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The interdisciplinary role of space geodesy—Revisited

Reiner Rummel

Institute of Astronomical and Physical Geodesy (IAPG), Technische Universität München, Arcisstr. 21, 80290 München, Germany

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ABSTRACT

In 1988 the interdisciplinary role of space geodesy has been discussed by a prominent group of leaders in the fields of geodesy and geophysics at an international workshop in Erice (Mueller and Zerbini, 1989). The workshop may be viewed as the starting point of a new era of geodesy as a discipline of Earth sciences. Since then enormous progress has been made in geodesy in terms of satellite and sensor systems, observation techniques, data processing, modelling and interpretation. The establishment of a Global Geodetic Observing System (GGOS) which is currently underway is a milestone in this respect. Wegener served as an important role model for the definition of GGOS. In turn, Wegener will benefit from becoming a regional entity of GGOS.

What are the great challenges of the realisation of a 10^{-9} global integrated observing system? Geodesy is potentially able to provide – in the narrow sense of the words – "metric and weight" to global studies of geo-processes. It certainly can meet this expectation if a number of fundamental challenges, related to issues such as the international embedding of GGOS, the realisation of further satellite missions and some open scientific questions can be solved. Geodesy is measurement driven. This is an important asset when trying to study the Earth as a system. However its guideline must be: "What are the right and most important observables to deal with the open scientific questions?".

1. Historical introduction

Since about 150 years geodesy can be regarded as an independent discipline of science. Baeyer's memorandum about the size and figure of the Earth "Über die Größe und Figur der Erde" (1861) may be seen as a starting point, even though important geodetic work had been done before by famous scientists such as Newton, Laplace, Gauss, Bessel. But their work was not referred to as geodesy and they did not regard themselves as geodesists. Baeyer's initiative resulted in an extension and unification of existing triangulation and levelling networks covering central Europe. This work was then expanded to the whole of Europe, before its transition to an international effort with the aim to determine the global figure of the Earth. It was one of the first international projects in science and the root of what is today the International Association of Geodesy (IAG), cf. Torge (2001).

In 2007, 50 years of space age was celebrated. With the launch of Sputnik 1 on October 4, 1957 (and shortly after of Sputnik 2) modern space age began. Already these two satellites had a fundamental effect on geodesy. Almost instantaneously a large part of 100 years of diligent geodetic work dedicated to the determination of the figure of the Earth became out-dated. From measuring the precession of satellite orbits the Earth's flattening could be determined much more accurately than with classical astro-geodetic work, compare, e.g. King-Hele (1992). Satellites opened new horizons for geodesy and no other discipline is known to me that has benefited more profoundly from space techniques. Positioning, gravity field determination, Earth rotation monitoring and geodetic remote sensing can be done much more accurately, completely and efficiently from space. Geodesy became truly global and three dimensional. Oceans, a "terra incognita" of the classical times turned with satellites into an area of great geodetic activity. Classical geodetic techniques did not allow the accurate measurement of zenith angles, due to atmospheric refraction. From space the vertical dimension of the Earth's surface can be determined almost as accurately as the horizontal components. Progress of space geodesy was fast and had a great impact. Hand in hand with the rapid development of geodetic space techniques geosciences became more and more interested in geodetic work.

2. The Erice workshop about the interdisciplinary role of space geodesy

Twenty years ago some of the most outstanding geodesists, Earth scientists and physicists were invited to a workshop in Erice/Sicily. It dealt with the interdisciplinary role of space geodesy and was organized by Mueller and Zerbini (1989). At this workshop the role of space geodesy for Earth sciences was carefully analyzed and recommendations formulated for the future. The introductory

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E-mail address: rummel@bv.tum.de.

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chapter to the book written by W M Kaula is especially worthwhile to read. He discusses five selected fields of Earth science and the possible role of space geodetic techniques for them. The five fields are (1) Earth rotation and core-mantle interaction, (2) mantle convection, (3) regional tectonics and earthquakes, (4) ocean dynamics and (5) Venus-Earth differences. The workshop in Erice marks the beginning of the era of space geodesy as being a discipline of Earth sciences.

