THE MEASUREMENT OF THE POSITIONS OF POINTS ON THE EARTH'S SURFACE USING AN ABSOLUTE GRAVIMETER AND A MULTI-WAVELENGTH GEODIMETER AS COMPLEMENTS TO EXTRATERRESTRIAL TECHNIQUES

James E. Faller* and Judah Levine†

Joint Institute for Laboratory Astrophysics‡
Boulder, Colorado 80309

ABSTRACT. The usefulness of extraterrestrial techniques and in particular lunar laser ranging in obtaining the position of points on the earth's surface with an accuracy of several centimeters is now recognized. The positional information obtained in this way cannot be unambiguously interpreted without ancillary surface measurements. The use of a geodimeter with an accuracy of 5 parts in 10^8 (over a 50 km baseline) would permit all of the points within a radius of several hundred kilometers around a ranging station to be tied together with centimeter level accuracy, thereby eliminating any local phenomena that could be associated with single-point sites and at the same time extending the coverage of extraterrestrially determined measurements. The use of an absolute gravimeter with an accuracy of 3 parts in 10^9 (which corresponds to a height sensitivity of about 1 cm) would serve as a check on vertical motions and, in combination with extraterrestrially determined height data, yield information on internal mass motions. The implications of these ground-based measurement capabilities for extraterrestrially determined position measurements are discussed.

---

*Staff member, Laboratory Astrophysics Division, National Bureau of Standards.

†Staff member, Time and Frequency Division, National Bureau of Standards.

‡Of the National Bureau of Standards and the University of Colorado.

J.D. Mulholland (ed.), Scientific Applications of Lunar Laser Ranging, 277-283.

The interpretation of extraterrestrially determined position measurements will require local measurements that tie the particular (single-point) site to the general surrounding region in order to separate region-wide effects from local phenomena. Accordingly, realization of a terrestrially determined local control for both vertical and horizontal movements is necessary for the understanding and interpretation of the extraterrestrial measurements. Two different precision measurement position-determining techniques are discussed here -- the use of a multi-wavelength geodimeter for horizontal control and the application of absolute gravity for vertical. Both can serve to complement as well as extend the coverage of extraterrestrially determined position measurements.

The concept of measuring distances on the surface of the earth, using the time of flight of electromagnetic signals is not new. Indeed Galileo's two-lantern method for measuring the speed of light contained the germ of the idea that was basic to the subsequent development of many different geodimeters (or earth-measuring instruments) with widely varying accuracy and range capabilities. The instruments currently used by the Geological Survey (Savage and Prescott 1973) for example, have a range of about 35 km and an accuracy of a few parts in 10^7. The instruments use only a single optical wavelength so that ancillary measurements are required to determine the index of refraction. These measurements are made using an aircraft that flies along the path while the optical measurement is in progress.

In an attempt to directly measure the index of refraction along the path, various multiple wavelength systems have been proposed (Wood 1971). All of these systems determine the index by measuring its dispersion, i.e., by measuring the difference in the optical paths at several wavelengths. The most sophisticated multiple wavelength system to date has been constructed by Huggett and Slater (1975). They report a standard deviation of about 5×10^{-8} for short-term measurements and 1.3×10^{-7} for long-term measurements over a 10 km path. The system required here would be an extension and improvement of this multi-wavelength idea. With it, ranges on the order of 50 km or more could be measured with an accuracy of a few parts in 10^8. This would represent a substantial improvement both in range and in accuracy over any currently available instrument, and, what is more important, would provide the type of horizontal measurement capability that will be required to understand and interpret measurements obtained using extraterrestrial techniques.

The instrument would utilize three wavelengths (two one-way optical and one round-trip microwave) to measure directly the integrated index of refraction along the path due to dry air and water vapor, thus providing a determination of the physical distance with no ancillary path measurements other than the temperature at the end points. Such a system would enjoy several advantages over existing single and multiple wavelength instruments (Huggett and Slater 1975, Earnshaw and Hernandez 1972, Bouricius and Earnshaw 1974). Most of the advantages are a result of the one-way (for the two visible wavelengths) nature of the system. Primarily, the effects of atmosphere beam spreading on signal strength for a given path length would be reduced by a factor of at least 16 and possibly much more, depending on the detailed character of the turbulence. Thus a one-way system will have at least a factor 4 greater range (to the extent that two-way systems are limited by the number of photons received back at the transmitter -- a limitation which is extremely important in any two-way system).

The main disadvantage of the one-way system is that the receiving end is not as easily transported as it would be in a two-way system, and because of this it is probably unrealistic to employ multiple receivers as can be easily done with two-way systems. Synchronization of the modulators at the two ends is an additional complication, but presents no real technical problem.

