IMPROVED METHODS FOR MEASURING PRESENT CRUSTAL MOVEMENTS

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Abstract. Improvements in geodetic measurement techniques are likely to play an important role in a number of types of geodynamics studies during the next decade. Increased accuracy for horizontal distance and gravity measurements at many sites is expected using multiple-wavelength measurements and falling-retroreflector gravimeters. Improved tiltmeters and crackmeters are being developed, with attention being given to decreasing perturbations due to very local ground noise. Geodetic receivers using signals from the Global Positioning System satellites probably will make possible rapid relative position measurements with 1 to 3 cm accuracy in and around seismic zones. An international program of worldwide position measurement with about 3 cm accuracy is planned, using both laser range measurements to the LAGEOS satellite and long baseline radio interferometry.

Introduction

Most of the subject matter covered in this volume is limited to plate interiors. However, the new space techniques for making geodetic measurements are likely to contribute strongly to studies of large scale tectonic movements between plates as well as within plates. In addition, the classical geodetic techniques which have provided much of our information on tectonic distortions at plate boundaries also are used to study local deformation and uplift in plate interiors. To avoid duplication, it was decided to discuss all of the geodetic measurement methods that are likely to contribute strongly to geodynamics studies in the present article, rather than repeating the discussions of some techniques in the reports of different ICG Working Groups. Recent developments in measurement techniques and the prospects for further improvements in the next few years will be emphasized.

So far, the direct determinations of strain accumulation rates at plate boundaries and of deformation related to seismic events have come mainly from resurvey measurements using triangulation, trilateration, and leveling. Additional results have been obtained from tide gauges, gravimeters, creepmeters, and tilt and strain observations. Some of the results are discussed in the report of ICG Working Group No. 10. Information on vertical movements in plate interiors obtained by leveling is discussed by Brown and Reilinger elsewhere in this volume.

We will discuss first the ground measurement techniques, and then the new space techniques. For the ground techniques, we will concentrate on modulated laser distance measurements, gravity measurements, and strain and tilt measurements using relatively long baselines. The space techniques include satellite laser ranging, long baseline radio interferometry using signals from astronomical sources, and radio interferometry using signals from the Global Positioning System satellites.

Improved Ground Techniques

A number of valuable articles concerning both conventional and new measurement methods have become available recently in three publications. One is the Proceedings of the 1977 International Symposium on Recent Crustal Movements [Whitten et al., 1979], which appeared as a special volume of Tectonophysics. The second is Application of Geodesy to Geodynamics [Mueller, 1978], which is the Proceedings of the Ninth Geodesy/Solid Earth and Ocean Physics Research Conference. The third is Proc. of Conf. VII, Measurement of Stress and Strain Pertinent to Earthquake Prediction [Clark et al., 1978]. In view of the availability of these recent sources of information, I have limited this article to discussions of the most accurate methods for determining changes in distance, tilt, strain, and gravity.

Electromagnetic Distance Measurements

The most accurate method at present for determining distances between points a number of kilometers apart is the use of laser beams modulated at radio or microwave frequencies. In com-
cially available instruments, the light goes out through a modulator, is reflected from a mirror reflector at the far end of the path, and then returns through the modulator again to a detector. The average signal from the detector is a maximum if the round-trip optical path length is an integral multiple of the wavelength of the modulating frequency, and thus the optical path length can be measured in terms of this wavelength. For the best instruments, the accuracy usually will be limited mainly by how well the atmospheric density along the path is known, and therefore how well the correction for the slowing down of light in air can be made. An uncertainty of 1% in the average temperature along the path corresponds to an uncertainty of one part per million in the corrected distance, even if the atmospheric pressure is known perfectly. This is a typical accuracy if measurements of the atmospheric temperature, pressure, and humidity at the end points are used to determine the correction, but no additional precautions are taken.

A successful program of repeat survey measurements with higher accuracy has been achieved by Savage and co-workers in the U.S. by flying an aircraft or helicopter along the optical path to measure the atmospheric conditions. The repeatability of the measurements has been found to be given by the formula

$$o = (a^2 + b^2 L^2)^{1/2}$$

where $a = 3 \text{ mm}$, $b = 2 \times 10^{-7}$, and $L$ is the path length [Savage and Prescott, 1973]. Roughly 800 lines/yr in the western U.S. have been measured in recent years. The percentage increase in cost for the airborne measurement is about 40%. Measurements with higher accuracy also have been achieved by Parfet [1976] over quite level terrain in Finland by means of very careful experimental procedures, such as taking data only when the wind is blowing along the line of sight.