3. Developments of the recent past

In recent years the general emphasis of Earth sciences has moved towards Climate Change and Earth System Science. Awareness grew that we need a much better understanding of the Earth as a system, of solar radiation as its driving force, of the thermal back radiation and how it is affected by even tiny changes in chemical composition of the atmosphere, and last not least of the impact of man. One fundamental deficiency became particularly evident in the course of the preparation of the last report of the Intergovernmental Panel on Climate Change (Climate Change, 2007) and has been addressed in several articles in Science and Nature, see Hogan (2005) and the articles quoted there: There is a clear lack of observations (Hogan, 2005). Space geodesy is able to provide important new and unique data to Global Change research by measuring mass and energy transport processes in the Earth system. Ben Chao (2003) wrote: "After three decades and three orders of magnitude of advances, space geodesy is poised for prime time in observing the integrated mass transports that take place in the Earth system, from the high atmosphere to the deep interior of the core. As such space geodesy has become a new remote sensing tool, in monitoring climatic and geophysical changes with ever increasing sensitivity and resolution." One can claim that geodesy, by merging geometry, Earth rotation, gravity and geoid, is in a position to provide "metric and weight" to Earth system research. Before this background the establishment of the Global Geodetic Observing System (GGOS) is the right step at the right time. The underlying concept is simple and well described by the scheme shown in Fig. 1 and due to Rothacher (see Rummel et al., 2005; see also Plag and Pearlman, 2007).

GGOS will combine the three fundamental pillars of geodesy: the measurement of the shape of the Earth, Earth rotation and the Earth's gravity field and geoid. The objective is to realize this with a relative precision level of 10^{-9} in one unified Earth fixed reference system and to keep this system stable over decades. Where does such a demanding requirement come from? In geosciences one usually deals with estimates accurate to only a few percent. Global change parameters are small und their temporal changes are slow and even smaller. In general they cannot be observed directly but have to be derived from a combination of several measurement systems and models. In order to be able to analyze them as a global process they have to be scaled relative to the dimension of the Earth. Let us take an example. Sea level at an arbitrary tide gauge may vary by a few metres, due to tides and storm surges. Measurement of sea level change with a precision of a few mm requires therefore a relative precision of 10^{-3} at this particular station. Local sea level monitoring can be transformed into a global monitoring system by satellite systems such as altimetry and GPS. Only then a global process can be deduced from local tide gauge records. In order to achieve cm- or mm-precision with satellite systems globally, orbit determination and altimetric measurements have to be delivered with a relative precision of 1 ppb.

In order to meet the goals set for GGOS a series of rather fundamental geodetic problems have to be dealt with. The three pillars of geodesy, geometry, Earth rotation and gravity have to be expressed in one and the same Earth fixed reference system with millimetre precision and stability (of the frame) has to be guaranteed over decades. This requires the space as well as the ground segments to function as one homogeneous entity as if all observations were done in one observatory encompassing the Earth. Each observation contains a superposition of a variety of effects, related to ionosphere, atmosphere, oceans, ice shields and solid Earth. In order to employ them for Earth system research strategies have to be developed for their separation and quantification by analysing their spatial, temporal and spectral characteristics. Satellite measurements represent time series along their orbit. Via the Earth's rotation and the choice of the satellite orbit elements these time series are related to a spatial and temporal sampling of the Earth. The reconstruction of the temporal and spatial geophysical phe-

