ESTABLISHMENT OF TERRESTRIAL REFERENCE FRAMES BY NEW OBSERVATIONAL TECHNIQUES

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ABSTRACT

The use of space techniques for establishing transcontinental and intercontinental distances is progressing very rapidly. We can think of the set of station locations used in either LAGEOS ranging or VLBI measurements as forming the vertices of a polyhedron. After correcting for tectonic plate motions using an adopted model, we expect the geometry of the polyhedron to be fairly stable over periods of the order of a year. However, after some period of time, a new set of station coordinates will be required because of improved data, unexpected station motions, etc. Methods for maintaining agreement with the previous set of station coordinates in some average sense are discussed in this paper. Some of the contributions expected from other new measurement methods also are described.

INTRODUCTION

This article is addressed to the question of how we can use new observational techniques to establish worldwide terrestrial reference frames. For simplicity, the main emphasis will be on geometrical reference frames that can be established by laser distance measurements to the LAGEOS satellite and by very long baseline radio interferometry (VLBI). These two techniques are likely to be the most important ones in the 1980s for establishing basic worldwide networks of geometrical reference points. However, it should be noted that much larger numbers of points in and around seismic zones are likely to be determined with similar accuracy by observing the signals from the NAVSTAR Global Positioning System satellites. These points will have to be tied to the basic worldwide reference frames in some way.

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One of the basic reasons for establishing accurate worldwide geometrical reference frames is connected with the definition of the earth's rotation. The angular motion of such frames with respect to a conventional celestial reference frame is likely to be used in the future to define UT1 and polar motion. Any inadequacies in the reference frames thus are likely to show up as limitations on the accuracy of the UT1 and polar motion determinations. In particular, this means that the coordinates for the different stations which make observations used in determining UT1 and polar motion should be as consistent as possible. Otherwise changes in the distribution of data between different stations, either at different times of the year or over shorter periods, will lead to errors in the results.

Because of the above requirement, it appears desirable to adopt a model for the motions of the various tectonic plates for use in determining the reference system. This question has been discussed previously (Bender, 1974), and may be considered further in other papers in this volume. For example, any of the four absolute plate motion models referred to in Table 8 of Minster and Jordan (1978) might be a reasonable choice until a substantial amount of new information on plate motions from space techniques becomes available. The important point is that some of the LAGEOS ranging and VLBI stations either are or will be on the relatively high velocity Pacific and Indian plates. Without a plate motion model, the coordinates of such stations will become inconsistent with respect to other stations quite quickly.

While there definitely is a possibility that present rates of plate motions will differ from the long-term average rates determined from the geological record and other information (Bender, 1974,1978), this would require a substantial change in the picture most geophysicists have of tectonic plate motions. It appears difficult to see how the present rates of motion out in the centers of the major plates can be much different from the long-term average rates unless there is a layer in the asthenosphere with much lower viscosity than is expected from studies of post-glacial rebound. This is because the main driving forces for plate motions at ridges and rises and the viscous stresses on the bottoms of the plates are likely to be quite stable in time. For values of the order of 10^{20} poise for the viscosity and 100 km for the thickness of the low-viscosity part of the asthenosphere, the transient effect of even a great earthquake at the front of the plate would not propagate out to the center of the plate during typical recurrence times for great earthquakes. Thus it seems best for geodesists to regard the null hypothesis which we wish to test as being that the present rates of motion in the centers of plates are equal to the long-term average rates.

One other question which comes up frequently concerning models of plate motions is based on the fact that only relative motions of the different plates are actually observed. Fortunately, studies by Solomon and Sleep (1974), Kaula (1975), and Minster and Jordan (1978) have shown that quite different geophysical assumptions about plate motions give fairly similar absolute plate motion velocities with respect to the bulk of the material in the mantle. The differences appear to be only about 1 cm per year. While the choice is necessarily somewhat arbitrary, it appears to make little practical difference which of the suggested geophysical constraints are used to determine the absolute plate velocities.

Another requirement on the terrestrial reference systems used in determining UT1 and polar motion is that they should be as close as possible to the systems that might be used at later times for more detailed analyses of worldwide crustal movements. In such crustal movement studies, scientists undoubtedly will establish new reference systems that are optimized for long-term stability. However, substantial differences from the systems used for determining UT1 and polar motion initially would lead to large revisions in these quantities. Also, stability of the defined reference frames will help in making it possible to detect anomalous motions of individual stations at an early date.