An instrument with this range and accuracy capability (i.e., better than 50 km range with an accuracy of a few parts in 10^8) would be useful for several different investigations. Of particular concern here, the instrument would be most useful as an adjunct to the extraterrestrial geodetic techniques. For example, a determination of the motion of the Pacific plate will shortly begin using the lunar ranging stations at Haleakala and at McDonald Observatory in Texas. A necessary part of this program will be the measurement of any possible motions of the Haleakala site with respect to the older islands to the northwest. A series of lines from Haleakala to Oahu, for example, would span a distance of order 170 km which must be measured to about 1 cm (corresponding to an accuracy of 6 parts in 10^8) in order for the full capability of the lunar ranging system to be realized. Furthermore, the measurement would have to consist of several lines, the longest of which might have to be as long at 70 km (from Nuuanu Pali on Oahu to Puu Nana on Molokai). Thus both the full accuracy capability and the full range capability of the instrument being discussed would be necessary. The instrument would also be useful to tie McDonald Observatory and the other sites involved in the NASA validation program (Goldstone or Haystack, for example) to reference points which may be from 100 to 200 km away.

A second major area in which the proposed measurements would complement extraterrestrial geodetic techniques is in the general field of geodynamics. Within the next five years or so a readjustment of the North American Geodetic Network will be made. In the continental U.S. there will be about 100 fundamental control points spaced roughly 300 km apart. These points are currently being determined with accuracies of 1 to 2 meters using the Doppler satellite technique. However, an accuracy of 3 cm appears to be achievable using a combination of lunar ranging, satellite ranging and very long baseline radio interferometry. Many geodynamically significant measurements can be made with respect to these points. Important questions that need to be addressed include the overall rates of tectonic movements in the interior of lithospheric plates, including particularly the strain rate in the Basin and Range province, and whether improved geodetic measurements will show strain accumulation near the sites of previous large earthquakes in the eastern U.S. and Mississippi Valley (NAS 1973). A reason for increased emphasis on crustal movements in plate interiors comes from recent evidence based on leveling data for relative vertical movements of up to 1.5 cm/yr between the Atlantic Coast and areas west of the Appalachians (Brown and Oliver 1976). If there are vertical movements of this magnitude, it seems useful to determine whether associated horizontal movements are also present. This was not possible earlier because of the relatively low accuracy of horizontal measurements compared with vertical measurements as determined by leveling, but the existence of such a geodimeter would make horizontal measurements much more reliable.

Although much work in seismic zones can be done using existing techniques, determination of the strain accumulation at sites along the San Andreas fault system using existing geodetic instrumentation will require annual observation of many line lengths over a period of at least 5 years (Savage and Prescott 1973). This time could be shortened by a factor of about 5 if the measurements are made accurate to 5 parts in 10^8. In addition, high accuracy measurements over a zone extending at least 100 km from the fault zone at various times after a major earthquake would be valuable in determining the fault plane motion versus time. If post-quake creep occurs at depth, quantitative information on it should be obtainable from the time history of the crustal displacements.

Finally, the existence of such an instrument would make intermediate distance geodesy (lines less than a few hundred kilometers long) faster and cheaper simply because fewer measurements would be required.

Virtually all our present understanding of vertical crustal movements rests on long-term geological evidence or on incremental evidence developed from leveling. Significant measurement capabilities, however, now exist that would permit "real-time" observation of vertical displacements at the 1 cm/yr level at widely separated locations without the need for measurements at intermediate points.

The extraterrestrial techniques will only yield vertical height information. The measurement of gravity provides a corresponding monitoring technique that is sensitive to a combination of vertical motion and mass redistributions inside the earth. In effect gravity provides a vertical reference tied to the center of mass of the earth which can tell us if the combination of elevation and local mass distribution is stable.

As a result, the combination of gravity measurements and extraterrestrially determined height information should, over a period of years, provide information on the rates of vertical tectonics and isostatic adjustments within the lithosphere and upon the magnitude of mass changes that may accompany secular changes in the gravity field. The establishment and use of these techniques to identify and interpret structural models of the outer levels of the earth would be important to our understanding of the mechanisms by which surface features of the earth are formed. The succeeding measurements of vertical dynamics and isostasy should provide tests of various interpretations obtained from structure models and analytical studies of the gravity field.

The main limitation on the interpretation of gravity changes probably will come from the complicating mass motions that can occur. Horizontal motions of material within the aesthenosphere or discharges of deep aquifers can occur over long periods of time, while changes in the local water table can offset gravity on a short time scale. Thus, the use of gravity variations would require that superficial geological effects such as changing water tables be subtracted on the basis of direct measurement, differential gravitational measurements, or differing characteristic frequencies.

To check on the extraterrestrially determined vertical height changes, given that the rate is of order 1 cm/yr, requires in effect a dc gravimetry capability with parts in 10^9 long term measurement stability -- in effect a requirement for accuracy as well as precision. With respect to this last requirement, the field of gravity is perhaps unique in that one has the capability for absolute instruments with accuracies equal to the precision of the best relative instruments (gravimeters).

