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LASER DISTANCE-MEASURING TECHNIQUES

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INTRODUCTION

The need to measure accurately distance on the surface of the earth arises in many different areas of science and engineering. The applications of geodesy range from simple surveys over distances of tens of meters to studies of the motions of lithospheric plates using measurements of transcontinental baselines.

It is clear that no one technique can hope to satisfy these widely disparate needs. Nevertheless some general principles emerge from a survey of the field. For distances longer than a few thousand meters the human surveyor and the steel tape are being replaced by automated machines that measure distance using electromagnetic radiation. The laser has proven very useful for these measurements because of its high brightness (i.e. its ability to produce intense beams whose divergence is limited largely by diffraction) and its excellent frequency stability. In this review I examine the various distance-measuring techniques currently in use or under development.

TECHNIQUES OF LENGTH METROLOGY

At the outset we must distinguish two broad areas of length metrology. First we have absolute length measurements in which the given result must be expressed in absolute meters. These measurements must be made using a length standard traceable to the definition of the meter. The "ruler" used in these measurements must be accurate and stable, and the measurement technique must be free from systematic errors. As an example of such measurements we may mention surveying. Second, we may think of measurements in which the change in the length of the baseline with time is more important than the actual length itself. Such measurements place a premium on stability rather than on absolute accuracy both in the length standard and in the measurement technique. We may not need to know the magnitudes of the various systematic corrections, being satisfied instead to know that they are constant in time. As examples of these measurements we may mention measurements of strain tides and studies of motions near or across plate boundaries.

Although this difference is clear in principle, the distinction between absolute and relative measurements becomes somewhat blurred in practice. The construction of a length standard of the requisite long-term stability for differential measurements near plate boundaries, for example, is nearly as difficult as construction of an absolute length standard. Furthermore, an investigation into the systematic errors of a measurement that is sufficiently detailed to insure that they are constant in time is often as difficult as calculating their magnitudes and removing them. Nevertheless the distinction is useful, as we see below. Accordingly we first discuss differential measuring instruments, principally strainmeters, and then absolute instruments.

DIFFERENTIAL MEASUREMENTS

Estimates of the Minimum Signal-to-Noise Ratio Required

The most common differential length measurement is a measurement of the fractional change in the length of a given baseline. We refer to this quantity as local strain.

The relationship between stress applied to the surface of the earth and the resultant strain is generally described in terms of a spherical coordinate system whose origin is at the center of the earth. The applied stress and the resulting strain are not usually colinear, and the local stress field is described in terms of a 3×3 matrix. If we limit our discussion to the surface of the earth, and if we assume that the matrix is symmetric (i.e. that the stress-strain relationship does not depend on the angle between applied stress and the local meridian), then the number of independent components is reduced from nine to three. Thus a complete specification

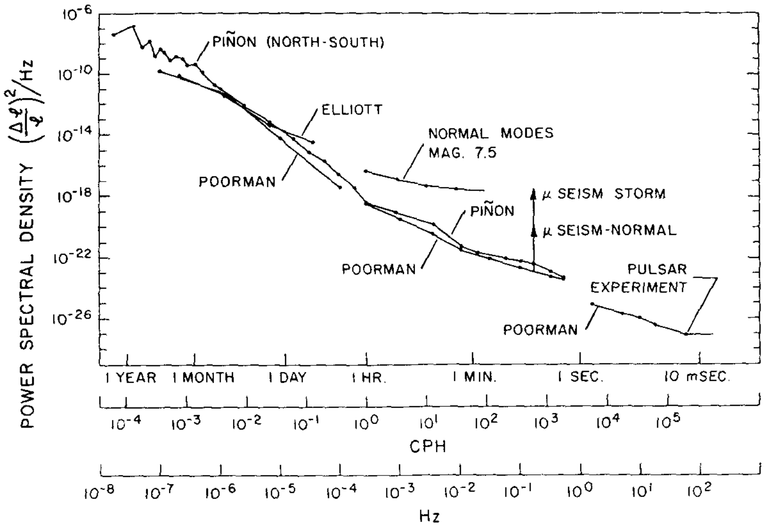

Figure 1 An estimate of the broadband strain noise measured at Piñon Flat, California, and at the Poorman mine near Boulder, Colorado.

of local strain requires three noncolinear measurements at every point. This is usually done by deploying three separate instruments at every site.

