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Committee on Geodesy
Assembly of Mathematical and Physical Sciences
National Research Council

NATIONAL ACADEMY OF SCIENCES
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Preface

The rapid evolution of geodetic techniques in recent decades and the development of new applications of geodesy, particularly in the areas of ocean dynamics and solid-earth geophysics, encouraged the relevant federal agencies to seek the assistance of the National Research Council in the examination of the present health of the science and to recommend future directions. The initial charge was to review the following problem areas and to make recommendations thereon: (1) scientific and technological advances in modern geodesy and related fields; (2) planning for spaceborne instrumentation pertinent to geodesy during the 1980's; (3) geodetic control for the oceans; (4) educational opportunities in geodesy and surveying; (5) current work in plane surveying and mapping; (6) current work on traditional geodesy; and (7) a senior scientist grants-in-geodesy program.

The general state of geodesy, and these specific problem areas, have not been reviewed by a National Research Council committee in recent decades, although aspects thereof were considered by problem-oriented committees, such as the U.S. Geodynamics Committee in 1973 and the Committee on the North American Datum in 1971, or by the agency-oriented committees, such as the Committee Advisory to ESSA (now NOAA) in 1967-1971. The nearest analogue is the NRC Committee on Seismology, which has been active since 1960, having begun as the Committee on Seismological Stations Advisory to the Department of Defense with a name change in 1964 when its functions were expanded. However, the Committee on Geodesy differs significantly from these former Committees in that it has a largely extradisciplinary membership.

This report is the principal product of the first two years of the Committee's existence. Although a comprehensive review is attempted, there is uneven emphasis, reflecting the Committee's sponsorship and membership. In particular, the scientific aspects of geodesy are treated more fully than the engineering or economic aspects.

It is desirable to consider some of the technical details of the geodetic problems discussed herein. Hence it is recommended that the next phase of committee activity be mainly in the form of specialized panels.

Acknowledgments

This study was undertaken early in 1976 by the Committee on Geodesy in the National Research Council's Assembly of Mathematical and Physical Sciences. The work is supported by the Defense Advanced Research Projects Agency (DARPA), Defense Mapping Agency (DMA), National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), Office of Naval Research (ONR), U.S. Air Force Office of Scientific Research (AFOSR), and U.S. Geological Survey (USGS). The Committee appreciates the interest and support of these agencies. We are also grateful to the liaison members for keeping us informed of agency programs.

We also appreciate the contributions of Harmer Weeden, Pennsylvania State University; Ben Buckner, Ohio State University; and Merlin McLaughlin, Board of Registration, Virginia; to the Committee's work on surveying and surveying education.

Contents

1 Summary

The body of this report consists of five chapters: Chapter 2, on what geodesy is; Chapter 3, on whom geodesy serves; and three chapters on how geodesy is done; Chapter 4, on standard methodology; Chapter 5, on current and potential instrumental developments; and Chapter 6, on the people and organizations of geodesy, both governmental and nongovernmental. In addition to reviewing the present state of these topics, these chapters include recommendations where appropriate. The final chapter, 7, emphasizes the main themes, problems, and future committee actions. Chapter 1 is a summary emphasizing the most important recommendations. This organization has led to some redundancies, which have largely been allowed to remain for the sake of textual continuity and completeness.

Geodesy is most succinctly defined as the location of points with respect to the earth and the determination of the earth's gravity field. These two tasks are connected because location techniques are strongly affected by the gravity field. The diverse evolution of observational techniques and earth-related studies in the twentieth century has resulted in many scientists and engineers doing geodesy by the above definition, although few identify themselves as geodesists.

The principal findings of the committee can be summarized as follows:

- *Most geodetic effort is in support of engineering applications.*
- *While most routine surveying is in free enterprise, advanced and precise geodesy is done almost entirely by federal agencies.*
- *The most challenging problems for geodesy lie in the area of geodynamics, such as measurements of tectonic motions.*
- *Most of the current advances in geodetic techniques come from other fields.*
- *Traditional geodetic techniques and results, past as well as current, have major application to current problems.*
- *The principal hindrance to progress is organizational separation of geodetic operations from the most challenging geophysical problems and from instrumentation development.*

The more important of the recommendations growing out of these findings are grouped herewith under five headings.

1.1 APPLICATIONS TO SURVEYING AND MAPPING (Refer to Section 3.1)

Surveying has always been essential to activities referenced to the land: agriculture, construction, and navigation, for example, and the legal implications thereof. In most of these applications, reliability (elimination of mistakes) is more important than accuracy (minimization of measurement errors).

However, the techniques and habits to attain both objectives are somewhat similar. Accuracy is more easily quantified than is reliability. Hence specifications are written to attain accuracy, even though the main goal is reliability. Important to the fulfillment of these specifications is geodesy, which provides the fundamental framework for systematic and economical surveying. Since most surveying is of local application, a variety of standards and procedures have evolved, so that there is appreciable wastage and duplication of effort. Hence the recommendations in this area have a common theme of unification and standardization of procedures and techniques, in which the federal government plays a key role.

The complex of monumented control–horizontal control points and vertical benchmarks–developed and maintained by the National Geodetic Survey (NGS) is fundamental to rational surveying, by providing starting points and checkpoints of assured reliability. A significant part of this assurance stems from the mathematical adjustment of the network to locate errors and to attain overall consistency. However, comprehensive adjustments have not been carried out for the entire United States since 1927 for the horizontal network and since 1929 for the vertical. Subsequent surveys with more accurate instrumentation have indicated inconsistencies damaging to confidence in the networks. Therefore:

We recommend that the computations and additional observations for the new adjustments of the North American Horizontal and Vertical Control Networks by the National Geodetic Survey be given the support necessary to bring about their completion in a prompt and orderly way.

In addition to accuracy and consistency of the fundamental network, maximum utility requires a certain density of control points. The value of control within a short distance–less than a few kilometers–has been particularly emphasized in recent decades with the trend toward urbanization and the related intensive construction and rise in land values. In addition, in heavily industrialized areas, oil fields, for example, there have been significant subsidences requiring resurvey to maintain sewerage, utility, and flood-control systems. However, the NGS budgets have allowed a level of survey effort hardly adequate to keep pace with the rate of destruction of control monuments, let alone to enable enhancement of control density. Therefore:

We recommend that horizontal and vertical control efforts be accelerated, especially in urban areas and areas of subsidence, including repeat surveys at the appropriate time intervals.

While geodesy must take into account the curvature of the earth's surface in detail, for surveying and mapping purposes it is much more efficient to utilize plane coordinate systems that are precise mathematical transformations of this curved surface to a plane. Several such systems exist, and of particular interest to the United States are two categories called the State Plane Coordinate System and the Universal Transverse Mercator System. This committee believes that the Universal Transverse Mercator is superior on technical grounds, but it did not explore legal, economic, and educational implications. It is evident that uniformity would significantly enhance efficiency, including easier use by surveyors of centralized computers, such as that maintained by the NGS. Therefore:

We recommend land-survey computations be made uniform by adoption of a national plane coordinate system, based on a Transverse Mercator projection.

The professional competence of practicing surveyors is in need of upgrading through education, in view of the development of more sophisticated techniques, the value of surveys, and the cost of manpower. Currently many surveyors lack even a basic formal education in surveying. In part this situation arises from the lack of suitable university programs in many states. However, this situation is currently being improved. Therefore:

We recommend that the current expansion of broadly based surveying programs in the universities be encouraged and that qualifications of the practicing surveyors be upgraded so that a baccalaureate degree is a minimum requirement for a professional surveyor.

Other areas of raising of standards and economizing effort entail transfer of technology and fostering of standards by the federal government:

We recommend that cooperative surveying programs between federal and local agencies be encouraged, that federal geodetic control specifications be utilized by all federal and state agencies, that special-purpose surveys be connected to the national geodetic network, wherever possible, and that acceptable survey data be incorporated into the national survey data base.

Finally, although significant advances in surveying effectiveness have been made in recent years, more progress could be made in nonfederal surveying by taking advantage of further capabilities developed by federal agencies.

We recommend that the transfer of federal instrument developments to nonfederal users be expedited by appropriate publications, technical assistance, and other means and that there be a more systematic revision and updating of federal manuals on surveying techniques and other material for the instruction of surveyors.

1.2 APPLICATIONS TO GEOPHYSICS (Refer to Sections 3.2–3.4)

The past ten years have been marked by a rapid evolution in geodynamics–the study of motions in the solid earth. This evolution has been mainly a consequence of the unifying influence of the plate tectonic concept but has also been forwarded by improved understanding of faulting and fracture, that is, of how earthquakes occur. An important practical aspect of the recent progress in geodynamics is the prospect of effective earthquake prediction. This problem area has reached the stage where the greatest need is detailed measurement of spatial and temporal variations in strain–the relative displacement of points in the solid earth with respect to each other—especially in areas where tectonic deformation is known to be occurring, such as the San Andreas fault region of California. Measurements by strainmeters and tiltmeters give essentially continuous records but are often excessively affected by local phenomena. Hence both horizontal and vertical differences of position need to be measured over distances ranging from hundreds of meters to tens of kilometers. Normally, the time intervals will be controlled by costs, but procedures should be readily adaptable if there are indications of changes in rates of strain. In any case, geodetic techniques are appropriate and, as a high priority:

We recommend increasing the accuracy and extent of horizontal and vertical control networks in fault zone regions.

Accompanying level measurements should be gravimetry of the highest accuracy feasible in the field—preferably 10^{-7} m $\sec^{-2}$ or better—to sense mass shifts that may accompany changes in surface elevation (Committee on Seismology, 1976).

Also of appreciable scientific interest would be measurements of relative motion across suboceanic fault zones (such as that examined by Project FAMOUS), which have a significantly different tectonic character. The ocean-bottom positioning system recommended in Section 1.4 would apply to this purpose.

Matters of geophysical debate are the maximum range from a fault to which geodetically measurable deformations may occur and the appropriate balance between frequent measurements at a few points and less frequent measurements at many points. Related geodetic debates are the ranges and repetition rates at which space techniques become more accurate than terrestrial techniques. However, it seems clear that space techniques, such as satellite laser ranging and long-baseline radio interferometry would determine tectonic motion over long distances (hundreds of kilometers) with a high degree of accuracy (a few centimeters) at reasonable cost. We believe that such information in broad areas of deformation surrounding fault zones would identify possible anomalous movements associated with regional stress accumulation around faults and indicate where more intense geodetic and geophysical monitoring is needed. Hence:

We recommend that efforts in the United States to establish large-scale geodynamic monitoring networks in broad areas surrounding fault zones be accelerated and that such networks be extended to other parts of the world, where possible, through cooperative projects with other countries.

The requirements for geodetic measurements over a variety of distances and time intervals entail appreciable planning and coordinating by several federal, state, and other agencies. This planning should take into account models of deformation, which would define which measurements would be most effective. Therefore:

We recommend the development of plans for monitoring tectonic motions in fault zones that are coordinated with other geophysical observations, that provide definitive tests for proposed models of deformation, and that suggest new and refined models.

Also contributory to understanding the geodynamic behavior of the solid earth are geodetic measurements in areas other than current fault zones.

There is a continuing need for more detailed gravity data to resolve questions of mantle flow and lithospheric-asthenospheric interaction. Over the oceans, this need will be met largely by altimetry from the forthcoming SEASAT satellite. But this leaves much land area unmeasured. Improvement of the gravity field is also needed to obtain the SEASAT orbit accurately. Finally, the ocean-dynamic application of the altimetry requires an accurate independent determination of the geoid, to which satellite techniques will contribute for wavelengths of several hundred kilometers or more. Satellite-to-satellite Doppler measurements appear capable of appreciable improvement by coherent oscillator techniques. Therefore:

We recommend a dedicated gravity satellite, maintained at as low an altitude as possible with satellite-to-satellite tracking, subject to further analysis of accuracy requirements and feasibilities.

Particularly valuable to the study of the solid earth are measurements of its response to external effects: tides, variations in rotation, and, most significant, its continuing readjustment to the melting of the great ice sheets 18,000-6000 years ago. The data type most obviously applicable to this rebound is leveling over distances on the order of hundreds of kilometers in the peripheral areas of the ice sheets. However the existing level network requires appreciable analysis and adjustment, and there are doubts as to whether the intrinsic accuracy of much of the data is sufficient. In the future, space techniques might prove more effective to obtain elevations. *We endorse for scientific, as well as practical, reasons the adjustment of the North American Vertical control network recommended in Section 1.1, and further recommend future determination of elevations in selected regions at intervals on the order of decades.*

Geodesy also contributes to study of the oceans through measurements of tides and the oceanic geoid. Gravity measurements are necessary to distinguish the geoid from the sea level measured by the SEASAT altimeter. The improvement of the vertical control network mentioned above should also relate to ocean dynamics by resolving some discrepancies in the differences of ocean heights along both coasts of the United States. A third measurement type that would help greatly to understand ocean dynamics is the pressure at the ocean bottom. A recommendation for the instrumentation to be used for this purpose is given in Section 1.4.

The committee also discussed the geodetic aspects of the planetary programs of the National Aeronautics and Space Administration (NASA). In general, the measurement of the gravity fields and geometric shapes of the moon and planets are given satisfactorily high priority in project planning. In particular, *we endorse NASA plans for a Venus Orbiting Imaging Radar, including an altimeter, and urge renewed consideration of a Lunar Polar Orbiter, if the opportunity arises.*

1.3 GEODETIC METHODS (Refer to Chapter 4)

The fundamental observables of geodesy are directions and distances, differences in elevation, the intensity of gravity, and the direction of gravity. Traditional techniques are triangulation, traverse and trilateration for directions and distances; spirit leveling for elevation; pendulums and gravity meters for the intensity of gravity; and the directions of stars relative to a spirit level for the direction of gravity. Modern techniques and instrumentation that have influenced the way geodesy is done include electronic distance measuring devices, ultraprecise free-fall devices measuring gravity, more precise photogrammetric techniques, radio-interferometric measurement of direction, devices for measuring gravity in moving vehicles, large-scale computers, and, of course, spacecraft with their associated instrumentation—radio range and range rate, laser ranging, laser and radio altimeter. Modern needs that have influenced the way geodesy is done include positional differences over great distances, for military, astronautical, and geodynamic purposes; variations with respect to time, for geodynamics, earthquake prediction, and geologic hazard evaluation (groundwater removal, for example); and measurements in new environments, such as the moon and the oceans.

The fundamental geodetic data base, constituted by the horizontal and vertical control points, is sound and useful, and *we endorse current NGS programs to put it in systematic order.* Our methodological considerations apply rather to the applications and extensions of this data base and to the new needs mentioned above. In particular, the current drive toward mineral exploitation of the harsher environment of the oceans may raise geodetic problems. We have not identified a need for a multipurpose geodetic control network in the oceans but believe that there should be further examination of requirements for accurate positioning in the oceans.

Satellite techniques are already being utilized to strengthen the fundamental geodetic network through Doppler receivers at intervals of about 200 km. Currently, more accurate measurement techniques are being developed, both terrestrial (such as multiwavelength ranging) and extraterrestrial (such as radio interferometry and satellite laser ranging). These techniques will enable broad-scale monitoring of deformation in the earth, as discussed in Section 1.2 on geophysical applications. This monitoring will require repeated measurements both at regular intervals for the general network and at an accelerated pace for regions where a pattern of motion is found to be developing. This time-varying geodesy will be an appreciable enhancement of the function of geodetic control and thus increase the task of the NGS.

Further development of instrumentation is required to accomplish the surveys to measure changes possibly precursory to earthquakes in a rapid and economic manner. In particular, better methods for releveling are required. Possibly the two wavelength angle measurement devices recommended in Section 1.4 may apply, but a variety of techniques should be studied.

For many surveying applications, new methods of obtaining locations—such as satellite tracking, inertial systems, and aerophotogrammetry—are already of sufficient accuracy and are becoming economically feasible enough for the densification of control required for regional and local purposes. Hence, their three-dimensional character should be taken into account in survey specifications, as is currently being implemented by the NGS.

The capability of satellite techniques may be further enhanced by the Department of Defense Global Positioning System, a constellation of satellites designed to give rapid positional fixes. This system is being designed for real-time navigation; however, its geometry makes it ideal for accurate geodetic purposes as well. Therefore, in order to optimize the return from this major investment of public funds,

We recommend that support be provided for the development and refinement of the Global Positioning System with the aim of achieving geodetic accuracy.

Examination should also be given to placing optical corner reflectors on more satellites of orbits helpful to laser ranging for geodetic purposes.

1.4 ADVANCED INSTRUMENTATION (Refer to Chapter 5)

Recent decades have witnessed an almost explosive evolution of mensuration techniques, in a variety of areas, including some of interest to geodesy: optical, electronic, and inertial. Therefore, it is worthwhile to examine these various areas for further potentials of geodetic application, as well as for aspects for which an extra stimulus is needed for development in the direction of geodetic needs. The latter category comprises mainly problems of adverse environment (such as oceanic measurements) or fundamental limitations (such as rapid leveling). Our recommendations are on matters for which there appear to be strong indications of both feasibility and significance.

We recommend increased support for long-range development of instrumentation, as essential for further geodetic progress in coming decades, with emphasis on the following systems as most feasible: (a) extension of the range capability of three-wavelength electronic distance measurements currently under development to 50 km with 5×10^{-8} accuracy; (b) development of improved portable gravity meters with 3×10^{-8} m sec^{-2} accuracy; (c) development of an optical-angle measurement instrument using multiple wavelengths to correct for atmospheric refraction; (d) development of deep-ocean pressure gauges with drift less than 0.5 mbar per year; and (e) development of ocean-bottom relative position measuring systems by acoustic techniques accurate to better than 10 cm over distances up to 10 km.

1.5 PEOPLE AND ORGANIZATIONS (Refer to Chapter 6)

The committee examined the background of scientists and engineers doing geodetic work, where geodetic work is done, education in geodesy, scientific communication, the funding and operation of geodetic work, research and development organization, and the international implications of geodesy. For this examination, a rather extensive questionnaire was circulated to people doing geodesy. Some of the principal themes that emerged from the examination are (1) most people doing geodetic work do not consider themselves geodesists; (2) the emphasis on formal training in geodesy in the United States is still drastically less than in some other developed countries, such as Germany and the Soviet Union; (3) the federal government dominates the precise and advanced aspects of geodesy, although there is a large amount of more mundane surveying done by local government and free enterprise; (4) the organizational arrangement of geodesy in a more and more mission-oriented government is highly fragmented; (5) the separation of operations from research and development in government agencies results in waste and failure to realize opportunities for improvement in an environmentally sensitive activity such as geodesy. Much of this pattern is either proper or unavoidable. More attention needs to be paid to the recruitment, utilization, and education of geodetic personnel and the effects of federal policies thereon. Our most important conclusions on organizational matters are:

We recommend that cost–benefit analyses be applied to surveying and geodesy, in order to develop firmer rationales for geodetic activities.

We recommend that the 1973 Report of the Federal Mapping Task Force on Mapping, Charting, Geodesy, and Surveying to the Office of Management and Budget be reexamined and updated. Additional emphasis of this reexamination should be on coordination of the capabilities of federal agencies in earthquake prediction, space techniques, and instrument development.

