SCIENTIFIC GOALS OF LASER RANGE MEASUREMENTS

Peter L. Bender

Joint Institute for Laboratory Astrophysics
National Bureau of Standards and University of Colorado
Boulder, Colorado 80309 U.S.A.

ABSTRACT

Two of the most important areas of geodynamics to which laser ranging appears capable of making fundamental contributions are discussed. These are worldwide plate tectonic motion measurements and the monitoring of the longer wavelength crustal movements in seismic zones. In both areas, the accuracy and reliability of the results are of great importance, since a factor 2 improvement in accuracy can reduce the time necessary for detecting anomalous motions by the same factor. The capabilities of other techniques are discussed briefly, and it is argued that laser ranging to satellites is likely to make major and unique contributions to geodynamics if it succeeds in demonstrating higher measurement accuracy than radio techniques. A strong emphasis on improving the measurement accuracy thus appears to be needed during the next two years.

INTRODUCTION

Accurate laser range measurements to satellites like LAGEOS can provide valuable and exciting new scientific information in geodynamics, as well as important information in several other fields. Rather than trying to cover most possible applications of laser ranging results, the next section will concentrate on discussing what I believe are the two most important scientific problems where laser ranging to satellites is likely to have a major impact in the 1980's. These are the measurement of present worldwide plate tectonic motion rates and the monitoring of the longer wavelength features of strain accumulation patterns in seismic zones.
An additional reason for focusing attention on these two topics, besides their intrinsic scientific importance, is that laser ranging may have a unique advantage in these cases. Other techniques are being developed which can address the same scientific problems, including particularly very long baseline radio interferometry (VLBI) for worldwide measurements and the use signals from the Global Positioning System (GPS) satellites for geodetic measurements in seismic zones. However, for both worldwide plate motions measurements and determining the longer wavelength strain changes in seismic zones, obtaining the highest possible accuracy is of great importance. The potential unique advantage of laser ranging is that its sensitivity to the water vapor content of the atmosphere is lower than for radio techniques. Thus, there appears to be very strong reason for the continued vigorous development of laser ranging, provided that the systematic measurement errors can be reduced to or below the level of uncertainties due to the dry part of the atmosphere.

In view of the importance of achieving high accuracy in laser ranging, some additional discussion of this topic will be given in the third section. Some of the capabilities of the radio techniques will then be reviewed in the fourth section, in order to encourage further discussion of the kinds of scientific problems for which laser ranging is most suitable.

The scientific returns expected from laser ranging and the other techniques include new information on the earth's rotation and polar motion. However, I won't say much about these topics because the network of stations needed for determining crustal movements is likely to produce very good results for earth rotation and polar motion also. Lunar ranging won't be discussed either, although it is likely to make important contributions both to determining the earth's rotation and nutation and to other important scientific questions such as the secular deceleration of the moon, lunar structure, and the validity of present gravitational theories.

Scientific Goals in Crustal Dynamics

One of the most important questions which laser ranging is likely to play a major role in answering is whether the rates of motion of the larger tectonic plates are within roughly 1 cm/yr of the presently estimated rates. Agreement with the estimates is likely if recent studies of the average motion rates over roughly the last 3 million years are correct and if variability over shorter times can be neglected. However, short-term variability appears to be a plausible possibility.

Over periods of up to roughly a thousand years it is possible to think of models where the back part of a plate moves quite uniformly away from a spreading center, but the front or sides of the plate move considerably less because of the lack of large earthquakes at the boundaries. Buildup of stress within the plates over such a period
would not necessarily be sufficient to trigger large earthquakes, and substantial distortion within the plate could occur. In looking for such internal distortions, one prime candidate is the Pacific plate, which is very large and also quite rapidly moving. Another candidate is the Australian plate, which might show distortion between India and Australia because of the episodic nature of crustal movement along the boundary between the Indian subcontinent and the Eurasian plate.

