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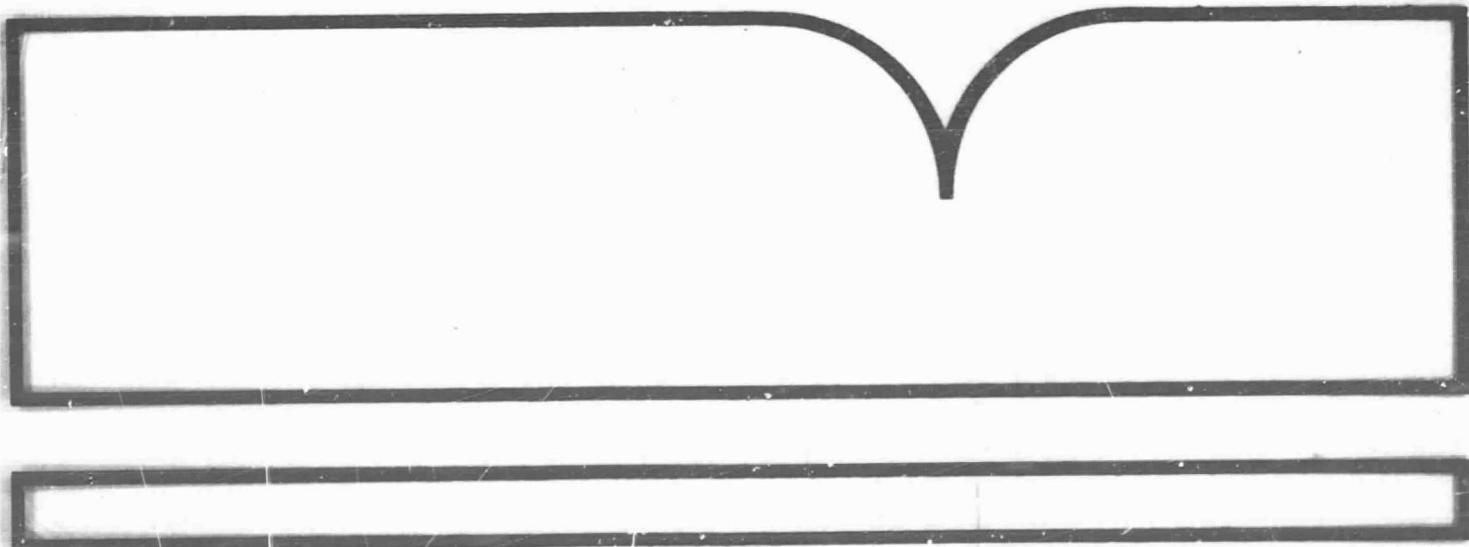
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Geodesy
A look to the Future

National Research Council, Washington, DC

Prepared for
Defense Mapping Agency, Washington, DC

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Geodesy

A Look to the Future

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Geodesy

A Look to the Future

**Committee on Geodesy
Commission on Physical Sciences, Mathematics, and Resources
National Research Council**

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NOTICE: The project that is the subject of this report was approved by the Governing Board of the National Research Council, whose members are drawn from the Councils of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine. The members of the Committee responsible for the report were chosen for their special competences and with regard for appropriate balance.

This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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FOREWORD

This background document was prepared by the Committee on Geodesy to be distributed to attendees at a forthcoming symposium on Geodesy in the year 2000. The document deals with the current and future uses of contemporary data and poses some questions and possibilities. The following subjects are considered: geodesy, instrumentation, and current and future applications of contemporary geodetic data. Under each of these subjects a number of similar topics are considered. This has led to some duplication; for completeness and clarity of each section the Committee believes that such duplication is warranted.

It is anticipated that this background document will generate interest in present and future geodetic data for the solution of problems in earth, ocean, and atmospheric sciences. It is also hoped that researchers in these sciences can assist the geodetic community in generating requirements for geodetic data today and in the future.

Geodetic science is in a state of transition. The likelihood that subcentimeter real-time position accuracy will be achieved within the next decade is high. The implications and impact of this breakthrough should not be lost on the scientific community. Therefore, the Committee on Geodesy will attempt to develop a dialogue with researchers in the various sciences in order to develop uses for these data.

The Committee on Geodesy has been supported by the Defense Mapping Agency, Department of Defense; the National Aeronautics and Space Administration; the National Oceanic and Atmospheric Administration, Department of Commerce; and the U.S. Geological Survey, Department of the Interior. The Committee appreciates this support and particularly thanks the liaison members of these and other federal agencies for their efforts in forwarding the aims and activities of the Committee.

Byron D. Tapley, Chairman
Committee on Geodesy

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GEODESY

1.1 POSITIONING

By positioning we understand the determination of coordinates of a point, or a point configuration, in a well-defined coordinate system. Positioning is the classical task of geodesy: positioning on land and on sea surface (the geodetic part of navigation) have been with us for several thousands of years.

Because of the generally different techniques used, it is usual to distinguish among (absolute) point positioning (with respect to a coordinate system), relative positioning (determination of coordinate differences), and areal positioning (determination of positions of a whole network of points).

Accurate positioning has always been a time consuming and thus expensive task. Up until a few decades ago an accurate transfer of position from one side of the continent to the other had taken many years to accomplish using the only available mode, i.e., the incremental mode of geodetic networks. Today, with the ready availability of satellite-determined positions, the situation looks dramatically different. The evolution has generally been from incremental to (absolute) point positioning, from a laborious and lengthy operation to an almost instantaneous one.

In the past 20 years, we have also witnessed an increase in accuracy of one to two orders of magnitude in positions separated by long distances. In addition, modern techniques allow us to position not only on land but, with almost the same ease, on the sea surface, and in the near future accurate positioning on the sea bed may also become commonplace (Committee on Geodesy, 1983).

Positioning is naturally and intricately related to the problem of realization (positioning and orientation with respect to the Earth) and maintenance (monitoring of the position and orientation) of the coordinate systems. Many such coordinate systems are used in geodesy (Vanicek and Krakiwsky, 1982) in connection with different positioning systems.

Temporal deformations of the Earth make positioning more complicated, especially in the network mode, when the assembly of a network takes many decades (and thousands of man-years). So far the accuracy of network point positions has been sufficiently low to allow

geodesists to neglect all deformation but the largest co-seismic deformations. This situation is changing, however, and the problem of time-varying positioning will have to be faced on a systematic basis.

1.1.1 Point and Relative Positioning

One may argue, with some justification, that all positioning is really relative in nature and that there is no such thing as absolute point positioning. The coordinate systems in which points are positioned are only realized with respect to other points--a typical bootstrap operation. We shall, nevertheless, adhere to this terminology, in absence of any better classification.

Point-Positioning Techniques

There currently exist only two techniques for point positioning: optical astronomy and positioning by means of satellites (satellite positioning). Using optical astronomy we can determine the so-called astronomical latitude and longitude (and astronomical azimuth). For these quantities to be useful for positioning, i.e., to give coordinates in a reasonable coordinate system such as the geodetic system (ϕ, λ), the direction of the local gravity vector must be known. This direction is normally given with respect to the normal of the desired geoid in terms of the deflection of the vertical components ξ (meridian deflection) and η (prime vertical deflection) (see Section 1.2). Because of this, an accuracy in position no better than several meters can be achieved.

Alternatively, if the position of an astronomical station is known, say in the (ϕ, λ) system, the astronomical latitude and longitude may be used to obtain the direction of the local vertical (gravity vector). Such points are known as deflection points. The accuracy of so-determined deflections is at best a few tenths of a second of arc. Astronomical azimuth can be determined to a similar accuracy, comparable with the accuracy achieved by modern gyrotheodolites.

Astronomical optical (Vanicek and Karkiwsky, 1982) observations have to be carried out during the night and only when the weather is clear. This requirement makes this technique expensive, and the necessary bulky equipment makes it unwieldy. The main accuracy limitations are optical refraction and uncertainties in star coordinates. In this context precession, nutation, polar wobble, and irregularities in the Earth's spin rate are all nuisance effects. But, as one man's noise is another man's signal, optical astronomy has traditionally been the main technique for measuring these effects, a role that is now being taken over by more accurate modern techniques such as radio interferometry. Astronomical optical measurements are too inaccurate for use in the meaningful detection of other geodynamical phenomena as, for instance, the Earth's body tides.

Point positioning by means of satellites requires the knowledge of the satellites' positions (orbital ephemerides). These satellite

positions play the same role as star positions play in optical astronomy--that of the external reference frame. The main differences between the two techniques is that satellite techniques can deliver three-dimensional (3-D) positions as compared with two-dimensional (2-D) positions for optical astronomy; and it is possible to make range measurements accurately to satellites, whereas it is not possible to do so to stars. Besides ranging, using either optical lasers or radiowaves, it is also possible to observe range differences (between satellite positions on the same orbital pass) using integrated Doppler shifts of a stable radio frequency, as well as to measure directions optically. We note that both range differences and directions are indeed used in astronomy. Range differences are the observables in radio interferometry; directions are the observables in optical astronomy.

The most successful and the most widely used satellite positioning system so far has been the TRANSIT (Doppler) system inaugurated in 1963 by the Navy and released for public use in 1967. Many thousands of Doppler receivers are used daily, and the accuracy achieved in point positions is around 1 m for several days of observations (Stansell, 1978). The main obstacles to a significant accuracy improvement are refraction, orbital uncertainties, clock performance, and antenna design (Kouba, 1983). The best results are obtained for orbits postfitted to a series of observations made during a certain period of time (precise ephemerides). Positions determined by means of predicted (broadcast) ephemerides are significantly worse. We note that accuracy of relative positions determined by the TRANSIT system (see Section 1.1.2) is indeed much better. The TRANSIT system is also being used to monitor the polar wobble (DMAHTC Polar Monitoring Service). Further details can be found in Section 2.3.2.

The TRANSIT system will be gradually replaced by another Department of Defense (DOD) product, the NAVSTAR Global Positioning System (GPS), which promises to be not only much faster but also somewhat more accurate in its point-positioning mode. The real geodetic interest in GPS is in its intrinsically high accuracy when used in the relative positioning mode. Consequently, the GPS will be discussed more fully in the context of relative positioning. Details on the system are also given in Section 2.3.1. Laser ranging systems using the moon (lunar laser ranging) and artificial satellites (satellite laser ranging), such as the NASA Laser Geodynamic Satellite (LAGEOS), are point-positioning systems capable of delivering extremely high accuracies (Hill, 1983). Laser ranging is also capable of monitoring polar wobble and Earth rotation very accurately. More detailed discussion of different satellite positioning systems is given in Section 2.3. Let us only mention here that all satellite-determined positions are in coordinate systems whose geocentricity is enforced through the equations of motions used in computing the orbits. The geocentricity enforced through laser ranging to LAGEOS is now thought to be accurate to about 0.2 m (1 s.d.). The orientation of these coordinate systems is established by the choice of the known positions of the set of permanent tracking stations.

Coordinate Systems

In general there are two kinds of Cartesian coordinate systems, and their derivates, used in geodesy: those based on physical principles (e.g., center of mass of the Earth, principal axes of inertia, geoid, direction of gravity) and those based on conventions [e.g., the Conventional International Origin (CIO), zero meridian, origin of a network, mean sea level, normal to reference ellipsoid].

In the case of the first kind of system the theoretical orientation (and possibly position) with respect to the Earth is known (defined) while the realization of the system's orientation (and position) can be only approximate. With the second kind of system, the orientation (and position) with respect to the Earth is only implied by accepted coordinates of either a minimal or a larger number of specified points. Then the theoretical orientation (and position) with respect to the Earth is not defined and can be determined only through a transformation into another coordinate system in which the corresponding coordinates of collocated points are known.

Different positioning techniques have different observable quantities (observables). These observables are more or less directly related to coordinate differences in one or another coordinate system. Depending on these relations, one system may be more natural to use than another with any specific positioning technique.

It is only when different coordinate systems are employed that we must wrestle with the orientation (and position) problem because transformation parameters needed for going from one into the other systems must be determined. Depending on the nature of the involved systems, these parameters may have to be determined from coordinates of collocated points and as such are affected by errors in both sets of coordinates.

Sometimes in geodesy the (Cartesian) coordinate system is positioned using a datum (i.e., a surface of a constant coordinate value) or one of the curvilinear coordinate systems associated with it. In such cases the mathematical expressions involved may be more complicated but the basic concepts remain the same.

Interesting problems arise when networks of different origin, different dimensionality, and expressed in different coordinate systems are to be merged. Such a merger is likely to become a vehicle for unraveling systematic distortions in the networks, should these exist. Problems of a similar nature arise from densification of networks.

The situation becomes more complicated when temporal variations have to be considered. In such a case the orientation (and position) of the coordinate system with respect to the Earth has to be defined or determined so that Earth deformations may be uniquely described. Thus, for instance, in a geocentric coordinate system, every point on or in the Earth may move except the center of mass. Clearly, even the transformation parameters will be functions of time. An explanation of the concepts involved is beyond the scope of this report.

Relative Positioning

As stated earlier in this section, relative positioning is the name for the determination of interstation vector (baseline) components.

Traditional terrestrial methods require intervisibility between the two end points, modern methods do not. This makes for the possibility of longer baselines and for almost arbitrary location of the end points. Since techniques used for 3-D, 2-D (horizontal), and vertical relative positioning are mostly quite different, it is expedient to distinguish these as separate issues.

Starting with 3-D relative positioning, one of the most accurate techniques is that of radio-astronomy very-long-baseline interferometry (VLBI), which uses compact extragalactic radio-wave emitting sources such as quasi-stellar objects (quasars) to determine relative positions to an accuracy characterized by standard deviations of $S \times 10^{-8}$ (S is the length of the baseline) from observing campaigns lasting one or two days (see Section 2.3). These relative positions, which may be many thousands of kilometers apart, are determined directly in the instantaneous terrestrial (geocentric) system of coordinates. This enables us to evaluate from the VLBI observations all the usual motions, such as precession, nutation, polar motion, and UT1, more accurately than by classical optical techniques (Tapley, 1983). Other geodynamical phenomena, such as body-tide or ocean-tide loading, are also clearly detectable.

All the satellite techniques described in the previous section can also be used in a 3-D relative positioning mode with the interstation distance limited only by the altitude of the used satellite. Accuracies (one standard deviation) vary from system to system but are generally of the order of $S \times 10^{-6}$ to $S \times 10^{-8}$ (see Section 2.3). The main limitations, depending on the interstation distance, are again refraction, orbit uncertainties, and clock performance. Roughly the same performance is delivered by lunar laser ranging, which has proved to be especially handy for monitoring the variations in UT1 (Langley et al., 1981).

A special note should be made of the TRANSIT system, which has been used extensively in the translocation mode in geodetic practice. Results indicate that standard deviations of a few decimeters can be achieved; the main applications are described in Section 1.1.2. The GPS promises to replace the TRANSIT system for most geodetic applications. GPS relative positioning accuracy is about one order of magnitude higher than that of TRANSIT. The speed of position determination by GPS is also one order of magnitude better than TRANSIT and will further improve when the full satellite system becomes available. It should be noted that height differences are determined at an accuracy perceptably poorer than differences in horizontal coordinates.

For shorter distances the standard geodetic measurements of angles and distances are still being used. The distinct advantage of this technique is that it is practically instantaneous. Distances of a few tens of kilometers can be observed now with an accuracy of $S \times 10^{-7}$ or better, horizontal angles to an accuracy 10^{-6} , and vertical angles only slightly worse (at least under special arrangements) (Hradilek,

1984). If such relative positions are to be expressed in a reasonable coordinate system, good knowledge of the Earth's gravity field is required. The main hindrance here is, again, the atmospheric refraction.

Analytical photogrammetry and inertial positioning are the other systems that can be used for 3-D relative positioning. However, a more natural mode for both of these systems is an interpolation of positions either along a profile or for a set of areally distributed points, given the end points of peripheral point control. Photogrammetry (see Section 2.2.1) is capable of an accuracy of 5×10^{-5} over distances of the order of tens of kilometers. Inertial positioning systems (see Section 2.1.5) are about one order of magnitude more accurate over distances of about $S = 100$ km. (In addition, inertial systems can also measure quite accurately the deflections of the vertical and gravity anomalies.) Both photogrammetry and inertial systems give positions in the same coordinate systems in which the peripheral control is given.

Two-dimensional (horizontal) relative positioning concerns the determination of either ϕ and λ on a selected reference ellipsoid or x and y on a chosen mapping plane. Given a 3-D interstation vector, it is easy to derive a set of horizontal coordinate differences by simply projecting the vector on the reference ellipsoid and, if desired, further onto the mapping plane. There are, however, special 2-D techniques that may be cheaper, more practical, or even more accurate. A typical example is the classical terrestrial geodetic approach whereby vertical angles are used only for the reduction of observations onto the reference ellipsoid. This is done because of the poorer accuracy (10^{-5}) of vertical angles measured under normal circumstances. This procedure ensures 2-D accuracies comparable with the accuracy of the more elaborate 3-D approach.

Two-dimensional techniques are used extensively in the marine environment, in the positioning of stationary or moving (navigating) objects on the sea surface. The most convenient technique used in navigation is hyperbolic positioning using long-wavelength radio signals. Owing to horizontal-radio-wave dynamic paths and vessel motion, the accuracy of marine positioning is, as a rule, a few orders of magnitude lower than that on land. However, stationary objects (e.g., oil rigs) can be positioned at sea with the same accuracy as objects on land.

Vertical positions (heights) are normally referred to either a selected reference ellipsoid (rarely) or to the geoid or quasi-geoid (mostly). One can be transformed into the other if the geoid-ellipsoid separation (geoidal height) is known. Heights above the reference ellipsoid are obtained directly from 3-D coordinates, if the position of the ellipsoid in that 3-D coordinate system is known. Heights above the geoid or quasi-geoid are determined from applications of physical principles such as in geodetic leveling or water-level transfer across lakes and rivers.

Geodetic leveling is mostly used for point-height determination. Bathymetry (see Section 2.5.2), satellite altimetry (see Section 2.3.3), and airborne laser profiling (see Section 2.2.2) are other profiling techniques used for sea bed, sea surface, and land, respectively.

1.1.2 Geodetic Networks

Networks of monumented points are the standard and still the most widely used tool to transfer accurate positions from one location to another. They represent the most advantageous way of chaining relative positions together, by making use of the redundant ties. The redundancy enables us to employ statistics to obtain the best estimates of positions and to estimate the accuracy of the positions so determined (problem of adjustment).

Three-Dimensional Networks

Three-dimensional networks are rare because efficient 3-D techniques have not been available that long. The first 3-D global network was the BC-4 satellite network determined from photographic registration of directions to satellites. Completed by the National Geodetic Survey (NGS) in 1973, its accuracy (one standard deviation) has been about 4.5 m (Schmid, 1974). Other global satellite networks exist.

The most accurate continent-wide 3-D networks are the networks of points established by the NGS and the Geodetic Survey of Canada by means of the TRANSIT satellite system. Coordinates from TRANSIT satellite Doppler observations have been determined at approximately 400 stations in the horizontal control network of the 48 coterminous states. In Alaska, TRANSIT-derived coordinates have been determined at about 200 stations in the basic network. These coordinates have provided valuable information in the evaluation of positional accuracies in the basic network of horizontal control. Also, ellipsoid heights from these data provide information on geoidal separations at each station where sea-level elevations are known. Test adjustments, using TRANSIT data as control, have shown that high-quality scale and orientation are introduced when these data are included. In a large network of stations in southwest Alaska, extending over an area of 8° in latitude and 20° in longitude, data from 29 TRANSIT stations disclosed positional discrepancies on the order of 10 to 15 m in length between some of the first-order triangulation arcs.

For network control purposes, the NGS has a requirement that TRANSIT coordinates determined at any network station must be based on a minimum of 40 satellite passes. Repeated TRANSIT results, and comparisons of these data with high-precision terrestrial survey results, indicate that standard deviations of so-determined latitudes, longitudes, and ellipsoid heights are on the order of 0.5 m, 0.7 m, and 0.6 m, respectively. Relative accuracies of adjacent points are even better, and standard deviations of 0.3 m in all three coordinates differences are not unusual.

Local (terrestrial) 3-D networks are used for engineering purposes and to achieve research goals. The accuracy of these networks is usually higher than that of other geodetic networks.

Horizontal Network

The horizontal network is the classical object of greatest geodetic interest. Various aspects of horizontal networks have attracted the attention of many a geodetic theoretician, and many hundreds of papers have been published on this subject. The original purpose of horizontal networks was to supply coordinated control points for mapping.

Before the advent of satellite positioning it was impossible to realize a geocentric coordinate system. Hence, all horizontal networks in the world are referred to more or less arbitrarily selected reference ellipsoids (horizontal datums) of which there are many in existence (National Aeronautics and Space Administration, 1973). With the availability of satellite-determined positions, the modern trend is to refer horizontal networks to geocentric reference ellipsoids. The task of so transforming horizontal network coordinates brought about an impetus to look into misalignments and deformations of existing networks and, eventually, the necessity to redefine and readjust them completely, using both the old and the new observations. This is what the NGS has been working on during the past 10 years. We should have the fruits of their labors in the near future (see below).

The existing U.S. horizontal control network (Figure 1.1), consisting of more than 200,000 stations, was developed from surveys performed during the past 100 years. Approximately 2700 stations, along 42,000 km of first-order triangulation arcs, were used in the North American 1927 adjustment. Scale and orientation for the adjustment were provided by 112 measured baselines and 175 (Laplace) azimuths. At that time, about 1927-1932, the requirements for length and positional accuracies (one standard deviation) in the primary triangulation arcs were to maintain $S \times (2/3) \times 10^{-4}$.

The triangulation arcs used in the 1927 adjustment formed 41 closed loops ranging in length from a few hundred kilometers to 3000 km. The use of such large loops resulted in a balancing of errors in the large number of observations involved, and the accumulated errors over the long arcs became evident when new surveys were adjusted to the basic control. The process of continuing to adjust new surveys to positions determined from previous adjustments produced undue distortions in observational data of the new surveys. In many cases the new primary surveys were forced to accommodate distortions of as much as $S \times 2/3 \times 10^{-4}$. These distortions were not due to the lack of quality of the angle observations; these have been made essentially with the same precision for more than a century (Committee on the North American Datum, 1971).

During the last 20 to 25 years it has been recognized by most users of geodetic data that positional accuracies in the U.S. network of horizontal control are not adequate to meet the increasing requirements in many surveys. Some of these surveys, which require accuracies (one standard deviation) on the order of $S \times 10^{-5}$, are various types of special-purpose surveys and, in particular, surveys of the high-density

FIGURE 1.1 Horizontal Control Network. →



urban areas throughout the country. In addition, the accuracy requirements for surveys of satellite tracking facilities exceed 5×10^{-6} .

In recent years, improvements in routine survey instrumentation have made it possible to obtain length accuracies exceeding 5×10^{-5} . As a result, many traverse surveys have relative accuracies that exceed the national network control accuracy. Then, when these traverses are adjusted to control in the area, excessive corrections must be applied to the observational data.

The U.S. networks of horizontal and vertical control have been developed from specifications and standards of accuracy as published in Tables 1, 2, and 3 of the Classification, Standards of Accuracy, and General Specifications of Geodetic Control Surveys (Federal Geodetic Coordinating Committee). Copies of the latest edition of this publication are available on request from Director, National Geodetic Information Center, N/CG17, National Geodetic Survey, NOAA, Rockville, Maryland 20852.

Inaccuracies Introduced in the 1927 Adjustment Results

The primary reasons for distortions in the North American 1927 adjustment (NAD27) are as follows:

1. The spacing of arcs used in the 1927 adjustment was too great to maintain the accuracy requirements of $5 \times 2 \times 10^{-5}$.
2. As new surveys were added to the basic net and adjusted to positions determined from previous adjustments, distortions between stations in the net continued to increase.
3. Some baselines and azimuths, used to scale and orient the network, have been found to be of inferior quality.
4. Deflections of the vertical and geoid separations were not available for the reduction of observed directions and measured distances to the ellipsoidal reference surface. The omission of these corrections produced small but systematic errors in the adjusted positions.

New Simultaneous Adjustment of Total U.S. Network of Horizontal Control

To provide the high-accuracy requirements needed for control in special-purpose surveys and to eliminate the large distortions that exist in the NAD27, a new adjustment of the total network of control is required. This adjustment is under way, and all observational data obtained in previous surveys have been placed in computer-readable format by the NGS. These data include observed directions, measured distances, zenith distance angles, astronomic azimuths, astronomic latitudes, and astronomic longitudes (at deflection points). Deflections of the vertical and geoid heights have been either observed or predicted at each of the approximately 160,000 theodolite-occupied points in the network. Accuracies of the computed deflections are 1 to 2 arc

seconds, and computed geoid heights have accuracies (one standard deviation) of 1 to 2 m. Astronomic coordinates ϕ , λ are required at each theodolite-occupied point used in the adjustment. Very few points have observed astronomic positions. For the majority of points, pseudo-astronomic positions are derived by simply applying the deflections of the vertical to preliminary geodetic positions. As a consequence, after each iteration, new pseudo-astronomic positions must be computed. The height used in the adjustment is the height above the ellipsoid, h , where, $h = H + N$; H = orthometric height (leveling) and N = geoid height (predicted) (Vanicek and Krakiwsky, 1982).

TRANSIT-derived coordinates based on the NWL-9D and the NSWC 9Z-2 systems, which meet the required standards, will be used in the new adjustment, and these coordinates will be weighted in accordance with standard deviations assigned. Before they are used in the adjustment, the TRANSIT coordinates will be corrected in order to agree with results obtained from VLBI and satellite laser ranging. Corrections to the TRANSIT coordinates will be on the order of -0.5×10^{-6} in scale / $+0.5$ arc seconds rotation around the Z axis (correction to longitude east), and $+4$ m applied to the Z coordinate (Hothem, 1982).

In addition to the high-precision scale and orientation that will be provided by TRANSIT data in the new adjustment, 545 taped baselines and 2007 Laplace azimuths will be used. Additional high-precision scale will be provided from about 2500 geodimeter distances. After the final adjustment, scheduled for completion in 1985, relative accuracies between widely separated stations in the primary net will exceed $S \times 10^{-6}$. The goal is to achieve a relative accuracy of $S \times 10^{-5}$ between any two stations a distance S apart.

National Geodetic Data Base

Geodetic positions of horizontal network stations, together with observations of directions and distances relating to network stations, are organized in the NGS data base. The number of observations and stations in the North American horizontal networks is so vast that their treatment calls for special handling, not only from the data-base point of view but also, and predominantly so, from the computational point of view. Computational procedures needed in an adjustment, densification, extension, and other tasks are subjects of ongoing lively research.

Plans are currently under way to develop a new integrated data base that will contain not only horizontal data but also vertical, gravity, and other extraterrestrial data.

(For information relating to geodetic data, contact Director, National Geodetic Information Center, N/CG17, National Geodetic Survey, NOAA, Rockville, Maryland 20852.)

Horizontal Control Networks of Other Countries

Most of the developed countries of the world have established networks of horizontal control. The primary networks of the various countries

were established under about the same accuracy standards as those adopted in the United States.

Connections to the U.S. network of stations have been made at numerous stations along the Canadian and Mexican boundaries. Observational data at approximately 7000 stations in Canada and about 2700 stations in Mexico will be included in the new simultaneous adjustment of the North American networks.

Vertical Networks

Leveling networks are easier to handle than horizontal networks even though the number of monumented points (benchmarks) in a continental network is large. Heights of individual benchmarks are referred to the geoid (quasi-geoid in the Eastern European countries). To derive heights above the geoid from leveled (i.e., observed in the field) height differences corrected for the effect of gravity, the network has to be anchored to one or several points at which the height above the geoid is known. These are normally sea tide gauges for which the mean sea level is assumed to coincide with the geoid/quasi-geoid. This assumption is true up to the so-called sea-surface topography (see Sections 3.1.1 and 3.2).

Leveling results have been sought after by researchers interested in the quantification of vertical crustal movements. Many of the studied movements are on, or below, the noise level of leveling that is responsible for the recent impulse to re-examine the sources, characteristics (random versus predictable), and magnitudes of leveling errors. This re-examination has focused on errors due to unequal refraction (Whalen, 1981), rod miscalibration (Strange, 1982), rod settlement, magnetic effect on level compensator, and others (Balasz and Young, 1982).

The first leveling route in the United States that can be considered to be of geodetic quality was performed in 1856-1857 under the direction of G. B. Vose, U.S. Coast Survey (now the National Ocean Service). The leveling survey was required to support currents and tides studies in the New York Bay and Hudson River areas. The first leveling line that was officially designated geodetic leveling by the Coast and Geodetic Survey followed an arc of triangulation along the 39th parallel. This leveling survey began in 1887, at benchmark A in Hagerstown, Maryland.

By 1900 the vertical control network had grown to 21,095 km of leveling that could be considered geodetic. These data included work performed by the Coast and Geodetic Survey, various components of the Corps of Engineers, the U.S. Geological Survey, and the Pennsylvania Railroad. A mean-sea-level reference surface was used by holding elevations fixed at five tide gauges. Two other tide stations participated indirectly. Subsequent readjustments of the leveling network were performed by the Coast and Geodetic Survey in 1903 (a total of 31,789 km of leveling and 8 tide gauge determinations were used), 1907 (a total of 38,359 km of leveling and 8 tide gauges were used); and 1912 (46,462 km of leveling and 9 tide gauges were used) (Berry, 1976).

The next general adjustment of the vertical control network did not occur until 1929. By then, the international nature of geodetic networks was well understood, and Canada provided its first-order vertical network, which was combined with the U.S. net. The U.S. network had grown to 75,159 km of leveling. Canada provided an additional 31,565 km. The two networks were connected at 24 vertical control points (benchmarks) that extended from Maine/New Brunswick to Washington/British Columbia. Mean sea level was held fixed at 21 tide stations in the United States and 5 in Canada. Although Canada did not adopt the Sea Level Datum of 1929 determined by the United States, the Canadian-U.S. cooperation in the general readjustment strengthened both networks.

Inaccuracies Introduced in the 1929 Adjustment Results

At the time of the 1929 General Adjustment it was known that tide-gauge observations at the various tide stations held fixed (at 0.0 elevation) during the adjustment could not, in reality, be considered as referring to the geoid. This is due to the earlier mentioned sea-surface topography. It was thought at that time, however, that the errors introduced by this approach were not significant, being of the same order of magnitude as terrestrial leveling observational errors. We now know that significant errors were introduced into the 1929 General Adjustment by considering each of the tide stations to be on the same equipotential surface geoid. The error is estimated to be as much as 0.7 m.

Recognition of this distortion and confusion concerning the proper definition of local mean sea level led in 1976 to the change in designation of the official height system from Sea Level Datum of 1929 to National Geodetic Vertical Datum of 1929 (Federal Register, 1976). The change was in name only; the same geodetic height system continues from 1929 to the present.

General Adjustment of the North American Leveling Network Datum in 1988

Approximately 625,000 km of leveling have been added to the National Vertical Control Network (NVCN) since the 1929 adjustment (Figure 1.2). In the intervening years, numerous discussions were held to determine the proper time for an inevitable new General Adjustment. In the early 1970s an extensive inventory of NVCN was conducted. The inventory identified thousands of benchmarks that had been destroyed, owing primarily to post-World War II highway construction, as well as other causes. Many existing benchmarks had their published height changed because of crustal motion associated with earthquake activity, postglacial rebound (uplift), and subsidence caused by the withdrawal of underground liquids. Other problems were caused by forcing the 625,000 km of leveling to fit previously determined NGVD 29 height

FIGURE 1.2 Vertical Control Network. →



TABLE 1.1 Problems with the Present NGVD 29 System

Problem	Maximum Elevation Changes (meters)	Corrections	
		New Surveys	New Adjustment
Adding 1225K km to old 75K km network	0.3		x
Constraining tide-gauge heights to NGVD 29	0.7		x
Lack of gravity data in NGVD 29 adjustment	1.0	x	x
Refraction errors	0.5		x
Postglacial uplift	0.6	x	x
Subsidence	9.0	x	
Crustal motion from earthquakes	6.0	x	
Frost heave of bench marks	0.5	x	
Destroyed bench marks	--	x	

values. These distortions, amounting to as much as 9 m, are itemized in Table 1.1.

A report of the Federal Mapping Task Force on Mapping, Charting, Geodesy and Surveying (Office of Management and Budget, 1973) recommended that the national vertical control network be expanded to meet the increasing needs for control. Also, in a National Research Council report (Committee on Geodesy, 1978) recommendations were made to (1) support the additional vertical control required and (2) carry out a new adjustment of the total U.S. network of vertical control. These reports provided the justification for a new General Adjustment of NVCN.

The dynamic nature of the vertical control network requires a framework of newly observed elevation differences in order to obtain realistic contemporary height values from the readjustment. To accomplish this, NGS has selected 100,000 km of the network for releveling. Replacement of disturbed or destroyed monuments precedes the actual leveling. Field leveling is being accomplished to first-order, class II specifications, using the double-simultaneous method.

An increase in leveling progress (while maintaining acceptable accuracy) is being accomplished by equipping NGS field leveling units with specially modified subcompact trucks for rodmen as well as observers. This form of motorized leveling promises to increase production by at least 30 percent as compared with former leveling procedures. To date, nearly 45,000 km of releveling progress have been accomplished. Completion of field leveling is scheduled for September 1986.

In order to provide automated retrieval capability and apply position-dependent corrections to the observations, a geographic position (latitude, longitude) must be determined for each benchmark. For those monuments not connected to the horizontal control network, the effort involves plotting benchmarks on appropriate maps and determining a scaled position using digitizing equipment.

Significant progress has been made to account for atmospheric-refraction error. This error, which until recently was considered insignificant, has been found to be of such magnitude as to cast serious doubts on many previous investigations of crustal motion. In mid-1981 the U.S. Geological Survey and NGS participated in a cooperative leveling survey to determine the magnitude of the discrepancy between elevation differences observed using either short- or long-sight distances for a line of leveling between Saugus and Palmdale, California; if existing atmospheric-refraction correction models would minimize the differences between observations obtained with short- and long-sight distances; and the adequacy of temperature-difference mathematical prediction models as compared with observed temperature differences. Based on this survey (a distance of 50 km), a refraction correction using observed vertical temperature differences reduced the discrepancy between the short- and long-sight distance surveys from +51.0 mm to -4.8 mm, while the correction using modeled (predicted) temperature differences reduced the discrepancy to +6.4 mm. This result implies that some of the movement in the area of the so-called Palmdale Bulge, which has been the subject of debate for several years, could be the result of leveling refraction error (Whalen and Strange, 1983).

NGS has begun observing vertical temperature differences for all new levelings and now applies a refraction correction based on these observed temperature differences. For past surveys (for which temperature differences are not available), corrections will be applied using modeled temperature differences. Other corrections applied by NGS to account for known systematic errors are given by Balasz and Young (1982).

Several other investigations must be completed before the readjustment. Some of the most important tasks (with proposed completion dates shown in parentheses) are the following:

1. Determine the influence of the Earth's magnetic field on precise surveys performed with compensator (automatic) leveling instruments (1984).
2. Develop and/or evaluate mathematical models to accommodate regional aseismic vertical movement of the Earth's surface (1984).
3. Determine the proper a priori standard deviation estimates for leveling observations, accounting for the wide range of instrument

types and observational procedures that have been used to develop the network (1984).

4. Investigate the role that GPS data can play in strengthening the vertical control network (1984).

5. Determine the optimum use of tide-gauge and water-level data for the readjustment (1985).

6. Select height system/datum for the readjustment (1985).

Other tasks required by the readjustment include the following:

1. Observing or interpolating gravity values for the 600,000 benchmarks in the network (1985).

2. Completing provisional analysis and adjustment of the network (1987).

3. Completing a general least-squares adjustment of the network (1988).

International Cooperation

Early in 1982 Canada and the United States reached agreement on many of their cooperative efforts for the new adjustment and signed a formal Memorandum of Understanding concerning the NAVD 88 readjustment project.

Similar cooperation will lead to the incorporation of leveling data from Mexico and the Central American countries, making the new vertical datum a truly international one. As reported in the Federal Register (1983), the designation of the new reference for the vertical control network will be the North American Vertical Datum of 1988, which will also be referred to as NAVD of 1988, and NAVD 88, to acknowledge the international scope of the cooperation in the project and the consistency in the resultant published heights. The improved geodetic heights are scheduled for distribution in 1989.

Proposed Future Extensions of the U.S. Vertical Control Network

There is an enormous work backlog and a growing demand for vertical geodetic control that cannot be addressed by NGS until after completion of the new NAVD 88 adjustment. The National Ocean Service (1982) estimates that 346,000 km of new leveling control must be added to NVCN to satisfy known requirements. Utilizing a newly developed motorized-leveling system, NGS has increased leveling data-collection efficiency by a factor of 2 over the last few years. The production rate must be increased much more, however, if the pent-up demand is to be satisfied at an affordable cost.

1.1.3 Temporal Deformation

Generally, only the most accurate techniques are used for the detection of unknown temporal deformations. (In cases of suspected gross

deformations it may be more economical to use less accurate techniques.) For convenience, we shall distinguish here among point movements, deformations along a profile, and areal deformations.

For investigations of a global character, e.g., tectonic plate movement (see Section 3.1), it is not practical to measure areal deformations, and the interest is thus confined to point movements. Thus, point and relative positioning techniques are used. Since the modern extraterrestrial techniques are the only ones suitable for really global applications, they are clearly the ones preferred (National Aeronautics and Space Administration, 1979). To assure that the motion of a monitored point is typical of a wider area around the point, the point in question is tied to the local geodetic network through repeated measurements.

Point information may also be of interest locally, either to supplement other kinds of information or to provide a test for theoretical models. We may be interested therefore in monitoring tilt at a point or along a short baseline (see Section 2.1.3) or strain in either a small neighborhood of a point or along a relatively short line (see Section 2.1.2). Secular point variations of mean sea level, determined from long-term recordings by tide gauges, are of interest in determining vertical crustal movements in both slowly and rapidly deforming areas of the Earth's surface (Vanicek, 1978). For a similar purpose, gravity-point variations may also be of considerable interest (see Section 1.2.3).

Profiling is the approach often used in the detection of differential vertical movements. Because of its accuracy, the preferred technique is repeated geodetic leveling. The usefulness of repeated leveling data is greatly enhanced by simultaneous repeated gravity profiling. Clearly, if both the elevation and gravity changes are observed simultaneously, then not only can the temporal variations of the geoid--the reference surface for so-determined elevation changes--be estimated (Vanicek et al., 1980) but also changes in the mass distribution can be inferred (Jachens, 1978).

Historical data collected through repeated levelings over the same leveling lines are a popular source of information on secular crustal movements (Brown and Reilinger, 1980) as well as spasmodic movements (Castle, et al., 1976). The interpretation of these data must be done carefully because of the presence of the above mentioned systematic errors. This is particularly true for data sets obtained at epochs for which either the observing procedures or instruments were significantly different.

On the other hand, monitoring lines leveled always under similar conditions and to identical specifications (designed especially for the purpose of minimizing systematic effects on computed vertical displacements) should be quite free of this unfortunate problem.

Areal deformations can be obtained from partially or fully reobserved networks. From the changes of network configuration that had occurred between subsequent observing campaigns, variations in strain, shear, and differential rotation in the area can be obtained. With careful field work and analysis, changes of the order of a fraction of 1 μ strain can be detected (Prescott et al., 1979). A

real challenge in this venture is the correct modeling of both spatial and temporal discontinuities of deformations. Also, there is still much room for improvement in designing geometrical models with physically justifiable constraints. The design of horizontal monitoring networks from the point of view of optimizing the accuracy of one or several strain parameters is a relatively new field in geodesy, and much work still remains to be done there.

The use of historical data collected from reobservation of existing horizontal geodetic networks is possible (Snay et al., 1982), but accuracy of these data is likely to be one order of magnitude worse than that currently achieved in good monitoring networks. When using data from existing networks (even first order) one has to be aware of the less accurate scale (distance observations) in pre-1970 work, which may have been accurate only to 10^{-5} or worse. On the other hand, as stated above, the accuracy of horizontal angles in the past 100 years or so has not increased significantly. Of course, the regular geodetic networks have always been used successfully to quantify coseismic displacements of large earthquakes (Wood, 1966).

During the period from the early 1930s to about 1970, the Coast and Geodetic Survey reobserved at periodic intervals various areas of the horizontal control network in order to determine crustal movements from changes in the observational data. Results obtained from these surveys, primarily in California and Alaska, disclosed conclusively that relative movement between stations could be detected in areas of seismic activity. In each area along the fault system in California where surveys indicated movement, the direction of movement was right lateral. That is, the west side of the fault moved northwest relative to the east side, or the east side moved southeast relative to the west side. Annual rates of fault slip in various areas along the San Andreas fault system are given in Figure 1.3. The maximum annual rate of 35 mm, between Stone Canyon and Parkfield, is based on differences between surveys over the 18-year interval, 1944-1962. Also, annual rates of 35 to 40 mm were obtained from precise geodimeter distance measurements in this area during the 10-year interval, 1960-1970. Surveys used to determine rates of slip in other localities shown in Figure 1.3 are discussed by Meade (1971).

Beginning about 1970, the U.S. Geological Survey started a program to measure precise distances in selected localities along the San Andreas fault system. Results obtained from some of these trilateration surveys are given by Prescott and Savage (1974) and Savage (1974). Some other reports that discuss crustal changes determined from geodetic data are Meade and Miller (1974), Savage et al. (1979), Snay and Cline (1980), Snay et al. (1982), and Thatcher (1979).

Three-dimensional monitoring networks are at least as rare as the above discussed positioning 3-D networks. This is in spite of the fact that 3-D modeling of deformations would be highly desirable (Committee on Geodesy, 1980) and the results revealing.

Reobserved leveling networks often provide good areal information on vertical movements, with the reservations quoted for releveled profiles. A map of vertical crustal movements in Canada was produced by Vanicek and Nagy (1981). A concerted effort is now being undertaken

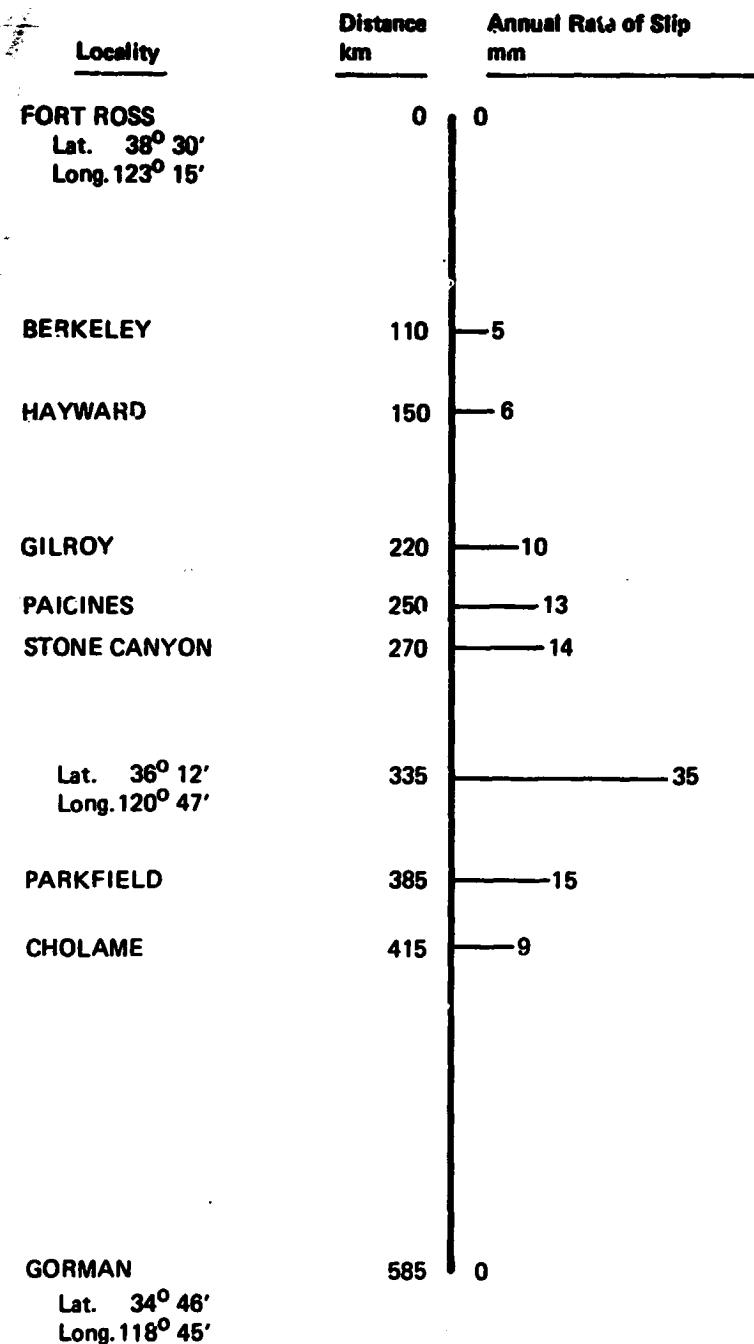


FIGURE 1.3 Annual rate of slip along the San Andreas fault system (Meade, 1971).

by the NGS and Cornell University to compile a map of vertical crustal movements in the United States from all the existing relevelings (Brown and Reilinger, 1983; Reilinger et al., 1977). Relative movements of the order of half a millimeter per year should be detectable.

1.1.4 Positioning in the Future

Expected Improvements by A.D. 2000

Dramatic improvement of the present situation in North America is expected to occur in two particular areas: extraterrestrial positioning systems and geodetic networks. Exactly how much of an improvement we will see by the year 2000 is difficult to say. The order of magnitude of the improvement, however, is predictable.

Extraterrestrial Positioning Systems

It seems fairly safe to predict that by the year 2000 there will exist a capability of determining positions globally with an accuracy (standard deviation) of 1 cm, by means of observing campaigns of a few hours or less. Probably several positioning systems will operate side by side [GPS, VLBI, and satellite laser ranging (SLR)--see Section 2.3], each system being possibly used for a different purpose.

The UT1 and polar-motion global-monitoring programs should, by that time, be capable of monitoring both parameters continuously to an accuracy (standard deviation) of 1 cm. Thus the almost real-time values of UT1 and polar motion will be available for studying the Earth's global dynamics and also for the transformation of instantaneous positions to mean positions.

The improvement of positioning capabilities combined with the improvement of global geodynamic parameters will allow positioning of coordinate systems within the Earth to a 1-cm accuracy (standard deviation). This clearly implies that transformations between individual coordinate systems should also be determinable to the same level of accuracy, and a 1-cm compatibility among results from individual positioning systems should be ensured. The improved accuracy will bring with it the need to understand some new error sources such as sea-tide loading, water-table variations, precipitation, and atmospheric-pressure loading. Conversely, the improved positioning will provide a tool to study these phenomena in greater depth.

By the year 2000, the satellite-determined sea-level height (altimetry) should be good to some 5 cm (1 standard deviation), and the geoid in North America and surrounding seas should be known to about 10 cm. From the combination of these and other kinds of data, the sea-surface topography should be detectable to the accuracy of 10 cm (1 standard deviation) or better.

Geodetic Networks

The National Geodetic Survey's objectives for the horizontal networks consist of at least one marked station in each 7.5-min quadrangle (approximately 15 km x 10 km), except in the mountainous regions of the west where at least one station in each 15-min quadrangle (30 km x 20 km) is the objective. In urban and highly industrialized areas where the value of land is higher, spacing between stations should be reduced to 3 to 6 km, in suburban areas to 5 to 8 km (see Section 3.3).

