APPLICATIONS OF PTTI TO NEW TECHNIQUES FOR DETERMINING CRUSTAL MOVEMENTS, POLAR MOTION, AND THE ROTATION OF THE EARTH

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ABSTRACT

New extra-terrestrial techniques for geodesy and geodynamics include laser range measurements to the moon or to artificial satellites, Doppler measurements with the Transit satellite system, and both independent-clock and linked-antenna microwave interferometry. The ways in which PTTI measurements are used in these techniques will be reviewed, and the accuracies expected during the latter half of the 1970's will be discussed. At least 3 of the techniques appear capable of giving accuracies of 5 cm or better in each coordinate for many points on the Earth's surface, and comparable accuracies for the Earth's rotation and polar motion. For fixed stations or for sites a few hundred km apart, baseline lengths accurate to 1 cm may be achieved. Ways in which the complementary aspects of the different techniques can be exploited will be discussed, as well as how they tie in with improved ground techniques for determining crustal movements. Some recent results from the extra-terrestrial methods will be mentioned.

INTRODUCTION

Since the mid-1950's a true revolution in our understanding of the Earth has taken place. From the mid-1960's the majority of earth scientists have come to regard the plate tectonics theory as a major unifying concept in describing the dynamical forces which have shaped the Earth as we know it today. I think that you are all aware of the general outline of this theory: tectonic plates roughly 100 km thick make up the surface, and they move about on a low-viscosity layer perhaps 200 km thick called the aethenosphere. The plates move away from the "ridges" or "rises", usually in the oceans, where new material coming up from the mantle is added onto the plates. Where two plates approach each other, one normally is pushed or pulled down and penetrates to depths of roughly 700 km in the mantle before evidence of its existance fades out. The geological and geophysical record of the past motions is written in the present materials and properties of the plates, the aesthenosphere, and the upper mantle.

We now know a great deal about the average motions in the past, but unfortunately this is like having watched cakes of ice floating on a swirling body of water, and trying to understand what is happening from the grindings, distortions, and relative motions of the semi-rigid cakes. If we are reduced to only knowing the long term average motions, the problem is even more difficult. Better measurement methods are just what is needed to determine the present motions and distortions of the plates, and these methods all involve Precise Time and Time Interval techniques.

The new extra-terrestrial techniques are Doppler measurements with the Transit satellite system, both linked-antenna and independent clock microwave interferometry, and laser distance measurements to the moon and to artificial satellites. However, it appears that these techniques will be very much complemented by new developments in ground measurement methods. These are the use of 2-wavelength microwave modulated laser devices for measuring point-to-point distances on the earth's surface and of portable high-precision gravimeters for measuring changes in gravity with time at a given point. The futures of both types of ground measurements look very bright. The first has an expected distance accuracy of better than 1×10^{-7} over distances of roughly 30 km, and the other enough expected accuracy to detect gravity changes due to 1 cm vertical motions.

MICROWAVE INTERFEROMETRY AND DOPPLER TECHNIQUES

One of the important developments in geodesy recently has been the use of Doppler frequency shift measurements with signals received from Transit satellites to determine the location of over 200 points on the Earth's surface. These points now can be used as a world-wide network of control points, which appear to have an accuracy of about 2 meters. The National Geodetic Survey now plans to make use of about 130 Doppler-determined points in North America as the basis for its work on readjustment of the North American Geodetic Network. The Doppler satellite method has been described in a number of places,[1-5] and will not be described further here. The main experimental limitations on accuracy come from inospheric effects, because of the relatively low transmitted frequencies which are used, and orbit determination problems due to the fairly low altitudes of the satellites. Future developments expected with the Global Positioning System are discussed later in this Meeting.

Microwave interferometry promises to be a major source of information on geodynamics. Basically, a comparison of the arrival times of radio signals from a very distant source at two antennas gives the component of the baseline vector between the two sites projected onto the direction toward the source. Extra-galactic microwave sources furnish the signals for most long-baseline work, with fluctuations in the emission in effect providing the events whose differences in arrival time are measured. Measurements with a number of sources in different directions give the vector baseline between the sites. If the two antennas are linked by cables or microwave transmission between them, then the time difference can be determined directly. If very long baselines are used, then ultra-stable independent clocks at the two sites are employed, with differences in the clock epochs and rates being solved for from the data.