2 Definition of Geodesy

Geodesy has been closely linked to the earth's physical environment, from the floodings of the Nile in Ancient Egypt to recent monitoring of tectonic motions. Through the centuries the relationship of geodesy to surveying, mapping, and charting has been well documented, but its scientific nature and basis are not widely known. In recent years, the growth of environmental and resource problems has had major impact on geodesy. In addition to the surveying, mapping, and charting functions, problems to which geodesy applies include subsidence due to extraction of oil, gas, and water; tectonic motion as a precursor of earthquakes; elevation changes due to the loading of water behind a dam; changes in the earth's gravity field; and even subsidence of the White House. However, geodesy is largely unknown to the layman, because its output is used immediately as input by other disciplines and very seldom reaches the public directly; the geodetic functions are often buried in such activities as mapping and charting, surveying, geodynamics, oceanography, and astronomy.

The dictionary defines geodesy as a branch of applied mathematics that determines by observation and measurement the exact positions of points and the figures and areas of large portions of the earth's surface, the shape and size of the earth, and the variations of terrestrial gravity. This committee considers geodesy as both an applied and a basic earth science and, as practiced today, a subdiscipline of both geophysics and engineering, with applications to the moon and the planets in addition to the earth. Historically, geodesy considered the solid earth to be static and separated vertical from horizontal measurements. With recent scientific and technological developments, earth measurements are possible in a three-dimensional time-varying space. Hence, the geodesist must learn how to deal with time-variant aspects of surface and subsurface features, while the geophysicist can learn more about the earth's dynamic behavior from the interpretation of geodetic data.

The technological advances of this electronic–space age have had major effects on geodetic operations. The following are some examples:

1. The introduction of the laser as a replacement for the conventional light source in distance-measuring instruments has increased the range (to 80 km) and allows measurements to be made both by day and by night. The fundamental method of measurement of short distances (1 km or less) is optical interferometry. With the development of modulated laser ranging devices, measurements to 1 mm of distances several kilometers in length under controlled atmospheric conditions are possible. Such accuracies are necessary to meet the demands of geophysicists studying tectonic deformation in connection with earthquake prediction.
2. Close artificial satellites have become the principal celestial means of obtaining geodetic positions. Their orbits are now tracked and calculated accurately enough that with an appropriate radio Doppler receiver the surveyor can recover positions accurate to about 1 m. In addition, through orbit perturbations and radar altimetry to the ocean surface, satellites have become the principal means of determining the broad variations in the gravity field.
3. Large electronic computers are essential not only to process observations and calculate orbits for the new satellite techniques described above, but they also now enable the complete and rigorous utilization of conventional terrestrial geodetic data (Mueller, 1973).

Apart from the refinement of existing techniques through the use of computers and the introduction of electromagnetic and optical distance measurement devices, instrumental research and development has been conducted by scientists and engineers outside the geodetic profession. This separateness of geodetic instrument research and development is seen as a deficiency by some, because of the reduced interaction between measurement techniques and the problems to which they apply. However, geodesy does not seem extraordinarily different from other environmentally oriented sciences in this respect and certainly has been quick to adopt new techniques once their benefits become evident.

In the United States, annual federal budgets for surveying and mapping total about $300 million (13,000 man-years). Related activities could increase these figures by more than 50 percent. These resources are distributed within thirty-three agencies of the federal government under the jurisdiction of seven departments and eight independent agencies. Table 6.2 gives the 1972 percentage breakdown of federal manpower in surveying, mapping, and related activities supported by these resources.

Since most of the geodetic research activity in industry and in academia is government funded, the same division can be considered as representative for research activities. However, a large portion of the appreciably greater operational activities is practiced in the private sector.

It is estimated that in the United States there are 30,000 land and geodetic surveyors, assisted by 100,000 technicians, and supported by 150,000 other personnel, as discussed in Section 6.1, all of whom are involved in surveying and geodetic activities; this represents approximately 0.3 percent of the total national work force. This percentage applied to the gross national product results in an estimate for these activities of 2 billion to 3 billion dollars per year.

2.1 FUNDAMENTAL GOALS OF GEODESY

The major geodetic goals may be summarized as follows:

1. Establishment and maintenance of national and global three-dimensional geodetic control networks on land, recognizing the time-variant aspects of these networks.

2. Measurement and representation of geodynamic phenomena (polar motion, earth tides, and crustal motion).

3. Determination of the gravity field of the earth including temporal variations.

These goals also extend to the oceans, the moon, and the planets.

2.1.1 Geodetic Networks

The geodetic networks of a country provide the control essential for its mapping and charting programs. Within the community of nations, it is important to maintain consistency between the geodetic networks covering a continent and even the entire earth. The ultimate goal is a global geodetic system providing horizontal and vertical, or three-dimensional, coordinates for national and international mapping and charting programs with the confidence that there will be no inconsistencies between the networks produced by individual countries.

Closely related to the mapping responsibility is the requirement for positioning boundaries—international, national, state, and smaller political subdivisions. Boundaries may be identified by physical features or monumented points. The positions referenced to the geodetic networks are descriptors of these boundary points. Because of the political and economical significance of boundaries, there is a continuing interaction between governmental groups and the courts. To avoid extensive litigation over border or boundary disputes, the geodetic data must be of the highest accuracy and reliability. Many countries maintain boundary commissions for this special work.

Most of the wealth of a nation is in the land or the improvements on it. The task of defining and describing tracts of land falls on the land surveyor. Because of the increasing value of land, the frequent sale, and the urban growth with resulting subdivision, the task of maintaining accurate land records is increasing in complexity. The land surveyor looks to geodetic agencies to provide adequate geodetic control and to furnish a reference system for land parcel identification. Land-use management and tax-map programs benefit from these records. This total service involves various groups at the federal, state, county, and city levels.

The contribution to the space program through the positioning of tracking stations and rocket-launch sites and the trajectory orientation at the launch sites has been significant. But even more important have been the contributions of space techniques to the fundamental accuracy of the global or continental geodetic networks. The uncertainty of the relationships between continental networks relative to each other and with respect to the center of the earth's mass has been reduced to a few parts per million (ppm). The use of space techniques is being extended further for establishing three-dimensional coordinates of points in the geodetic networks.

Another function for which geodetic surveying is a requirement relates to engineering structures such as highways, pipelines, transmission lines, and dams for large reservoirs. In earlier years, geodetic surveys had been made to provide the control for the construction of canals and railroads. The federal and state highway networks are examples of complex engineering structures designed for efficiency and safety, but they could not have been built economically without geodetic control. In a similar way, pipelines and transmission lines with their special transport function are dependent on accurate surveys. The site selection and construction of large dams for hydraulic power or for large reservoirs are also dependent on detailed surveys. Frequently geodesists are called upon to provide ultraprecise surveys for high-speed rail tests, for alignment projects, for range experiments, or for other activities for which a standard of distance or direction, or both, accurate to better than 1 ppm, is a requirement. These broad engineering services combine to be a significant subset of the geodetic networks goal.

The specifications for city surveys are more stringent than those for rural surveys. The high land value, the tolerances for structures above or below ground, the outward growth of the city, and, more recently, the definition of airspace above railroad yards, highways, or buildings are factors that establish the requirement for accuracies.

The above applications of conventional geodetic techniques are related to land-based operations. Over the oceans, the same or similar techniques are applied to a number of different problem areas or operations.

The earliest geodetic surveys were made along the coasts to provide the control for nautical charting. The charts for the harbor areas displayed lighthouses or other aids to navigation, the positions of which had been determined by the survey. Today, ships use electronic systems with controlling stations on land, positioned by geodetic means. This same concept has carried forward to air navigation with special charts for airports and for air route navigation displaying the various electronic aids for the navigator to determine his position in flight as well as remaining within his predetermined flight plan. These systems require geodetic control.

As the resources of the ocean bottom become more developed, the need for extensive surveys of its topography increases. Projections indicate that in the near future a third of the oil production will come from the oceans. Further, for laying cables and oil pipelines, for emplacing geophysical and geodetic stations on the ocean floor, for determining the dump sites and new land acquisition (similar to the Hawaii Experiment to acquire land from the ocean for airport expansion), and for bathymetric navigation, a good knowledge of the ocean-bottom topography is necessary.

One of the most recent geodetic control problems over the ocean is the boundary demarcation for national, international, or commercial purposes. The difficulty attending demarcation—an engineering problem—will depend on the boundary definition—a legal-political matter. International boundary limits, which include national limits, for territorial seas and fishing jurisdiction are between 12 and 200 nautical miles (n.m.) from the coastal baselines. Boundary demarcation up to 12 n.m. has been accomplished by conventional geodetic techniques, even where distances between opposing countries or states are separated by distances of less than 24 n.m., and between adjoining states, each circumstance requiring special agreement. Similar special agreements will make the boundaries at 200 n.m. a difficult demarcation problem.

Continental shelves and slopes and free oceans are being searched for mineral resources and fuel (gas and oil). As the existing port facilities are inadequate for huge oil tankers, plans are to construct superports in the ocean far away from the crowded coastal areas. Recommended are construction of large nuclear power plants in the ocean, as the ocean can serve as a logical coolant. To accommodate the groups interested in sharing the ocean, it must be divided into tracts and leases granted to the interested groups. This involves the legal definition of underwater boundaries.

2.1.2 Geodynamics

The dynamic behavior of the earth introduces another dimension to geodetic measurements—time. Tectonically significant rates are on the order of millimeters/year; to monitor these motions is a real geodetic challenge. The establishment and maintenance of a reference frame within which the time-variant phenomena can be represented is one of the important geodetic goals for the near future.

The task of maintaining accurate up-to-date control networks is made difficult by the changes occurring in the earth's crust, either natural or induced by man. Groundwater withdrawals have induced subsidence and some flooding along the sea coast and the shores of the Great Lakes and in the upper Mississippi Valley, where the tilting of the crust produces a similar effect. Periodic releveling may be used to monitor these changes and at the same time maintain the validity of the vertical control network. In areas of large withdrawal of water for industrial use or in areas where the production of petroleum is great, the same problem exists. In these latter cases, there is generally an associated pattern of horizontal displacement. In regions of seismic activity, the rate of crustal deformation is sufficient to justify a program for periodic resurveys, horizontal or vertical or sometimes both. The differentials from these surveys may provide essential information for determining stress patterns and rates of strain accumulation. In the event of an earthquake with a surface fracture, resurveys are needed to measure the displacements and to restore the network for its fundamental use. The furnishing to geophysicists, engineers, or others of this by-product from the network maintenance merits greater recognition.

Optical telescope methods for measurements of position of points on the earth, polar motion, and earth rotation have fundamental limitations arising from atmospheric scintillation that prevent any significant improvement beyond their present level of capability. Some improvement in measuring polar motion and earth rotation is obtained by forming weighted averages of measurements from a large number of stations or by using Doppler satellite techniques. The accuracy achievable is about 0.5-1 m.

The accuracy of baseline measurements with precision laser distance measuring instruments and differential leveling are also limited because the entire survey path is through the atmosphere. Two-color laser geodimeters under development offer a potential improvement by at least one order of magnitude. Another problem with the ground surveying techniques is that the length of each survey measurement is generally less than 50 km because of curvature of the earth, local terrain, and atmospheric attenuation. Thus a long baseline survey must consist of a series of short surveys in which errors may accumulate.

The space program has developed several new techniques that overcome certain limitations of the classical systems and thereby have the potential of centimeter-level accuracy for measurements of long baselines, polar motion, earth rotation, plate motions, and other small dynamic motions, such as solid earth tides and local crustal motions. Accurate laser tracking to both artificial satellites and to reflectors on the moon is one type of such techniques. A second type of technique is radio interferometric tracking of natural astronomical sources (quasars) and radio signals from satellites. With both types of techniques measurements of baselines involve signal propagation from the object in space to the ground stations at each end of the baseline. With such a configuration, the path length through the atmosphere is usually shorter than the horizontal atmospheric path of the ground surveying technique. In addition, the atmospheric path length is essentially independent of baseline length. As a consequence, for the long baselines needed to verify plate motions, the error due to the atmosphere for the space techniques is much smaller than the corresponding error in surveying techniques. The atmospheric limit to accuracy for the space systems appears to be about 1 cm.

The errors are also much smaller for the measurement of polar motion and earth rotation with the space systems because of their superior measurement geometry. With these systems, the accuracy of the measurement of the pole position, for example, can be comparable with the basic measurement accuracies of the stations.

At closer spacings, say less than 50 km, the conventional geodetic techniques become generally competitive with the extraterrestrial methods. It is measurements of these dense networks that provide input to an active fault model, which can indicate where strain energy is being accumulated along a locked part of the fault and where energy is possibly being released by creep or microearthquake activity.

The earth is continuously in dynamic motion. The motions due to the solid-earth tides, ocean tides, ocean loading, polar motion, earth rotation variations, and other such phenomena are of meter amplitude. For example, the main component of polar motion, the Chandler wobble, has an amplitude of 3-6 m and a period of roughly 434 days. Solid-earth tides have a range of about 35 cm at the equator. Thus, it is quite obvious that models of these dynamic effects must be included in the analysis of modern geodetic data for positioning to centimeter-level accuracies. This is both an advantage and a disadvantage. Data acquisition and analysis strategies enable one to solve for both the significant dynamic parameters and the positional or baseline vector, but incorrect modeling of a dynamic effect can cause errors in the determination of the other parameters such as the baseline components. In addition, each system has certain other parameters (such as those pertaining to the spacecraft or lunar orbit, lunar libration, or quasar position and structure) that also must be determined from the same measurements. Though these are added complications, the results are of great value to geodesy as well as to other sciences, such as astronomy. The history has been that as soon as the accuracy of the measuring system was improved, the better data resulted in better understanding and modeling of all the quantities just discussed and in a reduction of model errors in the solutions. This process continues until the final accuracy is comparable with the measurement accuracy. It is apparent that the key to centimeter accuracy determination is the early deployment of very accurate measurement systems.

2.1.3 Gravity Field

The goals discussed thus far have related to the geometric or "coordinate" aspects of geodesy—locating points, baselines, and ultimately the "size" of the earth. A companion set of goals related to the physical aspects of geodesy is needed for determining the "shape" of the earth related to its gravity field. Large portions of the sea surface and, if one considers the determinations deduced from satellite data, the entire gravity field has now been mapped in a general way but not in sufficient detail to meet the established needs of oceanography and geophysics. A geometrical representation of this field is the geoid, the equipotential surface of the gravity field of the earth, which most nearly coincides with the undisturbed surface of the oceans. It is the surface the seas would maintain if not subjected to tidal attraction of the sun or moon, waves, atmospheric disturbances, variations in water salinity, and circulatory patterns of the oceans.

The form of the geoid closely approximates an equipotential ellipsoid of revolution. Its polar radius is approximately 21.4 km shorter than the equatorial radius (6378.1 km). Its flattening has been determined very accurately from satellite data (1/298.25), an improvement over the value previously known from the variation of the land-measured values of gravity from the equator to the pole.

The smaller irregularities or radial differences between the geoidal and ellipsoidal surfaces (geoid undulations) seldom exceed 100 m and for most of the earth are less than 25 m. However, these irregularities are significant indicators of internal stresses and are essential for improving the accuracy of geodetic results.

A direct observation (such as satellite altimetry) of the height of the ocean-surface topography with respect to the ellipsoidal reference surface should reveal the significant features; although, as accuracies get better than 1 m, this surface will deviate from the geoid because of ocean currents. Accuracies of 10 cm would allow observations of ocean-surface deviations due to the stronger ocean currents, although the effects of time-averaged currents will be superimposed upon the effect of geoidal variations. The two effects can be separated either by geodesists, if they could estimate the geoidal variations to the necessary accuracies, or by oceanographers, if they could estimate the currents by geostrophic calculations. Time-dependent ocean currents should be simpler to identify, and such currents as deep-sea tides and oceanic eddies, with expected heights of tens of centimeters, should be identifiable, although a reproducibility in the signal of 1 cm would give a far richer set of observations. For precision time-dependent observations, aliasing due to oceanic roughness will become a major consideration. The success of analyzing data for the gravity field/geoid improvement, such as provided by the GEOS-3 or SEASAT altimeter experiments depends strongly on supporting oceanographic data (for example, sea roughness and sea state) as well as on instrumental calibration and other nongeodetic factors.

In terms of satellite orbit determinations, at the present time, global orbit accuracy is on the order of 10-15 m (~10 m along track, ~7 m cross track, and ~5 m radially) for a typical geodetic satellite. The largest portion of the orbital inaccuracies comes from the inadequate knowledge of the gravity field. In spite of this rather large global uncertainty, submeter results for station locations have nevertheless been derived with present data and analytical techniques. This has been achieved by processing the data so that orbit errors are compensated for over the area of interest (that is, by the use of multiple arcs or passes with varying geometry and filtering techniques) or by using high-flying geodetic satellites less affected by the gravity field, such as LAGEOS.

2.1.4 Lunar and Planetary Geodesy

Space scientists have adopted the Greek prefix "geo" (earth) to describe measurements pertaining to other planets; although not all techniques available for earth-oriented geodesy are applicable for lunar and planetary geodesy, the geodetic aims are the same. These are, for all bodies of the solar system, the determination of control networks, size, shape, and topography; the determination of their gravity fields; the determination of their rotation rates; and the detection of dynamic processes, if any. The primary remote-sensing instruments for the geodetic exploration of these bodies are telescopes and artificial satellites, involving radar and laser rangers, multispectral sensors, Doppler trackers, and cameras. Where the deployment of instrument packages on the surface has been possible, gravity meters and accelerometers have been used. The primary data to be analyzed are derived from the observation of the motion of orbiting and flyby spacecrafts and asteroids for determination of mass, shape, and gravity field; the measurement of topography by radar, spectroscopy, occultations, television stereogrammetry, television imagery, photogrammetry, and Doppler techniques; and radar astronomy for determination of rotation rate. The primary analysis techniques involve, for example, spherical harmonic expansions of the observed data and the examination of the derived harmonic coefficients, the interpretation of range and surface pressure data, and the application of the classical theory of figures.

The achievements in lunar and planetary geodesy in the last decade have been impressive. Accurate determinations of the gravity fields have helped in defining and understanding the mass distributions in the upper layers of moons and planets. The most striking feature is the positive mass concentration associated with Mars Olympus on Mars, much larger (in the sense of stress implication as well as excess mass) than any feature on earth. The determination of the potential harmonic coefficients for the major planets has established constraints on the allowable density distributions within these planets. The ratio of the mass of the sun to the mass of the planets has been obtained from the analysis of Doppler and flyby satellite data. The shape and radius of planets have been determined from radio occultation, radar range, and laser altimeter data; from such data, for example, a mean equatorial radius of 3397.2 ± 1 km and a polar radius of 3375.5 ± 1 km and an offset of the center of mass from the center of figure of almost 3 km have been found for Mars. Topographic information has been obtained for the moon from a metric camera system, a laser altimeter, and a radar sounder; for Mars from ranging stations on earth and from orbiters; and for Venus and Mercury from radar measurements. An analysis of radio tracking data from Viking I located the instrument package on the Martian surface and led to determination of the radius of Mars at the landing site and the orientation of the spin axis; thus the lander was located with accuracies of 0.02° in latitude and 0.07° in longitude and within 0.3 km from the center of mass. These radio tracking data provide reasonable reference points for topographic measurements.

