SLR analysis at DEOS: an overview

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ABSTRACT

Satellite Laser Ranging observations are being analyzed at the Delft Institute for Earth-Oriented Space Research for a wide variety of purposes. The main theme of these analyses is the computation of highly accurate orbits of specific satellites equiped with laser retroreflectors. Direct applications of these orbit solutions can be found in the areas of station positioning and crustal deformation studies, investigations of highly-temporal local deformations, studies of a wide variety of oceanographic phenomena, gravity field determination, investigations of geophysical issues, the study of station and satellite characteristics, etcetera. This paper gives a kaleidoscopic overview of the various research fields described above. It focuses on some aspects of the observation material, discusses the quality of the satellite orbits that can be computed with these data sets, and highlights in particular the scientific derivatives. In addition, the paper will look at future prospects.

INTRODUCTION

The Delft Institute for Earth-Oriented Space Research (DEOS) embodies two research groups of Delft University of Technology, notably the Chair of Astrodynamics and Satellite Systems (A&S) of the Faculty of Aerospace Engineering and the Section Physical, Geometrical and Space Geodesy (FMR) of the Faculty of Civil Engineering and Geosciences. The experience of both groups in the field of space geodesy dates back to the early 1970s, and they have been cooperating on an unofficial basis since then. In 1997, the cooperation became more firm with the installation of DEOS. In addition, the two Delft groups cooperate with the Geophysical Research Institute (GOI) of Utrecht University, forming the Vening Meinesz Research School for Geodynamics (VMSG) since 1996, and, together with Utrecht University and the Faculty of Earth Sciences at the Vrije Universiteit Amsterdam, in the Netherlands Research Centre for Integrated Solid Earth Sciences (ISES) (since 1998).

The work on Satellite Laser Ranging (SLR) by DEOS dates back to about 1980. At this time, the Faculty of Geodetic Engineering owned and operated the Kootwijk Observatory for Satellite Geodesy (KOSG). Initially, this observatory was equiped with a stationary SLR system only; in later years a transportable SLR system was developed and became operational in 1985 (cf. Vermaat, 1985). In 1991 the tracking facilities were further expanded with the addition of a GPS receiver (KOSG has been an IGS Core Station ever since). A&S has always contributed by means of its expertise and analysis capabilities in the field of celestial mechanics and orbit and parameter estimation. This paper gives a kaleidoscopic overview of the various activities, and focuses in particular on the results of SLR analyses that have been obtained in recent years. For a more complete description of the development in time, the reader is referred to *e.g.* (Ambrosius *et al.*, 1994). This holds in particular for the developments in the field of instrumentation, which are not covered by this paper.

OVERVIEW

The various SLR analysis activities are summarized in Table 1. To bring structure in the wide variety of activities, they are sorted by satellite and by research area. Typically, two kinds of satellites can be distinguished: cannonball satellites and non-cannonball satellites. Each category has its own specific research areas and applications, which will be discussed below.

Table 1. Overview of SLR analysis activities at DEOS.

satellite	general area	data period	specific topic
cannonball satellites:			
LAGEOS-1, LAGEOS-2	operations	1986 - present (LAGEOS-1) 1992 - present (LAGEOS-2)	semi real-time QC, semi real-time EOPs
	crustal dynamics	1983 - present (LAGEOS-1) 1992 - present (LAGEOS-2)	plate tectonics, earth orientation
	geophysics	1984 - 1998 (incl. Starlette, Stella)	mantle rheology
WESTPAC	orbit computations	1998 - 1999	precise orbits, SLR characterization
non-cannonball satellites:			
ERS-1, ERS-2	operations	1991 - 1996 (ERS-1) 1995 - present (ERS-2)	semi real-time orbits
	oceanography	1991 - 1996 (ERS-1) 1995 - present (ERS-2)	sea-level variations, ocean currents
	glaciology	1991 - 1996 (ERS-1) 1995 - present (ERS-2)	ice caps
	orbit computations	1991 - 1996 (ERS-1) 1995 - present (ERS-2)	gravity field
	RADS	1999 - present	as above, tides
TOPEX/Poseidon	oceanography	1992 - present	sea-level variations, ocean currents
	RADS	1999 - present	as above, tides

Cannonball satellites

At this moment, the research activities concerning cannonball satellites focus on the two LAGEOS satellites and on WESTPAC.