A major point to be made is that atmospheric corrections to the microwave path lengths through the troposphere are likely to be the largest source of error in future geodynamics measurements. If this is so, extending the baseline lengths doesn't help very much over some range of distances because the errors in the corrections become less well correlated. However, when the separation is large enough so that little correlation is left anyway, or so that one can obtain accurate enough measurements of the atmospheric corrections at the sites independently, then the resulting limitation on fractional baseline accuracy goes down with increased baseline length. For this reason, although very useful results have been obtained with linked antennas, the independent clock variety are likely to be more important for geodynamics.

Independent clock microwave interferometry, or very long baseline interferometry (VLBI) as it is usually called, is discussed in depth later in the Meeting. I will only say a few words about its accuracy here. The most stable frequency standards available are needed for geodynamics work, as well as the use of two observing frequencies to remove ionospheric effects, careful antenna calibration procedures, and the use of extra-galactic sources which show as little structure as possible over long baselines. However, these considerations are really factors in the ease of making the observations, and hopefully will not affect the final accuracy.

The one accuracy limitation which is not shared with laser range measurement techniques is the sensitivity of the microwave propagation velocity to water vapor in the atmosphere. This appears to require the use of water vapor monitoring at each antenna by means of microwave radiometers looking along the line of sight.[6,7,8] With this approach, an accuracy of at least 1 to 2 cm in the water vapor correction at any time for vertical propagation through the atmosphere appears to be achievable, and some experimental data on this question is now available.[9] This limitation may be worse for propagation at lower elevation angles, but it should be recognized that substantial benefits from averaging can be obtained for many applications of the data. Water vapor tends to lie mostly below 3 km in the atmosphere and to be rather patchy in distribution, so that averaging is probably more effective than for the dry part of the atmosphere which affects optical observations. Also, to the extent that the water vapor distribution is horizontally stratified, it can be taken out at least partially from the observations themselves.

A major advantage of the VLBI approach compared with laser range techniques is the all-weather capability of the method, which means that observations can be made a considerably larger fraction of the time than with the laser techniques. A number of papers are now available which discuss geodynamics applications of VLBI.[10-18] In addition to accurate determinations of UT1, polar motion, and plate tectonics measurements with fixed stations, the desirability of using mobile VLBI stations to measure crustal movements at a large number of points on the Earth's surface has been emphasized.

LASER DISTANCE MEASUREMENTS TO ARTIFICIAL SATELLITES AND THE MOON

The beginnings of a new era in worldwide geodesy can be tied to the introduction of satellite geodesy and, within the U.S., to the start of the National Geodetic Satellite Program. This program, which is now completed,[19-24] succeeded in tying together many points throughout the world with an accuracy of roughly 5 meters. The results were based mainly on angular position measurements of artificial satellites against the stars, although some Doppler measurements and laser distance data were included also.

It can be shown that optical or electromagnetic distance measurements are much less affected by atmospheric refraction uncertainties than are angle measurements. For this reason, laser distance measurements to satellites offer great improvements in geodetic accuracy over photographic methods. However, in order to take advantage of the improved measurement accuracy for determining a worldwide network of fundamental reference points, it is necessary to increase the satellite altitude greatly. This is required in order to stringently decrease the perturbations on the orbit, so that observations from different ground sites at different times can be tied together via accurate dynamical calculations of the orbit. Even if nearly simultaneous observations from a number of ground stations are used in order to reduce dependence on the orbit computations, a high altitude still is necessary in order to permit mutual visability from widely separated sites.

The Laser Geodetic Satellite[25] (LAGEOS), which is scheduled for launch by NASA in 1976, is intended to fill the need for a stable, high altitude retroreflector satellite. The currently planned orbit is nearly circular, with an altitude of about 6000 km and an inclination of 70 degrees. The satellite is as dense as possible, subject to the launch vehicle weight limitations and the surface area needed for the desired number of retroreflectors. It is completely passive and highly symmetrical, and the retroreflector arrangement is such that the geometrical offset between the center of mass of the satellite and the average optical reflection point is accurately known.