Another approach for improving the accuracy of the results has been developed by Slater and Huggett [1976] and has been demonstrated for a number of baselines near Hollister, California [Huggett et al., 1977; Slater, 1978; Slater and Burford, 1979]. Measurements are made with both red and blue lasers, and the difference in optical path length is used as a direct measure of the integrated atmospheric density along the path. Since the difference in distance for the wavelengths used is only about 5% of the total atmospheric effect on the distance, great care has to be taken to make the differential measurements as accurate as possible. However, the results indicate that the precision of the corrected distance is about one part in 10^7 and the accuracy may be the same. Microwave distance measurements over nearly the same path sometimes are used to determine and correct for the integrated water vapor along the line of sight.

So far the multiple wavelength method has been considerably more limited in range than single-wavelength optical distance measurements. However, by using a three-wavelength system where the red and blue light beams and a microwave signal travel only one way over the path, it appears feasible to achieve an accuracy of 5 parts in 10^8 for determining the atmospheric correction over paths as long as 40 or 50 km [Moody and Levine, 1979; Levine, 1978]. Such an atmospheric correction measuring device can be used with a separate instrument which determines the path length for red light, or this additional capability can be built into a single instrument. However, no test data with such instruments are available yet.

Gravity Measurements

One method of searching for evidence of vertical crustal movements is to make periodic remeasurements of the acceleration of gravity. 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 or 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. 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.

One type of instrument frequently used for gravity measurements is the LaCoste-Romberg gravimeter. By using several instruments and going back and forth between two sites, changes in the gravity difference can be detected at the level of roughly 10 or 15 microgals [Jachens, 1978a, b; Pett, 1978; Harrison and LaCoste, 1978; Brein et al., 1977; Kiviniemi, 1971]. Further instrumental improvements using electrical feedback may be feasible (W. E. Farrell, private communication, 1979). For comparing sites only a kilometer or two apart with nearly the same value of gravity, higher accuracy can be achieved [Lambert and Beaumont, 1977; Lambert, 1978; Lambert et al., 1979].

A number of networks for making repeated gravity measurements have been set up in different parts of the world. One of the interesting networks is one in southern California which includes about 300 sites with typical spacings of about 25 km, and 11 secondary reference sites which are carefully inter-compared [Jachens, 1978a; Jachens and Roberts, 1979].

During the past decade, substantial progress has been made on developing absolute gravimeters, which also may be quite valuable for crustal movement measurements. An instrument located in Paris has been operating for some time with an accuracy of a few microgals [Sakuma, 1974a, b] and another instrument with similar accuracy has been built in Japan. Transportable absolute gravime-
ters 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 Illiff, 1978], and in the U.S.S.R. [Boulanger, 1979]. The accuracy achieved is believed to be about 10 micro- 
gals. Work also is proceeding on a more portable absolute gravimeter which has an accuracy goal of 3 microgals [Faller et al., 1979].

A third type of gravimeter which has demonstrated very high stability in use at fixed sites is the superconducting gravimeter [Goodkind, 1979]. These devices have achieved a stability of a few microgals over several months [Goodkind, 1978]. This approaches the level at which effects such as vertical station displacements due to quasi-seasonal transport of water from the oceans to continental areas may become observable in some regions. The installation of supercon-
ducting gravimeters at tectonically interesting sites is one method of looking for both short term and intermediate term gravity variations. Such instruments also provide increased accuracy in the measurement of tidal gravity variations [Warburton and Goodkind, 1978; Goodkind, 1978].

Tilt and Strain

A substantial amount of work has been done in recent years on measurements of tilt with shallow borehole tiltmeters. However, it has become clear that a major limitation in such measurements is near-surface ground motions of meteorological or other non-tectonic origins [see e.g. various artic-
cles in Clark et al., 1978]. In order to improve the short-term stability, it seems necessary to have the points of support for the tiltmeters located further below the surface or much further apart. For improved long-term stability, either deeper borehole instruments or liquid level instru-
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tions along the tube [Beavan and Blihm, 1977; Plumb et al., 1978; Bilham et al., 1979]. How-
ever, the installation costs for very long instru-
mements in irregular terrain may be high. The second type uses two tubes containing liquids with different thermal expansion coefficients [Huggett et al., 1976]. The effect of tempera-
ture variations then can be corrected for. A third type uses a measurement of differential pressure at the center of a thin tube connecting two end reservoirs of large diameter [Horsfall and King, 1978].

