in direct view of stations, what created large gaps. The orbit was computed from laser ranges and one-way downlink Doppler measurements, using a tracking network (the same network as used for TRANSIT). The accuracy of the orbit for the radial component was about 2 meters. Nevertheless, GEOS-3 was very useful. Indeed finally, there was some large release of data in delayed mode. These data were extensively used and a special issue of the Journal of Geophysical Research was published (Vol. 84, B8, July, 30, 1979). In the Kerguelen islands area, it was even possible to compute a marine geoid and to evidence strong correletations between significant oceans features and the sea-floor topography (Balmino *et al*. 1979). The second issue was the reaction of the scientific community frustrated to have been pulled out without any advertising. That triggers a renewal of interest and watching among the scientists.

GEOS-3 also triggered interest from the space agencies and centers. The JPL decided to prove definitively the potential of space for oceanography. What JPL did for other planets could not be a problem for the Earth, and it became SEASAT (a dedicated satellite for oceanography) with altimeter, scatterometer (to measure wind), SAR and passive radiometer. When the launch of SEASAT was certain, scientists undertook some preparatory actions without awaiting final official policy. Let us give an example: at the European level some high level scientists met at an informal meeting in London in July 1977 and wrote together an unsolicited proposal from their group, they named SURGE "SEASAT User Research Group in Europe". Their chairman P. Gudmandsen put the proposal on the desks of ESA and NASA. It was the right time to do it and it was very successful. At this time, ESA also took the decision to convene a workshop with European scientists, the main purpose being to make recommendations for solid Earth missions. The main themes were supposed to be applications in geodynamics in the broad sense and navigation.

Based on the SURGE activity, oceanography was added to the objectives. The workshop was called SONG (Space Oceanography Navigation and Geodynamics), and it took place at Schloss Elmau (Germany) in January 1978; 100 attendees during a full week made clear recommendations.

The proposed first priorities were as follows (Figure 3):

– (Figure 3A) A solid Earth program to deal with gravity field and precise positioning (crustal dynamics features) with satellites such as POPSAT or GEOLE. These satellites were not approved, but other solutions replaced these projects (DORIS, PRARE, GPS for the positioning and STELLA, LAGEOS2, GFZ-1 for the study of the gravity field).
– (Figure 3B) A so-called surface studies program to deal with ocean and ice dynamics, with two main satellites; (ice, ocean satellite: ERS-1 and ERS-2 satellites) and geoid satellites (today the GOCE satellite).

The Figures 3A and B give in a synthetic view the priorities and the schedule written by the executive committee. The reader may recognize in the first line what will be the ERS satellite panel. Moreover, other applications were envisioned; for example, the direct local determination of the Earth radiation budget was proposed. Indeed the CACTUS accelerometer built by ONERA, France (Office National d'Etudes et de Recherches Aéronautiques et

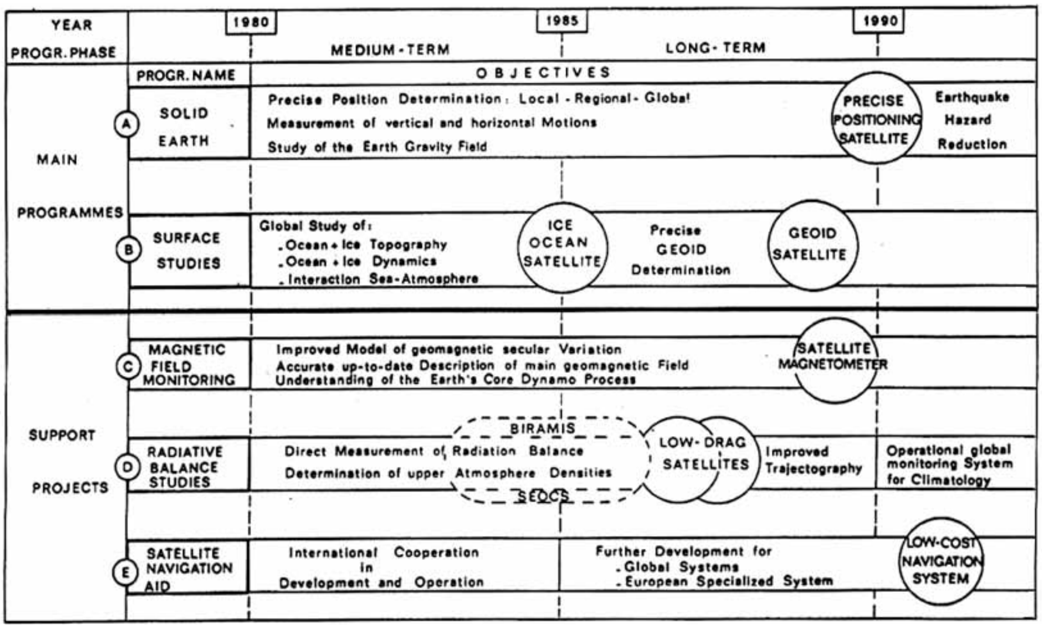

Figure 3 Chart of program proposal from the SONG workshop, Schloss Elmau, 16–31 January 1978. (From ESA-SP137 document, p33, 1978.)

spatiales) and launched by CNES in 1975 onboard the CASTOR satellite proved that such a system has the capability to measure many non-gravitational forces acting on a satellite. As a result, it can directly measure the local Earth radiation budget (the BIRAMIS project), as well as it can improve the upper atmosphere density models; it can also exhibit directly non-gravitational forces due to the Earth albedo (over ocean, land, and snow) and those due to the anisotropy of the satellite surface temperatures (it was the so-called thermal thrust effect or the photonic radiation thrust). However, the BIRAMIS project was not approved, but it was at the origin of many developments very crucial to geodesy; moreover, the Czech space project MIMOSA with the MACEK accelerometer onboard should be a very good opportunity to validate these interesting possibilities in the years to come (Sehnal 1994). Let us recall that ONERA micro-accelerometers will be used in the three gravity missions: CHAMP in 2000, GRACE in 2001, and GOCE in 2005. It will also used in the CNES/MICROSCOPE mission in 2004 to test the Equivalent Principle at the level of 10^{-15}. This illustrates very well the importance of developing new technologies a very long time in advance. It is of importance to recall that the non-gravitational forces are very probably today the limiting factor in the precise orbit determination of oceanographic satellites like TOPEX/Poseidon or JASON-1. New applications of accelerometry could be very usefully considered in the future.

SEASAT was launched in July 1978; the payload had all the major instruments for measuring the oceans from space. SEASAT had a short lifetime due to a satellite technical failure. In spite of this short lifetime and maybe thanks to that, SEASAT was really a starter. With only 3 months of data, a lot of investigations were successfully performed in many areas. The meeting "Ocean from Space" organized in Venice (1980), provided an opportunity to appreciate the results, and even the more sceptical attendees were convinced. So, for altimetry, the demonstration was convincing. The only missing component was the very precise orbit. SEASAT was put on a 3 days repeat orbit during 1 month: 9 collinear tracks were available and appeared to be extremely useful for learning a lot of things about the cross-over technique and about mean sea surface features.

4. THIRD PHASE MATURITY AND DECISIONS 1980–1990

4.1 Time and frequencies

Extremely accurate time measurements are essential components of any space system involved in practical operational missions as well as in scientific research. Consequently a continuous effort has been made to improve the basic time technology and to transfer the improvements from ground to satellite systems.

This temporal accuracy is required not only for individual measurements but also throughout the duration of the mission at any time when observations are made. Moreover the time scale used has to be linked with the same accuracy to the international standard time scale, the TAI (International Atomic Time). The TAI is presently maintained at the "Bureau International des Poids et Mesures" (BIPM at Sèvres, France). There is also a need to know the position of the rotating Earth as a function of time (UT1 or the Universal Time1). These quantities are provided by international services, as the difference between UT1 and TAI. There was always a continuity and a partnership between the time and frequency laboratories and the various users and contributors. Global time synchronisation, which has been a nightmare in the past, is today easily achieved at a level of accuracy which satisfies most users, by employing space technologies. However, the constant progress in the atomic frequency standard requires further efforts to improve time comparisons. The frequency stability of oscillators is also a major requirement. All progress in space metrology (laser, radio tracking, and altimetry) is due to the progress in the time-frequency field (see Figure 4). The permanent dialogue between people developing new technologies and space project teams has also been very fruitful. As a last example, the time and frequency advances provided the basis for the successful GPS design (Global Positioning System).

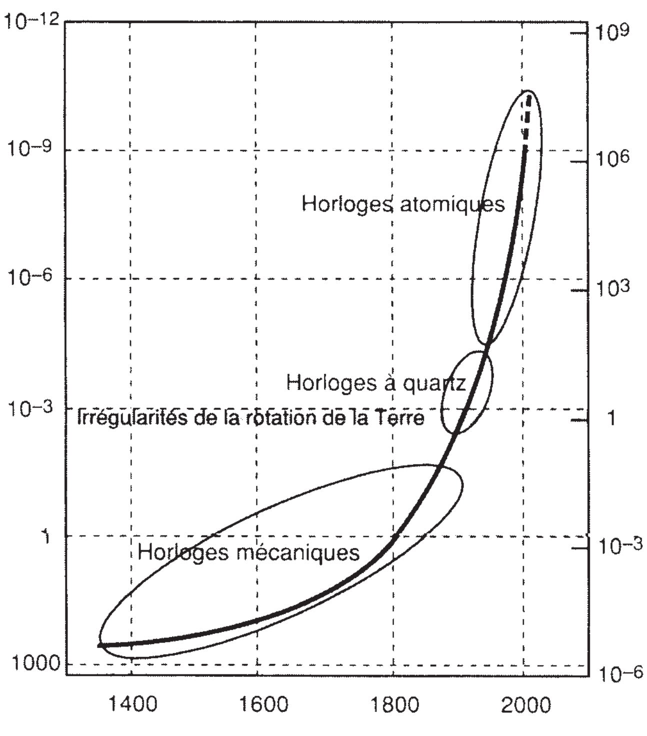

Figure 4 The y-axis gives the daily drift of clocks measured in seconds of time. The ordinate on the right gives the required number of years to obtain a drift of 1 second. On the (abscissa axis) x-axis the date is expressed in thousands years.

Note: Improvements in the mechanical clock, quartz clock and atomic clock in thousand years. A horizontal line gives the Comparison with the rotation of the Earth considered as a clock. (From "Les fondements de la mesure du temps" by Claude Audouin and Bernard Guinot, Masson, Paris, 1998, p. 47.)

