FUTURE ROLE FOR LASER RANGING INSTRUMENTATION: A PERSONAL VIEW

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In order to say something about future roles we need to have a good understanding of what the past and present roles have been. What have we learnt about the physics of the Earth or about physical principles and processes that we would not have learnt had there been no laser ranging to satellites. Only when this is answered can we ask the next question: What do we want to learn about the Earth that requires on-going and improved laser ranging to satellites or the Moon.

In attempting some answers I will give my own views: in the spirit of getting the debate going rather than trying to be correct. I doubt that there is a correct answer in any case, the nature of scientific investigation being what it is.

Scientific uses of satellite laser ranging (SLR) fall into at least two categories: geophysical applications (including the dynamics of the Moon), and fundamental physics (aspects of relativity theory, high-precision time transfer). I will comment briefly on the first and others hopefully can comment later on the second area.

In making these comments it is important to understand my strong conviction that the geodetic satellite observations are of little value unless they are considered in a broad geophysical and geological context. This comes about in two ways: The inversion of geodetic data for geophysical parameters is seldom unique, and geodetic estimates of rates invariably give snapshots of processes that occur over much longer time scales. Hence they need to be taken together with other geophysical or geological evidence in their interpretation.

The use of the laser ranging data in studies of the Earth can be illustrated by Figure 1. Here an Earth, with a response function $R$, is acted on by forces $F$, and in consequence is subject to deformation $D$. This last is the quantity inferred from the laser range data. Sought is either $F$ or $R$, or both. In some cases $F$ can be assumed known and the sought function is $R$. One example is the lunar and solar tidal deformation of the Earth. In other cases $R$ is assumed known and $F$ is inferred. One example of this is the Earth's rotation where the inference may be the zonal wind patterns. In most cases both $F$ and $R$ are unknown or at best only partially known. Examples here include the Earth's gravity field. In this case the "deformation" is the geoid or gravity anomaly map and the unknowns are the forces acting within the mantle and the internal response of the mantle to these forces.

Figure 2 illustrates a range of processes that act on the Earth from periods of seconds to hundreds of millions of years. One of the objectives of geophysics is to understand the response of the Earth, its rheology, over this large range, from $10^0$ to $10^{17}$ seconds, using a wide range of observational evidence. Geodetic measurements, particularly laser ranging to satellites, can contribute significantly to this problem.
Figure 1. Schematic illustration of the relation between force $F$ and the resulting deformation for a planet with a response function $R$.

Figure 2. Schematic spectrum of time-dependant processes deforming the Earth. One objective of the studies of the Earth is to define the response function between the elastic response at very high frequencies and essentially fluid response at very low frequencies.
The SLR applications to geophysics can be divided into two categories: one where the satellite laser ranging is used to examine dynamic aspects of the Earth: mainly its gravity field, the other where the measurements contribute to the setting up of a global reference frame with respect to which the planet's rotational motion, or the relative crustal motions of parts of the Earth can be examined.

The impact of laser ranging on the determination of the Earth's gravity field has been important, as is shown in Figure 3. The major improvement from the SE 1966 to SE 1969 models, for example, were largely the result of the incorporation of the first laser data. Subsequent improvements follow closely the increasing accuracy of ranging data and the increasing amount of data actually available.

The overall result is that the Earth's global gravity field is known with better precision and resolution than, with one exception, any other geophysical data set. (The exception is topography and even this would not be one if I included gravity field models incorporating satellite altimetry data.) The inversion of gravity for Earth structure is non-unique and unique solutions are possible only by incorporating other data or model assumptions. But if the other geophysical data bases are limited then I do not think that we will learn much more about the Earth by pushing for higher resolution, higher precision models.

Having said this, I immediately insist on two caveats. One important contribution to the gravity field studies is the measurement of the time dependence of some of the very long wavelength components in the field. Observations of such change constrain the Earth's rheology at intermediate periods and I think still have an important contribution to make to understanding the physical properties of the Earth. A difficulty here, and one to which I return later, is that a major contribution to these time dependencies comes from the hydrosphere-atmosphere and the fluid domains of the Earth will have to be better understood. In several instances one can point to such improved understanding having been driven by satellite laser ranging results, and an immediate example is the improvement in ocean tide modelling that was motivated largely by new results for the tidal perturbations in satellite orbits.