The magnitudes of the strains encountered in practice vary over a wide range. Earth-tide strain may be as large as 10^{-7} peak-to-peak while strains produced by teleseismic earthquakes rarely exceed 10^{-9}. We consider a strainmeter to be adequate if it is limited by earth noise over its entire operating frequency range.

The strain noise at quiet sites has been measured by Berger & Levine (1974), who used data from very different instruments located about 2000 km apart in very different geology. Nevertheless, their results are in good agreement over the frequency range extending from approximately 1 cycle month^{-1} to several cycles sec^{-1}. It is reasonable to postulate that their results represent a reasonable estimate of the earth noise (see Figure 1).

The measurement of strain at frequencies below 1 cycle hr^{-1} presents considerable experimental difficulty. In addition to the increasing level of broadband noise, measurement techniques using physical "rulers" (fused silica rods, for example) are limited by their relatively large coefficients of thermal expansion and by their unknown long-term stability outside of controlled laboratory environments. Furthermore, the difficulty of constructing a fused silica strainmeter increases at least as fast as the length, making long instruments (i.e. those greater than tens of meters) impractical.

Laser Strainmeter Technology

A laser strainmeter is simply an optical interferometer attached to the earth. The two most commonly used types are the Michelson interferometer and the Fabry-Perot interferometer.

In the Michelson interferometer (see Figure 2), the incoming radiation is split by beamsplitter B into two equal halves. The beams traverse the two paths L_1 and L_2, are reflected by mirrors m_1 and m_2, and are then recombined at the beamsplitter. The intensity of the recombined light is measured by detector D and is given by

$$I = \frac{I_0}{2}\left\{1+\cos 2\pi\left(\frac{L_1-L_2}{\lambda/n}\right)\right\}$$

where I_0 is the incident intensity, λ is the vacuum wavelength of the incident radiation, and n is the index of refraction of the air between the mirrors.

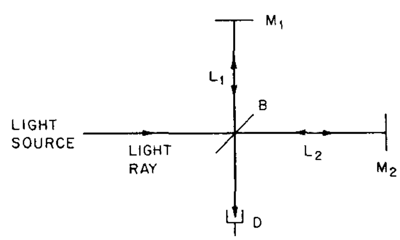

Figure 2 A Michelson interferometer; m_1 and m_2 are mirrors, B is a beamsplitter, and D is the detector.

In practice, L_2 is kept constant, and it is the variations in L_1 that are recorded. The quantity $(L_1 - L_2)/(\lambda/n)$ is simply the difference in path measured in units of the wavelength in the system. It may be rewritten in the form

$$\frac{L_1 - L_2}{\lambda/n} = N + \varepsilon,$$

where N is an integer and ε is a small number between zero and one. The intensity is then given by

$$I = \frac{I_0}{2}(\cos 2\pi\varepsilon + 1).$$

The intensity I thus reaches a maximum for $\varepsilon = 0$, i.e. when the difference in path length is an integral number of wavelengths.

The Fabry-Perot interferometer is shown in Figure 3. It consists of two partially transmitting mirrors (usually spherical) separated by a distance L. Light is incident from the left and bounces back and forth between the two mirrors. The intensity transmitted through the far mirror to the detector, D, is given by

$$I = I_0 \left\{ \frac{1}{1 + [4r/(1-r)^2] \sin^2 [2\pi L/(\lambda/n)]} \right\},$$

where r is the reflectivity of the mirrors and the other symbols are as defined above. The shape of the transmission maximum (the "fringe") is somewhat more complicated than the Michelson geometry, but the general idea is the same. The quantity $L/(\lambda/n)$ is the length of the path in units of the wavelength in the system. As above, we can choose an integer N such that

$$L/(\lambda/n) = N + \varepsilon.$$

The transmission thus is proportional to

$$\frac{1}{1 + [4r/(1-r)^2] \sin^2 2\pi\varepsilon},$$

and the intensity reaches a maximum when $\varepsilon = 0$ or $\varepsilon = 1/2$, i.e. when the path length is any integral number multiple of a half-wavelength.

