

## Oceanic loading on European laser-ranging sites

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**Summary.** The expectation for high accuracies in laser ranging in the years to come and the increasing geodynamical implications in satellite geodesy require the investigation of the effect of time-dependent geodynamical phenomena on the laser-ranging sites. In this paper we evaluate the radial and horizontal displacements of the surface of the Earth and the gravity perturbation due to the loading effect of the M2 oceanic tide for 13 European laser-ranging sites. Most of them are situated in coastal regions.

### Introduction

There is no doubt that the rapid evolution of satellite or, more generally, of space geodesy during the sixties decade, towards global geocentric positioning and modelling of the Earth's gravitational field, saturated around the early seventies. During the first half of this present decade geodesists realized that space geodesy should and could be involved in geodynamics contributing to a detailed and deep understanding of the dynamics of our planet, as a deformable irregular body within space–time (see Grafarend 1976). The high accuracies that satellite geodesy systems can achieve nowadays permit such geodynamical studies. We refer to Kovalevsky (1975) both for a comprehensive review of activities in space geodesy and the accuracy attained during the last five years, and for a prediction of the improvement of modern techniques of high accuracy for practical applications such as oceanography, seismology, crustal studies etc.

Satellite laser ranging is by far the most promising technique for geodynamical studies requiring high precision of positioning. For instance, the expected ranging accuracy of 1 to 2 cm with the corresponding positioning precision makes systems like the Close Grid Geodynamic Measurement System (CLOGEOS), (Mueller, van Gelder & Kumar 1975), a powerful tool for studying in detail Earth crust movements, marine geodesy etc.

Considering these applications and the prospective accuracies, one can ask whether the 'noise' of some time-dependent geodynamical phenomena can influence such high precision measurements, introducing errors in the analysis of the results. Mather (1974) for instance,

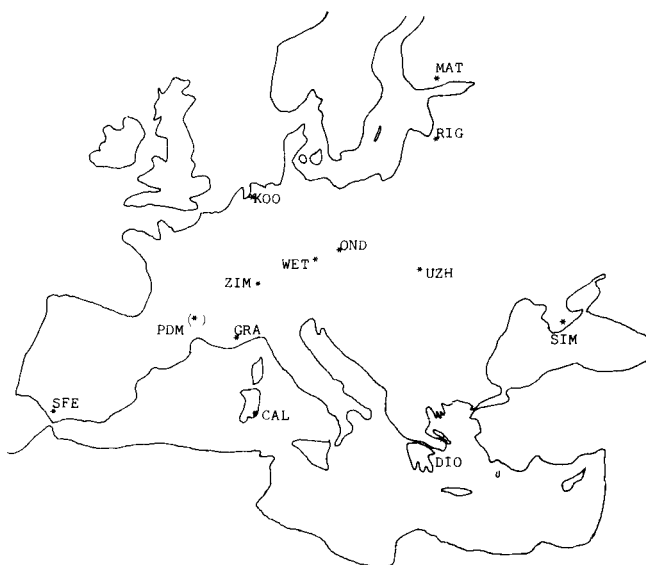
discussed the question from the general geodetic and oceanic point of view, giving orders of magnitude and noise levels. In a more recent paper (Mather, Masters & Coleman 1977) some orders of magnitude of geodetic interest due to secular gravity variations are given.

Tides are among the most important periodic phenomena which could perturb modern satellite ranging. The deformation of the Earth and of its gravity field is a consequence of the direct action of the tidal potential; several authors (e.g. Alsop & Kuo 1964) have shown that the computation of the direct Earth tide does not vary more than about 1 per cent for a wide number of different earth models in use by the seismologists. The oceanic tides influence the analysis of satellite orbits for they perturb the orbits (Kaula 1962); important aspects of this problem have been further elaborated, see, e.g. Lambeck & Cazenave (1973); Lambeck, Cazenave & Balmino (1973), (1974). The interaction between the solid Earth tides and the ocean tides is to be considered since the load of the oceans affects the yielding of the Earth and conversely the potential perturbation arising from the deformed Earth affects the motion of the water masses. These aspects were thoroughly discussed by Hendershott (1972) and simulated recently by Estes (1977).

As a contribution to the current and forthcoming European projects in satellite ranging, we have computed the theoretical radial and horizontal displacements due to the lunar semidiurnal oceanic wave M<sub>2</sub>, for 13 European laser sites, most of them situated close to coastal regions.

### The laser stations and the loading oceans

Eleven European satellite laser stations were considered as well as two Moon laser sites, well-distributed geographically, covering almost the whole of Europe. They are Zimmerwald (ZIM), Switzerland; Ondrejov (OND), Czechoslovakia; Wetzell (WET), W. Germany; San Fernando (SFE), Spain; Grasse (GRA), France; Dionysos (DIO), Greece; Cagliari (CAL), Italy; Kootwijk (KOO), The Netherlands; Matsuhovi (MAT), Finland; Riga (RIG), Uzhgorod (UZH) both USSR and the two Moon laser sites Pic du Midi (PDM), France and Simeis Crimea (SIM), USSR. The PDM Moon laser facilities have been moved to GRA, but we left the site in our computations.