On the other hand, the present ideas of most geophysicists about the viscosity and thickness of the asthenosphere, which underlies the plates, would not permit such distortion away from the boundaries of even large and rapidly-moving plates. The reason is that the calculated time constant for the effect of a major earthquake at the boundary to propagate out into the plate is quite long. For this reason, the effects of changes in the boundary conditions for the plate motion would not have much effect beyond perhaps 300 kilometers from the boundary over periods characteristic of the recurrence times for large earthquakes, such as perhaps 100 or 200 years. Thus, according to this picture, the main part of the plate would continue to move quite uniformly, with earthquakes around the boundary causing episodic strain changes only near the edge. However, we should keep in mind that quite a bit of our present information on the viscosity of the asthenosphere comes from post-glacial rebound studies in Canada and Fennoscandia, which are continental areas. Thus our information concerning the asthenosphere under oceanic plates may be less reliable.

For periods of time longer than roughly 1,000 years, the main question is whether the forces driving plate tectonic motions are likely to be fairly constant. At present, the three types of forces which generally are believed to be the largest ones for a plate such as the Pacific plate are: the gravitational force associated with sliding of the back of the plate off the East Pacific rise; the negative buoyancy force on the down-going slab at the front of the plate because of its higher density; and the resistance of the mantle to the downward motion of the front of the plate. The last two forces may roughly cancel each other for a given rate of motion, with the gravitational sliding pushing on the main part of the plate to keep it pressing against the back of the down-going slab. If these forces really are the dominant ones, it seems unlikely that they would change dramatically over periods of less than perhaps a million years. However, measurements which give direct information on these questions would certainly be valuable. If the present motions of the major plates are not within roughly a centimeter per year of the presently estimated rates, this would require a substantial change in our picture of how the plate motions occur.

Direct measurements of present plate motion rates also will be important for other reasons. For some minor plates, there is not enough information available to determine the long-term average rates. Also, in order to interpret measurements of the apparent motion of a plate, it is necessary to check on the basic stability of a major part of
the plate interior. Otherwise, internal distortions within the plate could lead to errors in the deduced plate motion rate. The measurements of crustal movements in plate interiors will be important also for determining how tectonic forces modify the plates. However, the rates of distortion expected are generally very small, and accuracies of 2 or 3 mm/yr are needed for studying most questions of interest.

A second major question concerns the nature of the larger wavelength crustal movements in and near seismic zones. In this case, there are strong differences of opinion about what measurement accuracy is needed. A substantial number of scientists believe that large displacements occur fairly frequently in some major seismic zones, such as the uplifts characteristic of the reported Palmdale bulge and the horizontal displacements given by the initial interpretation of earlier VLBI mobile station data. On the other hand, it has been suggested that atmospheric refraction or other effects had an important influence on the leveling data used to deduce the existence of the Palmdale bulge, and it seems possible that the reported motion of roughly 20 centimeters for JPL with respect to Owens Valley was due to a combination of ionospheric, tropospheric, and instrumental systematic errors. Thus other scientists would say that the probability of learning about strain accumulation in seismic zones isn't increased much by making measurements more frequently than a characteristic time $T$, which depends on the accuracy of the measurements and the baselines of interest. $T$ would be roughly the time required at the average strain accumulation rate for the area to accumulate displacements equal to the accuracy for measuring displacements. For the San Andreas fault system, the average rate is typically about 2 parts in $10^7$ per year.

It seems to me that the strategy for measuring crustal movements by space techniques needs to be "robust" in the statistical sense. Namely, the strategy should be designed so that it is likely to lead to useful results, whichever of the two opinions about the nature of the motion we are looking for turns out to be correct. Thus, a major part of the effort should be devoted to making the measurements as accurately as possible. But there also is a need for making other measurements rapidly, even if the accuracy is somewhat lower, in case large motions actually are occurring or might occur a short time before a large earthquake.

Laser range measurements seem likely to contribute mainly through the monitoring of a moderate number of sites with as high accuracy as possible. In California, for example, the accurate monitoring of 15 to 20 sites once per year can provide valuable new information on strain accumulation out to large distances from the main fault system. These sites will be coordinated with the accurate trilateration networks of the U.S. Geological Survey so that they provide both ties between the networks and intercomparison lines across the networks.