The two interferometers differ mainly in the width of the transmission fringes. The Michelson interferometer fringe has a cosine shape whose width depends only on the path difference, $L_1 - L_2$. The width of the fringe in a Fabry-Perot interferometer depends on its length *and* on the reflectivity of the mirrors. The fringe in a typical Fabry-Perot interferometer has a width which is 1/15 or less of that obtained in a Michelson instrument of comparable size. We can use this fact to increase

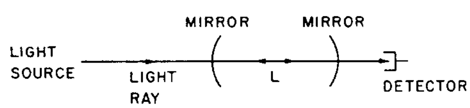

Figure 3 A Fabry-Perot interferometer.

the sensitivity of Fabry-Perot–type instruments by using a fringe-locking technique to be discussed later.

The two interferometers are quite similar in other respects. As described, neither system provides any direct way of measuring the integer number of wavelengths in the long path. Thus neither system can measure lengths absolutely and both are confined to relative measurements. (There are ways of measuring the absolute length of the interferometer, but none of them have been used in a geophysical field instrument to my knowledge.) In addition, both instruments are sensitive in first order to three problems: long term changes in the physical properties of the mirror coatings, changes in the index of refraction of the air between the mirrors, and changes in the wavelength of the incident light.

The condition for maximum transmission is really a statement about the phase shift suffered by the light in traversing the interferometer. In addition to the phase shift suffered by the light due to the transit time through the system, there is an additional, usually unknown, phase shift on reflection from the multilayer dielectric coated surface used as the mirror. Changes in this phase shift with time produce corresponding changes in the apparent optical length of the interferometer arm. This phase-shift change is proportionally less serious in longer instruments since it represents a smaller fraction of the phase change through the system, but it could be quite serious indeed for instruments only a few meters long.

The index of refraction of the air between the mirrors can also present a problem. The interferometers are usually evaluated to a few tenths of a N/m^2 (a few millitorr). Nevertheless, a significant amount of air remains.

The index of refraction of air at standard temperature and pressure differs from unity by about 300×10^{-6} in the red part of the spectrum. Thus, a change in pressure of 0.13 N/m^2 (1 millitorr) would change the index of refraction by about 4×10^{-10}, producing a spurious strain signal of this amplitude. This is a rather large change in pressure to remain undetected, often amounting to 5% of the system base pressure, but it can be easily generated by a small leak. The residual air in the path can also result in the instrument's being sensitive to ambient atmospheric pressure. This effect is very small in well-designed systems.

Finally, we must deal with the stability of the laser wavelength itself. The frequency stability of a laser is governed by the stability of the optical cavity and by the gain profile of the amplifying medium. In a well-designed system, the instantaneous frequency is governed by the optical cavity whose fringe width (i.e. the width in frequency units over which the cavity will support oscillations) is about 5 MHz. Expressed in terms of the laser frequency, 5 MHz is a fractional stability of about 1×10^{-8} and is therefore marginally acceptable for strainmeters. However, this instantaneous narrow line will shift its frequency in response to any change in ambient temperature or in other laser-operating parameters. The drift in oscillation frequency will be limited by the gain profile of the amplifying medium, which is of the order of 1 GHz. Thus the long-term fractional frequency stability of the laser will probably be no better than 5×10^{-6} and may approach 1×10^{-5} unless special precautions are taken to stabilize the cavity.

Although it is theoretically possible to stabilize a laser by directly stabilizing the length of its cavity, such systems have never been used in geophysical applications.

The most commonly used stabilizers are passive cavity references and saturated absorption stabilizers. A passive cavity reference is simply an ancillary Fabry-Perot cavity. The laser wavelength is stabilized by tuning the laser (usually by changing the length of the laser cavity piezoelectrically) until the laser wavelength corresponds to one of the fringes of the reference cavity. A servo system then maintains the laser at the top of the transmission maximum by locking to the point of zero first derivative of the transmission function.

At first sight instruments using a laser stabilized to a passive reference cavity would seem to be no better than instruments using a fused silica bar for the strainmeter itself since the reference cavity, which is a physical "ruler," is subject to all of the thermal expansion and long-term creep problems of fused silica strainmeters. However, the passive cavity can be made short and rigid, and the stabilization of its ambient temperature and pressure is easier than trying to do the same stabilization for the entire strainmeter. Indeed, a well-designed reference cavity can have adequate stability for earth-tide measurements. The behavior of a passive cavity over periods of months is, however, not well understood, and it is probably not adequate for secular strain measurements.