Beginning at the time when GPS becomes fully operational, the NGS plans to use the system for any extensions required in the U.S. national horizontal network. It has been estimated that the cost of so-determined station position should be of the order of one half (or less) of that for the standard terrestrial approach. Accuracy (standard deviation) of these GPS-determined positions should be a few millimeters, or $S \times 10^{-7}$ (where S is the distance between the two points), whichever is larger, i.e., 2 orders of magnitude better than available now.

Redefined geodetic leveling networks should have most of the systematic errors removed, and height differences of pairs of first-order network points should be accurate (1 standard deviation) to about $1 \text{ mm} \sqrt{S}$, where S is the length in kilometers of the shortest leveling route connecting the two points. So determined heights will be properly referred to an appropriately--compared with present data--defined vertical datum.

In principle, vertical displacements can be determined more accurately than heights. To expect an accuracy better than $0.5 \text{ mm} \sqrt{S}$ in displacements monitored by geodetic leveling networks would not be at all unreasonable.

The efficiency of field leveling may increase by a factor of about 5 before the end of this century while maintaining, or even improving, present accuracy. The NGS is actively pursuing the development of a system, based on present technology, capable of such efficiency. At the year 2000 this system will probably have to compete with extraterrestrial positioning systems for various applications.

New Concepts by A.D. 2000

In addition to the foreseeable improvements described below, the year 2000 should see some profound changes in geodetic thinking. Some classical concepts will have to yield to new perceptions of the role of geodesy in society and to new formulations of geodetic problems.

Impact of Extraterrestrial Positioning Methods

The gradual replacement of terrestrial by extraterrestrial techniques will accelerate as satellite receivers become cheaper, lighter, less power consuming, astronomical radio telescopes become more numerous, and SLR observing sessions become shorter. At the same time, as

refraction modeling, orbit prediction, and clock performance further improve, the differential satellite positioning will become more and more absolute. It will be possible to remove the foothold point further and further making the positioned point more and more independent. Thus the difference between absolute and relative positioning will eventually be nearly obliterated.

With position determination becoming cheaper and cheaper, the time will come when it will be more economical to position a point accurately than to monument it. That instant will mark the beginning of the decline of the utility of geodetic networks (except for crustal motion studies). Clearly, the justification for maintaining and expanding networks of monumented points against the background of cheap and accurate positioning capability will be more and more difficult to sustain, and the long-term future of geodetic networks will become highly questionable. In all probability, only a relatively small number of monumented points (the framework) are eventually going to be maintained and monitored to provide a continuing link between the (relatively) determined positions and the coordinate system (Vanicek et al., 1983).

It is not difficult to predict that the trend toward extraterrestrial positioning will have a profound effect on the surveying profession. We will witness a gradual shift toward more modern positioning techniques and a gradual reduction in requirements for geodetic control points, mainly in stable areas.

Integration of Horizontal Positions with Heights

Three-dimensional positioning has always been the ultimate goal for geodesists even though expediency and lack of pertinent data have dictated the separation of horizontal and height-control networks. Improved overlap between the two kinds of networks and the increased accuracy of the geoid by the end of the century will provide a strong temptation to switch into a truly 3-D mode of operation. The additional incentive for adopting a 3-D modus operandi will, of course, be the inherently 3-D positions as determined by modern positioning systems. It is easy to foresee the days when even orthometric heights needed for many practical applications will be determined simply from 3-D positions and geoidal heights.

Monitoring of 3-D positions--as compared with separate horizontal and height monitoring--will present new opportunities in crustal movement studies (Committee on Geodesy, 1980).

Integration of Positioning and Gravity Studies

Historically, geodesists became involved in the study of gravity to improve positioning capabilities. Gravity provided a relatively cheap additional or alternative source of information on the size and shape of the Earth. It has been pointed out by several authors (Sanso, 1977; Grafarend, 1980) that there exists a somewhat dual relation between

positions and gravity vectors. With positions becoming cheap and accurate it is easy to foresee possible exchange of the roles of position and gravity vectors. The harbingers of these exchanged roles are the transformation of satellite-altimetry-determined sea-level heights into gravity anomalies (see Section 1.2) and the transformation of 3-D positions to geoidal heights.

By the end of this century there should be enough gravity data and positions available to encourage an integrated approach to studies of the Earth's gravity field and of temporal variations of its shape. Such an approach will be of considerable value in revealing the causes of crustal movements in different regions.

Integration of Positioning and Time

The following dichotomy still prevails in geodetic circles: on the one hand, geodetic measurements have long been used to detect temporal deformations of the Earth; on the other hand, coordinates of control points are being disseminated and used by the vast majority of users as if the points were stationary. Such is the practice everywhere, except in the most active seismic regions. This dichotomy will gradually disappear as the understanding of the physical processes underlying the motions improves and reliable geophysical models become available. It will be possible to associate positions of network points with appropriate dates or temporally homogenize networks.

With increasing accuracy of positioning it will become necessary to account for temporal variations of positions (coordinates) even in areas previously considered stable. Also, practicing surveyors will have to start taking the ongoing Earth deformations into account in their daily work (see Section 3.4).

Another interesting but unrelated aspect of position/time integration will be the emergence of land navigation. Instantaneous point-positioning capability will allow us to position moving objects on land to a high enough accuracy to make navigation of cars and other vehicles not only possible but attractive. Attempts in this direction have already begun.

Integration of Land and Sea Positioning

With the advent of satellite-determined gravity field and satellite-determined positions the difference between land and sea positioning started to disappear. The same kinds of data are now being used to compute the land as well as the marine geoid; the same kinds of measurements to the same satellites are being used to compute positions on land as well as at sea. After the global geoid and the sea-surface topography are sufficiently well known, the land positions and ocean surface heights should match sufficiently well, and the same vertical datum can then be used for height as well as bathymetry.

The instantaneous global 3-D positioning capability will contribute toward the obliteration of existing differences between horizontal

positioning on land and sea, stationary as well as dynamic. Relatively accurate sea-bottom positioning may become a reality by the end of this century (Committee on Geodesy, 1983) with local precise relative positioning networks tied to distant reference points using satellite techniques (see Section 2.5.3).

Geodesy and the Atmosphere

One of the main obstacles to the increase in satellite determined position accuracy is the lack of knowledge of the instantaneous distribution of atmospheric properties. More effort will have to be expended to improve knowledge, and either direct measurements or sufficiently accurate models for atmospheric parameters will have to be used. The question arises as to whether geodesists should make the atmosphere a major focus of their interest along the same lines as was done with the gravity field. Clearly, there is much justification for doing just that.

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1.2 GRAVITY FIELD

The need to know the gravity field of the Earth was originally driven by the need to reduce geodetic measurements from the surface of the Earth to the reference ellipsoid on which computations were to be made and geodetic coordinates to be given. Therefore, techniques were developed to determine geoid undulations (the separation between the geoid and the ellipsoid) and deflections of the vertical (the direction differences of the normal to the ellipsoid and the normal to the geoid) from gravity data. These techniques required global gravity data, which limited the prospect of the actual application of the equations of Stokes and of Vening-Meinez (Bomford, 1980).

In the 1930s instruments were developed so that relative gravity measurements could be made using devices that were easily transportable. Such devices became the mainstay for geophysical prospecting using gravity methods. Although such instruments were primarily developed for use in land areas they were also used in the measurement of gravity in ocean areas. However, progress in this area was slow because of many technical problems involving ship accelerations and precise navigation.

In the 1960s it became clear that the Earth's gravity field could be described through the analysis of motion of artificial satellites. Through this analysis potential coefficient parameters in a truncated spherical harmonic series describing the Earth's gravitational potential could be estimated. The use of this series gave the community an alternate view of the gravity field of the Earth. This view changed from the point concept represented by individual gravity measurements to one where the gravity field was viewed as a continuous function.

The initial determination of the gravity field from satellite data used optical measurements of the satellites against the background of the stars. These measurements enabled the determination of the coefficients in a spherical harmonic series up to degree and order 12 (i.e., about 170 terms). As new data became available higher degree solutions have become possible. Today the most complete solutions are those that combine satellite and terrestrial gravity data.

Not all data today are acquired by the conventional techniques of the past. For close to Earth (e.g., 1000-m) measurements, helicopters have become a tool for the fast acquisition of accurate data in areas of limited geographic extent (say on the order of 50 km x 50 km). Inertial equipment can now be used as a precise interpolator for the estimation of deflection of the vertical and gravity values. New satellite techniques such as satellite-to-satellite tracking have enabled large-scale anomalies to be estimated in areas of the world where no gravity information was previously available. Of particular import here is the direct sensing of the ocean surface through satellite altimetry. Such information has supplied us with a better picture of the gravity field in ocean areas than was ever available for most land areas.

Today the application of gravity field data ranges from the classical geodetic needs to providing short- and long-wavelength information for geophysical and oceanographic studies. New measurement

techniques (Taylor et al., 1983; Jekeli, 1983) have been developed that have the potential for acquiring a substantially improved gravity field in the next decade. But before we look at the improvements to be expected, a first look at the current status of our knowledge of the gravity field.

1.2.1 Surface Gravity Data

Gravity data are collected on land using gravimeters (for gravity differences) in conjunction with known reference base stations for which values of gravity are usually given in the International Gravity Standardization Net 1971 (IGSN71). Absolute values of gravity can also be determined using instruments that are becoming more accurate and more portable. However, the number of gravity values is very small (30) when compared with the very large number of gravity values determined through relative measurements. Gravity data at sea are collected by organizations such as the Woods Hole Oceanographic Institution, Lamont-Doherty Geological Observatory, University of Hawaii, Scripps Institution of Oceanography, and Department of Defense. These data are usually acquired as continuous profiles; for most applications the profile is sampled at a certain interval to select specific point values.

The gravity values acquired from land or ship measurements are used to compute various types of gravity anomalies such as free-air or Bouguer. Such computations require a precise elevation for the station and a geographic position known to an accuracy sufficient for normal (or theoretical) gravity computations. The data are then usually collected in a center for retrieval purposes.

In the United States the prime center for the worldwide acquisition of gravity data is the Defense Mapping Agency Aerospace Center (DMAAC) in St. Louis. As of November 1, 1983, there were 11,583,246 gravity stations in their automated data system. Not all of these values are releasable for general use as some of the data have been acquired for use only by the Department of Defense.

The National Geophysical Data Center (NGDC) in Boulder, Colorado, serves as a general distribution center for land gravity data in the United States and worldwide oceanic data that have been submitted to it. The land-data set contains approximately 605,000 values, while there are 5,500,000 values in the ocean areas, (Wilcox and Scheibe, 1983). Details on the gravity data held at NGDC are given by Hittleman et al. (1982).

The NGS also maintains a data base of gravity data in North America that includes NGS data as well as data from DMAAC and other sources.

The Bureau Gravimetrique International (BGI), Toulouse, France, operates through the International Association of Geodesy. The Bureau has as its main task the collection and distribution of gravity data on an international basis. As of June 1982, the BGI had 2,680,000 measurements from 1501 sources. A detailed description of the operations of BGI (from submitting data to requesting data) is given by Balmino (1982). The DGI regularly publishes a Bulletin d'Information that describes the activities and acquisitions of the Bureau.

Counts of point anomalies that are available are not completely meaningful. For some purposes it is of greater importance to know the distribution of the data. Figure 1.4 shows the distribution of point gravity data that were used in the development of the Society of Exploration Geophysicists (1982) Bouguer gravity anomaly map of the United States. The point gravity densities represented in this figure are typical of those available in parts of Canada, Europe, and Australia. Coverage is substantially poorer in South America, Africa, and the polar areas. In the Soviet Union and China no recent gravity information is available, although such data exist for China (Gu, 1983). This situation is a typical example of one in which some countries will not release their gravity information for public use. Recent resolutions at scientific meetings strongly encourage countries to release as many gravity data as possible for scientific use, either as point values or as mean values in areas such as $1^\circ \times 1^\circ$ equiangular blocks.

For a number of geodetic and geophysical purposes it is necessary to aggregate the point anomaly values into mean values over various size blocks. Although 10° and 5° have been used in the past the most conventional size for global analysis is a $1^\circ \times 1^\circ$ equiangular block. The distribution of such data in a recent compilation (Rapp, 1983a) is shown in Figure 1.5, where anomaly estimates based only on direct observations are shown. The accuracy of the data is quite variable. In much of North America, Europe, and most of Australia the accuracy may be at the 2 to 5 mgal ($1 \text{ mgal} = 10^{-5} \text{ m sec}^{-2}$) level. In ocean areas the accuracy may be on the order ± 10 mgal, but it can be considerably poorer in areas of steep gradients. In some areas (both land and ocean) there can be considerable (200 mgal) disagreement between anomaly estimates from various sources (Balmino, 1983).

For some geodetic applications mean anomalies in smaller size blocks have been estimated. Torge et al. (1983) describe the estimation of 103,997 free-air anomalies in $6' \times 10'$ blocks for much of Europe including surrounding marine areas. Ganeko (1982) describes a large set of $10' \times 10'$ mean-free-air anomalies covering much of Japan and surrounding seas. Lachapelle (1978) has developed a $5' \times 5'$ data set for North America.

It is clear that in the past few years there has been a substantial increase in the number of gravity measurements made. However, the geographic distribution of the measurements remains quite skewed. It appears that there will remain a number of areas of the world in which gravity data will not be readily available owing to political or geographical inaccessibility.

1.2.2 Gravity-Field Information from Satellites

Potential Coefficient Models

Since 1958 our knowledge of the gravity field of the Earth has improved through the analysis of the orbits of satellites to deduce spherical harmonic potential coefficients. A review of the progress made in this

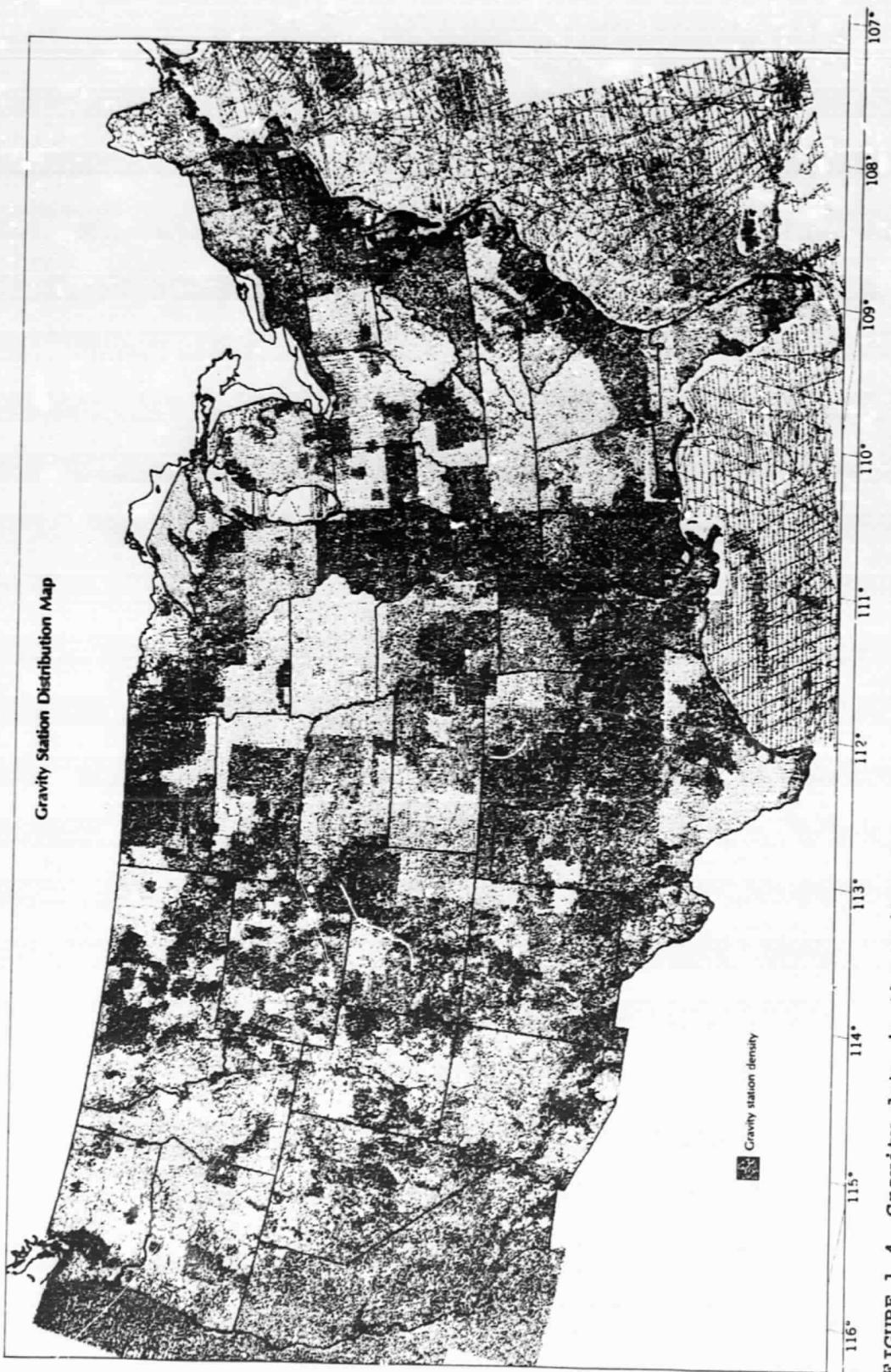


FIGURE 1.4 Gravity data in the United States. (SOURCE: Society of Exploration Geophysicists)

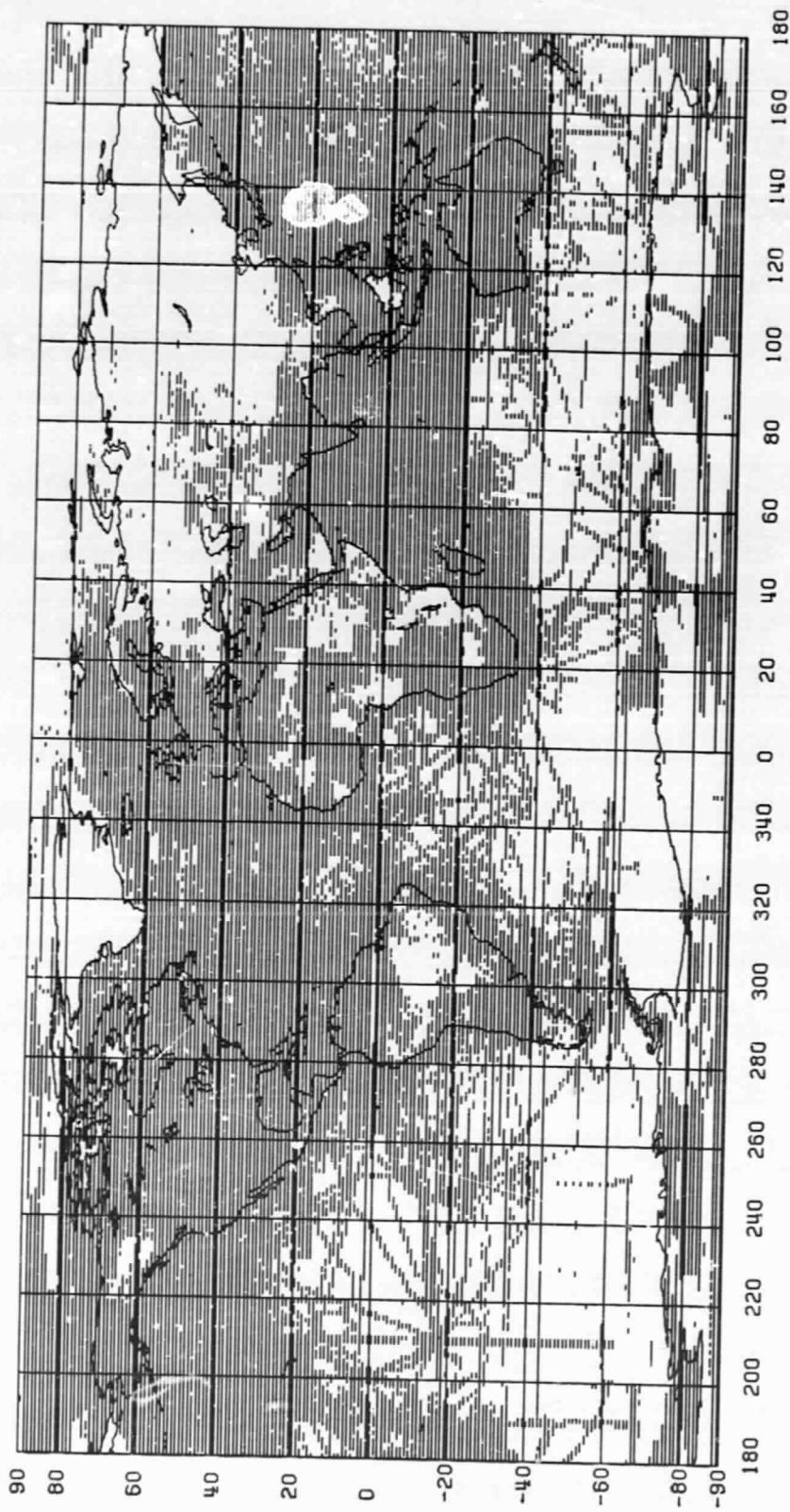


FIGURE 1.5 $1^\circ \times 1^\circ$ Anomalies (38152) based on actual measurements.

area since 1958 has been recently given by Lambeck and Coleman (1983). A summary of recent activities in the United States has been made by Lerch (1983).

Potential coefficients (\bar{C}_{lm} , \bar{S}_{lm}) are used to define the geopotential, \underline{V} , at a point whose geocentric coordinates are \underline{r} , $\bar{\phi}$, λ , in the following standard form (Lerch et al., 1979):

$$\underline{V}(\underline{r}, \bar{\phi}, \lambda) = \frac{kM}{\underline{r}} \left[1 + \sum_{l=2}^{\infty} \left(\frac{a}{\underline{r}} \right)^l \sum_{m=0}^l (\bar{C}_{lm} \cos m\lambda + \bar{S}_{lm} \sin m\lambda) \bar{P}_{lm} (\sin \bar{\phi}) \right], \quad (1)$$

where

\underline{kM} is the geocentric gravitational constant,
 a is a scaling parameter nominally the equatorial radius,
 \bar{P}_{lm} are the fully normalized associated Legendre functions,
 $\bar{\phi}$ is the geocentric latitude,
 λ is the longitude.

Many sets of potential coefficients have been derived in the past years. These coefficient sets vary depending on the maximum degree of the expansion and the types of data used in their determination. Some models use just satellite data considering orbital variations, while other solutions combine the previous data with satellite altimeter data and/or terrestrial gravity data. Table 1.2 summarizes the status of some current geopotential models.

The GEM solutions are produced at NASA's Goddard Space Flight Center. The GRIM solutions are a cooperative effort of several organizations in Europe (Reigber et al., 1983). Although the maximum degree for some may be 20 the solutions will also contain additional isolated coefficients determined through the effect of resonance perturbations.

Satellite-derived gravity models are of two general types. The first type is a general gravity model that incorporates data from as many different satellites as possible to derive a most representative gravity field. The second type is a tuned gravity field model that is designed to give the best orbit for a specific satellite. The GEML2 model (Lerch et al., 1982a) is in some sense a tuned model for the LAGEOS satellite since substantial amounts of laser tracking data to LAGEOS were used in its determination. However, it is also a general model to the extent that the GEM9 normal equations, involving data from many satellites, were used in GEML2 development. Tuned models have been derived for other satellites including SEASAT and Starlette.

Even though the expansions to degree 180 contain 32,761 potential coefficients, their use for certain computations has been made quite efficient for such quantities as geoid undulations, gravity anomalies, and deflections of the vertical (Tscherning et al. 1983). Efficient techniques to use these high-degree expansions for orbit generation are not yet available.

TABLE 1.2 "Current" Geopotential Models

Name	Date	NMAX	Data Used ^a
GEM9	1977	20	S
Rapp	1978	180	S + G(A) + G(T)
SAO	1980	30	S + A + G(T)
GEM10B	1981	36	S + A + G(T)
GEM10C	1981	180	S + A + G(T)
Rapp(OSU Dec 81)	1981	180	S + G(A) + G(T)
GFML2	1982	20	S
GRIM3B	1983	36	S + G(A) + G(T)
GRIM3-L1	1984	36	S + G(A) + G(T)

^aS, satellite data excluding altimetry; A, altimeter data; G(A), anomalies derived from altimeter data; G(T), terrestrial gravity anomalies.

Potential coefficients can be compared in terms of anomalies, deflections of the vertical, and undulations; by value; and by spectrum (or degree 1). For example, Figure 1.6 shows the undulation difference between the GFML2 coefficient set and several other sets. The GFML2 and the GRIM3-L1 coefficient sets should be the most accurate sets at low degrees as they incorporate a large amount of LAGEOS tracking data in their solution (Reigber et al., 1984). Also shown in Figure 1.6 is the estimated accuracy (1 s.d.), by degree, of the GFML2 solution. The commission error (i.e., the error due to potential coefficient errors) in the computation of geoid undulations, from the GFML2 solutions, considering all the coefficients to degree 20 is ± 1.6 m. At the individual degrees (or wavelengths) the undulation is much more accurately known. For example, at degree 2, the accuracy is ± 1 cm; at degree 4, it is ± 5 cm. This high degree of accuracy implies a gravity field that is sufficiently accurate for some large-scale ocean circulation studies (Engelis and Rapp, 1984).

The potential coefficients may also be compared to give a global root-mean-square difference between various sets. Such differences are given in Table 1.3 where the maximum degree considered is 20.

When the comparisons are made at lower degrees some of the differences are still substantial. For example, when comparisons are made up to degree 6 between GFML2 and GRIM3-L1 the root-mean-square (rms) undulation difference is ± 40 cm and the rms anomaly difference is 0.36 mgal. The maximum undulation difference is 1.1 m, and the maximum anomaly difference is 0.9 mgal.

One of the advantages of using spherical harmonic expansions to represent the gravity field is that we can obtain information on the spectrum of the gravity field. We have already seen in Figure 1.6 undulation differences and accuracies by spherical harmonic degree. Knowing the accuracy of the coefficients that have been estimated and a statistical estimate of the behavior of the high degree components of the field it is possible to compute the accuracy of mean quantities as

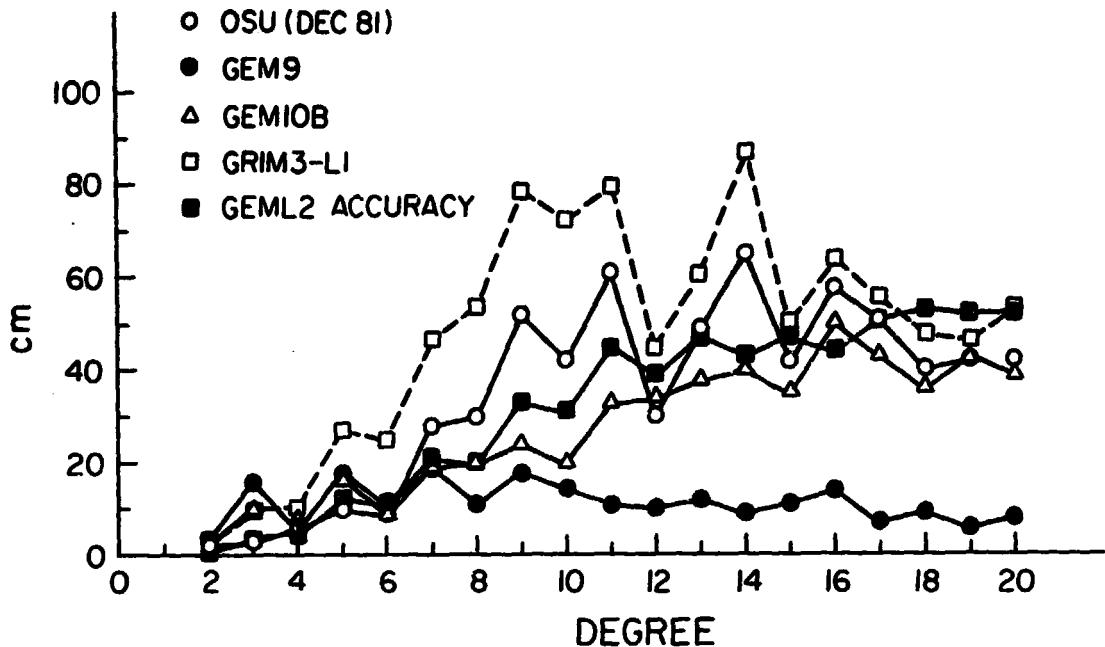


FIGURE 1.6 Geoid undulation differences between the GEML2 model and other selected models.

a function of the area (or resolution) in which the quantity of interest has been computed. Using the Rapp (1981) 180 solution, assuming an average anomaly accuracy [1 standard deviation (s.d.)] of ± 10 mgal the accuracy of a gravity anomaly computed from this field is shown in Figure 1.7 as a function of the size (or resolution) of the feature. At the short wavelengths (e.g., 100 km) the global accuracy of today's data is approximately ± 10 mgal; at long wavelength (e.g., 2000 km) the accuracy is ± 0.6 mgal. These numbers represent global averages; accuracies in specific geographic regions may be considerably poorer (or better). Also shown in Figure 1.7 are the undulation accuracies. At 100-km resolution the undulation accuracy is ± 1.0 m; whereas at the 2000-km resolution level it is ± 0.38 m.

The Estimation of kM

The determination of kM in Eq. (1) has improved considerably in the past decade primarily through the efforts of laser ranging to the moon and to artificial satellites. Specific results are described by Lerch et al. (1982a) and Dickey et al. (1983). A current representative value (including the mass of the atmosphere) is $398600.44 \pm 0.01 \text{ km}^3 \text{ sec}^{-2}$ (Rapp, 1983c). There is some indication that the actual standard deviation is somewhat smaller than quoted.

TABLE 1.3 Root-Mean-Square Differences between Potential Coefficient Sets in Terms of Gravity Anomalies and Geoid Undulations (max degree = 20)^a

	GEM 9		GBML2		GRIM3-L1	
	Undulations	Anomalies	Undulations	Anomalies	Undulations	Anomalies
OSU 81	+1.8 m	+3.6 mgal	+1.8 m	+3.6 mgal	+1.1 m	+1.9 mgal
GEM9	-	-	+0.5 m	+0.8 mgal	+2.4 m	+4.6 mgal
GBML2	-	-	-	-	+2.4 m	+4.5 mgal

$$\pm 1 \text{ mgal} = 10^{-5} \text{ m sec}^{-2}.$$

The Role of Satellite Altimetry

Satellite altimeter data (see Section 2.3.3) obtained from GEOS-3 and SEASAT have played a substantial role in our knowledge of the gravity field of the Earth as well as other quantities of interest such as bathymetry. The altimeter data have been used in at least three different ways for gravity field improvement.

1. Mean-Sea-Surface Determination. Given the altimeter measurements and orbit adjustment procedures the elevation of the mean sea surface above a defined reference ellipsoid can be determined. Although classically associated with the geoid, the mean surface is not an equipotential surface because of ocean currents, wind effects, and other effects. The accuracy of these elevations depends on a number of factors including altimeter measurement type (GEOS-3 or SEASAT), orbit adjustment procedures (orbit mode or crossing arc), and tides. A representative 1-s.d. estimate is +40 cm. Typical results are described by Marsh and Martin (1982) and by Rapp (1982).

2. Improved Orbit Determinations. The altimeter measurement is incorporated in the actual orbit determination and gravity-field improvement process. An example of this is the GEM10B model and a model for SEASAT described by Lerch et al. (1982b). The result of the SEASAT analysis was a set of potential coefficients complete to degree and order 36 that enabled the orbit of SEASAT to be computed for a length of 12 days with a rms radial accuracy of about 70 cm.

3. Direct Anomaly Recovery. Gravity anomalies in various size blocks can be recovered directly from the sea-surface heights. As the altimeter data almost completely cover the ocean between $\pm 70^\circ$ latitudes, an oceanwide recovery of gravity anomalies is possible. Such estimates for $5^\circ \times 5^\circ$ and $1^\circ \times 1^\circ$ as obtained from SEASAT data are described by Rapp (1983b). Sample estimates for 30' x 30' mean values (i.e., 50 km x 50 km) blocks across the Japan trench are described by Rapp (1983d) on the basis of a combined GEOS-3/SEASAT altimeter data set. These latter computations show the ability of the altimeter data accurately to imply anomaly changes of 250 mgal in adjacent 50-km blocks.

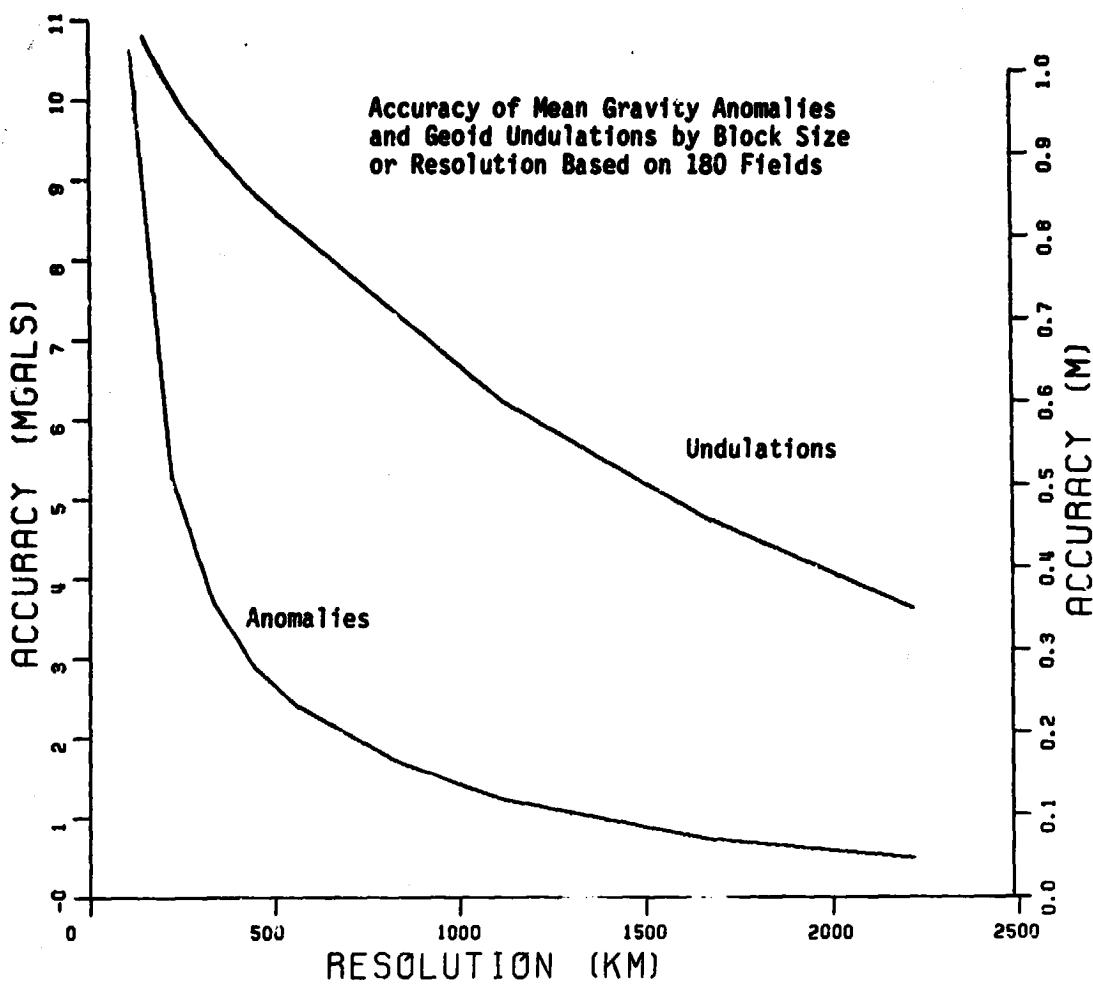


FIGURE 1.7 Accuracy of mean gravity anomalies and geoid undulations by block size or resolution based on 180 fields.

The accuracy of mean anomalies derived from altimeter data should be ± 3 mgal for 5° equal area blocks, ± 6 mgal for $1^\circ \times 1^\circ$ blocks, and ± 12 mgal for $30' \times 30'$ blocks. These accuracy estimates vary over the ocean depending on the roughness of the anomaly field and the accuracy of the actual altimetric data considering orbit, tidal, and sea-surface height corrections. It is also possible to derive point gravity anomalies from the altimeter data, but the accuracy will be poorer (± 15 mgal) than obtained from ship measurements. The accuracy range of anomalies derived from the altimeter data is not clear as the error range of such altimeter data has not been defined when the data are processed in a crossing-arc adjustment (Wunsch and Zlotnicki, 1984). This implies that such anomalies must be carefully used when long-wavelength implications are being sought.

Altimeter data have also been used for studies indirectly related to gravity-field information. Specifically the sea-surface signal implied by topographic features has been used to infer such features (Dixon et al., 1983, Dixon and Parke, 1983, Haxby et al., 1983, White et al., 1983, Sandwell, 1984). These studies vary from individual seamount detection to oceanwide maps of topographic relief implied by the altimeter data.

Satellite-to-Satellite Tracking

Gravity-field information is also obtained from the analysis of satellite-to-satellite tracking data. Unfortunately the data available are primarily from the GEOS-3/ATS-6 tracking data. The limitation of these data lies in the high altitude (800 km) of GEOS-3, which makes a range rate signal only slightly perturbed by local gravity anomalies.

Despite this, the data have been successfully used by Marsh et al. (1981, 1984) to improve the gravity field in the Pacific area and by Kahn et al. (1982) for 10° mean-anomaly improvement in parts of Africa and the Indian Ocean. Perhaps the greatest importance of this work is that it demonstrates the value of satellite-to-satellite tracking for gravity-field improvement. Such experiments have a great potential for a substantial improvement in the gravity field.

1.2.3 Temporal Variations of the Gravity Field

Much of the previous discussion has not considered the time variations of the gravity field. These time variations are due to a number of different reasons, including tidal variations, fluid (e.g., water or oil) withdrawal subsidence, seismic effects, intrusive and volcanic igneous effects, and isostatic rebound. More specific discussion of these effects are given in Section 1.2.4.

The measurement of time variations of the gravity field have been facilitated by improved relative gravimeters, special Earth-tide meters using a superconducting system, absolute gravity measurement devices, and the study of time changes of selected potential coefficients estimated from the analysis of LAGEOS data.

1.2.4 Gravity Field--Future Developments

The previous discussion was concerned with our current knowledge of the gravity field of the Earth. In the future, substantial improvement is possible in several different areas. This improvement is discussed in two areas: (1) terrestrial-based measurements and (2) satellite-based measurements.

Terrestrial-Based Measurements

In this section the primary concern is with data acquired from sensors that are on or close to the surface of the Earth.

The acquisition of ground-based gravity data is likely to continue to improve our general areal coverage of the world. However, land-based measurements are not expected to be available in many areas because of physical and political inaccessibility problems. This implies that there is no real hope in acquiring terrestrial data in Eastern European countries, China, parts of Asia, South America, and Africa.

The acquisition of ship gravity data is likely to continue on cruises of opportunity. These data are helpful for the high-density, along-track coverage that is provided. Such data can be acquired by almost no other means. However, these data are hampered by wide track spacing except in areas where areal coverage is obtained.

As the developments in absolute devices continue, to make them more accurate, more portable, and less expensive, we should see these measurements widely used for the measurement of a number of geophysical phenomena (see Section 3.1). The current accuracy of ± 10 μgal is sufficient for many studies. If a factor-of-10 improvement could be obtained, the interpretation of the time variations in an absolute sense could be quite interesting. For example, general proposals (Biro, 1983) have been made to form a worldwide net of gravity stations where gravity and height variations are measured.

Another area in which we would expect to see additional development is in the tidal area, where new instruments with very low drift give an accurate long-term record of gravity at a site. Such records can lead to a better understanding of the Earth's interior, ocean tides, and perhaps the measurement of polar motion (Richter, 1983).

A major new data source that will become available in the next few years will be that obtained from gradiometers. These measurements of the second derivative of the gravity potential will lead to improved estimates of the high-frequency part of deflections of the vertical and gravity anomalies at the surface of the Earth. Such measurements will be made primarily in aircraft flying at an altitude of, say, 600 m. A description of such a system is given by Jekeli (1984). Using a survey spacing of 5 km one would expect anomaly accuracies (the high-frequency part) on the order of ± 0.5 μgal and deflections on the order of ± 0.06 . A more complete description of the measurement techniques may be found in Section 2.1.4.

Satellite-Based Measurements

In order to improve the knowledge of the gravity field for geodetic, geophysical, and oceanographic purposes, satellite-based missions have been discussed for many years (e.g., Committee on Geodesy, 1979).

The most ambitious plan has been developed by NASA for a Geopotential Research Mission (GRM) (Murphy 1983, Taylor et al., 1983). If approved as a mission, in the next year or so, GRM could be

launched in the 1992-1993 time frame. This mission could improve both the gravity field and magnetic field on a global basis. The goals for the gravity-field improvement are to obtain gravity anomalies accurate to ± 1 mgal and the geoid accurate to ± 5 cm with a resolution of 100 km. The main features of the mission would be two spacecraft at an altitude of approximately 160 km each operating with a drag compensation system. The spacing between the spacecraft could vary from 100 to 600 km. The observation to be made would be that of the range rate between the two spacecraft. The accuracy of this measurement is expected to be $\pm 1 \times 10^{-6}$ m sec $^{-1}$. These data would enable spherical harmonic fields to be determined to very high degree (say, 300). The analysis of these data will require a large computational effort. Efficient techniques for processing such data are now being developed.

Figures 1.8 and 1.9 (Rapp, 1984) show the accuracy to be expected from the above mission for anomalies and geoid undulations as a function of resolution or area average. Below 100 km the error rapidly increases although information is present in the measured signal. These results are plotted with current accuracy assessments of the GEML2 field and an 180 \times 180 field from The Ohio State University. Since GEML2 is only complete to degree 20, resolution is primarily limited to about 1000 km.

Another sensor that has great potential for space applications is the gravity gradiometer (see Section 2.1.4). The very high gradient accuracies needed for space applications appear to be feasible for the cryogenic gravity gradiometer being developed by Paik (1981). The gradiometer can be designed to measure one or more components of the gravity tensor (Wells, 1984). Jekeli and Rapp (1980), Breakwell (1979), Colombo and Kleusberg (1983), and others have carried out approximate simulation studies to indicate the resolution and accuracy in the determination of gravity from satellite gradiometer data (primarily the second-order radial component). Using the procedures of Jekeli and Rapp (1980) with a radial-component gradiometer having an accuracy of $\pm 10^{-4}$ E (Eötvös unit) at an altitude of 130 km for a 6-month mission, the expected accuracies are shown for anomalies in Figure 1.8 and for undulations in Figure 1.9 (Rapp, 1984). The satellite-to-satellite tracking (SST) mission GRM would improve the current accuracy situation (on a global average) by a factor of about 10. The gradiometer mission is an improvement over the SST mission by about 60 percent except at very short wavelengths (i.e., < 20 km). The gradiometer mission could obtain anomalies to an accuracy of about ± 3 mgal with a resolution of 50 km. This is three times better than that expected from the SST mission.

The above missions are primarily global in extent. It is also possible to have a limited mission where only portions of the Earth are covered by a sensor. An example of such a mission could be a gradiometer in the Space Shuttle. Gullahorn et al. (1984) describe a system where a gradiometer could be held at an altitude of approximately 130 km, tethered from the Shuttle. The launch of such a system could take place in the late 1980s.

Another future gradient measurement technique has been described by Balmino et al. (1984) as Project Gradio. In this proposed mission

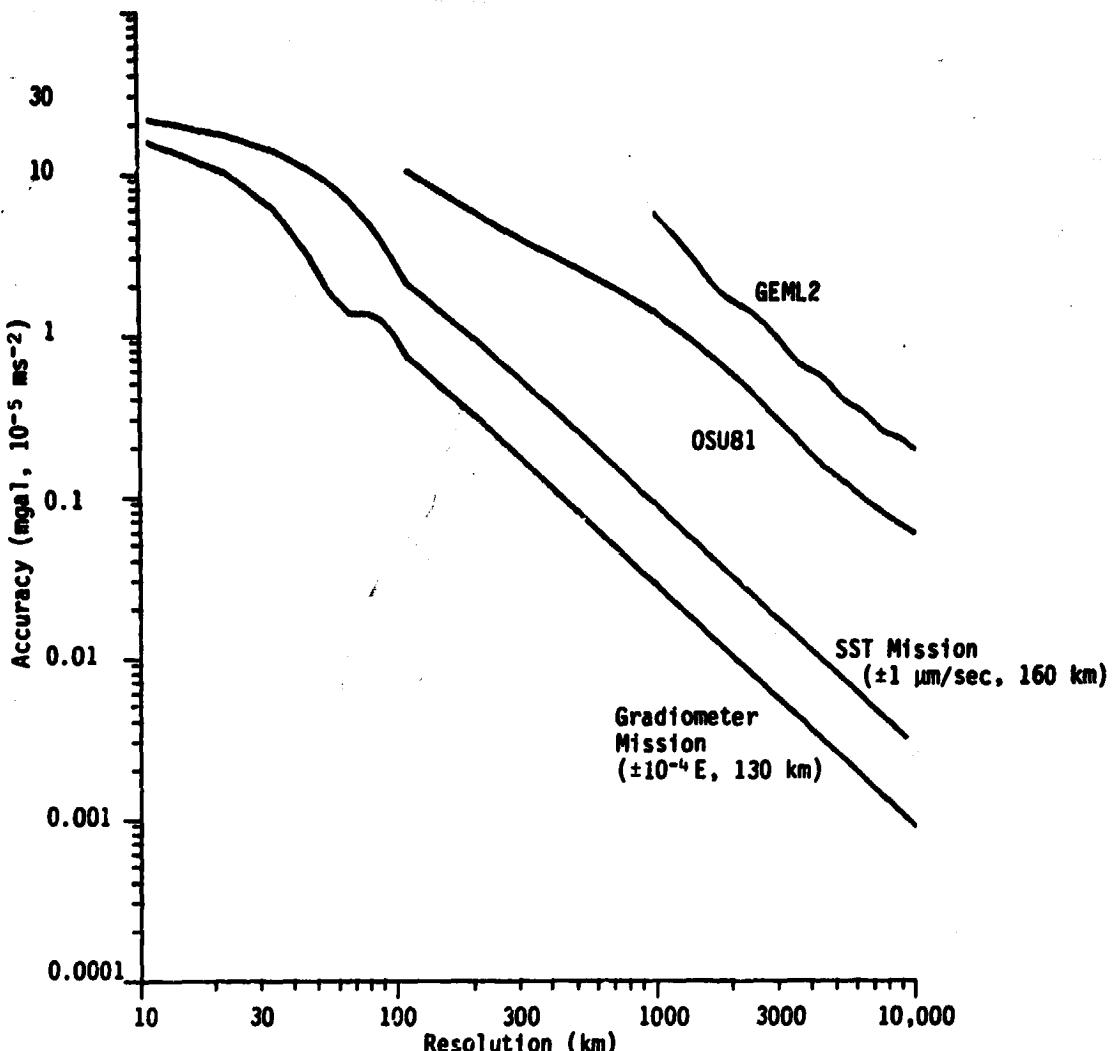


FIGURE 1.8 Gravity anomaly accuracies for current and future gravity field models.

microaccelerometers would be placed in a satellite to determine the components of the gradient tensor in a satellite-fixed coordinate system. The expected accuracy of the measurement would be on the order of $\pm 0.01 \text{ E}$. Although this is not so good an accuracy as would be associated with the Paik equipment, it should be sufficient to obtain a substantial improvement in the knowledge of the gravity field. The earliest possible launch date for this mission is 1990.