LAGEOS

The first area of analysis of LAGEOS is *operations*. This activity was initiated in 1986, the year of the first WEGENER-MEDLAS campaign (Wilson and Reinhart, 1993), and was one of the contributions of DEOS to this project. The operational, semi real-time analysis of the observations taken by the global network of SLR stations served (serves) two goals: (i) a relatively rapid quality control (QC) and performance assessment of the contributing stations, and (ii) the monitoring of the orientation and rotation rate of the Earth. The first element was a requirement of the WEGENER-MEDLAS project, in view of the rather short occupations of sites in the central and eastern Mediterranean area by the mobile SLR equipment; since then (the last SLR campaign on this scale took place in 1992) the operational analysis has evolved into a more general service to the SLR community, in particular to the stations. The computation of Earth Orientation Parameters (EOPs) has continued to this very day, with results being delivered to various customers such as IERS. Through time, the temporal resolution of the parameter solutions has increased from 5 days to 3 days, and quality improvements have been obtained by adding LAGEOS-2 data (launched in October 1992) and other model refinements. As a typical parameter indicating the quality of the solutions, the pole positions agree with the IERS Bulletin A values at the level of slightly less than 1 marcsec.

A very logical application of SLR observations is its use for *crustal dynamics* investigations. By virtue of the unprecedented absolute quality of the measurements (*i.e.* at the level of a few mm (ILRS, 2000)), they can serve to compute *e.g.* the coordinates and velocities of laser stations in an absolute reference frame, *i.e.* tied to the center-of-mass of the Earth around which the satellites orbit. As for DEOS, this activity was effectively initiated with its participation in the WEGENER-MEDLAS project too, and currently covers the period 1983 until 1999. As an example, Figure 1 shows the horizontal components of the motions that

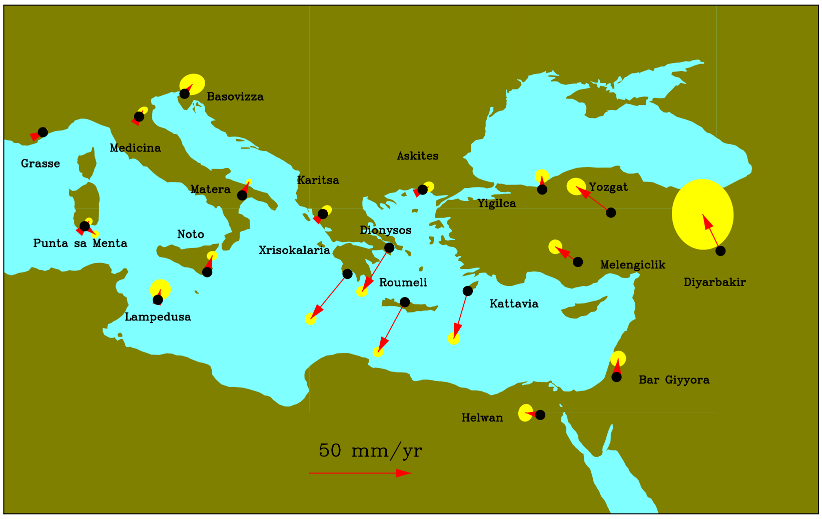

Fig. 1. Horizontal motion vector solutions for stations in the Mediterranean area, according to the solution SSC(DEOS)98C02. This solution was based on SLR and GPS data basically covering the time-span 1986-1997 (Wortel and Spakman, 2000).

have been derived for stations in the central and eastern Mediterranean area, where the Eurasian, Arabian and African tectonic plates collide, a process which can be held responsible for a wide variety of geophysical phenomena such as crustal deformation and earthquakes. This figure, which is based on analysis results from SLR campaigns in 1986, 1987, 1989 and 1992, and GPS campaigns in 1992 and 1994 (at least as far as the Mediterranean stations are concerned), in essence confirms the northward motion of Arabia, quantifies the westward escape of Anatolia and the SSW motion of Aegea, and clearly shows the important role of Africa in the Italian part of the network (all velocities are w.r.t. stable Eurasia).

