REFERENCE COORDINATE SYSTEM REQUIREMENTS FOR GEOPHYSICS
P. L. Bender

National Bureau of Standards and University of Colorado
Boulder, Colorado

Abstract

Five important geodynamical quantities which are closely linked are: 1) motions of points on the Earth's surface; 2) polar motion; 3) changes in UT1-UTC; 4) nutation; and 5) motion of the geocenter. For each of these we expect to achieve measurements in the near future which have an accuracy of 1 to 3 cm or 0.3 to 1 milliarcsec.

From a metrological point of view, one can say simply: "Measure each quantity against whichever coordinate system you can make the most accurate measurements with respect to". I believe that this statement should serve as a guiding principle for the recommendations of the colloquium. However, it also is important that the coordinate systems help to provide a clear separation between the different phenomena of interest, and correspond closely to the conceptual definitions in terms of which geophysicists think about the phenomena.

In any discussion of angular motion in space, both a "body-fixed" system and a "space-fixed" system are used. Some relevant types of coordinate systems, reference directions, or reference points which have been considered are: 1) celestial systems based on optical star catalogs, distant galaxies, radio source catalogs, or the Moon and inner planets; 2) the Earth's axis of rotation, which defines a line through the Earth as well as a celestial reference direction; 3) the geocenter; and 4) "quasi-Earth-fixed" coordinate systems.

When a geophysicists discusses UT1 and polar motion, he usually is thinking of the angular motion of the main part of the mantle with respect to an inertial frame and to the direction of the spin axis. Since the velocities of relative motion in most of the mantle are expected to be extremely small, even if "substantial" deep convection is occurring, the conceptual "quasi-Earth-fixed" reference frame seems well defined. Methods for realizing a close approximation to this frame fortunately exist. Hopefully, this colloquium will recommend procedures for establishing and maintaining such a
system for use in geodynamics. Motion of points on the Earth's surface and of the geocenter can be measured against such a system with the full accuracy of the new techniques.

The situation with respect to celestial reference frames is different. The various measurement techniques give changes in the orientation of the Earth relative to different systems, so that we would like to know the relative motions of the systems in order to compare the results. However, there does not appear to be a need for defining any new system. Subjective figures of merit for the various system depend on both the accuracy with which measurements can be made against them and the degree to which they can be related to inertial systems.

The main coordinate system requirement related to the geodynamic quantities discussed in this talk is thus for the establishment and maintenance of a "quasi-Earth-fixed" coordinate system which closely approximates the motion of the main part of the mantle. Changes in the orientation of this system with respect to the various celestial systems can be determined by both the new and the conventional techniques, provided that some knowledge of changes in the local vertical is available. Changes in the axis of rotation and in the geocenter with respect to this system also can be obtained, as well as measurements of nutation.

1. Introduction

A number of points mentioned in the abstract have already been discussed in previous papers or comments. For example, Lundquist has emphasized the need for an approximately inertial reference frame and for a second coordinate system "associated with the nonrigid Earth in some well-defined way such that the rotational motions of the whole Earth are meaningfully represented by the transformation parameters relating the Earth system to the space - inertial system". Also, Kovelevsky has listed extragalactic systems and the planetary dynamical system as two of his seven types of reference systems. VLBI measurements of polar motion, UT1, and nutation are made against the first of these, and lunar range measurements against the other. The possible limitation on planetary dynamical systems which was mentioned does not apply to planetary solutions such as those developed at JPL and MIT, since these
are based on radar data for the inner planets and spacecraft tracking data, as well as optical data. The accurate orientation of the planetary dynamical system against the radio sources is being carried out by JPL via differential VLBI measurements of the ALSEP transmitters on the Moon against nearby radio sources.

To avoid repetition, this paper will be limited to some comments on three topics. The first concerns the desirable characteristics for a quasi-Earth-fixed coordinate system, and includes a specific proposal for how to establish one. The second includes a few comments on the probable motion of the tectonic plates. The third concerns the use of the term "accuracy" in connection with geophysical measurements.

2. Quasi-Earth-Fixed System

The following criteria seem desirable for a quasi-Earth-fixed coordinate system:

a The system should be as invariable as possible with respect to changes in the number, distribution, and data acquisition rates of observing stations in different parts of the world.

b The system should facilitate the rapid determination of sudden changes in the position or motion of individual stations, as well as sudden changes in polar motion and the rotation of the Earth.

c The system should be approximately fixed with respect to the mantle in some average sense.