**Figure 1.** European stations for satellite laser-ranging and lunar laser-ranging. PDM facilities have been moved to GRA.

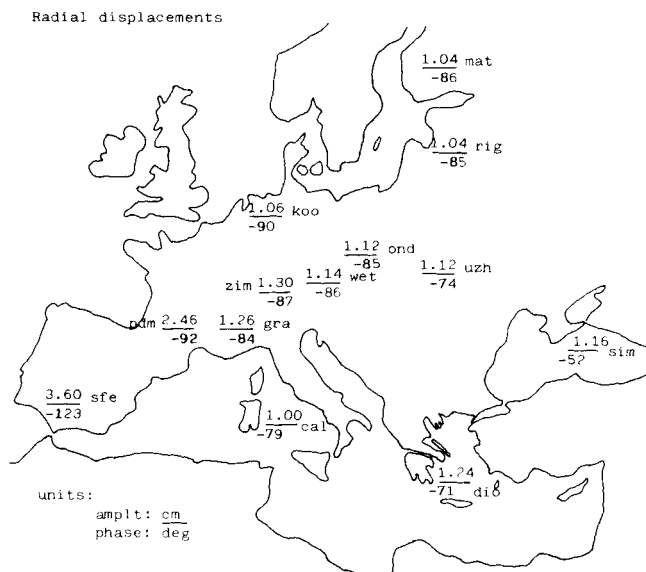
The above stations – especially the first group of satellite laser stations – are equipped with first, second or mixed-generation laser systems. They are participating in international satellite geodesy campaigns like the ‘Interkosmos’ project and the ‘European Ranging Observations to Satellites’, EROS, project.

As shown in Fig. 1, the satellite laser stations DIO, CAL and GRA are very close to the Mediterranean coast, SFE and KOO are near the Atlantic Ocean while MAT and RIG are adjacent to the Baltic Sea. Only the satellite stations of central Europe ZIM, OND, UZH and WET are more than 200 km from the coasts. The satellite-ranging facilities at these stations are described in numerous technical reports distributed at several recent specialized satellite meetings e.g. the two international laser workshops in Athens in 1973 and Prague in 1975.

The standard technique of the Green functions (Farrell 1972) was used in order to compute both the radial and horizontal displacements as well as the gravity perturbation at the surface of a spherically-symmetric, self-gravitating Gutenberg–Bullen model earth (see, e.g. Alterman, Jarosch & Pekeris 1961). For more details see, e.g. Chiaruttini (1976). The global M2 oceanic model by Hendershott (1973) is used for the North and South Atlantic, Pacific and Indian Oceans, together with the M2 model of the Arctic Ocean by Moens (1976) and with the M2 local models of the Mediterranean (Baxa *et al.* 1973), Adriatic (Polli 1959), Aegean (Livieratos & Zadro 1977) and North Sea (Doodson & Warburg 1941). We have not considered the Baltic and the Black Sea tides since they are very modest (Defant 1961; Zadro 1976). Computer outputs providing three-dimensional results of the displacements for the thirteen laser sites are summarized in the following figures. The detailed computer outputs for all stations – including the partial influences of each loading ocean – are available upon request.

### The displacements

Fig. 2 shows the radial displacements (positive upward). The figures are the peak to trough displacement and the local phase lag, i.e. the difference between the argument of the displacement and the argument of the M2 tidal potential at the same time.



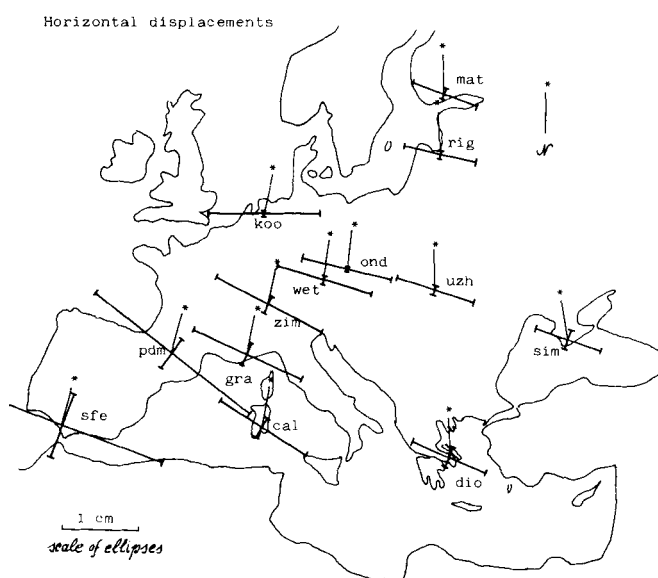
**Figure 2.** Radial displacement at European laser stations due to M2 oceanic tidal loading. Figures are peak to trough amplitude and local phase lag.