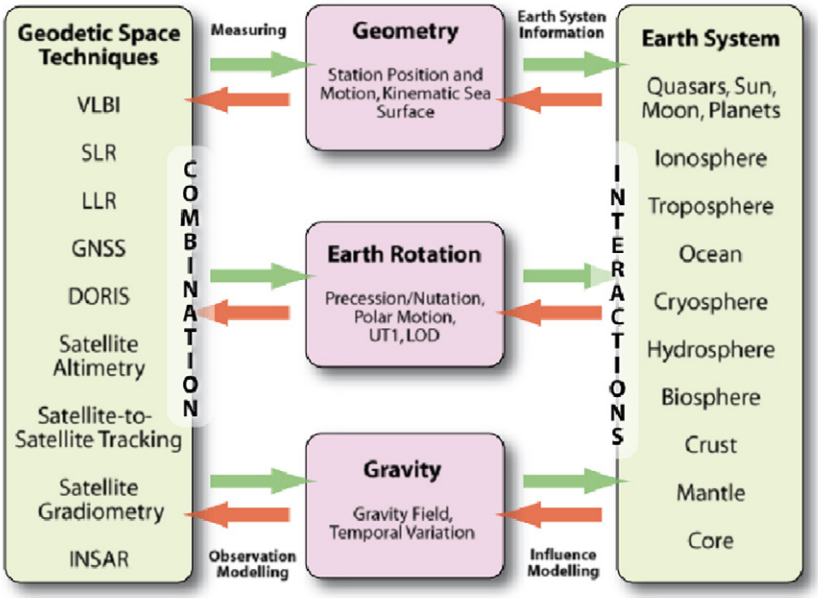

Fig. 1. Geodetic space techniques determine the shape of the Earth, Earth rotation and the Earth's gravity field and geoid. From these three geodetic entities a large variety of Earth system parameters are derived. In turn, any improvement of Earth parameters serves a better modelling of geometry, Earth rotation and gravity and a more accurate modelling of space geodetic measurements.

nomena poses a complicated problem of aliasing and inversion. The current investigations of the global water cycle or of the ice mass balance in Greenland and Antarctica from GRACE gravimetry are exactly problems of this type. The inclusion of terrestrial and airborne data, such as surface loading, ocean bottom pressure, tide gauges, gravimetry or altimetry may certainly help. However, this step is not easy either, because terrestrial measurements are affected by local influences and exhibit a spectral sensitivity quite different from that of satellite observations. Probably the most effective support to de-aliasing and separation of geophysical phenomena is the inclusion of prior information, such as models of solid Earth and ocean tides, atmosphere, oceans, ice, hydrology or glacial isostatic adjustment, however only if they are introduced consistently for all techniques of the observing system. Important work towards these goals is currently underway and we see geodetic techniques used much more widely in the various Earth disciplines.

Wegener developed over the years from an almost mono-disciplinary project to regional multi-disciplinary activity combining a large variety of geodetic and non-geodetic measurements techniques and involving all geo-disciplines relevant to its objectives. It is therefore an excellent example on how GGOS could operate on a global scale.

4. A look into the future

With an enormous pace space geodesy has made fantastic progress over the past 50 years. Do we have to fear this development to slow down in the near future? Let me try to look into the future.

Firstly, under what general boundary conditions will space geodesy have to operate in the years to come? Global Change activities are mostly organized on an intergovernmental level in international programs such as INSPIRE, IGOS or CEOS. GGOS must therefore strive to be integrated into such programs in order to attain the necessary impact and recognition. It is advisable that geodesy tries to activate its national governmental agencies towards this goal, in particular those agencies supporting already for years the geodetic scientific services under the umbrella of the International Association of Geodesy (IAG). Global Change is discussed nowadays in terms of so-called essential climate variables (ecv's). GGOS has to analyze in what way it can contribute to the determination and monitoring of the identified ecv's. To a large extent the major Earth oriented satellite programs of NASA and ESA are defined already for the next 5–10 years. If missions are missing which are essential for the progress of space geodesy, GGOS has to develop a strategy on how to get such missing elements approved by one of the space agencies.

What are the geodetic priorities and how can geodesy take advantage of non-geodetic space activities? Let me formulate a number of questions.

Several GNSSs will be available in parallel in the near future, the GPS, GLONASS, GALILEO, COMPASS and the associated augmentation systems. What can we gain from their combined use, what for example from their improved clocks? If one could establish inter-satellite ranging, one would get an orbiting precision polyhedron. What would we gain from such a constellation?

Let us assume geodesy would push for a third LAGEOS (e.g. counter rotating as proposed by Professor BERTOTTI a long time ago). Would it further strengthen our terrestrial reference system, e.g. its long term stability and the low gravity harmonics? It would certainly be an important bridge to gravitational physics.

After the great success of GRACE further gravimetric satellite missions are urgently needed to secure continuity of the measured time series, if mass transport should remain a central gravimetric theme. How should such missions look like? Compare also, Koop and Rummel (2008). In parallel the development of significantly improved geophysical "background" models of ocean tides, and coupled atmosphere-ocean circulation must have high priority on the geodetic agenda. They would serve the de-aliasing and separation of geophysical effect. Only then one could fully benefit from improved technological concepts such as inter-satellite laser link, drag free system, proof mass-to-proof mass measurement and satellite configuration flights.