The second caveat concerns the use of the geoid as a reference surface for measuring long-period fluctuations in the sea surface topography (SST). Many of the important climatic fluctuations occur on time scales of years to decades and they exhibit considerable ocean-atmosphere interaction. The time scales of some of the SST changes are longer than the typical lifetimes of satellite instrumentation and there is a need to have a high accuracy geoid so as to be able to link altimeter results from successive satellite missions. Accuracy requirements for these geoids are of the order of a few centimeters or better and SLR data remains the best tracking information to achieve this.

For these dynamical applications it is well recognized that SLR provides the best tracking method for obtaining high accuracy orbits. Electronic tracking will generally be less satisfactory on two counts: additional atmospheric propagation problems, including the ionosphere, and satellites not configured to reduce the surface area to mass ratios. These limitations are to a great extent overcome by the much higher tracking density that is usually achieved with electronic methods. This nearly tempts me to suggest that improved tracking coverage should be a higher priority than improved tracking accuracy for certain classes of geophysical applications.

In the second category of geophysical applications, laser ranging has made a significant contribution to the study of the Earth's rotation although here the method does not reign supreme. VLBI is my preferred method here because of its ability to give both long-term stability to the reference frame (something that SLR by the nature of satellite orbital motion cannot provide) and high resolution observations of very short (diurnal and less) duration irregularities in rotation.
Figure 3. (a) Error spectra of gravity field models as a function of spatial resolution for models published between 1966 and 1985. (b) Spectrum of geodetic positioning accuracies as a function of time.
Certainly the laser ranging results present a very major improvement over previously existing methods and has caused us to reconsider questions about the excitation and dissipation of the Chandler wobble, albeit it without resolution. What is required is a long series of high accuracy rotation data (length-of-day and polar motion) to enable questions about the multitude of forcing functions (Figure 4) to be answered. These include the already mentioned questions about the excitation and dissipation mechanisms of the Chandler wobble; the amplitude and phase of the tidal signals in the Earth's rotation from 12 hour to 19 year periods; the nature of the core-mantle coupling and its relation to "decade" scale changes in length-of-day; the secular and, 'decadel' oscillations in the pole path. Here one also runs into the hydro-atmosphere barrier, where "fluid" signals mask the solid-Earth signals. That this occurs over a broad spectrum has been known for several decades but unless the quality of the global meteorological, oceanographic and groundwater data bases improves little new physical information about the Earth will be obtained.

Figure 4. Schematic representation of excitation mechanisms driving the Earth's variable rotation.

Where SLR has made an important impact is in measuring crustal displacements, in particular the confirmation of the main aspects of plate tectonic motions and rates and the observation that average rates for the past few million years are essentially the same as decadal and shorter averages. But plate tectonics has gone much beyond the first-order theories of relative motions of a few major plates whose boundaries appear as simple lines on maps and the really important work will be the examination of the spatial and temporal strain distribution across the boundary...
zone. Figure 5 illustrates a complex but not unusual boundary zone between the Pacific and Australian plates where motions occur in orthogonal directions at rates from less than 1 cm/year to up to 15 cm/year. Up to 8 plates have been defined in this area and to determine their relative motions would require a minimum of 24 sites. But this would not give a complete picture of the deformation process because it would not establish the nature of the deformation across the broader deforming zones such as across the Papua New Guinea Highlands, between the eastern end of New Britain and New Zealand, or across the Woodlark Spreading Zone within the d'Entrecasteaux group of islands. The requirements here are to be able to measure positions at the cm or better level such that rates of displacement can be measured with very high accuracies even for short repeat times as is required for examining the strain cycles associated with large earthquakes. In many instances stations will lie within a few tens of kilometers, or less, of each other. In terms of accuracies SLR is clearly the most appropriate technique but in terms of cost and practicality GPS wins hands down. What I think the role of SLR is here is the provision of a regional 1000 km scale network of reference sites within which the GPS positions are fixed. In this context, the laser tracking of GPS satellites is most important and I would hope that this community can exert some influence to get more GPS satellites equipped with retro-reflectors.