4.2 Earth rotation

The way in which the Earth rotates depends on the way in which the Earth is constituted; core, mantle, crust, ocean and atmosphere are the basic constituents, the behavior of which allow us to interpret variations in Earth rotation. The progress concerning the determination of the Earth orientation parameter is illustrated in Figure 5, in which the results obtained in the beginning of the seventies by astrometric techniques can be compared 20 years later with new results obtained by using space based techniques. No erratic behavior is exhibited on the curve at the bottom of the figure. At the present time, the errors are of the order of a few

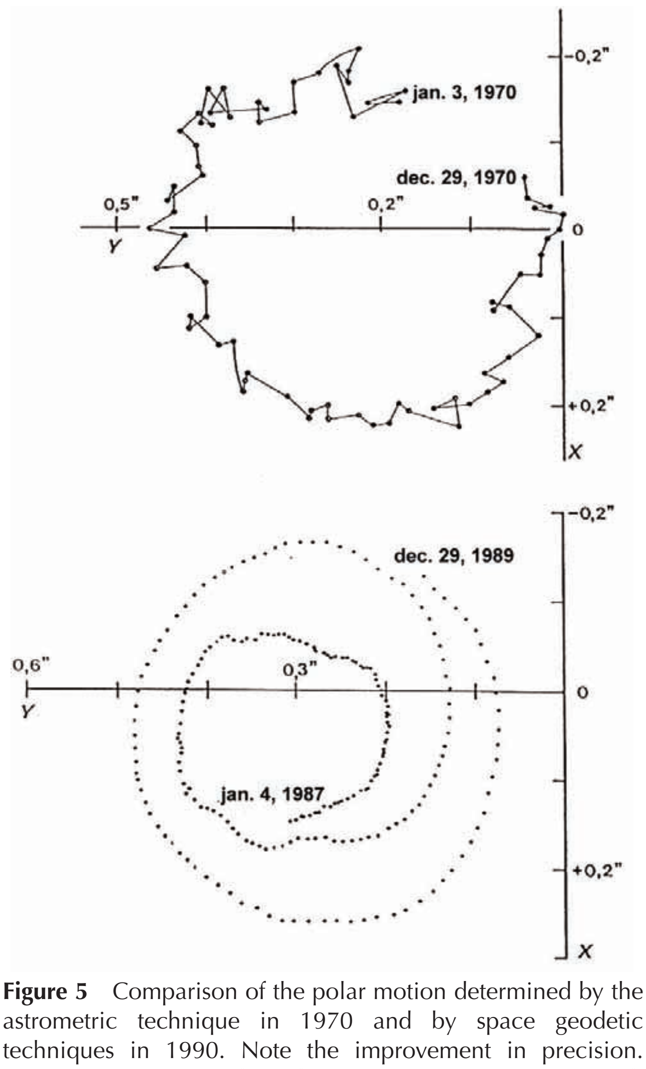

Figure 5 Comparison of the polar motion determined by the astrometric technique in 1970 and by space geodetic techniques in 1990. Note the improvement in precision. From the International Earth Rotation Service. (M. Feissel, Observatoire de Paris, 1990.)

tenths of milliarc second (less than 1 cm on the Earth crust). Anderle, in the U.S.A., formulated the first determination of polar motion in 1969, and then others in different countries undertook similar studies. The "Bureau International de l'Heure" (BIH) at the Paris Observatory started incorporating space geodesy results in 1974 for the determination of polar from motion, then UT1. The contributions of classical optical astrometry progressively decreased and was completely abandoned by the BIH in 1984.

Nowadays, the study of the Earth's rotation is based on GPS, SLR, VLBI and DORIS data. But the VLBI technique (Very Long Base Interferometry) has a specific role. It has no competitor for determining the direction of the rotation axis of the Earth in a celestial reference frame (quasi-inertial system defined by about 600 celestial radio-sources) and for linking terrestrial and celestial reference frames. This capability allows it to determine the length of day over long periods of time (a function equivalent to the determination by UT-1). VLBI is a fundamental and irreplaceable technique in the metrology of space.

4.3 The Earth gravity field status

It was important to better determine the zonal and tesseral harmonic coefficients in the Earth gravity field models, and regularly improved solutions were presented at the COSPAR meetings starting in the 60s. We have to keep in mind (cf. 2.5.1) that the first specific and historical civilian, effort was performed at the Smithsonian Astrophysical Observatory to arrive at a global solution, including determinations of the parameters in the gravity field model and the position of the observing stations, the so-called Standard Earth.

The basic principles of a dynamic solution were established during these first years of space geodesy and are still used today. In parallel to the pure dynamical solution, mixed methods using geometric constraints were developed. Then pure gravimetric methods were improved and finally also the mixed gravimetric, geometric and dynamic methods considered.

It is impossible to be exhaustive in this field but this period corresponds to a huge and fruitful international effort in America, in USSR, in Europe, in Japan, etc.… In conclusion, it is clear that between October 4, 1957 and at the end of the sixties a big advance took place in this field, which has continued to progress for 30 years and yet is not finished. For the first period, references can be found in the Space Science Review (Kovalevsky and Barlier 1967).

Today, the principles used in the early times to mix data of various origins (orbit analysis, gravimetric data and geometric measurements) together with statistical constraints (Kaula's rule of thumb) continue to be used; new data types are now added and the models have become more and more sophisticated, coming to include relativistic corrections and non-gravitational forces modeling. The determination of the gravity field by means of an orbital perturbations analysis is still in progress, due to the increased accuracy and coverage of tracking systems. The availability of a larger diversity of satellites being tracked by these systems is also an important factor; laser range measurements on STARLETTE, STELLA, LAGEOS, LAGEOS 2, Doppler measurements on GEOSAT, SEASAT and large sets of Doris data coming from the tracking of SPOT 2 and 3 are basic and crucial data. The geoid, such as it is determined from these gravity field models, is shown in Figure 6. Nevertheless, the upper limits of this approach is well known from the early beginning. A very high space resolution in the gravity field determination cannot be obtained only by orbital analyses. Therefore many projects have been studied at length both from a theoretical point of view and to take advantage of the new technologies.

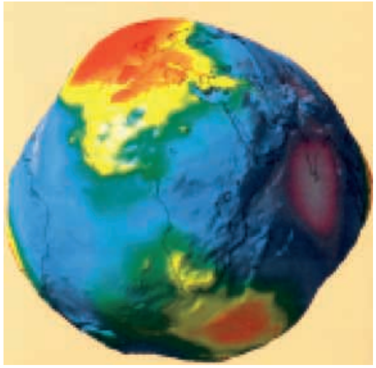

Figure 6 The geoid.

Note: The geoid of the Earth look like a "patatoid". The variations of the geoid are given by colours and are in the range of about a hundred meters.

Avocado? "patatoid"

Who built that? When NASA released the GEOID corresponding to one of the GEM (Gravity Earth Models) of GSFC the sketch had exaggerated bumps and troughs. During the press conference it was that this Earth said appears as a non-fresh avocado or like a kind of potato, a "patatoid". This new nickname was used and popularized. Obviously, there was a reply in a newspaper an unhappy citizen "I am paying enough taxes to have a decent Earth. What NASA will plan to rectify it?"

The two main approaches and techniques are:

(i) Satellite to Satellite Tracking (SST Technique) in two possible modes:
   - the High–Low mode, where the low altitude satellite is sensitive to the small scale gravity anomalies and is tracked by a high altitude satellite,
   - The Low–Low mode, where two low altitude co-orbiting satellites measure their relative velocity or/and distance.

(ii) Gradiometry

Here the measurements are determined directly from the second derivatives of the gravitational potential in spacecraft axes; the technique is not only a challenge for the main instrument (a gradiometer) but imposes constraints on the satellite: it must be drag free, have attitude control contain orbit maintenance subsystems etc. But it is agreed that the scientific community accept the risk and promote advanced technologies. The proposing teams were never discouraged and thereforce improved their projects again and again for almost 20 years in Europe. The first GRADIO project was born in 1981 in France and at the same time, the GRM/SST gravity project was initiated in the U.S.A. They were in competition with TOPEX/Poseidon, which only measures the variations of ocean circulation, whereas one also needs the mean absolute geoid. As a matter of fact, the scientific output for geophysics was convincing enough per se, but it was not perceived as such by the decision-makers, and these first gravity field projects were not approved.

4.4 Altimetry

GEOSAT was launched by the US Navy in 1985 and its useful lifetime was 4 years. In a 2-year "classified" part of the mission, GEOSAT was put on a geodetic orbit with a dense grid. The corresponding data were classified until ERS 1 was put in a geodetic orbit as well, after which its data were released thank to the efforts of a few determined US Navy and NOAA oceanographers. GEOSAT was then placed in an exactly repeating "declassified" orbit. GEOSAT, although not fully optimized, had a major impact. In fact thanks to the active and efficient help of NOAA (Laboratory for Space Altimetry (R. Cheney)), a growing number of people and laboratories learned how to play with the data and in return to provid new insights.

One of the major was the initiation of operational activities including some consequences quasi real time pilot experiments. The repeat track of 17 days appeared to be a good compromise. More and more geophysicists realized that this was indeed a complete new system to study the ocean tectonics, and they analyzed altimetric profiles.

GEOSAT was transmitting a couple of coherent frequencies compatible with the TRANET network, allowing it to perform Doppler measurements. But tracking data were released with some reluctance. When they became available, they were used firstly to compute a tuned gravity field and then a precise orbit. The precision of the radial component was claimed to be of about 30–40 centimeters, one of the limitations coming from the Doppler measurements of the TRANET network, which were not precise enough by comparison with new modern systems.

4.4.1 Scientific requirements: DORIS tracking system, radar altimeter

In the early 80s, it the time had come to make key decisions about the undertaking of ambitious projects to provide data that would have a decisive impact on the models of ocean circulation, and also a unique set of data for the geophysicists studying ocean tectonics. The requirements for altimetry as a system were based on scientific objectives in the geophysical and oceanographic fields. Thus, we need to look at the two sets of data we have access to. Indeed, the sea surface shape is the result of the superposition of the two sets:

(i) The geophysical data set reports on the distribution of densities inside the Earth. The long wavelengths of the sea surface are due to large-scale convection inside the mantle and are comparatively well understood nowadays. The medium and short wavelengths are related to bathymetry density contrasts as parts of the ocean tectonic on these scales.
(ii) The oceanographic data set.