Colombo and Kleusberg (1983) have also proposed a mission that would combine an altimeter with a gradiometer that would sense the second radial derivative of the potential. The basic principle is that the geocentric distance of the satellite could be determined given (1) the gradient measurement, (2) a fairly good set of low (~ 30) degree potential coefficients, and (3) an accurate KM value. The accuracy

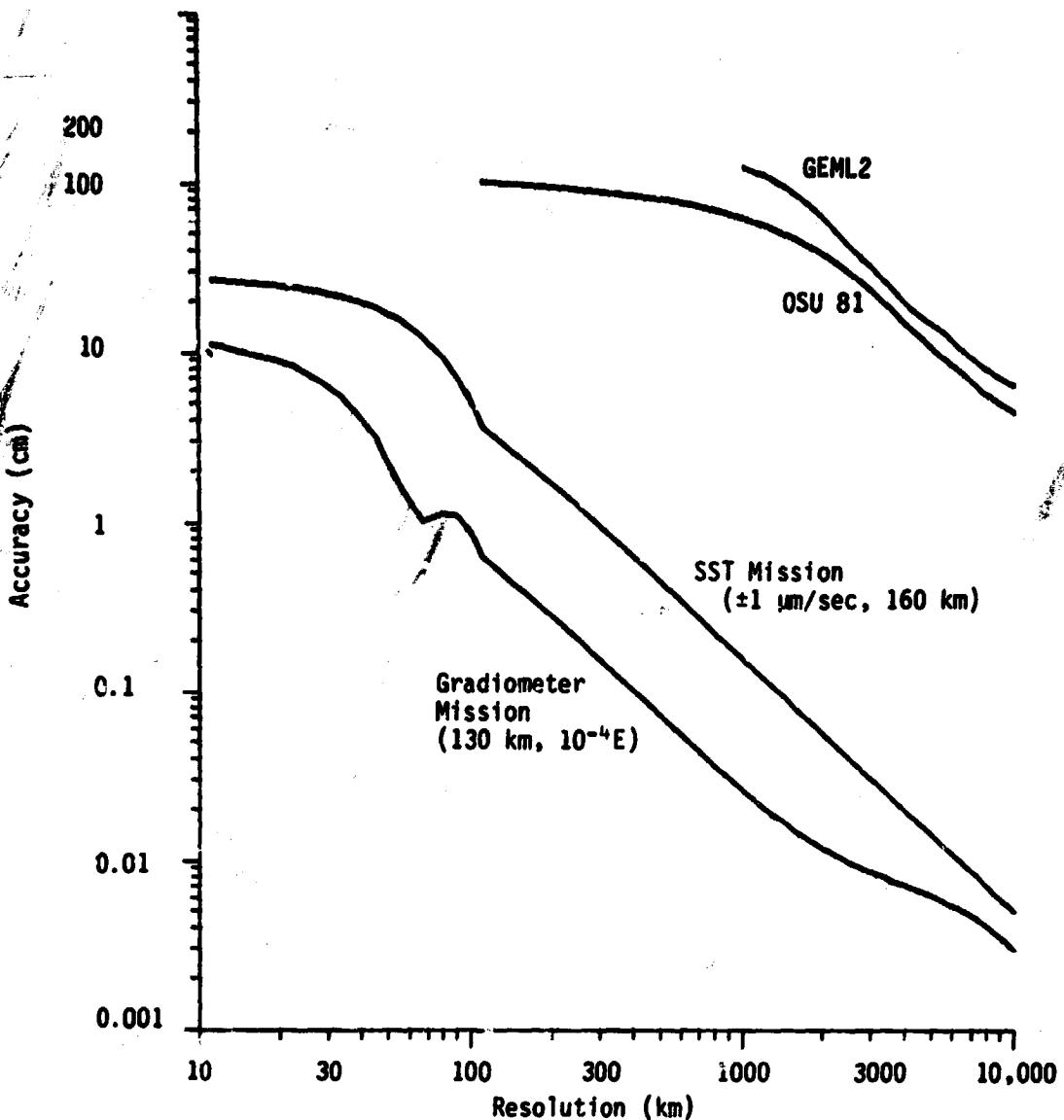


FIGURE 1.9 Geoid undulation accuracies for current and future gravity field models.

needed for the latter two quantities is well within that expected in the next few years. With this type of information the geocentric distance could be determined to an accuracy approaching 1 cm. If this can be done the need for extensive tracking of the altimeter satellites could be considerably reduced. A review of spaceborne gradiometer developments is described in a report edited by Wells (1984).

The above discussions have been directed toward improvements in the gravity field that can be considered in the next 10 to 15 years. However, there are developments in the shorter term that will yield improved gravity-field information. The first procedure relates to the

development of an interim gravity-field model using existing data and data that would be acquired through specific tracking comparisons. This interim field model (Murphy, 1983; NASA, 1982) could provide the basis for the tracking of altimeter satellite TOPEX, which may be launched in 1990 (Born et al., 1984; also see Sections 2.3 and 3.3). The tracking of TOPEX can also provide additional gravity-field information. The accuracy and resolution of the gravity field to be obtained from TOPEX will depend greatly on the accuracy of the tracking procedures used.

We should also note, in the near-term developments, the launch of LAGEOS II in 1987. This satellite can be expected to give improved low-degree gravity fields and their time variation. It will not help, because of its high orbit, in the determination of the short-wavelength gravity field.

Future developments for the gravity-field determination from space are needed. Since the accuracy to be expected from a single component gradiometer seems only to be a factor of 2 better than the SST mission of GRM, more studies need to be made to see the effect of knowing multiple components of the gradient tensor and to assess other techniques for gravity-field improvement from space.

The development of new data-acquisition systems will create new requirements for theoretical models and improvements in the analysis of large sensor data bases. For example, theoretical studies are needed on the downward continuation problem from space for an Earth with topography. We must better understand how to use and acquire detailed terrain models for use in the prediction of gravimetric quantities and for geophysical interpretations. With more detailed information (e.g., as obtained from altimetric data) it will be possible to develop improved statistical models for the Earth's gravity field. Such models can be used for improved estimation procedures as well as for the design of data-acquisition surveys.

The improvement of the global and local gravity fields in the future can best be accomplished by combining information from a number of data sources. In doing this, we will be faced with large amounts of data for which efficient processing algorithms will be needed in order for the gravity information to be extracted in a timely fashion.

One example of a combination of information is the use of terrain models to improve gravity prediction. With the availability of gridded height data over vast regions, automatic computations of terrain contributions on geodetic measurements are now routine. For example the National Geophysical Data Center, Boulder, Colorado, can furnish on magnetic tape height data files for the entire continental United States at approximately 1 km spacing and selected areas of Alaska at several spacings.

The success of using these data can be seen from inspection of several papers dealing with deriving products from the terrain-corrected data such as Forsberg and Tscherning (1981), Schwarz (1978), Schwarz and Lachapelle (1980), and Goad et al. (1984). A typical example of the success is given in Table 1.4.

TABLE 1.4 Terrain Correction Results, White Sands, New Mexico, root mean square of 400 points.

	Before	After
XI (sec)	2.7	1.6
Eta (sec)	6.4	2.8

NOAA's National Geodetic Survey used the above-mentioned terrain data file of the continental United States to terrain correct deflections of the vertical in the White Sands, New Mexico, area where a significant amount of surface gravity and astronomic data have been collected. As can be seen the contribution to the deflection components is quite dramatic, especially in the east-west (ETA) measurements. This is to be expected since the area is bounded by mountains running in a north-south direction on both sides. Some corrections reached the 15 arc sec level as the locations were chosen closer to the mountain chains.

The modeling of these gravitational effects employs a representation of the mass distribution. Disks or parallelepipeds are usually used with the parallelepipeds being used more now with computer processing. The theoretical representation of this anomalous potential and its derivatives can be found in MacMillan (1958).

Recent developments have utilized the fast Fourier transform to compute and store terrain calculations for a large area (for example, see Sideris, 1984; Parker, 1972). Terrain corrections in gravity appear to be accurate to the mgal level where nearby topographic heights are available at the kilometer-level spacing.

As our knowledge of the gravity field improves, in terms of long and of short wavelengths, temporal variations will play an increasingly important role. For example, polar-cap melting can have effects on sea level as well as on gravity. Will such change be detected by future gravity measurements? At what level of accuracy will we need to define a global gravity field in terms of a specific epoch?

In the near future, dramatic improvements in our knowledge of the gravity field at the long and short wavelengths will be possible. There will be a time at which the need for such determinations on a global basis will stabilize. But there will be continuing interest in the gravity field from the temporal point of view for geodetic, oceanographic, and geophysical applications.

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INSTRUMENTATION

2.1 CURRENT STATE OF TERRESTRIAL MEASUREMENTS

In this section are described instruments capable of measuring various parameters of geodetic interest including strain, tilt, and gravity. Our discussion is directed to those areas in which recent advances in instrumentation have made possible significant increases in both the accuracy and precision of field measurements. Many of the classical instruments that have been used for many years such as Invar tapes or the rods and telescopes used in first-order leveling are not discussed. A discussion of these techniques may be found in Bomford (1980).

2.1.1 Electromagnetic Distance Measurements

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 usually not sufficiently accurate for geodesy. The uncertainties introduced by spurious reflections become less serious as the wavelength is made shorter, and optical wavelengths are therefore most commonly used for the most precise measurements.

The minimum acceptable resolution and range vary depending on the application. The most demanding application is probably the determination of secular strain rates in seismically active areas. Experience in this area suggests that the minimum acceptable range for this application is 10-20 km with a fractional uncertainty of no more than 1 part per million (ppm). An increase of a factor of 2 or 3 in range and 1 or 2 orders of magnitude in accuracy would be most welcome and would substantially improve our ability to study temporal fluctuations in the secular strain rate in these active areas (Savage and Prescott, 1973). It is likely that various systematic errors will conspire to limit ground-based measurements to ranges of about 100 km or less and that the fractional uncertainties will probably never be less than 0.01 ppm.

In 1983, the meter was redefined in terms of the second by assigning a value to the velocity of light. In principle, it is

therefore a straightforward matter to measure distances directly in terms of the time of flight of an electromagnetic signal over the baseline. This method does not work in practice, since it is difficult to measure times of flight with sufficient accuracy; most of the work in electromagnetic distance measurement has used various modulation schemes. 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. Polarization modulation is most often used, but amplitude and frequency modulation are also possible. The optical signal is simply a carrier of the modulation; its frequency stability is unimportant, although many systems depend on the fact that the amplitude of the beam is constant. The frequency of the modulation, however, enters into the measurement directly. The fractional uncertainty of this frequency appears as a corresponding fractional uncertainty in the distance measurement. Carefully designed quartz-crystal-stabilized oscillators are adequate if they are periodically calibrated. Rubidium standards provide a considerable safety margin; usually they can be used with only infrequent calibration.

Most modulation schemes produce ranges that are ambiguous by an integral number of modulation wavelengths. This ambiguity can be removed in several ways and is not usually a serious limitation.

The most serious limitation in the conversion of an optical transit time to a physical distance is the uncertainty in the actual velocity of light along the path of the measurement. The ratio of the velocity in vacuum to the velocity in a given medium is called the index of refraction. The index of refraction of air differs from its vacuum value of unity by a small quantity called the atmospheric refractivity. It depends on the wavelength used in the measurement; for optical wavelengths, the refractivity is about 300 ppm, and uncorrected distance measurements will therefore appear longer by this amount (light travels more slowly in the air than in vacuum so that the apparent transit time is longer than it would be over the same path length in vacuum). The refractivity is almost a linear function of the density of air along the path; it therefore depends on both the pressure and temperature. Optical measurements may be converted to physical distances if the pressure and temperature profiles are known, and these may be determined by ancillary measurements made at the endpoints or, more accurately, by an airplane flying as closely as possible to the measurement path. Bender and Owens (1965) suggested that the index might be determined more easily by measuring the difference in the apparent distance as measured by light of two different wavelengths. Thus, the index would be determined by measuring its dispersion. It can be shown that the index must be determined to about 1 part in 10^4 if the final uncertainty in the length is to be no more than 0.03 ppm. Since the dispersion across the visible portion of the spectrum is only about 5 percent of the total refractivity, the dispersion must be measured substantially more accurately than the index itself, and the errors in the dispersion determination usually are the most significant experimental errors.

This relatively simple approach must be modified somewhat in actual usage since the atmosphere contains some water vapor. On a typical day, the presence of the water vapor changes the index of refraction by a few percent, but the contribution is almost nondispersive across the visible portion of the spectrum, making its determination by purely optical measurements very difficult.

The water-vapor contribution to the index is sufficiently small that it may be estimated by measurements at the endpoints if the atmosphere is sufficiently homogeneous. Alternatively, it may be directly measured by flying aircraft along the path. Several investigators have proposed adding a third microwave frequency measurement of the distance. A measurement of the microwave-optical dispersion is very sensitive to the water vapor content of the atmosphere; a three-wavelength system should reduce the measurement errors due to the atmosphere to 0.02 ppm or less.

Although multiple-wavelength systems have been discussed in the literature for several years, most of the measurements are still done with less sophisticated instruments. The U.S. Geological Survey usually uses single-wavelength devices whose measurements must be corrected for the index of refraction of the atmosphere using ancillary measurements. These measurements are often made from an airplane flying as closely as practical to the line of sight.

A two-wavelength instrument has been used by Slater and his colleagues (Bouricius and Earnshaw, 1974; Huggett and Slater, 1975) to measure several arrays in California. His measurements are typically conducted over baselines up to 10 km long and have typical errors of 0.1 ppm, although both the range and accuracy are occasionally better than this.

Levine and his colleagues (Moody and Levine, 1979) are currently testing a three-wavelength system, designed to measure baselines up to 40-50 km long with uncertainties of 0.02 ppm or less. In addition to using three wavelengths to measure the water-vapor contribution directly, this system uses an active receiver rather than the passive retroreflector of other designs. This change should increase the maximum range of the instrument at the expense of an increase in complexity.

An analysis of the error budget of various multiple-wavelength systems has been conducted by Thayer (1967); he shows that various atmospheric effects will limit the range of all ground-to-ground systems to about 50 km; measurement uncertainties much less than 0.01 ppm are also unlikely except under exceptionally favorable atmospheric conditions. If this analysis is correct, instruments currently being tested probably represent about the best that will be possible with ground-to-ground measurements over long baselines. Although improvements in instrumental design are likely, they are unlikely to increase the maximum range by more than about a factor of 2.

It is possible in principle to measure longer baselines using simultaneous ranging from two ground stations to an airplane flying roughly halfway between the two endpoints. Such a system would increase the maximum range by approximately a factor of 2, but at the expense of a considerable increase in complexity. The flight path of the airplane

must be carefully chosen so that the distances to the two endpoints do not change very rapidly.

2.1.2 Strain Measurements

Although the multiple-wavelength systems discussed in Section 2.1.1 can be used to measure local strain, such systems are not optimum for measurements over baselines shorter than a few kilometers. The reason for this is that for short baselines those techniques usually become limited by errors whose magnitudes do not scale with the length of the baseline; the resulting uncertainty in the determination of strain is, therefore, often unacceptably large.

There are many types of short-baseline strainmeters. The earliest instruments used a physical length standard such as a fused-silica tube. Other designs use wires or filaments of various materials. The change in the length of the baseline is observed by comparing the length of the physical length standard with the distance between two piers. These comparisons can be done using capacitance bridges, linear variable differential transformers, or other means.

One of the primary limitations in the use of such instruments is the stability of the length standard. Most materials have coefficients of thermal expansion on the order of 1 ppm per degree Celsius. In addition, the long-term stability of most materials is poorly known, especially when they are used in the sort of environment typically found in field installations. As a result, strainmeters using physical length standards are limited to those measurements in which adequate thermal stability can be maintained and in which secular changes in the length standard can be monitored. Various techniques for reducing the effective sensitivity to temperature using combinations of materials (such as fused silica rods joined by re-entrant aluminum couplings) have been suggested. Such methods may degrade the long-term stability of the combination and are unlikely to decrease the thermal sensitivity by more than about a factor of 10. On the other hand, strainmeters of this type are relatively simple to construct and are likely to be quite reliable. They can provide useful data provided their limitations are understood.

Several groups have developed laser strainmeters for the measurement of strain on baselines up to several hundred meters in length. These instruments are basically interferometers in which the strain is measured in terms of the wavelength of the source. The instrumental uncertainties in a well-designed system are small compared to the strain rates typically encountered in the field. A well-stabilized laser will have fractional fluctuations in its wavelength of no more than 0.001 ppm; stabilities 100 times better than this have been reported by Levine and Hall (1972) in a carefully designed system.

Although laser strainmeters are plagued by many systematic errors, most of them are well understood. In a well-designed system, the total instrumental error in measuring strain is unlikely to exceed 0.01 ppm.

The advantage of a laser strainmeter arises primarily from the advances that have been made in stabilizing laser wavelengths. The

first stabilizers used passive fused-silica cavities. Although such cavities are prone to many of the same instabilities that limited the earlier strainmeters, there are several important differences:

1. The cavity can be short, and it is therefore not too difficult to stabilize its temperature and isolate it from other environmental perturbations.
2. The difficulty and expense of constructing the stabilizer are essentially independent of the length of the strainmeter.
3. The cavity can be calibrated using primary wavelength standards.

It is also possible to use a wavelength standard directly thereby eliminating the need for a passive cavity (Levine and Hall, 1972).

Laser strainmeters are, however, subject to other types of errors that are more difficult to deal with. Strain records are often contaminated by spurious signals produced by motions of the piers at each end; the adequacy of the coupling between the strainmeter and the surroundings is difficult to evaluate; and the relationship between local and regional strain is often unknown. Laser strainmeters require dedicated evacuated paths; in addition to requiring ancillary vacuum pumps, the terrain must be reasonably flat if installation costs are to be kept reasonable. Finally, most laser strainmeters must be run continuously. If the instrument fails, it is often difficult to join the strain record across the gap without some ancillary measurements or some assumptions, although the fringe-locking system of Levine and Hall (1972; Levine, 1978) can usually provide continuity over gaps up to about a week in length.

As can be seen from the previous discussion, improvements in laser strainmeters will not come in the design of the instruments but in a better understanding of the coupling between the interferometer components and the regional strain field. The optical-anchor technique used at Pinon Flat Observatory* shows great promise of improving this coupling, although it adds considerable complexity to an already complex instrument. This technique monitors the motion of the piers at the ends of the interferometer by means of ancillary interferometers that measure the motion of the pier with respect to the deeper strata, which are presumably more stable than the near-surface material.

The work at Pinon Flat has emphasized the difficulty of evaluating the stability of endpoint monuments in general. These instabilities may ultimately dominate the error budget in carefully designed systems. Indeed, these motions may be the dominant source of the long-period noise at Pinon Flat (Berger and Levine, 1974).

*Pinon Flat Observatory is located in southern California and is operated by the University of California, San Diego. It contains a large number of geophysical instruments including three 800-m laser strainmeters and several different types of tiltmeters. An important function of the observatory is the evaluation of instruments at a well-characterized field location.

2.1.3 Tilt

Tiltmeters tend to fall into two categories: short-baseline instruments and long-baseline instruments. Both types of instruments are capable of adequate resolution or precision; accuracy is quite another matter.

Short-baseline tiltmeters are basically point measurements of the angle between an axis fixed in the crust and the local direction of gravity. Many types of sensors have been used: vertical pendulums, horizontal pendulums, and bubble levels, to name the three most common types. Although many tiltmeters were originally installed within a few meters of the surface, most of these instruments showed large secular tilts that were poorly correlated with data recorded using nominally identical nearby instruments (Wyatt and Berger, 1980). An unacceptably great sensitivity to various effects, such as pressure changes or rainfall, was also quite common (Edge et al., 1981).

Installations in deep boreholes have been more successful. Several groups have reported almost complete decoupling from spurious surface effects using instruments in boreholes about 30 m deep.

Deep-borehole tiltmeters are currently being used to study both secular and tidal tilts. Most of the instruments behave quite well in the tidal band, and signal-to-noise ratios in excess of 35 dB (for a 1-month record) have been reported by several groups (Levine et al., 1983).

Many investigators tried to isolate their tiltmeters from the effects of rainfall or temperature changes by installing the instruments in shafts or mines. Tilts recorded in this way may be difficult to interpret as a result of the coupling between tilt and strain generated by the cavity. The magnitudes of the tilts resulting from this coupling depend on the shape of the cavity and on the location of the tiltmeter; as a general rule these effects are comparable to the true tilt at most locations in a cavity. The presence of local cracks and other inhomogeneities may also complicate the analysis. (These comments apply equally to the installation of strainmeters, although careful installation can minimize the cavity effects in this case.)

The utility of borehole instruments to study secular tilts is less clear. The coherence between closely spaced instruments is often poor; whether this is due to local effects within the hole (or its immediate vicinity) or is simply a residual instrumental response to various spurious effects is not clear. Typical installations report secular tilts on the order of 0.5 to 1 μ rad per year; at least some of this tilt is presumably spurious instrumental noise.

In an effort to attenuate the sensitivity to local anomalies, several groups have designed and constructed long-baseline tiltmeters. A typical design would use a set of end piers connected by a pipe (or pipes) containing a fluid. The tilt is determined by measuring the difference in the fluid level at the two endpoints. The differential fluid-level may be determined using pressure transducers at the center or by directly measuring the fluid height relative to some fiducial marker at each end. (A portable version of this type of tiltmeter has been proposed by Bilham (1985) for use in first-order leveling. Such an instrument might improve the accuracy of leveling by eliminating the

need to make refraction corrections.) In all cases, the goal is to reduce the sensitivity to local anomalies by increasing the length of the baseline.

Although local effects are presumably attenuated, other difficulties remain. Long-baseline tiltmeters cannot be installed very deeply, since a trench must be dug along the entire length of the baseline. In addition to increased sensitivity to surface effects, the adequacy of the coupling of the end piers to the deeper strata is hard to evaluate. Although such instruments are relatively unaffected by spurious tilts of the end piers, vertical motion of the end piers enters as a first-order spurious tilt. These effects are similar to the problems encountered with laser strainmeters, and the group at Pinon Flat has proposed a similar solution: couple the end piers to the deeper strata via "optical anchors." These are ancillary interferometers, which measure the position of the pier with respect to the deeper strata. These ancillary measurements have shown that the motion of the piers is a serious problem. When the ancillary interferometers are used, the residual secular tilt rate is about 0.1 to 0.25 μ rad per year, between a factor of 5 and 10 less than the rates typically reported by deep-borehole instruments. The limitations due to the shallowness of the instruments are apparent, however. The sensitivity to various spurious effects is larger than one might like for tidal analysis. (Wyatt and Agnew, 1984).

A discussion of the future of tilt measurements, therefore, is similar to our discussion of strain. It is not too difficult to evaluate and remove instrumental effects (although it has taken quite a bit of work to be able to say that). It is much more difficult to estimate the correlation between the tilt reported by any instrument and the "true" regional tilt. Some of this comes from the sensitivity of all existing tiltmeters to various spurious effects, some of it comes from very local tilts whose magnitudes are not characteristic of the region.

2.1.4 Gravity

Absolute Gravity

Several types of absolute gravity meters have been constructed and used in field surveys (Cannizzo et al., 1978; Hammond and Faller, 1967). These instruments determine the local acceleration of gravity directly in terms of the SI units of length and time. In general, they require both a length standard and a time standard. The former is usually a helium-neon laser whose wavelength is stabilized using saturated absorption in iodine vapor (although other stabilizers that are more suited to field operation have been suggested), while the latter is either a rubidium or cesium frequency standard. (With the redefinition of the meter in terms of the second via the velocity of light, the acceleration of gravity could, in principle, be determined in terms of the second alone, but this is not feasible at present because it is extremely difficult to construct a field-qualified device to provide

both a convenient standard wavelength and a standard frequency simultaneously.) Although the instruments differ in mechanical details, the general operating principles are similar: the acceleration of an object in free fall in a vacuum chamber is measured. The object is a retroreflector that is part of an interferometer; its position is measured by counting fringes using a known wavelength. (We note that other wavelength-independent schemes have been proposed. These systems are described in the literature.)

The velocity and acceleration of the object are determined by measuring the time to traverse fixed distances (or, somewhat less conveniently, the distances traversed in fixed times).

Most of the current instruments claim to be able to determine g with an uncertainty on the order of 0.1 m sec^{-2} (Zumberge et al., 1983). This represents a fractional uncertainty of about 0.01 ppm in the determination of g . It is somewhat difficult to evaluate these claims. Simultaneous measurements with different instruments at the same site are rare, and the data that exist are somewhat ambiguous. Discrepancies of several times the reported standard error are not unusual. The significance of these discrepancies is hard to evaluate since the measurements are not simultaneous; transfers from the location of the measurement to a local reference point may also degrade the accuracy somewhat. It is possible that the short-term fluctuations in the local value of g are larger than have been appreciated. Alternatively, some of the systematic error estimates may be too optimistic. In any case, these discrepancies are troublesome and reduce the objective reliability of the technique to some extent.

Although they do not measure g in terms of the fundamental SI units, other types of gravity meters are in common use. Instruments such as those manufactured by LaCoste and Romberg measure g using a well-calibrated spring balance to measure the weight of a test mass. Measurement errors on the order of 0.1 m sec^{-2} are possible if great care is exercised in moving the instrument and if it is used to measure differences in g between points not too far apart.

Instruments to measure g using magnetic or electrostatic suspensions to balance the weight of an object have been proposed. Although such systems do not measure g directly in SI units, they are designed to replace the mechanical suspension typical of the LaCoste and Romberg instruments with a suspension that is more easily characterized and calibrated. Harrison and Sato (1985) have modified a standard LaCoste and Romberg instrument by adding a novel form of electrostatic feedback that has a much wider dynamic range and much better linearity than conventional feedback designs. Farrell (1984) has suggested a somewhat similar approach using a dedicated microcomputer to synthesize the appropriate feedback transfer function. Goodkind, Warburton, and Reineman (Warburton and Goodkind, 1977; GWR Instruments, 1984) are designing a portable version of their superconducting instrument. All of these systems are in various stages of development; although none would yield a truly absolute measure of g , this limitation would not be too serious if the calibration were sufficiently stable and could be done with sufficient accuracy.

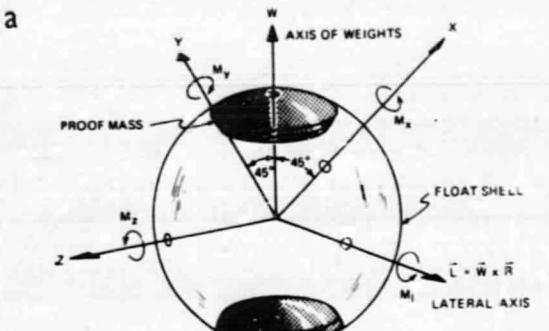
Gravity Gradiometer

The force due to the acceleration of gravity is a vector quantity. The "gravity gradient" is a spatial derivative of the acceleration and, therefore, a tensor with nine components of which six are independent (for a discussion see Vanicek and Krakiwsky, 1982). It is generally easier to construct a gravity gradiometer to measure a single tensor component than the full six independent components; but in order to obtain meaningful results in that case, some sensor attitude control is necessary.

Gravity gradiometer technology developments are reviewed by Gerber (1978), DeBra (1979), Heller (1981), Pisacane (1983), and Wells (1984). Laboratory tests have repeatedly given accuracies of 1 to 10 E (1 E = 10^{-9} sec $^{-2}$). Figure 2.1 illustrates three basic instrument designs.

One instrument developed at Hughes Laboratories (Figure 2.1b) uses a sensor consisting of two dumbbells in a differencing mode in which the sensor is rotated to distinguish the frequency of the signal from noise sources (Forward, 1982). The Hughes device was the first moving-base gradiometer to achieve laboratory operation. The development was suspended in 1978 because of severe axial vibration sensitivity.

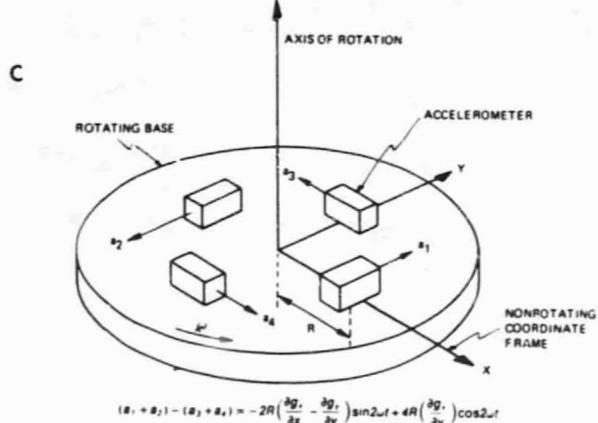
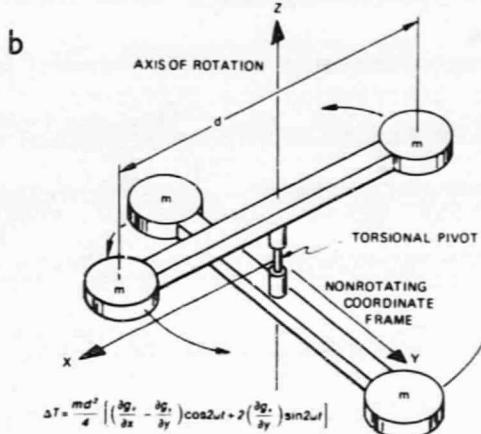
Another developed at Charles Stark Draper Laboratories (Figure 2.1a) uses a sphere with nonuniform mass distribution as a floated sensor element. The torque required to orient the sensor element against gravity is a measure of the gravity gradient. The successful laboratory prototypes operated near the theoretical noise limit. Some environmental anomalies were noted with the instrument, such as long transients, a memory, and null shift under vibration. Development and testing of this instrument terminated in 1980 (Trageser, 1981a, 1981b). Another technique has been developed at Bell Aerospace (Figure 2.1c) that uses two opposed accelerometers on a rotating platform. Several models have been fabricated with either ball or gas bearings. Since 1977, this type has been developed for two missions--one to improve inertial navigation for the U.S. Navy and the other for gravity surveys for land or airborne use (Metzger and Jincitano, 1981). As a result of this development, the U.S. Air Force Geophysics Laboratories has entered into a contract with Bell Aerospace Corporation to develop a gravity gradiometer survey system (GGSS). The purpose of the GGSS is to satisfy current and future requirements for the rapid acquisition of highly accurate data for terrestrial gravity data bases. The GGSS will be used to chart, with high accuracy, the gravity disturbance vector. For this reason the measured gradients, recognized as intermediate variables of interest, are secondary to the gradiometrically derived estimates of the deflection of the vertical components and the vertical disturbance. The fundamental objective is to provide surface point gravity disturbance data with a root-mean-square (rms) error of 0.90 mgal or less and surface point deflection-of-the-vertical data with an rms error of 0.18 arc sec (0.87 µrad) or less for the aggregate of all spatial frequencies greater than 0.002 cycle per kilometer (wavelengths less than 500 km). The GGSS includes self-contained gravity gradiometer instrumentation configured to measure and provide data from which the five independent elements of the gravity gradient tensor can be uniquely determined. It



$$M_x = \frac{\Delta I}{2} \left(\frac{\partial g_x}{\partial z} + \frac{\partial g_z}{\partial x} \right)$$

$$M_y = \frac{\Delta I}{2} \left(\frac{\partial g_y}{\partial z} - \frac{\partial g_z}{\partial y} \right)$$

$\Delta I = I_l - I_z = \text{INERTIA DIFFERENCE}$



$$(g_1 + g_2) - (g_3 + g_4) = -2R \left(\frac{\partial g_z}{\partial x} - \frac{\partial g_y}{\partial y} \right) \sin 2\omega t + 4R \left(\frac{\partial g_y}{\partial y} \right) \cos 2\omega t$$

FIGURE 2.1 Three gravity gradiometer designs: (a) Draper, (b) Hughes, and (c) Bell (from Gerber, 1978).

also includes associated isolation systems, the inertial navigation system, and data recording and monitoring equipment configured, with software, as a coordinated operating entity. A simplified block diagram is given in Figure 2.2.

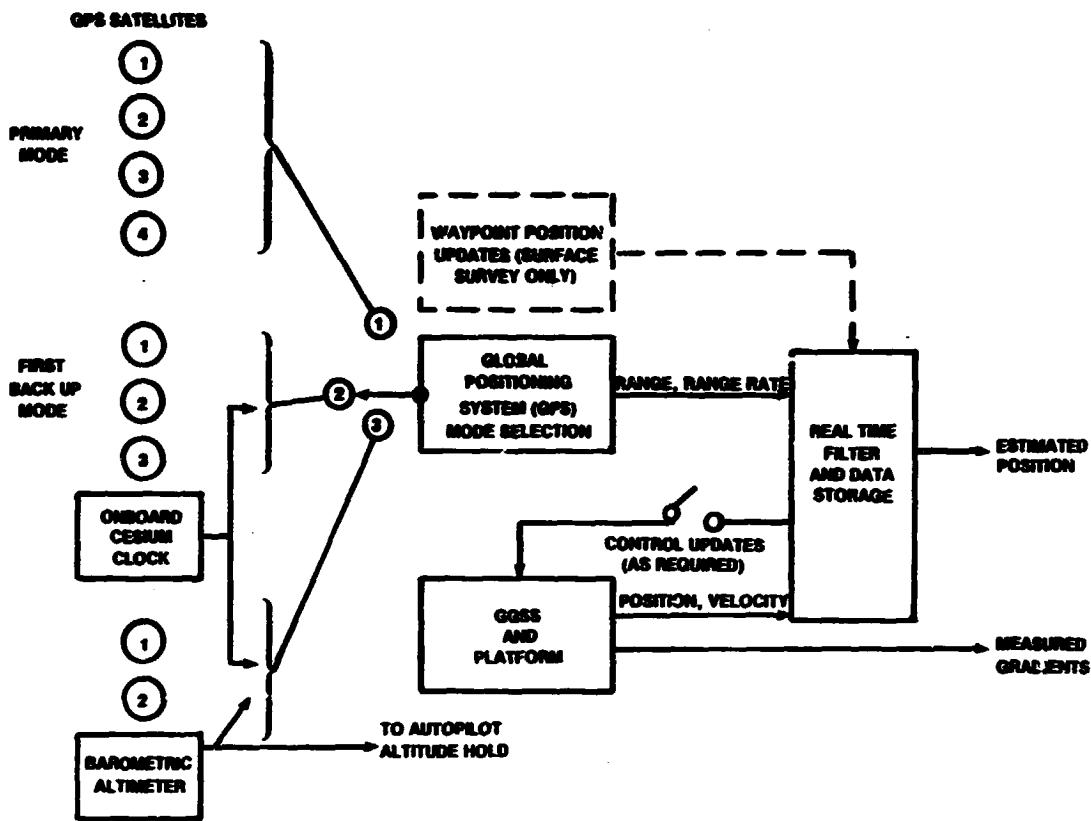


FIGURE 2.2 GGSS/GPS mechanization.

The heart of the system is the GGSS platform, which contains three gravity gradient instruments (GGI) stabilization gyros, and accelerometers. A receiver for the Global Positioning System (GPS) provides vehicle position as a function of time. Power supplies, microprocessors, atomic clock, central data-processing unit, appropriate displays and controls, and vehicle interfaces complete the system. If the proposed instrumentation performs according to specifications, it will provide a major source of information about high-frequency variations in the Earth's gravity field. The GGSS device has been instrumented in a surface version of the Navy's version and is being procured in quantity. The Navy version is not a three-dimensional instrument but does measure the deflection of the vertical. The sensitivity of the Navy system is sufficient for the above applications as of 1983.

Gravity gradiometers are susceptible to errors because of random motion of molecules in the mechanical structure and electrons in the electronic circuitry. Development of superconducting gradiometers has been initiated in order to minimize these effects. The U.S. Air Force Office of Scientific Research has supported development of a prototype single-axis model for use in a null experiment to test the inverse-square law of gravitation (Maples, 1980). NASA has supported hardware development of a single-axis model of the superconducting gradiometer.

for a potential follow-on to the Geopotential Research Mission (GRM) in the 1990s (Paik, 1981a; Fischetti, 1981). This instrument has as a goal an accuracy of 10^{-3} E over 3 sec averaging and uses two opposed superconducting proof masses on a soft suspension and two superconducting sensing coils in a pancake shape (Paik, 1981a, 1981b). Two SQUID amplifiers are coupled inductively and detect the motion from which the gravity gradient can be determined. Testing of a single-axis gradiometer has been completed. A superconducting cavity oscillator accelerometer has also been proposed for the follow-on GRM mission (Reinhardt et al., 1982). This design shows promise of achieving an accuracy of 10^{-4} to 10^{-5} E for 1- to 1000-sec intervals with high dynamic range.

The gravity gradiometer features of the versions by Hughes, Bell, and Draper and the superconducting version by Paik are listed below:

	Hughes	Bell	Draper	Superconducting
Design	Floating bars with measured torsion	Rotating accelerometers	Floating variable-density ball	Differential motion of proof masses
Status	Stopped	Development	Limbo	Research
Accuracy	5-10 E 10 sec MWA	4 E 10 sec MWA	0.4 E 10 sec MWA	0.01-0.1 E 10 sec MWA

NOTE: MWA = mean weighted average

Future Concepts and Problems to Be Addressed

Further gradiometer developments are in the planning stage. A French mission concept, known as GRADIO, plans a room-temperature instrument for space environments with a sensitivity of 10^{-2} E. The joint U.S.-Italy Tethered Satellite System includes a concept that employs displacement transducers on the tether in a gravity gradiometer mode. A concept by Bendix, Stanford University, and Goddard Space Flight Center employs a superconducting cavity oscillator to convert the displacement of a proof mass to an easily measured frequency shift.

Gradiometer design trade-offs involve questions of single-axis versus full-tensor measurements, spinning versus inertial orientations, and room versus cryogenic temperatures. In general, the second options listed above are more difficult to achieve but are expected to provide better results. In particular, cryogenic temperatures should improve system performance but are more difficult to maintain, especially in a remote spacecraft environment.

Some problem areas that must be addressed to provide significant gradiometer improvements for operation in a space environment include the following:

1. Evaluation of the various proposed instrument configurations.
2. Improvement of individual-component sensor technologies such as superconducting quantum interference devices (SQUID), low-temperature preamplifiers, and suspensions for proof masses.
3. Evaluation and construction of a space test environment.
4. Analytic simulation of a low Earth-orbiting gradiometer with a system noise level of about 3×10^{-4} E in a 1-sec integration period and attendant data analysis strategies for meaningful interpretation.

2.1.5 Inertial Positioning Systems

Inertial surveying employs a system of gyroscopes and three accelerometers that precisely measure the motion of a vehicle, enabling determination of coordinates in three dimensions. The instrumentation used in inertial surveys was originally developed as a navigational system for military aircraft. Adaptations, known as the Inertial Positioning System (IPS), have produced positions suitable for public-land and map-control surveys. The innovation that made this aircraft navigation system accurate enough for survey coordinate determination was the development of the zero-velocity update procedure, which requires that the vehicle be periodically brought to a standstill while the system checks and corrects itself for systematic error accumulated in motion. When used in a helicopter, the stops are achieved by landing or hovering.

An inertial traverse is performed between two known survey control stations, at which points the known coordinates are entered into the system through the control and display unit. After a preliminary warm-up and calibration period, usually lasting about an hour, the system is initialized at the beginning point. Once initialized, it continuously measures new positions as the vehicle moves along the traverse. The position of a new monument can be established by stopping the vehicle at the desired spot. As the traverse continues, with periodic stops for zero-velocity updates, the system accumulates information about and compensates for its own systematic errors and the systematic changes in the gravity field. At the end of the traverse leg the computer performs a smoothing of the raw data, i.e., an adjustment of the intermediate marked positions for the closing errors. If the system is measuring a network of lines, an area adjustment is performed.

In addition to the inherent precision of the inertial sensors, the accuracy of the survey is dependent on the sophistication of the smoothing software, the traverse duration, and the frequency of the zero-velocity updates. Results in the submeter range for coordinates of latitude, longitude, and elevation are achieved regularly. In one known case, horizontal closures on the order of 2-3 cm were obtained over traverse distances of 3-5 km. Longer traverses (over 50 km) can be measured with errors typically in the 20-30 cm range (Mancini, 1984).

Inertial navigation systems suffer from error growth with time, with the rate of the growth being a function of the quality of the gyroscopes. As better gyroscopes are developed, inertial positioning

systems will be able to operate for longer periods of time without unacceptable error growth. The zero-velocity updates and good sensor modeling bound the error and permit navigation platforms to be used for geodetic positioning. Currently instrumented inertial surveying systems do not give absolute results. Position values obtained are differential values relative to the control in the area.

The initial development of IPS for military land surveys was done for the U.S. Army in the form of the Position and Azimuth Determining System (PADS). In the early 1970s the Defense Mapping Agency funded the development of an improved PADS that would survey to geodetic standards. This resulted in the IPS-1, which has been in operation for 7 years. Although the intent of this development was to provide better positions, experimentation at the U.S. Army Engineer Topographic Laboratory showed that putting an improved accelerometer in the vertical channel permitted the system to measure gravity, and improved accelerometers in the horizontal channels allowed recovery of the deflection from the vertical.

With the use of three Litton Al000 accelerometers, the first laboratory static test gave a maximum error after smoothing of 3 cm compared with a maximum error of 20 cm with the A200 accelerometers (Roof, 1983). In field tests at the White Sands Missile Range in December 1982, on a 10-mile test course alongside the high-speed sled track, the following differential accuracies (1 sigma) relative to the initial point values were obtained:

Horizontal position	12 cm
Elevation	4 cm
North-south deflections	0.1 arc sec
East-west deflections	0.1 arc sec

In 1981 the National Ocean Survey and SPAN International, Inc., performed a series of tests intended to determine the accuracy of an inertial surveying system used under carefully controlled conditions. Using only the simplest statistical techniques, they found that the accuracy was equivalent to that of second-order, class II, control.

Research in error models and postmission adjustments of inertial networks is producing improved results both for positioning and gravity vector determinations. The Ohio State University work has shown that interlocking traverses provide better results of geodetic and error model parameters (Hannah, 1981, 1982) and that only "slight, if any deterioration between straight line and L-shaped traverses resulted when using optimum error models." Study of error characteristics of inertial systems and analyses of heading sensitivity (Schwarz 1981, Schwarz and Gonthier 1981) are also contributing significantly to improving results. Adjustment of data combining multiple measurements of the same traverse as well as a network adjustment were also developed.

The Litton systems can now provide 30-cm horizontal accuracy and 20-cm differential vertical accuracy on a regular basis for 2-h straight-line traverses. The gravity vector recovery is about 1 arc sec in deflection and 2 mgal for gravity. Optimal adjustments for a

network of traverses measured as a regional scheme will produce accuracies of 15 cm in position, 0.5 arc sec in deflection, and 1 mgal with the existing Litton system. If the A200 accelerometers in the horizontal channels of the Litton system are replaced by the A1000 accelerometers, indications are that the accuracies can be improved, particularly for the deflection determinations. As mentioned earlier, 0.1 arc sec accuracies for discrete points were achieved for each deflection component along a 10-mile test course.

The operational Ferranti system also appears to be obtaining about 30 cm in horizontal position and 20 cm in height under good conditions and straight traverses of about 1.5-h duration. The Ferranti system does not output data on the gravity vector in its present form, but the information is there to be retrieved.

Results with the Honeywell system still show differential survey accuracies of about 50 cm (30 cm under special conditions) for traverses of 2 h or less. This system is used extensively by World Surveys, Inc., in a variety of surveys. (The platform was recently integrated with a pulse laser altimeter such that the system can also serve as a terrain profiler and subsequently produce digital terrain models.) The differential gravity and deflection recovery with this system average about 10 mgal and 4 arc sec, respectively.

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2.2 AIRBORNE SYSTEMS FOR GEODESY

Geodesists have long sought airborne systems that would allow the collection of geodetic data over relatively large areas with suitable density and accuracy while at the same time realizing greatly reduced time and cost requirements. Until recently, however, most such attempts have not been able to produce a level of accuracy suitable for most geodetic applications. Within recent years four airborne techniques have shown or give promise of producing the necessary accuracy, efficiency, and timeliness. These are analytical aerotriangulation, airborne profiling of terrain system, airborne gravity, and airborne laser ranging.

2.2.1 Analytical Aerotriangulation

Photogrammetrists have known for a long time that the internal precision of point coordinate networks established by analytical aerotriangulation was equal to or better than the accuracy of the survey control for most mapping projects. It is common experience to question and find errors in the ground control whenever a photogrammetric network runs into difficulty in adjustment to the given values. In the National Mapping Division of the U.S. Geological Survey, supplemental control for stereocompilation of 1:24,000 topographic mapping is regularly established by block analytical aerotriangulation of 1:24,000-scale photographs acquired with mapping cameras of 152-mm focal length from an altitude of 3600 m above mean terrain. Natural terrain points (not signalized) are used and the standard error of planimetric positions is normally about $\sigma_{xy} = 1.5$ m. These procedures have virtually eliminated the need for field surveys for standard map compilation.

The densification of geodetic control networks as a basis for multipurpose cadastral systems requires a higher order of accuracy than that required for topographic mapping. The capability of photogrammetric control densification was demonstrated by Brown (1977) in a pilot project in the city of Atlanta. The horizontal coordinates of densification points, with a nominal spacing of 800 m, were determined with a standard error of less than 7 cm from photography taken at a scale of 1:17,500, a precision of 4 μm at the photo scale. At about the same time a precise photogrammetric survey system developed by the National Ocean Survey (NOS) was being tested at the Casa Grande, Arizona, test range. The results of this test, reported by Slama (1978), provided horizontal coordinates with standard errors of approximately 5 cm from a photo scale of 1:24,000, a precision of 2 m at photo scale. In 1979, in cooperation with Ada County, Idaho, NOS undertook the densification of approximately 900 km² in northern Ada County. The geodetic positions of 346 section corners were established from 1:24,000-scale photographs acquired with a camera of 152-mm focal length based on 17 ground-control points. The accuracy of positions established was again 5 cm, and the cost was about half that of conventional ground surveys. This project was documented by Lucas (1981).

Photogrammetric results with this level of accuracy are only obtained if all aspects of the system are carefully designed and executed. The characteristics of the NOS system are as follows:

Camera System. The lens is a Wild Aviogon II with 152-mm focal length and f/4 aperture modified by the manufacturer to yield maximum resolution in the orange part of the spectrum. There is also a 1 cm x 1 cm reseau projected in the focal plane to provide a means of removing the effects of film distortion.

Ground Targets. Each ground point to be established was targeted with a 75-cm orange disk centered in a 2.5 m x 2.5 m black background.

Flight Pattern. Photographs at 1:24,000 scale were taken at 3600-m altitude, and flight paths were planned to produce 67 percent forward and side overlap so that each terrain point was recorded on about nine photographs.

Mensuration. The 75-cm disk on the ground is recorded as an image approximately 30 μm in diameter on the film. A precise comparator (Mann Automatic Stellar Comparator, or MASC) with a least count of 1 μm was used to make five observations on each targeted point and the six nearest reseau intersections. Data are automatically recorded on magnetic tape.