A saturated absorption stabilizer exploits the overlap between a molecular absorption line and the laser frequency. The absorber is placed inside the laser cavity (Lee & Skolnick 1968). When the laser is tuned to the center of the absorption profile, the two oppositely directed running waves that make up the standing wave in the cavity interact with the same velocity group of absorbing molecules—namely those with velocity purely transverse to the laser beam. When the laser is not tuned to the center of the absorption line, the two running waves interact with two different groups of molecules whose velocity components along the laser beam provide the requisite Doppler shifts to bring them into resonance. Thus, there are twice as many absorbing molecules available off of the line center as there are at line center.

By proper choice of operating conditions, the optical power saturates the absorption at the center of the line, resulting in a power *increase* there. This feature is quite narrow. Its width is limited by cavity parameters and is usually of the order of 100 kHz for field-type systems. Its position is determined by the absorption line in the stabilizer molecule and is essentially independent of temperature, pressure, or cavity parameters. (There are certain systematic offsets that must be dealt with, but they are of the order of 10^{-11} or less in well-designed systems.)

The best saturated absorption-stabilized laser is obtained by stabilizing a helium-neon laser oscillating at 3.39 μm to a transition in methane; the parameters quoted above apply to this system (Barger & Hall 1969, Levine & Hall 1972). Other saturated absorption-stabilized lasers exist. The only other one used in the geophysical context exploits an overlap between I_2 and a helium-neon laser oscillating at 632.8 nm (Ezekiel & Weiss 1968). It is somewhat more difficult to use in a field situation, but has an accuracy capability almost as good as methane-stabilized devices. The full accuracy capability is often not realized in field devices, however, because the absorption profile must be measured in the presence of a baseline whose slope changes with time.

With either stabilization system, it is necessary to read out the length of the interferometer in terms of the wavelength. Again we may distinguish two types of readout systems.

The simplest system is a fringe counter. Each time the intensity passes through a preset value corresponding to some chosen value of ε, a counter is either increased or decreased by increments depending on the direction of motion. The direction of motion can be determined in various ways (Rowley 1966). The value in the counter at any time is converted to strain by noting that each count represents a strain increment of $\lambda/2Ln$. Although the fringe-counting system is simple to implement, its fundamental limitation is that it has a sensitivity limited by the least count. For example, a 100-m-long instrument illuminated by a 632.8-nm light source would have a least count of about 3×10^{-9}. Therefore, fringe-counting systems are only viable in very long interferometers where the least-count noise does not dominate the system response.

It is possible to reduce the least-count noise of a system by counting fractional fringes. If a system can be constructed to divide a fringe into m parts, then the smallest detectable strain is reduced by the same factor m. It is difficult to make m larger than about 10 without introducing problems with long-term stability. Levine and Hall (1974 unpublished) have proposed techniques to divide fringes into 500 parts using digital techniques, but these techniques have never been used in field instruments.

A second, more complex system employs fringe locking. A free running laser is tuned so that its frequency corresponds to the peak of the fringe of the system. A servo system then maintains the laser locked to this fringe by seeking the zero of the first derivative of the transmission function. As the path length changes, the servo tunes the laser to keep the integer N a constant. The frequency of the laser is thus given by

$$f = \frac{Nc}{2Ln},$$

where c is the velocity of the light and N is now a constant (note—it is an unknown constant). The frequency of this laser is then beat against the frequency of a second, stabilized laser. The difference frequency is extracted. If f_0 is the frequency of the standard, the beat frequency is given by

$$f_b = f_0 - \frac{Nc}{2Ln},$$

and the fractional change in the beat frequency is related to strain by

$$\frac{\Delta f_b}{f_0} = \frac{\Delta L}{L}.$$

Since f_0 is known to a high degree of accuracy, the system reads strain directly without any adjustable constants or calibration factors.