Results of the Aegean area in particular have been used by VMSG colleagues from Utrecht to study the dynamics (*i.e.* the relation between forces and motions) of this area. Meijer (1995) investigated various forcing mechanisms relevant for the dynamics of Aegea (slab pull along the Hellenic Arc, the EW push by Anatolia and the gravitational effect of high topography), and made conclusions on the relative importance of each of these mechanisms, using the SLR results as one of the "referees".

SLR plays a very important role in assessing vertical motions of stations, in particular, again because of the high accuracy of the observations. Figure 2 shows the results for one of the most interesting areas in this respect: Fennoscandia, where the crust of the Earth is in a state of uplift or rebound after the disappearance of the ice loads of the Late Pleistocene, some 15,000 years ago. The results that are shown in this plot are based on a combination of global SLR (Metsahovi in Finland is the only SLR station in this area) and regional (*i.e.* European) GPS data. The (daily) solutions for the European GPS network have also been computed at DEOS. They have been mapped into the well-defined global reference frame as determined by the SLR analysis (using the stations with overlapping techniques). The results for Fennoscandia, although not very detailed, are very clear and correspond well with expectations and models: an uplift of about 10-11 mm/year near the head of the Gulf of Botnia, and a vertical deformation of about 2-3 mm/year along the "rim" (please note the error bars). The large vertical deformation observed for the station on Spitsbergen is not related to uplift, but is caused by site instabilities and/or antenna problems.

In addition to using the very precise LAGEOS orbits for assessing deformation on the surface of the Earth, they may also be used to investigate the *internal physical state of the Earth*. Typically, the gravity field of the Earth is the source of the most important force acting on the satellites; in turn, the orbit solution may be used to derive information on the temporal and spatial variation of the gravity field, or, alternatively, the mass distribution of the Earth. Because of the strength of the corresponding disturbing signal, it are the low-degree zonal terms of the gravity field and their time variation which are best observable. Since the recovery of such variations requires a dedicated analysis of a preferably decadal dataset of SLR observations, and the LAGEOS analysis being performed at DEOS is tuned for observing crustal deformations, we have

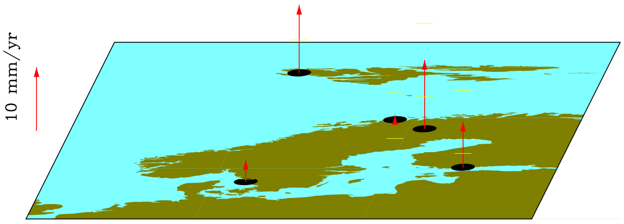

Fig. 2. Vertical motion vector solutions for stations in Fennoscandia, according to the solution SSC(DEOS)98C02. This solution was based on SLR and GPS data basically covering the time-span 1986-1997 (Wortel and Spakman, 2000).

Table 2. Overview of solutions for the linear rate-of-change of zonal terms in the gravity field (Devoti *et al.*, 2001).

coefficient	rate of change $[10^{-11}/\text{year}]$
$\dot{J}_2$	-2.9 ± 0.2
$\dot{J}_4$	0.6 ± 0.5
$\dot{J}_6$	0.3 ± 0.3
$\dot{J}_3 + 0.9\ \dot{J}_5$	0.5 ± 0.2

used solutions for the rate-of-change of zonal components as determined by other investigators. In particular the results obtained by Italian investigators (Devoti *et al.*, 2001) for $\dot{J}_2$ - $\dot{J}_6$ have been used here (Table 2).