Data Reduction. Observed image coordinates are corrected for film and lens distortion, and atmospheric refraction is included in the mathematical model. An efficient least-squares program required 12 min of central processor time per iteration to solve for 3780 unknowns from the total of 438 photographs and 13 min to compute the covariance propagation. The 5-cm precision of ground points represents a 2- μm precision in the image measurements.

NOS officials believe that the accuracy of results can be increased to about 3 cm and that the efficiency can be improved about 20 percent by refinements in the procedures. Also new cameras will produce higher-quality photographs with better geometry. The LMK of Zeiss Jena has a 152-mm focal length and built-in image motion compensation that will produce better resolution, thus allowing high flight altitudes and fewer photographs for a given area. The new Metritek camera from Itek will have 212-mm focal length, resolution better than 100 l p/mm ($\text{l} = \text{focal length}$), 23 cm x 30 cm format, image motion compensation, and focal-plane reseau. Use of these new cameras in the NOS system makes it reasonable to expect higher-quality results in the future.

2.2.2 Airborne Profiling of Terrain System

In 1974 the U.S. Geological Survey (USGS) entered into an engineering analysis contract with Charles Stark Draper Laboratory to study the concept of executing accurate surveys of the terrain from low-flying aircraft using a laser profiler and inertial guidance technology. This analysis and later studies concluded that the desired accuracy, 15 cm vertically and 60 cm horizontally, could be achieved for extended missions if positional updates are provided at 3-min time intervals. A

laser tracking instrument for ranging and measuring directions to ground reflectors was proposed to provide the update data (Starr and Chapman, 1983).

A schematic of the basic airborne-instrument group--inertial measuring unit (IMU) and laser tracker--is shown in Figure 2.3. An airborne computer accepts data from these sensors and performs the necessary computations for alinement of the IMU, navigation, and position and velocity updating. In addition, the computer outputs data to the onboard magnetic tape recorder and control/display unit. Adjacent to the IMU tracker is the laser profiler, which records the nadir distance from aircraft to terrain. There is also a nadir-oriented television camera that records the terrain overflown. Finally there is a control and display subsystem for the operation to sequence the system through its various operating modes and to monitor critical system parameters.

The Airborne Profiling of Terrain System (APTS) is capable of performing several different types of survey missions. The profiling mode is the application for which the system was designed. Another mode, the surveying mode, is used for establishing retroreflector positions using only the tracker and IMU. This mode shows promise in such applications as monitoring ground-surface subsidence. The system's highest accuracy can be achieved in measuring changes, since many systematic errors will cancel when subtracting the results from two surveys to obtain the amount of subsidence. Another mode uses the APTS to provide position and orientation information for a remote sensor, which would replace the laser profiler in the aircraft. For this mode, the mission would be similar to the profiling mission already described. The chief problem with this type of application is the flying height limitation of about 1500 m above the terrain. The low-power laser tracker pulse, suitable for eye-safety requirements, cannot range from a higher altitude.

A major problem with the system is the error caused by irregularities in the Earth's gravitational field, since the accelerometers cannot separate vertical acceleration from gravity changes. The accuracy is therefore limited to the uncertainties in short-wavelength variations of the gravity field. On the other hand, if the area to be surveyed has a sufficient number of surveyed retroreflectors, the APTS system can be used to derive the high-frequency variations in the gravity field.

Perhaps of greater significance than the terrain profiling applications is the inertial technology associated with this system and the potential it offers as a precise three-coordinate reference platform to provide the position and orientation data for other remote sensors that are commonly used today. The aircraft could be fitted with an aerial camera, side-looking radar, magnetometer, or infrared scanner, and the IMU-tracker system will provide precise X, Y, and Z coordinates for a reference point on the sensor. Reference data of this precision have great potential for increasing the utility of a number of sensors and would reduce the dependence on ground control and perhaps the data-reduction requirements associated with nearly all of the sensors.

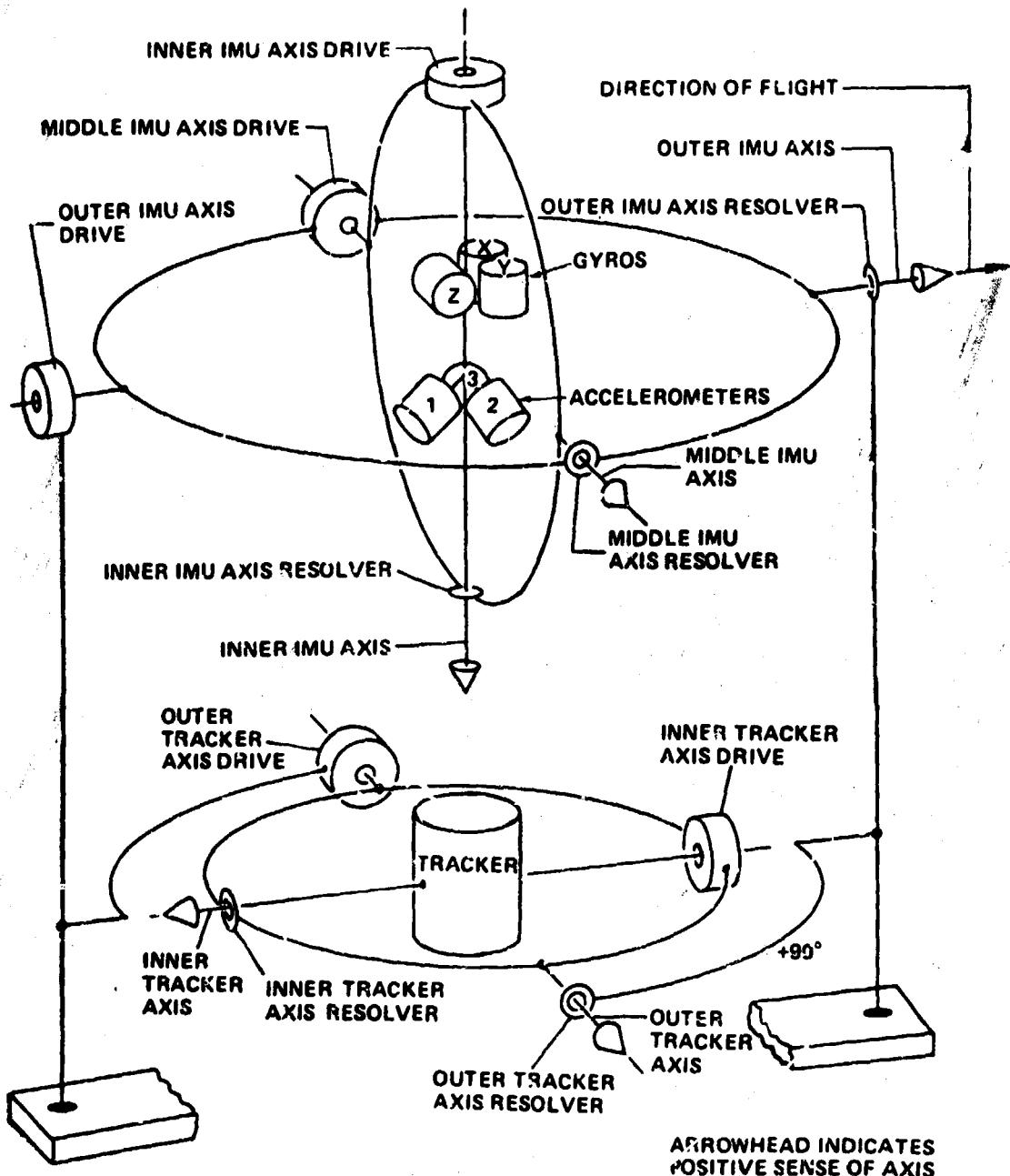


FIGURE 2.3 APTS mechanical schematic.

2.2.3 The Measurement of Gravity from Aircraft

Vertical ship accelerations are predominantly of less than 1-min period, and therefore gravity can be separated from the total sensed vertical acceleration by low-pass filtering. Averaging times of about 10 min are used, resulting in gravity values averaged over 1-2 miles,

which are adequate for most purposes. The difficulties in measuring from an aircraft stem from its high ground speed and the presence of long-period vertical accelerations. These latter make it necessary to observe the aircraft's altitude continuously, differentiate twice, low-pass filter, and subtract this averaged acceleration from the similarly averaged total sensed vertical acceleration in order to obtain gravity. The accuracy with which this can be done increases with the accuracy of the aircraft's altimeter and with the averaging time of the low-pass filter. However, the high ground speed requires that this averaging time be kept short if good spatial resolution is required, leading to a trade-off between accuracy and resolution.

The most sensitive altimeters in use are differential barometric altimeters with a short-term repeatability of about 7.5 cm. They are checked frequently against laser or radar altimeters over water or flat ground to give absolute heights. Other error sources include the Bötvös correction (Boaford, 1980, *Geodesy*, see Section 2.5.1) due to the aircraft's speed over the ground and systematic height errors due to miscalibration of the radar altimeter. Horizontal positioning accurate to 3 m, which is within the capability of special-purpose systems, is adequate to keep errors in the Bötvös correction below 1 mgal for 1-min averages.

There are currently two airborne gravity measurement systems in existence, a helicopter system and a fixed-wing aircraft system.

The Geoscience Division of Carson Helicopters, using a helicopter to reduce ground speed, obtains values averaged over about 2 miles at the flight speed of 60 knots with a relative accuracy of 2 mgal. The Naval Research Laboratory uses a fixed-wing aircraft system. There are advantages and disadvantages to each system. Greater accuracy and resolution are possible with the helicopter system owing to the relatively low flight speeds and good flight dynamics of rotor craft. Fixed-wing aircraft on the other hand provide greater range and payload at a lower cost per track mile than helicopters.

The prototype Navy system (Brozena, 1984) utilizes GPS navigation for determination of the Bötvös correction. Three-dimensional positioning is possible with accuracies greater than 15 m. The gravimeter is a LaCoste and Romberg air-sea meter. Vertical acceleration and altitude corrections to the gravimeter measurements are computed from a combination of sensitive radar and pressure altimetry. The radar provides absolute altitudes over water and some land surfaces accurate to a few centimeters. The pressure data are corrected to these values whenever possible. Undetected isobaric slopes result in errors in the gravity profiles. These errors are reduced by requiring that gravity surveys be performed as a bidirectional grid. The grid intersection crossover errors are minimized by a least-squares procedure that applies a linear correction to each profile.

A blind test of the fixed-wing system was performed over eastern North Carolina in 1984. A 60 mile by 45 mile square was surveyed with a nominal grid spacing of 5 nautical miles. The area was flown in less than 20 actual flight hours at a speed and altitude of 200 knots and 2000 feet, respectively. The rms error of the airborne survey was less than 3 mgal when compared with ground truth data (Brozena and Ziegler,

in preparation). The rms error of the helicopter system for this same area was 1.8 mgal. A major portion of the error in the fixed-wing system is probably due to the averaging along the track caused by the low-pass filtering of the data. The greater speed of the aircraft produces averages over larger areas than the helicopter thus reducing resolution.

The system in its present form appears capable of producing good-quality data over large areas in short periods of time. It is particularly advantageous for use over ocean areas where the transits to survey areas tend to be long. Over water the radar altimeter can be used exclusively, improving the accuracy of the system. The future incorporation of interferometric-mode GPS when available also promises further reduction in error and should eliminate the need for pressure altimetry over land. It would be highly advantageous to include a total field gravity measurement capability in the upcoming airborne gravity gradient measurement system. The errors characteristics of the two systems are complementary as the gradient device has excellent high-frequency response whereas the total field measurement has less low-frequency drift. The combination of two nearly independent measurements should reduce the total system error.

Prospects for improvement depend on improved aircraft positioning, especially in the vertical component. It seems likely that the necessary accuracies, 3 cm in short-term relative height variations plus 3 m in absolute vertical and horizontal position, will be attainable with the GPS.

2.2.4 Airborne Three-Dimensional Laser Ranging

A proposed method for measuring the three-dimensional positions of many points in seismic zones in a short time involves laser range measurements from an aircraft to retroreflectors on the ground (Degnan, 1981). Ranges to approximately six retroreflectors would be measured simultaneously on each shot, with measurements made about 10 times per second as the aircraft flew in a prescribed pattern over the area of interest. Such measurements would be carried out at two different altitudes on order to improve the solution. The expected cost of such surveys appears to be low enough so that results could be obtained many times per year in order to monitor possible accelerated strain changes before large earthquakes.

A study of the accuracy achievable by airborne laser ranging has been carried out by Kahn et al. (1983). The measurement accuracy of each shot was assumed to be 1 cm, and a constant bias for each of the six observation channels during the roughly 30-min total observing time was solved for. The number of observations used was about 7500 per target. The atmospheric correction error model included uncorrelated errors in the surface pressure at each site, with meteorological data available at, at least, one site. The results were encouraging, although more complete studies of the atmospheric and instrumental errors are still needed in order to make certain that the accuracy of the error model is consistent with the large number of observations assumed per target.

Apparently, the airborne laser-ranging system has not yet been developed because the cost per site is also expected to be low for the GPS. The main issue thus may be which system would give the higher accuracy in routine operations, assuming that water-vapor radiometers are used with the GPS receivers. An attractive feature of the airborne laser-ranging system is that it may be capable of further improvement by using multiple-wavelength distance measurements to reduce the atmospheric errors.

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2.3 SATELLITE SYSTEMS

With the launching of the first artificial satellites in 1957, the field of geodesy was presented with a unique method for performing conventional geodetic and geophysical measurements that had unparalleled accuracy and geographical coverage. The ability of satellite geodesy to look at the Earth from a global point of view and to collect data sets that measure global parameters has been established as a conventional approach for modern geodesy. The current satellite geodesy approaches grew out of the requirement for accurate orbit predictions, which necessitated more accurate geodetic coordinates for tracking stations, a common terrestrial reference system, and a more accurate description of the Earth's gravity field. Errors in each of these quantities cause signatures in the observations of the satellite motion that can be used to improve knowledge of these quantities. The long baselines between tracking stations located on different continents allowed the first accurate determinations of the various continental geodetic reference systems with respect to each other.

The measurements obtained using ground-based systems to observe satellites include optical systems that observe angles and directions, radiometric systems that measure both range (or altitude) and range rate, and laser systems that measure range. More recent interferometric measurements, patterned after the techniques developed for very-long-baseline interferometry, are being applied to determine the satellite's position with high accuracy. The evolution of these measurement techniques and the satellites to which they are applied holds strong promise for the field of geodesy in the decade beginning in 2000. The data collected by these measurements can be analyzed by either a geometric procedure, in which the relative position of stations that observe the satellite during a common period can be determined, or by a dynamical procedure, in which the observations collected over an extended time period by a set of globally distributed tracking stations are analyzed to determine both position information and information related to the dynamic model that influences the satellite's motion.

In addition to data accuracy, the development of appropriate software systems for orbit determination and geodynamic parameter recovery is a fundamental requirement for the application of satellite tracking to contemporary problems in geodesy and geodynamics.

To achieve the requisite geodynamic parameter recovery accuracy, the software systems must be intercompared to establish the consistency of the geophysical information extracted from a given data set. This effort requires the validation of the reference systems, integration procedures, and force-model coding and improvements in the force models where necessary to satisfy the current orbit accuracy requirements. This task includes not only the definitions of these quantities but the standardization of the reference system and force-model constants, a task that was recently accomplished during the MERIT Campaign (Melbourne et al., 1983).

The primary force models that influence the satellite motions include the Earth's gravity field, atmospheric drag, direct and

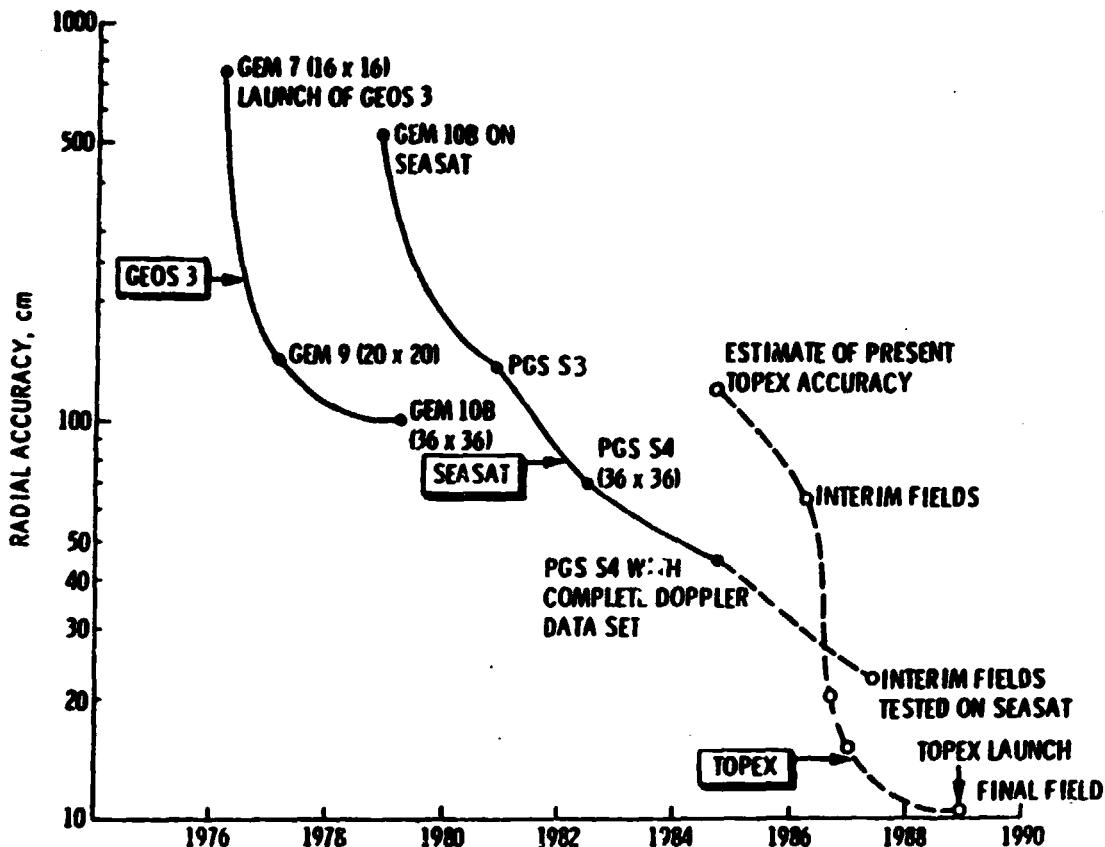


FIGURE 2.4 Accuracy of radial orbit determination capabilities for altimeter satellite missions.

reflected solar radiation pressure, and the effect of Earth and ocean tides. The most significant model discrepancy affecting the accuracy of the current satellite orbits is uncertainty in the model for the Earth's gravity field. For example, the TOPEX mission imposes a 13-cm radial-orbit accuracy requirement that will be a significant driver for future orbit computation improvement (TOPEX Science Working Group, 1981). The satisfaction of this requirement, using Earth-based tracking systems, is limited primarily by the model for the Earth's gravity field. This error source has been the primary limitation in the orbit accuracy for each of the satellite altimeter missions.

Figure 2.4 indicates the orbit accuracy evolution for the GEOS-3 and SEASAT missions. Note that the improvements in orbit accuracy have occurred primarily as a function of improvements in the gravity models. The figure also illustrates the accuracy anticipated for TOPEX as a result of planned gravity-model improvement efforts.

The further activity required to achieve the orbit accuracy for TOPEX will provide a positive stimulus for the evolution of the software systems used for geodetic data analysis. The goal of "10-cm" orbit computations may be realized by 1992 for TOPEX and may be close to realization for LAGECS.

In addition to the software systems, the accurate tracking data with wide geographical distribution will be required to achieve future goals set for satellite geodesy.

The following paragraphs summarize the current satellite tracking systems by grouping them according to the basic measurement technique: GPS, Doppler satellite systems, satellite laser ranging, satellite-to-satellite tracking, and satellite altimetry.

2.3.1 Global Positioning System

One of the more significant recent developments for satellite geodesy is the deployment of the GPS. The GPS is a satellite-based navigation system under development by the U.S. Department of Defense. The system is designed to operate as a worldwide, all-weather navigation and timing system (Milliken and Zoiler, 1979). The operational GPS, when fully deployed, will allow users with proper navigation equipment to determine, nearly instantaneously, their position at the 10 m and velocity at the 0.1 m/sec levels. Under current plans, the GPS will be complete in late 1988 or early 1989. The completed configuration will contain at least 18 satellites with 3 satellites in each of 6 different orbit planes. The satellites will be maintained in near-circular 55° inclination orbits at an orbital altitude of 20,200 km. The orbit period associated with each satellite will be 12 h, and the configuration is designed so that a minimum of 4 and as many as 7 satellites will be visible from each point on the Earth at all times. The conventional GPS measurement is a one-way range determined by the difference between the satellite-measured epoch of a transmitted signal and the user-measured epoch of the received signal. This time interval, along with knowledge of the GPS satellite position, which is included in the transmitted data stream, can be used to measure the distance of the user from the GPS satellite. Four such measurements can be used to estimate the user's position and his clock error. The accuracy of this technique, which is at the 10-m level, is limited primarily by errors in the GPS satellite ephemeris and user clock errors.

For precise geodetic and geophysical applications, the GPS signal can be analyzed to provide geodetic measurements in several ways. One method makes use of measurements of the phases of the "reconstructed carrier" signals, with knowledge of the original modulation code being used to generate these signals (Anderle, 1979a). A second method uses knowledge of the GPS signal structure, but not the code, to provide information equivalent to the phase of the carrier signals (MacDoran, 1979). A third method is analogous to the one used with astronomical radio interferometry and treats the GPS signals as "noise" sources (Counselman et al., 1983). Knowledge of the GPS signal structure or the code is not needed with this method.

Geodetic receivers, which provide these measurements from the GPS configuration, can be used to obtain accurate relative positions of points on the surface of the Earth for use in regional and continental surveys (Boseler et al., 1980). In alternate applications, the GPS

signals can be received by lower satellites in a satellite-to-satellite tracking mode. These measurements can be combined with comparable ground-based measurements to provide an extremely powerful data type for global satellite geodesy.

Ground-Based Surveys

For ground-based surveys, the GPS positioning systems have the following advantages: all-weather operation capability, portability, and a quick determination of position. Field-rated units can be left unattended on site and retrieved at a later time. Current geodetic positioning systems are designed to deliver a phase measurement with an internal precision at the 1-3 mm level. The overall accuracy of the measurements, including the influence of the atmospheric medium, is anticipated to be at the 1-3 cm level (Counselman et al., 1983; Remondi, 1984). Since the GPS signal is transmitted at two frequencies, dual-frequency receivers can be used to eliminate essentially all of the ionospheric error contribution. The third- and higher-order ionospheric effects must still be considered but are not anticipated to be a primary limitation at the 1-cm level (Clynch and Renfro, 1982). The atmospheric refraction effects are limited primarily by uncertainties in the atmospheric water vapor. For long baselines, these errors may be a factor in limiting the ultimate accuracy. Finally, the GPS ephemeris errors and errors in both the GPS and user oscillators are error sources that contribute to the overall error budget.

At present, the general GPS orbit-determination accuracy limits the level of geodetic determination to a few parts in 10^7 . However, future efforts to improve the GPS ephemeris by special high-precision geodetic ephemeris determination activities may reduce this error to approximately one part in 10^8 . Finally, completing the development program for the water-vapor radiometer should provide an important instrument capability that will lead to improved accuracy and utility of the GPS measurements. If an accurate and portable water-vapor radiometer can be developed for field operations, the routine operation of the GPS systems at the 1-cm level should be possible for baseline lengths up to a limit that is dependent only on the GPS ephemeris errors.

Another application of GPS positioning is the use of free-floating buoys as observation platforms for many oceanographic instruments such as hydrophones for seismic and acoustic signals, thermometers for temperature, and the buoy position itself for currents. Self-positioning buoys with GPS receivers and radio transmitters are now technically feasible. With further instrument development and volume production, expendable self-positioning equipment would be possible and would be an advance in oceanographic capability and efficiency.

The GPS-type field units operating in consort with the precise definition of global networks using positions from the very-long-baseline interferometry (VLBI) systems, such as the POLARIS Network (Carter and Strange, 1979), the very-long-baseline array (VLBA) and other international VLBI sites, and the global tracking stations

determined from the satellite laser-ranging systems hold high potential for getting rapid, accurate, and dense surveys of unparalleled accuracy.

Satellite-to-Satellite Tracking

The GPS system can be used in the satellite ephemeris determination mode by placing a space-rated unit similar to the ground-based receivers discussed in the previous section onboard a satellite. This will provide an extremely dense and accurate set of measurements of the satellite's motion.

Currently, such a system is being designed as an experiment to be flown on TOPEX (Melbourne, 1984). By double differencing range measurements between all GPS satellites visible to TOPEX and a given ground station, the GPS and TOPEX clock errors can be eliminated. This doubly differenced data measurement is accurate at the 1-2 cm level and, with as many as 13 GPS satellites being simultaneously visible to the geodetic satellite (e.g., TOPEX), will provide an extremely dense data set. This dense data distribution allows a simultaneous solution for the TOPEX satellite ephemeris at the 10-cm level, and the 18 GPS satellite ephemerides at the 1-m level. Such a solution will reduce significantly the ephemeris error effects in GPS ground-based surveys. In addition, the data from such an application have high potential for geophysical parameter estimation. In particular, significant improvement in the low degree and order terms of the Earth's gravity field can be determined from such a data set.

As an example, for a TOPEX-type mission at 1300-km altitude, an extremely accurate field to degree and order 30 can be determined. For an alternate gravity-type mission with a single satellite flown at 180 km in a polar orbit with a drag-free satellite configuration, it has been estimated that an accurate gravity field out to degree and order 120 could be determined.

The development of the satellite-borne GPS receiver for use in the doubly differenced range mode with a low-Earth satellite is an extremely important technique for future geodetic applications.

2.3.2 Doppler Satellite Systems

Doppler satellite systems have been used to establish global geodetic systems; to diversify, strengthen, and extend local geodetic networks; to compute reference orbits for the GEOS-3 and SEASAT altimetry satellites; and to compute the Earth's pole position. Currently it is planned as the primary tracking system for the proposed TOPEX/POSEIDON satellite altimeter mission (Anderle, 1979b; Anderle, 1983). The principal error sources in the results arise from

1. Random error for the given signal strength.
2. Satellite and ground-station oscillator frequency variations.
3. Neglected higher-order ionospheric effects.
4. Uncertainties in the gravity field.
5. Variations in atmospheric drag.

The significance of these factors varies according to conditions and applications. For example, atmospheric drag is not a problem for the new Navy Navigation Satellite NOVA, which senses and compensates for nonconservative forces in the direction of motion of the satellite. Drag and gravity-field errors can be negligible for the determination of the relative positions of sites observing the satellite simultaneously; their effects on computed satellite orbits or station positions can also be reduced by computing orbits for shorter time spans or, as in the case of the TOPEX satellite for which Doppler will be the baseline tracking system, by using a higher-altitude orbit and improved gravity field. The ionospheric errors vary with the 13-year solar cycle, the geomagnetic latitudes of the station, and the orientation of the orbit plane with respect to the Sun. (They will also be similar for neighboring sites.) Studies show that compensation for the neglected ionospheric effects can be made to 50 percent or better accuracy (Clynnch and Renfro, 1982; Tscherning and Goad, 1985).

With regard to oscillator stability, the shaded area of Figure 2.5 shows, as a function of averaging time, the oscillator stability that is required to maintain 1-10 cm accuracy in the range difference measurement from the beginning to the end of a satellite pass. The dotted curves show that typical quartz oscillators, utilized at mobile stations before 1983, were significantly above the requirement (Gouldman, 1982). On the other hand, the specification for rubidium oscillators, shown by the solid line, satisfy the requirement. Measured performance of rubidium oscillators, bracketed by the dashed lines, does not always meet the requirement as delivered, but they can be tuned to meet the tolerance.

The random error in phase measurement is a function of the signal-to-noise ratio in the receiver. Stations with high-gain antennas have demonstrated a tracking performance in which random errors in range-difference measurement of about 3 cm, whereas all other receivers, which have omnidirectional antennas, had random errors of 10 cm or significantly worse than 10 cm. In 1983, the omnidirectional antennas were replaced by antennas that, although still small and omnidirectional, had polarizations that match those of the NOVA satellite antennas. An improvement in precision of 50 percent or better over the data received previously was obtained by this modification.

The improvements in measurement precision and oscillator stability realized recently also give a potential system improvement that is not obvious. Computations performed to date have generally assumed that the Doppler count is discontinuous at the measurement interval when in fact it is actually continuous. This approach has been taken for two reasons: when the random error is high, one cannot be sure that phase lock has been maintained, and large oscillator errors correspond to systematic errors that are larger than the precision implied when data are treated as continuous count data. Using this approach, the standard error in the measurement of the range to the satellite is 3 to 5 times more precise for continuously counted Doppler data than for range-difference data. This increase in precision also allows a better determination of a systematic bias in the assumed troposphere. The

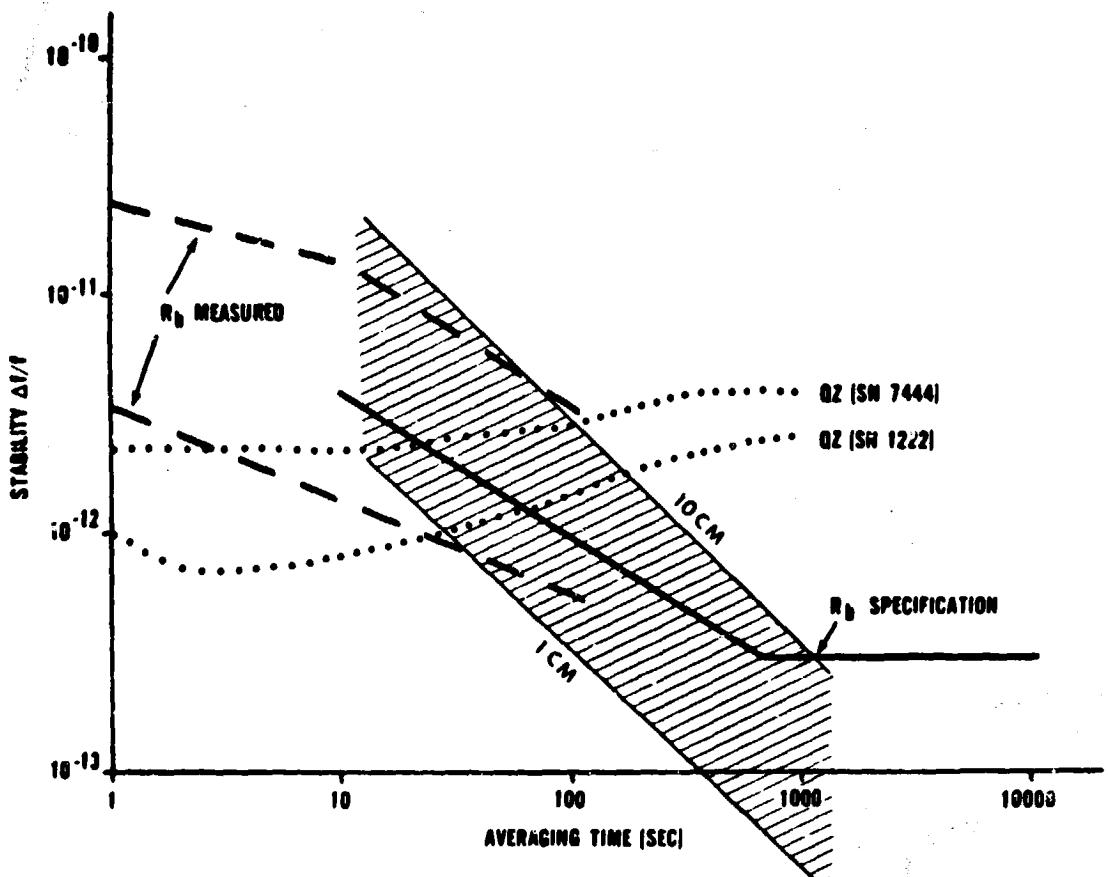


FIGURE 2.5 Oscillator stability.

benefits in improved measurement precision of the Doppler system have not yet been exploited, although they are a requirement for the proposed TOPEX program.

The Doppler satellite positioning techniques have been one of the single most important positioning methods during the past decades. The results obtained with this approach include not only the conventional geometric multi-lateration surveys but the calculation of polar motion, tectonic plate motion, and the Earth's gravity field. For a discussion of the results obtained with this method, see Section 1.

2.3.3 Satellite Altimetric Contribution to Geodesy

During its brief 10-year history, satellite altimetry has become the primary source of information on the marine geoid, from which important information can be inferred on the underlying structure of the solid earth (Wunsch and Gaposchkin, 1980; Marsh, 1983). In addition, the altimeter has demonstrated the potential to provide the surface-topography observations necessary for the description of the variable

and mean (time-averaged) circulation of the global oceans (Wunsch and Gaposchkin, 1980; Douglas et al., 1984; also Section 3.2.3).

A satellite altimeter measures the satellite-to-sea-surface range by determining the round-trip travel time of a radio pulse transmitted by the altimeter and reflected from the ocean surface. Such measurements, when corrected for instrument and atmospheric medium effects and combined with the orbit height obtained by precise satellite tracking, make it possible to determine the topography or shape of the ocean surface (Tapley et al., 1982a). The shape of the ocean surface, which deviates at some points by more than 200 m from the best-fitting reference ellipsoid, closely approximates the equipotential surface referred to as the marine geoid.

The capability of satellite altimeters has improved from the 1-m precision of Skylab to 30 cm for GEOS-3 and subsequently to a 5 cm precision for SEASAT. The GEOS-3 and SEASAT missions were instrumental in demonstrating the potential of satellite altimetry for geodetic and oceanographic applications. Not only have these missions substantially improved our knowledge of the marine geoid, they have demonstrated the value of the altimeter for studying mesoscale variability and have yielded impressive evidence of potential improvement in our understanding of general ocean circulation.

Available Altimeter Data

Currently two major satellite altimeter data sets exist. These are from the GEOS-3 mission (1975-1978) and from the SEASAT mission, which was operational for 3 1/2 months in 1978. The amount of data from each of these missions is roughly equivalent to 70 days of continuous observation. Much of the data from GEOS-3, which spans a 3-year period, were taken in the North Atlantic since data could only be acquired when the satellite was in view of a tracking station. SEASAT and GEOS-3 data are available to researchers from NOAA/NESDIS.

Altimeter Data Applications

These data have been used for numerous geodetic applications including mapping the marine geoid and improving models of the Earth's gravity field. The mean-ocean-surface information obtained from altimeter data has been used to determine the deflection of the vertical, to infer bottom bathymetry, and as a constraint on models to describe compensation of the Earth's topography at depth, as well as models describing processes in the crust and mantle (see Sections 1.2 and 3.1). The data also are being used for oceanographic applications such as the study of mesoscale variability and ocean tides (see Section 3.2). In addition, the first applications of altimetric data to the study of global mean circulation are now being made.

2.3.4 Satellite Laser Ranging

Soon after the development of the laser, the technique of satellite laser-ranging (SLR) was initiated (Plotkin et al., 1965). Since then, satellite laser ranging has become one of the predominant techniques for precise orbit determination, and it has been applied in a number of contemporary studies in geodesy, earth dynamics, and lunar science. The launch of the Laser Geodynamics Satellite (LAGEOS) in May 1976 initiated a major era in the application of SLR to satellite geodesy (Johnson et al., 1976). Under NASA's Crustal Dynamics Project, the laser systems have improved in accuracy by more than an order of magnitude, with current single-shot accuracies lying between 3 and 10 cm (Tapley et al., 1982b). During the last few years, the cooperative network of SLR systems has produced data from a globally distributed set of stations. These data have been applied to a wide range of problems in geodesy and geodynamics. A satellite laser-ranging station consists of a laser, transmitting telescope, and receiving telescope set up on a site marked with a permanent geodetic marker (Fitzmaurice, 1978). The laser transmits a pulse of energy toward a satellite equipped with optical cube corners on its Earth-viewing side. The incident laser pulse is reflected back to the laser receiver located at the station, and the round-trip travel time is measured. This process is controlled by the station computer, which automatically starts and stops the laser firing and pulse counter. The pulse duration depends on the laser design and may vary from a few nanoseconds to a few hundred picoseconds. The distance from laser station to satellite is calculated using the measured one-way time interval and the velocity of light.

Although simple in concept, there are several error sources that limit the accuracy of the measurement. These errors include uncertainties in the relative timing errors, atmospheric refraction errors, and uncertainties in the corner-cube location relative to the space-craft center of mass. The accuracy of the time interval measurement is dependent on the size of the systematic errors in the electronics within the time interval unit and also on the stability of the frequency standard used.

For calibration purposes, the system ranges to a ground target at a known distance prior to satellite tracking. Errors in the measurement of the calibration distance during the local survey must be considered. After this distance is established, the satellite laser system ranges to the calibration target, and the mean value of these measurements is adjusted to agree with the known distance. The possibility of physical shifts in the calibration distance with time must be considered. To improve calibration accuracy, continuous calibration measurements over an internal path are now being made during satellite ranging with some of the newer systems.

For geodetic and geophysical purposes, the primary target for satellite laser ranging has been LAGEOS (Johnson et al., 1976). LAGEOS was launched in May 1976 into a 5900-km, circular, near-polar orbit. It is a 411-kg, 60-cm-diameter aluminum sphere with a brass core, covered with 426 retroreflectors. Four retroreflectors are germanium,

for use with infrared lasers, and the remainder are fused silica for use with optical wavelength lasers.

The high altitude of the LAGEOS orbit combined with the satellite's spherical shape and large mass results in an extremely stable orbit. Laser stations have determined their position with respect to LAGEOS to a precision of a few centimeters. Using LAGEOS, stations in different parts of the Earth are able to measure their relative separations to similar precision. A series of measurements over a period of years has enabled the determination of the movement of various ground-station sites. From such measurements the tectonic motion of the plates on which they are located can be inferred. Recent solutions report accuracies in the vertical and horizontal displacements at the 5-cm level (Smith et al., 1985a; Tapley et al., 1985).

Other results of geophysical interest can be obtained from the LAGEOS data. During early analysis of the LAGEOS orbit, the observed along-track acceleration was found to be one or two orders of magnitude larger than expected, leading to a 1 mm/day decay in the semimajor axis (Smith et al., 1985a). Considerable attention has been given to this effect in an effort to explain its origin. Early calculations suggested that charged-particle drag was the principal cause. Recently, asymmetry in the Earth's albedo radiation has been proposed as a candidate for contributing to this orbital behavior. A continued monitoring of the evolution of LAGEOS will be necessary, along with further study of the upper atmospheric physics, and the models for the Earth's albedo will be required to fully explain this effect.

Geodetic satellites whose orbits have been determined by laser tracking include LAGEOS, Starlette, GEOS-3, Beacon-C, and SEASAT. In addition, the laser tracking is proposed for several future missions including LAGEOS-II, TOPEX, POSEIDON, and ERS-1. Laser data from numerous satellites including LAGEOS have been incorporated in the recent models for the Earth's gravity field (Lambeck and Coleman, 1983). GEM-L2, which is the latest "satellite-only" gravity field derived by the NASA Goddard Space Flight Center, has a long-wavelength geoid (to degree and order 4), which is assessed to be accurate to ± 8 cm (Ierch et al., 1982).

The SLR system has provided accurate measurements for orienting the Earth within a quasi-inertial reference system (Smith et al., 1985b). Global data, taken over 5-day intervals, provide a suitable means for directly solving for the Earth's polar motion and excess length of day (Tapley, 1983). SLR solutions (for data taken since May 1976) are routinely provided to Bureau Internationale de l'Heure (BIH) at 5-day intervals for use in the BIH Rapid Polar Motion Service. Annual solutions based on the full-rate data which include solutions for UT1 as well are reported in the BIH annual reports (Schutz et al., 1984; Smith et al., 1985b). When the SLR UT1 time series is compared with the VLBI UT1 time series, a long-period systematic error due to tide model effects in the LAGEOS node is determined (Carter et al., 1984). Current accuracies, which are routinely achieved for 5-day mean values, are 2 milliarc sec for X and Y coordinates of the axis of the rotation axis and 0.2 msec for change in length of day.

The analysis of the long-period changes in the node have been interpreted in terms of the secular and seasonal changes in the Earth's gravitational field coefficient J_2 . This term describes the Earth's oblateness. The secular change in this value has been related to the viscoelastic rebound of North America, Northwestern Europe, and Antarctica following the melting of large continental ice sheets subsequent to the last glacial maximum (Peltier, 1982; Peltier, 1983; Peltier and Wu, 1983; Yoder et al., 1983; Rubincam, 1984; Wu and Peltier, 1984).

Comparisons of the LAGEOS-derived length of day (LOD) with the LOD derived from the exchange of the angular momentum of the atmosphere with the Earth (Rosen and Salstein, 1983) has indicated a very high correlation between the two time series. Currently, an intense effort is under way to understand the origin of the differences between the two data sets and to further understand the mechanism whereby the momentum interchange between the atmosphere and solid earth occurs.

The other retroreflector-equipped satellites mentioned previously are in orbits that are closer to the Earth. Consequently, they experience a much richer spectrum of gravity and tidal effects than those experienced by the high-altitude LAGEOS (Smith et al., 1972). Of special interest is the French-launched Starlette satellite, which, like LAGEOS, is a dense passive ball covered by retroreflectors. It was launched exclusively as a laser target for geodetic applications. A great deal of highly accurate laser data have been acquired on Starlette and are undergoing current analysis to improve the models for the Earth's gravity field and ocean tides (Marsh et al., 1982).

Future Prospects for Satellite Laser Ranging

During the next decade, there will be a substantial improvement in both the accuracy and the distribution of the laser tracking network. New sites in Japan, China, Italy, Austria, Israel, and England will provide improved geophysical distribution of the SLR network. Densification of the permanent network will be made at sites visited on a yearly basis by transportable laser-ranging systems. More frequent reoccupations of selected sites by the transportable systems will be made for the purpose of investigating the rigidity of local networks. Improvements in the laser-system accuracies and in the model for the error sources will result in normal precision at the 5-mm level, and 1- to 3-cm orbit determination accuracy is anticipated. The development of daytime ranging capability for all systems will enhance the temporal coverage of the satellite's motion and allow more rapid and accurate recovery of Earth rotation and tectonic motions.

Efforts to fully automate the laser-ranging systems with the use of GPS time transfer will lead to reduced operation cost and increased data yields. The operational costs may be reduced by a factor of 10 owing to automation. The international commitment to continued laser ranging will be strengthened with the launch of new satellites. A new LAGEOS, LAGEOS-II, will be launched in 1987 as a combined mission between NASA and the National Space Plan of the National Research

Council of Italy. POPSAT, which may be developed as a European Space Agency (ESA) mission, would have both microwave and laser tracking. EGP, a combined photographic target and laser retroreflector satellite, will be launched by the Japanese. Finally, TOPEX, a joint U.S.-French oceanographic mission to map the general ocean circulation, will carry a satellite altimeter, the improved TRANET system previously described, and a laser-tracking system. This satellite is planned for a 1990 launch.

The areas where the SLR data may be used for geodetic and geophysical investigations in the 1990s are shown in Table 2.1. With three-dimensional positioning accuracy expected to be on the order of 1 cm, the permanent laser network will serve as a fiducial set of points distributed throughout the globe. This network of points will be capable of maintaining a global datum that is accurate at the 1-cm level. Continuous monitoring of the rigidity of this network will play a significant role in determining Earth rotation parameters and in modeling tectonic motions, plate deformations, and vertical station movements on a global scale. The study of intraplate deformation and stability will be enhanced through the three-dimensional determinations of SLR fiducial points.

With the global SLR datum, better than 1 milliarc sec polar motion and 0.1-msec LOD values determined each day may be anticipated. Earth orientation parameters of such accuracy can have a significant impact on a large number of scientific applications. These include the study of the polar motion frequency structure at, for example, Chandler, annual, semiannual, and diurnal periods, as well as the nature of the Chandler excitation. The relationship between polar motion, earthquakes, and mass displacements in the Earth may also be investigated, together with the yielding of the Earth with movements of the rotation axis. Finally, understanding the effects of atmospheric and oceanic movements on the orientation of the Earth and the core/mantle coupling can be studied also.

Reduction of SLR data requires the development of accurate models describing the forces acting on satellites. Orbital residuals therefore provide a highly accurate means of monitoring unknown forces acting on satellites. Long records of orbital evolutions, however, are necessary for understanding the structure of the signals and for decoupling the unknown signal from other candidate effects. Significant improvements in the capability of the data-analysis software systems will be required to achieve the full potential in this area.

Better categorization of the Earth and ocean tidal responses may have wide-ranging earth-science applications. These include the measurement of tidal dissipation, which is related to the rate of the Earth-Moon separation, and the modeling of the largely unknown zonal tides and their departure, if any, from equilibrium. In addition, computation of frequency-dependent Love numbers and load deformation coefficients could contribute to the study of the core-mantle coupling and the computation of the Earth's Ω at intermediate frequencies through observations of the 18.6-year tide. The computation of ocean-tide coefficients from orbital residuals will continue to be an important check on the quality of purely oceanographic solutions of the Laplace tidal equations.

TABLE 2.1 Future Applications of Satellite Laser Ranging**Positioning**

Mission support (altimetry, navigation)
Global datums
Tectonic motion
Plate deformation

Earth Orientation (Polar motion <0.6 msec; LOD <0.03 msec)

Polar-motion frequency structure
Polar wander
Earthquake excitation
Atmospheric excitation

Geopotential

Long-wavelength geoid and gravity field
Rheology--postglacial response
Mantle convection
Polar wander
Ice loading
Gravitational constant

Surface Forces

Albedo
Drag

Earth and Ocean Tides

Tidal dissipation
Earth-Moon separation
Zonal tides and departure from equilibrium
Improved length of day
18.6-yr tide for Ω at intermediate frequencies
Core-mantle resonances (K_1 tide)
Love numbers of load tides

2.3.5 Gravity Missions

The requirements for an accurate representation of the Earth's gravity field is one of the most important of the contemporary problems in geodesy and geophysics (see Sections 1.2, 3.1, and 3.2). The specific needs span a wide range of scientific and engineering applications (Committee on Geodesy, 1978; 1979). Before the development of artificial satellites, gravity surveys over small geographic regions were conducted by ground-based, airborne, and shipboard instruments primarily for geodetic and prospecting applications. However, for the past two decades, since the first artificial satellite was launched, global gravity-field modeling efforts have become an essential application of the data collected using artificial satellites. Significant improvement in the knowledge of the Earth's gravity field has been achieved through this approach. Since the Earth is essentially spherical in shape, the gravity field is commonly described as a series expansion in spherical harmonics (see Section 1.2.2). The primary task of the satellite geodesy gravity-field recovery is to estimate the constant coefficients in this series expansion. The second- and fourth-degree terms are related to the flattening, or oblateness, of the Earth. Through the efforts of satellite geodesy during the past two decades, reasonably accurate models of the Earth's gravity field up to degree and order 40 have been developed (Lambeck and Coleman, 1983; Lerch et al., 1982). It is estimated that when these models are used to evaluate a geoid at the Earth's surface the geoid height commission error is approximately 70 cm (see Section 1.2). Although there has been substantial improvement in knowledge of the gravity field, further progress in many geodetic and geophysical disciplines is now limited by inaccuracies in the gravity field model. Before the 1970s, most of the satellite data were optical observations of right ascension and declination gathered mostly from the Baker-Nunn camera network. The remainder of the useful information was gathered by the radio tracking of satellites with Doppler transponders supported by a limited number of primitive laser-ranging systems developed to supplement the optical and Doppler tracking networks. In addition, ground-based and satellite-to-satellite tracking using the S-band communication links were also used to provide useful range and range-rate data. These ground-based tracking systems were augmented by satellites that were specially designed for laser ranging (e.g., LAGEOS and Starlette).