Although a satellite like LAGEOS is needed in order to obtain very high accuracy geodynamics results, a large amount of work based on laser distance measurements to other artificial satellites already has been reported.[26-36] When LAGEOS is available, the main limitations on determining crustal movements and polar motion probably will be: 1) uncertainties in the orbit at the time of the measurements; 2) uncertainties in the atmospheric correction to the measured round-trip laser travel time; and 3) systematic and statistical errors in the travel time measurement. The second limitation has been considered by several authors,[37-39] and a correction procedure based on the assumption of hydrostatic equilibrium seems very powerful. The water vapor effect is about 100 times less than for microwave measurements, and horizontal gradients in the atmospheric conditions are likely to contribute less than 0.5 cm to the uncertainty. Deviations from hydrostatic equilibrium are small under almost all conditions when laser measurements are likely to be made, and the overall atmospheric correction error at elevation angles of down to 20 degrees thus is likely to be 1 cm or less. The third limitation-travel time measurement uncertainty - already is 10 cm or less even with laser pulse lengths of several nanosec. It seems likely to be improved to 0.1 nanosec (i.e. 1.5 cm) or better when sub-nanosec pulse length lasers are used. The timing accuracy referred to here is that of a "normal point" constructed from several minutes of data.

For the orbit uncertainty limitation, a simple numerical value is difficult to obtain. Simulations of geodetic measurements using LAGEOS are being carried out at the Smithsonian Astrophysical Observatory and the Goddard Space Flight Center. Once we have improved our knowledge concerning the lower harmonics of the Earth's gravitational field from studies of LAGEOS orbit perturbations or from other satellites to a sufficient extent, the main orbit perturbation which is likely to cause trouble is that due to inaccuracy in modeling variations in the Earth's albedo radiation pressure on the satellite. However, the extent of the build-up in orbit uncertainty depends on the distribution in location and time of range observations from all of the stations participating in the program. Also, the effect of a certain amount of orbit uncertainty will be less if the relative locations of several stations within a limited geographical area are being determined rather than station locations all over the Earth. In any case, with a sufficient number of well-distributed high-accuracy ground stations, the orbit uncertainty limitation is not expected to be substantially worse than the other two limitations.

For laser range measurements to optical retroreflectors on the moon,[40-43] the atmospheric and timing limitations are quite similar to those for ranging to artificial satellites. The orbit stability is much higher, which is certainly an advantage. The librations of the moon about its center of mass appear to be modelable down to below the usual systematic measurement error limits by fitting data from differential measurements to the different reflectors.

However, even if the lunar orbit and libration uncertainties are negligible, and even if the only object were to determine crustal movements, it would still be necessary to make frequent measurements from a number of fixed stations in order to monitor variations in the Earth's rotation and polar motion. Present information indicates that polar motion fluctuations are slower than those in rotation.[72] Thus how much less monitoring from fixed stations is needed for lunar ranging than for LAGEOS may depend on how large the power spectrum of fluctuations in the Earth's rotation is at short periods, compared with the fluctuations in the unmodelable orbit perturbations for LAGEOS.

The main disadvantage of lunar ranging for determining crustal motions, compared with the artificial satellite method or VLBI, is connected with the slow rate of declination change for the moon. Since the period for declination change is 27 days, a mobile lunar ranging station has to stay at one site for perhaps 3 weeks, allowing for weather, in order to make measurements over the whole range of declinations. Measurements at different declinations are necessary in order to determine all 3 components of the station location accurately. Assuming that the ultimate measurement accuracy of the other techniques is high enough so that the same site coordinate accuracy can be determined in a shorter time, lunar ranging would be at a disadvantage in terms of the number of sites covered per year per mobile station. On the other hand, if fewer fixed stations are needed than for satellite ranging, it is not clear how the trade-offs would work out. A related disadvantage of lunar ranging is that one cannot obtain all 3 coordinates of the site with good accuracy for station locations above 45 to 50 degrees in latitude. The range of declinations available with the moon at elevation angles of 20 degrees or higher becomes too limited, and the Z-axis coordinate accuracy is reduced.

GROUND MEASUREMENT TECHNIQUES

At present the main ground survey methods used in geodynamics studies are accurate point-to-point distance measurements with modulated laser beams (laser geodimeters) and classical leveling for vertical motions. The accuracy reported by the National Geodetic Survey for their high-precision traverses, which cross the U.S. both north-south and east-west at roughly 1000 km intervals to provide overall horizontal control, is 1×10^{-6}. These traverses have been carried out with laser geodimeters, and the main accuracy limitation is from uncertainty in the atmospheric correction to the measured distances. For a number of baselines ranging up to 35 km in length in the western U.S., J. C. Savage and W. H. Prescott of the U.S. Geological Survey have reported measurement precisions equal to the root-sum-square of 2×10^{-7} of the length and a 3 mm contribution independent of length.[44] This is achieved by flying aircraft along the line of sight to measure the atmospheric characteristics. However, Savage and Prescott state: "Even at this level of precision, determination of the strain accumulation at sites along the San Andreas fault system will require annual observation of many line lengths over a period of at least 5 years." The need for increased ground measurement accuracy is also stated strongly by the U.S. Geodynamics Committee.[45]