The above criteria apparently are consistent with the choice of a coordinate system based on all of the available observing stations, but in which our previous knowledge of the motion of the stations with respect to each other and to the mantle is used to model out the station motions. This means that a particular model of the tectonic plate motions would be adopted for some period of time for use in determinations of quantities such as UT1 and polar motion. These motions would be included in calculating the ranges or range differences for comparison with observations to determine the geodynamic quantities of interest. The models of lithospheric
plate movements relative to the mantle which are now being constructed by geophysicists agree to roughly 1 cm per year even though based on widely different assumptions, so this should not be a serious limit on studies of secular polar motion.

A major advantage of this approach compared with fixing the coordinates of only one station is that it works well even if observations at the defining station are interrupted or are less accurate than those at the other stations. If this happened with a single station definition, I believe that it would be necessary to switch to using other stations as the defining points. Also, the measurement uncertainty for the defining station comes in without reduction in determining the coordinates of any other point. With several measurement techniques likely to be contributing to geodynamic studies, any technique not having a station at the fundamental point would be limited in determining station position by the uncertainty of the other techniques.

Since the station motion model would need to be changed occasionally in view of new information on crustal movements, an organization such as the Permanent Service for Earth Tides, the BIH, or the IPMS might be asked to undertake the task of recommending changes in the model. The weighting of data from individual stations using different observing techniques to determine polar motion and UT1 on a time scale as close to real time as possible would still be done by the BIH and/or other organizations. The addition of data from new stations would be handled in the same way as is done now by the BIH.

In most studies of error propagation, the effect of systematic errors on the chord distance between two stations is usually considerably less than on the orientation of the baseline. Also, some sources of systematic error cancel out, if one can average over the time of day and over periods of months. Thus the chord distances between the various stations at any time are likely to be the best known quantities in the problem, and to be substantially better determined than the single day measurement accuracy. This is true for all three of the new techniques.

We can think of the permanent high-accuracy stations and the network of chords connecting them as forming a known geo-
metrical figure which rotates, wobbles, and translates in space. Essentially the full accuracy of the data from all the stations on a given day can go into determining geodynamic quantities which change unpredictably on short time scales. Ties between networks of permanent stations using different observing techniques will be established both by movable stations and by collocation of some stations. Measurements of crustal movements for additional points on each tectonic plate can be obtained efficiently with several movable stations which determine the locations of the points with respect to the network of permanent stations at intervals of perhaps two years.

3. Motion of Tectonic Plates

The relative motion of the major plates has been discussed widely, and most models agree quite well. Recently, there has been considerable interest in the question of determining motions relative to the mantle. It was proposed by Morgan (1973), Minster et al. (1974), and others that some linear chains of volcanic features were caused by tectonic plates moving across hot spots in the upper mantle. Assuming that the hot spots were fixed permitted solutions for the absolute plate motions. However, further investigations have indicated that the ages and distribution of such features in many cases are not consistent with uniform motion across fixed spots.

Another recent paper by Solomon and Sleep (1974) replaces the hot spot concept with several simple assumed models for the forces acting between the plates and the underlying regions. As examples, one model assumes a uniform effective viscosity under all the plates, while another assumes that the effective viscosity is three times higher under the continents where the low-velocity layer is less well developed than under the oceans. The conclusions are that the various models agree fairly well with respect to each other and to the earlier fixed hotspot models. Essentially, the American, Eurasian, and Antarctic plates move quite little, the Pacific and Indo-Australian plates move rapidly, and the African plate moves at a rate in-between the other two. The smaller Nazca,
Cocos, Philippine, and Arabian plates also move quite rapidly. Kaula (1974) has made similar calculations based on the assumption that the mantle's main function is to supply material at ridges and rises and reabsorb it at subduction zones. Again the velocities with respect to the mantle agree to roughly 1 cm/year.