In the latter half of the 1970s, the accuracy of data from ground tracking systems improved significantly, and these data were supplemented by data from the first satellite altimetry mission, GEOS-3. These data allowed the first accurate representation of the marine geoid and are used to augment surface gravity data to allow the determination of gravity models to degree and order 180. In 1978, SEASAT carried an altimeter into orbit that had a ranging precision of ± 5 cm. These two data sets allow accurate determinations of the mean ocean surface and are providing useful information in a number of geophysical and geodetic areas. The current marine geoid appears to be accurate to approximately 50 cm, but for oceanographers who wish to determine geostrophic current velocities from altimetry data, the model error must be reduced to the order of 10 cm.

To achieve this objective, plans for the Geopotential Research Mission (GRM) have been developed (Taylor et al., 1984). Under this program, two low-orbiting, drag-free satellites will be placed in polar circular orbits at an altitude of 160 km. The satellites will be maintained in this orbit configuration for a period of 6 months or more. The data gathered from this mission should allow resolution of the gravity field at the Earth's surface down to wavelengths of 100 km. This resolution coupled with its unique global coverage will provide an order-of-magnitude improvement in knowledge of the Earth's gravity field.

The mission will operate with each of the satellites in 160-km altitude orbit at distances that vary from 100 to 600 km. The gravity data will be computed from the measured change in distance between the two spacecraft. Precise measurements of the range rate will be made on each satellite. The expected accuracies of the geopotential research mission are gravity field, 1×10^{-5} m/sec² (1 mgal); geoid height, 10 cm at wavelengths of 200 km and longer.

Although the GRM is the most singularly important satellite mission for determining the Earth's gravity field, a number of other efforts are under consideration. Because of substantial improvement in the knowledge of the data characteristics, improvement in software system modeling and in other force models that influence the satellites and that in the past have limited the accuracy with which the gravity field can be recovered, there is substantial interest in reprocessing the historical satellite data in an effort to improve the lower degree and order terms in the gravity field. The current data set will be coupled with data to be collected during a number of international tracking campaigns that include MERIT, the proposed tracking campaign for TOPEX, and a special international tracking campaign to improve the gravity field. This reprocessing of the historical data could provide substantial improvement in the current knowledge of the long-wavelength features of the Earth's field and would provide valuable a priori information for the GRM, TOPEX, and other contemplated satellite missions.

In addition, new developments based on the GPS (see Section 2.3.1) provide the potential for gravity mapping missions by flying GPS receivers on board low satellites in either drag-free or non-drag-free environments. The data sets from GRM and GPS satellite receivers flown on low satellites coupled with the historical data sets from satellite geodesy missions and supplemented by the altimetry data from GEOS-3, SEASAT, and TOPEX will provide a rich data base for gravity model solutions during the latter part of the 1980s.

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2.4 SPACE SYSTEMS

2.4.1. Introduction

During the past decade and a half, the development of new space techniques for geodesy, which augment the satellite geodesy techniques described in Section 2.3, have made substantial progress (Shapiro, 1982). The term space techniques is used to differentiate from classical astronomical methods, which do not have the accuracies demonstrated by the new methods. However, as for classical astronomical methods, the observations of celestial objects are made from Earth. In this discussion, space techniques will connote the techniques of VLBI and lunar laser ranging (LLR).

The contemplated applications of these techniques in the areas of geodesy promise significant enhancements in both temporal and spatial resolutions (Bossler, 1982; Flinn, 1981; Coates, 1979). Measurements at 1-day intervals with 1-cm accuracies for geodetic baselines approaching an earth radius in length appear possible. Such measurements could provide geophysicists with measurements that would enable them to address in a global context a number of basic questions. Such measurements include the strain distributed as a function of time and position along, near, and within plate boundaries; rapid motions after episodes of decoupling earthquakes; slow and extensive deformations that occur in an earthquake epicentral area prior to the sudden failure; and crustal uplift that may occur as a precursor to earthquakes. Brought to maturity, the VLBI techniques promise a rich set of global high-accuracy geodetic measurements with unique spatial and temporal resolution, covering distance scales from a kilometer to the order of an earth radius.

2.4.2 Very-Long-Baseline Interferometry

A VLBI system consists of an array of at least two radio antennas that observe the same radio source simultaneously (Shapiro, 1982). Connection is not maintained between the antennas, thus allowing them to be separated by thousands of kilometers. The local-oscillator signals, used at each antenna to convert the radio-frequency signals from the source to the video (low-frequency) band, are derived from a frequency standard at the site. These standards (hydrogen masers) are sufficiently stable that the relative phases of the signals from the source received at any two antennas are well preserved.

The video signals are recorded on magnetic tape at each site, with the time base for the recordings being derived from the same standard used to govern the local-oscillator signals. The tape recordings are then transported to a common center where they are cross-correlated to obtain the basic VLBI observables. It is possible technologically to transmit the video signals by direct satellite link and perform the cross-correlation in real time. However, for the very wide bandwidth of geodetic VLBI systems such as the MARK III systems, which exceed 100 MHz, it may prove more economical in the near future to use the fiber-optic technology developed by the telephone companies.

The basic observables in geodetic VLBI measurements are the difference in the times of arrival at two antennas of a signal from a single source and the rate of change of this time difference. The measurement of the time-of-arrival difference can be of two types: the phase-delay difference and the group-delay difference. The time derivatives are called the phase-delay rates and the group-delay rates. The arrival time differences, or delays, and their time derivatives, delay rates, are the observables used in a least-squares analysis to estimate geodetic quantities of interest. The accuracies of the delays and delay rates, and therefore of the geodetic quantities, depend fundamentally on the capabilities of the VLBI instrumentation. The third-generation MARK III instrumentation developed by a consortium of scientists, engineers, and technicians at the Massachusetts Institute of Technology, Haystack Observatory, NASA Goddard Space Flight Center, and the National Radio Astronomical Observatory, under funding from NASA and the National Science Foundation (Rogers et al., 1983) has been adopted by a majority of the participating laboratories.

For the MARK III VLBI data-acquisition system, two receivers, at s and x bands, observe simultaneously. The receivers have relatively wide bandwidths, typically 400 MHz in x band and 100 MHz in s band. A total of 14 channels each of 2 or 4 MHz can be recorded simultaneously. The dual-band capability provides the means to measure and remove dispersive propagation medium effects, such as refraction by the ionosphere and the solar corona. The capability of recording multiple frequencies distributed over the full bandwidths of the receivers facilitates bandwidth synthesis. The MARK III system also includes phase and cable calibration units. Meteorological sensors and water-vapor radiometers (WVR) are used to determine the tropospheric refraction (Beckman, 1984). While the MARK III instrumentation is necessarily complex, the system is so highly automated and fail-proof that even inexperienced personnel are able routinely to conduct geodetic VLBI observing sessions.

Projects POLARIS and IRIS

Project POLARIS (POLar-motion Analysis by Radio Interferometric Surveying) was initiated by the NGS to exploit this new technology (Carter and Strange, 1979).

Under project POLARIS, three permanent geodetic VLBI observatories have been developed: Westford, in Massachusetts; the George R. Agassiz Station (GRAS), in Texas; and Richmond, in Florida. The Federal Republic of Germany (FRG) has constructed a dedicated geodetic VLBI observatory at their Satellite Observation Station in Wettzell, Bavaria, and the responsible geodetic agencies in the FRG and NGS jointly initiated project IRIS (International Radio Interferometric Surveying) in 1982 (Carter and Robertson, 1985) to exploit the combined observational capabilities. In addition, the Onsala Space Observatory, Sweden, participates in one IRIS observing session per month, and in the future, the Kashima Observatory, Japan, and the Shanghai Observatory, China, will also be participating in IRIS.

Other stations that are not dedicated to geodetic observations but that have provided observing time for measurements include Effelsberg Observatory in Bonn, FRG; Chilbolton in England; Haystack Observatory, Massachusetts; Maryland Point, Maryland; the National Radio Astronomy Observatory (NRAO) in West Virginia; and the Mojave and Owens Valley (OVRO) observatories in California.

Scheduling, Reduction, and Analysis Procedures

The usual VLBI observation included in the IRIS program lasts from 100 to 400 sec, depending on the strength of the source being observed. Fourteen 2-MHz channels are recorded simultaneously. Once the data tapes are processed through the correlator they are returned to the observatories for reuse, and the delay and delay rate observational data are sent to NGS on magnetic tape for final processing.

In current VLBI geodynamic applications, the atmospheric refraction effects are usually computed from surface meteorological measurements only. Poor reliability of the water vapor radiometer (WVR) has limited their application thus far, but as improved units become available, they are expected to be used routinely (Beckman, 1984). There is evidence that the accuracy of the longer-baseline measurements are actually currently limited by the dry atmospheric refraction effects (Davis et al., 1994). The differences between the observed s- and x-band delays are used to compute the ionospheric refraction effects on the x-band delays and delay rates. Finally after editing the outliers and removing group-delay ambiguities, the x-band delays and delay rates are combined in a least-squares adjustment in which various parameters are estimated. In the estimation process, values for clock-bias oscillator drift (and often drift rate), additive correction terms for the atmospheric models at each observatory, polar motion, and UT1 are estimated. Occasionally, the radio-source coordinates are estimated. Also for special applications such parameters as global or station-dependent Love numbers, nutation parameters, and the relativity parameter λ can be estimated.

Polar Motion, UT1 Results

The polar motion and UT1 time series produced under projects POLARIS and IRIS now span roughly 4 years, beginning in September 1980. Until June 1981, the observations were spaced at approximately 2-week intervals, and most of the sessions were conducted with the solitary Haystack-GRAS interferometer--although the Onsala Space Observatory did join in a number of sessions. In June 1981 when the Westford Observatory became operational the density of the sessions was increased to weekly, and in September 1983, coinciding with the start of the project MERIT main campaign (Wilkins, 1980), the density was increased to every 5 days.

The single-interferometer (Haystack-GRAS or Westford-GRAS) observations produced estimates only of the x component of polar motion and

UT1. In reducing such observations, the Bureau International de l'Heure (BIH) Circular D values for the y component of polar motion have been used. When at least three stations participate, both components of polar motion and UT1 can be estimated from the VLBI observations.

Comparisons of the POLARIS-IRIS UT1 time series with lunar laser-ranging and satellite-laser ranging results have confirmed that for UT1 there is considerable power at periods as short as a few days (Robertson et al., 1983; Carter et al., 1984). The need to monitor UT1 at intervals of 1 to 2 days or less is a topic of current concern. To define this need further, the IRIS participants organized a series of special observing sessions during April-June 1984. During this time special daily sessions of approximately 1-h duration were conducted with the Westford-Wettzell interferometer (Carter and Robertson, 1985). Each of the daily sessions produced an estimate of UT1 with a typical formal standard error of ± 0.1 msec. The daily values track smoothly between the 5-day values but do depart by 0.3 to 0.4 msec from values obtained by interpolation of the 5-day series during some periods (Carter et al., 1985);

Baseline Length Measurements

With the limited number of observatories currently operational, changes in the orientations of baseline vectors caused by tectonic processes cannot be separated from changes in the orientation of the Earth. However, the lengths of the baselines should be independent of the orientation of the Earth, and to the extent that crustal motions cause changes in the baseline lengths with time, these motions should be observable. The results of intensive measurements of baselines indicates that measurement repeatability is at the level of 1 part in 10^8 in measuring the lengths of baselines several thousand kilometers in length.

Figure 2.6 shows the repeated measurements of the Westford-GRAS baseline (Carter et al., 1985).

The slope and formal uncertainties (1-sigma) of the weighted least-squares best fitting line is -0.8 ± 0.1 cm per year. Over the 3.5-year time span of the measurements, the accumulated apparent changes in the lengths of the baseline is still only a few centimeters, and systematic errors in the VLBI measurements at that level cannot be ruled out. However, the indicated shortening of the Westford-GRAS baseline could be caused by compressional deformation of the North American plate (Zoback and Zoback, 1980; Gough et al., 1983).

Mobile VLBI Activities

The majority of VLBI observations have employed permanent observatories originally built for radio astronomy and therefore located without any particular regard for measurements of crustal movements. While the exact locations of the observatories are ordinarily not critical for

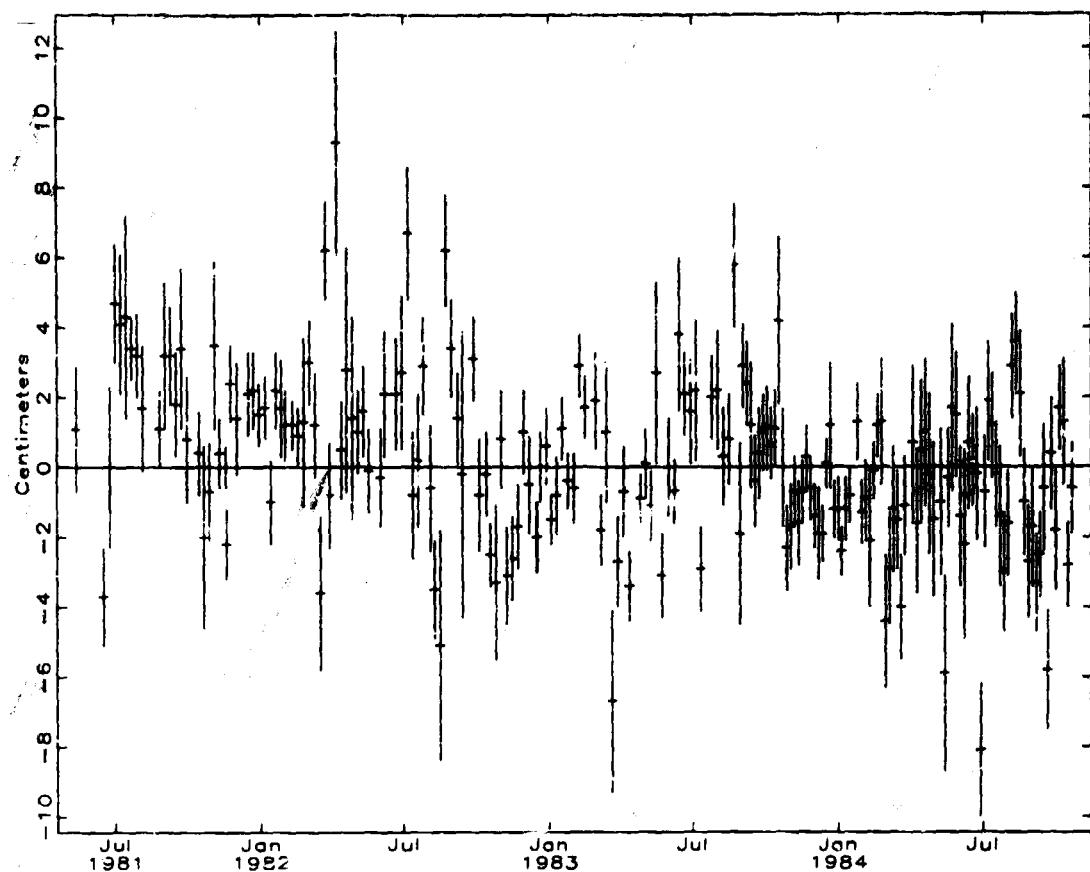


FIGURE 2.6 Westford-GRAS baseline.

determining the large-scale average motions between continents, it becomes essential for measurements of regional or local movement. Self-contained mobile VLBI radio observatories that can be moved to a specific site and conduct VLBI observations have been developed. Working in combination with larger fixed antennas, these smaller-aperture ($<10\text{-m-diameter}$) units allow VLBI measurements to be made at a relatively large number of remote sites situated in the most geophysically interesting locations.

Three mobile VLBI units are currently operational. The units were built at the Jet Propulsion Laboratory, Pasadena, California (Renzetti et al., 1982; Trask et al., 1982), to support the NASA Crustal Dynamics Project (CDP) (Coates 1979; Flinn 1981). Each of these units is equipped with the same MARK III VLBI data-acquisition system found at fixed VLBI observatories.

Mobile VLBI Operations

Two principal features distinguish mobile VLBI from fixed-station VLBI operations: the fact that the antennas are movable and the smaller diameter of mobile VLBI antennas.

For a mobile VLBI system, the location of the antenna reference point is different each time the system (or different system) returns to a site to reobserve a given baseline. Therefore, the vector connecting the mobile VLBI reference point to a fixed monument on the ground at each mobile site must be included as part of each position measurement so that subsequent measurements can be compared.

The smaller-diameter antennas required to allow highly mobile VLBI operations yield a less-sensitive interferometer than is normally achieved between larger fixed antennas. This decrease in sensitivity can, in principle, be compensated by increasing the amount of data recorded for each source. However, in practice the integration time cannot be increased beyond the amount of data that can be put on a single recording tape (typically about 1000 sec). The observations are limited to the stronger sources, and it is a greater challenge to develop adequate observing schedules for mobile VLBI. It should be noted that the sensitivity of the interferometer between pairs of mobile systems is so low that only the strongest one or two sources are able to produce fringes. Therefore insufficient data exist to obtain directly a reliable estimate of the baselines between the mobile units, and these vectors must be obtained indirectly by differencing the vectors between individual mobile units and a common fixed observatory.

Mobile VLBI Observing Campaigns

The mobile VLBI units were developed primarily to study the crustal deformations associated with the interactions between the North American and Pacific tectonic plates. Currently a network of 17 sites in California is routinely revisited by mobile VLBI systems using fixed observatories located at Haystack, Massachusetts, and Owens Valley and Goldstone, California. An additional five sites have been established and occupied in other western states to monitor regional plate deformation, and seven new sites were occupied for the first time in Alaska and Canada during the summer of 1984 as a further part of these regional deformation studies.

In addition to observations conducted on behalf of the CDP, NGS plans have been formulated to occupy approximately 15 new mobile VLBI sites as part of the NGS National Crustal Motion Network (Strange, 1982). These new sites were selected to provide nearly uniform distribution across the United States. They will then be used in conjunction with GPS receivers to provide a denser network that is tied directly to the VLBI reference frame.

Future Prospects for VLBI

The POLARIS and IRIS geodetic VLBI observing sessions are now quite routine, and, except for occasional instrumental failures and severe weather conditions at individual observatories, the entire cycle of scheduling, observing, correlating, solving, analyzing, and publishing the results runs smoothly. The most basic IRIS network, i.e., the

combination of the POLARIS and Wettzell observatories, has already demonstrated an ability to produce polar motion and UT1 time series accurate to $\pm 1\text{-}2$ msec of arc and ± 0.05 msec of time, respectively, in observing periods of 1 day. No other technique currently known can match VLBI in accuracy, reliability, long-term stability, and cost-effectiveness for monitoring variations in Earth orientation. As new stations join the IRIS network, the accuracy and reliability will improve even further.

The IRIS network will also play a major role in the long-term monitoring of the motions among the tectonic plates, as well as large-scale deformations within certain plates. With the improvement of WVR technology and the development of better models for the dry atmospheric refraction, subcentimeter geodetic measurements appear feasible. By the 1990 time frame a global network of 10 to 15 permanent dedicated geodetic VLBI observatories should exist that will permit the monitoring of the motions among the major plates with resolutions of a few millimeters per year.

The mobile geodetic VLBI units are beginning to yield acceptable data on a regular basis. The operating procedures are gradually being better defined, and the reliability is improving. First epoch measurements of comparable quality with the fixed observatory measurements have been made at some 20 sites in the California-Utah-Arizona area to study crustal motions in the active plate margin zone. These stations will be revisited in years ahead to develop a time history of the deformations associated with interactions of the North American and Pacific tectonic plates. The mobile VLBI units also have already begun, and are expected to continue, to play a major part in the validation of the less-costly, more-portable GPS-based surveying system.

2.4.3 Lunar Laser Ranging

Introduction

In its 13-year history, LLR has demonstrated its value as a valuable multidisciplinary tool contributing to many of the scientific objectives of the geodynamics program (Dickey and Williams, 1982). The ability to model accurately the lunar orbit over the full span of the observations allows relatively long-term studies of variations in the Earth's rotation as well as highly accurate determination of many parameters of the Earth-Moon system. LLR has produced new information about the exchange of angular momentum between the solid earth and its atmosphere (Feissel and Gambis, 1980; Langley et al., 1981b), provided a more accurate value (2 parts in 10^8) of the principal geopotential term (GM) (Dickey and Williams, 1982) and tidal dissipation in the lunar orbit (Calame and Mulholland, 1978; Dickey and Williams, 1982), and contributed substantially to improved determinations of Universal Time (UT1) and polar motion (Langley et al., 1981a; Dickey and Williams, 1982; Shelus et al., 1982). Lunar-laser-ranging data allows the unification of coordinate systems by providing an accurate tie between

the planetary and lunar ephemerides and the Earth's orientation, permitting the dynamical equinox to be used as the fundamental zero point of the right ascension system (Williams and Melbourne, 1982). In planetary science, LLR measurement of apparent dissipation of lunar rotation (Ferrari et al., 1980; Cappallo et al., 1981) and free librational motion in the lunar rotation (Cappallo et al., 1982) have provided constraints for models of the lunar interior and simulated theoretical studies about the existence and nature of a lunar core (Yoder 1981). In gravitational physics the test of the principle of equivalence in general relativity has placed strong constraints on competing gravitational theories (Shapiro et al., 1976; Williams et al., 1976).

In the following sections, the potential contribution of a LLR to the global geodynamics programs are discussed.

Lunar-Laser-Range Measurement

In lunar laser ranging, a concentrated light pulse is transmitted from an observatory situated on the Earth's surface toward a corner-cube reflector placed on the lunar surface. The basic equipment at an observatory consists of a telescope, a powerful laser, and a clock. Five retroreflectors have been placed on the lunar surface, of which four are observed regularly at the McDonald Observatory in Texas. Return photons from the same reflector obtained over a period of some 3 to 15 min are compressed to produce a normal point (Abbot et al., 1973). Several thousand normal points representing about 25,000 returns have been acquired at McDonald since the first returns were obtained there in 1969. The typical measurement accuracy is 15 cm at present. Stations have been built in Australia, Hawaii, Japan, and France. West German geodesists plan to range to the Moon from the Weizell satellite-laser-ranging station.

The basic lunar-laser-ranging measurement is the time taken by a photon, which is emitted from an observatory on Earth, to travel to the Moon and back. To perform the calculation of this value, values for (1) the position of the transmitter at transmission, (2) the position of the reflector when the photon reaches the Moon, and (3) the position of the receiving telescope on the photon's return are required. The calculations are performed in a heliocentric coordinate system because heliocentric coordinates enter the expression for the deflection of the photon path by the Sun's gravity field and because the Earth and the Moon experience accelerations in space that would not show up in a purely geocentric calculation.

The basic models required for the analysis are (1) the orbital motions of the Earth and the Moon, (2) the observatory coordinates and their variation due to solid-body tides, (3) the reflector coordinates, (4) the space orientation of the Earth and of the Moon, and (5) the atmospheric refraction and geodesic curvature of the photon path. From these models, the time-delay residuals and their partial derivatives with respect to the parameters of the problem are calculated. Least-

squares statistical adjustments are subsequently employed for improving the model parameters.

Current Capabilities

Four retroreflector arrays currently are in operation on the lunar surface, separated by distances of roughly 1000 km. Measurements of the distances to these arrays have been carried out since 1969. Most of the data were obtained from the McDonald Observatory in Texas, using an astronomical telescope that was made available for laser measurements during periods totaling about 50 h per month (Silverberg, 1978).

Recently, a new lunar-laser-ranging system has begun operation at McDonald, and it will be available a much larger fraction of the time.

Two other lunar-laser-ranging stations will be in regular operation soon with considerably higher accuracy than has been achieved previously. These are the Australian station at Orroral Valley and the Hawaiian station on Mt. Haleakala. Both have large receivers dedicated to laser ranging and subnanosecond-pulse-length lasers. The normal point accuracy achievable appears likely to be better than 3 cm. In addition, the accuracy of results from the French station in Grasse recently has improved considerably.

Future Prospects for Lunar Laser Ranging By early 1985 there are likely, for the first time, to be enough lunar-ranging stations in operation to avoid substantial weather-related gaps in high-quality data, and with much improved coverage when the Moon is at southern declinations.

It is expected that about six worldwide stations capable of high-quality lunar-ranging as well as satellite-ranging observations will be in regular operation in the 1990s. With improved pointing capability and range gate lengths of less than 50 nsec, efficient operation throughout the lunar cycle is likely. Higher-power subnanosecond-pulse-length lasers may contribute to normal-point uncertainties well below 1 cm under good observing conditions. The main accuracy limitation at lower elevation angles may be from horizontal gradients in the atmospheric density.

In terms of Earth rotation information, the most valuable results are expected to be on moderate to long-term variations in UT1 and on nutations and precession. The accuracy of the results with respect to those from VLBI may depend on the relative accuracy that can be achieved for the atmospheric propagation corrections at visible and radio wavelengths. Useful results also are expected for polar motion.

For the Earth-Moon system, all the present geodetic results are expected to be improved strongly. Until recently, such results have been affected by the difficulty of separating out UT1 and polar-motion variations with data mostly from a single station. By combining the results of multistation lunar-ranging data with satellite-ranging and VLBI data, the effects of shorter-period UT1 and polar-motion variations can be reduced. Because of the great stability of the lunar orbit and the absence of appreciable nongravitational external forces, the

combined accuracy of many normal points can be used in solving for the longer-term motions of interest. In addition, for the important scientific questions involving the free and forced nutations of the Moon and its low-degree gravitational harmonics and radial mass distribution, the only measurement errors of significance are those that are differential between observations of the different retro-reflector arrays. Since the atmospheric instrumental errors are essentially the same for ranging to the different arrays, systematic error contributions to be quantities of interest may be reduced to below the 1-mm level.

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2.5 SEAFLOOR GEODETIC TECHNIQUES

Geodetic observations at sea fall into two broad categories--those related to determining the shape of the geoid and those concerned with accurate measurement of positions of points on the seafloor. Both are close to geophysical fields of interest. Physical oceanographers have long been concerned with small-amplitude, long-wavelength variations in ocean surface height as indications of geostrophic circulation phenomena. Sea surface gravity measurements have been strongly motivated by the insight they provide relative to crustal structure, and the beginnings of measurements concerning buildup of strain and tilt at the seafloor are an essential part of understanding the dynamics of crustal processes.

2.5.1 Gravity

Gravity measurements at sea have the longest history of any oceanic observations relevant to geodesy. Moving from submarines, the first surface ship gravimeters were adaptations of land instruments and used the geometry of the simple destabilized balance beam with a restoring spring plus long-period pendulums or stabilized platforms. These instruments produced accuracies of 1-2 mgal in good weather in areas where excellent navigation control was available. Accuracies decreased with worsening sea state owing to the nonlinear cross-coupling between vertical and fore and aft (along the beam) accelerations. Errors from this source could exceed 50 mgal but could be corrected by simulation and subtraction of the error. Later mechanical designs, first by Bell Aerospace and later by Askania and by LaCoste and Romberg, possess mechanical symmetry that eliminates the cross-coupling effect. The Bell design uses an inertial navigation grade accelerometer and is now in its third generation. It has been used primarily in the exploration and military fields and only now is entering the academic market. It differs in principle from earlier beam models in that it makes use of force feedback to minimize mass movement. The later Askania KSS 30 design uses a combination of spring and electrical force feedback, whereas the LaCoste and Romberg SL-1 straight line meter uses the now classic zero-length spring for destabilization.

These improvements over the past decade or so have brought about little improvement in performance under excellent conditions but offer markedly improved results in immunity to ship motions (see, for example, Valiant, 1983). The KSS 30 specifications quote 1-mgal accuracy in the presence of 0.2 g vertical and 0.3 g horizontal accelerations without, of course, complicated nonlinear corrections.

Given the present levels of primary instrument capability, the uncertainties of the supporting measurements control the overall errors and advances just becoming available promise significant improvement in this regard. The principal problem arises because the ship at the sea surface does not necessarily have the same centrifugal acceleration as the Earth itself and thus the east-west component of platform velocity relative to the Earth's surface must be measured to make the proper

(Eötvös) correction ($2\omega y \cos \phi$, where ω is the angular velocity of the Earth, y the east-west velocity component, and ϕ the latitude). Current practice in the open ocean relies on Transit satellites and Doppler speed logs, leading to rms crossing errors of about 5 mgal. With a good inertial navigation system to provide the interpolation between satellite fixes this can be improved by a factor of 3 to 5. The arrival of the GPS will produce an improvement in this situation. With a proper receiver (e.g., Ward, 1982) an accuracy of 0.1 m/sec should be available, although it may be necessary to use further auxiliary measurements to compensate for wave-induced motions of the shipboard antenna. While this is not an order of magnitude better than the velocities that can be achieved with Transit plus Doppler or inertial systems, the fact that the information will be continuously available and can be averaged over appropriate intervals may lead to a submilligal capability.

2.5.2 Position Determination

Measurements of the positions of seafloor points in either the horizontal or vertical for strictly geodetic purposes have not been made beyond shallow depths, although the necessary basic technology and environmental understanding to carry out such observations in some areas appear to exist.

The problem of determining relative horizontal positions among points on the seafloor has been reviewed recently by a panel of the National Research Council (Committee on Geodesy, 1983). While under specialized circumstances a variety of techniques (optical and mechanical, for example) can be used, acoustic signals will continue to provide the primary means for direct determination of the horizontal components of positions below the depths at which airborne electromagnetic signals can be detected.

The nature of sound transmission and background noise in the sea are such that environmental factors rather than engineering ones will control achievable accuracies and ranges of effective operation. While useful general characterizations of the limiting natural and man-made phenomena can be made in any situation that may push the limits of performance, one should carry out local surveys, particularly of the sound velocity and background noise fields, to determine both their average properties and the time and space scales of their variability.

The frequency-dependent attenuation of sound transmission (due primarily to chemical effects) and the nature of background-noise spectra combine to produce a coupling between available signal bandwidth and the ranges to which acoustic signals can be used. These effects are summarized in the Committee on Geodesy (1983) report, which includes references to relevant literature. Sound absorption (e.g., in decibels per kilometer) increases roughly as the square of the frequency. The noise generally decreases with frequency, but not with steep enough slope to counteract the effects of absorption. Thus, long-range systems must operate at lower frequencies (and thus smaller bandwidths) than short-range systems. The result is that travel time

measurements can be made to within 10 μ sec at ranges of the order of 10 km, while at a few hundred kilometers the limit is in the range of 1 msec.

The limitations, plus those on knowledge of velocity of propagation of sound in the sea (discussed below), restrict the accuracy of distance measurement using purely acoustic systems to about 1 in 10^5 . In many oceanic situations (spreading centers, transform faults), however, the zones of principal distortion are apparently quite narrow (a few kilometers--Normark, 1980), and the relative motions across them are large (5 to 20 cm/yr). The 1- to 10- μ m strain per year inferred from geological/geophysical observations are thus compatible with direct acoustic measurement potentials.

Converting travel-time measurements into distances requires knowledge of the sound speed averaged over the propagation path. As yet, there is no remote-sensing method for measuring the effective sound speed over large distances. Two approaches are currently available, both requiring successive observations that are essentially point measurements made continuously along the trajectory traversed by the measuring instrument. First is the use of a sound velocity meter--a device in which a source/receiver combination is held in a dimensionally stable frame and the acoustic travel time is measured over a distance that is usually a meter or less. Sound propagation speed in seawater is not a measurable function of frequency, thus these instruments can operate at a few megahertz and produce results relevant even at a hundred hertz. The best laboratory instruments are good to a few parts in 10^6 , whereas those for use at sea are in the 1 in 10^4 range. It appears feasible to build survey units an order of magnitude better (e.g., 1 in 10^5).

The other measurement approach exploits the fact that sound speed depends on other factors, specifically pressure, temperature, and chemical composition (salinity). The relationships must be determined empirically, and the best efforts (Lovett, 1978) to fit curves to the laboratory data of various workers all have standard deviations of the order of 0.05 m/sec (about 3 in 10^5). To achieve that level of accuracy implies measurement of temperature to a few millidegrees, pressure to about 1 decibar (meter of depth) and salinity to a little better than a part per ten thousand (about 0.1 percent accuracy for normal 35‰ seawater). Since all three of these accuracies are easily achievable with today's pressure, temperature, and salinity measuring techniques it appears that some progress could be made by a definitive laboratory effort to improve our description of the relationships between these controlling parameters and the sound speed.

In any event, the conclusion is that in the near future it may be possible to make *in situ* measurements of the sound speed at points along the ray path with an accuracy of 1 in 10^5 (1.5×10^{-2} m/sec). Since the measurements must be made by moving one or more instruments through the water, and thus take an appreciable amount of time, the question arises as to the stability of the medium. In shallow regions in which water with significant vertical or horizontal temperature or salinity gradients is in motion and interacting with a rough seafloor, one may not be able to know the averaged sound speed to

better than a part in 10^3 . On the other hand, in deep water near-bottom measurements of thermal microstructure (even in the vicinity of spreading centers--Spiess, 1980) imply that the values could be known, averaged over the ray path, to 1 in 10^5 . This value probably represents the limit that will be achievable realistically in deep water until considerably more is known about the environment itself.

The substantial variation of sound velocity with depth leads to another system limitation. In deep, nearly isothermal, water sound rays will all curve upward, thus limiting the ranges between which near-bottom points can be linked by real ray paths. For a source 10 m above level terrain in the deep sea a receiver also 10 m off bottom will move into the shadow zone at a range of about 2.5 km.

The existence of time-varying currents of at least a few centimeters per second almost everywhere in the world's oceans, with extreme upper-ocean values reaching a meter per second or more, implies a further limitation in establishing the sound speed. The simplest means for coping with that aspect is to use round-trip propagation time measurements involving either reflectors or transponders. This sensitivity to water motion implies that one can use the difference between simultaneous measurements of travel times in opposite directions to determine the average current over the path traveled by the sound.

Although there are no real engineering obstacles to achieving the highest accuracies implied by the environmental limitations, today's commercially available acoustic systems are built primarily to achieve position accuracies of 1 to 10 m over ranges of a few hundred meters to 10 km. The reasons for this are clear. Most applications involve manned or unmanned vehicles operating in an observational or survey mode, and this level of accuracy is adequate to the purpose. Moreover, much of their use is in relatively shallow water environments in which it is often not easy to determine the proper value of sound speed to better than 1 in 10^3 . The principal systems in use today utilize transponders in either a long or ultra-short baseline mode. Long-baseline (an array of seafloor transponders spaced at distances of a kilometer or more and used in range-range mode) systems are favored for deep-ocean tracking of near-bottom vehicles. The ultra-short baseline systems (range and angle measurement) are favored for tracking vehicles in shallow water or for dynamic position keeping (e.g., for drilling ships). Enough engineering expertise exists in the commercial and academic ocean acoustic communities to assure that if demand for greater accuracy arises it can surely be met at least to the limits imposed by the environment.

Because of the limitations on knowledge of oceanic sound velocity and the lack of ability of electromagnetic radiation to penetrate seawater to any useful long-range extent, any approach to measurement of underwater baselines of more than about 10-km length with accuracies relevant to geodynamic problems must use combinations of in-water and above-water techniques (e.g., acoustic transponders and GPS interferometry) (Committee on Geodesy, 1983). No such systems have yet been put in operation.

Inertial navigation systems--gyroscopes, accelerometers, and their related control and output components--constitute a potentially useful means for relating points to one another, whether they are on the seafloor, on land, or even near the surface of the sea. As such they are not independent geodetic tools but are used in conjunction with other types of systems that can define specific locations in some particular set of coordinates.

Systems of this type are discussed in the context of terrestrial measurements earlier in this report. Their prime use in geodesy arises in tying sets of points to some recognized local control; however, because of their rate of error growth, the vehicle must come to a stop every few minutes to maintain appropriate error bounds. Given the slow speeds of underwater vehicles (compared with those of the helicopters used on the systems described in Section 2.2) the distances that could be covered within acceptable error limits (e.g., 10-20 cm) are too small to be of interest at this time.

Depth can be determined either acoustically or by measurement of pressure. In either case it is essential that supporting environmental understanding be brought to bear in order to convert the directly measured quantity into depth, and in both cases the environmental considerations rather than technology usually limit the accuracy.

Conversion of pressure to depth must take account of the increase of water density due to the gravitational attraction on the overlying water as one goes down plus the variation of temperature and salinity. The most recent treatment of this problem, using the currently accepted equation of state for seawater (Millero et al., 1980) is given by Saunders (1981). He calculates the conversion for the case of a standard ocean (temperatures 0°C and salinity 35‰) plus a correction term for the small effects of temperature and salinity differences. Using the Millero et al. (1980) equation with salinity and temperature data at about 50-m intervals in the upper part of the water column and 200 m for the remainder it is estimated that the pressure-to-depth conversion can be made to about 5 cm in 5 km (Reid, 1983). This conversion accuracy is compatible with the performance of well-calibrated quartz-crystal pressure gauges. It should be noted that this approach has only been used to determine the depths of particular isobaric surfaces in the ocean, not the depth of the seafloor.

Water depth is usually measured acoustically, and, with good signal-to-noise ratio, the round-trip travel time measured from a ship in calm weather over a smooth, deep seafloor can be determined to within a millisecond using today's systems. This is adequate for conventional geological purposes and only requires knowledge of the sound speed to within a part in 10^4 , which can be achieved with feasible, careful environmental observations (sound velocity meter or temperature and salinity versus pressure).

Echo-sounder data have usually been compiled and mapped for geological and navigational purposes rather than geodetic ones, although such data are useful in the interpretation of both gravity and magnetic-field measurements. While round-trip travel-time measurements with millisecond accuracy are common, this is not the sole criterion

for overall survey accuracy. The three other factors that must be considered are the echo-sounder beamwidth, conversion of travel time to depth, and navigation of the survey ship. Much existing data have been collected with wide beam sounders (30°), and thus the usually tabulated first arrival will only measure the slant distance to the closest seafloor point, which in general will be uphill from the point directly below the ship. Some data, however, come from stabilized narrow-beam (typically $2\text{--}2/3^\circ$) systems, including multibeam swath mappers, such as Seabeam, which has 16 beams, arranged shoulder to shoulder across the track. Such systems add significantly to the usefulness of gravity data observed simultaneously by providing nearby off-track data for making appropriate topographic corrections. Whatever sounder is used will have a finite footprint that limits its resolution of small-scale features in proportion to the height of the sounder off bottom. Thus a narrow-beam system towed 50 m above the seafloor will have 100 times better lateral resolution than one operated at the surface in 5000 m of water.

Navigational accuracy associated with sounding data is quite variable, depending on availability at the time of the survey, although most open-ocean data are controlled by Loran C, where coverage exists, or by intermittent TRANSIT satellite fixes plus dead reckoning.

Conversion of acoustic travel times to depths will vary also from one presentation to another--so-called "uncorrected" soundings may be based on either a nominal 1500 m/sec or on 4800 ft/sec (800 fm/sec), and "corrected" data may simply use regional thumb rules (e.g., Mathews Tables) or may be based on actual sound velocity or hydrographic measurements. These can give rise to systematic differences of a few percent.

In the compilation of large-area representations the primary uncertainties will arise simply because of lack of data, particularly in areas far from shipping lanes or of little scientific interest. If one contemplates using a particular data base it is essential to ask the provider for auxiliary information showing track density as it varies throughout the region covered.

Underwater maps, when carefully made, could be useful in detecting geodynamic processes that involve alterations of seafloor shape (faulting or constructional features), producing changes of relief in the order of 10 m or more. Again, the advent of swath mapping systems has improved the situation in this regard, since today's surveys have density equivalent to multiple tracks separated by only the narrow-beam footprint, where the single-beam surveys of the past lacked that density and always required imaginative interpolation between nonoverlapping profiles. Subtler changes on scales relevant to shifting magma chambers or creeping phenomena could in principle be made by establishing depths of specific reference points with 1- to 10-cm accuracy. The necessary observations would have to be made from the seafloor using precision pressure gauges or uplooking sounders, accompanied by auxiliary water-column measurements of temperature and salinity or sound velocity, as functions of depth (pressure) as discussed above.

2.5.3 Seafloor Measurements--Future Developments

Our ability to make geodetically relevant measurements in ocean-covered areas should have advanced substantially by the year 2000. Particularly in relation to the situation of the 1980s the change should be dramatic because of the minimal capability that exists today. Three sets of circumstances can be expected to lead to this improvement. The first is motivation. Geodesy has in general been a terrestrially oriented activity, driven by its relevance to a variety of situations of practical interest to those who use the land. As awareness of the applicability of geodetic techniques to geophysical/geological problems has entered land-oriented geodynamic science, it is gradually becoming apparent that there are strong reasons for making similar measurements in relation to the seafloor. Interest and activity by the ocean science and technology community can thus be expected to grow and to drive progress in ocean geodetic measurement methods.

Two quite different, though not unrelated lines of action will contribute to this instrumentation-oriented progress. First will be increased detailed knowledge of the ocean environment itself, and second will be the development of methods for building and installing devices on the deep seafloor. Some aspects of advance in both areas will occur whether or not geodesy is considered to be important, while others will not likely be achieved unless those interested in this type of measurement make a good enough case to generate the necessary support.

The approaches that will benefit from improved knowledge of the environment are those that utilize propagation of sound or light through ocean water.* Acoustic measuring systems will benefit in the first place from ability to optimize system design choices through improved knowledge of sound absorption and background noise for frequencies from 5 kHz up. At present the manner in which the absorption varies with depth is poorly documented, and the nature of the variation of high-frequency background noise with depth and location has not even been adequately measured. With improved knowledge of these phenomena one will be able to make better selections of working frequencies, wave forms, and power requirements for measurement of acoustic travel times and directions of arrival. These considerations are discussed in a National Research Council report (Committee on Geodesy, 1983).

The major problem in using acoustic signals for distance measurement will remain the description of the effective sound

*The propagation of electromagnetic radiation outside the optical band is understood well enough to know that there is strong attenuation for most short-wavelength forms (e.g., frequencies of a megahertz or more) and that the more deeply penetrating radio waves are of such long wavelength (kilometers) as to make their use for precise position measurement (centimeters) extremely difficult. Thus only the optical window is likely to be used.

velocity. No new approach to sound-speed measurement is now anticipated, thus we must expect that only point-by-point determinations, perhaps to a part in 10^6 , will be available. Since internal waves and turbulence can give rise to substantially larger alterations of structure along any given sound path as a function of time, one might feel that the part in 10^5 limitations cited in the literature (e.g., Committee on Geodesy, 1983) will remain as the limiting value. There are, however, a number of lines of investigation of these dynamic phenomena in progress at this time. While their fundamental purposes are to learn about the basic nature of phenomena such as turbulence and mixing in the sea, there will be by-products describing the statistical nature of these motions and relating them to fluctuations of sound speed. Of particular usefulness will be outputs concerning the spatial coherence and temporal variability of temperature and salinity structure. With such descriptions in hand we should be able to select favorable instants at which to make measurements and approaches to averaging that will lead to substantial improvements. For example, by 1990 we should be able to tie GPS antenna locations to seafloor points with uncertainties in the 3- to 10-cm range in the open sea based on today's knowledge. By the year 2000, uncertainties smaller than 1 cm may be achievable in many locations. Similarly the distances over which direct, near-bottom acoustic ranging can be done to centimeter accuracy should increase from a few kilometers to over 10 km.

It should be stressed that these improvements in performance should be achieved without a requirement for any appreciable advance in technology--the key is in the ability to make better system design choices and to be able to cope more effectively with a continually varying sound-velocity environment.

In the case of optical ranging systems the situation is similar. As discussed in a National Research Council report (Committee on Geodesy, 1983), our knowledge of the group velocity of propagation of light in the sea suggests an uncertainty of a part in 10^3 in our present knowledge. A laboratory measurement program to establish dependence on pressure, salinity, and temperature is required. Other interests in ocean optics seem unlikely to provide the motivation for such a program, thus if in-water laser strain measuring systems are contemplated they must include such an investigation. Given that information and the many advances being made in optical technology in other contexts it is reasonable to assume that by the year 2000 laser ranging could be used over in-water paths of 500 m or more with accuracies approaching 5 mm. Since the propagation velocity varies with water temperature, pressure, and salinity (although in general with about an order of magnitude less sensitivity than sound speed), knowledge of the dynamic aspects of water motion will play a useful role. In addition, however, since, unlike the acoustic situation, the propagation of light in seawater is dispersive, there may be possibilities for determination of its effective speed through use of multifrequency approaches. This will not be so easy as in the atmosphere because only the blue-green end of the spectrum can be used over any appreciable range.

Advances in ocean technology will also play a major role in advancing seafloor-oriented geodesy. Most important will be the development of unmanned, remotely controlled seafloor work vehicles. Their initial use will be in connection with reasonably simple activities such as the installations of acoustic transponder benchmarks on a wide variety of types of seafloor, ranging from the rough volcanic terrain at spreading centers to the smooth, thick sediment columns of the abyssal plains or the seaward flanks of ocean trenches. Particularly in areas in which strain buildup patterns are required, such work vehicles will contribute to the financial feasibility of implementing appropriate observational networks. They can install inert foundations at many sites and then, whenever a resurvey is made, emplace a small number of the necessary active units in any one area, removing them afterward for use at other locations. Since today's estimates of precision transponder costs are in the \$10,000 to \$15,000 range, this would make the use of hundreds of points, surveyed in groups of 5 to 10, a practical matter from a cost/effectiveness viewpoint.

In a similar vein, but on a smaller distance scale, retroreflectors could be placed in considerable number with spacings of 100-200 m in areas where strain accumulation might be localized (e.g., spreading centers--Normark, 1980), and a laser-ranging system could then be operated from a seafloor work vehicle to carry out successive surveys

From both of the above examples it is clear that benchmarks or monuments on the seafloor may be more complex than the simple visible objects that support terrestrial geodetic networks. They may, in themselves, include electroacoustic devices (e.g., transponders), or they may actually be mounting foundations on which such devices may easily be placed in exact registration. Monument integrity, however, can usually be expected to be better on the deep seafloor than on land, primarily because the environment is a much more stable one. The temperature is unlikely to vary by more than a tenth of a degree, and both rocks and sediments will be in equilibrium as to water content relative to the overlying ocean. Techniques already have been developed for shallow-water use to drill mounting holes and to cement objects into rocks of all types. Sediment-covered areas usually have sufficient bearing strength that, with careful design to maximize both surface bearing area and depth of penetration, the light loads that these structures must support can be maintained in position with appropriate integrity. In spite of a mental image that many have of a very soupy seafloor, any marine geologist will attest that it takes considerable loading and careful operation to drive a core barrel 10 m into the sediment in most locations. The problem of fresh sediment being deposited that might obliterate such a benchmark is not a serious one (maximum deep-sea sediment deposition rates are the order of 20 m per million years) and can be forestalled by providing structures projecting slightly above the seafloor. Seafloor work systems should be able to remove both inert and biological fouling just as one now does for terrestrial monuments.

By the turn of the century this seafloor work capability should have advanced to the point at which almost any local measurement technique in use on land will be equally capable of being installed and

operated on the seafloor. Tiltmeters, laser strain measurement systems (e.g., Berger and Lovberg, 1970) and absolute gravity measuring instruments (e.g., Zumberge et al., 1982) are examples that could be adapted and properly installed on the seafloor. Seismographs of considerable sophistication are currently operated routinely on the seafloor, whereas existing shallow-water bottom gravimeters (e.g., LaCoste and Romberg models W or H) can easily be adapted for deep seafloor use. Some of these systems (e.g., laser strain) utilize substantial amounts of power, yet should be operated, once installed, for prolonged periods. Availability of seafloor work vehicles would allow for replenishment or replacement of power sources, as well as instrument repair.