Attempts to achieve higher accuracy by using two laser wavelengths, one in the red and the other in the blue, have been made at several laboratories. Microwave modulation is used in order to achieve the highest possible accuracy in determining the red-blue path difference. A correction proportional to the measured path difference is then applied in order to remove the effect of the atmosphere. Work at NOAA with this type of device has been reported,[46-49] and more extensive measurements have been obtained with an improved instrument developed by Huggett and Slater at the Applied Physics Laboratory, University of Washington.[50,51,73] Work is also under way at the National Physical Laboratory in England. The measurements by Huggett and Slater currently are over fixed baselines of up to 10 km near Seattle, and a microwave distance system has been added in order to correct for water vapor. The present measurements use retroreflectors at the far end of the path, so that the light beams have to travel both ways over the path. If improved signal-to-noise ratios are needed in order to achieve the geodynamically desirable goal of 1×10^{-7} or better accuracy over paths of roughly 30 km length, an approach in which only one-way laser propagation is used may be needed. This would correspond to having the microwave modulator and demodulator at opposite ends of the path, with synchronization provided by a round-trip microwave link.[52]

It would be very desirable if gravity measurements could be used in place of leveling as a monitoring technique for vertical motions. This is because the cost per km of leveling is high. It now appears that relative gravity measurements with accuracies of 3 microgal or better are achievable with existing instrumentation.[53] This means that the sensitivity is sufficient to detect relative vertical motions of roughly a cm if other processes are not going on. Such vertical motions are expected in seismic zones from the theory of dilatency. In addition, in connection with the interiors of tectonic plates, the U.S. Geodynamics Committee refers to evidence for widespread vertical motions at rates as high as a cm per year, and states:[54] "The rates of vertical motion determined by leveling surveys are so high that such motions cannot continue for very long intervals of time. Perhaps oscillatory or episodic movements occur." Improved methods for looking at such motions, both locally and regionally, certainly are desirable.

The main limitation in interpreting gravity changes probably will come from complicating mass motions which can occur. Horizontal motions of material within the aesthenosphere can occur over long periods of time, while changes in the local water table can offset gravity on a short time scale. Thus, the interpretation is not unique. However, stable gravity measurements still give evidence against vertical motion, and leveling or other techniques then can concentrate on making measurements where gravity is changing.

There also is a need for portable absolute gravimeters with roughly 3 microgal accuracy. They are necessary both to detect regional gravity variations over large areas and to provide scale calibrations for relative gravimeters. A portable absolute gravimeter with roughly 50 microgal accuracy was developed by Hammond and Faller, and measurements were made with it at 8 sites in North America, Europe, and South America.[55,56] A fixed-station gravimeter of accuracy approaching one microgal has been described by Sakuma,[57,58] so that accurate checks on portable instruments can be made. Recently joint French-Italian efforts have resulted in a portable absolute gravimeter with 20 microgal accuracy.[59] Further improvements to achieve the desired accuracy of about 3 microgal appear to be feasible. In regions of long term elevation changes, it clearly is important to understand how gravity is changing also in order to determine what is going on.

GEODYNAMIC APPLICATIONS OF THE NEW TECHNIQUES

In high accuracy geodynamics studies, one of the problems will be how to separate polar motion and earth rotation variations from motions of the observing stations. The general question of coordinate systems for geodynamics was discussed at IAU Colloquium No. 26 in Torun, Poland. A general view expressed was that there is a strong need for a worldwide geophysical coordinate system which approximates the motion of the solid part of the Earth as well as possible.[60-64] The rotation and tipping of this frame against an external reference frame, such as the planetary-plus-lunar dynamical frame[65,66] or the extra-galactic frame,[65] would determine what we mean by UT1, polar motion, and nutation. General agreement seems to be developing that the geophysical system should be defined in terms of a large number of points throughout the world for which geocentric coordinates are assigned, as well as assigned linear drift rates for the points based on the best available geodynamic models. It has been suggested that updating of the models used would be needed at appropriate intervals of perhaps several years, as our understanding of crustal movements improves.[63]

