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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 worldwide. 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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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 …).

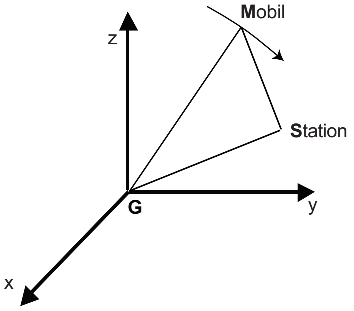

Figure 1 A simplified scheme for geodesy.

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

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