2.2 THE GEODESIST

From what has been presented, some notion of the ideal geodesist emerges (Mueller and Buckner, 1974). Such a person would have a basic degree in the sciences or engineering and would be well grounded in the physics, mathematics, geology, and engineering of activities supported by geodesy. The ideal geodesist would be familiar with the surveyor's instruments and measuring and computational techniques; would solve sophisticated surveying problems related to unusual engineering structures, such as the roof of the Olympic Stadium in Munich or alignment of nuclear accelerators and tunnels; and would plan and direct operations for control surveys and execute the calculations, should the survey be performed by the traditional methods (triangulation, trilateration, leveling, for example) or using satellite techniques or even extraterrestrial geodetic methods (lunar laser ranging, very-long-baseline interferometry, for example). The ideal geodesist would determine the earth's gravity field and the size and shape of the earth and would design and execute projects leading to geodetic networks that detect fault motions or the dynamic behavior of the oceans. In the area of marine surveys, such a person would be familiar with hydrographic and bathymetric surveys and with gravimetry and calculations on the geoid as they relate to improvement of inertial navigation systems. In the mapping and charting area it would be necessary to be knowledgeable about restitution instruments, analog and analytical techniques, and integrated photogrammetric systems. The ideal geodesist would be familiar with remote-sensing technology and data acquisition and storage facilities and would be an expert in mathematical cartography, familiar with automated mapping systems. The ideal geodesist would also be acquainted with map compilation and reproduction procedures and with the design of aeronautical and nautical charts and the mapping of the moon and the planets. To accomplish these tasks the thoroughly prepared geodesist must have some familiarity with, and in certain specific cases must be quite expert in, land surveying, structural and mining engineering, terrestrial and astronomic observing, celestial mechanics, galactic energy sources, tectonophysics, seismology, oceanography, navigation, photogrammetry, interpretation of remote sensing data, drafting, and printing.

The reader should now have a keener appreciation of the fundamental aspects of geodesy in relation to other scientific and engineering disciplines. Geodesy, the oldest earth science, is still contributing significantly to the development of the resources of the oceans and the exploration of the moon and other planets, as well as supporting many of the engineering and civil programs of mankind—boundaries, property surveys, highways, pipelines, and all types of maps and charts. For a comprehensive outline of modern geodesy in the United States, see the U.S. National Report to XVI General Assembly of IUGG (Bell, 1975).

3 Practical and Scientific Values of Geodesy

The uses of geodesy are conveniently divided into engineering and scientific, even though some of the latter may have appreciable practical implications, such as earthquake prediction.

The engineering applications are surveying and mapping for the entire range of land uses, including construction, agriculture, mining, and property and political boundaries. These applications constitute the greater bulk, economically, of activity supported as geodesy. Although the traditional surveying techniques largely apply, modern techniques have appreciably enhanced the reliability and efficiency of this work, and considerable potential for improvement remains.

The scientific applications are mainly measurements of variations: temporal changes in relative location and both spatial and temporal irregularities in the gravity field. Most of the variations, such as those required to infer changes in strain in the solid earth, are rather small, and hence they afford the greatest challenge to modern geodesy. The same scientific objectives apply, in principle, to the moon and terrestrial planets as to the solid earth, although the techniques involved are necessarily different. For general discussions of scientific applications of geodesy, see the Proceedings edited by Mueller (1975).

3.1 SURVEYING AND MAPPING

Geodesy supplies the basic foundation for most surveying activity. The surveyor—whether he is locating a highway, determining a property boundary, or preparing a map for an environmental study—is dependent on the geodesist for the framework upon which his survey is based, the directions of the surveyed lines, the scale factors to be utilized, and the elevations required. It is estimated that in the United States there are 30,000 professional surveyors, assisted by 100,000 technicians and supported by 150,000 other personnel; this constitutes a work force of about 280,000 persons engaged in surveying activities in the United States. The number of surveyors will increase by 59 percent during the next decade according to Labor Department projections. The surveying community is the largest user of geodetic information. The most obvious benefits of geodetic data to the general public are evidenced by the surveys and maps produced by the surveyors.

Surveyors and cartographers have a great challenge to meet during the next decade if they are to provide the necessary surveys and maps for an increasing amount of construction, transportation, and utility system activity; basic information to be used in environmental studies and land-use planning; the establishment of a national land register; positioning of all kinds of information that is stored in data banks; efficient development of our natural resources; and increasing activity in the oceans.

3.1.1 Classification of Surveying Activity

Surveying activity may be classified into four general categories: geodetic or control surveys, construction or engineering surveys, property or land surveys, and cartographic or topographic surveys. There are no rigid boundaries between these classifications. Most professional surveyors are competent in more than one of the fields, and their practice often includes work in all the classifications. A typical project handled by a surveying firm might include the establishment of accurate control surveying monuments in an area; a property survey for the purpose of establishing ownership and boundaries; a topographic survey and map for planning and environmental purposes; construction stakeout for buildings, utilities, and roads; and finally an accurate as-built survey for record purposes.

Geodetic or Control Surveying

Geodetic or control surveying includes the determination of the size and shape of the earth; the selection of coordinate systems; the establishment of horizontal and vertical control monuments; collection, storage, and dissemination of geodetic information; and research and development, as discussed in Chapter 4.

The National Geodetic Survey (NGS) has responsibility for the basic geodetic control network of the United States, but a number of other federal agencies and state and community surveying organizations perform geodetic surveys for their own mapping and surveying projects, as discussed in Sections 6.4 and 6.5.

A considerable amount of geodetic surveying is done by private surveying firms and surveyors working for utility and industrial firms. The projects accomplished by the private sector are usually for a special purpose such as the establishment of a subdivision, the construction of a plant, the installation of a utility system, or the mapping of a particular area. Even though each of the control survey projects is small when compared with a government project, the total effort by the individual surveying firms exceeds the government efforts in manpower and cost.

Construction or Engineering Surveying

The construction or engineering surveyor performs the measurements required for major construction projects. The surveyor is usually the first person on the site and designates the proper positions for piling and building foundations, the area to be excavated or filled for a road, the position of a bridge pier, and the route of a water or sewer line. During construction, the surveyor provides the correct elevations for floor slabs, steel beams, sewer pipes, and road surfaces. When construction is completed, the construction surveyor's field notes and as-built drawings provide the permanent record to show the dimensions and placement of all the items constructed.

Property or Land Surveying

The determination of property boundaries and the rights of ownership is the function of the property surveyor. Most of the property surveying is done by private surveyors who must not only be competent in the science and art of measurements but must have a knowledge and understanding of the laws relating to property. All 50 states specify that a property survey must be made by a qualified land surveyor who has been examined and determined to be competent. Each state has a land surveyor examination and registration process to ensure that the public is properly protected. Most states are upgrading their qualifications for those who practice land surveying. By 1980, a four-year degree in surveying or its equivalent will be required for land-surveyor registrants in two states.

The initial land boundaries in the 30 public land states of the United States are established by cadastral surveyors of the Bureau of Land Management (BLM). This agency is responsible for the subdivision of lands owned by the United States into tracts that are suitable for sale or lease. The BLM is also responsible for the designation and description of tracts of land or water in the offshore areas adjacent to the United States that are subject to lease for petroleum or mineral development.

Cartographic or Topographic Surveying

The preparation of maps and charts requires the combined efforts of many disciplines. The cartographic or topographic surveyor using conventional field methods, photogrammetry, and other remote-sensing techniques provide the basic information for the mapping projects.

The U.S. Geological Survey (USGS) has the responsibility for preparation of topographic maps of the United States. In addition to the topographic maps, this agency prepares geological, hydrological, and other special-purpose maps. Marine mapping and charting is the responsibility of the National Ocean Survey and the Defense Mapping Agency. A number of other federal agencies perform some mapping functions; these include the Federal Highway Administration, the Soil Conservation Service, the Forest Service, the National Aeronautics and Space Administration, and the Corps of Engineers.

Most of the states have a mapping organization, and a number of counties and municipalities maintain their own mapping group. These organizations prepare and maintain maps of all types that are required for planning and development in their particular locality.

There is a considerable amount of mapping done by the private sector. Large-scale detail maps are prepared for subdivision planning, plant site construction, utility-system planning and construction, and environmental studies. The most extensive mapping projects performed by the private sector are done by the oil companies. The exploration and development of our natural resources requires detailed topographic and geological maps of extensive land areas and nautical charts and bathymetric maps of water-covered areas.

3.1.2 Status of Surveying in the United States

Federal Government

The surveying and mapping activities of the military organizations were unified under one organization in 1972—the Defense Mapping Agency. A similar unification of civil surveying and mapping would bring a comparable enhancement of efficiency, in the opinion of many surveyors and cartographers. As discussed in Section 6.4, an extensive study was made of the federal civil mapping, charting, geodesy, and surveying agencies during 1972 and 1973 by the Office of Management and Budget. The report of the Federal Mapping Task Force on Mapping, Charting, Geodesy and Surveying (1973) recommended a reorganization and realignment of duties of the numerous agencies performing surveying and mapping functions. Few of the Task Force recommendations have been effected to date; however, some of their suggested recommendations have resulted in better cooperation between agencies and improvement in collection, filing, and distribution of surveying and mapping information.

As noted above the National Geodetic Survey (NGS) has responsibility for the fundamental geodetic control network, both horizontal and vertical. The techniques for establishing this network are described in Section 4.1. From the point of view of the user activities described in Section 3.1.1, the essential products of this effort are the positions of 200,000 horizontal control monuments and 500,000 vertical control monuments (Bossler, 1977b). The National Geodetic Information Center (NGIC) distributes all geodetic data, responding to direct requests and those processed through USGS's National Cartographic Information Center (NCIC).

Because of land movement, lack of accuracy in the original surveys, and the destruction of benchmarks, approximately 80 percent of the 500,000 vertical control monuments are considered inadequate to meet the needs of current users (Federal Mapping Task Force, 1973). The NGS is releveling about 20 percent of the basic framework; this program is scheduled for completion in 1985 and will cost about $26 million. Plans are formulated to place the vertical data under control of a data-base management system in an automated data file similar to that for the horizontal control data. The current level of effort by the NGS is not sufficient to keep pace with the network's deterioration, much less to satisfy the increasing demands for elevations that are required for establishing land-use policies, flood-control systems, building codes, and detection and monitoring systems for earth movements.

The National Ocean Survey (NOS) has prepared about 1000 nautical charts of U.S. waters (Munson, 1976). The NOS is currently updating the information and improving the accuracy and reliability of the information shown on the charts. All the ships and launches have been equipped with automated data-acquisition systems. The shore-based processing units are utilizing new techniques to shorten the production schedule of the nautical charts so that current information is available for the shipping interests, exploration companies, commercial and sports fishermen, and others operating in coastal waters.

The positioning of the information shown on nautical charts is based on accurate geodetic control stations. Conventional horizontal control stations on land are used for river and nearshore operations. The transmitters for medium-range positioning systems are positioned from the national horizontal network, and the space-oriented navigation systems utilize accurate ground positions for calibration of the space coordinates of the satellites.

The basic topographic map for the United States is the 1:24,000 scale; about 68 percent of the country, excluding Alaska, has been mapped (Lyddan, 1976). About 84 percent of Alaska is mapped at a scale of 1:63,360. There are 1:250,000 scale topographic maps of all of the United States. The U.S. Geological Survey (USGS) is currently producing about 4000 orthophotoquads each year; orthophotoquads of all the areas not previously mapped at a 1:24,000 scale will be produced by 1979. Photogrammetric methods are used to produce most of the maps prepared by the USGS. The USGS is the largest civil user of photogrammetry. In addition to the topographic information derived from photographs, much of the control used for mapping is established by aerotriangulation methods. Approximately 8,000,000 topographic maps are distributed by the USGS each year.

Systematic conversion of the USGS National Mapping Program to metric units has been initiated. All new and completely revised small-scale and intermediate-scale maps will be prepared using the International System of Units (SI). The standard map scales will be 1:25,000, 1:100,000, 1:250,000, 1:500,000, and 1:1,000,000. The basic contour interval will be 1, 2, 5, 10, 20, 50, and 100 m.

The NCIC, established by the USGS in 1974, provides a national information service to make cartographic data of the United States more easily accessible to the user (Swinnerton, 1976). The Center received 60,000 inquiries and orders during 1975; projecting the historical growth rate, it is estimated that there will be 169,000 inquiries by 1980. The USGS Earth Resources Observation Systems (EROS) Data Center has been designated as a national repository for EROS satellite imagery and conventional aerial photographs. The Center has an automated system for indexing and cataloging over 6 million frames of imagery, and it provides information about the imagery at 10 remote terminals scattered throughout the United States.

The Defense Mapping Agency (DMA) is responsible for the surveying and mapping needs of the Department of Defense, as discussed in Section 6.4 (Andregg, 1976). In addition to the usual charts and maps, all types of geodetic information are collected, filed, and readily accessible for military use. The DMA prepares maps and charts for all the areas on the earth that are not mapped by the U.S. civilian agencies, usually by adapting foreign maps but by its own surveys for a few areas of special interest. The DMA is involved in much of the research and development of instruments, systems, and data-handling procedures that are used by the surveying and mapping community. Currently, it is developing the instrumentation to be used with a Global Positioning System, which will benefit all surveyors.

The Bureau of Land Management (BLM) is responsible for the cadastral surveys for federal lands in the 29 Public Lands states of the conterminous states and of Alaska. The surveys are almost complete in the 29 states, but only a small portion of the required surveys in Alaska have been completed. A number of areas that were surveyed before 1910 must be resurveyed to provide boundary information required for the management of federal lands.

Numerous other federal agencies are performing surveys and preparing maps for special purposes, including the Forest Service, Tennessee Valley Authority, Federal Highway Administration, Bureau of Reclamation, Corps of Engineers, and Department of Housing and Urban Development.

These various agencies and the state and local government counterparts often perform surveys that satisfy only their particular needs. This has led to the resurvey of the same areas by different agencies at some considerable cost to the taxpayer, which could have been avoided had the first agency performed its survey to federal specifications, tied the survey to the national control network, and published the data on the National Reference System.

We recommend that Federal Geodetic Control Survey Specifications be utilized at every opportunity by all federal and state agencies, that special-purpose surveys be tied into the National Control Network, and that survey data be referenced to the National Plane Coordinate Reference System.

State and Local Governments

Much of the surveying and mapping effort at the state and local level is for the construction of highways, streets, and utilities. Seventeen states have surveying departments that are devoted to control surveys or topographic mapping. Arkansas and Missouri have an agency responsible for the cadastral surveys within the state. A number of cities and communities have conducted their own geodetic control surveys with the cooperation of the NGS and have surveying groups to maintain a data file that is available for use in the community. Some communities have a surveying organization that checks the work done by private surveyors and other organizations to ensure that it satisfies the standards required by state and local regulations. A considerable savings and improved efficiency would be achieved by the upgrading of state and local government geodetic functions. Each state should encourage the use of a remote computer terminal system for direct access to the NGS data base and computation programs; establish standardized surveying procedures; encourage the use of the National Plane Coordinate Reference System; and disseminate surveying information to local users.

We recommend that each state establish an office for implementing the use of geodetic control at the local level.

For many years the NGS has had Mark Maintenance representatives who monitor the NGS geodetic control monuments in an assigned area and assist local surveyors with control surveying problems. One representative usually covers several states and has responsibility for about 30,000 monuments. If no maintenance work is done in an area, it is estimated that 20 percent of the monuments are damaged or destroyed in a ten-year period. With the cooperation of state and local surveyors, the Mark Maintenance representatives can re-establish monuments that are damaged, or about to be destroyed, by measurements from witness marks at a small fraction of the $6000 cost to establish a horizontal control point monument by a full resurvey.

During the last three years, the NGS has established a geodetic state advisor program, which provides an NGS representative in the state office who coordinates state-federal control surveying programs in the state; advises state employees about control surveying procedures; inspects state surveys and encourages the use of Federal Control Specifications; assists in the acquisition of survey information from federal agencies; and helps local surveyors with control surveying problems. Four states now have geodetic advisors assigned to them, and others are considering the use of advisors.

We recommend the NGS geodetic state advisor program be accelerated to facilitate implementation of this program.

Private Practitioners

Much of the surveying and mapping in the United States is done by surveyors in private practice and those working for construction, industrial, and utility companies. The private surveyors do a lot of contract surveying and mapping for various government agencies. Most of the work is related to a special project for an individual agency rather than for general usage: an environmental study of a particular area, a navigation or drainage project for a small section of a river, an urban development program, a site for a large bridge, or a new port facility.

The quality of surveying by the private sector varies considerably. The larger and more progressive organizations utilize electronic distance measuring (EDM) equipment for measurements; computers for their computations, data storage, and mapping; and photogrammetric methods for mapping. As the relative cost of EDM equipment and computers continues to decrease, many of the smaller surveying firms are beginning to improve their surveying techniques. There is an increasing amount of communication between surveyors, which has resulted from the expansion of national and state surveying organizations. Most of the private surveyors and those working for state and local organizations are dependent on the federal agencies for information about surveying procedures, projection tables, and mapping methods; a considerable number of publications have not been revised to reflect recent developments in instrumentation and surveying methods, and some of the usable material is out of print. A greater effort by the major federal surveying organizations to inform the private surveyors about information that is available and to make that information readily accessible to the private surveyor is needed. This communication, use of government data and State Plane Coordinate Systems, and improved methods and instrumentation will improve the caliber of surveying considerably.

Some communities have fairly rigid standards for surveying that is performed in making property surveys, reestablishing original land corners, laying out subdivisions, and recording survey plats. This has resulted in a high caliber of surveying within those communities. In areas where laws and regulations regarding surveying standards are lax, the quality of the surveying is usually substandard. As a general rule, the quality of surveying is directly related to the cost of land in the area or the cost of improvements being constructed.

We recommend that the educational material distributed to surveyors and mappers by various government agencies about surveying and mapping methods, instruments, computations, and mapping projections be revised and updated so that it is more useful for the practicing surveyor.

Surveying and Mapping Education

Geodetic education is discussed in Section 6.2. The curricula described there are aimed primarily at achieving the expertise in fundamental geodetic techniques that are described in Chapter 4. There is a considerably larger educational effort required to educate and train personnel to accomplish the tasks outlined in this section.

Between 1945 and 1970, there were very few universities that offered baccalaureate programs in surveying and mapping. Prior to 1945, an adequate surveying program was taught as a specialty of civil engineering at a few universities. Beginning about 1945, the number of surveying courses presented as a part of the civil engineering curriculum was reduced because of the increasing number of other courses deemed necessary for a civil engineering program. The one or two courses remaining in the usual civil engineering program were designed as orientation or discipline courses for the civil engineer rather than for the future surveyor. Several universities offered graduate programs in surveying even though there were no baccalaureate programs.

Since 1970, baccalaureate surveying programs have been developed at 13 universities in the United States. The four-year programs are generally broader based than the specialty programs previously offered as a part of the civil engineering program. Courses in property surveying are much more prominent in the new programs than those prior to 1945. The Engineers' Council for Professional Development has established standards of surveying education in the United States. The American Congress on Surveying and Mapping has recommended that the basic education for a professional Surveyor be a baccalaureate degree.

We recommend that the current expansion of broadly based surveying programs in the universities be encouraged and that qualifications of the practicing surveyors be upgraded so that a baccalaureate degree is a minimum requirement for a professional surveyor.

In addition to the increasing number of four-year surveying programs being developed, about 35 two-year programs for surveying technicians are in operation. These programs are supplying better qualified technicians for the surveying profession and provide an introduction to surveying for many young people who continue their education in surveying.

The practicing surveyor is well aware of the need for continuing education in order to keep pace with a rapidly developing society; to learn how to utilize new instruments and surveying methods; to take advantage of developments in data processing, computations, and plotting; and to make use of the vast amount of data that are acquired by the federal and state surveying and mapping agencies. The professional surveying and mapping societies are conducting numerous seminars and workshops for surveyors. Several states have developed procedures and are operating voluntary programs to establish standards for formal continuing education requirements.

We recommend that a greater effort be made to encourage students to enroll in surveying baccalaureate programs, to continue in graduate programs, and to maintain their competency through continuing education programs.