With at least 3 of the new techniques, it appears feasible to determine the locations of points over most of the Earth's surface with an accuracy of 5 cm or better. Progress in this direction already is very impressive. For example, a satellite ranging experiment in 1971 using long laser pulse lengths gave agreement for two stations 25 m apart to about 4 cm in each coordinate. A 1972 experiment with similar apparatus on a 900 km baseline across the San Andreas fault in California gave a scatter of 30 cm in the baseline length measurements, with much of this presumably due to uncertainties in the satellite orbit. With sub-nanosecond pulse length lasers and much better knowledge of satellite orbits in the future, the same baseline is expected to be recoverable in different years with an accuracy of 1.5 cm.[36] Satellite laser ranging systems with 10 cm or better accuracy and 6 or 7 cm rms single-pulse jitter already are available, and the scatter obtained on a transcontinental baseline even with existing satellites seems encouraging.[67] For lunar ranging, studies indicate an expected accuracy of 3 cm or better in each coordinate for determining the location of a mobile station in most parts of the world.[42,68] However, baseline measurements must await the availability of data from a second station besides McDonald.

For VLBI, a one meter scatter in baseline length was observed over a 845 km baseline from Haystack to Greenbank with data from as early as 1969.[10] For a 16 km baseline in California, a 5 cm or less scatter in each coordinate was obtained for 3 runs made in 1972.[15] Measurements on the 3,900 km Haystack-Goldstone baseline gave an rms variation of less than 20 cm for the baseline length for 9 separate experiments carried out in 1972 and 1973.[13] For very short baselines, a recent comparison with survey results for a 300 m baseline between a portable 9 m antenna and a fixed antenna in California has given agreement in each coordinate to within the $\pm$ 3 cm measurement uncertainty.[18] An even more recent result for the 1.2 km Haystack-Westford baseline length gives an 0.6 cm rms scatter for 5 measurements made over a 3 month period, and an agreement with survey results to 0.5 cm.[69] It is impressive that all of these results have been obtained even without the use of dual frequency capability and of water vapor radiometers, which will be added to the existing systems soon.

The major contributor to polar motion determinations so far among the new techniques is the Doppler satellite network. Normal variations in the polar position are determined regularly every 2 days with an accuracy which is believed to be about 30 cm in each coordinate.[4] The results are now being incorporated along with data from the classical techniques in the BIH adjustments. Laser range measurements to satellites have been used to determine polar motion to roughly one meter accuracy,[27,31,34] while VLBI measurements have given comparable accuracy for polar motion and for UT1.[13]

Recently lunar ranging data has been used to obtain preliminary individual-day checks on the BIH values of UT0 (a combination of UT1 and one component of polar motion) for the McDonald Observatory on 153 days.[43] The median accuracy of 22 cm which was achieved is encouraging, but it should be remembered that the fraction of days on which sufficient data was available from the single station is fairly small. A network of 6 fixed lunar ranging stations is expected to be in operation by late 1976, and hopefully data from a similar VLBI network also will be available by then. Additional high-accuracy information on polar motion and on short period fluctuations in the Earth's rotation rate are expected from satellite range measurements soon after LAGEOS is launched. However, the continuation of classical observations for a decade longer is needed in order to complete a careful comparison of the methods.

With the achievement of 5 cm or better accuracy on a worldwide basis highly probable, it is clear that a new era in geodynamic/geodetic measurement accuracy is approaching. The initial goal will be to measure the positions of hundreds of control points throughout the world with as high accuracy as possible. From our present vantage point it is difficult to tell just how low the costs of using the extra-terrestrial methods can be made, but it seems clear that the separations between the fundamental geodynamic/geodetic control points should be 300 km or less in most areas. The frequency with which points should be redetermined will depend on the local conditions, but will be chosen so that the probability of deviations from linear motion between measurements by more than the measurement accuracy is small. Improved ground techniques also will be used to keep track of more local motions within geodynamically interesting areas such as seismic zones or regions of unusual vertical motions. When unexpected motions or gravity changes are detected in a particular area, both the extra-terrestrial methods and improved ground techniques can be used on a fast-response basis to find out what is going on.

It should be emphasized that a combination of the new techniques may be more efficient for rapid establishment of the desired worldwide geodynamic/geodetic control network than any one of the techniques alone.[70] For example, one can think of first using one technique to establish and maintain 3 to 6 fundamental reference points on each major plate, and then using another technique to establish the much larger additional number of reference points within a given plate which are needed. For the first part of the job, the most important factor would be accuracy and reliability over long distances. An independent check by using at least 2 of the methods would be desirable for this phase of the work. For the second phase, a regional approach in which most of the effort is concentrated on a particular continent or area for a certain period of time seems desirable. For example, putting perhaps 6 mobile satellite ranging stations in one area, with some of them at the pre-determined fundamental points, would give minimum dependence of the results on uncertainties in the satellite orbit. Although simultaneous 4-station measurements would not be required, the intensive tracking over a limited region would give excellent knowledge of the orbit in that region. In this way, the desirable features of two or more techniques could be utilized in a complementary way.