Both strain (laser, wire, or quartz types) and tilt measuring systems should operate more effectively in the seafloor environment since their attachments to the crustal rocks will not be subject to such effects as diurnal and seasonal temperature changes and rainfall.

Improvement of gravity measuring accuracy will only be of interest in geodesy and geodynamics if the effects of the local terrain (which itself may change with time in active volcanic/tectonic areas) and the overlying water column are taken into account. Effects of the overlying water (depth and density structure) can be accounted for using existing techniques as discussed in connection with depth determination in the earlier parts of this Section. The existence of near-bottom or on-bottom vehicles will support the operation of high-resolution scanning echo sounders that can delineate the local topography in the vicinity of each measurement site out to ranges at which the resolution of surface-ship-operated (e.g., Seabeam) echo sounder systems will suffice to define it.

Technology for seafloor photography should improve substantially over the next decade, primarily through implementation of advances in illumination. Present limitations, arising from degradation of images because of backscatter, can be overcome and areas perhaps 100 m or more across included in a single picture. This sort of performance is achievable by use of strong illumination and by having the light source(s) remote from the stereo camera assembly. The most desirable is a set of light sources masked so that their direct radiation is not in view from the cameras, with all units remotely controlled to fire simultaneously. Accuracies in deriving separations of previously placed markers should, with care in design of cameras, be of the order of a centimeter in a 100-m field of view. Present-day systems can achieve this accuracy in a 30 m x 30 m field (McNeil, 1972; Pollio et al., 1979).

Determination of the vertical coordinates of specific points should be improved by a factor of 3 to 5 compared with the 5-cm accuracy asserted for today's capabilities. The improvement can take place primarily because of the combination of ease of installation of high-grade, well-calibrated pressure sensors at benchmark points and better understanding of water-column dynamics (e.g., turbulence, internal waves), leading in turn to appropriate choices of averaging times and treatment of data from individual vertical profiles of pressure, temperature, and salinity. Satellite sea-surface altimetry

data will then allow one to establish (and re-establish) the vertical coordinates of the reference points relative to some useful global reference coordinate systems, taking sea-surface topography into account.

Since radio communication is not usable for contact with seafloor instruments, other means must be used to retrieve information from them. In situations in which occasional surveys to relate benchmarks are carried out by ship-supported near- or on-bottom vehicles, existing cable systems are quite adequate to this task. Acoustic telemetry to nearby surface ships or buoys can also be used, since overall data rates are quite modest, presuming appropriate conditioning of raw measurements by computers contained in the instrument packages. From the nearby surface platforms, data can be sent back to the users with any of a wide variety of radio systems.

A significant advance in data-transmission capability can be expected in the area of fiber-optic links. These are developing rapidly in other contexts and should be available for on-bottom use over distances of hundreds of kilometers, providing that the sending unit has an adequate power-supply capability. Here again the capability of unmanned seafloor vehicles to replace or replenish power packs will be important. Such links, in shorter lengths (100-500 m) could be used in connection with laser-ranging systems to extend the range by using a fiber-optic return path rather than relying on reflected light. This is useful in optical systems but not in precise acoustic ones, since in the latter case the need for a round-trip travel path in the water is dictated by the requirement to cancel out water motion effects. These are appreciable for acoustic systems since near-bottom currents frequently exceed 3 cm/sec, which, relative to sound speed of 1500 m/sec, is 2 parts in 10^5 , while relative to 3×10^8 m/sec it is only 1 part in 10^{10} .

In some instances it may be useful to monitor strain accumulation as a function of depth in the crust of the Earth beneath the sea. The technology for drilling the necessary holes has existed for some time in the National Science Foundation's funded Deep Sea Drilling Program. Technology for insertion of instruments in such holes, with or without use of the drill string, is in a primitive state of development. Enough interest exists, however, that methods for monitoring any distortions in shape of drill holes and installing instruments in them should be in common use by the end of this decade.

In summary, one should expect within the next 20 years to be able to install and maintain instruments and benchmarks on the seafloor to give geodetically useful and geodynamically significant measurements of strain buildup over distances ranging from 1 cm to thousands of kilometers. Similarly one should be able to relate the depths of selected seafloor points to satellite orbit coordinates to within a centimeter. Finally, gravity-measurement accuracy at the seafloor should be comparable with that achieved on land.

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CURRENT AND FUTURE APPLICATIONS OF CONTEMPORARY GEODETIC DATA

This chapter contains descriptions, not necessarily exhaustive, of the applications of geodetic data to aid in our understanding and definition of the solid earth, physical oceanography, mapping and land surveying, and engineering. For each subject, background and current applications are outlined that serve as a framework for a discussion of some of the future applications of geodesy.

3.1 SOLID EARTH

Geodetic measurements have always been of fundamental importance to the earth sciences, with the applications ranging from the most pedestrian of identifying the measurement of a physical quantity with a coordinate system (x, y, z), to the more glamorous of using contemporary earth deformation to understand and predict earth dynamics. The ties between geodesy and geophysics, in particular, are so close that many national and international organizations, such as the American Geophysical Union, the Canadian Geophysical Union, and the International Union of Geodesy and Geophysics, encompass both disciplines. In fact, it becomes impossible to distinguish between geodesy and geophysics for many studies, including investigations into the Earth's figure, wobble, and rotation.

It would, therefore, be naive to suppose that the revolution in geodetic science effected by such space age technologies as radar altimetry, the Global Positioning System (GPS), very-long-baseline interferometry (VLBI), laser satellite tracking, and satellite-to-satellite tracking would not spawn a commensurate advance in the earth sciences. As data become available from new geodetic technologies, there will begin a new era of hypothesis testing and model refinement in many areas of earth science in which development was or is stalled by inaccuracy and poor coverage of conventional geodetic measurements. The availability of superior geodetic data from the new systems will redirect the emphasis of earth science in the next few decades.

In this discussion of the ways in which geodetic data contribute to studies in solid-earth science, we have divided the applications into two categories, those in which time is a variable and those in which it

is not. This distinction is made because the nature of the instrumentation, process of making measurements, and assumptions necessary for analysis are distinct in the two cases. Of course, since the Earth is a dynamic planet, all earth-science problems are fundamentally time dependent. However, in many applications time is either unimportant (e.g., economic resource assessment) or of such a long scale that repeated measurements over several decades at the centimeter or microgal accuracy level will not bear on the problem. These sorts of problems we define here as time invariant, principally because from a geophysical standpoint accurate geodetic measurements need only be made once. Often the time-dependent aspects of such problems can be addressed by assuming that various geologic features at present display different stages in the same evolutionary cycle.

Progress on time-invariant problems has been hindered by lack of global coverage, poor accuracy in the data, and spatial aliasing (i.e., undersampling the wavelengths of interest). By overcoming these obstacles, data from new geodetic tools such as satellite radar altimeters are already making significant contributions to earth-science studies. Progress on time-variant problems has suffered from these same difficulties and, in addition, the great expense in time and money to make repeat measurements over a region such that the time variations are adequately sampled. It is in this area that new geodetic technology holds the greatest promise of spurring significant advancement.

For each category, we begin by reviewing recent progress in the earth sciences brought about by already completed missions or operating systems such as SEASAT and Lageos. These sections are by no means meant to be a complete listing of projects and principal investigators, but rather samplers of the scope of earth-science problems addressed by geodetic technology. We next discuss the sorts of studies proposed for geodetic systems that will become available within the next decade, such as VLBI, GPS, and the Geopotential Research Mission (GRM). Many of these projects are already under way using preliminary data sets. Finally, we will attempt to identify problems whose resolution will still be beyond the capabilities of already designed systems. Estimates of the accuracy and spatial or temporal resolution required from geodetic measurements in order to address these problems may guide future systems design.

3.1.1 Time-Invariant Problems: Recent Progress

Marine Geoid and Gravity

Our present knowledge of the marine geoid is principally derived from two satellite missions bearing radar altimeters in the 1970s. Global measurements from space of sea-surface height were obtained by the GEOS-3 mission in 1975 and the SEASAT mission in 1978 to an accuracy of about 20 cm and a wavelength less than 200 km (as short as 30 km in polar regions). Neglecting dynamic oceanographic effects, with signals of the order of a meter or less, sea-surface height closely approximates the marine geoid. The altimetric geoid is far superior to that obtained

from analysis of perturbations to satellite orbits because it does not suffer from loss of resolution at satellite altitudes owing to measurement of an upward continued potential field. Unfortunately, it is not possible to sample the continental geoid in a similar fashion because land surface does not follow an equipotential. While shipboard gravimeters will remain a useful tool for regional studies, they do not provide efficient global coverage. For example, it would take two centuries of ship time (plus a billion dollars) to repeat the SEASAT mission.

Many diverse geophysical investigations are already under way exploiting this improved determination of the marine geoid. To begin with, the large amount of information and global coverage have prompted the development of several techniques for mapping, interpolating, and calculating various derivatives (gravity, deflection of the vertical) from the geoid data (Haxby et al., 1983; Rapp, 1983; Sandwell, 1984; Shure et al., 1984). Efficient algorithms for mathematically representing large data sets on the surface of a sphere will find wide applications in many areas of earth, atmospheric, and planetary sciences beyond the specific geoid implementation.

The SEASAT mission has placed earth scientists in the unusual position of actually knowing more about the marine geoid than about marine bathymetry, particularly in the southern oceans. Principally under Navy sponsorship, this situation has led to numerous attempts to detect large, uncharted seamounts, which could present navigational hazards to nuclear submarines, by looking for short-wavelength anomalies in the geoid. The techniques include visual comparison between geoid and topographic maps (Sandwell, 1984), use of matched filters from signal detection theory (White et al., 1983), and complete inversion for topography given the geoid and assuming a spectral filter (Dixon et al., 1983). Such attempts are most successful at high latitudes where track coverage is essentially two dimensional. Weissel et al. (1980), however, have pointed out that not all short-wavelength geoid anomalies are due to bathymetry. In highly sedimented regions such as the northern Indian Ocean, geoid anomalies are caused by basement irregularities. To the extent that bathymetry is already mapped in these regions, geoid anomalies can be used to constrain subsediment structure. Regardless of the source of the geoid anomalies, interpretation of SEASAT data in terms of topography on density interfaces requires some assumptions on the mechanism by which that topography is isostatically compensated, a topic to which we shall return later.

The altimetric geoid has also found application in plate reconstructions. Derivatives of the geoid data, e.g., gravity, act as high-pass filters that accentuate sharp features such as fracture zones. Since fracture-zone traces represent small circles about the pole of rotation at the time they were active transforms, they constrain spreading history. Parsons et al. (1983) and Sandwell (1984) and colleagues at MIT have used SEASAT and GEOS-3 data to fill in fracture-zone orientation where bathymetric data were lacking for use in plate reconstructions.

In a more unusual application of SEASAT data, Sailor and Okal (1983) have been able to identify intraplate earthquakes with features

in the geoid over poorly charted areas of French Polynesia and thus determine whether seismicity is due to volcanic events or reactivation of old sites of weakness such as fracture zones. This distinction must be made before intraplate earthquakes can be interpreted in terms of state of stress to constrain plate-driving mechanisms.

Since, as noted earlier, the amplitude of geoid anomalies over bathymetric features is the sum of the contributions from the mass excess of the topography and the mass deficiency of the compensation, geoid anomalies in areas of well-charted bathymetry can be used to distinguish locally compensated features from regionally compensated features (Schwank and Lazarewicz, 1982). As shown by Watts et al. (1980), locally compensated features form at or near mid-ocean ridges where the lithosphere is too hot and ductile to support large stress differences. Regionally compensated features are produced off-ridge via hot-spot activity on older lithosphere. Thus by estimating the compensation mechanism from geoid data, one can determine the plate setting in which the feature formed (Dixon et al., 1983; Sandwell, 1984; Watts et al., 1985).

At longer wavelengths of the order 1000 to 3000 km, geoid anomalies are also correlated with long-wavelength positive-depth anomalies in the seafloor called bathymetric swells. The origin of the features is a topic of considerable debate. One school of thought contends that the swells are the surface expression of mantle convection (McKenzie, 1967; McKenzie et al., 1980; Watts et al., 1985), whereas others attribute the uplift to thermal expansion within the lithosphere itself (Detrick and Crough, 1978; Menard and McNutt, 1982). The source of heat for this "lithospheric rejuvenation" is still ultimately derived from convection in the mantle, but the form of the swell would not necessarily reveal the plan for mantle convection, as argued by McKenzie et al. (1980). Haxby and Turcotte (1978) used GEOS-3 profiles over the Bermuda rise to conclude that the swell is compensated at 50-km depth. Crough (1978) interpreted this result in favor of lithospheric rejuvenation since the low-density material buoying up the seafloor lies within the lithosphere. However, Parsons and Daly (1983) have shown that such observations do not preclude the convection hypothesis. By convectively transporting heat into the lower thermal plate but still below the mechanically competent lithosphere, it is possible to match the observed geoid-swell correlation. In the absence of a viable mechanism for rapidly reheating the lithosphere itself, Watts et al. (1985) conclude that mantle convection remains the best explanation for the correlation between depth and geoid anomalies in the Pacific. On this assumption, the spacing of the geoid highs constrains the horizontal wavelength of convection to about 1300 km. More recently, McNutt (1984) has invoked flexure data from seamount compensation partially constrained by GEOS-3 altimetry to argue that the thermal weakening effect from elevated temperatures extends well into the upper lithosphere beneath swells. From all the observations so far obtained, it now appears that some combination of lithospheric rejuvenation and mantle convection is required. The lithosphere could be thinned by a convective instability in the lower lithosphere, which then alters its temperature structure. While such studies are impor-

tant for determining the horizontal scale of mantle convection and the thermal properties of the lithosphere, none constrains the depth extent and viscosity structure of the convecting mantle.

Recent advances in seismic tomography have resulted in images of long-wavelength lateral heterogeneity in seismic velocity, presumably related to density variations in a convection mantle. The geoid anomalies resulting from these seismically inferred density anomalies can constrain the depth extent and viscosity structure of the convecting mantle (Hager et al., 1985). The convective flow induced by these density contrasts results in dynamically maintained topography at the earth's surface and at interior chemical boundaries. This dynamic topography, which is sensitive to viscosity variation, has a large influence on the geoid. By combining tomographic results with models of mantle flow, Hager et al. (1985) can account for over 80 percent of the variance in the geoid harmonics of degrees 2 and 3. They also find that at these wavelengths hotspots at the Earth's surface are accompanied by hot lower mantle.

Hager (1984) has also investigated the implications of the correlation between the mass excess of subducted slabs and geoid harmonics from $\ell = 4$ to 9. He concludes that for a Newtonian viscous earth, viscosity increases with depth, and it is unlikely that the upper and lower mantle form separate convection systems unless their density structures are highly correlated. These results are correlated with the results of the tomography study.

In the few years since the SEASAT mission, it is obvious that there has been a plethora of marine geoid and gravity studies addressing a wide range of earth-science problems. It is ironic that the premature termination of the SEASAT mission due to hardware failure was largely responsible for much of the resulting science, in that funds originally appropriated for completing the mission were redirected to data analysis. Clearly the availability of dense, accurate geodetic measurements will be of little use in earth-science studies unless the federal funding agencies such as National Science Foundation, National Aeronautics and Space Administration, Office of Naval Research, and U.S. Geological Survey are given increased budgets to fund university and in-house applications of geodetic data.

Continental Gravity

Earth scientists have also been using conventional terrestrial gravity measurements to probe the density structure of the continental crust and lithosphere, although recent progress stems more from improvements in rheological models and computer techniques than from new geodetic technology. For example, statistical methods from time-series analysis are now used to extract the gravity signature correlated with topography in order to study continental isostasy (Dorman and Lewis, 1970; Banks et al., 1977; McNutt and Parker, 1978). Elastic plate models of the lithosphere, first developed to explain flexure of the oceanic lithosphere, have been modified for the composition and temperatures in the continents in order to explain gravity anomalies in mountain belts

(McNutt, 1983, 1984; Karner and Watts, 1983). In turn, the continental gravity anomalies constrain the extrapolation of laboratory-derived rheological laws to geologic strain rates. Preliminary evidence indicates that the continental lithosphere can be much stronger than oceanic lithosphere in spite of its relatively weak, quartz-rich crust (Karner et al., 1983). Much work remains to be done before we understand how deformation in the continental crust is coupled to motions of the underlying lithosphere. Unfortunately, suitable terrestrial gravity data for detailed tectonic studies are available from the United States, Canada, Australia, and Western Europe only. Elsewhere, the expense of land surveys, rugged terrain, and political barriers have prevented data acquisition.

Mapping the Seafloor

Our view of the seafloor has been remarkably improved through the development of swath mapping systems such as the Navy's SASS and university research versions Seabeam and SeaMARC. By imaging an area of seafloor using an array of surface narrow-beam echo sounders, these systems provide real-time contour maps of the seafloor over an area two thirds as wide as the water depth. Typical contour intervals are 5 m. These new mapping tools have increased by orders of magnitude the resolution of bathymetric features without the time commitment and expense of deeply towed instrument packages. Data from multibeam sonar surveys have already been used to study morphology of undersea volcanoes (Batiza and Vanko, 1983), ridge crests (Lonsdale, 1983; MacDonald and Fox, 1983), and back arc basins (Husson and Fryer, 1983). In the very near future, applications beyond mere mapping and geomorphological studies are certain to increase. For example, conversion of free-air gravity anomalies to Bouguer anomalies requires accurate off-track bathymetry. Without the knowledge of off-track bathymetry, the uncertainty in the Bouguer correction precludes precise determination of seamount density and compensation mechanism. Inversion of sea-surface magnetic anomalies for paleomagnetic parameters also requires two-dimensional bathymetric coverage to define the extent of the magnetized feature. In a comparison of two magnetic surveys over the same group of seamounts on the flanks of the East Pacific Rise, McNutt and Batiza (1984) found that navigation errors could be effectively eliminated from the second survey by using Seabeam swaths to position the tracks. The reduction in the standard error in modeling seamount magnetization was a factor of 2. Terrain corrections from the seabeam bathymetry were so accurate that volcanic rift zones could be mapped from their variation in magnetization. The most powerful application of these systems is yet to come when university research ships become equipped with GPS receivers so that the sonar swaths can be precisely positioned with respect to each other and with different data types such as SEASAT tracks.

3.1.2 Time-Invariant Problems: Future Applications

Having noted the diverse applications of existing geodetic systems in earth sciences, it would not be possible to predict all the future studies that will rely on geodetic technology, even for systems whose design specifications are already known. As pointed out by Bossler (1983), the changes to come from the new technologies will be far more profound than merely replacing old equipment with new.

Certainly data available from new geodetic technology will be used to continue to improve on models obtained from studies discussed above. Many of the results cited are considered controversial because the conclusions are at the resolution limit of the data. In addition, new problems in earth science that were beyond the spatial resolution with the old methods of geodetic science can be addressed with the new systems. It is the new opportunities opening up that we discuss here.

Continental Gravity

Within the next decade, NASA's GRM will provide an improved model of the Earth's gravity field that will provide new impetus to studies of continental structure and tectonics. Earth scientists have long needed a gravity field for the Earth with better resolution than the 1000+ km wavelengths provided by conventional analysis of satellite orbit perturbations. Terrestrial measurements suffer from uneven sampling owing to the difficulty in accessing certain regions of the globe, are expensive, and suffer large inaccuracies when tying separate surveys to a constant datum. While satellite altimetry overcomes these obstacles in the oceans, the gravity field cannot be so defined over the continents. GRM utilizes satellite-to-satellite tracking to convert range rate into gravity anomalies. Low satellite orbit assures adequate sampling of wavelengths as short as 100-200 km. Furthermore, because range rate depends directly on the potential, the field over both continents and oceans is recovered without contamination from dynamic effects.

Specific studies that will benefit from the GRM data are listed in the document "The Geopotential Research Mission: Scientific Rationale," prepared in 1983 for NASA by the GRM science steering committee, chaired by W. M. Kaula (University of California, Los Angeles) and C. G. A. Harrison (University of Miami). The earth-science applications include the following:

1. Structure and evolution of collision belts and rift valleys,
2. Structure of continental margins,
3. Pattern and energetics of thermal convection in the mantle, and
4. Thermal structure of the deep continental lithosphere.

These studies at present are hampered either by lack of terrestrial data in remote regions or by problems in piecing together separate sea-surface and land-based surveys.

The 100- to 200-km wavelength resolution of the GRM will still be too coarse for many continental gravity studies. Once airborne gravimetry is perfected, it will be a useful tool for mapping short-wavelength gravity anomalies on a regional scale. There are several advantages to airborne gravimetry. Compared with a land-based survey, it is faster and cheaper, especially over rough terrain. From the standpoint of data analysis, topographic corrections are greatly simplified if the measurement surface is everywhere above the topography. Finally, airborne gravimeters provide essentially continuous coverage along the flight path, as opposed to point values from a land survey. The availability of airborne gravity data, particularly in mountainous regions that are poorly sampled at present in North America and elsewhere, will give new impetus to continental crustal studies directed both at resource assessment and broader scientific questions.

Except for calibration of relative gravimeters it is not clear that the availability of portable absolute gravimeters will have a significant impact in the study of time-invariant problems. Errors due to uncertainty in drift, calibration, and reference level for relative gravimeters are still minor compared to the difficulties in making density and topographic corrections. There would be little impetus to use absolute gravimeters in the field unless they were as small, portable, reliable, and cheap as the relative instruments.

Marine Geoid and Gravity

Missions such as the GRM will increase the usefulness of altimeter measurements from SEASAT and TOPEX by providing a gravimetric geoid with 100-km resolution uncontaminated by dynamic oceanographic circulation. Although oceanographic effects are not considered severe enough in the altimeter data to prevent applications in geoid and gravity studies, nevertheless earth-science projects would benefit from their removal, especially for cases in which we expect correlations between geoid and circulation. For example, large seamounts are associated with roughly circular geoid anomalies, the interpretation of which leads to estimates of the seamount's size, density, and compensation mechanism. Unfortunately, the existence of such a large irregularity on the seafloor perturbs the deep circulation, causing eddies at the site of the seamount that can persist to the surface (Colton and Chase, 1983). The sea-surface height therefore may not truly reflect the seamount's potential.

Deployment of satellite altimeters has by no means rendered obsolete use of sea-surface gravimeters. These instruments sample coherent gravity anomalies at wavelengths of less than 10 km (Cochran, 1979; McNutt, 1979), which is far better than the 30 to 60 km available from SEASAT-type altimeters (Brammer and Sailor, 1980) even assuming that two-dimensional coverage is available. In addition, most tectonic studies require knowledge of bathymetry, which supplies over 50 percent of the power in the gravity spectrum at wavelengths less than a few hundred kilometers (McKenzie and Bowin, 1976). The principal road block to using satellite-derived gravity anomalies in marine geo-

physical studies has been the difficulty in reconstructing subsatellite bathymetry from other surveys (Dixon et al., 1983). Sea-surface gravimetry avoids this problem by simultaneously sampling bathymetry.

As discussed in Section 2.5.1, advances in marine gravimeters have eliminated cross-coupling errors, enabling precise measurement of gravitational accelerations even in rough seas. The two remaining error sources are inaccurate Bötvös corrections due to errors in ship speed and heading and lack of two-dimensional bathymetric coverage to remove completely topographic effects from the gravity field. For example, error in the topographic correction due to neglect of off-track bathymetry can exceed 10 mgal (Dixon et al., 1983). The new geodetic tools address both of these problems. As soon as ships can be navigated with GPS systems and bathymetry is routinely sampled with multibeam sonar systems, marine Bouguer gravity anomaly accuracy will approach 1 to 2 mgal, which is comparable with results from surveys on land.

In addition to the earth-science problems currently addressed by sea-surface gravimetry, such as isostatic compensation of oceanic topography and flexure of the oceanic lithosphere, the more accurate marine gravity data can be applied to new problems formerly below the noise level. For example, gravity anomalies will be used to map subsurface structures of possible economic importance on continental margins and in ocean basins. Gravity data may resolve the details of ridge-crest structure by revealing buried magma bodies. We will be able to merge seismic reflection and gravity data together in a more useful and accurate manner in order to study structure of hot-spot chains such as the Hawaiian ridge. In general, GPS-derived navigation will allow us to merge sea-surface gravity data with other information without offset problems. Significant improvements are likely in such tasks as removal of a gravimetric geoid from altimeter data in order to study dynamic ocean processes.

3.1.3 Time-Invariant Problems: Problems That Remain

In spite of the numerous investigations in earth science that will enormously benefit from the existing technology when fully deployed, there are a number of problems still beyond the limitations of the data. Many of these shortcomings remain only because of experimental design and could be alleviated simply by redeploying existing equipment. For others, there do not seem to be, at present, instruments available for making the required measurement.

An example of the former problem is the lack of resolution in the SEASAT data at equatorial latitudes. To be fair, these gaps in track coverage of 100-200 km were not due to experimental design but equipment failure that prematurely terminated the mission. Detailed studies of hot-spot volcanoes, fracture-zone traces, and other plate features require better sampling. Certainly there is no technological barrier to obtaining a two-dimensional map of sea-surface heights resolving 30-50 km features at all latitudes, but the decision as to whether such a mission actually takes place is likely to be based on political

rather than scientific rationale. For example, the GEOSAT satellite, which will be launched in 1985, will fill in the SEASAT gaps, but that information will not be in the public domain. Other satellite altimeter missions that will contribute to this data base are planned (TOPEX, NROSS, and ERS-1). Sea-surface gravity will fill in some gaps but will not provide global coverage.

An example of a problem that falls somewhere between the two categories is the lack of elevation information in continental interiors to complement the GRM or airborne gravity data. Again, there is no technological barrier to sending out ground crews to measure elevation directly using standard techniques, but the data are lacking in only the remote and inaccessible regions of the continents. It would take too long and cost too much to produce the required topographic maps for areas such as South America, Africa, and Asia. Ideally one would like to obtain measurements of land-surface elevation from space, but topography does not cleanly reflect the pulse from a radar altimeter. While the GRM or airborne gravity data alone are of value in resource assessment and many subcrustal studies, both elevation and gravity data are required for tectonic studies of structure and dynamics of orogenic belts. A microwave altimeter mission might be capable of supplying this essential data set.

More detailed studies of the continental gravity field will need wavelength resolution on the order of 30-50 km as compared with the 100-200 km to be provided by GRM. Airborne gravity may sample the gravity field at these wavelengths in specific areas, but cost and political barriers prevent global coverage. For example, in order to distinguish between various models of compensation mechanism and compensation depth, it is necessary to sample wavelengths comparable to the depth of compensation (generally at or near the Moho). The GRM wavelength limit is set by the mission altitude and measurement accuracies. A lower orbit would resolve shorter wavelengths, but the satellites would experience greater drag, require more fuel, and be more difficult to track. Therefore, it is not clear whether high-resolution continental gravity can be achieved with a low-low satellite-to-satellite tracking mission. Perhaps other satellite configurations or a gradiometer-type instrument would meet the need.

3.1.4 Time-Variant Problems: Recent Progress

For many geodetic measurements, as discussed above, we adopt the assumption, possibly false, that geodetic parameters are time invariant. This may be due to either the high cost of a single survey or the low accuracy of a measurement relative to possible temporal variations, or both. However, for many types of geodetic data it is clear that temporal variations occur that are resolvable with current measurement techniques. For example, without the benefits of modern technology, early man was able to observe and measure certain types of crustal distortion. In the earliest historical records, the rapid motion and destruction caused by earthquakes are well documented. Intriguing observations of slow ground motion as a precursor to a major earthquake

were made in Hamada, Japan, in 1872 (Rikitake, 1976), where fishermen saw a remarkable retreat of the sea caused by a 2-m ground uplift. The earthquake struck about one-half hour later. An even slower and more subtle ground uplift was observed in Sweden. The Viking city now called Old Uppsala was a major port for Viking ships sailing Lake Malaren. However, the port and city of Uppsala were forced to move downstream around the eleventh century because of a 1 cm per year uplift in the Fennoscandian region, while the lake remained at a level connected with the worldwide mean sea level. The ground uplift resulted from the removal of the weight of glacial ice that covered the area during the last ice age.

It is now well established that significant crustal distortion, especially uplift, occurs before major volcanic eruptions such as those that occurred in Kamchatka, Mount Saint Helens, Washington (Lipman and Mullineaux, 1981), and the intensely studied Hawaii events (see, for example, Decker et al., 1966; Dvorak et al., 1983). Therefore, geodesy is playing a major role in the monitoring of volcanic areas that exhibit renewed activity in the form of increased seismicity and distortion such as in New Guinea, the Naples area of Italy, and Mammoth Lakes/Long Valley, California.

Current measurement techniques that are being used to monitor crustal distortion are the following:

- Leveling
- Horizontal angle networks (triangulation)
- Gravity
- Electronic-distance-measurement (EDM) networks (one and two color) (trilateration)
- Borehole dilatometers
- Strain and tilt meters
- Fault creep monitors (wire strain meters and alignment arrays)
- Ocean and lake tide gauges
- Laser ranging to satellites
- VLBI (regional, transcontinental, intercontinental)

Laser-ranging and VLBI techniques, which have been in operation for only the past 10 years, are in the process of revolutionizing the measurement of tectonic processes because of their high accuracy over long baselines (see, e.g., Whitcomb, 1979). A possible addition to this list is the technique of radio ranging to satellites of the GPS in that National Geodetic Survey field crews are now making observations in areas of tectonic interest such as the Mammoth Lakes/Long Valley volcanic area of California.

Gravity

The acceleration due to the force of gravity, commonly termed gravity, is sensitive both to a station's elevation change, which changes its distance from the center of mass of the Earth, and to a change in the mass distribution beneath (and above) the station. The measurement of

gravity at stations on the Earth's surface is a useful indicator of elevation shifts or density changes due to distortion within the Earth's crust. These distortions can be due to processes related to earthquakes, volcanic eruptions, rebound of previously glaciated areas, or water and oil withdrawal from reservoir rocks. Gravity in conjunction with other geophysical parameters, especially elevation change, provides greatly increased analysis capability (for example, see Kisslinger, 1975; Whitcomb, 1976).

Most of the world's earthquakes and volcanic activity occur at or are associated with plate boundaries. However, many earthquake and volcanic events that are significant, especially in their destructive potential, are not near boundaries of the major plates and are considered intraplate events. Applications of gravity techniques to these events do not significantly differ between plate boundary and intraplate regimes except perhaps in the modeling of crustal distortion to explain the data. For example, one would expect more vertical distortion in regions with thrust or normal dip-slip faulting (trench and seafloor-spreading plate boundaries) as compared with areas of strike-slip faulting (transform fault boundary) simply on the basis of elastic rebound theory.

Gravity data from China gathered before the extremely destructive magnitude-7.8 Tangshan earthquake in 1976, an intraplate event, showed significant changes before the earthquake. Comparison of gravity from a survey made 6 months before the earthquake to readings made just before it show changes varying from -90 to +167 μgal , a total horizontal gradient of 257 μgals over a 120-km separation. It is almost certain that this gravity change represented a substantial differential elevation change, perhaps of 0.86 to 1.29 m, before the earthquake. Similar changes were seen before the 1975 magnitude-7.3 Haicheng earthquake (Chen et al., 1979, 1980). While large gravity changes such as these have not been observed elsewhere, it is also true that no gravity or elevation monitoring data have been gathered in a region prior to a magnitude-7 or larger event outside of China.

Gravity measurements are extensively used to monitor crustal distortion, and no attempt is made here to list all the investigations that have been done or are in progress. Certainly gravity was an important part of the analysis of the distortion related to the Matsushiro earthquake swarm in Japan (Kisslinger, 1975). Later Japanese work documented a large distortion on the Izu peninsula (Hagiwara et al., 1980). Canadian regions with histories of major earthquakes are being monitored on Vancouver Island (Dragert et al., 1981) and in the Charlevoix Region of Quebec (Lambert and Liard, 1981). A major project has been under way since 1966 to monitor the distortion due to the previously mentioned Fennoscandia uplift (for a summary see Grotten, 1983). This latter is of the class of important geodynamic free-air gravity anomalies that are not related to topography; in this case it is associated with the glacial isostatic adjustment process (for example, see Wu and Peltier, 1983).

As an example of work in the United States, a gravity network has been monitored since 1974 on an approximately bimonthly basis in the seismically active Southern California region (Whitcomb et al., 1980).

This network, a group of 30 stations concentrating on the Los Angeles-Transverse Ranges tectonic region and extending to Owens Valley to the north, Goldstone in the Mojave desert, and Pinon Flat in the San Jacinto mountains is reported by Whitcomb et al. (1980). This network now has the added feature of four key stations whose absolute gravity has been measured in 1982 to an accuracy of about ten μgal by means of the National Bureau of Standards-University of Colorado Joint Institute for Laboratory Astrophysics absolute gravimeter (Zumberge and Faller, 1980; Zumberge et al., 1983). These measurements will provide an absolute frame of reference for the monitoring of gravity changes over the entire network and for the calibration of relative gravimeter instrument parameters. Gravity changes from this network from 1974 to 1979 correspond well with leveling changes over a vertical distortion of about 20 cm in an area of the Transverse Ranges, California (Whitcomb, 1980). Similar correlations have been reported for the region by Jachens et al. (1983) for the 1977 to 1982 time period.

A more recent application of gravity to volcanic- and earthquake-related distortion is to the Long Valley Caldera-Mono Craters area in the California Sierra Basin and Range boundary area. An abrupt increase in seismic activity in the region began in 1978 (Ryall and Ryall, 1980) with a series of events about 30 km to the southeast including a $M_I = 5.7$ and its aftershock series on October 4, 1978. In 1980, an unusual series of four $M_L = 6$ and larger earthquakes occurred between May 25 and May 27, in and south of the Long Valley south moat area near the city of Mammoth Lakes. The 1980 series was accompanied by a general expansion beneath the Long Valley resurgent dome as deduced from leveling and trilateration data (Savage and Clark, 1982). Extensive gravity measurements were begun by the U. S. Geological Survey and the Department of Energy in the Long Valley area and Mono Craters area to the north in order to complement the leveling and trilateration and give better temporal and spatial resolution of the distortion. More recent distortion events, especially in January 1983, have led to conflicting models of either dike injection in the south moat area of the Caldera (Savage and Cockerham, 1984) or continuation and upward migration of the subresurgent dome expansion (Rundle and Whitcomb, 1984), presumably owing to magma injection. Gravity data may be a key to resolving the conflict between these two models. The clear earthquake-volcanic hazard and the geothermal potential of the Long Valley-Mono Craters system has led to numerous geophysical investigations in the area of which gravity is a major contributor. Fortunately, this intensified study and data collection has captured a significant distortion event that will provide a unique insight into the as-yet unclear relationship between seismic and magmatic activity in a known active volcanic system.

Plate Motions

One of the truly revolutionary concepts in the earth sciences is the theory of global plate tectonics. However, the driving forces that underlie this global process are unknown. Many hypotheses have been

put forward to explain the driving mechanism; the testing of these hypotheses is of primary interest in tectonophysics. There are often competing hypotheses that attempt to explain the same crustal behavior, and it becomes difficult to discern the correct model. Accurate crustal motion measurements often permit discrimination between competing hypotheses that predict similar behavior. There are many such uniqueness problems in geophysics today that are awaiting more precise geodetic measurements.

Historically, broad-scale horizontal crustal motions have been difficult to measure because there was no convenient worldwide frame of reference to use to measure them. For example, there are no historical accounts describing the slow drifting of the continents, as indicated by geological evidence. In fact, advanced and revolutionary geodetic techniques and tools that utilize baselines in excess of 100 km and produce accuracies of a few centimeters are only beginning to be able to measure the current slow plate motions. These new tools, which resulted from technological advances in the space program, derive their long-term stability from extraterrestrial frames of reference, such as the Moon, artificial satellites, and quasars. Quasars, the most distant objects known to man, are so distant that they appear fixed in the sky. Thus they provide a frame of reference uninfluenced by processes on Earth or even within our own Galaxy.

A graphic example of the need for direct plate-motion measurements arises from the application of plate-tectonics theory to the estimation of recurrence rates of great earthquakes along the San Andreas Fault in California. A typical slip of the San Andreas Fault in the region of the great 1857 Fort Tejon earthquake was a few meters. If we knew the rate of plate motion between two blocks, and were sure that the motion had to be relieved only in great earthquakes, we could estimate how often the earthquakes had to occur on the average. For example, the most recent magnetic anomalies in the oceanic crust (which provide a record of seafloor spreading on a time scale of a few million years) predict that the motion between the plates on either side of the San Andreas Fault (the North American and Pacific Plates) is about 5.5 cm/year (Chase, 1978; Minster and Jordan, 1978). A typical magnitude-8 earthquake on the San Andreas Fault has a slip on the order of 6 m. A simple calculation with these numbers gives a rough estimate that a great earthquake must occur on a given segment of the San Andreas Fault every 110 years or so. Recent geological evidence implies that the recurrence interval over the last few hundred years in Southern California may be variable, and considerably longer than 100 years (Sieh, 1978). Still, this type of reasoning has been the basis for concern about the southern portion of the San Andreas Fault, where the last magnitude-8 earthquake occurred more than 120 years ago (in 1857). However, this reasoning is based on several assumptions, the main one of which is that the plate motion has been constant over this period of time. In reality, plate tectonics can at present tell us only what the average rate has been over millions of years, and the present models are inadequate to predict movement over periods as short as a century. The basic question is whether the movement of plates, and the distortion and deformation that accompany their gross movement, is smooth or irregular.

Direct measurements of plate motions have been under way using extraterrestrial laser ranging and VLBI techniques for a number of years. Accuracy of these techniques has steadily improved, especially since 1979, owing to advances in our knowledge of the Earth's gravity field and improvements in electronics, recording, and clock technology. The accuracy of both laser ranging and VLBI over long baselines of 1000 to 10,000 km is now better than about 1×10^{-8} of the baseline for intercontinental distances. Typical baselines that now have 5 or more years of measurement history are the San Andreas Fault Experiment from northern California to the San Diego area (Smith et al., 1979); the Owens Valley-Pasadena-Goldstone triangle in California (Davidson et al., 1983); the Haystack, Massachusetts, to Owens Valley, California, and Fort Davis, Texas, baselines (Ma et al., 1983); and the Deep Space Network of Goldstone, California, to Spain and Australia baselines (Treuhhaft et al., 1983). All of these baselines are beginning to provide significant contributions to tectonophysical modeling of plate motions. In particular, data from these baselines can be compared in a meaningful way to plate motions predicted by the averaging of seafloor-spreading rates, transform fault azimuths, and earthquake slip vectors. Averaging times are a few million years for the former two data types and a few tens of years for the latter (Chase, 1978; Minster and Jordan, 1978).

Mantle Rheology

Geodetic measurements have traditionally been an important source of information on mantle rheology. Vertical uplift following continental deglaciation inferred from former shorelines, tide gauge measurements, and leveling has been used to constrain the thickness of the lithosphere and the viscosity and depth extent of the asthenosphere (Cathles, 1975; Kukkamaki, 1975). More recently, important information regarding the earth's rheology has been gained from the analysis of the evolution of the nodal position of LAGEOS. After correcting for the effects of the Earth's tides, the residual nodal acceleration can best be explained as being due to a change in the Earth's oblateness, described as a change in the 2nd-degree zonal harmonic, J_2 , owing to viscous rebound of the Canadian Shield after deglaciation (Yoder et al., 1983). Peltier (1982), in fact, had made preliminary quantitative predictions of the J_2 term that should be occurring at present owing to glacial isostatic disequilibrium. His prediction was confirmed by Yoder et al. (1983) and subsequently and independently by Rubincam (1984). A detailed assessment of the constraint on the viscosity of the deep mantle, which this observation provides, was given in Peltier (1983). A more recent and somewhat more detailed discussion has been elaborated in Wu and Peltier (1984). The main conclusion from this work is that the viscosity contrast between the upper and lower mantles is weak, with the upper mantle value fixed near 10^{21} Pa-sec and the lower mantle value no more than a factor of about 3 higher. This result is important because it demonstrates that there is no purely mechanical impediment to whole-mantle convection. In fact, the observation that

viscosity of the mantle is essentially uniform can be invoked to imply that convection is mantlewide (Peltier and Jarvis, 1982).

Observations of the wander of the Earth's pole of rotation provided by the International Latitude Service (ILS) can also be invoked to constrain mantle rheology. The secular drift of the pole toward Hudson's Bay at the rate of 0.95 ± 0.15 deg per million years is also a consequence of glacial rebound (Peltier, 1982). This physical effect is sensitive not only to mantle viscosity, however, but also to the thickness of the lithosphere. Preliminary analyses reported in Peltier and Wu (1983) suggested that a continental lithospheric thickness near 300 km might be required by these data. Later analyses reported in Wu and Peltier (1984) suggested an average continental thickness near 200 km. That the continental (cratonic) thickness is, in fact, this much in excess of the 120-km thickness appropriate to old ocean basins has recently been demonstrated rather conclusively by independent means. Peltier (1984) has demonstrated that relative sea-level variations during the last 8000 years on the east coast of the United States require a continental lithospheric thickness near 245 km, if the viscosity of the mantle is a constant 10^{21} Pa-sec independent of depth.

Pole Motion and UT1

There are a number of physical processes, both internal and external to the Earth, that cause variations in the Earth's rotation. The relevance to geophysics depends on the extent to which observations of the rotation might be used to learn about these processes or about the dynamical behavior and structure of the Earth. Observed variations include perturbations in the rate of rotation, in the geocentric position of the rotation axis (polar motion), and in the position of the rotation axis with respect to inertial space (precession and nutation).

Until recently, rotational data were obtained solely from astrometric techniques. Over the last decade, however, space techniques have evolved to where they are now providing the most useful rotational results. The improvement in the data is evident at all periods, but it is particularly noticeable at periods of a few weeks or less. Results from conventional astrometry require long averaging times to reach acceptable error levels, and this degrades their usefulness at short periods. The data from the space techniques should become increasingly accurate as the system accuracies improve.

Variations in the Earth's rotation rate can be usefully separated into those terms with periods of less than 3 or 4 years, with remaining terms at longer periods. The shorter-period variations are primarily due to processes in the atmosphere and oceans and to the luni-solar tides and are reasonably well understood.

Earth and ocean tides induce variations in the rotation rate at fortnightly, monthly, semiannual and annual periods by perturbing the Earth's inertia tensor. Elastic models have, so far, proven adequate to explain the observational results (see, e.g., Merriam, 1982a). As the observations improve, particularly of the fortnightly and monthly

terms, it should become possible to infer information about the Earth's anelastic behavior at these periods.

The atmosphere and oceans affect the rotation rate primarily, although not exclusively, at semiannual and annual periods. The most important relevant mechanism at these periods is the transfer of angular momentum between zonal winds in the atmosphere and the Earth. There are also smaller, but still significant, effects from the seasonal redistribution of mass in the atmosphere and oceans and from seasonal variations in the Antarctic circumpolar current (see, e.g., Lambeck and Hopgood, 1981; Wahr, 1983).

It has recently become evident that atmospheric winds cause perturbations at other periods as well. Winds are responsible for observed biennial and 50-day variations in the rotation rate. In fact, there is good correlation between winds and the Earth's nontidal rotation rate at all periods less than 3 or 4 years (see, e.g., Lambeck and Hopgood, 1981; Barnes et al., 1983; Rosen and Salstein, 1983; Eubanks et al., 1985). Probably the primary significance of these results is the implication that both the meteorological and geodetic data sets are of high quality. For example, the correlation demonstrates that the surprising 50-day periodicity in the atmospheric data is real and deserves attention from meteorologists. Perhaps, as the two data sets continue to improve, the semiannual and annual effects of the atmosphere and oceans can be removed adequately enough to isolate the tidal effects at these periods to learn, again, about the Earth's anelasticity.

There is also an observed secular decrease in rotation rate, due primarily to tidal dissipation within the Earth and oceans. Most of this dissipation occurs in the oceans. As models for the oceanic dissipation improve, it may be possible to use the geodetic results as a further constraint on mantle anelasticity. There is a smaller contribution to the secular variation in rotation rate due, presumably, to the rebound of the Earth following the last period of global glaciation. This hypothesis has been used to constrain the effective long-period viscosity of the mantle (see, e.g., Dicke, 1969; O'Connell, 1971; Nakiboglu and Lambeck, 1980, 1981; Sabadini and Peltier, 1981; Peltier, 1982; Yuen et al., 1982; Wu and Peltier, 1984).

Observed polar motion is composed almost entirely of an annual wobble, a 14-month wobble (the Chandler wobble), and a secular drift. The annual wobble is caused, primarily, by annual variations in the redistribution of atmospheric and oceanic mass (see, e.g., Wilson and Haubrich, 1976; Merriam, 1982b; Wahr, 1983), and is reasonably well understood. There are also smaller effects due to groundwater storage (Van Hyckama, 1970) and atmospheric winds.

3.1.5 Time-Variant Problems: Future Applications

The first question that long-baseline geodetic data will answer is, "Are the plate motions smooth or irregular?" Calculated plate rates are mainly based on the seafloor-spreading data. Thus, there is a great unknown gap in the temporal spectrum of plate rates between a

few-million-year period and, say, the typical recurrence time of earthquakes. Certainly, close to seismically active plate boundaries, plate motions are irregular because slip at the boundary takes place mainly as major earthquakes. But within the plate interiors it is a matter of current debate as to whether the plate motions are even partially governed by physical processes at the plate boundaries or whether the plate driving forces are dominant, resulting in smooth motion at locations distant from the intermittent boundary behavior.

If today's measured rates agree with the few-million-year averages, then it is reasonable to postulate that the plate rates are smooth. This argument is preferable to the alternative hypothesis that would hold that plate motions are irregular, and it is a coincidence that today they equal the average rates. Evidence that appears to favor the smooth-rate hypothesis derives from the fact that the few-million-years average spreading rates and transform fault directions can be fit with the same model as the earthquake slip vectors from the past few tens of years. However, it should be pointed out that plate rates can be irregular, and the transform fault and slip vector directions still agree with a smooth model.

If today's measured rates are not equal to the long-term averages, then it follows that rates must change, that is, motion is irregular. Irregular plate motions can make the problem of earthquake prediction much easier in that the input stress that must be relieved as an earthquake or aseismic creep can be monitored in a direct and timely manner. This of course assumes that the rupture of faults in response to a stress load is not an instantaneous process. Some justification for this point of view comes from evidence of a finite delay of rupture in laboratory data (for example, see Kranz and Scholz, 1977).

If the basic question of smooth or irregular plate motions has been resolved in favor of smooth plate motions, further testing of the models such as those of Chase (1978) and Minster and Jordan (1978) will require measured rate accuracies better than the uncertainties of the models--a few millimeters per year. With current accuracies of long-baseline measurement, this means that several more years of observation are required to help resolve discrepancies/predictions of the models such as deformation of the Indian plate, deformation within western North America, lack of closure around the Azores triple junction, and relative motions of the North American/Caribbean/South American plate.

Another application for the future derives from the fact that long-period variations in the Earth's rotation rate are not so well understood as those of shorter periods (see, e.g., Lambeck, 1980, for a complete review). Observed decade fluctuations are presumably caused by motions in the fluid core associated with the Earth's magnetic field. However, quantitative comparisons are virtually nonexistent at present. If geomagnetic and geodetic data improve to the point where these comparisons are feasible, they may help to extend our knowledge of dynamic processes within the core and of mantle conductivity.