Although the fringe-locking system is more complicated than a fringe counter in that it requires two lasers and roughly twice as much electronics, it has several distinct advantages. First of all, it possesses no least count as such, because its minimum detectable strain is limited instead by noise in the electronics. Second, it can take full advantage of the increased fringe sharpness obtainable with Fabry-Perot interferometers and can easily resolve changes in the length of the path of order $10^{-5} \times \lambda$ with a reasonable quality Fabry-Perot. Third, its output is in the form of a frequency. The measurement of a frequency is very easy and can be implemented using digital counting circuits that can be made almost totally insensitive to drifts in gain or changes in offset voltage. This greatly increases their reliability.

Typical Laser Strainmeters

The principles I have outlined have been used to construct several laser strainmeters. Two of the best designed instruments are the 800-m Michelson instruments operated by the University of California near La Jolla (Berger & Lovberg 1970) and the 30-m Fabry-Perot instrument operated by the National Bureau of Standards near Boulder, Colorado (Levine & Hall 1972).

Applications of Laser Strainmeters

Although laser strainmeters have extremely wide band widths extending from tens or hundreds of Hz down to d.c., they are not usually used at frequencies above about 0.01 Hz because this frequency range can be covered adequately using conventional instruments. [An exception is the attempt by Levine & Stebbins (1972) to detect gravitational radiation from various pulsars using a 30-m instrument.]

They are most useful for investigations of the earth normal modes in the frequency range from 1 to 30 cycles hr^{-1}, in earth-tide studies, and in measurements of secular strain.

These investigations require instruments that are long enough to average over the local inhomogeneities inevitably present at any site. At the same time, the instruments must be as insensitive as possible to the large thermal and pressure effects present at these frequencies.

Detailed analyses of the earth tides have been carried out by Levine & Harrison (1976) and by Beaumont & Berger (1975). Analyses of long tidal series have shown that the strain tides are sensitive to local topography, local crustal inhomogeneities, and to various other site effects, and that incorporation of these effects into the theory substantially improves the agreement between theory and experiment. The residuals in the published data are of the order of 1% of the amplitude of the tides and are almost certainly the result of inadequacies in the estimation of the contamination of the record by local effects.

Long-term strain accumulation has also been monitored (Berger & Wyatt 1973). This is especially significant near the San Andreas fault system where long-term strain data may prove useful in understanding earthquakes. Continuous records of long-term strain can also be analyzed to measure steps in the baseline associated with earthquakes.

Limitations of Strainmeters

The fundamental limitation of laser strainmeters is that they are not absolute length-measuring instruments. They achieve their excellent sensitivity not by eliminating the various systematic corrections (refractive index of the residual air in the path, for example), but by eliminating or at least recording the changes of these corrections with time. Thus, a measurement of long-term changes in strain requires that the instrument be operated at a given site for long periods of time. A breakdown of any part of the system makes it impossible, at least in principle, to recover the baseline. [In practice, data gaps of a few days or less can be patched using the earth tides and the measured parameters at the site (Levine & Harrison 1976).] The instrument must be extremely reliable. In practice, the entire system must have a mean time between failures of several thousand hours with a mean time to repair of a day or two. This is not a trivial requirement, and it, more than any other single factor, has limited the use of laser instruments.

The differential nature of laser strainmeter measurements has a second, equally serious implication in the measurement of secular strain. Although these strain rates are very slow and could be adequately monitored by only occasional measurements at any one site, the differential nature of strainmeters requires that the strainmeter be operated continuously at a single site. This is an extremely inefficient use of a very complicated and expensive apparatus. A portable instrument of equal complexity capable of making absolute measurements could be used much more efficiently in secular strain determinations, since it could be used to monitor the secular strain at many sites simultaneously.

The ultimate limitation to accurate strain measurement is due to our ignorance of local crustal inhomogeneities. The only practical solution to this problem is to average these effects by making instruments with longer and longer baselines. Although this increases the cost of the pipe and hence the cost of the instrument, the real difficulty with increasing the length of the instrument is the difficulty of finding suitable sites, and the cost of site preparation. It is clear that, except in exceptional cases (e.g. old railway tunnels or mines), finding sites for instruments much longer than 800 m would be a very difficult task indeed.

ABSOLUTE MEASUREMENTS

The previous discussion suggested that secular-strain measurements could be done more efficiently using absolute measuring techniques capable of measuring long baselines directly through the atmosphere. There are, in fact, several ways by which this may be accomplished. The techniques fall into two broad categories—totally ground-based and extraterrestrial.