The next section will describe the worldwide position measurements by LAGEOS ranging and VLBI which are likely to be carried out in the 1980's. Part of the material in this section is taken from another article which was prepared recently (Bender, 1980). This will be followed by a discussion of possible procedures for maintaining terrestrial reference systems. Finally, the expected contributions from other new observational techniques will be described briefly.

WORLDWIDE POSITION MEASUREMENTS

The basic approach used in the space techniques is to measure the distance or difference in distance from points on the ground to extraterrestrial reference points such as satellites or astronomical radio sources. The accuracy that appears to be achievable in such distance measurements is roughly 0.3 to 3 cm, and depends on many factors. For laser distance measurements, the inaccuracy is mainly due to uncertainty in the integrated atmospheric density along the line of sight and to the inadequacy of most present procedures for measuring the round-trip travel time. For radio measurements, the main problem is the uncertainty in the correction for the integrated amount of water vapor along the path. The effect of the ionosphere also has to be considered, but this can be corrected for accurately by comparing results of measurements made at two substantially different frequencies.

The LAGEOS satellite (Smith *et al.*, 1979a,b; Smith and Dunn, 1980) is in a nearly circular orbit with 110° inclination and 5900 km altitude. It is spherically symmetric and has a high density to minimize perturbations due to radiation pressure and atmospheric drag. About 15 ground stations currently are making range measurements to

LAGEOS, which probably is at least as many as are needed to maintain good coverage of the orbit. However, changes in the locations of some of the ground station would be quite helpful in improving the southern hemisphere coverage and in making use of sites with better weather, where the gaps in the data obtained would be considerably shorter.

The basic approach is to make range measurements to LAGEOS whenever possible from roughly 10 to 15 fixed or semi-fixed stations, and to determine the orbit and variations in the Earth's rotation from the data (Smith et al., 1979a). Arc lengths of a week or so may be used in such fits. At suitable intervals, solutions involving a considerably larger amount of data can be carried out in order to obtain corrections to the station coordinates (Smith et al., 1979b), to some of the gravitational harmonic coefficients, to the ocean tide models (Eaves et al., 1979; Smith and Dunn, 1980), and to a few other parameters. Simulations (Bender and Goad, 1979) have indicated that such solutions can give accuracies of 4 or 5 cm for intercontinental distances, even without additional new information about the Earth's gravity field from other sources beyond that contained in NASA's GEM-10 gravity field model and the LAGEOS ranging data itself. Information on changes in the station positions should be considerably more accurate.

The main improvement required in LAGEOS ranging is in the basic measurement accuracy. At present many of the stations have 10 cm accuracy for the average residual over 100 returns, and the precision is considerably better. A few stations have 2 to 4 cm accuracy. What is needed is to upgrade roughly 10 of the stations to 1 cm basic measurement accuracy for 2 or 3 minute intervals as rapidly as possible.

For very long baseline radio interferometry, a number of fixed stations already are involved in accurate measurements for geodynamics studies. These include five in the U.S., the Onsala Observatory in Sweden, the Effelsberg Observatory in the Federal Republic of Germany, and the NASA Deep Space Network stations in Spain and Australia. With the introduction of the new Mark III ground systems at a number of the sites, the accuracy of the results is expected to be limited mainly by the uncertainty in the tropospheric propagation velocity due to water vapor.

A network of three stations in the U.S. to monitor the Earth's rotation at least several times per week is being set up by the National Geodetic Survey (Carter et al., 1979; Carter, 1980). Hopefully, this will become part of a worldwide system in the future. A number of countries have expressed interest in taking part in such a program. Encouraging results already are being obtained by several groups (Fanselow et al., 1979; Robertson et al., 1980). The total number of stations required to monitor the Earth's rotation is smaller than for LAGEOS because measurements can be made even during cloudy weather or moderate rain. Thus about eight stations may be sufficient for this purpose, with some additional ones in the southern hemisphere needed part of the time to serve as reference points for crustal movement measurements.

The main area where improvements will be needed concerns the determination of the water vapor correction. The most promising approach is to use water vapor radiometers to measure the emission from water molecules along the line of sight. The observed power in a H_2O molecular emission line can be combined with an estimate of the average atmospheric temperature to give the integrated water vapor content of the atmosphere. Results obtained with several somewhat different types of radiometers have been reported by Guiraud et al. (1979), Moran and Rosen (1980), and Resch and Claflin (1980). The most extensive results so far are those of Guiraud et al. (1979), but observations were reported only for vertical paths. Seven additional radiometers have been designed and assembled recently by the Jet Propulsion Laboratory for use in VLBI measurements (Resch and Claflin, 1980).