3.1.3 Future Demands for Surveyors

There are a number of developments in the United States that will cause increasing requirements for surveying.

Construction, Transportation, and Utilities

As the population of the United States increases, additional housing, transportation, factories, and schools will be required. All of this requires surveying. The development of land, the construction of drainage ditches and dams, the withdrawal of water, petroleum, and other resources from beneath the surface may cause significant movement of the earth's surface. This, combined with the natural tectonic motions, creates a need for frequent observations and measurements of the earth's surface in many areas. When the population density increases, more exacting surveying is required; therefore, more control survey monuments are necessary, and better surveying methods must be used.

Environmental and Land-Use Studies and Planning

The United States is becoming increasingly aware of environmental problems and the decisions that must be made when raw land is developed. Before major projects are undertaken, whether they be federal, state, local, or private, studies must be made and plans formulated. All of these studies require maps and the position of data that are collected. The determination of data points and map preparation will increase the work of the surveyors.

National Land Register (Cadastre)

Those concerned with the titles to land—the county recorders, assessors, attorneys, planners, and surveyors—are attempting to provide a system that will eliminate the confusion that now exists in our recording systems. The most likely result will be a land-record system that is based on parcel identification. Each parcel of land will have an index number that is based on its position on the earth. The location of the parcel may be described by geographic position (latitude and longitude), Universal Transverse Mercator Coordinates, State Plane Coordinates, or subdivision of a particular index map. The surveyor must prepare the accurate property map and make the necessary field surveys to locate each tract that is indexed. A tremendous amount of field work and large-scale mapping will be required if this system is developed throughout the United States.

Data Banks for Information

Most government agencies, utilities, and companies are utilizing the tremendous capacity for filing and data handling of large computer installations. The common reference point for much of these data is position: location of a traffic accident or burglary in police files; position of a transformer or cutoff valve in a utility system; or the location of a park, playground, or school in a community. Determinations of these positions is a job for the surveyor and mapper.

Exploration and Development of Natural Resources

With the depletion of easily exploited natural resources, future recovery will require a much more detailed exploration, as has developed in Europe. This exploration requires the support of a comparable mapping effort. Maps must be prepared showing detailed topography, bathymetry, geological features, forest lands, soil conditions, and water resources. Detailed surveys must be made in areas that show potential resources. The development of these resources requires a tremendous amount of surveying both on land and in the water.

Marine Surveying

A considerable amount of surveying is done in water-covered areas. The navigation of streams, lakes, harbors, and oceans is dependent on reasonably accurate maps. The development of resources in inland waters, the continental shelf, and deep oceans requires maps for exploration, boundaries for leases and concessions, positioning for dredging and platforms, and rights-of-way and alignment surveys for pipelines and cables. The recreation and commercial fishing industries require maps and navigation aids for their use and safety.

The inland waters and nearshore areas of the United States are mapped fairly well; however, constant changes in bottom conditions require frequent surveys in many areas. Very little of the deep-ocean area is adequately mapped, as indicated in Section 3.3; there is a critical need for general bathymetric data in most of the frontier areas, and baseline oceanographic and meteorological data are lacking in most of the deep-water areas.

3.1.4 Geodetic Requirements for Surveyor Usage

The surveyor is primarily a user of geodetic information. Even though the geodetic surveyor may be classified as a geodesist or as a surveyor, most of the other surveying specialists depend on the geodesist to provide some of the basic information that they use.

Ellipsoidal Reference System and Geodetic Datum

Traditionally, surveying has been categorized as plane surveying or geodetic surveying. With increasing use of State Plane Coordinate Systems, electronic distance-measuring devices, and computers, the surveyor has become fully cognizant of the effect of the earth's curvature, different definitions of direction, elevations, and gravity on his measurements. The distinction between plane and geodetic surveying is losing some of its importance—future surveyors will be using geodetic methods even though the area covered by the survey may be relatively small. In order to provide the most accurate data, the surveyor needs accurate parameters of the ellipsoidal reference system—radius, flattening, orientation, effects of gravity at different points, and sea-level determinations—or the geodetic datum. The new adjustment of the horizontal control of North America is presently under way, with completion scheduled for 1983. The new adjustment of the vertical control is only now getting under way. The entire surveying community applauds this effort, which will provide more accurate and consistent data that, in line with the newer procedures and instruments available, will reduce the surveyor's workload and costs as discussed by the Committee on the North American Datum (1971).

We recommend that the National Geodetic Survey proceed with all deliberate speed to accomplish the new adjustments of the national control networks.

Control Networks

The surveyors in the United States, both government and private, are increasing their use of the horizontal and vertical control networks. The OMB Report in 1973 indicated that the use of horizontal control was divided as follows: federal agencies, 47 percent; state and local governments, 17 percent; industry and commerce, 17 percent; and the general public, 19 percent. Most surveyors recognize the benefits of tying their surveys into the basic networks of the country: permanency of their positions, correlation with other surveys that are defined by the same system, means of easily checking the accuracy of their survey, basic direction is easily established, and results can be presented in a convenient form. Many of the federal and state regulatory agencies require positions based on the national network to describe features. With the increasing demands for accurate surveying in urban areas, additional horizontal and vertical control data are required. A typical densification program was conducted in Monroe County, New York, during the 1960's (Johnson, 1976). The number of horizontal control monuments was increased from 20 to 552 at a cost of $555,000. This was a cooperative program by the Monroe County Geodetic Survey and the NGS. The area of the county is approximately 1745 km^2, so there is one station for each 3.16 km^2. It has been estimated that this densification project results in a savings of $630,000 annually in surveying costs alone.

There is an urgent need for more and better vertical control throughout the United States to obtain accurate data on ground movement, flood plains, tides, and rate of subsidence. To protect the public, accurate surveys have been performed for several years to monitor the movement of 31 dams in California. Accurate measurements are made regularly to determine slope stability at the open-pit Anamax Mining Company's Twin Butte Mine in Arizona. Surveys are required to determine the amount of subsidence caused by a lowering of the water table in developing the areas along the Gulf Coast and the removal of petroleum from oil fields in California. Subsidence in relatively flat terrain has caused serious problems in existing underground utility and sewerage systems and affects the design of new systems that must be connected to older systems. The determination of flood-plain elevations for insurance purposes is most critical in some areas and is affected by the lowering of old monuments because of subsidence.

Networks structured to meet the collective needs for control would include the following:

1. Horizontal Control Network
    (a) A basic network throughout the country to provide control for the special needs of defense, for scientific studies such as crustal movement, and an accurate primary framework for many lower-order surveys (Federal Mapping Task Force, 1973). Since systematic errors inherent in all surveys accumulate with distance, superior accuracy (1:100,000 to 1:1,000,000) is needed in the primary framework so that general-purpose control tied to it will not contain intolerable errors.
    (b) Dense coverage in urban areas to provide control for surveys of property, utilities, transportation facilities, and the like. Stations should be spaced at 3- to 6-km intervals at an accuracy of 1 part in 100,000.
    (c) General area coverage for use in major federal programs and for general use by state and local governments and the public to be accomplished consistent with federal priorities. Stations should be spaced according to area needs at an accuracy of 1 part in 50,000.
    (d) Dense coverage with high accuracy is needed in tectonically active areas of special interest (e.g., regions of anomalous deformation, areas of detailed seismological investigations), with measurements repeated every one to two years. In addition, after moderate to large earthquakes involving significant horizontal displacements, horizontal control surveys should be repeated approximately monthly for several years after the event.
2. Vertical Control Network
    (a) Releveling of the primary lines of the network (at intervals of 160 to 480 km and on a 10- to 30-year cycle, depending on the area needs—shorter intervals will be required in active tectonic regions) to establish destroyed benchmarks, detect areas of crustal movement, and upgrade accuracy (Federal Mapping Task Force, 1973). High accuracy in the primary network is necessary to ensure that deterioration occurring in each subsequent survey (at intervals of 40 to 80 km) does not produce unacceptable errors.
    (b) Releveling and new leveling at high accuracy and close line spacing in areas of known or suspected subsidence or uplift. Measurements should be made on a one- to two-year cycle in tectonic regions where uplift is detected. After a moderate to large earthquake accompanied by significant vertical displacements, elevations should be determined monthly for several years in the vicinity of the earthquake.
    (c) Less accurate new leveling for area coverage to meet specific federal project requirements.

We recommend that the programs by the National Geodetic Survey and state and local organizations for the establishment of horizontal and vertical control monuments, particularly in urban areas, be accelerated.

National Coordinate System

The rapid development of data storage and handling by computers and the use of geographic positions as the common denominator for most data points has increased the need for a common reference framework in the United States tremendously in the last ten years. The surveyor who locates points on the ground and in the water and prepares the maps that are used to identify features requires a usable coordinate system to define the positions. A number of coordinate systems are in use in the United States today: geographic positions based on the 1927 North American Datum, State Plane Coordinates, Universal Transverse Mercator (UTM) Coordinates, various Military Grids, and independent coordinate systems for particular communities.

The State Plane Coordinate Systems were prepared by the U.S. Coast and Geodetic Survey during the 1930's and consist of 129 zones (72 Lambert conformal conic projections and 57 Transverse Mercator projections) having a width of about 254 km each and a maximum scale distortion of 1 part in 10,000. The UTM system was prepared by the military in the 1940's to provide a worldwide system of 60 zones, each 6° wide and a maximum scale distortion of 1 part in 1500 in the United States.

Those engaged in surveying and mapping recognize the need for a national reference system with a uniform projection system that can be used throughout the United States. If a new system is to be adopted, the time is now. With the new adjustment of the North American Datum, the positions of all stations will be revised, thus requiring a change in coordinates on the plane coordinate systems. The conversion to metric units necessitates a revision of maps, grid lines on maps, and values listed in projection tables. There is a need for a plane coordinate system for referencing points in many data systems and for the anticipated establishment of land-data systems. All of these factors emphasize the importance of adopting a national reference now so that the required revisions can be made at the same time as the other developments in surveying and mapping.

There is general agreement that a Transverse Mercator projection is the best plane coordinate system for most of the United States. There is some disagreement about the zone width for the projection. The accuracy of the UTM 6° zone is sufficient for the positioning required for most data systems. Generally, the cartographic community advocates that a 6° zone be used (UTM is based on a 6° zone), while those engaged in construction surveying, urban surveying, and large-scale mapping advocate a 2° zone. Some wish to perpetuate the State Plane Coordinate Systems, which have been legally adopted in 35 states. A comparative discussion of the 6° zone and the 2° zone is given by Doyle (1973), Pryor (1973), and Meade (1973).

We recommend that a Transverse Mercator System be adopted as the national plane coordinate system, that the National Geodetic Survey issue projection tables such that the projection error of a coordinate within a zone boundary will never exceed 0.1 mm as a result of computations, and that the advantages of the Transverse Mercator System be demonstrated to the states with legalized State Plane Coordinate Systems.

Research and Development of Surveying Instruments

Most private surveyors and those in smaller government agencies are dependent on the major government surveying agencies and other countries for surveying instrument research and development. The positioning required for the exploration and development of resources in the ocean areas is usually performed by electronic systems that measure the speed of radio waves or sound waves through the atmosphere or water. Research is required to determine the absolute accuracy of the systems being used and the optimum survey patterns for various projects and to develop better positioning systems for marine areas. The research and development activity by surveying groups in the United States has been inadequate for many years; most of the recent developments have been fallouts from the military and space programs or other scientific endeavors or have occurred in other countries. If the surveyor is to be supplied with instruments that will be required to accomplish the tremendous surveying and mapping tasks in the next 20 years, a greater government effort will be required.

We recommend that the research and development activities of the federal agencies be better coordinated so that multiple use of some of the instruments and methods can be achieved and so that the transfer to nonfederal users can be expedited by appropriate publications, technical assistance, and other means.

3.2 GEODYNAMICS

Conventional geodetic methods have long played an important role in contributing to fundamental understanding of geodynamic processes such as earthquake-related crustal deformation, postglacial uplift, and aseismic secular deformation. A series of articles on geodetic measurements of crustal movement from 1960 to 1971 is given in a report of the U.S. Department of Commerce (1973). Now, in addition to the standard techniques, new instrumentation such as multiwavelength distance measuring devices and ultrastable gravimeters and new techniques such as extraterrestrial ranging are available for addressing geodynamic problems.

During the next decade, geodetic measurements can be expected to produce notable progress in outlining the pattern of tectonic deformation ranging in scale from the size of the major lithospheric plates down to the dimensions of local active crustal fault zones. For the first time, extraterrestrial ranging techniques will provide direct measurements of the current rates of plate motion, in addition to testing the internal rigidity of plates and determining whether rates of movement are steady on short time scales. In regional studies, a mix of old and new geodetic techniques will be used to measure deformation along plate boundaries, monitor fault zone movements in seismically active areas, and search for geodetic precursors to damaging earthquakes.

New methods will improve the measurement of earth rotation and polar motion, providing important constraints on processes as diverse as earthquake occurrence and fluid flow of the earth's core. These improvements will make important contributions toward resolving such long-standing questions as the excitation and damping of the earth's Chandler wobble, atmospheric effects on the rotation rate, and large-scale aseismic motions associated with faults.

Geodetic measurements can also provide constraints on the flow properties of the earth's mantle and their variation laterally and as a function of depth. In particular, precise determinations of uplift rates in formerly glaciated regions will be useful in delineating a low-viscosity layer in the upper mantle, and long-wavelenth variations in the gravity field provide constraints on postulated convective flow patterns in the earth's deep mantle.

3.2.1 Tectonic Deformation

The relative motions of the earth's major lithospheric plates, the slow steady secular deformation that occurs between major earthquakes along plate boundaries, and the occasional episodes of more rapid crustal deformation observed near plate margins are all surface manifestations of the tectonic processes that drive plate motions. Since point measurements may be unduly influenced by local nontectonic effects, measurements made over distances of more than a few hundred meters are most appropriate, and geodetic methods are well suited for these purposes. Geodetic measurements can thus determine the rate, orientation, and spatial character of these deformation fields, and such data provide important constraints on the causative processes.

Plate boundary deformation is of particular interest to seismologists because of its relation to earthquake-generating processes. The purely coseismic movements that accompany faulting in large earthquakes are now largely understood and can be quite successfully modeled using the elastic theory of dislocations. In contrast, the character of pre-earthquake crustal deformation is known only imperfectly and is of particular interest at present because of its importance to earthquake prediction research. Under the Earthquake Hazard Alleviation Act, support for geodetic surveys in the California earthquake zones was increased by $1.7 million for fiscal year 1978.

We recommend an increase in the number of horizontal and vertical geodetic control measurements in active crustal fault zones, as well as improvement in their accuracy. Obtaining a detailed and accurate record of tectonic motions before and after large earthquakes is essential to understanding the underlying processes. Hence we further recommend at least a tripling of measurements within the United States over those in fiscal year 1978. In addition, to obtain a significant sample of motions associated with large earthquakes within the next decade, comparable geodetic measurements should be undertaken is seismic zones outside the United States.

Interseismic secular deformation observed along plate boundaries provides clues to the mechanism responsible for strain accumulation and rough estimates of the recurrence interval between large earthquakes. Repeat horizontal and vertical control surveys at several-year intervals with good spatial coverage parallel and perpendicular to active faults are needed to determine the areal pattern and rate of secular strain accumulation. Such data provide observational tests for suggested models of strain accumulation, and theoretical models can in turn be used to explain observations and guide field measurements. Typical rates of horizontal shear straining observed on or close to major plate boundaries in California and Japan are close to 3×10^{-7} per year, and coastal subsidence rates observed on tide gauges located onshore facing the Japan trench average 5-10 mm/year. Deformation rates appear to decrease fairly rapidly away from the San Andreas plate boundary, and some data (e.g., Owens Valley of California) suggest that lower deformation rates observed on minor faults are correlated with longer recurrence intervals between major earthquakes.

It is worthwhile pointing out that although the major research efforts in measuring tectonic deformation are concentrated on land, most of the boundaries of the major plates lie beneath the world's oceans. Furthermore, in many of these sub-sea zones deformation rates are likely to be significantly greater than those observed on continents. Detailed marine geophysical studies such as the French-American cooperative project FAMOUS, carried out on the Mid-Atlantic Ridge, have provided important constraints on tectonic processes operative at plate boundaries. Development of geodetic techniques for detecting both vertical and horizontal movements of the sea floor would produce corresponding progress in understanding the deformation occurring at the midocean ridges and near deep-sea trenches.

For *earthquake prediction research*, strain accumulation data are valuable in establishing the "normal" pattern of crustal movements, and models of secular deformation can be useful in suggesting critical parameters or advantageous locations for precursory monitoring. A significant problem in identifying premonitory deformation is the occasional episodic deformation that occurs in tectonic regions and is not obviously related to impending earthquakes. Such fluctuations are particularly conspicuous in the historic geodetic record of vertical deformation in the western United States and are not well understood at present. The dilemma posed by these anomalies is vividly illustrated by the recently discovered ground uplift in Southern California (Castle *et al.*, 1976): Current understanding of vertical tectonic processes is insufficient to assess unambiguously the earthquake risk posed by this unexpectedly rapid and widespread episode of deformation. A long-term geodetic monitoring program, with frequent repeat surveys every one or two years, is clearly needed in such anomalous regions.

The regional scale of the southern California uplift, encompassing an area of nearly 90,000 km^2, also points out that unexplained anomalies that may be earthquake precursors can be very widespread indeed. Although the current emphasis of the earthquake prediction program is on shorter-range geodetic measurements in active fault zones, wide-scale monitoring cannot be ignored.

Accordingly, we recommend that U.S. efforts to establish large-scale monitoring networks in broad areas surrounding fault zones be accelerated and that such networks be extended to other parts of the world, where possible, through cooperative projects with other countries.

Geodetic monitoring will play an important role in conjunction with other geophysical measurements in programs specifically designed to search for earthquake precursors. The requirements are similar to those for monitoring interseismic secular deformation except that coverage should, ideally, be more concentrated in areas of special interest, and more frequent repeat surveys are crucial if short-term precursors of days to months (if they exist) are to be detected. *An important contribution to precursory monitoring of vertical tectonic movements would be the development of a capability for rapidly and inexpensively measuring elevations with an accuracy of 1 cm or better.* For the detection of short-term precursors, the continuous recording of crustal deformation at permanent sites is an attractive complement to intermittent resurveys. The three wavelength electronic distance measuring devices and ultrastable gravimeters now being developed will be particularly useful for these purposes. For many crustal movement studies, including precursor monitoring, geodetic gravimetry can often be an attractive complement or an inexpensive alternative to conventional leveling for inferring elevation changes and possible subsurface density changes. However, for both continuous recording and survey mode usage, the tidal gravity variations caused by the ocean tidal load must be known and corrected for in order to attain precision of a few microgals or better (Beaumont *et al.*, 1975).

Postseismic crustal deformation, which may persist for many years following large shallow focus earthquakes, provides unique information on the response of the lower lithosphere and perhaps the upper part of the asthenosphere to the impulsive loading produced by sudden seismic slip (Fitch and Scholz, 1971; Nur and Mavko, 1974; Thatcher, 1974). The important scientific issue here is to understand the mechanism responsible for these adjustments, either aseismic fault slip beneath the earthquake rupture zone or lower lithosphere relaxation or some combination of the two. The principal unresolved question is the nature of the coupling beneath the shallow seismic zone and the underlying material, an issue that is central to many diverse geodynamic problems.