Let us assume we know the marine geoid perfectly; the circulation of the ocean modifies the sea surface topography in several ways: sea level variations due directly to the warming, and more important, due to the tides, the atmosphere and the variations of the ocean circulation (upper part and deep part). This is a major point to be better studied. Like the other instruments used in remote sensing altimetry to measure parameters at the surface. But this surface measurement is an integral of the field of densities from bottom to the surface. Thus, it is a quantitative measurement to be used to adjust models. The spectrum of this ocean data varies from meso-scale features like eddies to large western boundary currents in relationships with the climate.

A few bits of information, such as the seasonal effect between the two hemispheres, have amplitudes of 10–15 centimeters. The tropical variations linked to the ENSO-EL NINO phenomena have amplitudes of 20–25 centimeters on the scale of 10 000 kilometers. To make some advances, it is necessary to determine these values with an error of 10% or less. If we want to give a specification to a system, we can use the following slogan:

One Centimeter for a Monthly Value on an Ocean Basin Scale

To achieve these objectives, we have to look at the corresponding requirements for the system components. A precise orbit is not too critical for observing the eddies; their high frequency signature can be recovered in adjusting polynomial coefficients. It is a critical issue for large-scale variations, the most important for climate studies. At the time that the decisions for the DORIS system were being taken there was no adequate tracking system. We recall in a summary table (Table 1) the characteristics of existing systems and try to investigate where the source of error occurred and how to try to overcome them.

The main uncertainty was due to unknown parts of the gravity field and especially to those generating high

Table 1 Mean errors on different measurements over the years, which played a role in the determination of the sea surface (CNES document, Paris 1999). For the clocks, the best accuracy, which it was possible to get at a given time, is also indicated in brackets

	Accuracy of measurement			
	1975	1985	1995	2000
Laser	1.50 m	30 cm	3 cm	1 cm
Doppler	5 cm/s	1 cm/s	0.03 cm/s	0.01 cm/s
Altimeter	20 cm	5 cm	2 cm	0.5 cm
Accelerometer	10^{-9} m/sec^2		10^{-10} m/sec^2	10^{-13} m/sec^2
Clocks	10^{-11}	10^{-12}	$3{\cdot}10^{-13}$	10^{-14}
	(10^{-12})	(10^{-13})	(10^{-14})	$(5{\cdot}10^{-16})$

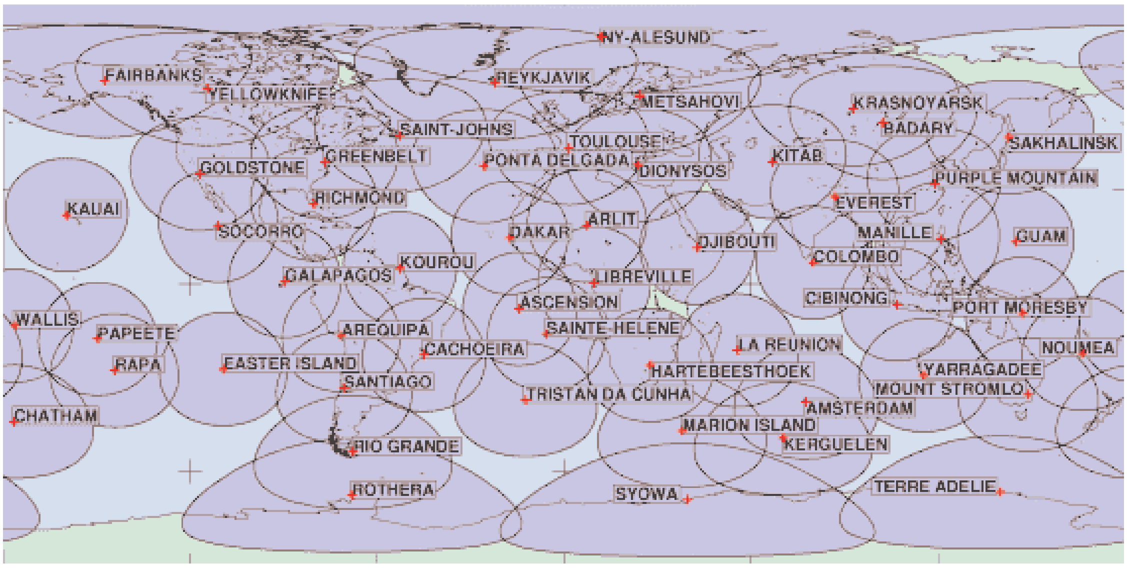

Figure 7 DORIS tracking network with its coverage for TOPEX/Poseidon satellite. (AVISO/CLS/CNES document.)

frequency perturbations, and to the unknowns coming from surface forces like air drag or solar radiation pressure, either direct or reflected. Both were had to be dealt with to increase sampling and accuracy.

Thus, it was decided to develop a new system taking the best points of previous systems and avoiding the worst ones: the DORIS system (Figure 7). It was based on a network of 50 tracking stations transmitting upward 2 frequencies driven by an USO (ultra stable oscillator) through a simple non-pointing antenna. The 2 frequencies are high enough and different enough to filter out the ionosphere effects. The transmitted frequencies are compared to the onboard receiver, also driven by an USO. The difference between then makes the Doppler measurements possible. The system operates in a one way up-link mode. The critical point is the stability of the USO frequencies. Research and technology were able to provide this new generation equipment even for remote sites. The short-term stability of the USO was 10^{-12} over 1000 seconds. The expected accuracy of the radial velocity measurement was about 0.5 mm/s. All the observations were dated in the time scale of the onboard clock, which was then compared with the TAI.

The design allowed ground stations to be almost fully automated and easy to install. The 50 stations were placed in well-distributed sites around the world and even in remote sites. More specifically, a well-balanced distribution between the 2 hemispheres has been achieved as well as extra coverage over stations oceans using island. This yields an orbital coverage of around 80% depending on the orbit height.

In the DORIS proposal, the ultimate accuracy was quoted as 5 cm for the radial orbital component. This value came from expertise acquired during several years of orbital analysis in Doppler tracking programs (MEDOC, GEOSAT

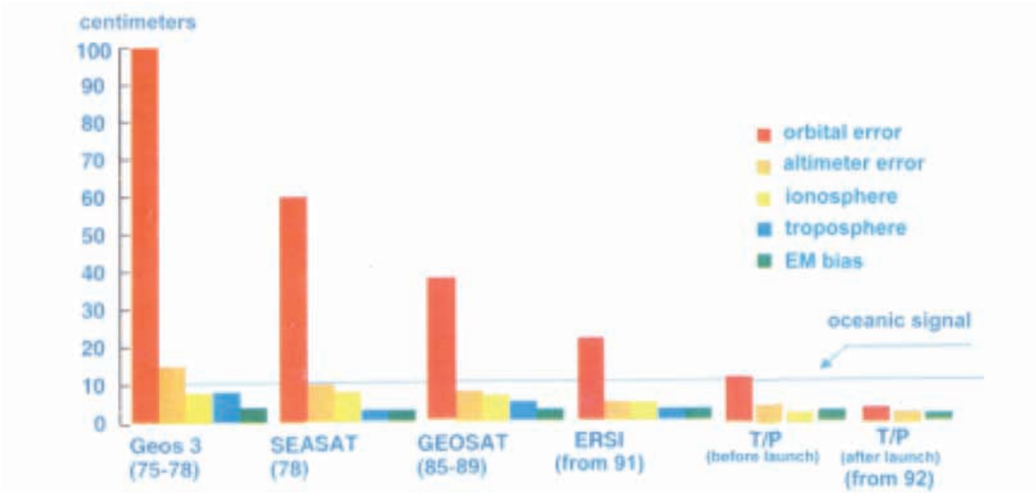

Figure 8 Shows progress in the orbit determination of oceanographic altimetry. Orbital error, altimeter error, ionospheric error, troposheric error and electromagnetic bias of the altimeter are given by the colours ranging from red to blue, respectively. The blue line in the figure gives the amplitude of the oceanic signal to be detected. For TOPEX/Poseidon the status is given for the beginning of the mission and for the present. (GRGS/CNES document.)

and SEASAT). In these earlier projects Twenty stations were involved with a measurement precision of 7 mm/s. DORIS was based on fifty stations with a measurement precision of 0.5 mm/s. Today the accuracy of the radial orbital component is about 2 centimeters. The DORIS system was specified and designed for rapid, precise and automated orbit determination and navigation. It will be improved for the next missions. DORIS will play a major and irreplaceable role in space oceanography missions in the years to come (with JASON-1 and ENVISAT), which will also benefit greatly from laser tracking. Progress in orbit determination for altimetric satellites is shown in Figure 8.

The radar altimeter instrument measures the height range at nadir between the center of mass of the satellite and the center of the reflecting spot on the sea surface. Corrections are of three kinds, instrumental (e.g., drifts, center of mass), path delays (e.g., ionosphere, drag and wet troposphere), and surface effects (sea-state bias). The path delay corrections are made as follows:

– for the ionosphere, by combining the Doppler measurements of two coherent frequencies 13 GHz and 400 MHz,
– for the atmosphere "dry part", by using the fields of atmospheric pressure and temperature given by the meteorological centers,
– for the atmosphere "water vapour content part", by using data from the radiometer.

The problems of sampling and of determining a precise geoid to detect the mean ocean circulation have now to be considered. A single altimetric satellite provides insufficient sampling in space and time to cover the whole variability of the spectrum. Two satellites provide a much more adequate coverage, even if rapid phenomena are still inadequately observed.

Ideally speaking, it would be better to determine the geoid separately. Such a practice requires dedicated missions (see the planned gravity missions, discussed in this paper). In ensuring that the satellite has a repeat track, we restrict our access to variations alone but they provide nevertheless crucial and basic information.

4.4.2 ERS 1 and 2

Two majors programs were recommended to ESA during the SONG workshop in 1978:

– a surface study program with two complementary projects: an "Ice and Ocean satellite" (1985) followed by a "geoid satellite" (1989),
– a precise positioning satellite (1990).

Unfortunately, they were unexpectedly rejected due to the scientific structure of the ESA. At that time, the study of the Earth was strictly under the responsibility of the applications directorate, but fortunately though, ESA was able to take decisions for other satellites devoted to related applications: ERS 1 and his twin brother ERS 2.