There is a good theoretical basis for expecting that 1 cm accuracy can be achieved with water vapor radiometers, even at elevation angles as low as 20° (Westwater, 1978; Wu, 1979). But direct measurements of radiometer performance for low elevation angles and under varying atmospheric conditions still are needed (Resch and Claflin, 1980), in support of both VLBI and Global Positioning System measurement programs.

Measurements of baseline accuracy and reproducibility now are available for a number of VLBI baselines. Results obtained with a 1.24 km baseline over a period of 15 months show rms variations of 3 mm, 5 mm, and 7 mm respectively in the baseline length, azimuth, and elevation (Rogers et al., 1978). The mean results agree to 6 mm or better in each coordinate with the values obtained by careful ground surveying (Carter et al., 1980). Measurements at different times with a 9 m mobile station at two sites separated by 42 km gave a baseline length which agreed with ground survey measurements to 6±10 cm (Niell et al., 1979). And measurements over a 4000 km baseline between the Haystack Observatory in Massachusetts and the Owens Valley Radio Observatory in California have given results with a 4 cm rms reproducibility over a two-year period (Robertson et al., 1979). Recently, the first measurements of intercontinental distances with sub-decimeter reproducibility have been reported (Herring et al., 1980). It is encouraging that the above results were obtained even without the use of water vapor radiometers.

It appears likely that there will be a total of 20 to 25 fixed LAGEOS ranging and VLBI stations by the mid-1980's which will be accurate enough to contribute substantially to determining worldwide reference frames. In addition, the positions of a considerably larger number of sites probably will have been determined by high-mobility stations using both of the techniques (Silverberg, 1978; Niell et al., 1979). Such stations are expected to take from two days to one or two weeks to determine their locations. One question which undoubtedly will arise is how to make use of the results from such stations for determining reference frames. At first glance, it might seem desirable to use such sites only to determine secondary reference systems. On the other hand, information from sites that are visited more than once at intervals of 1 or 2 years will be valuable in determining where relative motions are occurring within the plates. It may be desirable to incorporate such information into the definition and maintenance of the primary reference frames in some way.

Another important question concerns whether it is desirable to keep the sets of coordinates for LAGEOS ranging stations and VLBI stations separate, or whether to combine them in a joint set of coordinates. There can be a large number of ties between the two sets of station locations which are made by the high-mobility stations. If the sets of coordinates are not combined, a six-parameter transformation between the two networks still would be determined. This transformation could be used in combining the UT1 and polar motion results, as well as for putting the coordinates of the VLBI stations on a geocentric basis. The argument against using a combined set of coordinates is that any distortions introduced by one technique would influence the accuracy of the UT1 and polar motion results from the other technique.

It should be noted that lunar laser range measurements also are likely to contribute to worldwide position measurements, UT1, and polar motion. However, almost all lunar laser ranging stations are likely to be located at sites where LAGEOS range measurements also are made. For this reason, it does not seem necessary to treat lunar laser ranging separately in considering terrestrial reference frames.

It may be worthwhile to comment briefly at this point on the fact that many people are reluctant to use the term accuracy in discussing the results of geophysical measurements. The statement sometimes is made that accuracy can be established only by comparison with results obtained with a more accurate technique. This is incorrect, since the preparation and publication of careful error budgets which include allowances for systematic errors has been found to be very useful for determining the accuracy of measurements in other research areas such as primary frequency standards (Bender, 1974). The statement as given also is self-contradictory, which can be seen as follows. If one technique were believed to be the most accurate one, there would be no way to determine its accuracy. Thus there would be no way to determine that it was more accurate than the method believed to be the next most accurate. It therefore could not be used to determine the accuracy of that method, and so on down the line.

PROCEDURES FOR MAINTAINING TERRESTRIAL REFERENCE SYSTEMS

To be as specific as possible, we will assume that a decision is made at some particular time to adopt certain sets of coordinates for the LAGEOS ranging and VLBI stations and a plate motion model. These would be used for determining the earth's rotation and the positions of high-mobility stations until evidence began to accumulate that some of the adopted coordinates were inconsistent. At that point there would be justification for modifying the sets of coordinates, and possibly the plate motion model. For convenience, we assume that only the coordinates will be adjusted. Three possible approaches for carrying out the adjustment in such a way that the average orientation of the coordinate system is maintained are discussed below.