Such time-variations can also be derived theoretically, by modeling the effect of the most important global-scale phenomena: post-glacial uplift in Fennoscandia and ice melting in Antarctica and Greenland. Of course, each of these phenomena has a large uncertainty, and the effect on the mass distribution of the Earth and hence the variation of specific terms of the Earth's gravity field may therefore also be quite variable. Additional parameters which affect the outcome of such so-called "forward modeling" computations (*cf.* (Sabadini *et al.*, 2001) for more details on the technique) are the viscosity of the upper mantle and that of the lower mantle. Examples of such extrapolations are given in Figure 3, for $\dot{J}_2$ - $\dot{J}_6$ and a combination of $\dot{J}_3$ and $\dot{J}_5$, respectively. The solid line represents the effect of deglaciation since the Late Pleistocene (for various values of the lower mantle viscosity), whereas the dashed and the dotted lines also include the propagated effects of maximum melting in Antarctica and Antarctica plus Greenland, respectively. The observations as derived by the Italians (Devoti *et al.*, 2001) are indicated by the red bars (the green bars indicate similar solutions computed by (Cheng *et al.*, 1997)), and can be used to accept or to reject a certain theoretical model (which consists of a combination of melting rates at Antarctica and in Greenland, and the viscosity values of the lower and upper mantle of the Earth). From a comparison of the forward models of Pleistocene glacial isostatic adjustment (post-glacial rebound) and present-day ice-mass variations of Antarctica and Greenland with the data of Devoti *et al.* and Cheng *et al.* (Figure 3), it can be seen that in most cases the curves for Pleistocene deglaciation-only and those for Pleistocene + Antarctica + Greenland ice melt straddle the observations. This implies that present-day ice melt of Antarctica and Greenland is occuring, but at a rate which is less than the maximum values that are given in the 1995 report of the Intergovernmental Panel on Climate Changes (IPCC); values from the latter were used in the forward simulations underlying Figure 3.

WESTPAC

The third cannonball satellite that is studied at DEOS is WESTPAC. This satellite, launched in August 1998, is unique in the sense that its retroreflectors are limited in number and are baffled. Because of