For measurements in major seismic zones in other countries, the ways in which laser ranging can contribute will vary. In
Japan, where excellent ground measurement networks already exist and frequent measurements are made in special study zones, the role of laser ranging may be similar to that expected in California. In areas such as western South America, sites monitored by laser ranging are more likely to serve as reference points for measurements made using other types of instruments, such as GPS geodetic receivers. Such combined networks could provide quite high accuracy, at relatively low cost, for monitoring long-term strain accumulation patterns in areas where extensive ground measurement networks do not exist at present. They also would give valuable initial epoch measurements at an early date, so that coseismic and postseismic displacements after a large earthquake could be determined effectively.

A third type of seismic zone investigation is represented by proposed measurements in the Hellenic Arc, where substantial chances of a major earthquake in this century appear to exist, and other tectonically active areas of southern Europe and the Near East. Another application in the future might be to determine where the relative motion between the Indian subcontinent and central Asia is being accommodated. Ground measurements in the USSR have indicated relative motions of about 2 cm/yr between two mountain ranges in the region near Garm, but it is not known where the rest of the expected motion is occurring. Other important applications may be in New Zealand, where a major strike slip fault system can be studied relatively easily, and in the major seismic zones in China, India, Pakistan, and the USSR.

RELATED QUESTIONS CONCERNING MEASUREMENT ACCURACY

In view of the necessity of achieving high measurement accuracy and reliability for the scientific problems considered above, some additional discussion of accuracy seems desirable. Some useful methods for evaluating accuracy are as follows: (a) construction of systematic error budgets, (b) investigation of the stability and reasonableness of results, (c) comparisons with other laser ranging systems over short baselines, and (d) consistency of global solutions. While all of these methods have some advantages, none of them is sufficient by itself. For example, important effects can be left out of systematic error budgets, and the stability and reasonableness of experimental results over some period of time would not show up errors which correlate strongly with the azimuth or elevation angle of the observations, since they would produce consistent effects in the apparent station position. Also, consistency of global solutions cannot be established until after systems with high accuracy have collected data for a substantial period, such as a year or so. It thus seems necessary to proceed using all four of these approaches.

The confidence level for measuring crustal movements has to be high if the results are to influence geophysicists. Some prior information exists on long-term plate motions plus reasonable theoretical reasons for suspecting constancy of motion over long times, as
discussed earlier. Thus, geophysicists aren't likely to change their ideas based on discrepancies which have only 70% confidence limits, which really constitute "just another opinion." Testing hypotheses at the 95% confidence level is widely accepted in biology, medicine and other areas of science. It seems essential to reach the same level of confidence in deciding whether anomalous motions have been detected. This is particularly true for conclusions about whether the present rates of plate motion disagree with the long-term average rates.

It should be emphasized that dealing with 95% confidence intervals is substantially different than taking 70% confidence intervals and then roughly doubling them. That procedure would work for Gaussian error distributions or any other error distributions for which the tails cut off rapidly. But with some systematic error sources, the error level for 95% confidence may be 4 or 5 times larger than for 70% confidence. For example, wavefront correction errors may average out fairly well at the 70% confidence interval because of changes in the pointing error during the course of a run or over a couple of days. However, at the 95% confidence level it is much harder to be sure that correlated effects aren't present, such as the pointing being considerably better later in the run than early in the run, coupled with smaller wavefront correction errors in the center of the beam. This could give an apparent offset in the station position. It seems necessary to make up separate systematic error budgets at the 95% confidence level, rather than assuming that the ratio of 95% and 70% confidence estimates for different error sources is the same.

One particularly disturbing thing about systematic errors is associated with the fact that they can vary systematically with time during a pass so that they cause an error in the station position. The magnitude of the station error can then drift roughly linearly over long periods of time because of gradual changes in the instrumental errors. Thus, one could remeasure a baseline many times over a period of 2 or 3 years and see a roughly linear change in length. However, the confidence level for being able to say that a real change in length occurred may be little better than if most of the intermediate measurements hadn't been done. This is because, at the 95% confidence level, the magnitude of the systematic errors could indeed have changed roughly linearly 5% of the time. Additional intermediate measurements still are valuable, of course, in giving consistency checks.