It is hoped that tests of the three types of long baseline liquid tiltmeters between the same end piers can be made soon in order to determine the instrumental accuracy. But research on the stability also will be needed in order to find out what instrument length is required to obtain a given long-term stability. A substantial amount of data on fairly deep borehole tiltmeters is available [Cabaniss, 1978; Herbst, 1976; Akashi and Fukuuo, 1977; Sato, 1979], but tests at the same site as the long baseline liquid instru-
mements are highly desirable.

For strain measurements, many types of instru-
mements have been developed. The most stable kind appear to be laser strainmeters [Berger and Wyatt, 1978; Berger and Levine, 1974; Levine, 1977; Beavan and Goulty, 1977; Seino et al., 1977]. However, even with a length of nearly a kilometer, the main stability limitation for instruments in-
stalled at the surface is the pier stability. Attempts are being made to overcome this problem by using optical anchors to measure pier motions with respect to reference points below the sur-
face layers [Wyatt et al., 1979]. Research also is in progress with a new type of strainmeter using a bundle of carbon filaments as the reference [Hauksson et al., 1979] instead of a laser beam, an invar wire, or a fused silica tube.

Space Techniques

The basic approach used in the space techniques is to measure the distance or difference in dis-
tance from points on the ground to extraterres-
trial reference points such as satellites or astronomical radio sources. The accuracy which appears to be achievable in such distance mea-
urements 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 present pro-
cedures 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.

To be as specific as possible, the discussion will be limited to the following space tech-
niques: laser range measurements to the Laser Geodynamics Satellite (LAGEOS); long baseline radio interferometry (LBI) using random noise emitted by extragalactic radio sources; and radio interferometry using signals from the Global Positioning System (GPS) satellites. The first two are expected to be used throughout the 1980's to measure tectonic plate motions and large scale distortions within the plates directly. The GPS approach is expected to be most useful for mea-
urements at considerably larger numbers of points in and around seismic zones and at much shorter time intervals. Networks of continuously operating GPS receivers in seismic zones appear to be a real possibility, although the trade-offs with ground techniques in both accuracy and cost...
will have to be considered carefully. Mixed networks containing both improved ground instruments and GPS receivers may turn out to be desirable.

LAGEOS Ranging

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 stations 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 CGM-10 gravity field model. Information on changes in the station positions should be considerably more accurate.

To obtain information on crustal movements at many more sites, a high-mobility LAGEOS ranging station is being constructed by the University of Texas [Silverberg, 1978], and two or three more probably will be built in Europe and the U.S. We can think of the orbit as being continually determined with respect to the fixed stations by range measurements from those sites. The high-mobility station then only has to obtain range measurements when LAGEOS is in three roughly perpendicular directions as seen from the ground in order to determine all three of its coordinates. In principle this could take only two satellite passes, but in practice four or more passes probably are needed. This is expected to take an average of one week or less per location for sites with 50% clear weather.

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.

Long Baseline Radio Interferometry

Although the radio noise arriving at the Earth from an extragalactic source is random in its amplitude and phase variations, it still can be used in high-accuracy distance measurements [see e.g. Counselman, 1976, 1980]. If two ground stations at the same site record the received signals for a fixed time, the cross-correlation between the two records will be maximum only if there is no time offset between them. If the stations are at different sites, the difference in travel time from the source to the two sites can be found by finding the delay time for one record with respect to the other that maximizes the cross correlation. The projection of the baseline onto the direction toward the source can be determined from the delay time, minus the clock difference between the two stations. For measurements with four or more sources in different directions in the sky, all three components of the baseline between the sites can be determined, as well as the clock difference. A number of fixed stations already have been involved in accurate long baseline radio interferometry (LBI) 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.

As with LAGEOS ranging, it is expected that the large majority of crustal movement measurements will be made by high-mobility stations. The NASA Jet Propulsion Laboratory has operated a mobile
LBI station with a 9 m antenna at various sites in California during the past few years [Niell et al., 1979]. A new high-mobility station using a 4 m antenna will soon be in operation. The measurement time at each site is two days or less with either station, although the 9 m antenna takes substantially longer to move from site to site. If both stations were equipped with 4 m antennas, the number of sites which could be redetermined per year is quite large. Or, alternatively, the 9 m station can serve as a reference station for the 4 m station when it is operating at very remote sites where fixed reference stations cannot observe the same sources simultaneously.