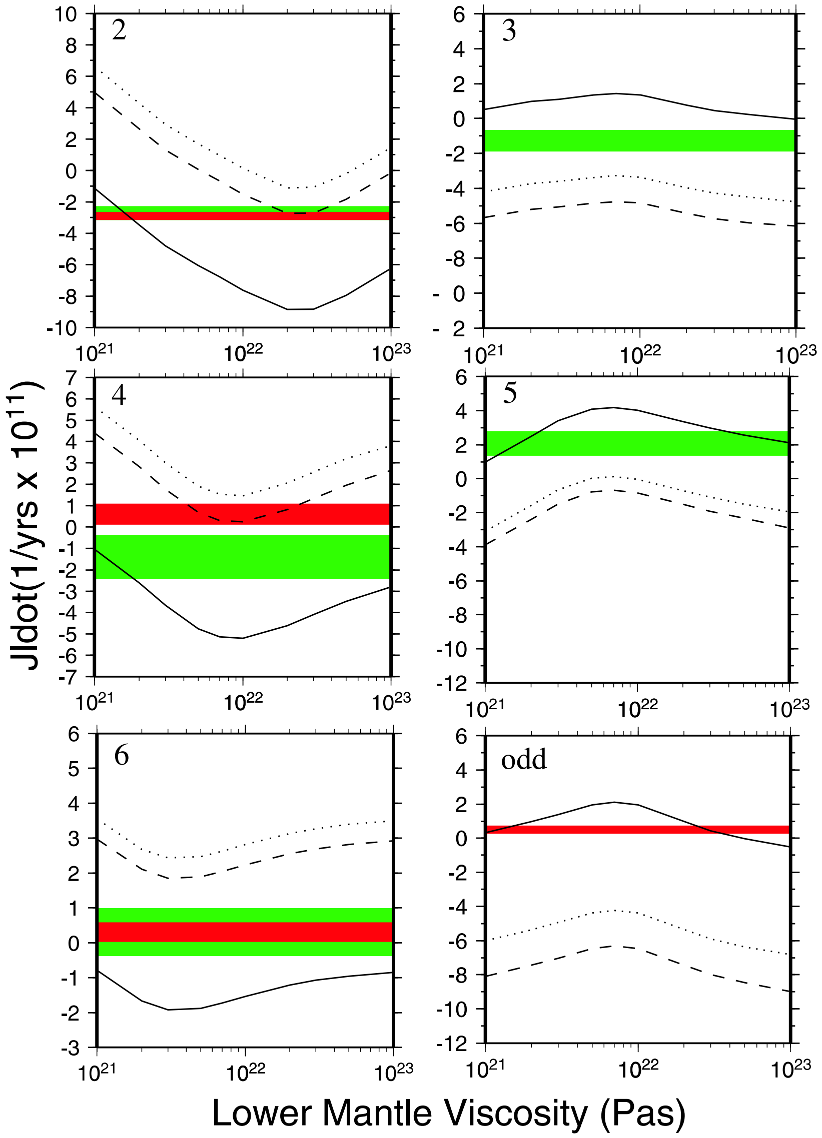

Fig. 3. $\dot{J}_l$ as a function of lower mantle viscosity (upper mantle viscosity is fixed at 5×10^{20} Pas). The red and green stripes represent the Devoti *et al.* (2001) and Cheng *et al.* (1997) solutions, respectively. Solid curves correspond to Pleistocene deglaciation, dashed ones to Pleistocene plus maximum IPCC95 ice loss in Antarctica, and the dotted ones also include maximum IPCC95 ice loss in Greenland. The modeled results for $\dot{J}_{odd}$ stand for a combination of uneven zonals.

Table 3. Summary of WESTPAC orbit investigations (Rutkowska and Noomen, 2000). The abbreviations AT and CT stand for along-track and cross-track, respectively.

	scenario	
	A	S
gravity field model	EGM96	GRIM5-S1
atmospheric density model	DTM 87	MSIS 86
intervals for C_D	1 day	0.5 day
intervals for C_R	8 days	8 days
empirical accelerations	AT(cos+sine), CT(cos+sine)	AT(cos+sine), CT(cos+sine)
ocean tides	EGM96	Ray
weighted rms-of-fit	1.10	0.59
rms-of-fit [cm]	6.32	3.68
radial orbit overlap [cm]	14.7	11.4
cross-track orbit overlap [cm]	11.2	5.6
along-track orbit overlap [cm]	40.8	20.6

these characteristics, laser pulses can be reflected by one reflector at a time only, which in turn allows for an unprecedented accuracy of the center-of-mass offset of this satellite (Shargorodsky, 1997). One of the products that is required for the exploitation of the unique features of WESTPAC is a highly precise orbit solution. To this extent, a study has been performed (Rutkowska and Noomen, 2000), a summary of which is given in Table 3. This table shows the main elements of the computation model of two so-called scenarios (in the original study, 19 different scenarios were investigated), and the results in terms of parameters which express (in some way) the quality of the orbit solution. The statistical numbers for scenario S are significantly better than those for scenario A, clearly indicating that the elements as mentioned in Table 3 for scenario S are necessary to achieve the best possible orbit solutions.

At this moment, the WESTPAC investigations are continued with a study on the precise characteristics of the SLR observations on this satellite (in conjunction with a similar study on LAGEOS-1 and LAGEOS-2).

Non-cannonball satellites

As for the second category of satellites, the DEOS research activities based on SLR observations focus on (three) altimetric satellites: ERS-1, ERS-2 and TOPEX/Poseidon (Table 1). The highlights of the analyses will be described below.

ERS-1, ERS-2

For the satellites ERS-1 and ERS-2, launched in July 1991 and April 1995, respectively, a different number of analysis activities can be distinguished, again. One of the activities is *operations*: for ERS-2 (and ERS-1 in the past) orbit solutions are derived on a semi real-time basis, currently on a twice-weekly basis, with a delay of 2 days after the epoch of the latest observation. These so-called fast-delivery orbits have a radial accuracy of approximately 7 cm, and are further improved in subsequent computations, resulting in so-called preliminary orbits and precise orbits (both of these products are updated monthly). Since 2 years the operations are extended with a rapid orbit service: every day, an ERS-2 orbit is computed for the last day plus a prediction for the next. These near real-time and fast-delivery orbits are used for a variety of purposes: a rapid-turnaround quality assessment of the contributing SLR observations (the results are made available to the community through the DEOS web pages), and in combination with the provisionary radar altimeter data and geophsyical and atmospheric corrections yielding the DUT/NOAA fast-delivery altimeter data products.