Would mini-satellites be useful, e.g. for atmospheric sounding or for a satellite based synchronisation of two or several techniques, such as GPS, DORIS, VLBI and laser ranging?

The GNSS signal emitters and receivers are distributed over three spatial layers: the GNSS satellites at high altitude, a large number of low Earth orbiters (LEO's) equipped with GNSS receivers between 300 and 1000 km altitude and many permanent receiving stations on ground. Could this add, literally, a further dimension to GNSS atmospheric sounding and to the modelling of the wet troposphere?

Several space agencies are preparing missions to our moon. A lander mission could be used to deploy geodetic laser transponders. This would greatly facilitate and improve lunar laser ranging and strengthen its role among the geodetic space techniques and for gravitational physics. In addition, the far-side gravity field of the moon is still not known very well; thus any mission opportunity for satellite lunar gravimetry would be welcome.

What are the technological building blocks of future space geodetic missions? A new generation of ultra-high-precision clocks in space and on ground, such as optical clocks, active transponders for tracking systems, GNSS reflectometry and new types of accelerometers may soon become available for space geodesy. These could have a tremendous impact on the development of geodesy.

This leads to the question about the challenges and opportunities of future space geodesy. The three traditional enemies are non-gravitational forces acting on satellites, atmospheric refraction and local ties.

Uncertainties and gross errors in local ties between measurements systems sound like a trivial question of diligence and organisation but strangely enough this problem is not yet globally resolved. Great progress has been made in measuring and modelling local tropospheric effects for the various ground receiver systems. However a uniform and consistent approach for all techniques is still not routine and should be pursued with high priority. Modelling of the satellite environment (residual air drag and solar radiation) is still far from solved and should also be given high priority. Possibly, low Earth orbiters without accelerometers might be used for gravity field monitoring in the future.

What about clocks, time measurement, synchronisation and transfer? The great progress of the past in space geodesy can be intimately linked to a corresponding progress in the measurement of travel times and time keeping. Important new developments have lead to optical clocks (and counters) at a precision level of 10^{-18} in the laboratory. Precisions better than 10^{-16} can and will have important implications for geodesy. The materialisation of a global unified height system could be achieved using the relativistic dependence of time on the gravitational potential. Time synchronisation at this level of precision via satellites would open several new perspectives for geodesy. Time measurements made by satellites might be considered as real observables and not only as a device for "tick marking" measurements. One could start dreaming of the direct measurement of gravitational potential differences between satellites as well as between satellites and ground stations.

During the pioneering days of satellite geodesy direction measurement with cameras to satellites against the stellar background was one of the primary techniques. With the advent of laser and radio tracking range and range rate replaced angular measurements which always suffered from the effect of atmospheric refraction. But are angular measurements really obsolete for ever? Should one not think about new concepts of angular measurement, e.g. with synchronised twin laser telescopes, and about what their impact would be?

Finally, considering all this amazing progress one can wonder whether there is not a natural limit of precision beyond which further progress of geodetic space techniques does not make sense anymore because the ever increasing precisions cannot anymore be reproduced in nature. Is 10^{-9} already such a limit or 10^{-10}?

5. Concluding remarks

In the quoted book "The interdisciplinary role of space geodesy" (Mueller and Zerbini, 1989), Kaula wrote on page 9: "...Theoreticians get the impression that experimenters operate according to problem definitions that are a decade or more obsolete, while experimenters probably think that theoreticians are sporadic in their attention and underestimate technical difficulties. Better communication is particularly important now that measurement capabilities can yield valuable constraints, provided that they are applied in sufficient detail". This is a remark about the relationship between theory and experiment. Kaula, being both an outstanding geodesist and geophysicist, saw that there was a problem in this relationship at that time. Traditionally geodesy is very "measurement and technique driven". Even during the definition phase of GGOS the underlying rationale started from the observing system and not so much from the Earth science problems that could be addressed with such a system. Such an approach may be logical but it is essentially wrong. Experiments have to be derived from theory and new hypotheses from the experiments; to be successful an intimate relationship between the two must exist. From this I conclude that geodesy and geodesists have to get much deeper into Earth sciences. Geodesists have to have a profound understanding of the geophysical problems. Only then the fantastic tools of modern space geodesy will develop their full potential for the understanding of our Earth as a system. This poses a great challenge to geodetic education and science.

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