3.1.6 Time-Variant Problems: Problems That Remain

One major topic that will undoubtedly continue to receive much attention is the study of the viscosity structure of the Earth as a function of depth, stress, and strain rate. Observed surface deformation caused by flow at depth is the sum of the Earth's responses to many forcing functions. We generally know the expected period of the Earth's response, especially for external loads such as tides, far better than we know the amplitude or phase. In order to separate different signals, it is necessary to sample Earth motion and deformation frequently enough so that no important response is aliased. One of the principal advantages of new systems such as satellite laser ranging, GPS, and VLBI is that they will provide accurate measurements more frequently. Simply stated, if geodetic technology provides only meter resolution, we need to collect 100 years of data to resolve the amplitude and pattern of many important sorts of Earth motions. If the data are accurate to a centimeter, models can be updated yearly.

While two-frequency microwave systems such as VLBI and GPS will provide centimeter accuracy for horizontal positions if the water-vapor distribution is homogeneous, the local vertical reference frame for these radio-frequency-based systems will not be equally well determined because of unknown delays due to water vapor in the atmosphere. Therefore, in order to avoid effects due to water-vapor inhomogeneity and to make rapid measurements of vertical distortion to comparable accuracy, such as postglacial rebound and isostatic adjustments far from tide gauges, it is necessary to develop water-vapor radiometers that are accurate and reliable in the field in order to remove water vapor as an unknown.

The Chandler wobble is a free rotational mode of the Earth. The observed period and damping of this mode have been used to constrain models of mantle anelasticity (see, e.g., Smith and Dahlen, 1981). However, the complete excitation source for the wobble is currently unknown. The atmosphere and oceans appear to have provided no more than about one quarter of the necessary excitation power during this century (Wilson and Haubrich, 1976; Wahr, 1983). The largest earthquakes are capable of shifting the pole a noticeable amount. For example, the 1960 Chilean earthquake probably displaced the pole by about 1 m (Smith, 1977). However, it does not now appear that the cumulative seismic excitation provided more than about 10 percent of the observed excitation over the last few decades (see, e.g., Dahlen, 1973; Kanamori, 1976; O'Connell and Dziewonski, 1976; Mansinha et al., 1979). One possible excitation source now receiving attention is slow aseismic motion at plate boundaries and in the asthenosphere. An identification of the excitation source is not only desirable in its own right but could lead to improved estimates for the anelasticity as derived from the observed spectral characteristics of the mode. Finally, the secular drift, if it proves to be real, could be a further consequence of postglacial rebound, and so could be used as an additional constraint on mantle viscosity.

The Earth's precession and nutation are caused by luni-solar torques on the Earth. Elastic models (Wahr, 1981) give good agreement

with observation. The most striking departure of the elastic results from the corresponding results for a rigid Earth, is a nearly diurnal resonance in the elastic values associated with inertial coupling between the mantle and the fluid core. As observations of this resonance in the nutations improve, the results could help to constrain the ellipticity of the core-mantle boundary, the possible dissipation between the core and mantle, and mantle anelasticity. Measurements of the ellipticity of the core-mantle boundary would help to constrain models of dynamic topography and the geoid similar to that proposed by Hager et al. (1985).

In the near future, attempts to monitor crustal motions will continue to be hampered by environmental noise, such as temperature changes and rainfall, as well as by the geologic complexity of continental fault zones. By the twenty-first century geodetic technology will have advanced to the point of allowing precise fault monitoring in the oceanic crust beneath the sea. The homogeneity in environment and rock type on the seafloor could lead to development of simple models of the earthquake cycle and rupture process, which could later be adapted to the more complex continents where damage is more severe.

Specifically, improvements in seafloor positioning (see Section 2.5.3) will lead to the ability to map the buildup of strain at spreading centers and transform faults using direct, near-bottom measurements among discrete benchmark positions, with centimeter accuracy over 10-km ranges. Composite systems using GPS interferometry with local acoustic ties to the seafloor should be able to achieve accuracy for the acoustic portion and beyond that be limited only by GPS performance.

This latter composite GPS/acoustic approach in particular will allow description of strain distribution across trenches most of which lack island features on their oceanic sides from which purely space-based techniques can be used. It also means that the motions (rotational as well as translation) of the smaller oceanic plates (e.g., Juan de Fuca, Rivera) on which there are no islands, can be determined. One can also study intraplate distortions that may take place between the oceanic and continental sections of composite plates (e.g., Northwest Atlantic relative to North American Continent or Raja California and California Borderland relative to adjacent Pacific Ocean seafloor) or within the Pacific plate itself.

On a local scale, the improvement of seafloor work systems should make it feasible to install and operate on the seafloor most of the instruments now used on land to measure crustal strain, tilt, and both absolute and relative gravity (see Section 2.5.3).

3.1.7 Earthquake Prediction

The objective of this section is to identify a few key areas of current research concentration, following a comprehensive review, that bear on the planning needs for future geodetic measurement technology. At present there is a wide range of scientific perspectives regarding this topic, and future workshops and discussion should prove useful.

Earthquake prediction is a long-standing and fundamental research problem in geophysics. The stages of prediction are now seen as long, intermediate, and short term, a concept that was established by the Chinese. Wallace et al. (1984) have suggested corresponding time scales of (1) few years to few decades, (2) few weeks to few years, and (3) few hours to few weeks.

Current geodetic measurements have contributed substantial data for research regarding long-term prediction. These data, together with earthquake and geologic fault information, are useful for work to estimate earthquake recurrence rates for time scales on the order of decades. Trilateration measurements by Savage and co-workers (e.g., Savage et al., 1981a, 1981b, 1981c; Savage, 1983) have now established horizontal strain rates along approximately 30-km-wide zones along the Pacific-North American plate boundary of about 0.4 μ strain/yr. Data from these numerous long-baseline arrays, with average measurement spacings of 15 km, have stimulated research to determine the long-term patterns of crustal straining.

A problem of current interest centers on whether strain accumulation is linear or nonlinear in space and time over the 150-year average repeat time between major (M 8) earthquakes. Thatcher and Rundle (1979) have studied linear and inelastic effects, particularly with regard to postseismic phenomena. Recently, geodetic measurements before and after the great 1906 San Francisco earthquake have been scrutinized to estimate the magnitude and duration of postseismic transients from large earthquakes (Thatcher, 1983). The character of these transients has important implications for the mechanics of the earthquake cycle and the accuracy with which short-term measurements of strain rate can be used in recurrent estimates. The 1906 geodetic data, together with modern measurements, suggest a nonlinear strain cycle in which most strain accumulation near the fault zone occurs within the first 30 years following a major earthquake. Thereafter, strain accumulates at a comparatively low rate and over a broader region, until the next large earthquake (Thatcher, 1983). Studies of postseismic deformation using geodetic data, such as the work of Stein and Thatcher (1981), Stein and Lisowski (1983), and Stein and King (1984), hold promise for refining these models. If postseismic strain near the fault is accelerated as Thatcher's model predicts, i.e., $>2.0 \mu\text{rad}/\text{yr}$, geodetic measurements immediately following a major earthquake and through the following decade could provide new information of fundamental importance. In fact, knowledge of the coseismic strain drop and the spatiotemporal (postseismic) strain changes might be used to make long-term predictions of the next large or great earthquakes along major plate boundaries. Rundle (1983) reviews models of crustal deformation and Thatcher (1984a) discusses earthquake recurrent and the deformation cycle.

3.1.8 Earthquake Predictions: Problems That Remain

- (1) Postseismic measurements of horizontal deformation are needed at 10-km spacing over the source region of a magnitude-7 to -8+ earth-

quake, and spanning an area about 60 km wide by 60 to 300 km long, for strike-slip earthquakes. (2) Measurements are needed both before and immediately following the earthquake. (3) Measurements should be maintained for a decade. Since major strike-slip earthquakes are rare, (4) the measurement capability should be highly mobile in order to obtain information across rough terrain and where the earthquake(s) occurs. Candidate faults are the San Andreas, in California; North Anatolia, in Turkey; Alpine, in New Zealand; and Atacama, in Chile. These requirements suggest the need for developing a type of geodetic beaming capability. Such a technique is a challenging concept and would likely require an airborne or space-based laser capability, in combination with (e.g., GPS) receivers, to compensate for visibility limitations due to the atmosphere. If, in addition, the postseismic crustal deformation following a major subduction zone earthquake were to be measured, including both horizontal and vertical data, the mechanical structure of the lithosphere might be resolved.

Geodetic data enter the problem of long-term prediction in yet another fundamental aspect, namely that of establishing fault slip rates for estimating earthquake recurrence. Minster and Jordan (1984) recently combined satellite geodetic measurements along the Quincy-Otay baseline in California with geologic data inferring the distribution of slip across the broad zone of deformation separating the Pacific and North America plates. The study considered the region from the Colorado Plateau to the faults offshore from California. Their results indicate that slip along the offshore faults west of the San Andreas may range between one quarter to one half of that along the San Andreas itself. While the limited geodetic data now available limit the confidence in predicted slip rate, this type of study indicates the value of long baseline measurements, which can be used to integrate local geologic and geodetic data, for breakthroughs with long-standing problems of plate motions and slip distributions.

Very-long-baseline geodetic measurements across broad plate boundary regions are extremely valuable and well suited to new geodetic capabilities. More measurements of this type are needed, at more frequent intervals in time and space. Data obtained from regional geodetic networks, such as those operated by Savage and co-workers, are highly complimentary to the very-long-baseline measurements and contribute information of fundamental importance. These networks are expensive, however, and rapid repeat measurements are difficult. Perhaps future geodetic measurement technology using, e.g., GPS receivers, will one day replace the regional network measurements. Using geodetic measurements across a wide region spanning a fault, the errors may be only a few tens of percent, while restricted short-term measurements of strain rate near the fault may produce errors that are a factor of 2 or more. The former method is useful for determining fault slip rates and, if the coseismic slip of the previous event is known, for estimating earthquake recurrence times.

The last few years have witnessed increasing trends toward integrating geologic, geodetic, and seismologic data for studies of the earthquake problem. A geologist's perspective (Allen, 1984) is that new geodetic technology, such as inexpensive and accurate GPS measure-

ments, could provide detailed maps of strain fields across major faults. This information, in combination with detailed geologic data from specific sites, is likely to provide important new information regarding earthquake hazard. Furthermore, measurements of vertical deformations might prove diagnostic of subsurface fault geometries producing fault "asperities" and points of fault locking. Reilinger (1984) presents an example where geodetically measured vertical deformation proved useful for defining subsurface fault mechanics (i.e., creeping versus locked sections of fault). A common impression is that measurements that could map temporal variations in crustal deformation could be very revealing, especially in terms of the earthquake prediction problem.

The detection and monitoring of temporal variations for, e.g., intermediate to short-term precursory or episodic strain changes before large earthquakes, are costly owing to the frequency of measurements required to avoid time aliasing. One major advantage of modern techniques is that measurements might be performed much faster, and possibly be automated, so that short-term phenomena will not be missed between surveys. Evidence for a rapid aseismic strain change on the San Andreas Fault near Palmdale, California, has been reported by Savage et al. (1981a, 1981b, 1981c) and MacDoran (1980) and compared with seismicity changes in the same region by Raleigh et al. (1982) and Sauber et al. (1983). Rapid strain changes could serve as "triggers" for large earthquakes and have been discussed by several authors, including those listed above, in the United States and Japan. Also, if such episodic strain changes are real, they could account for major contributions to the average rate of crustal straining and, hence, affect the estimates of earthquake recurrence times for long-term predictions (e.g., Thatcher, 1982, 1984a). At present, however, few definitive measurements exist for determining whether such occurrences are significant and whether they are frequent or extremely rare.

The National Research Council report (Committee on Geodesy, 1981) states: "The development of networks of fixed instruments along major fault systems for detecting possible short-term precursors before large earthquakes is a major task. We have no assurance that such precursors will have a substantial probability of occurrence, and their possible spatial patterns and amplitudes can only be estimated." Nevertheless geodetic measurements are expected to play a major role in earthquake prediction research; the 1981 report questions whether a valid prediction is likely without (preferably) both geodetic and seismic observations of precursory information. Substantial work is now needed in order to evaluate the requirements for instrumentation, models of expected precursory movements, and existing observational geodetic information.

Several studies point toward the technical difficulties in measuring precursory strain events. Wyatt (1982) reports: "Most techniques currently used to monitor continuously the deformation of the earth's crust employ instruments which measure over a limited baselength, almost always less than 1 km. Associated with this limitation is a requirement that the reference monuments, used as the fiducial points in the measurements, be well coupled to the crustal

rocks. Because crustal deformations are both small in magnitude and occur very slowly, monument instabilities are likely to be the limiting factor in many crustal dynamics studies." Savage (1983) endorses Wyatt's results: "Difficulties in coupling fiducial marks to the earth have generally made short-baseline measurements of strain accumulation questionable." Wyatt has studied the stability of the piers of the 731-m laser strainmeters at Pinon Flat, which are set on competent weathered granite in a region of low topographic relief, using tiltmeters mounted on the piers, shallow borehole tiltmeters, and optical anchors. He finds that over period ranges of 2 to 19 months, the standard deviations of nonpredictable horizontal displacements are 50 m down to depths of 4 m. Assuming that the motions of the two piers are independent, the total monument position uncertainty is 2.5 m \times 50 m. Therefore, a baselength of ± 7 km is required for a precision of $\pm 0.01 \mu\text{strain}/\text{yr}$, which is that needed to monitor tectonic strain changes, since the average rate in tectonically active regions is on the order of 0.1 $\mu\text{strain}/\text{yr}$ (e.g., Savage, 1983).

Critical evaluations of existing geodetic information regarding precursory Earth movements are needed. While theoretical and laboratory studies might indicate precursory deformation, there are few, if any, definitive observations of precursory tectonic deformation prior to earthquakes. The following reports update the work to detect precursory strain changes:

1. Continuous measurements of near-field tilt (four instruments) and strain (one instrument) with sensitivity greater than 0.01×10^{-6} within 30 km of the $M_g = 6.7$ 1983 Coalinga, California, earthquake were noneventful during the last few hours to last few seconds before the mainshock, following the removal of Earth-tide and other nontectonic periodic signals (Johnston et al., 1983).
2. Near-field dilatational strain anomalies previously reported before the $M_g = 7.0$ 1978 Izu Peninsula, Japan, earthquake, are no longer found, following the removal of Earth-tide and other nontectonic periodic signals, and the records are noneventful immediately preceding the mainshock (Johnston et al., 1983).
3. Four continuously recording creepmeters across the Imperial Fault provided clear records that no discernible fault creep occurred on the fault during the minutes, hours, or days before the $M_g = 6.6$ Imperial Valley, California, earthquake of October 15, 1979 (Allen, 1980).
4. Several well-water level changes were previously reported to suggest strain changes before the October 15, 1979, Imperial Valley earthquake. After removing signals due to rainfall, no anomalous changes of tectonic origin are suggested (Merifield and Lamar, 1983; oral report to USGS southern California data review, 1984).
5. A high strain rate, 1.8 rad/yr, during the 50 years before the 1906 earthquake has previously been reported. However, this interpretation is now considered in doubt because of too few data (Thatcher, 1984b).
6. The Morgan Hill, California, earthquake ($M_g = 6.1$) of April 24, 1984, ruptured within a dense geodetic network, and displacements

are relatively well determined. No anomalous deformations were found before this event. A 32-km line that crossed within about 1 km southeast of the mainshock epicenter was measured monthly from late 1981 and also 8 days and 1 day before the mainshock. A small-aperture geodetic network 5 km northwest of the epicenter was also surveyed 2 weeks before the mainshock and showed no anomalous deformation (Bakun et al., 1984).

In concurrence with the recommendations of the National Research Council report (Committee on Geodesy, 1981), the present review also indicates that "Implications of existing data should be thoroughly studied in the formulation stage of new experimental [geodetic] programs,"

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3.2 PHYSICAL OCEANOGRAPHY

The primary problem facing oceanographers for which highly precise geodetic data are required is the determination of the general circulation of the world's oceans (both mean and time varying). It is possible that one could determine the mean flow fields and time-varying quantities by deploying modern recording current meters in the ocean. To measure circulation changes on spatial scales on the order of 100 km or less, however, would require an impossibly large number of spatially independent observations. Further, in most regions of the ocean the energy of the temporal variability exceeds that of the time-averaged flow by an order of magnitude (Wyrtki et al., 1976), with a structure requiring several years of data to obtain a stable, mean velocity. Hence, the only feasible means to sample globally the oceans on the required spatial and temporal scales is through the use of satellite-borne instruments such as altimeters and scatterometers. Reports prepared by the Committee on Geodesy (1979) and the Committee on Earth Sciences (1982), both of the National Research Council, discuss future oceanographic and geodetic needs. Much of the material given here is discussed more fully in these reports.

A satellite altimeter measures the satellite-to-sea-surface range by determining the round-trip travel time of a radio pulse transmitted by the altimeter and reflected from the ocean surface. Such measurements, when combined with the orbit height obtained by tracking the satellite, make it possible to determine the topography or shape of the ocean surface. The shape of the ocean surface, which deviates at some points by as much as 100 m from the best-fitting reference ellipsoid, closely approximates an equipotential surface referred to as the marine geoid.

The small deviations (± 1 m) of the ocean surface from the marine geoid are caused primarily by quasi-geostrophic currents and tides. Generally speaking, water movements having spatial scales greater than about 30 km (the Rossby radius of deformation) and time scales longer than about a day are in quasi-geostrophic balance to a good first approximation. This means that, to lowest order, the velocity field is such that the Coriolis force is balanced by the pressure field. Water movement tends to be along, rather than down, the pressure contours, just as winds in the atmosphere circulate around highs and lows. The pressure field in the ocean manifests itself as a slope of the constant-density surfaces (dynamic topography) in the sea relative to level (equipotential) surfaces apart from the tides. The slope of the sea surface is a direct result of that part of the surface flow field that is geostrophic. As an example, the slope of the ocean surface relative to the geoid across the Gulf Stream is approximately 10^{-5} . It is desirable to measure slopes as small as 10^{-8} across ocean basins. Measurement of these slopes would thus provide direct observation of an important component of large-scale oceanic flow.

In order to calculate these slopes, knowledge of the marine geoid and the dynamic ocean topography relative to the geoid are required. Satellite altimetry, together with accurate knowledge of the satellite orbit, can provide the dynamic topography. Figure 3.1 illustrates the

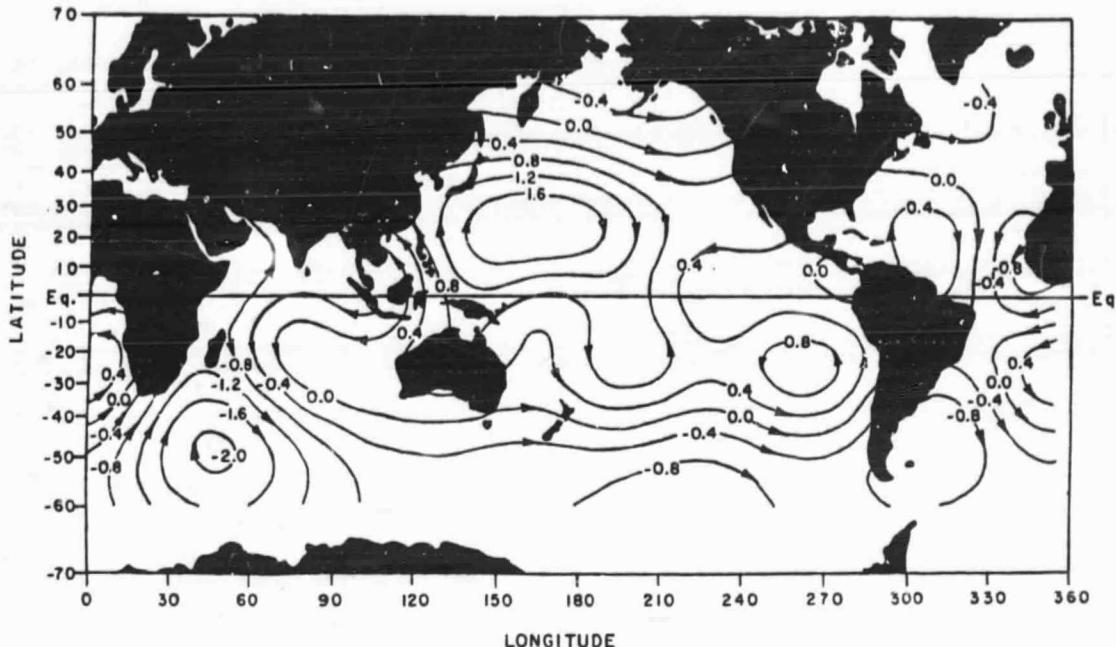


FIGURE 3.1 Long-wavelength ocean topography.

calculation of long-wavelength ocean topography through the use of SEASAT altimeter data and knowledge of the marine geoid (Tai and Wunsch, 1984).

Several satelliteborne altimeters are planned for launch in the late 1980s (Born et al., 1984). These include NASA's TOPEX satellite (TOPEX Science Working Group Report, 1981), the U.S. Navy's GEOSAT and N-ROSS satellites, and the European Space Agency's ERS-1. TOPEX will fly an altimetric system capable of measuring sea-surface height with a precision of 2 cm. Application of this data to determine ocean circulation will impose centimeter-level accuracy requirements on geoid and orbit accuracy. The remaining missions will fly SEASAT-class instruments with 5-10 cm precision. Review articles illustrating potential applications of satellite altimetry and describing its current status have been written by Brown and Cheney (1983), Fu (1983), Marsh (1983), and Tai and Wunsch (1984).

3.2.1 Altimetric Mission Survey

Table 3.1 summarizes pertinent information about past and future altimetric satellite missions. The row labeled repeat cycle contains the time required for a near or exact repeat of the satellite ground track. Hence, it represents the time between repeat samples of a given area of the ocean. The last three rows address the accuracy and precision to which the ocean surface height can be measured by the various missions. Errors in knowledge of the satellite position, which

TABLE 3.1 Altimetric Satellite Missions

	SKYLAB	GEOS-3	SEASAT	GEOSAT	NROSS	TOPEX	ERS-1
LAUNCH DATE	NOV 1973	APR 75	JUNE 78	FALL 84	88	88	88
MISSION DURATION (yr)	0.25	3.5	0.3	1.6	3.0 ⁽¹⁾	3.0	3.0
ALTIMETER DUTY CYCLE		10%	GLOBAL	GLOBAL	GLOBAL	GLOBAL	GLOBAL
REPEAT CYCLE (days)		(2)	17.3	3 ⁽³⁾	3 ⁽⁴⁾	10 ⁽⁴⁾	3 ⁽⁴⁾
ALTITUDE (km)	425	840	790	800	870	1334	800
INCLINATION (deg)	50	115	108	108	98	63.4	98
BASIN SCALE ACCURACY (cm)	1000	120	50	150 ⁽⁵⁾	(6)	13	150
SMALL AND INTERMEDIATE SCALE ACCURACY (cm)	100	25-50	5-7	10-12 ⁽⁵⁾	(6)	2-3	8-10
PRECISION (cm)	85-100	25-50	5-7	5-7	5-7	2-3	5-7

(1) IF FLOWN ON NOAA-D BUS, POWER CONSTRAINTS MAY DICTATE A REDUCED DUTY CYCLE

(2) DUE TO DRAG AND DUTY CYCLE CONSTRAINTS, THERE WAS NO SYSTEMATIC REPEAT CYCLE

(3) GROUND TRACK DISPLACED 40 km TO EAST EVERY 3 DAYS

(4) THESE REPRESENT EITHER BASELINE OR INITIAL CALIBRATION ORBITS

(5) GEOSAT CARRIES NO ON-BOARD INSTRUMENTATION TO PROVIDE IONOSPHERIC OR TROPOSPHERIC CORRECTIONS

(6) NROSS CURRENTLY CARRIES NO HIGH-PRECISION TRACKING DEVICE

are the largest contributor to the height-measurement error budget, are predominantly long wavelength (10,000 km). Consequently, the accuracy to which basin scale (1000 km) topography can be recovered is a reflection of how well the radial component of the orbit can be determined. For small- and intermediate-scale (50 to 1000 km) topography, various filtering and crossing arc techniques can be used to eliminate orbit errors, and here the ability to correct for refraction due to the ionosphere and the wet component of the troposphere as well as the precision of the altimeter becomes important. Finally, the row labeled precision represents the instrument noise or the consistency of the altimeter in repeating a given height measurement.

As seen from Table 3.1, there will be no satellite altimeter in space from 1978 until sometime in 1984 when the GEOSAT spacecraft is launched by the U.S. Navy. The primary mission for GEOSAT is the collection of topographic data for computation of a very-high-spatial-resolution global-mean surface. Waveform data and backscattered power observed by GEOSAT will be unclassified. However, raw altimeter height measurements from the nominal 18-month mission will be classified, and only residuals relative to a classified reference surface will be released. Hence, nearly a decade will exist between the launch of SEASAT and the next altimetric mission whose topographic data are fully accessible to researchers in an unclassified environment. These data

may come from the TOPEX, ERS-1, or POSEIDON missions, which are being planned for the late 1980s.

The TOPEX mission goal is to measure the surface topography over entire ocean basins for a period of 3 years (TOPEX Science Working Group Report, 1981). However, the spacecraft will carry sufficient expendables for an additional 2 years. Its orbit, mission duration, and instrumentation are optimized to meet this goal. The TOPEX satellite will carry a two-frequency altimeter to allow the height measurement to be corrected for a ionospheric delay and a three-frequency radiometer to allow correction for the wet component of the troposphere. In addition, it will carry a TRANET Doppler beacon with a highly stable oscillator to provide tracking data for precision orbit determination. This will be supplemented with a laser retroreflector and possibly a highly precise experimental GPS radiometric tracking system. The mission is proposed to begin in FY 1986, with launch in early 1989.

The Navy Remote Ocean Sensing System (NROSS), which is being proposed for a FY 1985 project start, will also carry an altimeter, together with a wind-field scatterometer and a microwave radiometer. The current payload configuration for NROSS does not include a laser retroreflector or a TRANET Doppler beacon to provide tracking data; hence, unless this configuration changes, the knowledge of its position will not be comparable with those of previous altimetric missions, which have relied on these tracking methods to provide high-precision positioning.

The European Space Agency Remote Sensing Satellite, ERS-1, is scheduled for launch in 1988. It will carry a SEASAT-class altimeter, as well as a microwave radiometer and combined synthetic-aperture radar/scatterometer. POSEIDON,* a French program, also is proposed to carry a SEASAT-class altimeter, together with a radiometer containing visible, infrared, and microwave channels on the SPOT-3 satellite. Both ERS-1 and SPOT-3 will be in sun-synchronous orbits. In addition, the Japanese plan to launch a SEASAT-class altimeter on their Marine Observation Satellite (MOS-II) late in this decade.

GEOSSAT and TOPEX are the only proposed missions that have recovery of ocean topography as their primary goal. NROSS, ERS-1, and POSEIDON have as their primary mission goals recovery of information on winds, waves, sea-surface temperature, and sea ice. The latter objective necessitates a high inclination orbit to provide polar coverage.

Table 3.2 indicates in a relative sense the potential science payoff of the missions introduced in Table 3.1. Where a symbol other than x appears, some characteristic of the mission prevents a substantive realization of that science objective. For example, the symbol SR (spatial resolution) for ERS-1 indicates that the 900-km track spacing of the initial calibration orbit prevents the recovery of

*Currently, discussions are under way concerning the possibility of making TOPEX and POSEIDON a joint mission between the United States and France.

TABLE 3.2 Potential Benefits from Altimetric Satellite Missions

		GEOS-3	SEASAT	GEOSAT	TOPEX	NROSS	EHS-I
MEAN CIRCULATION							
BASIN SCALE	>1000 km	AO	X	AO	XXX	AO	AO
INTERMEDIATE SCALE	300-1000 km	X	MD	X	XXX	X(Z)	SR
SMALL SCALE	50-300 km	X	MD	X	SR	X(Z)	SR
VARIABILITY							
"SYNOPTIC" MAPPING							
BASIN SCALE	>1000 km	AO	MD	AO	XXX	AO	AO
INTERMEDIATE SCALE	300-1000 km	XX	X	XX	XXX	X(Z)	SR
SMALL SCALE	50-300 km	X	X	X	X	X(Z)	SR
STATISTICAL SAMPLING							
BASIN SCALE	>1000 km	AO	AO	AO/TR	XXX	AO/TR	AO
INTERMEDIATE SCALE	300-1000 km	TR	MD	TR	XXX	TR	XX
SMALL SCALE	50-300 km	TR	MD	TR	XX	TR	X
GEODESY							
BASIN SCALE	>1000 km	AO	AO	AO	XXX	AO	AO
INTERMEDIATE SCALE	300-1000 km	XX	XXX	XXX	XXX	X(Z)	SR
SMALL SCALE	50-300 km	XX	X	XXX	SR	X(Z)	SR

AO - LACKS ACCURATE ORBITS

X SOME POTENTIAL

SR - LACKS SPATIAL RESOLUTION

XX MORE POTENTIAL

TR - LACKS TEMPORAL RESOLUTION

XXX MOST POTENTIAL

MD - LACKS MISSION DURATION

(Z) - HIGH INCLINATION ORBIT DEGRADES
RECOVERY OF ZONAL COMPONENTS
OF TOPOGRAPHY

intermediate- and small-scale topography other than along track. Also, the only mission currently planned to have orbits accurate in the radial component to the 10-cm level over ocean-basin length scales is TOPEX. Hence, it is the only mission that can recover basin-scale topography to a corresponding accuracy.

3.2.2 Ocean Circulation and the Gravity Field

The past few decades have witnessed significant progress toward understanding the ocean circulation. In the years since World War II, oceanographers have developed a good understanding of the fundamentals of the physics of fluid flow, and now geophysical fluid dynamics provide a theoretical framework into which could be placed observations

from a number of novel instruments that have become available recently. The computer has made possible the creation of numerical models that describe the dynamics of entire ocean basins and has provided the means to process large data sets necessary to initialize and drive these models.

As a result of the advances in computer and instrumentation technology, the oceanographic community is now ready to undertake the fundamental problem of understanding the general circulation of the world's oceans. As recently as 10 years ago, too little was known about circulation, and instrumentation was unavailable to attempt a program such as mapping the global general circulation. However, the development of altimeters and scatterometers has provided the capability to measure globally and nearly synoptically sea-surface topography and winds, and satelliteborne microwave radiometers provide the necessary corrections for atmospheric influences on the altimetric and scatterometer data. Data from these instruments significantly enhance the feasibility of understanding global circulation, especially when coupled with conventional and novel in-situ measurement techniques such as acoustic tomography, inverted echo sounders, satellite-tracked drifting buoys and floats, and improved current meters and hydrographic instruments, as well as programs to measure passive trace elements such as fluorocarbons or tritium.

Fundamental requirements for the extraction of the circulation signal from altimetric data are (1) altimetric height measurements accurate to a few centimeters, (2) knowledge of the marine geoid to an accuracy of a few centimeters on scales of a few tens to thousands of kilometers, and (3) knowledge to a few centimeters of the altimeter's position in space relative to the center of the mass of the earth. With this information, the topography of the ocean relative to the marine geoid can be determined. The topography, together with wind data and appropriate in-situ data, will allow oceanographers to test hypotheses of the linkage between ocean circulation and winds. The temporal variation of dynamic topography obtained from altimetric repeat-track data will yield information on the time-varying component of circulation.

Knowledge of the mean and time-varying components of global circulation would help to provide the answers to a number of questions being asked by society. These include: (1) What is the role of the ocean in determining our present global climate and its fluctuations, for example, the rate at which the oceans will absorb the increasing amount of CO₂ being emitted into the atmosphere and an understanding of the atmosphere/ocean interaction during the El Niño/Southern Oscillation phenomena are topics of critical interest? (2) What is the trajectory and ultimate fate on long time scales of wastes in the ocean, particularly those associated with radioactive materials? (3) What factors control and modulate the oceanic upwelling that supports the world's fisheries? The answers to questions such as these require knowledge of the general circulation of the oceans.

Climatologists and meteorologists are currently forced to parameterize the effect of the oceans on climate and weather in grossly oversimplified ways. Ultimate understanding of how climate and weather

are controlled and changed requires first a comprehensive description of the global-scale ocean circulation and, second, a much deeper understanding of its physics and chemistry.

The magnitude and horizontal scales of important oceanic flows vary. Mean flows such as the eastern and western boundary currents and large gyre circulations have pressure signals on the order of 10-100 cm on length of scales of 100 to 10,000 km. Time-dependent eddies (weeks to months) and seasonal variations have signals on the order of a few centimeters to a meter and scales of 30 to 10,000 km.

The change in the sea-surface height associated with the surge of water from the western to the eastern Pacific during an El Niño event can change relative sea level from 10 to 50 cm depending on the severity of the event. For example, during the El Niño event of 1972, a change in sea-level height of approximately 50 cm was observed between the Galapagos Islands in the eastern Pacific and the Solomon Islands in the western Pacific (Wyrki, 1977). However, the initiation of an El Niño can begin with subtle and almost imperceptible changes in the atmosphere and ocean. Hence, very small anomalies in the ocean-atmosphere system in such quantities as sea-surface temperature, pressure, and sea level must be detectable. Because El Niño is a basin-scale phenomenon, highly accurate altimetric measurements of sea level over these length scales are desired. This implies the need for either repeat-track orbits or an accurate geoid as a reference surface for sea-level variations.

An equally accurate gravity field at satellite altitude for determination of the satellite position relative to the sea surface also is necessary in order to minimize the long-wavelength error in ocean topography. A rule of thumb is that the gravity field for orbit determination must be known at wavelength equal to or greater than the satellite's altitude. For TOPEX, this implies a knowledge of the spherical harmonic representation of the gravity field through degree and order 30 plus a few higher degree and order terms with which the orbit is in resonance.

For time-dependent oceanic processes, it is important to note that the gravity determination requirement is somewhat weakened, as any time-dependent change in the sea surface must be oceanic. A mission such as TOPEX, with 3 to 5 years of repeat-track orbits, should separate the time-dependent sea-surface elevations from the means. However, auxillary measurements from in-situ instruments will be required for greater understanding of the structure of time-dependent ocean processes.

On short time scales, there are other important flows that manifest themselves as surface-pressure gradients without geostrophic balance. Among these are tsunamis, which are long gravity waves, storm surges, and tides. Storm surges and tsunamis are phenomena of great importance along coasts and large lakes. Tides are global phenomena that until recently were observed in highly restricted locations--tidal stations along coasts and even inside estuaries. The recent development of deep-sea pressure gauges has helped to clarify the picture of how tides progress around the globe, and accurate measurements of sea-surface elevation on a global basis from space should make a substantial

contribution to the modeling of tides. Tidal dissipation influences the ocean circulation and is important in the evolution of the Earth-Moon system. Tides in the solid earth are sensitive functions of the physical properties of the crust, mantle, and core. The tidal signal also appears in measurements of gravity, tilt, and strain, and improved knowledge of the tides will result in more accurate measurements of these quantities. For astronomy and for space-geodetic measurements, the tides are an important factor in station locations in three dimensions relative to the Earth's center, the Earth's moment of inertia and, hence, the length of the day, the secular retardation of the rotation of the Earth, measurements of polar motion, satellite positions, and the deceleration of the lunar longitude. While the requirement for a precise marine geoid for the extraction of these short-time-scale phenomena is not nearly so severe as for stationary or quasi-stationary oceanic signals, precise knowledge of the geoid would significantly enhance the detection and modeling of the short-time-scale phenomena.

In a broad sense, the large-scale circulation of the ocean is also at least partly a product of the instantaneous configuration of the seafloor. As the seafloor subsides with age, as continents drift relative to one another, and as global-spreading rates vary, mean sea level can change, new avenues can be opened for major bottom currents, and the bottom boundary condition will slowly evolve. An understanding of ocean circulation and its influence on climate in the geologic past and in the future is closely tied to an understanding of the changes in ocean bathymetry through time associated with plate dynamics.

3.2.3 Present and Near-Future Knowledge of the Gravity Field

While the gravity field at long wavelengths (10,000 km) is known to better than 5 cm, knowledge of the geoid at 2000-km resolution is ± 0.4 m and at 100-km wavelength is on the order of 1 m (see Section 1.2). Since it is desired to measure ocean topography to a few centimeters at all wavelengths, more than an order-of-magnitude improvement of the marine geoid at short wavelengths is required for direct applications of altimeter data to the problem of mean circulation.

Also, knowledge of the gravity field at wavelengths greater than 1000 km needs improvement by a factor of 2 to 4 in order to support the orbit determination and oceanographic requirements of missions to be flown late in the 1980s. Four-year gravity-model-improvement programs began in 1983 in both Europe and the United States directed at an improvement of the long-wavelength (1000 km) gravity field by this amount. This goal will be accomplished by using improved mathematical models and by reprocessing historical satellite tracking data as well as tracking data that have not previously been used for gravity recovery. Figure 3.2 illustrates the cumulative geoid undulation for current satellite and satellite-plus-altimeter data gravity models. Also shown are the anticipated results from the gravity-model-improvement activity under way to improve the gravity field for TOPEX applications and the estimate of results for the GRM. Also illustrated

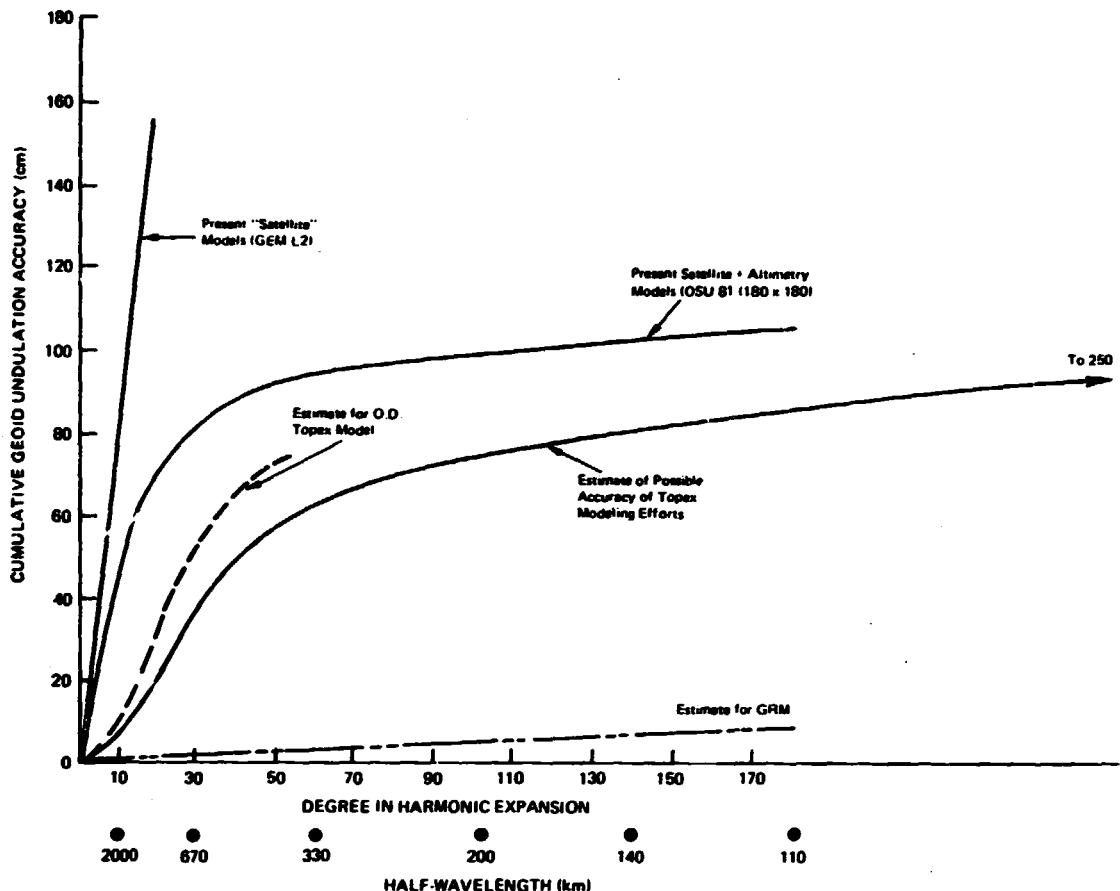


FIGURE 3.2 Cumulative geoid undulation accuracy for present/Topex gravity models.

is the accuracy anticipated for TOPEX as a result of gravity-model-improvement efforts.

The GRM, planned to be flown in the 1990s, will improve the short-wavelength portion of the geoid (200 km to 2000 km) to the 5-cm level. For political and logistical reasons, there are clearly no acceptable alternatives to satellites for gathering gravity data on a global scale. Hence, it is necessary that the GRM be flown to realize the goal of describing the global mean circulation. However, to meet the requirements of geoid knowledge to a centimeter or better ultimately required for oceanographic circulation, a concept other than satellite-to-satellite tracking being employed on GRM will be necessary. To reach this accuracy, cryogenic gradiometers or techniques with similar potential accuracy are needed.

3.2.4 Physical Oceanographic Requirements for Geodetic Data

Assuming that the slate of altimetric missions scheduled to be operational in the late 1980s and early 1990s are successful, what will be the oceanographic requirements for geodetic data in the year 2000? At this time, it is likely that the global geoid at wavelengths greater than about 200 km should be known to the 5-cm level. If the GPS receiver proposed for TOPEX is flown and functions as expected, the ability to determine the orbital altitude of a satellite will be at a comparable level.

The ultimate goal in knowledge of the global circulation requires knowledge of the dynamic topography to the centimeter level at all wavelengths greater than about 30 km. This would allow the use of altimetric data for mapping of eddy and current meander fields and for the initialization of numerical circulation models. In particular, high accuracy of the geoid is required in the vicinity of seamounts in areas of circulation activity. In these areas, there is high correlation between topography due to geostrophic flow and the geoid anomaly due to the seamount.

The technology to build altimeters to the requisite accuracy exists today. However, it is impossible to obtain both high temporal and spatial resolution from a single nadir-looking altimeter; therefore, the development of multibeam altimeters should be pursued (Bush et al., 1984). The multibeam altimeter with a nadir-looking beam and two beams spaced approximately 50 km on either side of the ground track would provide mesoscale resolving capability with sufficient temporal resolution for mapping mesoscale features.

The most challenging requirement in the coming decades is determination of the marine geoid and the satellite orbital height to the centimeter level. As stated earlier, the short-wavelength requirement for the marine geoid probably cannot be met by the satellite-to-satellite tracking techniques used for the GRM. Hence, a gradiometer mission or other alternatives should be explored. In addition, advances are needed in the areas of data processing, storage, and handling in order to accommodate the large satellite and in-situ data bases required to meet the high-resolution geodetic and oceanographic requirements of the coming decades.

The GPS receiver to fly onboard TOPEX should allow orbit determination to the 5-7 cm level in the radial component of the orbit. Future improvements in this concept will facilitate orbit determination at the centimeter level. However, significant improvements in our ability to model the forces that perturb an orbiting satellite must be made. In particular, modeling improvements are necessary in the areas of atmospheric drag and solar radiation pressure, both direct and reflected from the Earth. In addition, enhancements in the GPS satellites must be made to allow more accurate positioning of the constellation relative to the center of mass of the Earth. For example, cross-link ranging between the GPS satellites accurate to a centimeter combined with centimeter ranging from the GPS satellites to a few ground stations would be desirable.

In order to provide the necessary topographic, geodetic, and orbit data required for determination of oceanic circulation in the year 2000, a number of programs are needed. These include the following:

1. A geodetic mission that improves knowledge of the global marine geoid to the centimeter level for wavelengths greater than 30 km.
2. Continued precision and accuracy improvements in altimeter hardware to allow ranging to the centimeter level.
3. Multibeam altimeter technology to remove the spatial and temporal sampling constraints imposed by a single-beam altimeter, multibeam-altimeter technology.
4. Improvements in orbit determination technology with emphasis on perfection of satellite-to-satellite tracking techniques being considered for the TOPEX mission.
5. Continued advances in techniques for data processing, handling, storage, and distribution in order to accommodate the needs of future geodetic and oceanographic missions.
6. Continued improvement of mathematical techniques and models in oceanography, geodesy, and orbit determination.

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3.3 MAPPING AND LAND SURVEYING

The horizontal control network established by the National Geodetic Survey (NGS), as described in Chapter 1, defines a spatial reference framework through which all the mapping and field measurements in any given area can be spatially integrated. Nevertheless, many maps and land surveys, typically those devoted to a single purpose or project, are performed with no attempt to orient them to a geodetic framework or to the general reference maps or surveys of the local area. Even a large-scale map in which all relative positions are shown accurately to within a fraction of a meter may give no indication of positions in relation to the geodetic reference framework. Unless a map is oriented to that framework, its contents are like an island with a floating location.

A map or a land survey that brings together positional data from several source maps or prior surveys requires some framework for spatial registration of all of these sources with each other. The standard method of registration is to assure that all the positional data from each source are oriented to the standard geodetic reference system. Rectangular coordinates (eastings and northings), which refer to a plane-coordinate grid system, provide a reliable method for stating geodetic positions. The orientation of the grid is given by determining the precise coordinates of the positions of a network of control points, constructed as monuments that can be readily located on the ground and included in any map or survey of that area. These geodetic control points are used for spatial registration of the different maps or other sets of overlapping geographic data. They are like the pins used to keep the overlays of a map system in correct physical alignment with each other, as illustrated in Figure 3.3.

A multipurpose cadastre is a system of large-scale maps and survey records designed to support an array of local uses, incorporating definitive source records for each use, including land ownership. The foundation for a cadastre is the geodetic reference framework, as indicated in Figure 3.4. Registration to the geodetic reference framework is essential for maps or surveys intended to serve several users. This assures that their contents can be oriented to other sets of geographic data, including those of future users whose other sources may be unknown at the time of the initial mapping or survey.

Geodetic data serve in other mapping-related areas, such as providing a unique reference system for measurement of land movements, whether of continental or more regional scope. They are widely used by local surveyors and engineers as checks against blunders and against the accumulation of excessive errors in developing maps for extensive projects or programs, e.g., for transportation facilities. In terms of the need for systematic error control, a modern map is similar in many ways to any other data base, a fact that was not apparent in the days when maps were produced with quill pens.