In addition, and very similar to the LAGEOS structure, the observations are also used for scientific purposes. To this aim, the SLR observations are reduced to the above mentioned precise orbits, which in turn are used as an accurate reference for the radar altimeter observations taken by the spacecraft. The results are used for *oceanographic studies*, which encompass the study of global ocean circulation (ocean currents) and sea-level variation. As an example of the latter, Figure 4 shows the height deviations of the

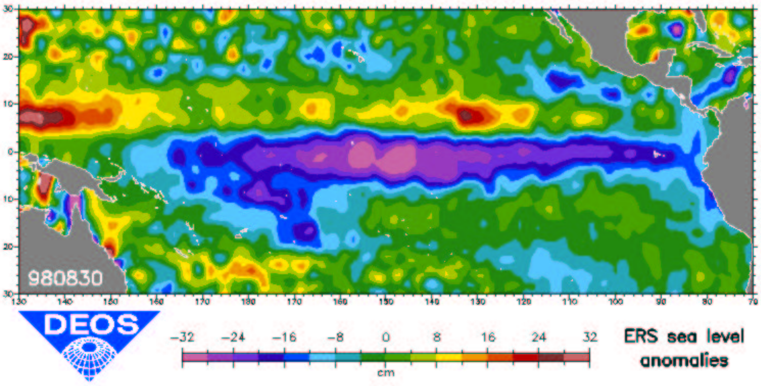

Fig. 4. An example of sea-level anomalies in the Pacific Ocean, as observed by ERS-2 around August 30, 1998.

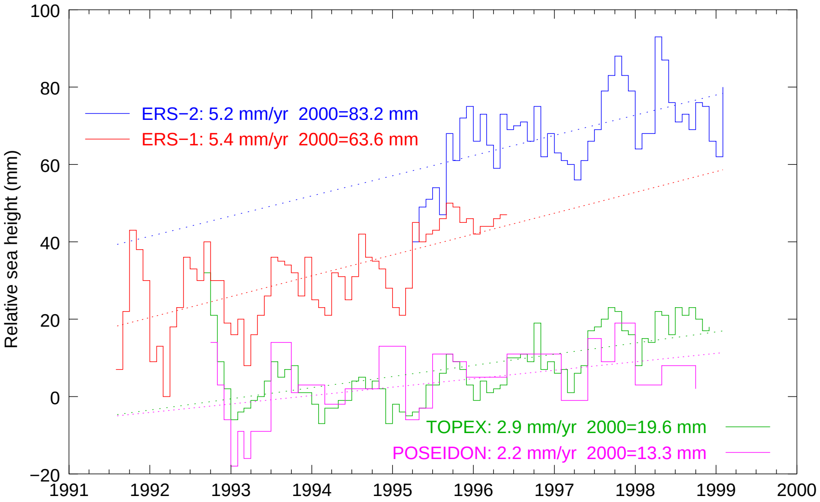

Fig. 5. The general trend in the global sea-level, as observed by ERS-1, ERS-2 and TOPEX/Poseidon (Scharroo, 2000).

surface of the Pacific Ocean w.r.t. an average level, deduced from the observations taken during 16 days centered around August 30, 1998. The picture shows clear offsets from the normal situation in the order of decimeters, an effect which can be associated directly with the well-known phenomenon El Niño. By studying a time-series of such results, it is possible to study the temporal behavior of phenomena such as El Niño (or La Niña, or more general ocean currents for that matter). Using techniques like these, investigators have been able to detect the so-called Rossby and Kelvin waves which propagate across ocean basins and along the coasts.