Returning to the question of relative plate motions, it seems desirable to keep an open mind and to assume that some of the phenomena will behave differently than predicted by simple models. It should be remembered that much of the information used in determining the relative motion of the plates is based on the integrated motions over periods of 100,000 years or longer. It usually is assumed that plate motions will be smooth in time and at very nearly the mean rate deduced from the geological record—except at the times of major earthquakes. Even then, little sudden motion usually is expected at distances from the fault which are large compared with the length of the fault break.

The argument given for uniform motion is that the nature of the driving forces requires them to be quite constant in time. This seems reasonable in many cases, whether the driving force is predominantly a push due to gravitational sliding off a mid-ocean ridge, a pull at the front of the plate due to gravitational force on the cooler and denser down-going part of the plate at a subduction zone, a pull over most of the plate due to flow in the aesthenosphere underneath, or something else. The retarding forces due to stress on the fault planes at the edges of the plate cannot play a major role in the picture, otherwise heat generation at the plate edges would be considerably larger than has been observed.

There are models which defeat the above arguments, but whether they are really plausible is open to question. For example, if almost all of the driving force comes from gravitational pull on the down-going front of the plate, then this is nearly balanced by the highly nonlinear resistance of the plate to being forced into the upper mantle to depths of 700 km. Thus, a change in stress along perhaps a 500 km-long segment of the plate boundary at the time of a major earthquake could, in principle, change the creep rate in the aesthenosphere and
allow plastic readjustment to the changes in stress at the boundary over some period of time.

An alternate failure mode for the uniform motion assumption could occur along predominantly strike-slip faults such as the San Andreas fault in California. Here the sudden motion at the time of a major earthquake is limited to the top 15-20 km of the fault plane. The remaining perhaps 60 km below these depths are certainly heavily stressed by the motion occurring above, and it thus seems likely that accelerated creep in the fault gouge in the lower part of the plate boundary will occur after the quake. Evidence for this happening after the 1906 San Francisco earthquake was presented recently by Thatcher, with some evidence also for aseismic motion along the fault before the quake. If the depth of the plate plus the aethenesphere below the brittle rupture part of the fault is taken to be about 200 km, and if the delayed earthquake-related creep on the fault plane is perhaps 5 meters at 20 km depth and zero at the bottom of the aethenesphere, the amount of material displaced near the fault could be about 5 times the amount displaced during the quake. However, allowing the free-boundary condition to go down to 200 km depth rather than 20 will also allow the resulting elastic strain to propagate considerably further out into the plate away from the boundary, so that the total increase in mass motion could be large.

The above effect could be called a delayed elastic distortion of the plate, even though creep at depth on the fault plane is needed for it to occur. With the very high accuracy expected from the new measurement techniques, such effects might be observable even a number of fault lengths from the fault after a major earthquake. The time scale for this to occur apparently is not known at present. It will be very interesting if aseismic motions of this kind can be observed at some distances from the fault, or if other aseismic motions or low-seismic efficiency motions such as those discussed by Kanomori can be studied. It also will be interesting if large-scale distortions within oceanic plates which depend on the effective viscosity of the aethenesphere under the oceans can be measured, since most of our information on the effective viscosity at present appears to come from elastic rebound.
data in continental regions. For example, motions of Hawaii, Tahiti, and Wake Island with respect to each other would be valuable, since all are on the same plate and well away from the edges.

4. Definition of Accuracy in Geophysical Measurements

In discussing the results of geophysical measurements, many people are reluctant to use the term "accuracy." However, this is quite different from the practice in other fields of metrology, where accuracy is a very useful concept and is used with a specific meaning. To illustrate this, the example of atomic frequency standards is a convenient one.

In a laboratory working with a primary standard, an important part of the work is to establish the accuracy capability of the standard. This is done by considering each individual physical effect which anyone has suggested as having an effect on the frequency of the standard. An error budget is established which is based on direct measurements concerning each suggested source of error. Statistical errors are included, but usually they are small compared with systematic errors. The result of all the errors is referred to as the accuracy capability of the standard.

The above procedure does not mean that the results of comparisons between primary standards in different countries always will agree within the combined accuracy capabilities, since a simple error in procedure or an unknown physical effect can be present. However, experience has shown that the agreement usually is good, and the effort of constructing error budgets seems worthwhile when the cost or time lag involved in direct comparisons is high. As long as the steps leading to the individual entries in the error budget are reported carefully, other workers can check the reasonableness of the results for themselves.