During the 1974 International Symposium on Recent Crustal Movements, the following resolution was sponsored jointly by the Inter-Union Commission on Geodynamics and the Commission on Recent Crustal Movements, and was adopted:[71] "Instrumented systems capable of precise geodetic measurements such as Geodetic Satellites, Lunar Ranging, and VLBI are of the greatest value to the study of recent crustal movements and geodynamics. The Commission on Recent Crustal Movements and the Inter-union Commission on Geodynamics together strongly recommend that earnest attention be given to the further development of these systems so that such basic questions as the instability of the earth and the causes of movements can be investigated. The Commission on Recent Crustal Movements and the Interunion Commission on Geodynamics particularly emphasize that not only is doing the measurements important, but it is also important that the measurements be made in the optimum places in the light of geodynamics." Essentially all of the new techniques make heavy use of Precise Time and Time Interval measurements to achieve their high accuracies. Whether the need is for the highest possible stability in frequency standards suitable for use in rapidly moving mobile VLBI stations, or for relatively cheap and reliable laser frequency standards with 1×10^{-9} accuracy for use in portable absolute gravimeters, the needs from geodynamics for continued improvements in PTTI techniques are likely to be strong.

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QUESTION AND ANSWER PERIOD

MR. KEATING:

Mr. Keating, Naval Observatory.

I heard a lot about accuracy here, one centimeter, five centimeters. Yet, I heard nothing about the systematic errors you might have. In particular, the velocity of light.

Recently, I ran across two radio astronomers. One was using a velocity of light which was recently obtained by the NBS, and the other one was using another one which was almost one kilometer different from the recent NBS value. I don't quite understand how one can speak of accuracy under such circumstances. Really, you mean differential precision, don't you?

DR. BENDER:

No, I don't. In talking about accuracy for distance measurements, one has to specify what the standard is for the meter, for the length. Actually, the International Astronomical Union a year ago recommended that in all astronomical measurements of very high precision, a particular new value that had been recommended for such use by the consultative committee on the definition of the meter be used so that there would be no problem whatsoever in the comparisons of results obtained by different investigators because of the uncertainty in the speed of light.

It is also recommended that when a new definition of the meter is adopted, which hopefully will be within a few years, this value of the speed of light will be retained exactly.

Now, what this amounts to is a refinement of the definition of the meter so that it agrees within the precision with which the krypton meter can be realized with the old definition. However, it is in effect an auxiliary way of realizing the unit to better accuracy than the roughly 4 in 10^9 that the krypton lamp is capable of giving.

So I think until recently, there may have been such problems, but I believe these new measurements of the speed of light and the recommendations by the CCDM and the IAU really will remove this problem. It really is not a basic problem anyway except one of confusion because it is really the changes in distance in which everyone is interested. The present measurements are good to 4 in 10^9 for the speed of light. I don't know of any measurement where one wants to use distance measurements with higher accuracy than that other than just in a relative sense.

So I think there are really two answers. One is there is now a better speed of light which is likely to survive. And the second is the measurements are basically relative anyway.

DR. REDER:

Reder, Fort Monmouth.

If the measurements are relative, I don't understand why you said when you showed the slide showing the Goldstone and Haystack results with the transmitter on the moon and you mentioned that some of the deviations may have been due to a modulation of the transmitter, why would that come in?

DR. BENDER:

I am sorry. Let me say I didn't mean that the geodetic measurements point to point on the earth's surface were relative. I only meant, for example, that if you are looking at the distance to the moon or to a satellite where the basic quantity is the length to the moon, it is really differences in that distance to the moon which come into determining the distances between stations on the earth's surface. The same is true for the satellite geodesy.

So that it is only relative in the sense that until we get the 4 in 10^9 for the accuracy of baseline determinations on the earth we wouldn't have to worry even if we didn't know what the speed of light was, even if we didn't have a better definition of the meter.

DR. REDER:

How does the modulation of the transmitter come in that?

DR. BENDER:

It is nothing fundamental at all; it is just a noise source that is present in the data that makes it look more noisy than it really is.