The time-series of sea-level observations deduced in such a way are also exploited to study the trend in the absolute sea-level, either locally or globally. Results of such an analysis are shown in Figure 5, which shows that ERS-1 and ERS-2, although active sequentially, yield similar estimates of global sea-level rise of slightly more than 5 mm/yr. In addition, the plot clearly shows that there is an offset in the absolute height of the sea-level as observed by ERS-1 and ERS-2, in spite of the similar trend. This emphasizes the importance of decadal time-scales of studies such as this and others, aimed at detecting time signals in the earth system, and should be interpreted as a recommendation both to the geodetic community (ILRS in this case) for continuous and consistent tracking and to governments and governmental organizations to provide political and financial support covering such missions for long periods. Figure 5 also shows the results that have been obtained using the TOPEX/Poseidon satellite, yielding a value for the yearly rate of change of sea-level which is about half the ERS estimate.

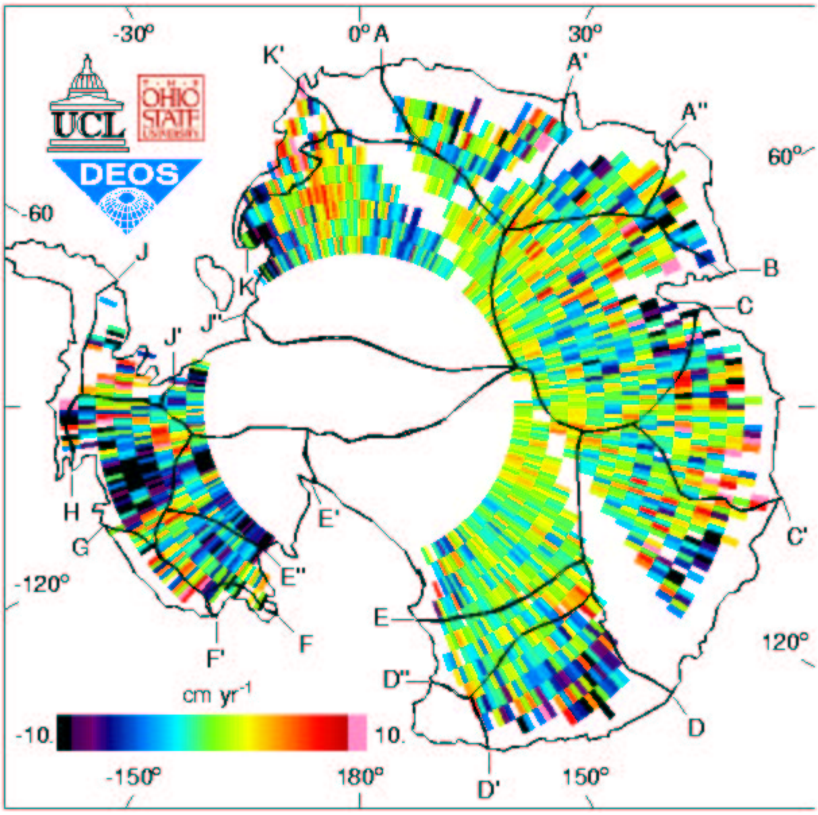

Fig. 6. The elevation changes on the South Pole, as estimated from 5 years of ERS-1 and ERS-2 altimeter observations (Wingham *et al.*, 1998).

In addition, the combination of the precise satellite orbit solution computed by DEOS and radar altimeter data has been used to study the *variations of the ice caps* of the Earth. The results that have been obtained for Antarctica are shown in Figure 6, which shows the linear variations of the ice/snow surface for blocks measuring 1×1 deg (Wingham *et al.*, 1998). On average, in East Antarctica the positive and negative trends look relatively small and seem to balance each other. The situation in West Antarctica is very different, however: here, yearly rates of change of -10 cm or more can be observed. A closer analysis yields that for certain areas the elevation of the ice cap has dropped by about 40 cm in the period 1994-1996, a value which is well beyond any error budget of the observing system, and hence must be considered as very strong evidence of significant changes taking place at the South Pole. When averaged over the entire South Pole, the mean value for the elevation drop is 9±5 mm/year, which corresponds with a mass loss of 60±76 Gt/year. This estimate may be compared to the results of the analysis of gravity field variations, and can be considered as another contribution of the SLR technique to a better understanding of the phenomenon "global change". However, this melting of ice is not of sufficient magnitude to explain the observed sea-level rise as reported above.