As part of the payload, there was a radar altimeter designed just for sea state-wave height measurements. But in the first design, the satellite was at low attitude, 650 kilometers, and had only a laser system as a precise tracking device. The proposed idea was to put the satellite in a three-day repeat orbit. However, step by step, actions were undertaken: the height was raised to 777 kilometers, the repeat orbit was planed to move to 35 days after a validation period, and Germany proposed a precise radio tracking system PRARE, doing double way range and range-rate measurements between satellite and ground pointing antennas. Our emphasis on this point is just to show that relatively minor modifications can greatly increase the scientific return of a mission (ESA proceedings, 1997).

4.4.3 TOPEX/Poseidon

Another decision was taken in 1987 by NASA and CNES to launch a fully dedicated satellite for satellite altimetry: TOPEX/Poseidon. NASA would build the satellite. CNES would launch it using an Ariane 42 P from Kourou (French Guyana) directly to the selected optimized orbit inclination of 65 degrees. The height of 1300 kilometers was chosen in order to avoid aliasing with solar tides, to decrease the air drag effect and the gravity field sensitivity, and to have a repeat period of 10 days. The payload was also shared:

– NASA took care of the 2 frequency radar altimeters, the microwave radiometer, the laser cubes and as an experiment, a GPS receiver,
– CNES took care of the fully dedicated tracking system DORIS, including the ground network of 50 stations, also providing, as an experiment, a new generation of radar and an altimeter using a solid state technology. This experimental altimeter was to use the new antenna for 10% of the time.

The expected lifetime was 3 years with a possible extension for two more years. The expected total error budget for the radial component was 13 centimeters, at least 3 times larger than the requirements. But there were some expectations that the main source of error was coming from the precision of the orbit and that this error could be later removed thanks to a better gravity field model and to better station positions. It proved to be true. TOPEX/Poseidon was decided mainly for scientific objectives and was supposed to be the starter for a long-range program. A Science Working Team (SWT), with all the selected Pi's (Principal Investigators) and project teams, was associated with the project to the end of the mission (in mid 2001 it is still operating). TOPEX/Poseidon was designed as the core for the program conceived as the WOCE (World Ocean Circulation Experiment) in 1988 at the International Oceanographic Conference at the UNESCO (Fu and Cazenave, 2001).

5. TIME OF RESULTS – TIME OF NEW DECISIONS 1990–2000

5.1 Some results – Scientific progress along the years

It is important to appreciate now how the space programs have totally changed and revolutionized our understanding of our planet (remember we are just looking at measurements of the metrologic type). There are several ways of gaining such an appreciation. We can first list some main results, along with a crude mechanism of comparison of what we knew before the space era and what we know today in terms of a series of progress that we can call gradients.

5.1.1 Gravity field

Before the space geodesy era, we had only an inaccurate idea of geodynamic flattening. Now, a complete determination of the gravity field with a space resolution up to 500 kilometers or even better has been made (Figure 9).

Recent models (from 1995) have been formulated at the Goddard Space Flight Center (GEM-T, JGM, EGM models), at Texas University (TEG models) and at GRGS (Toulouse, France) and GFZ (Potsdam, Germany) (GRIM Models).

5.1.2 Temporal variations of gravity field

This information was not accessible in the past. Now, accurate determinations of the C_{20} temporal variations (flattening of the Earth) with preliminary detection of variations of the first following terms (C_{30}, C_{40}, C_{50},) have been made. Seasonal and inter-annual variations of C_{20} are very important and are due to atmospheric and oceanic mass transports. They are not negligible in efforts to determine precise orbits. Secular variations of C_{20} are due to the post-glacial rebound and can be decorrelated from the 18.6 year tide thanks to very long terms analyses of LAGEOS and STARLETTE orbits over 18 and 15 years, respectively. Averaging techniques have been employed very usefully in this field for the orbital analyses.

5.1.3 Plate tectonic motions

No direct geodetic measurements were possible before the space geodesy era. Now, the horizontal and vertical motion of geodetic stations can be detected by using space based techniques along with tracking stations on all the different tectonic plates (Figure 10). The accuracy is around 1–2 millimeters/year. The big effort carried out by NASA to co-ordinate international capabilities in the Crustal Dynamics Program between 1980 and 2000 has to be emphasized (D. Smith) as well as the Wegener program in Europe (P. Wilson).

5.1.4 Center of mass of the Earth

The location of the Earth's center of mass was only known within several hundred meters before the space geodesy era. The position of the center of mass can be located now with an accuracy of a few millimeters; some temporal variations are significant (Figure 11).

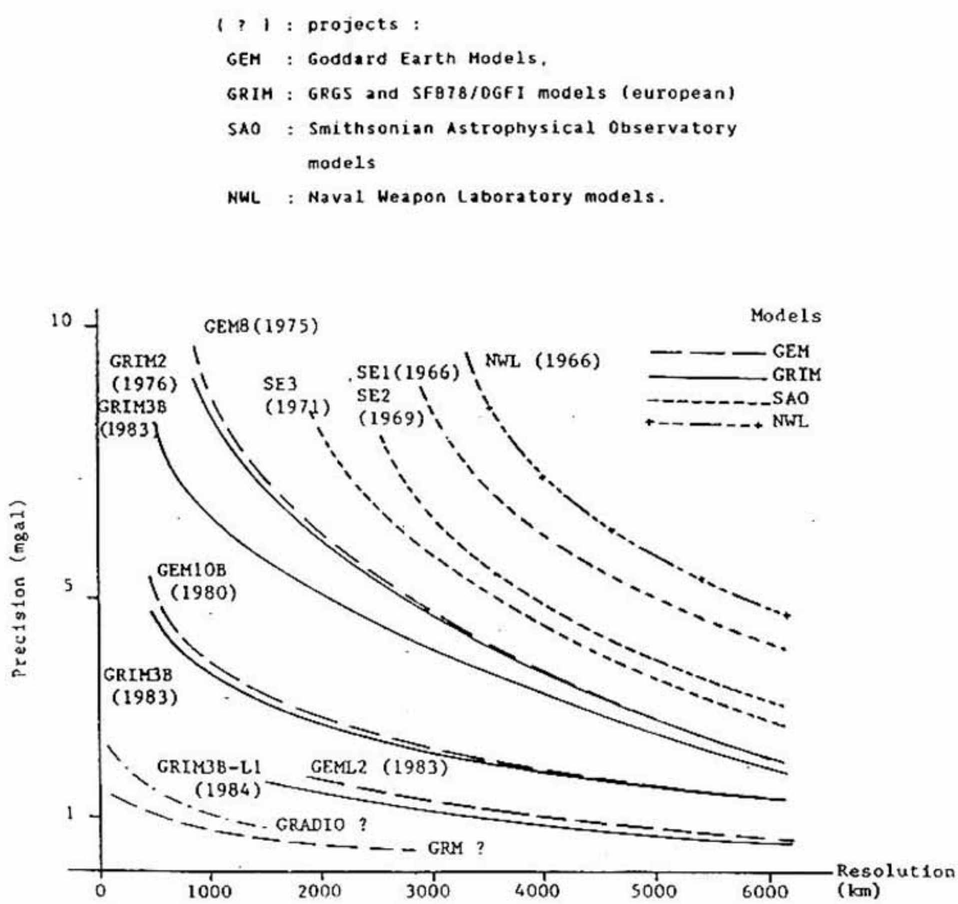

Figure 9 Precision of different gravity field models obtained from the space geodesy between 1965 and 1985, expressed in milligals as a function of the space resolution expressed in kilometers. This historical chart was constructed to gain approval for new missions.

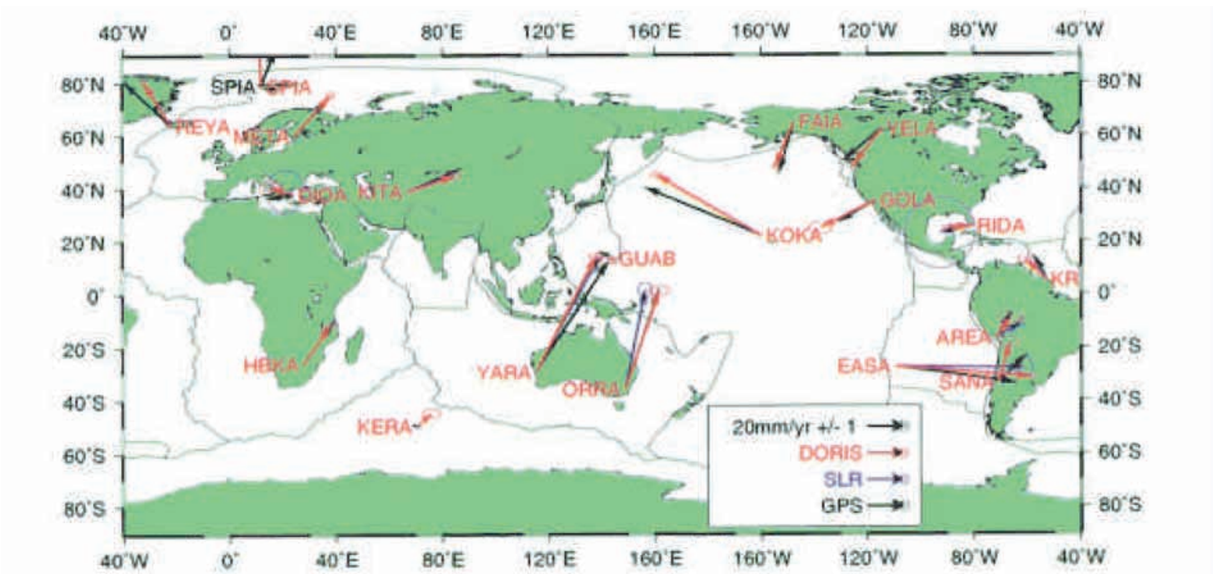

Figure 10 Velocities of plate tectonic motions deduced from three space geodetic techniques DORIS, SLR, GPS. (CNES/GRGS document, Toulouse, 1998.)