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$_2$O 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 Claffin [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 LBI measurements [Resch and Claffin, 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 Claffin, 1980], in support of both LBI and Global Positioning System measurement programs.

Measurements of baseline accuracy and reproducibility now are available for a number of LBI baselines. Results obtained with a 1.24 km baseline over a period of 15 months show rms variations of 3 cm, 5 cm, and 7 cm 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 the 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 [Herrington et al., 1980]. It is encouraging that the above results were obtained even without the use of water vapor radiometers.

Global Positioning System

The third space technique to be discussed involves the use of microwave signals at 1575 and 1227 MHz transmitted by the satellites of the Global Positioning System [Parkinson, 1979]. This system is being established by the U.S. Government for navigation purposes, and is intended to include either 18 or 24 satellites when it is completed in about 1987. The satellites are being placed in 12 hour orbits, with about 60° inclination and 20,000 km altitude. The first six satellites were in orbit by mid-1980. Each of the signals transmitted by the GPS satellites is 150° phase modulated with a 10.23 MHz pseudo-random code, so that the power received is spread out over about a 20 MHz bandwidth and the carrier is suppressed [Spilker, 1978]. However, by using a similar code generator in the receiver on the ground, it is possible to produce a sinusoidal output frequency which will change its phase by one cycle each time the distance from the satellite to the receiver changes by one wavelength. This signal is called the reconstructed carrier, even though it is at a much lower frequency than the satellite transmission. By making nearly simultaneous phase measurements on the reconstructed carrier with two receivers, information on the projection of the baseline in the satellite direction can be obtained. By switching both of the receivers to a new satellite every six seconds, and observing at least four satellites, the three components of the baseline and the difference of the receiver clocks can be determined [Rosaler et al., 1980; Counselman et al., 1980].

An alternate approach is to treat the received signals from the GPS satellites as noise, and use the conventional LBI method [MacDoran, 1978, 1979]. The received power per unit bandwidth is about 10$^5$ times stronger than for extragalactic radio sources, so that much simpler ground equipment can be used. This approach has the advantage that knowledge of the code is not required. However, directional antennas with roughly 20 dB gain are needed in order to pick out which satellite is being observed.

The descriptions given above of the two main methods for using the GPS signals to determine crustal movements are very brief. However, the basic interferometric approach underlying both methods has been checked out thoroughly in astronomical LBI measurements [Counselman, 1976]. Both methods are expected to give accuracies limited mainly by the uncertainty in the water vapor corrections for short baselines. There also will be some error introduced by the GPS satellite orbit uncertainties. But this will be
only 1 cm per 100 km of baseline length for 2 m orbit uncertainties, and accurate differential tracking of the GPS satellites from 4 or more well-separated ground stations at known locations can reduce the orbit errors considerably further.

The main point to be made is that the use of GPS signals with one of the two methods discussed above is likely to give just as high accuracy for short baselines as VLBI measurements with astronomical sources, and to be much simpler. GPS methods thus are likely to be useful whenever frequently repeated measurements are needed in seismic zones. For example, nearly continuous measurements over many baselines up to 100 km or more in length will be possible after all of the satellites are up, if they are needed.

It should be mentioned that the Doppler method, which has been used extensively for geodetic measurements with signals from the U.S. Navy Navigation Satellite System, also can be used with the GPS reconstructed carrier signals (Anderle, 1979). By making differential measurements between two ground stations, the effect of satellite clock instability is removed. In addition, the limitation because of instability in the ground clocks can be removed by rapid switching between the different satellites. However, the apparatus required is essentially the same as for the reconstructed carrier phase method, and the accuracy is not likely to be as good.

One other method for using signals from the GPS satellites has been suggested (Counselman and Shapiro, 1979). The approach would be to add low power transmitters to each satellite which would emit up to 10 sinusoidal signals at frequencies between 1000 and 2000 MHz. With a number of sinusoidal signals available, the receivers could be much simpler than for the other methods discussed. However, it is not yet known whether it will be possible to have the necessary transmitters added to future GPS satellites.

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