Another general study area of the ERS satellites is the development of *highly precise satellite orbits* (in addition to the operational orbit computations which have been mentioned above). This activity focuses in particular on (the estimation of) the gravity field. To this aim, DEOS has developed a series of gravity field model solutions, the latest of which is DGM-E-SPX1 ("Delft Gravity Model, ERS, version SPX1") (Visser *et al.*, 2000). This solution has used the general-purpose NASA/NIMA model EGM96 (Lemoine *et al.*, 1998) as a priori, and has used SLR, PRARE and altimeter cross-over measurements of the ERS-2 satellite taken in the period May 1996 to December 1998 as observational input. The results are summarized in Table 4, which clearly shows a very significant improvement of the observation residuals. The confrontation with WESTPAC SLR data, not included in the derivation of DGM-E-SPX1, has led to similar conclusions (Rutkowska and Noomen, 2000).

Finally, DEOS is also involved in the development of the *Radar Altimeter Database System* (RADS)

Table 4. Summary of some of the results of the computation of DGM-E-SPX1 (Visser *et al.*, 2000). Listed are the rms-of-fit of SLR and PRARE data (in [cm] and [mm/s]), obtained with the a priori model EGM96 and the new model DGM-E-SPX1.

year	SLR		PRARE (range/range-rate)	
	EGM96	DGM-E-SPX1	EGM96	DGM-E-SPX1
1996	8.0	4.9	7.5/0.42	6.0/0.34
1997	7.8	4.5	7.1/0.44	5.6/0.34
1998	8.6	5.3	6.2/0.44	4.8/0.35

(Table 1). This database has an Internet interface, meeting the demand for precise sea-level data and products for both scientific and non-scientific users (Naeije *et al.*, 2000). It includes analysis results based on the ERS-1, ERS-2 and TOPEX/Poseidon altimeter instruments; these results are connected to the precise satellite orbits which rely heavily on the range measurements taken by the global network of SLR stations.

TOPEX/Poseidon

The third altimeter satellite which is study object at DEOS is the US/French TOPEX/Poseidon. Since the initiation of this satellite project, DEOS has been involved as a member of the TOPEX/Poseidon Science Team. Until a number of years ago, DEOS did compute precise orbits of the spacecraft, using SLR observations and other types of tracking data (Smith *et al.*, 1994). Currently, however, DEOS relies on the orbit solutions as computed by colleague institutes (still partly dependent on SLR data). These TOPEX/Poseidon orbits are used for purposes very similar to those already mentioned for ERS-1 and ERS-2: oceanography, in particular sea-level variations. In addition, the TOPEX/Poseidon orbit solutions that are available for the science team members have also been used to study ocean tides (Smith, 1999). TOPEX/Poseidon data and results are also included in the RADS data base (Table 1).

FUTURE

Based on the (scientific) results presented and discussed in the previous sections, it can be concluded that the technique of SLR has been and will remain a very important contribution to a variety of studies dealing with many different aspects of "system Earth". SLR plays an important role, particularly when absolute values of certain parameters are sought for. To continue such analyses and further improve the quality of the outcome in view of questions being posed by the global community, it is of utmost importance to carry on the operations of the global network of stations and of the analysis institutes into the foreseen future. As for the tracking network, it is important not only to continue the acquisition of such highly accurate range observations on a host of dedicated satellites, but also to improve the global station distribution (something which is in constant motion by virtue of the ILRS). As for the analysis aspect, a steady improvement of observations and computation models can be expected to take the current analysis quality one or several steps further. Many analysis institutes are involved in this. Finally, it is essential that the analysis results and interpretations converge to unique numbers, which can be understood by politicians and the general public in an unambiguous way. It is only then that the global community will benefit fully from the unique capabilities that SLR has to offer.

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