Ground-Based Measurements

INTRODUCTION The idea of measuring distances using the time-of-flight of electromagnetic signals is not new. Indeed, for applications requiring ranging to an uncooperative target, and where resolution of a few meters is acceptable, the familiar radar time-of-flight techniques can be used. These techniques are not sufficiently accurate for geophysically motivated measurements.

It is difficult to estimate the minimum acceptable resolution needed for geophysical measurements. Experience with the application of existing techniques to secular strain determination suggests that the minimum acceptable range is 10–20 km with an absolute fractional accuracy of less than 1×10^{-6}. Furthermore, increases of factors of 2 to 3 in range and 50 in accuracy would be most welcome and could substantially improve our knowledge of secular strain rates in seismically active areas. As I show below, various systematic errors will probably conspire to limit ground-based measurements to ranges less than about 100 km with fractional accuracies that will probably never be better than 1×10^{-8}. With these limits in mind, we can proceed to evaluate the various techniques.

TIME-OF-FLIGHT MEASUREMENT The time-of-flight of a light beam is about 3 μsec/km. Thus measurement of distances by optical time-of-flight measurements with an accuracy of 1 part per million or better requires absolute timing accuracies in the picosecond range. This is not impossible in principle, but is well beyond the current state of the art. An absolute timing accuracy of 25 psec has been reported in a prototype instrument (Querzola 1974), but the ranges measured were only 5 to 10 km long so that the fractional accuracy was just slightly better than 10^{-6}.

MODULATION TECHNIQUES Most of the work in electromagnetic distance measurement has used various modulation schemes. The basic idea is quite simple: The light is modulated at some high frequency, and the distance is determined by measuring the phase shift of the modulation due to the transit time along the path.

Evaluation of systematic errors The most serious limitation to the measurement of distances through the atmosphere is the correction required to account for the deviation of the index of refraction from unity. Bender & Owens (1965) suggested that the index might be determined most easily by measuring the difference in the apparent distance as measured by light of two different wavelengths. Thus, the index is determined by measuring the dispersion it produces.

We can quantitatively evaluate this method using the formulae for the dependence of the index on wavelength and on composition (Edlen 1953).

The group index of refraction of dry air at standard temperature and pressure is

$$N_g = 1 + 10^{-6} \times \left\{83.4213 + 24060.3\left(\frac{130+\sigma^2}{(130-\sigma^2)^2}\right) + 59.97\left(\frac{38.9+\sigma^2}{(38.9-\sigma^2)^2}\right)\right\},$$

where σ is the wave number in inverse micrometers. For any other temperature T (in K) or pressure P (in mm Hg) we have:

$$n(P, T) - 1 = (n_g - 1)\left\{\frac{P/760}{T/288}\right\}.$$

The index of refraction differs from unity by about 282×10^{-6} at 632.8 nm and 299×10^{-6} at 441.6 nm, so that the dispersion results in a fractional change in the measured length of about

$$17 \times 10^{-6}\left\{\frac{P/760}{T/288}\right\}.$$

Thus, we can see that the index must be determined to 1 part in 10^4 if the length is to be determined to 2 parts in 10^8. The fractional requirement on the index translates into an identical fractional requirement on P/T. This in turn places a heavy burden in the dispersion measurement since the magnitude of the dispersion is only about 8% of the index itself.

This relatively simple approach must be modified somewhat in actual usage since the atmosphere contains some water vapor. The presence of a partial pressure of f torr of water vapor results in an additional term in the index whose magnitude is (Barrell & Sears 1940)

$$-f\{5.722-0.1371\sigma^2\}\times 10^{-8}.$$

Thus, the water vapor contributes about 8×10^{-6} to the index of refraction in the visible for reasonable values of f, but the contribution is almost nondispersive across the visible, making its determination by optical dispersion impossible. However, the water vapor contribution to the index is sufficiently small that it may be estimated by directly measuring the dew point at the ends of the path. Alternatively, several investigators have proposed adding a third microwave-frequency measurement of the distance. The index of refraction at microwave frequencies depends strongly on the water vapor in the atmosphere so that a measurement of the microwave-optical dispersion can be used to measure the water-vapor density.