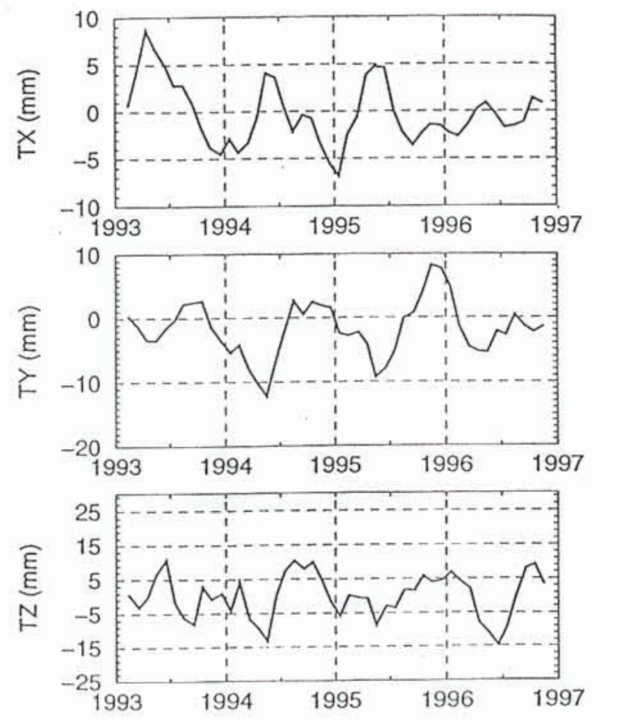

Figure 11 Temporal variations of the geocenter in a geodetic system defined by satellite laser ranging stations linked to the crust of the Earth. These variations are deduced from the LAGEOS Satellites. (From "l'étude des systèmes actuels et futurs de positionnement spatial DORIS" by Florence Bouillé, PhD-Université Paul Sabatier, Toulouse, 2000.)

5.1.5 Precise positioning

Within some continents, the relative precision of the positioning of geodetic stations was a little better than about 10^{-5} (10 meters over 1000 kilometers) before the space geodesy era.

Now, the terrestrial reference frames are coherent and controlled at the international level. Within these frames, the positions of individual stations are known with an accuracy of about one centimeter (Figure 12). The International Terrestrial Reference System (ITRS) has been developed at the "Bureau International de I' Heure" (Observatoire de Paris, B. Guinot, M. Feissel) in co-operation with the "Institut Géographique National" in France (C. Boucher and Z. Altamimi) in the 80s. The geodetic WGS 84 system was very closely linked to the ITRS from its beginning in 1984.

5.1.6 Earth rotation parameters

Before the space geodesy era, the determination of the Earth rotation parameters was based upon astronomical observations. They only permitted the detection of large-scale variations. Now, accurate determinations of the

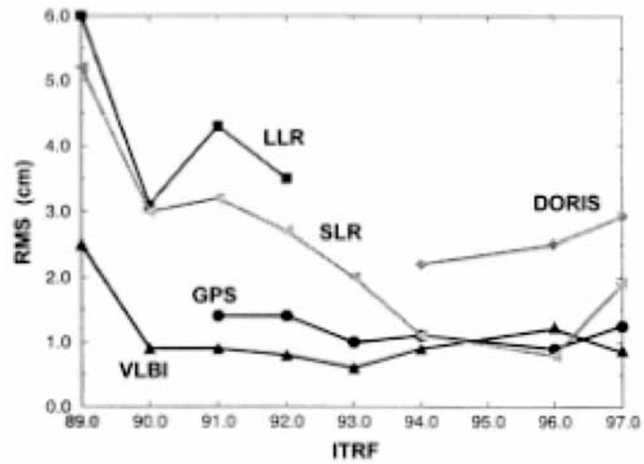

Figure 12 Precision of positioning by different space techniques over the years. (From the "modélisation des systèmes de références terrestres" by P. Sillard, PhD, Observatoire de Paris, 1999.)

Earth's rotation parameters can be made with a precision corresponding to errors less than 1 cm on the Earth's crust. Quantitative relationships between variations of speed of rotation and zonal variations of ocean and atmospheric mass displacements can also be determined.

It is the opportunity to emphasize the successful international effort performed in this field by the IERS under the co-ordination of the International Association of Geodesy (IAG) and the International Astronomical Union (IAU). Without such co-ordination, progress in space geodesy would have been impossible, nor would the progress accomplished in the various techniques have occurred (SLR, GPS, GLONASS, DORIS, VLBI), as they also require permanent co-ordination and dialogues. The progress much is shown in Figure 5.

5.1.7 Tides

Before the space geodesy era, a few long running series of tidal gauges and records existed but only involving a limited number of stations, as for example in Brest, France for more than 150 years. These records are performed along the coasts and yield the best estimate of the mean sea level that we can have for the last century. On the other hand, in the middle of oceans, no direct measurements could be performed except along the coasts of islands, and the modeling of the tides in the deep oceans was difficult. Now, the situation has drastically been improved with the availability of precise altimeter data. The improvement of hydrodynamic models is another factor for assimilating the altimeter data and for having now a very good model of the main tidal waves, with an accuracy of about 2 cm in many parts of the oceans. The tidal dissipation process and its location can also be precisely studied. The intercalibration between the altimetric systems and the tide gauge networks has to be undertaken on a continuous basis.

5.1.8 Ocean circulation

Before, there was a large set of descriptive knowledge about ocean circulation, but it was based upon discrete measurements. (Cruises of research vessels measuring accurate density profiles; these profiles were averaged in space and time, providing "climatic maps"). There was not a homogeneous accuracy on a planetary scale. TOGA and WOCE experiments were approved and set up to increase such worldwide coverage. Nowadays, the determination of the whole spectrum of sea surface topography has been completed thanks to altimetry. Models of the ocean circulation exist and first assimilation experiments of new space based data have been performed using these separate models. Nevertheless, the limitations of this approach have been well known from the early beginning of altimetry (for example the importance of knowing the geoid). Therefore many projects were studied at length both from a theoretical point of view and from a perspective established to take advantage of new technology (better and very precise

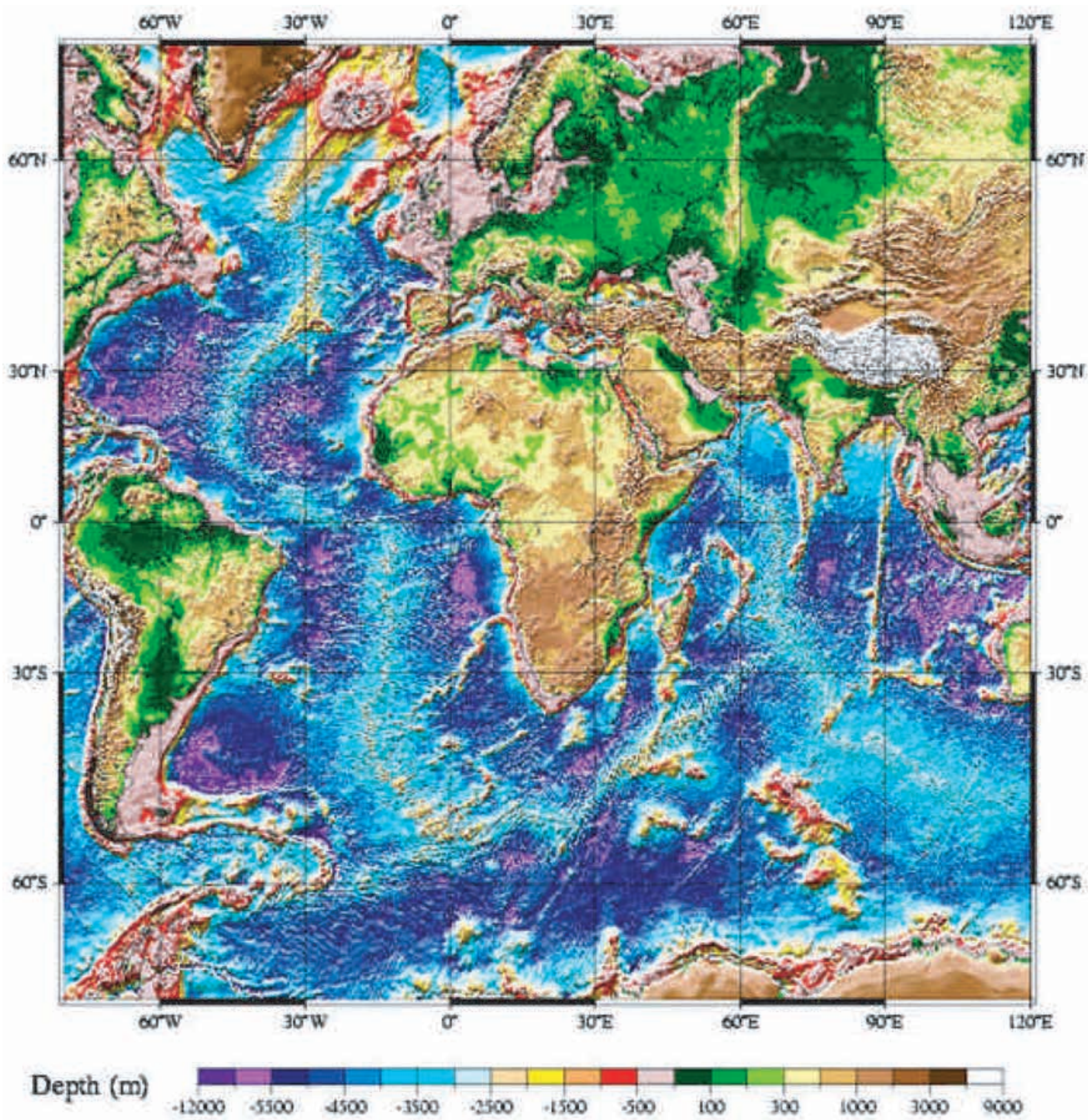

Figure 13.1 Global sea-floor topography in Africa, Atlantic ocean and Indian ocean zones from a least-squares inversion of altimetry-based high-resolution mean sea surface and shipboard soundings. (From S. Calmant, IRD, Noumea M. Bergé-Nguyen and A. Cazenave, LEGOS-GRGS/CNES, Toulouse, 2000.)

geoid, *in situ* measurements of various data in the deep oceans)

5.1.9 Sea-floor topography from satellite altimetry

New and original results have been obtained in research into the sea-floor topography. In the past, the determination of geoid was only possible on regional or local scales. Now, a global determination of the geoid can be computed from gravity field models with a space resolution of about 500 kilometers or a little better. These models, as explained above, combine much data of various origins including altimeter data.