The approach of constructing careful error budgets and publishing a discussion of how the individual error magnitudes were estimated has been used very widely in connection with measurement of the fundamental constants in physics. Realistic error estimates are needed so that the results of experiments measuring different combinations of the fundamental constant can be combined. While the degree of over-determination in the available experiments is not very high, it is sufficient to show how consistent the results are. Discrepancies certainly occur, but historically the number of experiments which have turned out to be in error by considerably more than the quoted uncertainties has been fairly small.
As an example of the extent of accuracy improvement which is needed, the error budgets for the NASA stations given in the Laser Ranging System Development Plan (NASA, 1980) are shown in Table 1. The error contribution due to the dry part of the atmosphere has been reduced to 0.7 cm to correspond to the results obtained by Gardner (1976) at 20° elevation from radiosonde data without any correction for horizontal gradients in the atmospheric density. Fortunately, at least one of the MOBLAS stations currently is being substantially upgraded in accuracy, as discussed in another paper, and it is planned to upgrade three of these stations to 1 to 2 cm accuracy at the 70% confidence level by 1983. However, further accuracy improvements certainly are needed in the next 2 years.

Table 1
Current Error Budgets* for the GSFC Satellite Laser Ranging Systems

<table>
<thead>
<tr>
<th>Error Source</th>
<th>STALAS</th>
<th>MOBLAS 1-3</th>
<th>MOBLAS 4-8</th>
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<tbody>
<tr>
<td>Transmitter</td>
<td>0.5 cm</td>
<td>2.5 cm</td>
<td>6.0 cm</td>
</tr>
<tr>
<td>Atmosphere</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Satellite (LAGEOS)</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Receiver</td>
<td>1.5</td>
<td>4.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Timing</td>
<td>0.7</td>
<td>0.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Calibration</td>
<td>1.0</td>
<td>1.0</td>
<td>1.0</td>
</tr>
<tr>
<td>Total (RSS)</td>
<td>2.1 cm</td>
<td>4.9 cm</td>
<td>10.1 cm</td>
</tr>
</tbody>
</table>

*Normal point accuracy, 100-point average.

CAPABILITIES OF OTHER TECHNIQUES

In discussing the scientific contributions which laser ranging is likely to make, it is important not to underestimate the capabilities of other methods. Some of the capabilities demonstrated by VLBI measurements for determining baselines are listed in Table 2. The subcentimeter demonstrated accuracy and repeatability over a 1.24 kilometer baseline and the 3 centimeter repeatability over 4 years for a 3,929 kilometer baseline are accomplishments which laser ranging has not yet equaled. Also, actual measurement times as short as 1 day at a site have been demonstrated by the mobile 4 m ARIES VLBI station.

For measurements with either VLBI or GPS signals, the uncertainty in the tropospheric correction due to water vapor seems likely to be the most serious limitation. Even with water vapor radiometers in operation at each site, the uncertainty in the water vapor correction is likely to be about a centimeter, as discussed elsewhere (see e.g. Resch, 1980; Guiraud et al., 1979; and other references given in Bender, 1980). However, the situation is really too complicated to
Table 2
VLBI Baseline Measurements

<table>
<thead>
<tr>
<th>Length (km)</th>
<th>Precision, Repeatability, or Accuracy (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.24</td>
<td>0.3, 0.5, 0.7 (three components)</td>
</tr>
<tr>
<td></td>
<td>&lt;0.6</td>
</tr>
<tr>
<td>42*</td>
<td>10</td>
</tr>
<tr>
<td>3929</td>
<td>3 Repeatability (4 yrs)</td>
</tr>
<tr>
<td>5600 to 7914†</td>
<td>6 to 8 Precision</td>
</tr>
</tbody>
</table>

*Difference of 353 and 387 km baselines measured by mobile station.
†U.S. to Sweden baselines; precision estimated from effects of different assumptions in analysis.

be described by a single number. In addition to the calibration errors of the water vapor radiometers, the effects of uncertainties in the effective emission temperature of the atmosphere and in the distribution of droplet sizes in clouds also have to be considered. Radiometer calibration errors are not likely to introduce azimuth-dependent measurement errors, so horizontal coordinates may be affected relatively little by this source of error. On the other hand, the one centimeter water vapor correction error estimate mentioned above has not yet been demonstrated experimentally, and the effect of such an error on the vertical coordinate of a station may be larger by as much as a factor 2.