There are other systematic errors associated with multiple-wavelength systems. These include errors produced by the curvature of the path and by the fact that the different wavelengths do not traverse the same path and hence may sample different atmospheric conditions. These and other errors have been analyzed in detail. Thayer (1967) concluded that ranges of the order of 50 km can be measured with an accuracy of several parts in 10^8 using triple-wavelength devices and with perhaps a factor of ten lower accuracy using only two optical wavelengths and estimating the water density from ancillary measurements at the endpoints.

Results Although multiple-wavelength systems have been in the literature for several years, most of the measurements have been done with less sophisticated instruments. The U.S. Geological Survey (Savage & Prescott 1973) uses single-wavelength devices that must be corrected for the index of refraction using ancillary measurements. These measurements are often made from an airplane flying as closely as practical to the line of sight. The Geological Survey has reported a reproducibility of about 2 parts in 10^7 for ranges up to 35 km (Savage & Prescott 1973). At that 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.

Two- and three-wavelength optical and optical/microwave distance-measuring instruments have been constructed by various groups (Earnshaw & Hernandez 1972, Huggett & Slater 1975). Standard deviations as low as 1 part in 10^7 over 10 km baselines have been reported.

Summary The majority of distance measurements using electromagnetic distance-measuring equipment do not exploit the various multiple wavelength schemes proposed in the literature. Several groups have constructed two- and three-wavelength devices, but so far they have not been widely adopted. This situation will almost certainly change as the multiple wavelength devices are made simpler and more reliable.

Extraterrestrial Techniques

Finally I discuss below extraterrestrial techniques. These include satellite ranging, lunar ranging, and very long baseline interferometry (VLBI). Although VLBI is similar in concept to satellite ranging and lunar ranging, it uses microwave radio antennas and so is technically outside of the scope of this paper. Nevertheless, many of our discussions concerning the use of the other techniques for distance measurement on the surface of the earth can be applied to VLBI with little change.

GENERAL PRINCIPLES The general principles of these techniques may be simply stated. Distances on the surface of the earth are determined using triangulation by measuring the distance from the extraterrestrial object to several stations at different points on the surface of the earth. These observations may be made simultaneously, or, if the orbit is sufficiently well known, at different times. The data obtained in this way may be analyzed to yield the distance between the two stations.

EVALUATION OF SYSTEMATIC ERRORS I do not discuss the systematic errors in these techniques in detail. Rather we concern ourselves with the uncertainties that arise in the extraction of the distance between the two stations from the raw ranging data.

Extraterrestrial techniques do not directly measure the line-of-sight distance between the stations. The distance between the states is extracted by (loosely speaking) taking the difference between two ranges which are the same to first order. The determination of the station separation is therefore very sensitive to small errors in the range measurement made at either station.

Published analyses of the various techniques have shown that the distance between two points on the surface of the earth can be determined to a few centimeters (Bender & Silverberg 1975, Coates et al 1975).

If we take 1 cm as an optimistic estimate of the accuracy capability of these techniques, then measurement of strains at the level of one part in 10^7 can only be achieved over baselines exceeding 100 km in length.

SUMMARY Measurements of distances on the surface of the earth using these techniques have just begun in the last few years. The development of mobile ground stations should make it possible to measure accurately motions in tectonically or seismically active regions in the near future.

CONCLUSIONS

The development of saturated absorption-stabilized lasers has resulted in a substantial improvement in the state of the strainmeter art to the point that instruments are now limited by our ignorance of the properties of the site. For baselines less than 1000 m long, these instruments can reliably measure strain to an accuracy limited by earth noise and site inhomogeneities.

In the next few years we should see a substantial improvement in the techniques for measuring longer baselines. Multiple wavelength geodesy will be used to provide strain measurements over baselines up to 50 or 100 km with accuracies exceeding 1 part in 10^7. The various extraterrestrial techniques will be used to provide comparable accuracies over baselines longer than a few hundred kilometers.

It is not yet clear if a significant range or accuracy gap exists between the maximum range capability of ground techniques and the minimum range (given the accuracy requirement) obtainable with extraterrestrial ones. We will almost certainly see substantial progress in these areas in the next few years.

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