Nevertheless, the long wavelengths of these models are well determined by space orbital data only and can be removed from the mean sea surface topography obtained from altimetric data. In the mean sea surface topography, the variable part of the oceanic signal (tide, oceanic circulation on different scales, atmospheric effects) can be removed directly when known, then the remaining variable part can be eliminated by averaging the sea surface topography over a certain period of time. Consequently, it is possible to determine a marine geoid. From this, it is then possible to inverse the problem of the geoid determination and to deduce the sea-floor topography generating the marine geoid. Much better results are obtained in combining bathymetric data obtained from shipboard soundings. Examples of accurate and high frequency sea floor topography for two large areas are given in the Figures 13.1 and 13.2. Dense altimetry data over the oceans from ERS1 data (geodetic

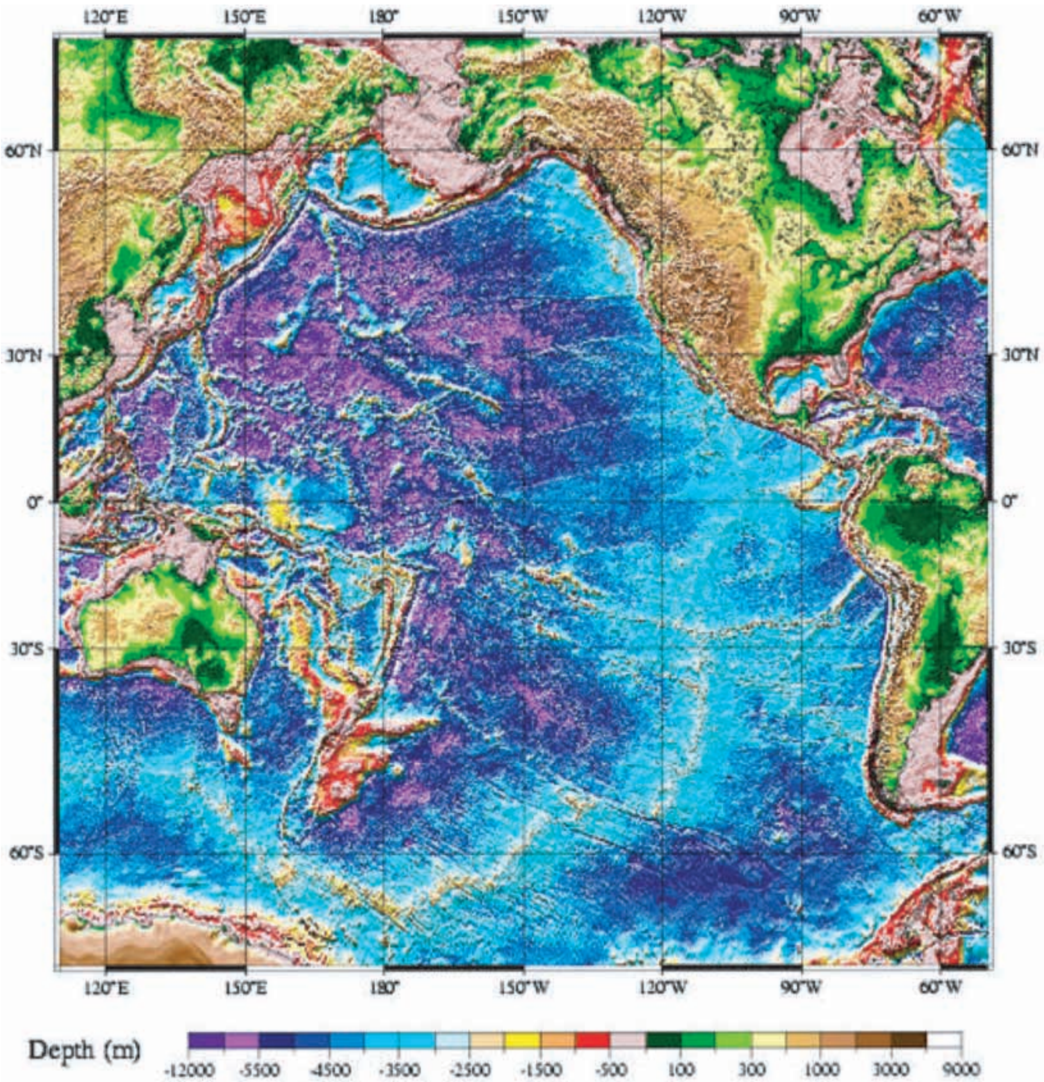

Figure 13.2 As in Figure 13.1 but for the Pacific area.

orbit of 168 days) were used to construct such images (CLS/ARGOS, Toulouse, Hernandez and Schaeffer 2000).

5.2 A Major turn: GPS, GLONASS, and GNSS/GALILEO

The DOD (Department Of Defense) initiated GPS (Figure 14) during the 70s in the USA. The US Navy had planned to replace their operating Navy Navigation Satellite System (NNSS) but had to join with the Army and the Air force to develop a common navigation system. This collaboration caused a few delays but augmented the capability of the system. The objective was clear: detection of any object, whatever its speed, in position in real time any where on the Earth.

To achieve this ambitious objective, the DOD decided to begin by setting up and maintaining a constellation of 24 satellites in high orbit (20,000 kilometers). Each satellite is equipped with atomic clocks and transmits downward 2 frequencies in the L-band (2 frequencies to filter the ionosphere effect). These two frequencies are coded: the first one by a Coarse Acquisition code (C/A) and the second one by a cryptic classified precise code (code-P). The idea was to make only the C/A code available for civilian uses. Some users (scientists being among them) were clever enough to perform precise positioning using differential methods and thus to eliminate the unknown part of the codes.

The DOD was worried about this fact and used other techniques to maintain the confidentiality of their system. But there was such pressure from non-military users that the US government took the decision to fully open the system to the public. The system, when used with highest quality receivers but not in real time, can provide positioning to an accuracy of one centimeter on even better. Progress in technology with miniaturized equipment made it easier. At this level, many applications are made and invented every week for the benefit of everybody. One of the most recent and spectacular uses is the decisive contribution to the discovery close to the coast of Egypt of two very old large cities (early 2000 B.C.). In this particular case, the essential role of GPS was to make possible the link between physical soundings and to establish precise geographical maps under the sea.

In science, the GPS outputs are obviously also very important. They concern the polar motion and the Earth rotation determined by the International Earth Rotation Service (IERS). They also include contributions to gravity missions (such as CHAMP, GRACE, and GOCE) and contributions to the International Terrestrial Reference Frame (ITRF) determination and to crust deformation studies.

It is important to draw attention to the fact that some other similar projects complement GPS, such as the existing Russian Global Navigation Satellite System (GLONASS), and that there are also new projects such as the

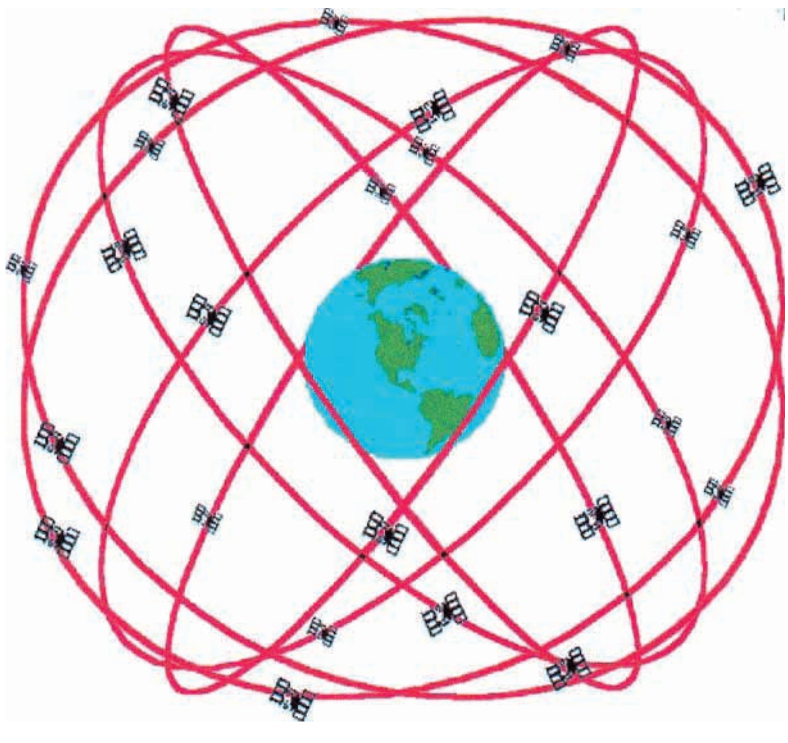

Figure 14 American GPS satellite constellation. There are 25 satellites orbiting at 20 200 km in 6 different orbital planes with an inclination of 55° with respect to the equator. (JPL document.)

GNSS/GALILEO system in Europe (Global Navigation Satellite System) for completing previous systems.

One of the potential customers will be international air-traffic control and also maritime and land navigation systems. Now, the scientists have the obligation to look carefully at the new coming systems and study whether they will have the same level of performance or not, a factor that can play a big role in the cost. As a result, scientists must have access to the data and be involved in the decisions. In other terms and based upon past experiments, one has to take care that, at this high level of metrology, one has the capability of controlling the systems by comparing them to other systems based on other techniques and by maintaining several teams working on them, so as not to have an isolated team of experts. This is especially important when faced with very large and superabundant sets of data in which too many parameters might be adjusted, such modifications hamper the detection of possible systematic errors. The international GPS service (IGS) plays an important role in these issues.

5.3 Gravity decisions

In the previous section, we were uncertain about decisions concerning the gravity missions. The ESA ARISTOTELES project was for a while the common candidate for this application nominated by both the European and the American geodesists, as discussed at the NASA workshop in Coolfont, USA (1989), but finally it was not approved. Fortunately, at the end of the decade 1990–2000, after many discussions and fights, three positive and very complementary decisions were taken:

– The first mission is CHAMP (CHAllenging Mini-satellite Payload), a German satellite successfully launched on July 16, 2000 in a polar orbit. The gravity mission is based on satellite-to-satellite tracking in the high-low mode, the high satellite being the satellites of the GPS constellation and the low satellite being the CHAMP satellite. This satellite was implemented by the GFZ (GeoForschungs Zentrum) Potsdam in Germany with some cooperation for providing science instruments by NASA (USA), CNES/ONERA (France), the Air Force Research Laboratories (USA).
– The second program is a joint project between NASA and the Deutsches Zentrum für Luft und Raumfahrt (DLR) led by the University of Texas and the GFZ potsdam. It is based on the low – low satellite to satellite tracking mode. The two low satellites will measure their relative velocity with an accuracy of 1 micrometer/second. In addition, the 2 low satellites will be tracked by GPS. GRACE was launched on March 16, 2002; the lifetime is expected to be of 3–5 years. It will provide the static part and the monthly temporal variations of the Earth gravity field (Figure 15.1).
– The third project GOCE (Gravity Field and Steady-State Ocean Circulation Explorer) is an European ESA project, the first mission of the new Earth Explorer program. It is the more ambitious of all and is based upon an accurate gradiometer put inside a satellite equipped with an air drag free system. It will be put in a very low orbit of 250 kilometers. Launched in mid 2004, this mission should provide unprecedented accuracy of 2.5 millimeters for the geoid and of 0.08 milligal for the gravity field, with expected resolutions of 100 to 50 km (Figure 15.2)

Marketing Advice from Users!