Geodetic methods may be used to address this problem by detailed studies of the spatial character and temporal history of postseismic movements. Rapid field deployment of instrumentation immediately following earthquakes larger than about magnitude 6.5, good areal coverage around the rupture zone, and monthly repeat surveys for several years appear quite feasible in geographically accessible areas. Even in very remote areas such as island arcs, a relatively small number of simple geodetic measurements repeated for several years following a great earthquake could be significant geophysically. Instrumentation and areal coverage will be strongly influenced by logistical considerations, but where feasible, strain changes determined by repeated electronic distance measurements and tilt and elevation changes inferred from repeated leveling and gravity surveys and from tide gauges would be valuable. Following great earthquakes, extraterrestrial techniques can also provide important constraints on possible longer range (~100 km or more) postseismic effects.

We recommend the development of a coordinated set of instruments for postseismic monitoring of strain, tilt, and gravity over a wide range of distances and time intervals.

At the same time, theoretical models, particularly those that take account of lithosphere-asthenosphere coupling, can be used to suggest key measurements and experimental tests. For example, several relatively simple theoretical models predict strain diffusion away from the seismic rupture zone in the years following a major earthquake (e.g., Savage, 1971, 1977; Bott and Dean, 1973; Anderson, 1975), and such models could be tested by a few key measurements repeated for perhaps five years following a great earthquake. The observations might, in turn, suggest further theoretical refinements or the need for radically different models.

We recommend the development of models of deformation related to earthquake processes that can be field tested by geophysical measurements.

The uniformity of *relative plate motions* and the *relative rigidity of the major plates* are two crucial unifying principles of global tectonics, and while these postulates are undoubtedly valid in a long-term average sense, significant departures over short time intervals and both regional and local scales could well exist, and if so have important geodynamic implications. Such fundamental postulates can be tested geodetically using a combination of existing data, conventional geodetic methods, and the currently evolving extraterrestrial ranging techniques.

Using existing data and techniques, rates of relative plate motion can be estimated across those few plate boundaries that traverse continents, such as the San Andreas fault system in California. However, since boundaries on land are the exception rather than the rule, because continental plate boundaries tend to be broad and complex, and because accumulated random errors severely limit conventional geodetic methods beyond distances of roughly 100 km, the long-baseline capabilities of the new extraterrestrial techniques are uniquely suited to relative plate motion measurements. For studying diffuse plate boundaries, testing the internal rigidity of plates, and investigating complex regions containing minor plates or undergoing internal distortion, the entire deformation pattern can be synthesized by using historic geodetic data and conventional methods to determine the local crustal movements and longer-range extraterrestrial techniques to obtain the broad-scale motions.

We recommend the careful planning of observation programs to determine the current rates of plate motion, test the relative rigidity of the plate interiors, and search for temporal variations in plate motions.

On the basis of examination of historic leveling data in the eastern United States, Brown and Oliver (1976) have suggested that differential vertical movements as great as 6 mm/year are occurring there. The existence of such large rates in a region of presumed low tectonic activity would be surprising. Also, there are reasons to be suspect of the leveling data and their adjustment. Hence further work is needed to establish more firmly the reality of this deformation and to determine its areal extent (Brown, 1978).

In determining crustal movements by geodetic means, it is important to emphasize the value of *the existing geodetic record* and acknowledge the contributions that have been made and the services that will continue to be provided by federal, state, and local agencies that are themselves not specifically concerned with tectonic deformation. It should be a high priority to alert all agencies and individuals carrying out geodetic surveys in tectonic regions that control networks are continually being distorted by active tectonic processes and that these distortions may significantly affect the practical uses to which their survey data are put.

During the past few years, these historic geodetic data have provided valuable information on pre-earthquake and postearthquake processes, anomalous crustal deformation, and secular motions near active faults and in the future will continue to contribute significantly to these studies as well as to research related to earthquake prediction, intraplate seismicity, and internal plate deformation. It is perhaps also worth emphasizing that commonly used methods of data reduction and network analysis used by geodesists can often distort or obliterate important effects of crustal deformation of special interest to geophysicists. Therefore, as a general rule, special analysis of the unadjusted field data is usually required in studies specifically oriented to the detection of crustal deformation.

3.2.2 Response of the Solid Earth to External Effects

The solid earth is measurably affected by phenomena such as the tides raised by gravitational attraction of the sun and moon, both direct and indirect, through ocean loading; atmospheric pressure variations; mass shifts of water from glaciers to oceans; and lake filling and emptying. Because the magnitudes and extents of most of these exogenic effects can be estimated fairly well, they constitute experiments in solid-earth rheology. Some of these analyses pertaining to gravity, rotation, and polar motion, are discussed in Sections 3.2.3 and 3.2.4.

Tidal effects on the solid earth average about 50 cm in displacement and 1.5×10^{-6} m sec^{-2} in acceleration, as measured by strainmeters, tiltmeters, gravity meters, and satellite orbit perturbations. The response to tidal attraction by a solid planet of spherically symmetric elastic properties accounts for the major part of these observed deviations from purely lunar and solar attraction. The geophysical interest lies in (1) lateral variations in amplitude of the response and (2) temporal phase lags of the response behind the lunar and solar attractions. These lateral variations and phase lags are largely accounted for by the loading of the solid earth by the ocean tides, whose amplitudes and phases are greatly modified by the irregular shape of the ocean boundaries. However, there may be detectable residuals that relate to tectonic structure, lateral variations in elastic properties, and dissipation in the solid earth. These tidal effects, together with the polar motion effects discussed in Section 3.2.4, are the main evidences of solid-earth material properties in the frequency range intermediate between seismic effects (>1 cycle/hour) and glacial loading (~1 cycle/10,000 years) (Farrell, 1973; Lambeck, 1977; Melchior, 1978). An additional geophysical interest would be the possible role of tidal stresses as triggers for earthquake occurrence; however, if such an effect exists, it is complex and indirect (Heaton, 1975).

The most important measurable exogenic effect on the solid earth is the transfer of mass from northern North America and Eurasia to the oceans when the great ice sheets melted 18,000 to 6000 years ago. The amount of water involved was sufficient to raise the average level of the oceans about 80 m. A consequence of this surface transfer of mass was a counterflow of matter throughout the mantle, which is still going on. The main data used are radiocarbon dates of past shorelines, indicating the relative motions of the sea surface and solid earth. These data indicate that the isostatic compensation of the mass shift from ice cap to oceans is largely completed, at a rate that can be accounted for by an essentially elastic lithosphere of 100 km thickness overlying a mantle of uniform viscosity of 10^{22} P (P = poise = 1 g cm^{-1} sec^{-1}) (Cathles, 1975; Peltier, 1976; Peltier and Andrews, 1976). However, geodetic leveling suggests there may be an uplift of 2 cm/year near the center of the Laurentide Ice Shield (Walcott, 1973). Such a rate would require in addition either a nonlinear rheology or a low-viscosity layer, or asthenosphere, of perhaps 10^{21} P viscosity and 100-km thickness.

More detailed information on the current uplift rates is necessary to infer the rheological properties of the mantle. An accuracy of about 0.5 mm/year is desirable and should be inferable from standard leveling data. However, the state of processing and adjustment of the leveling data is such that its inherent accuracy is not being realized. Therefore, for scientific, as well as practical reasons, *we endorse the completion and adjustment of the North American Vertical Control Network recommended in Sections 1.1 and 3.1 and urge the redetermination of elevations at decade intervals in the area of the ice sheet and its peripheral bulge*—roughly, a circle of 2000-km radius centered on southern Hudson Bay. Analysis of the data in this zone would allow more precise determination of asthenospheric viscosity and thickness and their lateral variations. A sufficiently detailed mapping of uplift rates (coupled with plausible constraints on the variation of asthenospheric viscosity) may also allow inference of nonlinear effects of strain rate on stress, which would have significant implications for mantle convection.

3.2.3 Gravity

The spatial variations in the gravity field, of about 3×10^{-4} m sec^{-2} magnitude, are the most comprehensive measure of density and stress irregularities, since gravity anomalies imply density anomalies, which in turn necessarily entail stress in any cohesive medium. Because a gravity attraction is an integration of many effects (rather than of something sharply locatable in time or space, such as a seismic source, a radioactive date, or a magnetic seafloor striation), and because stress unavoidably induces some compensatory yielding, gravity is useful geophysically only in combination with other data, primarily geological (more for local kilometer-scale features) and seismological (for broader scale and deeper features). While a regional-scale survey with spacing of about 10-30 km is desirable for any area to indicate general patterns, more detailed surveys are warranted only in conjunction with special studies for either prospecting or scientific purposes.

In recent years, the most marked progress in the scientific interpretation of the gravity field has related to suboceanic structure. It is now generally understood that all the suboceanic crust and lithosphere have been created within the last 180 million years by seafloor spreading from ocean rises. The magnitudes and wavelengths of gravity anomalies have been used to infer the change in lithospheric thickness with time off the rise, plus variations thereof dependent on spreading rate (Sclater *et al.*, 1975; Cochran and Talwani, 1975). Currently, attention is directed mainly to departures from standard models of a spreading cooling lithosphere, with the hope to infer the scale and nature of asthenospheric flow. Fluid-dynamical theory predicts scales of a few hundred kilometers, considerably smaller than the extent of typical oceanic tectonic plates. Correlations of gravity anomalies with topography and volcanism suggest interactions of this scale but are obscured to a considerable extent by such factors as the temperature dependence of viscosity and the finite strength of the lithosphere (Kaula, 1972; McKenzie and Richter, 1976).

The principal geophysical utilization of gravity anomalies is now shifting to the compression belts of the plate tectonic system, the main locus of continental crust creation. Probably the most systematically marked correlation of gravity anomaly with topography is the narrow negative over an ocean trench and the broad positive over the adjacent island arc and the marginal sea and continental area beyond it. This pattern has not yet been satisfyingly explained by models of subduction zones. Even more complex are the gravity irregularities associated with continent-continent collision belts, such as the Asian portion of the Alpide belt (Bird *et al.*, 1975).

On a global scale, there are some general correlations of the gravity field with features of the plate tectonic pattern, but this correlation is far from completely systematic. In principle, gravity anomalies should provide one of the few significant constraints on deep mantle convection (along with the broad variations in topography, the plate velocities, and possibly certain systematicities in isotope ratios), but the realization of this constraint requires better integrations of broad convective systems.

Applicable to these problems of mantle flow and plate tectonics is the low-altitude gravity satellite recommended in Section 4.2.

If some improvement in long-term stability of gravity meters is attained, then measurement of the temporal change in the gravity field would be of tectonic interest. This interest would center mainly on the earthquake zone. Since the vertical gradient of gravity is -3×10^{-6} (m sec^{-2})/m, a gravity-meter accuracy of 10^{-8} m sec^{-2} would be compatible with the 3 mm attainable for level differences over horizontal distances on the order of 1 km. This accuracy is currently being approached (see Section 5.1). Measurement of *both* levels and gravity is required, because the mass motion accompanying a rise in ground surface is uncertain (Whitcomb, 1976). Therefore:

We recommend that, when field gravimetric accuracies better than 10^{-7} m sec^{-2} are consistently attained, the vertical geodetic control measurements for tectonic deformation should be regularly accompanied by gravimetry.

3.2.4 Earth Rotation and Polar Motion

Observing programs for the determination of the earth's rotation and of polar motion are considered an integral part of both geodesy and astronomy. Geodesists need to know the orientation of the earth in space mainly because stellar observations are used to determine the orientations of control networks and to reduce distortions in them. Astronomers use the results to correct their observations of star positions. Variations from uniform rotation for the quasi-rigid outer parts of the earth are determined in terms of an earth-rotation-based time scale called Universal Time (UT). Tipping of the quasi-rigid parts with respect to the rotation axis is described in terms of the coordinates x and y of the rotation pole with respect to a conceptual earth-fixed reference pole.

The estimated accuracies for the values of UT and polar motion derived by the Bureau International de l'Heure (BIH) are 2 msec of time (90 cm) for UT and 40 cm for x and y (Guinot, 1973). The precision of the raw five-day average BIH values is about twice as good. Independent analyses of polar motion are carried out by the International Polar Motion Service (IPMS). Both services now incorporate Doppler satellite data in their results, along with conventional astronomical observations from over 50 observatories in various parts of the world.

Geophysicists have shown strong interest in the earth's rotation and polar motion. Many possible sources for both irregular and periodic variations in rotation rate have been studied (Munk and MacDonald, 1975; Rochester, 1973; Lambeck and Cazenave, 1977). These include exchanges of angular momentum between the ocean, the atmosphere, and the crust; torques between the liquid core and the mantle; seasonal effects on the density distribution of the hydrosphere and atmosphere; and tidal distortions of the earth and oceans. A possible connection between changes in the rotation rate, polar motion, and the occurence of large earthquakes also has been suggested (Anderson, 1974; Chinnery and Landers, 1975).

Polar motion for the earth consists mainly of the 14-month-period Chandler wobble and an annual term. Both motions are roughly circular retrograde rotations with typical amplitudes of about 3 m. The beats between the two frequencies give large changes in amplitude of the combined motion with a period of approximately 7 years. The annual term is a forced motion caused mainly by changes in the atmospheric density distribution.

The Chandler wobble is a free mode of the earth, which has been discussed and looked for since the late 1700's. What excites this mode is not known for sure, although both atmospheric motions (Wilson and Haubrich, 1976) and great earthquakes (Mansinha and Smylie, 1967) may be responsible for substantial parts of the excitation. The damping time for the mode may be of the order of a century, although both considerably longer and shorter times have been derived from the observations. The location in the earth where the damping occurs also is not known. Despite an intensive program of polar-motion observations at 39° 8′ N latitude by the International Latitude Service stations since 1895, the noise in the measurements has prevented a clear understanding of the phenomena involved from being obtained.

For the earth's rotation rate, variations with periods of decades to centuries have been recorded over the past several hundred years. The record can be extended even further back by including reports of astronomical phenomena such as eclipses from as long as 3000 years ago. However, the interpretation then becomes less certain. It is not clear at present whether there are fluctuations in the rotation rate with periods as long as thousands of years, in addition to the secular deceleration due to tidal interaction with the moon and postglacial mantle mass transfer. The larger variations in rotation rate are presumed to be due to interchanges of angular momentum between the core and mantle, since there are limits to how large the changes in angular momentum of the atmosphere are likely to be. The rotation effects due to the core are of particular interest in connection with attempts to understand the dynamic driving motions in the core that generate the earth's magnetic field and the irregular pattern of secular variations in the field.

Present interest in the Chandler wobble has been strengthened considerably by the realization that changes in polar motion due to great earthquakes may contain information on preseismic and postseismic motion, which is difficult to obtain in other ways. Such changes should be clearly observable with the new long-baseline interferometry (LBI) and laser-ranging techniques. For example, the 1960 Chilean earthquake (magnitude 8.3) has been calculated (Smith, 1977) to give a change in polar motion corresponding to a 65-cm offset in the axis about which the pole moves, if the coseismic fault plane motion derived by Kanamori and Cipar (1974) is used, and a possible additional 87-cm offset due to the preseismic motion for which they have presented evidence.

Seismologists generally believe that the "seismic moment" corresponding to the coseismic motion can be derived accurately from observed long-period seismic-wave amplitudes. However, motions occurring over periods of minutes, days, or even several months before and after the quake are difficult to determine in other ways. Thus changes in polar motion over a period of several months around the time of the quake can give a check on the total fault displacement, which complements the information available from resurveys of the surface area surrounding the fault. Nearly continuous excitation of polar motion variations also may be present because of small but frequent aseismic motions on faults or meteorological excitation. Studies of the damping rate for polar motion and of where the damping occurs are important to geophysics because no other information is available on dissipation in the earth at long periods.

The new techniques of LBI, laser ranging to artificial satellites, and laser ranging to the moon appear capable of achieving about 3-cm accuracy for determining UT and polar motion with a one-day averaging time. However, it is not yet known whether real fluctuations will be observed at this accuracy level and averaging time. The first tasks undertaken with the space techniques should include the following: determining the amplitudes of short-period variations and their causes; detecting changes in pole position after large earthquakes; correlating rotation rate changes with variations in the atmospheric circulation; and studying the excitation and damping of the Chandler wobble. Since systematic errors that are different for the various techniques are likely to be among the main limitations, a mixed international network including stations using both the laser-ranging and LBI techniques seems desirable for at least the next decade, as discussed in Section 4.2.

The same stations that determine UT and polar motion will also serve as the reference points for measurements made by mobile stations of plate tectonic motions, deformations in plate interiors, and crustal movements in areas surrounding fault zones. In view of the importance of such crustal movement measurements for understanding geodynamic processes, as well as because of the inherent scientific value of improved UT and polar motion information, we believe that the United States should support the construction and operation of stations designed for making the necessary high-accuracy measurements on a daily basis.

We recommend that the United States support three long-baseline-radio-interferometry stations and approximately six laser ranging stations at fixed locations as part of a new international service for determining UT and polar motion on a continuing basis with sufficient accuracy to meet current geodynamics needs.

The reasons for recommending support for these particular numbers of stations are discussed in Section 4.2. It should be noted that most of these stations also will fulfill other important scientific or applied objectives and that a number of them are already available or will be soon.

3.3 OCEAN DYNAMICS

The geoid is considered to be the equipotential surface that would enclose the ocean waters if all external forces were removed and the waters were to become still. The surface of the real ocean departs from this geoid because of wind-driven currents, tides and tidal currents, storm surges, tsunamis, large-scale oceanic turbulence, turbulent flows in the surface-mixed layer, and various other oceanic and atmospheric phenomena. There is little direct information about these departures at the present time, yet a clearer understanding of dynamics phenomena could be attained with such information.

There are two types of geodetic observation that are currently available to physical oceanographers along this line. The first type consists of observations of the variations of time-averaged sea level from one place to another. This gives information about steady ocean currents. The second type consists of intercomparisons of time-varying sea-level measurements at fixed stations. This gives information about inherently time-dependent and therefore usually wavelike flows, as, for example, tides, storm surges, and tsunamis.

3.3.1 Mean Sea Surface

Variation of the mean sea surface with respect to the equipotential geoid has only been directly measured in association with geodetic surveys between stations. Nevertheless, it is believed that deep-sea variations of the sea surface with respect to the geoid almost certainly exist. The time-independent variations of the sea surface are due to currents that have a large mean component such as the Gulf Stream, the Antarctic circumpolar current, and the Kuroshio current. If the surface were measured accurately, the absolute magnitudes of these large ocean currents could be estimated to a higher degree of accuracy than the present-day estimates. This would enable physical oceanographers to make a much more precise census of the movement of water masses by such large currents and to estimate fluxes of various solutes in the water such as silicates and oxygen more accurately. Such measurements would also allow physical oceanographers to observe long-time variations in these currents and to compare them with measured variations in the global wind and temperature field. The studies could lead to a better understanding of the coupling between oceans and atmosphere.

Measurements of sea-level variations have almost exclusively been confined to ground stations located upon one contiguous land mass or between islands spaced closely together. The measurements have been taken both along the shore of one body of water and across land areas that connect different bodies, such as the Isthmus of Panama (Roden, 1963). For measurements along one body of water, disagreement exists between the geodetic data and predictions by physical oceanographers as to the expected variation in sea level between the same stations due to ocean currents (Sturges, 1967; Montgomery, 1969). Moreover, new considerations of the dynamics of circulation of continental shelf waters have raised several new questions about sea-level variation along and across the shelf (Stommel and Leetmaa, 1972; Csanady, 1976). It is not known whether the errors exist principally in the geodetic data, in present understanding of ocean dynamics, or in both. At present, no direct sea-level measurements have been made from the shore across the shelf and into the deep sea, and it is not known whether the deep-sea surface couples closely to coastal-sea surface. A reconciliation of the geodetic information with the proper oceanographic measurements should lead to insight into both fields.