The largest radial displacements appear at SFE (3.60 cm) and PDM (2.46 cm), while the smallest are at MAT (1.04 cm), RIG (1.04 cm) and CAL (1.00 cm). The analysis of the separate effect of each ocean shows that the strongest influence is that of the North Atlantic tide for all stations except UZH, RIG, MAT and DIO, where the Pacific Ocean shares the influence with the North and South Atlantic, and SIM where the Pacific tide has the strongest influence. The effect of the South Atlantic is almost the same at all sites and yields a peak to trough displacement below 0.5 cm. The influence of the Indian Ocean is generally less than 0.2 cm and only at DIO and SIM is it as high as 0.32 cm, while the effect of the Arctic Ocean is even smaller reaching 0.2 cm (MAT). Finally the Mediterranean Sea with its two connected basins, the Adriatic and the Aegean, has almost negligible influence at all European stations, except at the Mediterranean sites CAL, GRA and DIO where the effect is small anyway (0.26 cm at CAL, 0.16 cm at GRA and 0.12 cm at DIO).

In Fig. 3 the horizontal displacements are shown by means of the displacement ellipses, i.e. the periodic paths followed in time by a point of the surface. The E–W component is obviously greater than the N–S one (almost three times) since the main loading oceans are the North Atlantic and the Pacific in order of importance.

As far as the N–S component is concerned, the North Atlantic influences especially SFE and PDM – where the peak to trough displacement is about 0.5 cm – while the Pacific influences mostly the non-Atlantic sites yielding a peak to trough displacement of about 0.2 cm. The influence of all other oceans, especially the influence of the Mediterranean Sea, can be neglected.

Concerning the E–W component, the effect of the North Atlantic causes a peak to trough displacement of about 1 cm at SFE and PDM; while at CAL, GRA, ZIM, KOO, WET and OND the influence of the North Atlantic and that of the Pacific are in the same range from 0.3 to 0.5 cm. Finally MAT, RIG, UZH, DIO and SIM are influenced mainly by the Pacific but the displacement is small anyway (0.3 cm peak to trough) as a consequence of the distance of these sites from all oceans. The remnant basins have everywhere almost negligible effect below 0.1 cm.



**Figure 3.** Horizontal displacement at European laser stations due to M2 oceanic tidal loading. The displacement ellipses are given by means of their principal axes.

**Table 1.** Gravity perturbation due to M2 tidal loading of the world oceans, amplitude and local phase lag.

	Amplitude ( $\mu\text{gal}$ )	Phase lag (deg)
CAL	1.09	-51
DIO	0.66	-83
GRA	1.54	-63
KOO	1.34	-62
MAT	0.60	-81
OND	0.95	-58
PDM	3.55	-83
RIG	0.65	-66
SFE	5.19	-119
SIM	0.45	-21
UZH	0.70	-46
WET	1.07	-59
ZIM	1.58	-65

### Gravity variations

By means of measurements on the ground alone one cannot determine the absolute movements of the Earth's surface; conversely it is possible to measure some effects of the displacements, like gravity perturbation, tilt and strain of the surface. Moreover the gravity perturbation is closely related to the radial displacement and, as the distance from the load increases, it decays in roughly the same way as radial and tangential displacements. Thus the measurement of gravity is an easy way to monitor the radial deformation of the Earth.

The results of the computation of load gravity variations are given in Table 1. The figures are the amplitude of the overall effect — i.e. both the direct Newtonian attraction of the water masses and the result of the deformation of the Earth — and the local phase lag. The analysis of the contributions of each single basin shows that the load of the North Atlantic is overwhelming at SFE, PDM, GRA, CAL, ZIM, KOO and WET. At OND, UZH and RIG all four main oceans (North and South Atlantic, Indian and Pacific) yield perturbations of similar amplitudes and at MAT, DIO and SIM the effect of the North Atlantic is small compared to that of the other three oceans. The load of the Arctic Ocean has very small influence at every site except at MAT and RIG where the amplitude of the perturbation is 0.36 and 0.26  $\mu\text{gal}$  respectively. At all the 13 sites the phases of the South Atlantic, Indian and Pacific effects are incoherent, so that even in the last two cases the resultant effect resembles that of the North Atlantic. The effect of the Mediterranean and that of the North Sea are negligible except for the stations close to those basins where even so they are at most 30 per cent of the resultant perturbation (GRA: 0.21  $\mu\text{gal}$ , CAL: 0.35  $\mu\text{gal}$ , KOO: 0.29  $\mu\text{gal}$ , DIO: 0.15  $\mu\text{gal}$ ).

Melchior, Kuo & Ducarme (1976) have recently published the results of a tidal gravity profile of Western Europe. Fig. 4 displays a comparison of the measured gravimetric factors and phase lags with the ones we obtained from our computations. The gravimetric factor  $\delta$  and the phase lag  $\alpha$  for an earth irregularly covered by oceans are given by

$$\delta \exp(i\alpha) = 1.16 + \frac{L}{A} \exp(ik)$$

where 1.16 is the gravimetric factor for the earth without oceans,  $L$  and  $A$  are the amplitudes of the load and astronomic tide respectively and  $k$  is the local phase lag of the load tide.



M2 oceanic loading are rather modest – between 1 and 4 cm – recalling the accuracy of current laser-ranging systems. But the effect is still there and being a periodic function of time could be easily filtered out for geodetic applications or could be retained as new information in ocean-tide researches.

### Acknowledgments

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