Figure 5. The complex zone of deformation between the Pacific and Australian plates. Arrows indicate directions of relative movements, and rates are in cm/year. The region includes a number of subduction zones, a spreading ridge in the Woodlark basin, transform faults and a fold belt in the New Guinea Highlands. Circles indicate the location of GPS sites.
With the conventional views of plate tectonics, most emphasis is placed on the horizontal displacements. But vertical motions are often more indicative of physical processes than are horizontal motions and high-accuracy vertical positioning is essential. Vertical motions are usually an order of magnitude or more smaller than horizontal motions and this is perhaps where the SLR community's biggest challenge lies. The vertical rates are particularly important because it is sometimes possible to obtain good long-term \((10^3 - 10^5\text{ year})\) estimates of uplift or subsidence using geological or archaeological observations so that it becomes possible to compare "instantaneous" and long-term rates. Rates of uplift along the Antarctic margin, for example, provide good scientific targets but the rates are small, of the order of 1 mm/year and less. Such measurements would contribute to understanding earlier ice volumes over the polar continent.

The vertical motion determination also is most important in the context of trying to measure secular changes in ocean volumes. Tide gauges measure changes in sea level with respect to the rock or pillar upon which the gauge is mounted and will experience its own movements relative to the Earth's centre of mass. To interpret the tide gauge record in terms of changes in ocean volume, caused for example by anthropogenic factors, requires that both components of the motion are known at the mm/year level. This is probably the most exacting requirement from SLR or any other form of tracking because what is sought is long-term accuracy, not just precision. Also, it will not be adequate to have this measurement from a single site because there is no such physical quantity as a globally uniform sea-level rise or fall. Because of mutual gravitational self attraction of land ocean and ice sheets and because of the Earth's response to changing water loads, even in the absence of tectonic factors sea-level change will not be uniform.

I haven't discussed laser ranging to the Moon (LLR) at this point. I believe that this should not be ignored because ultimately one may learn more about solid planet behaviour by studying the Moon than by studying the Earth because of this satellite's freedom from the hydro-atmospheric disturbances. I think that studies of the Earth's rotation are better done with VLBI and the sole rationale for LLR is to examine the rotational dynamics of the Moon and fundamental physics experiments, much as was argued when the method was first proposed. The rotational deformations of the Moon are at least an order of magnitude smaller than those of the Earth and the requirement for the highest accuracy is clear. But more important than this is to get data on a regular basis from a southern latitude site.

To summarize: for geophysical purposes high accuracy (sub-cm) SLR will continue to be important for:

(i) Providing the critical tracking system of satellite altimetry missions to provide a long-term stable surface for measuring changes in sea-surface topography.

(ii) Provide the essential data base for measuring time-dependent changes in the Earth's gravity field by tracking passive satellites such as Starlette and Lageos.

(iii) Provision and maintenance of a global reference frame for measuring tectonic motions and for providing the standards (calibration) for GPS work over much shorter distances. These stations would provide the reference frame for high-density regional GPS surveys rather than be used as mobile stations for the latter surveys.

(iv) Providing ultra-high accuracy for vertical crustal motions and for calibrating GPS determinations of changes in height.

(v) Providing information on the rotational and orbital dynamics of the Moon (including tidal deformations).
Two more general comments are also appropriate.

(vi) With the increasing measurement accuracies one hits the hydro-atmosphere noise barrier and improvements in the knowledge of the Earth-ocean-atmosphere system will be essential if the improved data is to provide new insights into the workings of the Earth.

(vii) The geodetic measurements provide new insights into the workings of the Earth only if they are accompanied by other geophysical and geological data sets, new scientific concepts and numerical modelling schemes.