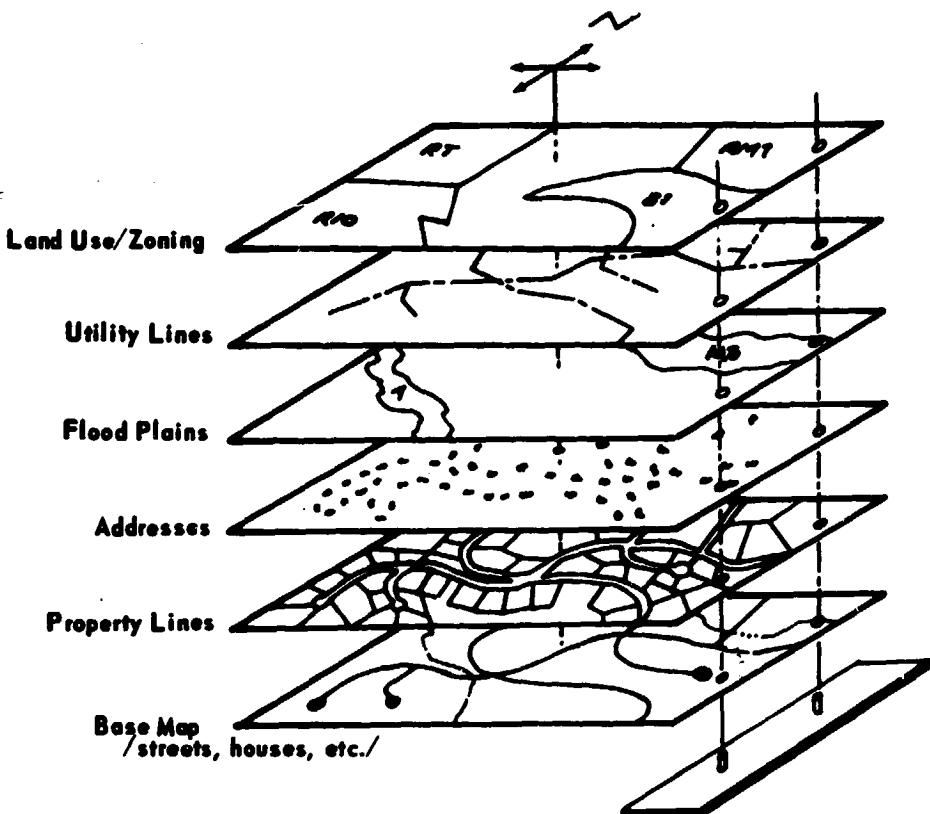


FIGURE 3.3 A registered overlay system. Committee on Geodesy, 1983, p. 42.

3.3.1 Use of Geodetic Control in Mapping

Where land mapping currently is tied to geodetic control, the control points must be dense enough to assure that positions scaled from the map are accurate with respect to the control within some stated tolerance. The latter is a function of map quality. The density and the precision of the network of geodetic control points needed for a mapping project depends on the scale of the eventual map product. The larger the scale of the map (i.e., the closer to the scale of the actual landscape), the greater the precision of mapping required and, therefore, the more precise and dense the network of control points needed. Smaller-scale maps cannot be scaled with such high precision and therefore are less demanding in the precision of geodetic control required to orient them.

Map scales vary according to intended use. Land of any significant value normally has been mapped at several different scales, providing a hierarchy of map systems serving their respective users. The general ranges of typical map scales are as follows, of which the largest scales of maps normally are found only for dense urban areas or other construction sites, and the second-largest only in areas with some urban development.

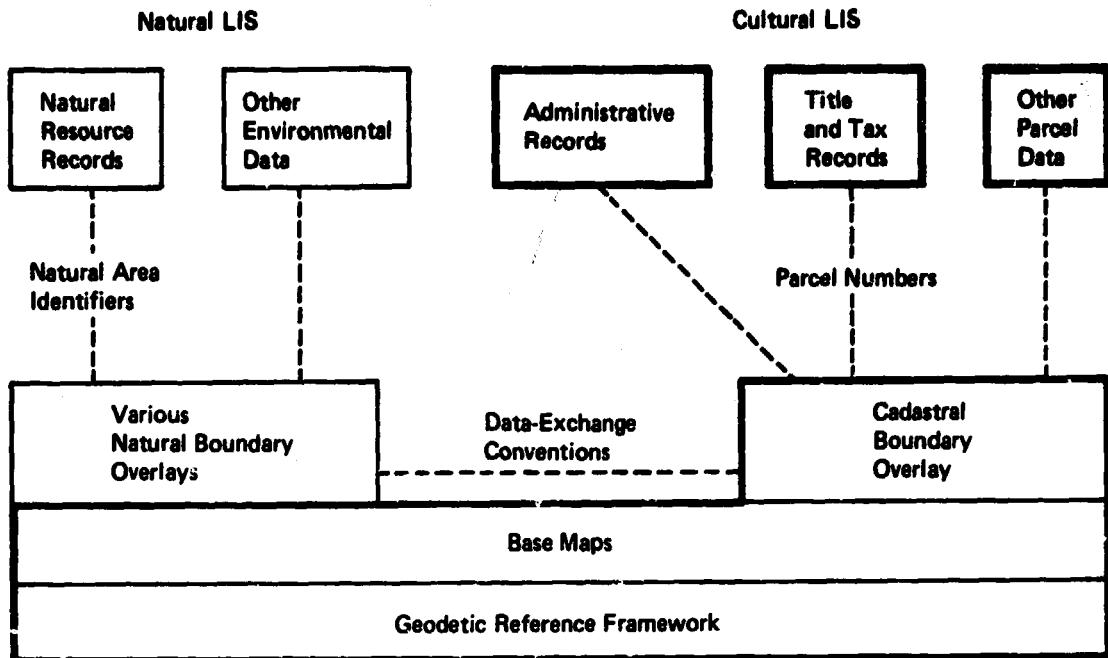


FIGURE 3.4 Components of a multipurpose cadastre (in heavy outline) as the foundation for Land-Information Systems (LIS's). Committee on Geodesy, 1983, p. 16.

General Ranges in the Hierarchy of Map Scales

Individual maps of specific sites:	1:500 or larger
Large-scale maps for local applications:	1:500 to 1:5000
Medium-scale maps for regional applications:	1:5000 to 1:100,000
Small-scale national map series:	1:100,000 or smaller

Standards of Accuracy, Relative to Scale of the Map

National map accuracy standards refer to the positioning of the graphic elements on the final mapping product, whatever its scale. The standards for maps with scales of 1:20,000 or larger require that at least 90 percent of the positions plotted on the map be within 1/30-inch of the projection of their true positions. For scales of less than 1:20,000, which includes most federal mapping, the standard is 1/50-inch (Committee on Geodesy, 1983). Thus, the familiar 7-1/2-minute quadrangle maps published by the U.S. Geological Survey at a scale of 1:24,000 are expected to show most positions within 12.2 m (40 feet) from their true positions on the geodetic grid.

Applications that require measurements to be made with greater precision must use maps with an appropriately larger scale. For example, if the distance between two plotted points must be measurable to within 30 cm (1 foot), e.g., for site planning, then the map must

have a scale of 1:360 (30 feet per inch) or larger, if produced to national map accuracy standards. When map measurements as precise as 30 cm are needed, however, this is normally a requirement for the relative distances between nearby points, rather than for positions on the geodetic grid. The base maps used for most site development plans, for example, are tied only to local control points and not to a geodetic grid.

However, the use of local control assumes that all the other overlays or surveys from which the precise measurements are needed also are tied to the same pins of local control. Local control is seldom adequate for the mapping that supports engineering and development of large projects, such as transportation or utility lines, which may extend for many miles. Standard practice for mapping and recording of rights-of-way includes referencing the boundaries to geodetically-based coordinate systems, as described in Section 3.4.1.

The precision required for ties to the geodetic network depends on needs for measurements using other overlays not tied to the large-scale local control, e.g., maps of flood plain boundaries, soil types, or highway easements that cover larger areas. Land-development projects often manage without geodetic control except for the use of these integrated, areawide maps produced by others, recognizing that there may be variations of up to 1 m in measurements taken from standard maps at the common urban scale of 1:1200. Any recognized monuments in the vicinity can then be used for the more precise site-planning data, e.g., for positions of property lines and existing structures, even though the local monuments may not carry geodetic coordinates precise enough for geodetic registration of these local field measurements.

Densities of Geodetic Control Needed for Mapping

Most map information comes from aerial photography. Except in very flat terrain, the photographs must be taken with sufficient overlap so that adjacent pairs of photographic images can be combined in "stereo models." There must also be sufficient overlap among the stereo models to establish their relative positions with respect to each other, that is, to tie them together into a composite "block" covering the entire mapping project. The block of stereo models is then scaled, rotated, and translated to fit to the geodetic control.

The photography used to build the stereo models also can be used to determine accurately the relative relationships among a network of selected points visible in the photographs using aerial triangulation. This can tie the maps to the positions of all local control points of importance to the local users, such as legal boundary markers. The entire block of stereo models can be oriented to the geodetic grid with a much smaller number of geodetic control points--perhaps one such point per map sheet, where a dozen or more map sheets are involved.

The horizontal control network of geodetic control points already available from the National Geodetic Survey (NGS) appears to be sufficient to support even the largest-scale maps produced in the national mapping programs, specifically, the 7-1/2-minute quadrangle

maps at the scale of 1:24,000. The ratio of 1 control point per 7-1/2-minute quadrangle has been suggested as the minimum standard. This ratio has already been exceeded in the coterminous 48 states, on the average, but not in all areas. The 1:24,000 map series uses about 54,000 quadrangles to cover the these states. As noted in Chapter 1, the horizontal control network maintained by NGS currently contains about 150,000 points with positions measured to third-order accuracy or better (when Alaska and Hawaii are excluded). The density of available survey control thus is not often a problem for federal mapping programs, although it often is for the larger-scale mapping programs of state and local governments.

Geodetic Positioning for Nautical Charts

Referencing of positions for nautical charts must be treated differently (except for the land portions of these charts, which are treated the same as land mapping). Positional systems are established ashore and tied to control points, so that positioning of sounding vessels is consistent with geodetic control. In the future it may be possible to use the GPS, in the Precise Positioning Service mode, instead of shore stations, depending on the outcome of studies now under way. The adequacy of the GPS for these purposes will depend on the scale of development as well as the inherent accuracy of the Precise Positioning Service.

The Geodetic Survey of Canada and NGS have agreed to adopt the North American Datum of 1983 (NAD 83) in agreement with the Geodetic Reference System 1980, as approved by the International Association of Geodesy of the International Union of Geodesy and Geophysics in December 1979. This redefinition of the North American Datum envisage the use of the world reference ellipsoid and a simultaneous adjustment in a geocentric system of all available observations, including geocentric positions derived from Doppler data.

It is expected that the National Ocean Service (NOS), which includes NGS, will begin converting all nautical charts to NAD 83 when final datum computations and adjustments have been completed. This is now tentatively scheduled to begin in 1985 and as workload dictates will be accomplished by the eventual reconstruction of existing nautical charts and constructing new nautical charts on the new datum. In the interim, a selection of notes will be available that are designed primarily for use on certain long-term and other nautical charts before 1985 and for those charts on which the projections cannot be changed because of resources or other constraints.

In recognition of the implementation of NAD 83 and until guidance to the contrary is received from the International Hydrographic Organization, NOS intends routinely to place one of these notes, as appropriate, on nautical charts of scales 1:1,000,000 and larger where numerical data for the note can be furnished. While the text of the notes will refer only to plotting uses, it should be understood that the numerical differences stated (although they are a mean value for that chart) may also be used in simple calculations.

The first NOS nautical chart to be produced on NAD 83 is the new edition of chart 26194 of Navassa Island, 4th Edition, September 4, 1982, covering a small U.S. island lying about 30 miles west of Haiti. It takes full advantage of hydrographic and topographic surveys conducted by NOS at the request of the Defense Mapping Agency (DMA) and uses the most up-to-date positional reference system available. The adjoining nautical charts produced by the DMA are on the equivalent World Geodetic System of 1972 (WGS 72). The ellipsoid used for NAD 83 has very nearly the same defining parameters as those of the WGS 72 ellipsoid, with changes in horizontal positions not exceeding 5 m.

Bathymetric and topographic/bathymetric maps will be compiled on NAD 83 when final datum computations and adjustments have been completed. In addition, newly published 1:24,000- and 1:100,000-scale topographic/bathymetric maps have either a note or ticks to convert the map projections from North American Datum 1927 (NAD 27) to NAD 83.

The Great Lakes region is an area where much horizontal reference datum work remains to be done. Many of the nautical charts of the Great Lakes are on North American Datum 1902, and neither sufficient shoreline topographic surveys nor adequate triangulation is available to reconstruct these charts on either NAD 27 or NAD 83. NOS will need to establish new control in much of the Great Lakes and to conduct shoreline surveys before the charts are placed on one common datum and the joint chart production program with the Canadian Hydrographic Service can continue as planned.

The Automated Information System of NOS uses data collected chart by chart. Thus, individual charts can be retrieved from the data base without loss of graphic integrity regardless of horizontal datum. However, individual features may be loaded more than once, for separate overlapping charts. Specialized products that use data from sources of different geodetic origin require off-line routines to adjust horizontal datums. Only when all data in the data base are keyed to the same datum is one assured that any subset of data retrieved can be used to produce an integrated graphic without some additional massaging of the geographic positions of some selected features. The necessary parameters for writing these software routines will have to be provided by geodesists.

Positioning of Other Geographic Data Sets

In the mapping of geophysical data, such as gravity and magnetics, ties to geodetic control are made in much the same manner as soundings for nautical charts, but the methods of determining positions will vary greatly. In any event, surveys used for federal maps or charts start from control, or positioning systems are established on control, so that the surveys are compatible with geodetic control.

One should not draw the conclusion that all existing maps and charts are tied to geodetic control as we know it today. Many charts relate to local or obscure geodetic systems with little chance of being tied to a preferred datum such as NAD 27 or ED 50 (the 1950 European Datum). Even the positions used for points in these preferred datums

must be revised from time to time, as evidenced by the effort going into NAD 83 and ED 79 (the 1979 European Datum). The upgrading of maps with inadequate geodetic control for current users is a long, evolutionary process.

3.3.2 Use of Geodetic Control in Land Surveying and Cadastral Records

Most land surveys in the United States today are completed for an individual transaction or land development. The professional surveyor normally is free to set the standards of quality of the survey work, depending on needs of the client. Where public standards are established for the work (a function of local governments in the United States), requirements are normally set relating to the specific purposes of the survey, rather than for the use of survey results for other purposes. For example, survey standards typically concern the accuracy and performance of monumentation of the boundaries, if the transaction is a land subdivision, or relative certainty of the positioning of structures within an individual site, for a land-development survey. In most parts of the United States there remains a gap in what ideally should be a continuum of land-management information, from the fine-grained and detailed local surveys to the coarse-grained and general areawide surveys and mapping. At the coarse-grained end are the natural-resource data systems, which are relatively comprehensive and are oriented to geodetic control but lack the precision or spatial resolution to be considered, say, in site planning or in valuation of urban land parcels. At the fine-grained end are the property surveys and records, precise in their measurements of positions relative to their immediate surroundings but typically unrelated to each other or to the geodetic framework. Because of the gap, these two sets of land-management information essentially are noncomparable (Dahlberg, 1984).

The typical natural-resource data systems are closely tied to the national mapping systems, especially at the 1:24,000 scale. Through this mapping system they take advantage of the geodetic reference framework for spatial registration of other data sets at their respective scales, in the manner described in Section 3.3.1. Local land surveys, in contrast, remain mostly unrelated to geodetic control. Furthermore, it appears doubtful that most local land surveys will reach beyond their present realm of local relative positioning until local governments assume the task of building and maintaining at least the survey control component of a cadastre.

The value of integrating the different levels of land-information systems with spatial control has been demonstrated by local initiatives in various parts of the United States. Typically, these are efforts of county governments responsible for managing the rapid subdivision of rural land for urban uses, at the edge of an expanding metropolitan area. Several examples are cited in the latest report on multipurpose cadastres by the Committee on Geodesy (1983). These local programs are developing the experience needed eventually to tie the land records of

all the 3143 county-level jurisdictions in the United States to geodetic control.

Recording of Local Surveys

Standards for the practice of land surveying in continental Europe stand in strong contrast to the transaction-oriented approach of the United States, as described above. There, the maintenance and continuing improvement of the combined results of all local land surveys are a responsibility of the cadastre office of each local district. The professional surveyor is responsible to the public authorities for the accuracy and consistency of the measurements in the context of all available records of prior surveys in that area. The work must be adequate to support other, future uses of the results beyond the needs of the present client.

The extent to which geodetic data have an application in land surveying thus will depend heavily on the extent to which local governments choose to require the results of land surveys to support other needs beyond the immediate transaction. Local government initiatives of this type are seldom taken without support from the state government, including enabling legislation and administrative guidelines, and may even require state financial assistance. State governments, in turn, are likely to be slow in taking this leadership without at least technical support from the responsible federal agencies.

A case for leadership of both state and federal governments in sponsoring cadastral record systems at the county level was made in two reports by the National Research Council (Committee on Geodesy, 1980, 1983). Such systems would integrate the results of the many, overlapping local mapping and land surveying projects, using a network of geodetic control points as the basic spatial framework. All surveys recorded in the system would be tied to the first- and second-order horizontal control established by or in conformity with the standards set forth by the Federal Geodetic Control Committee (1974). Figure 3.4 shows the components of a multipurpose cadastre as set forth in the National Research Council reports (Committee on Geodesy, 1980, 1983).

Access to Geodetic Control

To make such an effort a viable option at the local level, it is essential that monumented stations of the primary network of the NGS be readily available to the local agency involved. For local applications, adherence to the specifications of the Federal Geodetic Control Committee (FGCC) need not be rigorous for all elements, although some of them must be strengthened. At this level requirements for positional certainty with respect to adjacent stations supersedes requirements for overall network certainty. In metropolitan areas, relative uncertainties may need to be less than 5 mm between adjacent control

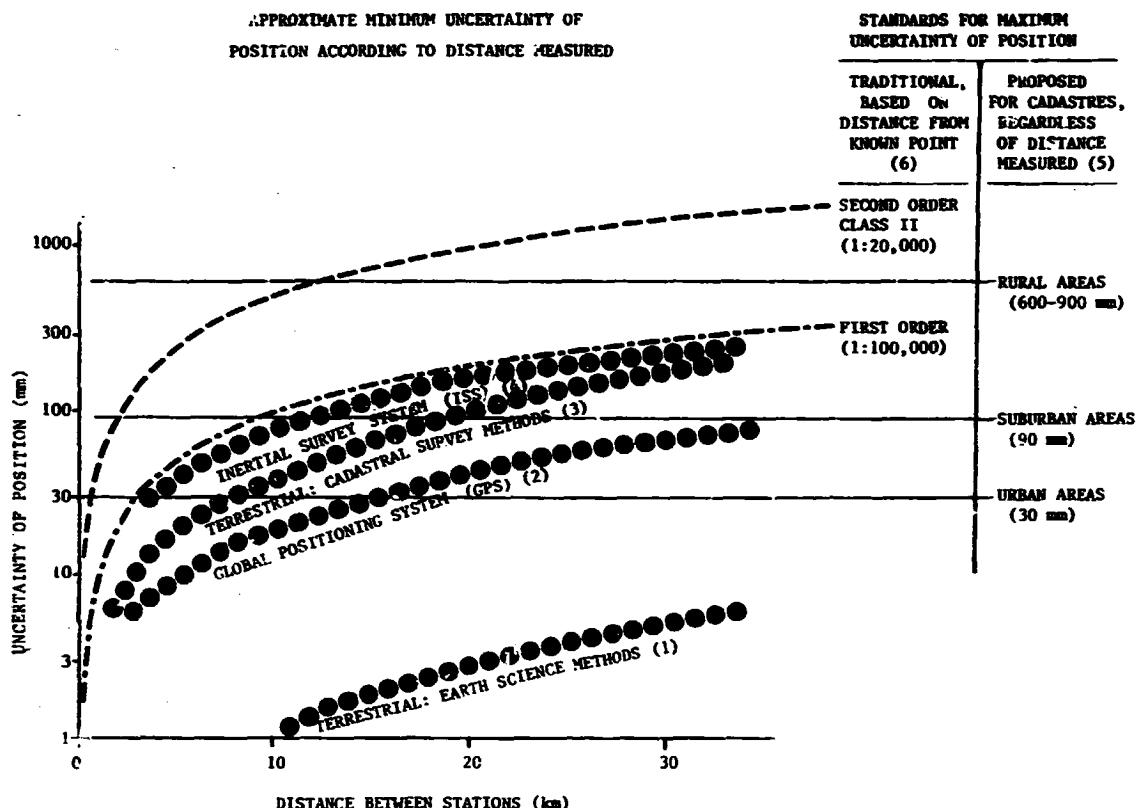


FIGURE 3.5 Approximate best (minimum) level of uncertainty available compared with maximum acceptable.

REFERENCES: (1) Savage and Prescott (1973); (2) Bock et al. (1984), Chrzanowski et al. (1983); (3) Chrzanowski et al. (1983); (4) Chapman (1983); (5) McLaughlin (1977); (6) Federal Geodetic Control Committee (1974).

stations, while in rural areas uncertainties of up to 20 mm may be acceptable.

The Committee on Geodesy (1983) has advanced less-stringent standards for the accuracy of cadastral surveys, which determine the positions of the actual property boundaries. Citing a study by McLaughlin (1977), the Committee suggested maximum uncertainties in boundary positions of ± 30 mm in urban areas, ± 90 mm in suburban areas, and ± 300 mm to 600 mm in rural areas. These maxima are represented by the horizontal lines in Figure 3.5, which compares alternative survey technologies. Where land values are relatively high, these levels of uncertainties of position may be unacceptable. They were suggested by the Committee on Geodesy as national maxima, to promote at least a basic expectation for cadastral surveying in all parts of the United States that will not appear prohibitive in cost to local governments.

The requirements stated above obviously are much higher than those needed for mapping alone. Nevertheless if a control system is to be established, the positions of its monuments should be certain enough to be used in resolving conflicts between adjacent owners. Lesser positional certainties of 0.1 to 0.3 m at ground scale will allow gross blunders in existing records to be picked up in the graphics process at scales of 1:1000 and 1:500 (e.g., for the benefit of tax-levying agencies) but are not sufficient to position improvements on the land itself.

Attention must be given not only to the certainty of positions but also to the density of available control. Most land surveys today are accomplished by terrestrial methods, measuring distances and angles directly from other points on the ground. The points in a geodetic reference framework for terrestrial surveys need to be spaced closely enough to be incorporated in any significant local survey. The surveyor in private practice can probably make an angle and distance tie to a visible existing station within the budget limit for almost any project and reasonably pass this burden on to the client. In the case of a survey being made to facilitate a land division or major land improvement, angle and distance ties to two or three visible stations within the range of his EDM device can reasonably be required. (For a comparison of these single-wavelength instruments with the current state of the art of electromagnetic distance measurement, see Section 2.1.1.)

To provide the required density of geodetic control, the Committee on Geodesy has recommended that networks of control points be maintained for use in local surveys, spaced at average intervals of 300 to 800 m (0.2 to 0.5 miles) in urban areas and 1.6 to 3.2 km (1 to 2 miles) in rural areas (Committee on Geodesy, 1983). The latter, rural-area requirement amounts to one control point per 3 to 10 km². The closer spacing of control points in urban areas responds to the greater difficulties of extending a line of sight to a control point.

The recommended spacing of geodetic control points comes close to the density of the system of property boundary corners established in most of the United States under the Public Land Survey System (PLSS). The corners of the mile-square sections of the PLSS mark the boundaries of rural land ownerships in the 30 states that have been subdivided according to this system and also have become the spatial framework for most urban areas in these states. A complete delineation of property boundaries in terms of the national geodetic coordinate system would require coordinates for the quarter-corners of the PLSS system, which are four times as numerous as the section corners. Use of the quarter-corners of all sections as the local control network has been recommended, both to locate precisely the boundaries of rural ownerships and to identify geodetic control with a network of familiar local markers spaced at intervals of one-half mile (Committee on Integrated Land Data Mapping, 1982).

Although the required control surveys can be accomplished with existing equipment and methodologies, their costs may be prohibitive. In 1984 dollars and with 1984 equipment first-order control costs between \$5000 and \$10,000 per station (including the establishment of

the monument, the triangulation, traverse and trilateration, and the adjustment) in an area with an existing density of one station per 50 km².

Accomplishment of the desired national cadastral will be dependent on reducing the above stated costs by a factor of about 10. The GPS and inertial systems and possibly photogrammetric and airborne/spaceborne laser-ranging systems now coming onto the market give promise of accomplishing this cost reduction. Once this is accomplished, the maintenance of the federal network at its present level should provide a sufficient geodetic framework to support cadastral requirements of the year 2000.

3.3.3 Future Possibilities

GPS is expected to produce a succession of changes in geodetic referencing for local land surveys, owing to its capacity to determine positions at levels of certainty that equal or exceed those of the traditional terrestrial methods for cadastral surveys. This has not been the case, to date, for the other recent positioning technologies such as the Inertial Surveying System (ISS), as suggested by Figure 3.5. (Also shown in this graph are the even lower uncertainties of position being achieved by the multiwavelength EDM systems described in Section 2.1.1, which have yet to be achieved by GPS for the distances shown here--30 km or less.)

Thus, by the year 2000, a land surveyor may find it more economical to determine the positions of the points he is surveying with electronic equipment oriented to a remote first-order control point, than with measurements directly from the established local third-order control points.

Geodetic Control Points

How much of the practice of land surveying will have been converted to the use of the revolutionary satellite-oriented positioning technology, such as the GPS as described in Section 2.3, by the year 2000? The possibilities depend on both the capital and manpower costs of operating this equipment, both of which can be expected to decline. Even the first-generation GPS equipment already has become a major factor in geodetic control surveys, for example, by the NGS. Some idea of how pervasive their use will become for smaller surveys is given in a paper by members of the Surveying Engineering faculty of the University of New Brunswick (Vanicek et al., 1984, pages 8-10):

. . . The modern [positioning] systems would be ideal if it were not for the cost, bulk and power demands of present instrumentation needed. Fortunately, the trend in modern electronics is toward lower cost, smaller and less power-hungry equipment (Langley et al., 1982).

In spite of the present drawbacks, the trend in the evolution of positioning systems is towards these space techniques. They are potentially more accurate, more "absolute", and less time consuming than the classical terrestrial techniques. With the miniaturization and cost reduction being experienced continually, it . . . is conceivable that, say 25 years from now, there will be highly portable (back packable) locators which will be capable of delivering 'almost instantaneous' positions (in 5 minutes?) good to a few centimeters. These may cost the equivalent of a few thousand 1983 dollars and will operate in a quasi-absolute mode, i.e., with the foothold point removed up to several thousand kilometers. These locators will, presumably, be owned by professional geodesists/surveyors rather than being everyday household items. However, it has been predicted that less accurate equipment will be an optional automobile accessory by the turn of the century (Yiu et al., 1982).

These locators will set the stage for a completely new era of positioning when accurate instantaneous position will become as commonly available a commodity as accurate time is now. The advent of this era will see many more uses for positioning than there are now, as discussed in, for instance, the publication by Chrzanowski et al., (1983).

If satellites are to be used as the basis of positioning for future land surveys, will there be any further need for the network of geodetic control points previously envisioned as the basis for a multipurpose cadastre? Whether the future land surveyor can make any use of the precise geodetic coordinates of the points he is surveying will depend on whether precise coordinates for the rest of the key points in the environment of his survey also are available. His primary responsibility still will be for the relative certainty of the positions of the new points with respect to that immediate environment. Thus, the new GPS technology provides the opportunity to enhance greatly the value of each new local survey, by maintaining some general system for recording the geodetic coordinates of all previous GPS surveys, for any important elements of the local survey environment. As a minimum, this should include the results of all new qualified surveys of property boundaries, as they become available. On the assumption that such a general record system is only likely to occur as a public function, it will mean creation of the cadastre as envisioned in the reports by the Committee on Geodesy (1980, 1983).

The paper by the faculty of the University of New Brunswick, quoted above, projects that the need for geodetic control points per se will diminish greatly with the shift to absolute positioning systems. Their conclusions are summarized as follows (Vanicek et al., 1984):

. . . it is easy to predict that the need for geodetic networks will fade out. There will be less and less need for "bringing positions close to market" because locators will not require "close-by" known positions of network points. Monumentation

will become more and more expensive compared with position determination itself and will be dispensed with. We cannot see that maintaining geodetic networks, the "crutch of positioning," would be viable in the long run.

We foresee that two exceptions to this will be (i) the networks for local surveys, aerial photography, and layouts, where it may pay off, during the intermediate stages at least, to have points temporarily monumented; and (ii) the networks for monitoring geodynamical and local deformations. In the second case, the need for continuing monumentation appears justified. But one may argue that these "monitoring networks" are really point information arrays, where the information associated with the markers is the movements rather than positions. Perhaps, to keep the terminology straight, we should call them geodynamical and deformation arrays.

The question then remains as to what will happen with [geodetic] frameworks. It seems to us that frameworks are here to stay: there will always be the need to have some reference points for the coming positioning systems. The frameworks will have to supply the foothold points; they will have to monitor the state of health of the positioning system and monitor the global deformations of the earth with respect to the selected coordinate system. Maintenance and operation of the frameworks will probably become the major geodetic task.

The networks will be with us for another 25 to 50 years, during which time they will or should be maintained, densified and strengthened as needed. However, the long-term future looks bleak for the "lovers of geodetic networks," the "densifiers," and the "network optimizers": geodetic networks are bound to go the way of the dinosaurs.

We foresee that the emphasis in geodetic efforts will shift gradually to the frameworks, their maintenance and real-time monitoring.

What new skills must be acquired by the operators of these revolutionary satellite-oriented technologies? What support will they need from the custodians of the geodetic control system? Again, the paper by the faculty of the University of New Brunswick suggest some of the possibilities (Vanicek et al., 1984):

The more "absolute" the positions become and the more accurate, the more the temporal variations caused by the body tide, tidal loading, ground subsidence, crustal rebound, tectonic movements, etc., will be in evidence. While most of these effects play only a marginal role in present day relative and/or inaccurate positioning, their effects will have to be taken seriously in the positioning of the future.

. . . In order to realize the potential of a [modern satellite-oriented] locator, the framework behind this locator will have to account for, understand, and model the ongoing deformations of the earth. Also, the contribution of

geodesists to the understanding and prediction of geodynamic phenomena (e.g., earthquakes) will become far more pivotal, as we approach the advent of such a location system. Serious and coordinated programs monitoring the irregular earth deformations will have to be put in place. Strategies for positioning on the ever-deforming earth will have to be devised, and a philosophy of how to deal with geodetic networks on a deforming earth during the next 50 years will have to be formulated.

Once the satellite-oriented positioning systems are in common use, the local geodetic control points recommended for a multipurpose cadastre will still be needed as markers for the more-frequent, interim positional referencing that may not justify a new land survey with modern positioning equipment. In other words, control points will continue to be significant to the extent they are also monuments that carry some legal, cultural, or scientific significance--as discussed in the following section.

Monumentation of Legal and Scientific Reference Points

Will the widespread use of the "absolute" positioning devices such as GPS result in legal definition of boundaries with reference to a geodetic coordinate grid, rather than to local monumentation, as at present?

The issues of "monuments versus coordinates" have been debated often in the surveying and legal professions. Specifying the position of a boundary corner by coordinates essentially gives a relative position with reference to an array of points, usually remote, the geodetic position(s) of which is known. The alternative is to give preference to a nearby marker or monument that can easily be located in relation to the boundary, even though its geodetic position may not be known. This latter type of boundary marker is easier to use for the occasional informal determinations of boundaries often needed with less accuracy than a new survey would provide (e.g., for defining the edges of a field for planting). A boundary corner position given by coordinates alone would be of only limited value for such day-to-day references, unless the coordinates of the other relevant, nearby points also are available. Furthermore, it has been the opinion of the courts that boundaries are located with greater authority by monuments that are visible than by coordinates.

Will there be sufficient incentives for any organizations, public or private, to invest in the upgrading and conversion of property boundary records to a geodetically oriented data base? This possibly could be required as part of any new survey of property for land development, which involves substantial financing and is subject to various types of public regulations. However, for all other properties, the retroactive determination of coordinates for the legal boundary definitions already on record would be a massive project. To date, such work seldom has been undertaken except to cure clouds on the

title or to register the positions of existing boundaries with a court. A "day-forward" requirement use of coordinates to define boundaries is more likely. This would amount to establishing a dual system, in which the existing, noncoordinate definitions would predominate for decades to come except in the most rapidly developing localities.

Nevertheless, a much stronger demand for the geodetic positions of important local points, such as property corners, is being created by the broader use of GPS for new surveys and of computers for storing, analyzing, and displaying the spatial data. A key step in responding to this demand will be to determine the actual positions of historically defined monuments that are in common use, by geodetic surveys at levels of accuracy appropriate for the land in each locality. Such a program was the primary recommendation of the Committee on Integrated Land Data Mapping of the National Research Council (1982) and has been endorsed by the Committee on Geodesy (1983).

Given that the ownership boundaries of about four fifths of the land area of the United States are oriented to the section corners of the PLSS, the PLSS corners comprise an invaluable network of reference points that also could tie together the local legal monuments and the geodetic coordinate system. The first of the two reports cited above recommends that all users of the PLSS section corners submit any coordinate locations that they determine for any of the estimated 2.8 million PLSS section corners in the United States for entry into a national digital cartographic data base (Committee on Integrated Land Data Mapping, 1982). The second report recommends the establishment of survey data depositories at the county level and their linkage with regional and national depositories maintained by higher levels of government.

Standardization of Large-Scale Mapping

Will the increasing use of computer graphics for maintaining large-scale maps as a digital data bases lead to common use of a single, coordinated system of such maps for each locality, tied to geodetic control?

The application of computer graphics technology to the building and maintaining of large-scale digital mapping systems has spawned the new field of automated mapping/facilities management. Several national associations are including this as one of the fields covered in their annual conferences, and private vendors are beginning to market digital mapping systems and services for cadastral boundaries. Almost without exception, however, the new digital maps are being built and maintained separately by the several organizations that formerly maintained their own, separate hard-copy mapping systems: local governments and the individual public utility companies.

The one significant exception is the Regional Mapping and Land Records (RMLR) project of the Philadelphia metropolitan region, described in a report of the Committee on Geodesy (1983). Possibly this is simply the exception that proves the rule of proliferation of

independently maintained computer mapping systems. Quite possibly, however, the RMLR project points the way to conversion of the large-scale mapping system in each metropolitan area to a jointly maintained digital data base at an opportune time, e.g., when two or more of the major mapping organizations are ready to invest in upgrading their map systems.

Although the independent local engineering offices continue to maintain separate digital maps, there remains the possibility that they will start to share the files of positional data that they need for certain basic local point arrays such as street rights-of-way. Offices that do primarily thematic mapping of census data are already finding it economical to purchase computer-readable files of the boundaries of statistical areas, such as states, counties, or census tracts, rather than attempt to digitize these boundaries themselves.

What institution could become the custodian of the digital files of at least the skeleton for all the large-scale maps in each locality, e.g., of all street rights-of-way and center-lines, in the manner that the U.S. Census does for census tracts and larger areas? The logical possibility in each area would be the county-level government office responsible for mapping, such as the County Engineer or, where such offices exist, the County Surveyor or County Land Records Office. Agreement on standards for data definitions and accuracies will be important for such sharing to occur and may depend on the leadership and research efforts of federal agencies. Among the essential standards will be the method of orientation to the geodetic framework.

3.3.4 Prospects for Multipurpose Cadastres

Traditionally, a cadastre ties together the land surveys, the legal boundary definition, and the large-scale mapping, discussed in the three preceding sections, in a coordinated system of maps and records. Such a legal cadastre could be visualized as the second layer of the diagram of a cadastre-based land information system in Figure 3.6. It relies on the first layer, geodetic control, to orient the mapping to the results of the land surveys. A multipurpose cadastre would then build on this system of legal property records to also coordinate other parcel-based registers of the locality, such as administrative and tax records. Additional overlays may be needed for mapping other sets of geographic elements, such as structures. With a multipurpose cadastre, a local government has the additional possibility of coordinating the mapping of infrastructure networks or other natural features that are not parcel-based, as an extension of its cadastre-based land information system.

The Committee on Geodesy (1980 and 1983) has described its recommended programs for multipurpose cadastres in some detail. Will local governments in the United States find sufficient incentives to coordinate their land records in this fashion, based on geodetic control, as has become standard for most of continental Europe and many parts of Asia and Africa?

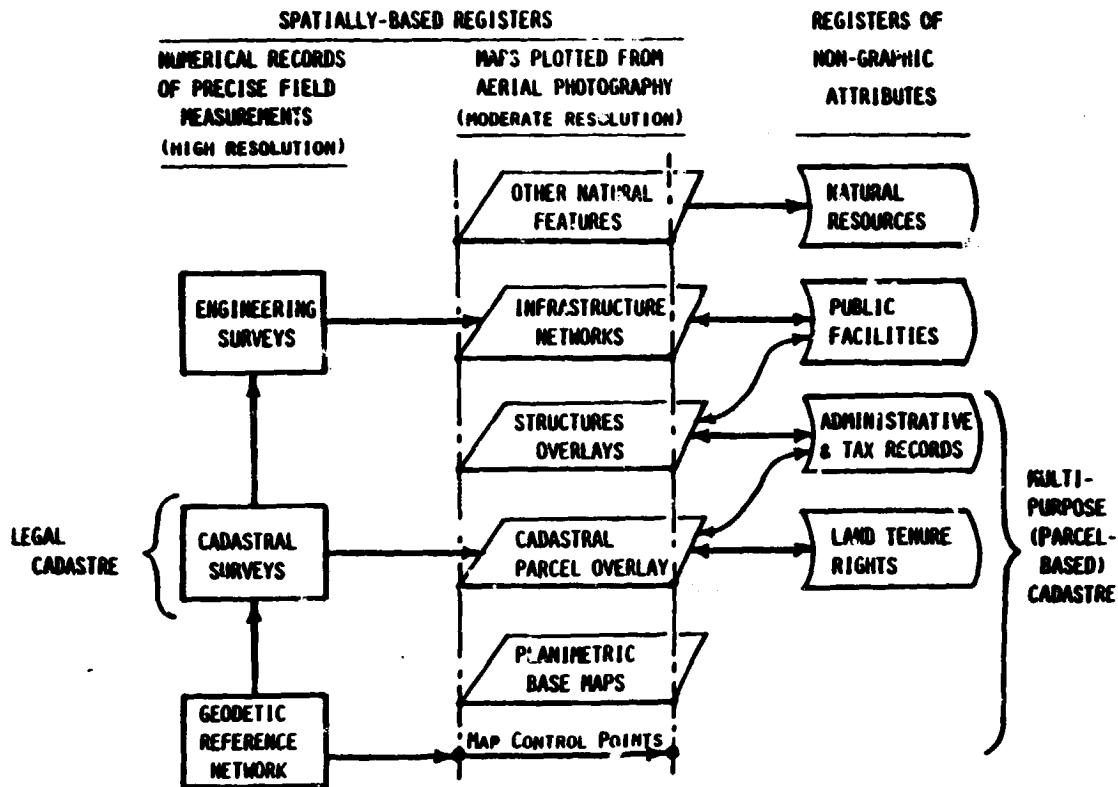


FIGURE 3.6 Components of a cadastre-based land information system.

The ties among these currently uncoordinated records systems are likely to be developed in stages. Possibly the most attractive first stage will be coordination among the several applications of large-scale mapping, depicted vertically through the center of Figure 3.6. This has the advantages of permitting sharing of basic map data as described in the preceding section. Geodetic control provides the pins for these maps and overlays, but the map contents are grid oriented only at the moderate resolution of map accuracies. The massive work of determining geodetic coordinates for all cadastral boundaries on record, at the high resolutions of field surveys depicted on the left side of Figure 3.6, can then be left for a later stage of development of the information systems.

County governments in several parts of the United States have seen it to their advantage to begin the long-range conversion of their maps and legal records to cadastre-based land information systems. Among the major benefits are eliminating the duplication and confusion among separate records systems and enhancing the base of land information available to support county services. References on the pioneering efforts of Forsyth County, North Carolina, Jefferson County, Colorado, and Racine County, Wisconsin, for example, are given in a report of the Committee on Geodesy (1983).

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3.4 ENGINEERING APPLICATIONS

3.4.1 Present Requirements

Geodetic methods are frequently applied to a number of engineering problems related to the stability (or instability) of structures and land masses. Laws administered by the Federal Energy Regulatory Commission and the California Department for Safety of Dams, among others, require periodic observations of dams to assure that all movements of and within both masonry and earth-fill structures are within the limits of the designed elastic properties of the materials of their construction and within the limits of predicted settlements of the foundation materials. In the larger concrete structures extensive networks of triangulation, trilateration, and traverse are required, and lines of precise leveling extending well away from the structures themselves are run. Horizontal shifts of a few millimeters are significant, and vertical movements in the millimeter and submillimeter range are of interest. On earthfill dams, with their lesser homogeneity, somewhat greater movements can be anticipated. On these structures, lines of monuments set parallel to the axis of the dam and in both upstream and downstream faces can usually be checked for alignment, using as control monuments set in natural ground only a few hundred meters outside the fill. In some cases the stability of these control monuments may be verified by triangulation or traverse from stations further away.

The design of each structure includes the design of the survey system by which it will be monitored. The design will include shafts, drifts, tunnels, and instrument platforms for this purpose. Bridges are similarly monitored; however, in shorter structures the primary interest is usually limited to foundation stability. In long, statically indeterminate suspended and arched bridges the elastic behavior of the structure under both traffic and wind and temperature loadings becomes important. For a few structures extensive systems of control are needed in the preconstruction period. The Lake Pontchartrain Bridge (Tuttle, 1961) the Chesapeake Bay Bridge and Tunnels, and various crossings of the San Francisco Bay provide examples of these surveys.

The American Society of Civil Engineers in its Guide to Right-of-Way Practices advocates that rights-of-way be related to the appropriate state plane coordinate system and hence to geodetic survey control. In the past, geodetic control surveys of first- and second-order accuracy have been effectively used on major highway/freeway, aqueduct, power transmission, and pipeline projects to control blunders in subsequent surveys, to relate projects to affected property lines, to provide control for photogrammetric mapping, and to facilitate the indexing of mapping products. Such surveys, except the vertical aspects of aqueducts, seldom play an important part in the construction and maintenance phases and may or may not be incorporated in the as-built maps of the project. The monumented stations, not destroyed by the construction, remain for use as control for future

surveys and may be used to relate the earlier surveys to the new project.

Very accurate surveys are required in the layout of such facilities as particle accelerators and very-high-speed transit test facilities. However, since these facilities are confined to small areas their classification as geodetic surveys may be questioned.

Subsidence due to the removal of subterranean water and other materials (oil, coal, salt, and sulfur, to mention only a few) necessitates monitoring using precise geodetic methods. (Large transit and utility tunnels in metropolitan areas present similar challenges to the survey engineer.) The vertical component is usually the more significant; however, removal of oil in the Long Beach-Terminal Island area of California resulted in relative horizontal movements of as much as 7 m accompanied by a 10-m vertical movement at the center of the subsidence. The movements caused both tensile and compressive failures of railroad trackage and port-related structures. In the Long Beach area, triangulation and Invar-taped traverse were used in conjunction with first-order leveling to quantify the movements before the advent of EDM equipment. With the advent of EDM the number of lines observed was greatly reduced without reducing the strength of the network. First-order leveling to a tide-related benchmark continues on a semiannual basis to assure that repressurization programs are being continued at adequate levels. Triangulation lines exceeded 32 km in length. Horizontal movement rates on the order of 60 to 100 mm/yr have been noted. In another case, vertical movements of over 1.3 m have been observed in a 100-km² area of the Antelope Valley of Southern California. The movements affect flows in both sanitary and storm sewerage.

Geodetic monitoring of landslides (Mitchell, 1972) provides geological data that can be used in the consideration of stabilization programs as well as evidence to be used in litigation required to fix liability. Movement rates of 3 to 30 mm/day are common in extremely high-value portions of the Los Angeles County coastline. Areas range from 0.1 to 10 km². Again, triangulation, trilateration, traverse, and differential leveling techniques are used; however, second- and sometimes third-order techniques may suffice. Relative positional certainties in the 3- to 6-mm range are sought.

Geodetic measurements are also important in studies of movements that result from earthquakes (Savage, 1971; Mitchell, 1971; Ellingwood and Williamson, 1971). The geologic and seismic community use the movement vector data in evaluating stress-strain and energy-release relationships. The engineering community uses the data to evaluate structural behavior and to estimate damage to subsurface utilities. The postearthquake survey data are also used as control for the reconstruction of public works and may be used in studies of the displaced boundaries (Mitchell, 1973) of land parcels or jurisdictional units. Topographic and cadastral maps at scales of 1:500 are common in intensely developed areas and may require revision that will be based on the postearthquake geodetic resurvey.

The extent of the resurveys will be dependent on two primary factors: (1) the severity of the earthquake and (2) the amount of

pre-earthquake control available in the area. The 1971 San Fernando earthquake presented an outstanding opportunity for study because of the great density of previously established first-order benchmarks and horizontal control stations in the area. The Prince Williams Sound earthquake, of somewhat similar magnitude but in a less densely developed area, provided a lesser amount of data.

Accuracy levels at least as great as those of the pre-earthquake survey data are required in the resurveys; however, positional certainties greater than ± 10 mm in the horizontal plane or ± 1 mm in the vertical plane are seldom required. Existing instrumentation is capable of providing this accuracy level even at the distances that may have to be observed to make connections to stations not affected by the earthquake.

While the scientific community wants the geodetic data as soon as possible, it might be noted that, in the case of the 1971 San Fernando event, difficulty was encountered in maintaining first-order leveling standards while aftershock activity continued. In retrospect it was noted that the survey plan should have provided for an immediate running of third-order levels to be followed by first-order leveling 4 to 6 months after the earthquake. Horizontal movements resulting from the aftershock activity did not appear to affect the work started only a few days after the earthquake.

A major problem in dealing with any of the aforementioned stability or movement-related engineering studies is that of finding and confirming the stability of points away from the structure or outside the limits of the moving mass. Using currently available equipment and procedures this aspect of the resurvey problem adds greatly to the cost of and time consumed in the resurvey and greatly delays the availability of the data. The full cooperation of the geodesist and those working in other involved disciplines is and will continue to be an absolute necessity.

Two other engineering-type geodetic survey situations should be mentioned. First, it is obvious that studies of the movements of glaciers are similar to studies of moving land masses but are compounded by the harsh environment in which glaciers are located and by the need to establish and maintain a system of identifiable and recoverable monuments. The second involves vertical movements in basins subjected to reservoir loadings. These basins may and probably will extend long distances away from the reservoir itself. It is improbable however that the time factor will be as critical in these studies as in those previously mentioned.

The close cooperation of the engineer, the geodesist, and the geologist is required to make any of these surveys effective.

3.4.2 Future Requirements

With respect to the engineering applications of geodesy, it is believed that currently available technology and achievable accuracy standards will suffice for structural and land-movement investigations. The greatest need with respect to these applications will center on

timeliness and cost effectiveness. The 1- to 5-mm accuracy-level point-positioning equipment (Bossler and Hanson, 1984) now in the development stages will be used as soon as cost effectiveness can be demonstrated. Point positioning will have the outstanding advantage that each measurement will be independent of any other and will be time determinate to the nearest hour (this is significant when movement rates of 3 to 15 mm per day are being observed). Point and relative positioning techniques will also have the advantages that line-of-sight will not be required and that it will greatly facilitate the identification of points outside the moving areas. Highly mobile inertial positioning equipment, also still in the development stages (Hannah, 1984) may well be called on to make postearthquake investigations at the accuracy level needed immediately after the event (within a few days). Whether the accuracy level of this equipment will be developed to the level needed for long-term use is uncertain at the time of this writing.

One other major requirement will be the continuous program of monumentation, remonumentation, and the intensification of the monumentation of geodetic control stations in earthquake-prone areas. Some of this monumentation can be accomplished by photogrammetric methods (Henrikson, 1984) using low-level aerial photography with suitable side laps and cross flights and then relying on the availability of photoidentifiable targets. In some terrain types this will not be feasible nor will current technology permit the identification of targets at the 1- to 10-mm level noted earlier. In these cases other, and perhaps traditional, techniques of monumentation and position determination will have to be relied on for the foreseeable future. In seismically active areas monumentation spacing of 1 to 2 km is desirable and will contribute to the public safety and welfare.

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