3.3.2 Time-Varying Sea Surface

Large current systems in the ocean have been observed to exhibit variations in their strength with time. The amplitude of these changes are often of the same strength as the errors in the standard oceanographic measurements that are used to determine the mass flux and strength of these large currents so that the character of the variations is not well documented. In some cases these variations are caused by instabilities of the currents such as the breakup of the main Gulf Stream into eddies after the Gulf Stream leaves Cape Hatteras. If time-dependent sea-surface measurements could be made of the surface of the ocean over these eddies, important new information could be gained about the dynamics of these eddies. In the open ocean, away from the large time-averaged currents, other turbulence-like eddies appear to exist. The mechanism by which such background oceanic turbulence is generated is poorly understood. The statistics of the background oceanic turbulence likewise is poorly understood, and a large view of sea-surface topography over time would give valuable new information about oceanic turbulence.

The second class of time-varying variations of the sea surface that exist are associated with tides. Deep oceanic tides have now been measured in a few places by deep pressure gauges (Snodgrass and Wimbush, 1974; Snodgrass *et al.*, 1975). With the advent of the modern computer, solutions of Laplace's tidal equations in a realistic ocean have been advanced (Pekeris and Accad, 1969), but the few checks that have been done to date indicate that there is agreement in some regions of the ocean and disagreement in others. As observations progress, solid-earth tides will also be part of the signal (Hendershott, 1972). It will not be possible to advance these calculations to a status of accurately representing the world's tides until extensive deep-sea tides have been measured and careful intercomparisons between tidal prediction and field data indicate that a predictive scheme is satisfactory to a given degree of accuracy.

Other waves are also excited on the deep ocean. For example, internal waves and shorter surface waves may be excited by various atmospheric and climatological forcings that are not yet suspected. A class of waves that is well understood theoretically propagates around the edges of the oceans. These waves are generally exemplified by storm surges, tsunamis, and other shelflike waves. The large waves are of practical importance to the safety of harbors and cities and the safety of navigation as well as of importance scientifically. The bulk of the information about such waves is now derived from tidal land stations operated by the National Ocean Survey. Measurements along the full breadth of the continental shelves as well as the deep seas would give valuable new information about the structure and behavior of such waves. At present, tide gauges and shelf pressure gauges yield information about such waves. In all cases, instrumental output represents contributions from many time-dependent sources superimposed, along with various sources of noise and bias in the instrument itself. The problem of inverting signals from one or more of these instruments to get a particular piece of information is considerable.

Time variations that are observed on tide gauges in tectonically active regions may be due to vertical tectonic movements. If time-varying sea-surface characteristics are not known, we cannot extract the tectonic signal, and vice versa; hence, we must know tectonic movements to extract oceanographic effects. In such a case the pressure signal would need to be combined with a knowledge of sea-surface height and calculated pressure due to density variations in the water column.

3.3.3 New Developments

It can be expected that new data are going to augment the traditional sea-surface information in the next few years. One new source of data will be satellite altimeters, which may give indications of time-dependent sea-level variations and in association with gravimetric surveys will give information about the change in the mean sea levels from station to station. SEASAT-A is expected to measure the satellite-to-sea surface distance with 10-cm accuracy. However, long-wavelength variations in the orbit will not be known to comparable accuracy, because of gravity modeling errors and insufficient tracking. Reduction of the ocean dynamics data from the SEASAT altimeter will be a major task because the signal will record the contributions of many processes simultaneously. Since SEASAT repeats its pattern of coverage every 180 days during the first year, a close interaction of data processing with *in situ* observations and theoretical calculations appears to be vital to unscramble the contributions of various oceanic flows. The full exploitation of the data will require adjustment of the orbits, including the measured altitudes as a data type thereafter, with special weight on cross-track intercomparisons.

Some unique data-analysis constraints will arise in the SEASAT data. For example, a Gulf Stream ring will move approximately its own radius before it is sampled again, and sophisticated techniques may be necessary to track such features properly. Deconvolution of the contributions of tides to signal, of up to 1 m, will be necessary before other long-wavelength features can be identified, yet the procedure to do this is by no means trivial or clearly understood at present. Lastly, the sea-surface height arising from time-averaged flows will not be known until the gravity field, and hence the local geoid, is determined over the same area by other methods to the resolution accuracy of the altimeter. Such a task may involve extensive ship surveys, if wavelengths of less than 1000 km are needed.

Many details of the oceanic flows require resolution better than 10 cm, and an improvement of the altimeter to 1-cm resolution would increase the potential uses of this instrument. Likewise, knowledge of the position of the satellite to the same accuracy would greatly ease the data-reduction problems.

Another set of instruments that have just recently been developed and that will reach more potential in the coming years will be the deep-sea pressure gauges (Snodgrass and Wimbush, 1974), which give some indication of the overburdened water over each station. These devices have already given new information about deep-sea tides.

At present, the deep oceans are virtually unexplored geodetically. It is clear that both types of instrument will help to extend geodetic measurements to the deep oceans.

3.4 MOON AND PLANETS

The variations in the gravity field and surface elevations of the moon and planets are important indicators of their levels of tectonic activity and degree of crustal differentiation, as they are for the earth. In addition, a mean radius combined with the mass from flyby or natural-body perturbations yields the mean density, an important constraint on bulk composition, while the dynamical oblateness combined with either a precession rate due to a torque or (for a rapidly spinning body) the hydrostatic assumption gives the moment of inertia.

The NASA Planetary Exploration Program, together with the great radars at Arecibo, Goldstone, and Haystack, have led to a significant increase in our geodetic knowledge of the moon and planets in recent years.

The great variety in the inherent characteristics of the planets, the degree of detail of which has been measured and the prospects for future measurements make a planet-by-planet discussion appropriate. For a general summary, see Anderson (1975).

3.4.1 The Moon

By virtue of Doppler tracking of close lunar satellites, there exists a rather detailed gravity map of the near side of the moon, with resolution varying from 100 to 300 km. The most pronounced features of the map are gravity highs associated with ringed maria, impact-created basins filled with lava flows. Estimates of the far-side gravity field require a rather complex process of indirect inference from longer-term orbital perturbations. The accuracy of determination of the longer-wavelength variations of the gravity field further indicate that the moon is closer to hydrostatic equilibrium than is the earth, the stresses implied by the gravity field being only one third as much (Kaula, 1975).

Rather accurate elevations of about 20 percent of the moon's surface were obtained by the mapping cameras on the later Apollo missions. Lower-accuracy information about topography is inferred for other regions by radar, laser altimetry, and reconnaissance photography. Combination of this altimetry with the gravimetric map enables the extrapolation from seismometry in the Apollo landing-site area to obtain global estimates of crustal thickness. The mean crustal thickness is estimated to be about 75 km, a striking difference from that of the earth; this is a major constraint on theories of lunar origin. An appreciable offset of the center of figure from center of mass, about 2 km, is also inferred.

Laser ranging from the earth to retroreflectors at three Apollo sites enables measurement of the moon's wobble, which in turn can be used to estimate the moment of inertia. The degree of central densification of the moon indicated thereby is very slight.

A major improvement in knowledge of the moon's shape and gravity field would be obtained by a Lunar Polar Orbiter, as proposed by NASA in, but deleted from, the fiscal year 1977, 1978, and 1979 budgets. It was planned to incorporate a relay satellite in this project, in order to measure variations in the gravity field on the far side of the moon (Toksöz *et al.*, 1977). The scientific interest in such measurements remains, of course, and if changing circumstances lead to revival of an unmanned lunar orbiter, they should be pursued.

3.4.2 Mars

Doppler tracking of Mariner and Viking Orbiters obtained a rather complete coverage of the Martian gravity field. The resolution of this field varies significantly with latitude because of the eccentricity of the orbits. The most marked feature of this gravity field is a maximum associated with the great high of Mount Olympus and the nearby Tharsis mountains. The magnitude of the variations of the gravity field indicate that Mars is appreciably further from hydrostatic equilibrium than is the earth–about three times as much in the sense of stress implication (Gapcynski *et al.*, 1977).

Topographic altitudes on Mars are inferred most comprehensively by the variations in the amount of atmosphere indicated by infrared and ultraviolet detectors. The range of altitudes is significantly greater than on earth–about 30 km. The higher elevations are supported in part by lithospheric strength, but a combination of this topography with gravity indicates a minimum mean crustal thickness somewhat greater than the earth's–about 30 km.

Mars is rotating fast enough and is large enough that a rough estimate of the moment of inertia can be made by applying the assumption of hydrostatic equilibrium to the flattening of the shape inferred from the perturbation of satellite orbits. This process results in the inference that Mars has a moderate degree of central concentration of density compared with the earth, indicating either a small core or an enhancement of the FeO/MgO ratio with depth.

As with the moon, scientifically valuable refinement of the gravimetry and altimetry could be obtained by a low-altitude polar orbiter. Determination of the precession constant and, thence, refinement of the moment of inertia, would be feasible with automated astronomical observations from a lander (Toksöz *et al.*, 1977).

3.4.3 Mercury

Geodetic information about Mercury is slight compared with that from the moon or Mars. The Mariner 10 flyby set an upper limit on the gravity-field irregularity appreciably higher than the lower limit required for the stabilization of the 3:2 spin-orbit coupling. Some analyses of the photography to determine the shape have been made, but the data are insufficient to infer any crustal thickness or to refine the determination from earth-based radar that the offset of the center of figure from center of mass is slight.

Again, a close polar orbiter is desirable to get gravimetric and altimetric information. Determination of the moment of inertia from rotational variations seems feasible by a radio tracking system requiring a lander.

3.4.4 Venus

At present, Venus is much more poorly known geodetically than the other terrestrial bodies. Earth-based radar indicates topographic variations on the order of 3 km and an offset of center of figure from center of mass of about 1 km. Mariner 10 set a rather loose upper limit on the departure of the gravity field from sphericity (Masursky *et al.*, 1977).

The situation will greatly improve with the 1978 Pioneer Venus Orbiter (PVO), which will obtain estimates of the gravity field and altitudes to 100 m over an appreciable band of latitude. The altimetry coverage will be complemented by more data from the Arecibo radar. Again, a comprehensive gravimetric and altimetric coverage requires a close polar orbiter. Such data are expected to be obtained by the Venus Orbiting Imaging Radar (VOIR), a satellite proposed for 1983 launch primarily for radar imaging of the planet. Because of the slow rotation of Venus, inference of its moment of inertia seems hopeless (Toksöz *et al.*, 1977).

3.4.5 Jupiter

Significant constraints on the structure of Jupiter have been obtained by the Pioneer 10 and 11 flybys (Anderson, 1976). The oblateness of the gravity field measured by the perturbations of these spacecraft implies an appreciable degree of central concentration of density, requiring an icy or rocky core of some tens of earth masses in addition to the compression of hydrogen and helium (Hubbard and Slattery, 1976). More accurate determination of the zonal variations of the gravity field is desirable to refine these constraints. However, the severe radiation environment close to Jupiter and the wish to learn more about the satellites and the magnetosphere lead to orbits for the Galileo, to be launched in 1981, that are too far out to help very much. Measurement of longitudinal variations in the gravity field or of topographic variations seem even more out of the question.

3.4.6 Other Bodies

Improvements in the radii of solar-system bodies and discovery of additional satellites are continually being made by planetary astronomers from a variety of techniques. Thus, within the past two years, the radii of several asteroids have been determined more accurately by combination of spectrophotometry and polarimetry; the radii of three Galilean satellites have been measured by radar; the radius of Uranus has been improved, and five rings have been detected by occultation; and a thirteenth satellite of Jupiter has been found. In addition, determination of the masses of the Galilean satellites has been made from the Pioneer 10 and 11 flybys.

Further knowledge about the Galilean satellites, Saturn, and Titan can be anticipated from the Voyager Spacecraft launched in 1977 and Galileo, the Jupiter Orbiter, to be launched in 1981. However, the greatest scientific interest from geodetic measurements of bodies beyond Mars probably would be in masses of the larger asteroids in order to constrain their densities, and thus composition, more strongly. There is hope of some asteroid masses being improved by analysis of Viking orbit perturbations, but significant improvement would require a mission dedicated to the asteroids.

3.4.7 Conclusions

In general, geodetic interests seem to be satisfactorily looked after in the configuration of lunar and planetary projects. The geodetic data to be returned are limited, as the Pioneer Venus Orbiter and Galileo are severely constrained by physical circumstances. The anticipated Lunar and Venus Orbiters seem particularly well optimized for geodesy. Therefore, we limit our recommendation to the following:

We endorse NASA *plans for a Venus Orbiter Imaging Radar, including an altimeter, to be launched in 1983, and urge reconsideration of a Lunar Polar Orbiter, if the opportunity arises.*

4 Geodetic Methods

Prior to the rapid advances in electronics and space techniques following the Second World War, geodetic operations were essentially earthbound and consisted of angle measurements, or triangulation, using theodolites; distance measurements using tapes or some similar devices; differences in elevation by spirit levels and rods; star observations for position and azimuth determination using telescopes; and gravity measurements using pendulums and spring-balance devices. Although the electronic-space age has greatly enhanced several capabilities, in computation as well as measurement, many of the earlier procedures continue to be necessary and hence should be studied by the nongeodesist who wishes to analyze these measurements to infer spatial and temporal variations. For some phenomena, the data analyzed may include measurements taken several decades ago.

This chapter considers current measurement techniques and new techniques likely to come into use soon and concludes with a discussion of theoretical problems. Geophysical research and surveying developments requiring support from geodesy are considered in Chapter 3, while instrumentation development in support of geodesy is considered in Chapter 5. Statements of accuracy, resolution, and other parameters in Chapter 4 are in accordance with the definition given in the introduction to Chapter 5.

A fairly comprehensive review of the current state of geodetic techniques is given in the symposium proceedings edited by Uotila (1977). A compendium of photogrammetric techniques is to be published by the American Society of Photogrammetry (1979). The principal text on physical geodesy in English is that of Heiskanen and Moritz (1967). A definitive presentation of satellite geodesy from 1957 to 1974 is given in the report compiled by the American Geophysical Union (1977).

4.1 TERRESTRIAL TECHNIQUES

In Chapter 2, which gives the definition of geodesy, several types of terrestrial geodetic measurements are identified. Their practical and scientific values are discussed in Chapter 3. This section presents brief descriptions of terrestrial geodetic survey methods in order to provide some insight and appreciation for the skills of geodesists and the data they produce.

Traditional geodetic survey techniques are divided into horizontal and vertical control because of the dominant effect on observations of atmospheric refraction. Angles measured about a vertical axis by a theodolite are affected by lateral gradients in atmospheric density. Because these gradients are varying and irregular, it is desirable to make observations at times when their effects are minimized, using lines of sight that may be tens of kilometers in length. But angles measured about a horizontal axis are affected by the systematic vertical gradient. Hence it is desirable to keep lines of sight short—less than 50 m—and level, by using spirit levels and graduated rods to determine elevation differences. A few measurements are truly three dimensional; these include photogrammetry, satellite tracking (radio Doppler and laser ranging), and vehicle-mounted inertial systems.

4.1.1 Horizontal Control

The figure of the earth as defined by the geoid—the equipotential surface most closely approximating mean sea level—is an ellipsoid of rotation within 100 m. Hence it is convenient to calculate differences in horizontal position with respect to a *reference ellipsoid*. *Geodetic latitude* and *longitude* are defined as the direction of the *normal* to this reference ellipsoid at a particular point. A horizontal control network is a set of points whose observed relative horizontal locations are expressed in terms of geodetic latitude and longitude. Such a horizontal control network may extend over a country, a continent, or the entire earth. The *orientation* of a network with respect to its reference ellipsoid is determined by directions with respect to the "fixed" (for geodetic purposes) stars, but the *location*, in three dimensions, must be arbitrarily prescribed. This prescription is most conveniently stated as the latitude, longitude, and height with respect to the ellipsoid of a fundamental reference point, an origin, to which all other points can be referred.

Datum Determination

The direction of the gravity vector at a point is called the *vertical* in geodesy. *Astronomic latitude* and *longitude* are the direction of the vertical. Classically, the position of the origin is obtained by determining its astronomic latitude and longitude using a small portable broken telescope (i.e., a telescope that contains a prism that reflects the line of sight at right angles to the instrument's objective) transit or theodolite, the latitude being the angle between the true vertical and the equatorial plane and the longitude being the angle between the local meridian of that vertical and a fixed meridian (Mueller, 1969). By observing twenty or more stars on at least two nights, these angular values may be determined to an accuracy of about 0.3 second of arc (Robbins, 1977). This astronomical position is the direction with respect to the stars (allowing for earth rotation) of the vertical at this point. The vertical has a systematic curvature due to the oblateness of the earth, plus, in general, a small amount of curvature because of the irregularities in the surface of the earth and the variations in the densities of the nearby crustal material (Bomford, 1971). These irregularities and variations are the primary contributing factors to the deflection of the vertical from the normal to the ellipsoidal reference surface. This deflection angle may be several seconds of arc; it is usually less than 5 seconds of arc, but instances of 60 seconds of arc exist.

In order that angles measured with respect to the vertical be as close as possible to angles defined with respect to the ellipsoid normal for computation, it is desirable that the deflections of the vertical be small. In practice, astronomic latitudes and longitudes are determined at a large number of stations, and by means of these data the horizontal network is positioned so that the sum of the deflections of the vertical approach zero. The third coordinate, the height of a station, is traditionally taken as the height above sea level; this coordinate is also obtained by an averaging process, which results in a zero mean height of the reference surface with respect to sea level. The reference figure size, shape, orientation, and position with respect to the origin are designated the "Geodetic Datum" for the area under consideration.

Today, in an unsurveyed area, satellite techniques, as described in Section 4.2, would be used in preference to the classical astronomical method to establish an origin point. These newer techniques for determining three-dimensional coordinates, which can be transformed to latitude, longitude, and height, are not affected by any local deflection of the vertical.

The next logical step, after positioning, is that of orientation or azimuth. This is accomplished by measuring the horizontal angle between the normal section to an adjacent survey point (at least 5 km distant) and the local meridian, which is defined by the gravity vertical. In practice, the horizontal angle between the point and a circumpolar star, for the northern hemisphere Polaris, is measured and then corrected for (1) the angle between the star and the local meridian and (2) the difference between the local and geodetic meridians. The two meridians differ because of irregularities in the direction of gravity. The time of observation, the declination of the circumpolar star, and the astronomic latitude of the observation point are required. In the equatorial zone, where circumpolar stars would be difficult to observe, a similar technique may be used by observing on east and west stars with declinations close to the celestial equator.

Terrestrial Network

The terrestrial survey techniques for establishing a horizontal control network are triangulation, trilateration, traverse, or some combination of these three. Nowadays, photogrammetric, Doppler satellite, or inertial system techniques may be more feasible for some operations. Triangulation (Gossett, 1959) is best suited for a survey in which the points to be positioned form a network or chain of triangles in which the vertices are intervisible or can be made intervisible by elevating the theodolites and targets on portable towers up to 40 m in height. Generally, the observations are made shortly after sundown, when the effects of horizontal refraction are minimal. Small electric lamps with parabolic reflectors are used for targets. Angles about the vertical, as defined by a level bubble, are measured with a theodolite to an accuracy of a small fraction (less than a quarter) of a second although the uncertainty due to refraction may be several times larger. Because of the distance between adjacent points and the size of the triangle, corrections must be made for the curvature of the earth, or spherical excess of the triangle (i.e., the sum of the angles on a curved surface is more than 180°).