The level of uncertainty in the range due to horizontal gradients in the dry part of the atmosphere also is uncertain. Since such uncertainties affect laser ranging as well as radio methods, the potential accuracy advantage of laser ranging would be small if the dry part of the atmosphere should turn out to introduce as much uncertainty as the water vapor does. Hopefully some reduction in the horizontal gradient error below the 0.7 cm value at 20° elevation angle found by Gardner (1976) can be achieved by using airport radiosonde data or other meteorological information, since much of the effect comes from gradients at the higher elevations. Such gradients may exist over fairly large areas and be stable over periods of a number of hours, except near frontal systems. However, Pearce et al. (1981) have raised the question of whether gradients with shorter wavelengths than those studied by Gardner may give larger uncertainties for an observation campaign of limited duration. Such questions certainly need to be resolved.
While the size of the effects discussed above is considerably more uncertain than we would like, it still seems fairly likely to me that the errors for laser ranging will be a factor 2 smaller than those for radio techniques. Thus, if we can make the other sources of systematic error for laser ranging small enough, I believe that the overall accuracy may be better than for any other technique.

The crustal dynamic problems for which an accuracy advantage would be particularly important are those discussed in Section 2; i.e., measurements of plate tectonic motions and of the longer wavelength distortions in seismic zones. For plate tectonic motions, in particular, the total number of measurements needed per year is limited, so the overall cost hopefully can be kept at a reasonable level. A factor 2 difference in accuracy will have a major impact scientifically, as mentioned earlier, because it reduces the time necessary to compare present motions with the expected rates by about the same factor. If this means obtaining new scientific information in 5 years which otherwise would have taken 10 years of measurements, then the probability of affecting the work done in a considerable area of geodynamics over a substantial period of time is considerably enhanced. For determining where large-scale distortion is taking place in plate interiors, the advantage of improved accuracy is equally strong.

There are important types of problems, however, for which laser ranging from mobile ground stations does not seem likely to be the most efficient approach. This includes, particularly, cases where large numbers of measurements need to be made per year, either with moderate times between measurements at a high density of points in seismic zones, or at very short repetition times for a lower density of points. In cases of this kind the cost per measurement is a very important factor, as well as the accuracy. It now appears likely that measurements using GPS receivers can be made with 1 or 2 centimeter accuracy in times as short as half an hour or less if the Global Positioning System is completed as planned. If not, VLBI measurements with highly mobile stations will still be quite competitive because of the considerable cloud cover problems for laser ranging, and the fact that one doesn't have to wait for a LAGEOS pass to make observations. While the cost of high mobility laser ranging stations is likely to be less than that for their VLBI counterparts, the operating budgets probably will be the most important factor over long times. However, if new information on the relative accuracies achievable by optical and radio methods favors laser ranging, the use of a larger number of high density satellites in lower orbits needs to be considered (Wilson et al., 1978). The launch of a second LAGEOS satellite also might be desirable in that case.

In addition to the measurements discussed above, a few words should be said about the possible future capabilities of airborne laser range measurements. NASA has been involved in investigating the accuracy achievable by pulsed laser range measurements from aircraft to ground reflectors. This approach might well be competitive for
frequent repeat measurements in seismic zones with the use of high mobility VLBI stations and possibly also with GPS receivers if higher accuracy can be achieved. In addition there is a possibility that airborne measurements using a line crossing method with microwave modulated cw lasers would be desirable in the future. The potential advantage would be high measurement accuracy, with the two-wavelength approach used to correct for atmospheric refraction. However, the vertical coordinate would not be determined well with this approach.

REFERENCES