One approach which appears attractive is to carry out a free network adjustment using some suitable block of data. The station coordinates would be adjusted jointly with solutions for UT1 and polar motion as functions of time. Constraints are needed in order to remove the ambiguity between changes in all the station coordinates due to a rotation about some axis and fixed offsets in UT1 and polar motion. For LAGEOS ranging, one possibility that has been suggested is to minimize the weighted sum of squares of the horizontal position changes for the stations under rotations about three orthogonal axes (Bender and Goad, 1979). This leads to the following constraint equations:

$$\sum_i w_i (x_i \sin\phi_i \cos\lambda_i - y_i \sin\lambda_i) = 0$$

$$\sum_i w_i (x_i \sin\phi_i \sin\lambda_i + y_i \cos\lambda_i) = 0$$

$$\sum_i w_i (x_i \cos\phi_i) = 0 \quad .$$

Here x_i and y_i are the changes in the station coordinates in the eastern and northern directions respectively, ϕ_i and λ_i are the latitude and longitude, and w_i is the weight for a particular station. For VLBI stations the corresponding approach would be to minimize the weighted sum of squares of three-dimensional position changes under both rotations and translations.

Another possible approach would be to use principal value decomposition in order to reduce the number of degrees of freedom being solved for by three. I am not familiar with the literature concerning the use of such methods in geodesy, and hope that another paper in this volume will cover the subject better. The generalized inverse method and the Bjerhammar inverse method presumably are closely related. If the station coordinates were the only parameters being solved for, these methods probably would give essentially the same results as the free network adjustment approach. However, since UT1, polar motion, and possibly orbit parameters are included in the solutions, it seems likely that the size of the corrections needed in these quantities might influence the results, since the covariance matrix wouldn't be diagonal. For this reason, my guess is that the principal value decomposition type of approach is less desirable than a free network adjustment method.

A third possible approach can be called sequential adjustment. In this approach the values of UT1 and polar motion derived from the available data using the initial set of coordinates are kept fixed. An appropriate block of data is then reanalyzed using the previously determined values of UT1 and polar motion, and a new set of station coordinates are derived. The solution should be well determined in this case, and no constraints will be needed. This approach is similar to the one used by the BIH for maintaining the origin of longitude.

The main advantage of the sequential adjustment approach is that it is simple to carry out and minimizes any discontinuity in UT1 and polar motion at the time that the new set of coordinates are adopted. This is because the new coordinates are required to be as consistent as possible with the old UT1 and polar motion values during the adjustment period. If the time interval between the end of the data set that is fit and the switch to the new station coordinates is fairly short, there is little time for discrepancies in UT1 and polar motion to build up.

The main advantage of the free network adjustment method is that it does not appear to introduce any unnecessary errors in the resulting station coordinates. Thus the fluctuations in comparing sets of station coordinates obtained at different epochs would be minimized. However, there probably will be somewhat larger offsets in UT1 and polar motion when the switch to the new coordinates is made.

The choice between the free network adjustment approach and the sequential adjustment approach may be a difficult one. My own preference would be for the free network approach, since I think that the scientific benefits of keeping the reference system for position measurements with the high-mobility stations as stable as possible are substantial. Also, the resulting offsets in UT1 and polar motion are likely to be quite small. However, both approaches appear to be viable.

Another important question involves the extent to which the expected geophysical stability of sites is taken into account in weighting the results. There are strong arguments in favor of having a LAGEOS ranging station at the European Southern Observatory in Chile, for example. The weather is good enough so that observations might be obtained on nearly 300 days per year. Thus the efficiency of such a station for determining UT1 and polar motion is extremely high, and it would be an excellent reference site for high-mobility station measurements. On the other hand, we know little about the possible frequency of irregular crustal movements in this area, even well away from the time of great earthquakes.

One way of handling the site stability problem is to carry out solutions in which different weightings of data are used for stations in different types of areas. Another approach is to use high-mobility stations to tie questionable sites directly to stable locations on the same continent, possibly as often as several times per year. A third approach is to use GPS receivers or high-mobility stations to tie in the sites with respect to the surrounding areas. The entire question of site stability and of weighting data from different sites is a complicated enough one so that recommendations may be needed from some group that is familiar with both the geophysical factors involved and the sources of systematic measurement errors.

EXPECTED CONTRIBUTIONS FROM OTHER NEW TECHNIQUES

As mentioned earlier, it seems likely that measurements using signals from the NAVSTAR Global Positioning System satellites will be used extensively in the 1980's to study crustal movements in seismic areas and for other geodetic purposes. This topic is discussed elsewhere in this volume by Goad, and thus will be mentioned only briefly here. Measurement times of about 2 hours or less per site are expected. For moderate baseline lengths, measurement errors due to other sources apparently can be made small compared with the uncertainties in the water vapor corrections determined by water vapor radiometers. The GPS receiver and a water vapor radiometer could be mounted in a light truck, with only a driver needed, and measurements made with respect to a receiver and radiometer at a fixed site in the area. For differential measurements over moderate baselines, the water vapor correction accuracy appears likely to be about 1 cm, even at low elevation angles of about 20°.