In many cases including Earth space projects, you are required to have strong interest from so-called users. Although it seems to make sense it is not always so simple, as shown in a few past examples. CNES in the 60s proposed to implement the tracking of a fleet of stratospheric balloons in a two-way range and range rate measurement system on a satellite. This system, named EOLE, was finally successfully launched in co-operation with NASA.

Oceanographers were asked to express their possible interest and none was displayed. Two years later a group of oceanographers came back and made a strong pleu "we want a second EOLE". In the mean time, it happened that a major discovery, had occurred: the eddy activity was not limited to the meandering of large currents. Eddies were everywhere and their total energy was as large as the energy of involved in the main currents. There was a happy ending, and the ARGOS system was designed to respond to the request of oceanographers. Operational in 1978, it has been operating without any break from this time on:

Another example comes from the late 60s, when a rather negative attitude for measuring the plate tectonic motions was generally held, as the Earth rotation could only be determined with poor precision.

Consequently, we proposed altimetry to argue for ocean circulation. The reply was even more negative. The typical value of the amplitude of large scale data was in the range 10 to 20 centimeters and any significant progress would request a precision of 10%, that means an accuracy of one to two centimeters. What does it mean? Just that people with vision have a main part to play in satellite geodesy, as it is in many scientific domains. All scientists must be open to discussion but ready to defend their opinion with a lot of energy, persuasiveness and patience! Above all, they have to welcome the expertise of users rather than asking them for their advices on requesting their support scientists have to offer users opportunities.

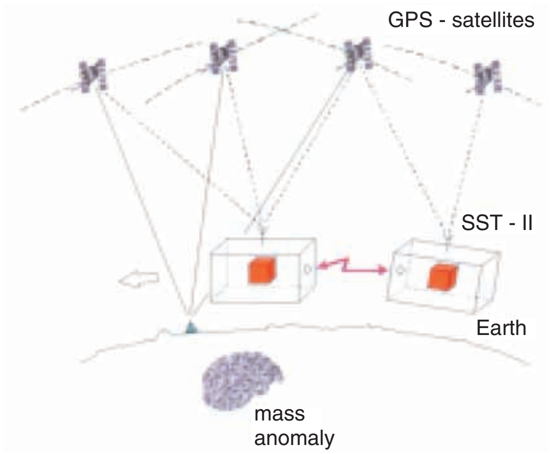

Figure 15.1 This mission will be realized in the USA by the GRACE Project with German co-operation. (From ESA-SP1233 (1) document, p. 20, 1999.)

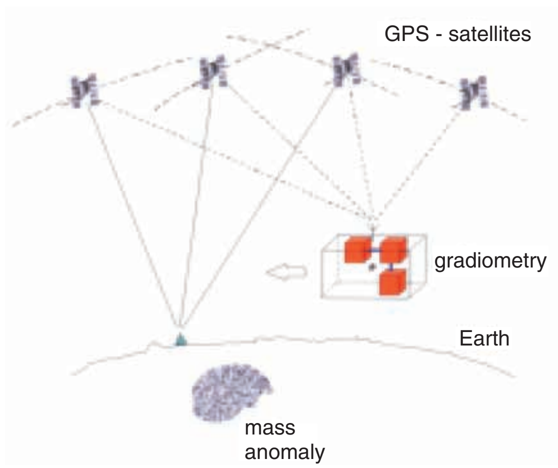

Figure 15.2 This mission will be realized in Europe by the ESA/GOCE satellite. (From ESA-SP1233 (1) document, p. 20, 1999.)

consequently, the decade 2000–2010 should be the decade of gravity.

One of the reasons for the positive decisions is the success of altimetric missions that obviously inspired further gravity missions. The GOCE mission will enhance altimeter results. The dialogue between oceanographers, geophysicists and geodesists has finally become fruitful. This dialogue originally involved altimetry programs, where the three fields of study are mixed together.

6. SUMMARY: SPACE SCIENCE AND EARTH

6.1 Metrology of the Earth

After almost 40 years, it is now possible to enhance the main features of this new geodesy with key words: global scale and sampling, observing system and system accuracy, redundancy, advanced technology, data management.

The first one is the access to the global scale. For the first time we can speak about the physics of the globe, and we are able to study the Earth on planetary scales. Regional studies are possible as well, but as part of global studies. However, the largest benefit from satellite missions is the unprecedented sampling capabilities both in space and time. The scientists must realize that they have some power, at least in the first phases of a project, to propose some sampling schemes. In some cases, it will be necessary to use a multi-satellite strategy to optimize the sampling.

Another specific feature is the observing system with its two parts: the onboard instrument and the ground network. The onboard instrumentation is the core component, which has the big advantage of using the same instruments throughout the mission, but such a practice requires calibration and a validation plan. The second component is a ground network, which is a prerequisite and has to be deployed all over the Earth providing data with an accuracy compatible with the onboard instruments. We have received from the analysis of existing data sets a better understanding of the type of observing systems we need; We need to infer the requirements for the observing system not only in terms of sampling but also in terms of accuracy. In fact, although very important, it is not easy to make assessment of the system accuracy. One of the methods used is to compare observations from satellites with *in situ* observations from calibration and validation sites to gain some insight into the observational errors but the real assessment has to be done on the global level. In fact, the next step is to use in the same scheme both ground based and satellite observations by assimilating them into the same model. The global sampling will give some hope to delineate systematic errors in the observing systems of inadequate modes resulting from the physics or in the assimilation methods. The final accuracy of a system will be the consequence of convergent independently gathered results.

Some redundancy on the metrological level is necessary. We need external checks using other systems of observations, other teams working independently with the same observations, or results coming from other disciplines. Ultimately, assessment can come later, when appropriate, by verifying the forcasting of specific events.

Speaking about the metrology of the Earth means there is a need to look carefully at new advances in technology and to investigate the possible benefit of medium or long range observing systems. Just to give a few significant examples:

– The triaxial microaccelerometer CACTUS onboard the CASTOR satellite (1975) drives currently the new generation of accelerometers used in the gravity space missions (CHAMP, GRACE, GOCE).
– The improved short-term stability of quartz oscillators was the basis of the DORIS system, baseline of a precise orbit for TOPEX/Poseidon, Jason1 and ENVISAT jointly with the laser technique.
– The progress in stability of the atomic clocks and the capability to put such devices onboard satellites is the basis of new navigation and positioning satellite systems such as GPS, GLONASS and GALILEO.
– The new device to detect very low levels of optical energy provides an impetus to the satellite laser ranging either in decreasing transmitted energy or in using very small array of reflectors onboard.

There are also major steps in computers, and other hardware and software to collect, distribute and archive the data. Data handling, management, formatting and access, along with time consumed in data processing were a big subject of discussion; it is a not only a domain where the techniques go fast. The real issue is or will be technical but also, it will be to find resources, mainly human means, and to watch the quality of the data including the feedback for reprocessing the data by taking observations from users and scientists into account.

Data exchange may be still difficult for political reasons but, sometimes, there is probably no way to prevent any scientists or users from acquiring a copy of a data set from a friend! An interesting point has to be noted. In the past, geodesy was in many countries more or less controlled by defense authorities, but any classification was circumvented very quickly; satellites ignore frontiers. The real problem is to archive the data, especially for future studies over very long periods of time. What will be left as data sets for our successors in 10, 20 or 50 years?

It is also necessary to take care to maintain a set of very long-term or even permanent well-equipped sites. These permanent sites, also called geodetic fundamental observatories, will be used as long-term references, or to construct images that act as anchors.

The outreach to the public is also very important and often occurs very quickly. We remember a time, when looking every hour at the occurrence and development of the oceanic phenomenon El Nino 97, we were very proud to see the images coming from TOPEX/Poseidon. We were happy to realize that in a few weeks the cumulative audience of people watching the event on TV channels would increase drastically, maybe to one billion around the world. But it remains an ethical problem especially in the sensitive areas like the rôle of oceans in possible climate changes.

6.2 Comments about scientific results

Before concluding, we want to clarify an important issue. Scientists often acknowledge the potential of satellite data but are reluctant to be fully committed to the space system and think that they have no way to change anything neither in design nor in data processing. They frequently think that future programs will be driven by the so-called applications without any focus on scientific objectives. We just want to give two examples here to highlight persistent scientific capabilities. Indeed, there are many examples where new results come out, although they were not a part of the original main objectives.

When we look at late 70s maps of the sea surface computed with GEOS 3 altimetric data, the input from geophysicists was rather minor. The first papers were considered as a curiosity. Ten years later we could personally remember an AGU session entirely devoted to ocean tectonics and altimetry. The chairman was obliged twice to change the session room to welcome an overcrowded audience of geophysicists. The marine geoid was thus considered as a prime objective interesting enough to convince ESA to move the ERS 1 satellite to a dedicated orbit allowing a grid of 8 kilometers at the equator and triggering the release of altimetric observations made by GEOSAT in the first part of its mission. This new set of data was the basis for computing the sea-surface topography used now as a reference. It was not a primary objective of the mission, but we can label that as one of its associated objectives (Figures 13.1 and 13.2). A message to the scientific community could be given: look at the design of a mission with enough vision to be able to discern such associated objectives so that minor modifications of design can provide a large scientific return.

As a second example, a recent major result was obtained from the study of the area of dissipation from the lunar tidal component on the Earth. The M2 tide (the role of other tides is smaller) provides an energy of about 3 Terawatts. The total amount of dissipation can be detected by a laser aimed at the Moon and the determination of the increase of the Earth–Moon distance by 3.8 centimeters per year and by the spin slow-down of the Earth or the increase of the length of day (about 2 ms per century). We have, with new space based techniques, more accurate determinations of the polar motion and the rotation of the Earth, making possible a tentative realistic scheme for the Earth-Moon system evolution. In the past, it was thought that most of this energy was dissipated in shallow seas or coastal zones.