If the survey consists entirely of triangulation, it is necessary to measure the length of one side of an initial triangle from which the lengths of the sides of the connecting triangles may be computed. In the years 1900-1950, when much of the basic U.S. horizontal net was established, geodetic baselines were measured with steel or invar tapes. Invar wires were used in other countries (Clark, 1953). In earlier times, iron bars submersed in ice or more elaborately constructed apparatus using temperature compensating principles were used. Since 1950, Geodimeters, or some other type of electronic distance measuring (EDM) equipment, have been used (Tomlinson and Burger, 1977). The geodimeter measures the distance to a cornercube retroreflector by modulating an intense light source with a Kerr cell (Bomford, 1971), taking the velocity of light as known. In about 1965, the geodimeter was modified by inserting a laser for the light source. The accuracy of the results was improved by almost an order of magnitude. Under normal conditions, a standard deviation of a few parts in 10^7 is obtained with a reliance that the actual error seldom exceeds one part per million. The principal source of this error is atmospheric refraction. (See Section 5.1.1 for developments of multiwavelength devices to overcome refraction.)

The accumulation of errors in triangulation are such that when computations are carried through 15 or 20 triangles, the uncertainties of the computed lengths might be 1 part in 100,000 or greater. Therefore, to maintain a high order of accuracy it is necessary to measure additional baselines. The same applies to the azimuth, so that it is necessary to measure additional astronomic azimuths and longitudes (to convert to geodetic azimuths). These astronomic points in a horizontal control network are sometimes called *Laplace stations.*

The national horizontal control network (Plate 1) of the United States consists primarily of triangulation with the density of points basically conforming to economic growth and national needs. Recently, this network was strengthened through the incorporation of a geodimeter traverse network crisscrossing the 48 conterminous states. The network was further strengthened with the occupation of about 200 uniformly spaced points (including Alaska) with Doppler receivers. This latter series of measurements permits incorporating the entire network of North America into an earth-centered, world geodetic system.

Because of the greater accuracy of electronic distance-measuring instruments, trilateration is used for those operations in which the maximum precision is essential. Examples are the surveys for monitoring crustal movement in seismic areas or the deformation of large structures such as dams. For lower-accuracy surveys, microwave distance-measuring techniques provide all-weather capabilities in regions where observing conditions prevent the use of optical techniques. In all surveys by distance measurements there is still a requirement for azimuth. In some instances, the geometric strength of a trilateriation net can be improved by measuring selected angles.

Traversing, as discussed in Section 3.1, is the most widely used engineering survey operation. Most construction surveys, those for large buildings, highways, pipelines, and transmission lines, for example, and practically all land surveys are based on some form of traverse. Angles are measured with a transit or theodolite, and distances are taped or measured with EDM equipment (Tomlinson and Burger, 1977) with slope corrections reducing all values to the horizontal. If the traverse is long, with many angles, azimuth control is essential. Some traverses are quite limited in extent, each closing on itself. Others are more complex, with connections to the national horizontal control network. If such surveys meet federal specifications (Federal Geodetic Control Committee, 1977), the newly established points of the survey can be incorporated into the national network.

A very significant aspect of a horizontal control survey is the monumentation. Stations must be marked in a permanent manner to facilitate their identification for future occupation. Standard practice is to use a bronze disk with identification that includes the name of the agency responsible for the survey, the name assigned to the point, and the date (year) of the survey. If possible, the disk is set in bedrock. If bedrock is not available, the disk is set in a concrete monument sufficiently deep to extend below the frost line. Also emplaced are an underground mark below the monument, and reference marks are placed a few meters' distance to aid in locating or repositioning the primary point if required.

Oceanic Geodetic Location

Programs for the development of resources on and beneath the continental shelf require locations with respect to the land. In the Gulf of Mexico, horizontal control has been extended to all drilling platforms using combinations of triangulation, trilateration, electronic position-fixing systems, and, more recently, satellite Doppler measurements. The Doppler determinations using translocation techniques are probably the most practical and least expensive. These techniques can be extended to distant islands.

Temporary positions on the deep-ocean floor can be accomplished by the deployment of three or more transponders, which are periodically triggered by a shipboard pinger. The pinger is connected to a precision clock, and the return signal of the transponders is accurately timed. Computations can then determine the position of the ship's pinger with respect to the deployed transponder to approximately 1 m in the vertical and horizontal directions. Other transponders on scientific instruments, submersible vehicles, or bottom fixtures can then be introduced into the grid and their positions determined to approximately 1 m.

The area of ocean that can be surveyed with one grid pair is about 15 km in radius, although this varies with depth of ocean, acoustic characteristics of the water column, and the topography of the local ocean floor. The transponders must be periodically retrieved and recharged, although they can be left for periods of a year or two with a reasonable hope of reactivation.

The absolute position of the transponder network can be accomplished by precision navigation methods, either satellite or Loran-C, the most accurate method being a function of the location of the ship with respect to satellites and Loran-C stations. Under ideal circumstances, a position can be determined to approximately 10 m, although many times this is degraded up to a factor of 10.

The only requirement for geodetic accuracies of fixed points within the oceans that this committee could envisage was for relative locations over relatively short distances for tectonic studies, as discussed in Section 3.2. Other uses of the oceans entail moderate accuracies sufficient to recover sea-floor devices. So far, there does not appear to be any prospect of high-density, multiple use of the sea floor warranting a horizontal control network analogous to those on the land. However,

We recommend that the accuracy requirements for location in the oceans for operational and scientific purposes be examined, in order to determine what development of more efficient and reliable systems are needed.

North American Network

The desirability for computational consistency throughout a network necessitates the mathematical adjustment of new surveys into the existing network (as discussed in Section 3.1.2). At present, the geodetic agencies of North America are engaged in a new adjustment of all the national networks. One phase of the computational operation will involve the solution of a set of approximately 500,000 simultaneous equations with as many unknowns.

The final results will include latitude, longitude, and plane rectangular coordinates of approximately 200,000 control points. For 20,000 points, which are also benchmarks of the vertical control network, heights above sea level will also be listed. These geodetic locations will be given to 1 mm. In addition, geoid heights of control points will be given to 0.1 m, and elevations of the other points, whether determined by trigonometric leveling or scaled from topographic maps, will be listed to the nearest meter (Bossler, 1977a).

Coordinates obtained from new techniques, such as satellite tracking, inertial systems, and analytical photogrammetry, are three-dimensional. Hence it may someday become standard practice for the surveyor and cartographer to ask for three-dimensional coordinates from the new geodetic control network in preference to the conventional plane coordinates. However, for many surveying applications the most useful information is the height above the water table, which is obtained through classical measurements.

Densification of Control

The density of geodetic control remains inadequate to meet state and local demands (Federal Mapping Task Force, 1973). To remedy this need, each state should be encouraged to establish an office that would be responsible for working with the federal agencies in cooperative surveying programs. As an example, in the 30 public land states, programs could be developed for connecting the section (and quarter) corners of the public land survey to the federal horizontal control network. This can be done by analytical aerotriangulation, with inertial positioning systems, or Doppler determinations providing control, if the spacing of geodetic control is not satisfactory. The lengths and azimuths of all section lines could be determined by computation. Also, states along the coasts have unique problems relating to seaward boundaries and would need tidal surveys to support large-scale mapping.

We recommend that cooperative surveying programs be developed with the states, giving consideration to the particular needs of each state, the techniques best suited for densification in each state, and the acceptance of the state survey data into the national survey data base.

See Section 3.1 for further discussion of this coordination.

4.1.2 Vertical Control

There are two principal techniques for measuring height: spirit leveling and vertical angles (or trigonometric leveling). Spirit leveling determines difference in heights above the geoid. For U.S. practice and conditions there is estimated to be an average random error of about $0.7\sqrt{K}$ mm, where K is the distance between benchmarks in kilometers, plus a systematic error of about 0.06 mm/K, for lines observed in both directions. The systematic error arises from imperfections in the leveling instruments and rods, instability of the benchmarks, solar effects on the field measurements, and irregularities in refraction (Rappleye, 1948; Bomford, 1971).

There are two types of leveling instrument. The most common type uses a level vial to establish the horizontal. A newer type, known as the automatic level, uses a prism (or compensating reflecting mirrors) suspended under gravity. Both types achieve better than 0.1 second of arc instrumental accuracy.

A high-precision geodetic level rod contains a subdivided invar strip that is supported within the rod without constraining its length and is protected, as far as possible, from thermal effects such as direct rays of the sun. These invar strips must be standardized, as well as calibrated periodically in the field, to assure the maintenance of their precision.

The benchmarks, which are permanent reference points, should be set in outcrops of bedrock if possible. A good alternative is to set the mark on the end of a stainless steel rod that has been driven into the ground to refusal. Marks set in monuments or structures are subject to subsidence and other disturbances.

The observing methods used in the field are equally critical. The simple procedure of balancing, or making equal, the backsights and foresights cancels errors due to collimation within the instrument, the curvature of the earth, and the symmetrical vertical refraction of the atmosphere. The lengths of the sights should never exceed 50 m. A principal source of error not eliminated is the unequal refraction effect when leveling on a slope. To correct for this effect satisfactorily, it is necessary to determine the vertical gradient of the temperature.

In addition to releveling the line in the opposite direction for checking purposes, greater strength is added by observing a network of crisscrossing lines forming many loops. The vertical control network (Plate 2) of the United States conforms to a specification that the closing error of a primary loop not exceed $4\sqrt{K}$ mm, where K is the distance around the loop in kilometers.

The equipotential surfaces at different elevations converge as they approach the pole, and, as leveling observations provide the difference in elevation between two equipotential surfaces at each setup, a significant discrepancy accumulates between benchmarks on north–south lines for which a correction, known as orthometric, must be applied to obtain the height above the geoid. For the most precise level surveys, gravity is measured along the level line. Its integration over elevation differences thus gives differences in geopotential. Heights determined in this way are known as geopotential numbers.

Vertical control networks are referenced to primary tidal benchmarks. The heights above sea level of these marks are based on tidal measurements made over long periods of time—several decades in most cases. A vertical datum may be referenced to a single such mark or adopted by an averaging process using several widely spaced marks. Coastal engineering applications may make local tidal datums more appropriate, so that differences can exist between elevations provided by the geodetic network and those measured locally. Similar engineering requirements exist in the interior of the country.

In remote areas or for elevations not easily reached by spirit leveling, heights are determined by measuring vertical angles with a technique known as trigonometric leveling. The lengths of the lines of sight may be from 2 or 3 km to 100 km or more. The effects of refraction are minimized by observing reciprocally, but, even then, the uncertainties are at least an order of magnitude greater than with spirit leveling.

4.1.3 Three-Dimensional Control

As mentioned in Section 4.1.1, new techniques do away with the classical geodetic distinction between horizontal and vertical.

Photogrammetry

Fundamentally, a carefully calibrated camera serves the same function as a theodolite: the perspective center of the camera lens represents the geometric center of the theodolite. By measuring on a precise comparator the rectangular coordinates of image points on the photograph, a set of directions from the camera exposure station to the observed points can be determined. To a series of such photographs, resection and intersection can be applied to determine the relative three-dimensional space coordinates of all points, including the exposure stations themselves.

As with any measurement system, corrections must be applied: radial and tangential distortion of the camera lens, deformation of the film between exposure and measurement, atmospheric refraction, and calibration of the measuring instruments. When all of these corrections have been applied, it is possible to determine relative directions at the camera station with a precision of 1 part in 50,000 using conventional aerial cameras, and higher precision using special cameras.

Analytical photogrammetry is now the standard method for establishing supplementary control for topographic mapping, and in many countries it is routinely applied for cadastral surveys in both urban and rural areas.

Computer techniques for analytical photogrammetry can now treat precisely blocks of several hundred photographs and thousands of ground points. In addition, photogrammetrists have developed computational techniques to include camera calibration, constraints imposed by auxiliary measurement devices, such as altimetry, and various control configurations (Brown, 1977).

The lunar control network from the cartographic camera photographs acquired by the Apollo 15, 16, and 17 missions was one of the largest analytical triangulation projects completed successfully. It employed 1244 exposure stations and over 5000 ground points.

The user of geodetic control is concerned primarily with quality and cost and not necessarily with the techniques used to establish it. The appropriate mix of geodetic and photogrammetric techniques for extending and densifying

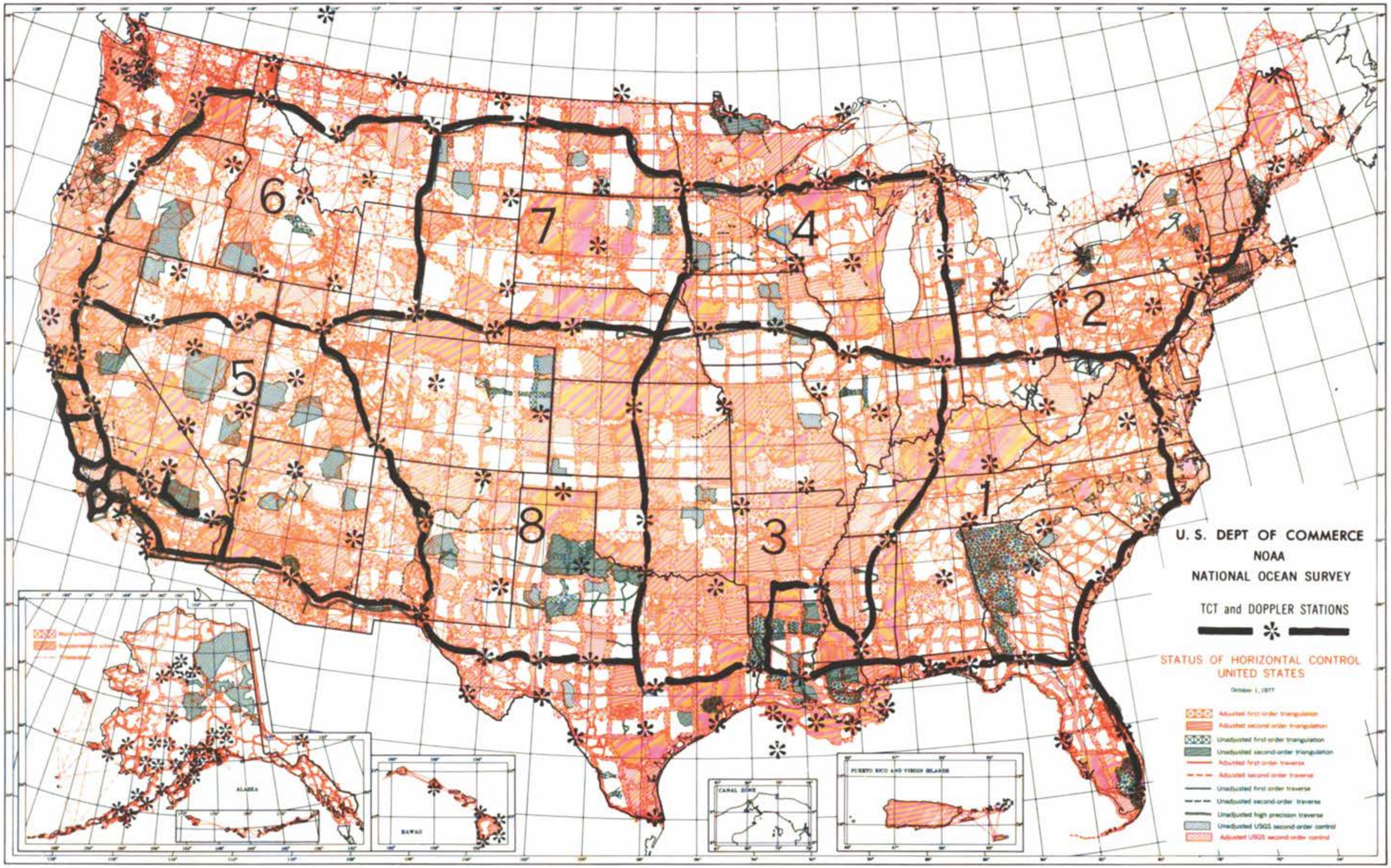
6
7
4
2
5
1
8
3
U. S. DEPT OF COMMERCE
NOAA
NATIONAL OCEAN SURVEY
TCT and DOPPLER STATIONS
STATUS OF HORIZONTAL CONTROL
UNITED STATES
October 1, 1977
Adjusted first-order triangulation
Adjusted second-order triangulation
Unadjusted first-order triangulation
Unadjusted second-order triangulation
Adjusted first-order traverse
Adjusted second-order traverse
Unadjusted first order traverse
Unadjusted second-order traverse
Unadjusted high precision traverse
Unadjusted USGS second-order control
Adjusted USGS second-order control
ALASKA
HAWAII
CANAL ZONE
PUERTO RICO AND VIRGIN ISLANDS

PLATE 1

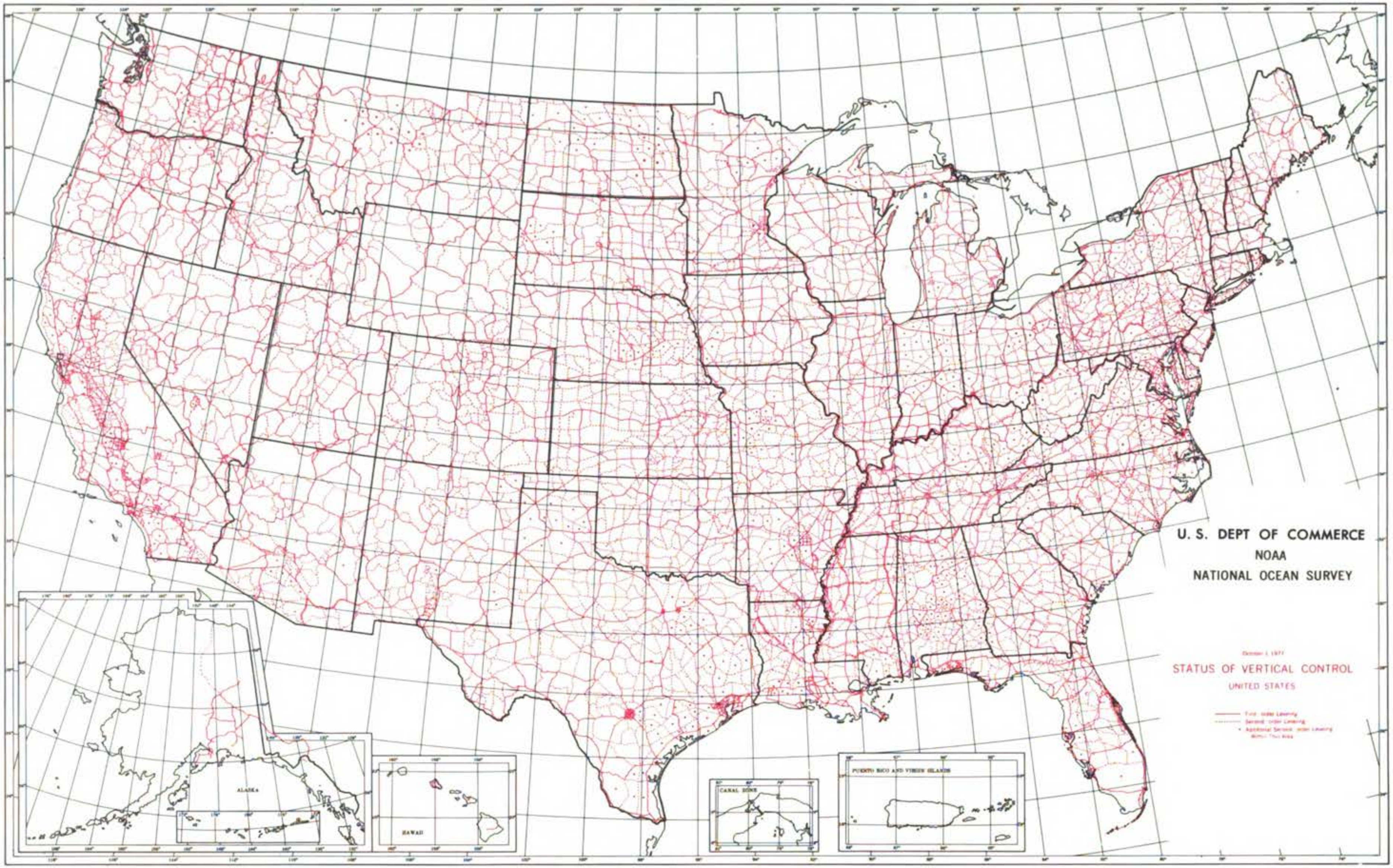
U. S. DEPT OF COMMERCE
NOAA
NATIONAL OCEAN SURVEY
October 1, 1977
STATUS OF VERTICAL CONTROL
UNITED STATES
First Order Leveling
Second Order Leveling
Additional Second Order Leveling Within This Area
ALASKA
HAWAII
CANAL ZONE
PUERTO RICO AND VIRGIN ISLANDS

PLATE 2

national control networks must be established by the surveying and mapping agencies. Control properly established by analytical aerotriangulation can meet the specifications and standards of accuracy for Second-Order, Class II (Federal Geodetic Control Committee, 1977), and can make a significant contribution to the national network. It will generally be found that if the control requirements are for a few high-accuracy points widely separated, geodetic methods will be preferred; if many points of medium accuracy and dense distribution are required, photogrammetric methods will be more cost effective.