Recently, additional studies of the GPS accuracy capability have been carried out by Larden and Bender (1980). A modified form of "worst case error analysis" was used in order to obtain as reliable accuracy estimates as possible. This approach was needed because of the probability that the water vapor correction errors would be far from random from measurement to measurement, and would vary with a similar time scale to that of the satellite motions. Despite the type of analysis used, expected accuracies of 1 to 2 cm for the baseline components were found when 1 cm errors were assumed for the water vapor corrections.

Another technique that is likely to make important contributions to maintaining terrestrial reference frames during the 1980's is absolute gravity measurements. Substantial progress has been made in the past decade in developing absolute gravimeters. An instrument located in Paris has been operating for some time with a reported accuracy of a few microgals (Sakuma, 1974a,b), and another similar instrument has been built in Japan. Transportable absolute gravimeters were first used to provide some of the reference points for the 1971 International Gravity Network. More recent transportable instruments have been developed in western Europe by joint Italian and French efforts (Cannizzo et al., 1978), in the U.S. (Hammond and Iliff, 1978), and in the U.S.S.R. (Boulanger, 1979). The accuracy achieved is believed to be about 10 microgals, although the discrepancies found at a few sites have been considerably larger. Work also is proceeding on a more portable absolute gravimeter which has an accuracy goal of 3 microgals (Faller et al., 1979).

If the sources of occasional discrepancies in absolute measurements with present transportable instruments are found and eliminated, as seems likely, and particularly if higher accuracy can be achieved, then absolute gravity measurements can provide valuable checks on vertical movements. While there are some situations where elevation changes can occur without variations in gravity, this probably is rare. The change in some important cases is roughly two to three microgals per centimeter of uplift. If both gravity changes and elevation changes can be measured, the combination provides an additional constraint on the physical mechanism responsible for the variations. Thus absolute gravity measurements at many of the fixed sites for worldwide terrestrial reference networks are highly desirable.

The one major restriction on the use of gravity measurements concerns local hydrology. Sites for gravity measurements have to be chosen carefully, since effects such as the withdrawal of water from aquifers can change the results. However, the choice of adequate sites on crystalline rock outcrops appears to be feasible in many non-sedimentary areas. Use should be made of absolute gravity measurements at such sites whenever they exist close to the sites used for geometrical position measurements.

It has been suggested that absolute gravity measurements also should be used to monitor variations in the position of the center of mass of the entire earth-oceans-atmosphere system with respect to points on the crust. However, the expected amplitudes of the seasonal and longer-term center-of-mass motions are quite small, as indicated by studies such as those of Stolz and Larden (1979) and Larden (1980). In view of the hydrology problem and the difficulties of the measurements, it seems best during the 1980's to use the combination of LAGEOS range measurements and absolute gravity measurements at crystalline rock sites to look for evidence of center-of-mass motion, rather than using gravity measurements alone.

So far the discussion has been limited to terrestrial geometric reference frames. However, space techniques also are likely to contribute to tying together the vertical control networks on different continents. This question was discussed recently by Colombo (1980), and results were given on what could be achieved with worldwide gravity field models complete to degree 20. Leveling, position, and gravity measurements over 5° or 10° caps on two continents were assumed in order to relate the equipotential surfaces of the worldwide model to the local undulations of the real surfaces.

If one extrapolates to the type of gravity field model expected from a GRAVSAT mission, considerably improved results could be expected even with ground measurements over 1° or 2° caps. Looking even further into the future, superconducting gravity gradiometers (Paik *et al*., 1978; Paik, 1980) or possibly laser interferometry measurements in orbit (Bender *et al*., 1980) might some day improve the worldwide gravity model resolution down to 40 to 50 km. Ground measurements might then be needed over only perhaps $0^{\circ}\!.5$ to 1° caps in order to be able to identify points of equal gravitational potential on different continents.

CONCLUDING REMARKS

De facto terrestrial reference systems for geodynamics studies which include adopted plate motion models may well come into use quite soon for analyzing both LAGEOS ranging data and VLBI data. It will be helpful if the practical choices involved in establishing and maintaining such systems are discussed clearly at IAU Colloquium No. 56. Hopefully, this will reduce the number of changes needed later in the procedures for maintaining the systems.

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