However, in the 60s, best estimates from different authors were converging, claiming that the so dissipated energy is only 40 or 60% of the total energy and questions of how and where the remaining part was dissipated remained broadly open, and involved the possible role of the Earth's tides (Melchior 1973).

At the NASA Williamstown meeting (1969), this problem was also on the priority list of scientific questions, but no future program was expected to provide answers. Within the Science Working Team (SWT) of TOPEX/Poseidon, there was a subgroup in charge of the tidal model; the tidal model was considered as important and indeed was one of the drivers in the decision to put TOPEX/Poseidon in a non-heliosynchronous orbit; a prograde orbit with an inclination of 65 degrees was adopted.

Scientists started to develop new global tide models (see, e.g. Le Provost 2001). For most of the members of SWT, the tides were important enough to isolate tidal data, to have access to the filtered dynamical topography and to use it in models of ocean circulation. For example, Le Provost *et al*. (1994) set up a new global tide hydrodynamic model taking account of the new global map of bathymetry. Before any assimilation of altimetric measurements, it was clear from this model that, at least, a part of the dissipation occurs in the North Atlantic. However, Egbert and Ray (2000) went further in analyzing long term sequences (7 years) of the most accurate sets of TOPEX/Poseidon altimetric data. In addition to the well known areas, they found that dissipation also occurs in the areas of deep ocean. Consequently, they were able to construct a global map of the zones of dissipation. The proposed explanation is that the M2 tidal wave is reflected by tectonic ocean features, generating coherent energetic internal waves. The corresponding data is obtained from in the altimeter. As suggested in the past by Munk and Wunsch (1998), this tidal mixing provides the extra energy required to maintain circulation in the deep oceans (Wunsch 2000 and Kerr 2000). This result highlights the basic link between these questions and the exchanges of energy and momentum within the Earth-Moon system.

What we learn from this example is as follows: to get decisions, we need to have prime objectives that will be achieved if the baseline requirements are fulfilled. In addition, we should set associated (not secondary) objectives that may be more interesting but assume that we may be able to modify the specifications. In the example above (that we can call "tidal mixing"), it was possible to get a new result only because the system accuracy was 1–2 centimeters and the lifetime larger than specified. To provide a good image, we can use a sentence of Kerr (2000):

> Oceanographers needed a global tide gauge which they found in the TOPEX/Poseidon satellite.

To provide such a "tide gauge" it is essential to have scientists involved in all the phases of the project.

6.3 As a conclusion from "end-to-end" to "happy end"

Both of us started to work together in 1960 at the observatories of Paris and Meudon. At this time, we were sharing the first computer, the famous old IBM 650 called "the washing machine". One of us was involved in the determination of the Earth's rotation using the observation of stars with the Danjon astrolabe. The other one was already watching satellites and starting to study the density of the low atmosphere from visual observations.

40 years later, we recognize that we were lucky to have been involved in all the stages in this exciting period, when everything was new. The Earth as a living planet was the object of our research, an idea which was the dream of generations of geophysicists, geodesists, astronomers, and navigators.

We would like to share with the reader some major findings if not feelings. The major thing is the scale. Changing scale involves not just enlargement of each field. It produces global multi-disciplinary approach. We worked closely with teams from other fields, teams with new people and with expertise that they were anxious to share with others; this was really a new behavior. Until recently, each discipline of geosciences had enough interesting questions and observations for itself. But studying the Earth as a global planet makes progress only if scientists start a dialogue in depth.

The second finding is based upon the fact that space activity depends on projects having their own organization, schedule, rules, specifications, budget, and resources. In the beginning, it seems you have two different worlds and indeed, on the basis of efficiency, the relationships are organized through what we call interfaces.

We have experienced that real efficiency requires much more interactive relationships between the actors. The scientists have to know the technical constraints; project teams have to understand the impacts of decisions on scientific results. Such teamwork is even more crucial for data management. It is easier to ask the users about their requirements to build up a data processing system that will be stabilized after some period of validation. But the real success only comes if you have feedback, as for example, in reprocessing sets of data by taking account the findings of scientists which may require changes to the processing system. In the Earth sciences, it is necessary to understand the systems proposed for applications. In most cases, we have seen that the requirements in terms of sampling, continuity, mission parameters, data management are so close that differences are artificial. Again, the best is to have the active participation of scientists in the system.

Specific to Earth science is that a part of your system comes from the networks of *in situ* measurements and these ground networks are as important as the space instrumentation. The role of *in situ* is sometimes considered as one involving calibration of remote sensing. Such an idea is misleading; the different data have to be complementary and assimilated jointly in adequate models. Such a method is now favoured under the label of integrated programs.

In fact working together is the rule and requires scientific involvement in an "end-to-end" process. In our jargon, end-to-end means that one has to take care of all the tasks but that the links between the different tasks will be very important.

As a general conclusion, this contribution does not cover, by far, all the works made by the international community; but our goal was to testify through our limited experience that the improvement of scientific knowledge of the planet Earth is a reality, that a multi-disciplinary community exists and that a new way to associate the scientists is possible, necessary and efficient. New techniques, like the SAR interferometry, new themes like the ice cap dynamics, the extension of previous studies to planetary studies, are extremely promising and are in full development having produced with rewarding results. But we cannot present here all these new fields.

Let us borrow the words of our Australian colleague Neville Smith speaking for partnership in international programs: "You are a good player but nobody knows even you. Come and play with us and you will realize how good you are and how much we need you in the team. Play together and we will win and will have a lot of fun". We would like to finish with this remark: on our stage we play, we have a good casting, a good scenario called "The New Earth" but we have just to play at the same time, and so we will have a lot of fun and contribute to a "happy end for mankind". "We" means the geonauts.

We made some successful tests in proposing a new myth to express this feeling.

The GEONAUTS:

EARTH is a space station put successfully in orbit around the Sun 4.5 billions year ago. This station is manned and has welcomed 6 billion people; to emphasize our common venture we rename inhabitants of the Earth the GEONAUTS.

GE is EARTH, our ship; we are Nautes on it and navigate in the solar system (as Internautes are surfing on the web).

GEONAUTS are anxious to control the behavior of their Earth ship and to send around it automated and manned stations. This extra vehicular activity provides the requested observations to forecast their future.

6.4 As another conclusion: Plato

Research and applications from "The Republic" – Plato

EDUCATION OF THE PHILOSOPHER

RESEARCH AND APPLICATION, FOR.... MY OWN SATISFACTION?

…

And the third should be astronomy. Or don't you agree?

– Yes, I certainly agree. A degree of perception in telling the seasons, months and years, is useful not only to the farmer and sailor but equally to the soldier.

"You amuse me", I said, with your obvious fear that the public will disapprove if the subjects you prescribe don't seem useful. But it is in fact no easy matter, but very difficult for people to believe that there is a faculty in the mind of each of us, which these studies purify and rekindle after it has been ruined and blinded by other pursuits, though it is more worth preserving than any eye since it is the only organ by which we perceive the truth. Those who agree with us about this, we give your proposals unqualified approval, but those who are quite unaware of it will probably think you are talking nonsense, as they won't see what other benefit is to be expected from such studies. Make up your mind which party you are going to reason with-or will you ignore both and pursue the argument largely for your own satisfaction, though without grudging anyone else any profit he may get from it?

That's what I'll do, he replied; I'll go on with the discussion chiefly for my own satisfaction.

Acknowledgements

First of all, we are indebted to Prof. R. Rummel and Dr. G. Balmino; they were supposed to write this chapter and generously proposed that we should be substitutes in order to acknowledge our pioneering role. We were very sensitive to this and took this opportunity to give a personal account. We thank them very much for their advice and encouragement. We both were happy to provide our testimony on these 40 years, which was an exciting time. A testimony may contain some biases or misses. We take responsibility for them.

When 30 years ago we wrote a proposal after the Williamstown meeting, it was just a vision. We thought that after 30 years everything was going on except a dedicated mission to determine the gravity field of the planet Earth. But, fortunately, the decision to go ahead with GOCE was taken by ESA in 1999. We can testify that without the constant, competent and obstinate work over 20 years of our two friends and colleagues over 20 years, GOCE would be not here.

All that was undertaken in these fields was achieved in close co-operation with many colleagues during an exciting time. We can testify that the situation was stimulating, but also developed strong and friendly relationships. We would like to dedicate this article to our friend Dr. J.G. Marsh, who displayed a new spirit of cooperation. We want to thank again the numerous scientists and engineers with whom we worked, but also tell them that we deliberately chose to give a personal account rather than a compendium.

When accepting this task, we did not realize that the time was so short. Therefore we asked the DAG company in Toulouse (25, rue Saint Guilhem – http://www.dag.fr) at the last minute to help us. Without them and especially Lise Nobileau, Isabelle Labadiole and Emmanuel Ventura nothing would have been done. We shortened the possible delays thanks to the fact that DAG had organized several workshops for us and thus had acquired some basic knowledge of the subject.

Christiane Berger, Olivier Laurain, and Joëlle Nicolas from CERGA (Observatoire de la Côte d'Azur), Bernard Guinot, Philippe Gaspar, Raymond Zaharia, Victor Zlotnicki gave some extra help in reading and improving the text. We thank them very much. We are also indebted to the reviewers and to the editors for their help.

GENERAL REFERENCES

In space geodesy, looking at the number of symposia, books, reference papers over the first 40 years of this new field is amazing; several tens of thousand of references, hundreds of symposia, colloquia, many books… In the beginning, the leading rôle and enthusiasm were found in the USSR, USA, European countries, and Japan, but progressively most of the countries in the world became involved. Space geodesy has more and more applications in many fields including cartography, navigation, sea level research, etc.… So space geodesy has become an important field of research and application. All continents and many islands now have, permanent geodetic stations equipped with either a GPS, GLONASS receiver, or and a DORIS beacon, or several of these.

How to describe all this enthusiastic effort in the beginning and this acceleration in the use of all these techniques? To us, it quickly appeared that it was impossible to give all the references. Moreover, very often many works have been duplicated or parallelled by several authors and teams in different countries. No doubt historians will have great difficulty describing precisely all this evolution of such a young discipline. Therefore, we decided to illustrate only a part of it and to select arbitrarily a certain number of books, proceedings and symposia in which many names of the first scientists can be read as well as the names of the new generation. We do that with a great feeling of modesty and humility, knowing that so many names and so many things will be forgotten. In any event, space geodesy appears as a very enthusiastic worldwide success story.

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