The technical basis for this rests on the methods of Sakuma (1971,1973,1974), Faller (1965,1967), Hammond and Faller (1971a, 1971b) and Faller and Hammond (1974) for the free-fall determination of g. In brief, since "g" -- the acceleration of gravity -- involves the dimensions of length and time (LT^{-2}), an absolute determination necessarily requires that both length and time be measured on an absolute basis. An interferometer conveniently lends itself to a length measurement in terms of the wavelength of light, and, at the same time, permits an effective utilization of present-day technology in the measurement of time.

These free-fall methods use one element of an optical interferometer as the dropped object. Stabilized lasers provide the required brightness and coherence to achieve high-quality fringes over the required half-meter or so dropping distance. The problem associated with the use of an interferometer, the extreme sensitivity of the pattern to the parallelism of the plates, is circumvented by using corner cubes rather than plane mirrors for reflectors. The signal-to-noise ratio is such that it permits the dynamic length measurement to be made to better than $\lambda/100$. The time base is obtained from highly stable crystal oscillators. Utilization of high-speed electronics results in timing accuracies of better than a nanosecond.

Finally, recent work by a graduate student at JILA, Robert Rinker, has resulted in substantial progress toward the development of a new type of long period ($T > 40$ sec) suspension for isolating the reference mirror (corner cube) in the interferometer from all background disturbances. Improvements here over the isolation methods available in the past should make it possible to achieve a few parts in 10^9 accuracy level in a field-type instrument.

Such absolute instruments could be used for drift control on the less expensive La Coste-type relative instruments as well as a direct monitor at some crucial locations. The existence of this type of gravity capability would, in addition to complementing the extraterrestrial methods in the study of tectonic deformation, prove valuable in the areas of earthquake prediction, geothermal exploration, volcano surveillance, and studies of subsidence detection over geopressured areas.

Though in the past vertical height information was chiefly derived from leveling data, the cost per kilometer of leveling is high (Castle, Church and Elliott 1976). Thus, gravity offers an economical tool for initial reconnaissance as well as the high (centimeter-level) sensitivity required to complement that of the extraterrestrial techniques.

In conclusion, the extraterrestrial methods that yield horizontal position information, as well as vertical height information, are seen to be complemented by geodimeter horizontal distance measurements and gravity-determined vertical height data. As measurement capabilities now equal the level at which geophysical things are happening, the utilization of these new methods and techniques (both extraterrestrial and terrestrial) to study, understand, and disentangle the variety of effects should make for an exciting next decade of study of the earth on which we live -- an era in which direct crustal movement measurements in geophysics should come of age.

REFERENCES

Bouricius, G.M.B. and Earnshaw, K.B.: 1974, *J. Geophys. Res.* 79, 3015.

Brown, L.D. and Oliver, J.E.: 1976, *Rev. Geophys. Space Phys.* 14, 13.

Castle, R.O., Church, J.P. and Elliott, M.R.: 1976, *Science* 192, 251.

Earnshaw, K.B. and Hernandez, E.N.: 1972, *Appl. Opt.* 11, 749.

Faller, J. E.: 1965, *J. Geophys. Res.* 70, 4035.

Faller, J. E.: 1967, *Science* 158, 60.

Faller, J. E. and Hammond, J.A.: 1974, in *Bulletin d'Information* No. 35, Bureau Gravimetrique International, pp. I-43 - I-48.

Hammond, J.A. and Faller, J.E.: 1971a, *J. Geophys. Res.* 76, 7850.

Hammond, J.A. and Faller, J.E.: 1971b, in D. N. Langenberg and B.N. Taylor, Eds., *Proceedings of the International Conference on Precision Measurement and Fundamental Constants*, Nat. Bur. Std. Spec. Publ. 343, U.S. Government Printing Office, Washington, D.C., pp. 457-463.

Huggett, G.R. and Slater, L.E.: 1975, *Tectonophysics* 29, 19.

National Academy of Sciences: 1973, *U.S. Program for the Geodynamics Project, Scope and Objectives*, pp. 49, 72, 82, 84, 152, 173.

Sakuma, A.: 1971, in D.N. Langenberg and B.N. Taylor, Eds., *Proceedings of the International Conference on Precision Measurement and Fundamental Constants*, Nat. Bur. Std. Spec. Publ. 343, U.S. Government Printing Office, Washington, D.C., pp. 447-456.

Sakuma, A.: 1973, in *Proceedings of the Symposium on Earth's Gravitational Field and Secular Variations in Position*, Sydney.

Sakuma, A.: 1974, in *Bulletin d'Information* No. 35, Bureau Gravimetrique International, pp. I-39 - I-42.

Savage, J.C. and Prescott, W.H.: 1973, *J. Geophys. Res.* 78, 6001.

Wood, L.E.: 1971, *E.O.S.* 52, 17.