Satellite Systems

Satellite Doppler receivers are now in common use, and the method has promise of wider application. These techniques are most effective when used in combination with continental horizontal and vertical control networks to establish and maintain their scale and orientation. The accuracy of the Doppler determinations is such that the requirements for baselines and azimuths to control the extension of triangulation are essentially eliminated.

The photogrammetric and satellite Doppler techniques provide data of geodetic caliber, and, therefore,

*We recommend that the federal Specifications to Support Classification, Standards of Accuracy, and General Specifications of Geodetic Control Surveys (*Phillips, 1977*) be revised to include:*

(a) Recognition and acceptance of analytical aerotriangulation techniques for establishing Second-Order, Class II Control.

(b) Reconsideration of the spacing of baselines and Laplace azimuths when appropriate space techniques can be used to establish scale and orientation.

See Section 4.2 for further discussion of satellite systems.

Inertial System

Inertial techniques show great potential for interpolations between existing control. The system now operational can be mounted in a jeep, helicopter, or similar vehicle. The cost of the equipment is currently a half million dollars or more per unit, but its productivity may be such that the cost per point established is fully competitive with the conventional methods. The measuring unit consists of a four-gimbal platform, stabilized by a pair of two-degree-of-freedom gyroscopes, on which a triad of accelerometers are mounted orthogonally. Variations in the intensity and direction of gravity are also determined. Field tests have demonstrated that the standard errors are better than 1 m in position, 2 mgal (1 mgal = 10^{-5} m sec^{-2} in gravity), and 1.5 seconds of arc in deflection of the vertical (Cordova, 1977).

4.1.4 Variations with Time

In the discussion of geodynamic applications in Section 3.2, great emphasis is placed on time-varying aspects. Some short-range distance and tilt measuring devices obtain a continuous record. However, most monitoring of the temporal effects is accomplished by repetition of geodetic survey. So far, resurveys have been limited by lack of resources but have demonstrated significant value. Quoting from a National Academy of Sciences report, "Virtually everything we know about the nature of strain buildup that leads to earthquakes in the western United States comes from geodetic studies that began in the late 1800's" (U.S. Geodynamics Committee, 1973). Most of the early surveys were carried out for other purposes, although some special surveys were made after the 1906 San Francisco earthquake.

In the 1920's, the U.S. Coast and Geodetic Survey (USC&GS) began a program of repeating special fault-crossing surveys, both horizontal and vertical, at 10-year intervals. In more recent years, the type of survey has been modified.

Beginning in 1959, a program of remeasuring precise trilateration networks crisscrossing the major California faults was instituted by the California Department of Water Resources. The U.S. Geological Survey has considerably expandedthese California seismic-zone trilateration networks and extended them into Nevada. In addition, a substantial area of southern California has been releveled recently during a fairly short time interval in order to provide a reference surface for future measurements of vertical motions. The present U.S. Geological Survey trilateration networks are illustrated in Figure 4.1.

Between 1964 and 1967, 30 fault-crossing triangulation, trilateration, and leveling networks were established by the USC&GS at various sites along the faults for the purpose of monitoring fault creep along the route of the aqueduct. The networks consisted of 5 to 8 points with lines 200 to 500 m in length. These nets have been reoccupied at 1- to 2-year intervals.

High-precision traverses accomplished by the National Geodetic Survey and the Defense Mapping Agency were measured in the 1970's to form a fundamental framework for monitoring crustal motion over the entire San Andreas fault system. Figure 4.2 illustrates the location of the high-precision traverses, the basic triangulation network in California, and the distribution of the regional surveys for monitoring crustal motion in California and Nevada.

For future monitoring of crustal movements in and near seismic zones in support of earthquake-prediction research, the use of both ground and space techniques is likely to be important. However, for measurements of strain and tilt over distances of the order of 10 km or less, ground measurements probably will have a substantial advantage over space techniques in terms of the accuracy that is achievable.

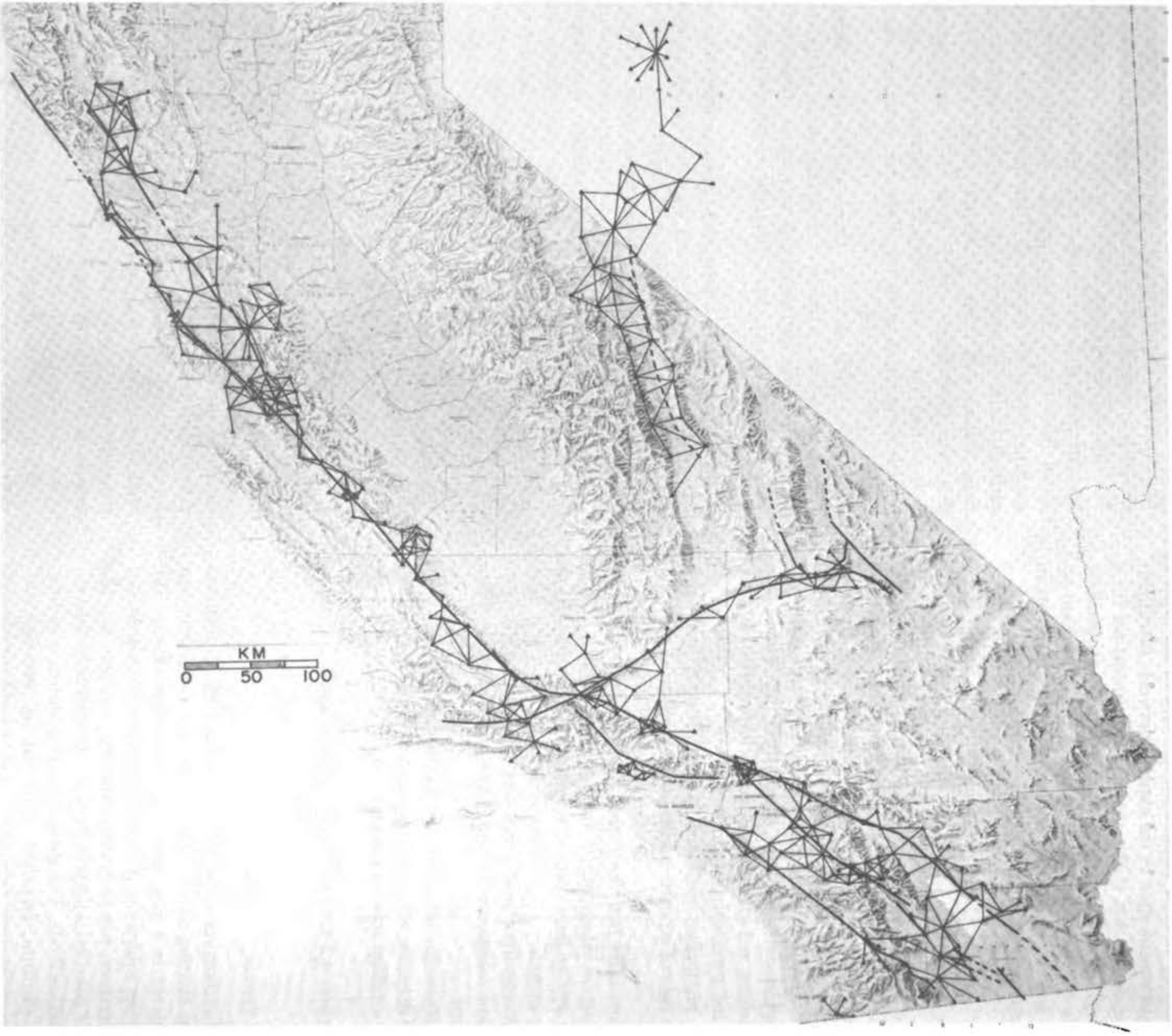

FIGURE 4.1 Geodimeter lines in California and Nevada. (Data Source: U.S. Geological Survey and California Division of Mines and Geology.)

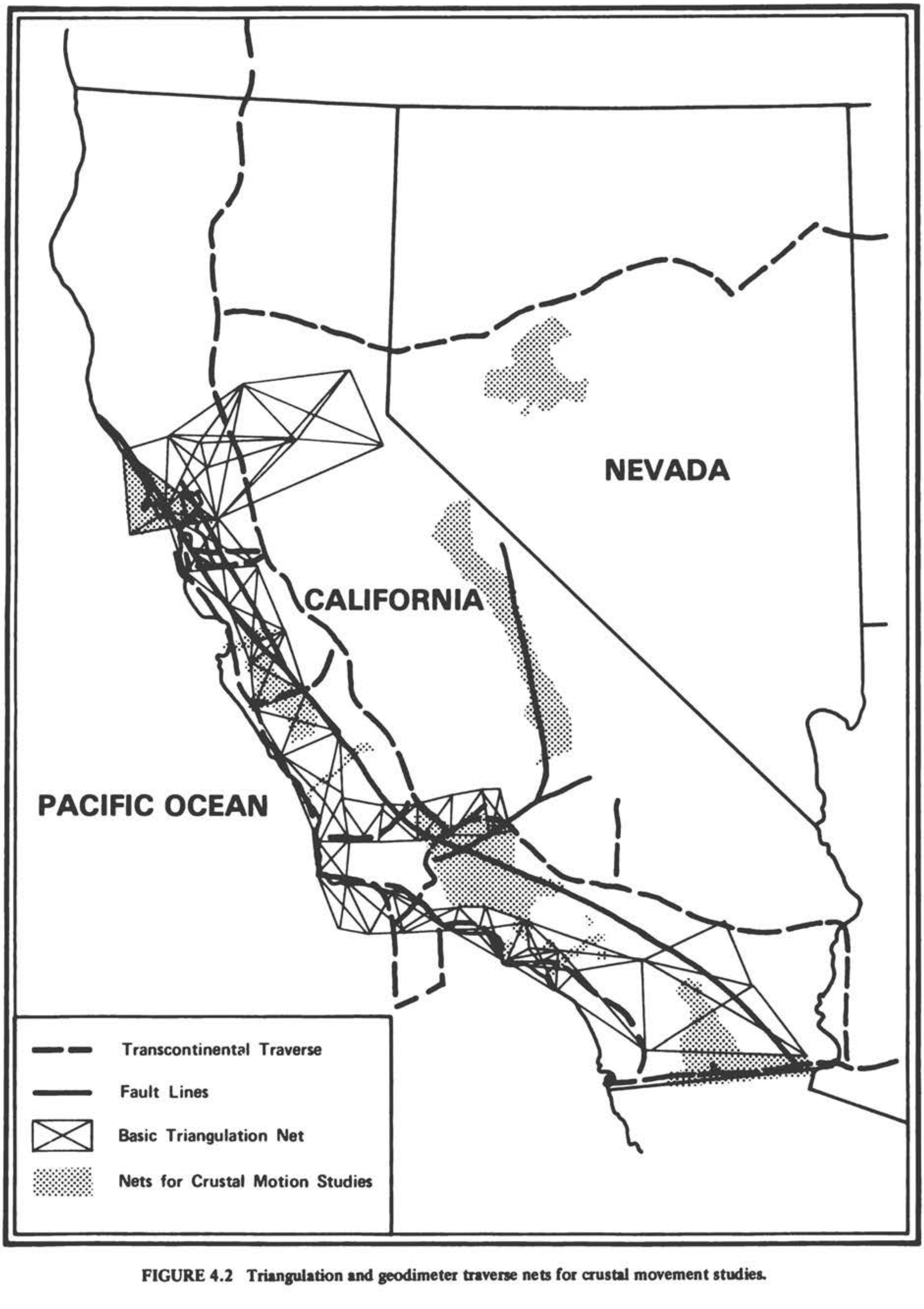

FIGURE 4.2 Triangulation and geodimeter traverse nets for crustal movement studies.

Improved long-baseline tiltmeters (see Section 5.1.3) appear capable of providing continuous tilt data with 10^{-7} rad accuracy, so that the stability of the piers and the effects of local nontectonic ground motions in the areas of interest are likely to be the main limitations. The results can be checked occasionally by leveling over 10-km distances with an accuracy of about 3×10^{-7}. For continuous laser strainmeter measurements, a ground stability of roughly 3×10^{-7} over a year has been observed for three 732-m paths at the Pinon Flat Observatory (Berger and Wyatt, 1973, 1978), which is located between the San Jacinto and San Andreas faults. Either occasional or nearly continuous three-wavelength distance measurements over distances of up to 10 km with present instruments appear capable of giving a long-term stability of about 1×10^{-7} (Slater and Huggett, 1976) if the ground stability permits. In contrast, even measurements of 1-cm accuracies over 10-km baselines with space techniques would correspond to tilt or strain accuracies of only 1×10^{-6}. Thus for monitoring small geodetic figures or for observatory-type measurements, the ground techniques appear preferable.

The situation may be quite different for the case of monitoring crustal movements over a connected network of points covering a substantial area. We assume that the distance between points to be monitored is in the range of 20 to 100 km and that the desired time interval of remeasurement is between one month and one year. If the area to be covered is several hundred thousand square kilometers, then the cost of using leveling throughout the network would be very high. To avoid this limitation, two alternate approaches are being studied, which could make the cost of monitoring vertical displacements comparable with or less than that for horizontal strains. One is the use of gravity measurements, which can be made in some cases with enough sensitivity to detect elevation changes of about 1 cm in locations where normal variations in groundwater are known or are not significant (Lambert and Beaumont, 1977). However, some evidence exists for gravity changes over periods of years, which do not agree with those expected from leveling, even in areas of near-surface crystaline bedrock where groundwater problems are not expected to be significant (Kiviniemi, 1974). Thus more experience is needed in monitoring gravity changes in seismic zones in order to find out how often anomalous changes may occur that have to be checked by other more expensive techniques. The second alternate approach is the use of segmented leveling, in which only perhaps 10 or 20 percent of the network is releveled. If the half wavelengths of the surface displacements are longer than the separation between points in the network, then the segmented leveling results can give information on tilts in the area.

For distances between control points in excess of 20 km, there exists the possibility that satellite-to-ground laser ranging techniques (see Section 4.2) may become competitive in economy as well as accuracy. The costs of terrestrial surveys appropriate for comparison purposes are difficult to state because of the differing costs of horizontal and vertical surveys and the dependence on environmental conditions. A systematic horizontal resurvey system in a region with good road net and favorable climate, such as most of California, might cost on the order of $1500 per point.

The need to monitor tectonic motions has led to a tightening of survey specifications. There is a widespread interest in surveys of this type. Some of the measurements are required by legislation. Several federal and state agencies as well as universities and research institutes are making measurements, formally under the guidance of a Federal Geodetic Control Committee. More elaborate plans are being developed. For example, the U.S. Geological Survey and the National Science Foundation have strong interests in the overall problem of crustal movement measurement, both for understanding basic tectonic plate processes and for monitoring to detect possible earthquake precursors in seismic zones. The National Geodetic Survey is considering the future use of mobile LBI, laser-ranging, or Global Positioning System stations (see Section 4.2) at roughly 100-km spacing over the United States. The National Aeronautics and Space Administration is supporting the development and testing of mobile stations suitable for this purpose, as well as for other applications. Therefore,

We recommend that a detailed and fully coordinated plan for monitoring crustal movement in seismic zones be established and that there be more effective management of the planning of projects, exchange of observational data, and analysis and dissemination of the results.

4.1.5 Polar Motion and Rotation

As discussed in Section 3.2.4, variations in the earth rotational state are of interest to indicate mass shifts in the earth and its rheological response thereto (Mansinha *et al.*, 1970). In addition, precise geodetic measurements involving the celestial reference or the space surrounding the earth are affected by these variations and must be corrected for their effects.

In 1892, the International Association of Geodesy (IAG) set up a program for monitoring the variation of latitude. A later program was set up to measure variations in the time of rotation. More than 50 observatories in many different countries participate in these programs. The International Astronomical Union (IAU) and the IAG provide the general guidance for the services, which collect, analyze, and disseminate these observational data and reduce results. These services are performed by the International Polar Motion Service (IPMS), which includes the International Latitude Service (ILS) and the Bureau International de l'Heure (BIH). The types of astronomical instruments and the time-keeping devices have been improved over the years, and Doppler tracking of satellites now is providing valuable data on a regular basis, which are used by the BIH. In this era of space technology, it seems likely that laser-ranging and long-baseline-interferometry measurements will soon replace the conventional techniques for determining the earth's rotation and polar motion, as will be discussed in Section 4.2.5.

4.1.6 Gravity

Section 3.2.3 discusses the needs for gravity measurements and for greater knowledge of the gravity field.

Pendulum techniques used prior to about 1950 measured gravity to an accuracy of about 10^{-5} m sec^{-2}. Modern free-fall devices now measure the absolute gravity in the laboratory to about 10^{-8} m sec^{-2}.

Relative values of gravity are measured to the same sensitivity by gravimeters, which measure the change of length of a spring supporting a fixed mass when the apparatus is moved from one point to another (or, alternatively, the change in tension on the spring required to return the mass to a null point after gravity has changed). The actual accuracy may be significantly poorer than the sensitivity because of environmental and systematic effects. A modern gravimeter survey can be made by one man, with only a few minutes needed at each point for the instrument to stabilize itself. The greatest expense in accurate gravity surveys is the vertical control to obtain the height above sea level needed for the interpretation. Relative gravity values are referred to the *International Gravity Standardization Net–1971 (IGSN-71)*, a worldwide network of gravity stations developed between 1962 and 1971 by the cooperation of an international group organized within Study Group #5 of the International Association of Geodesy. The *IGSN-71* was adopted as an absolute gravity reference system by the XV Assembly of the IUGG in Moscow in August 1971 and replaced the previous gravity reference system called "Potsdam Datum." The *IGSN-71* consists of 1854 adjusted stations obtained from a single least-squares adjustment of absolute, pendulum, and gravity-meter data. Standard errors of the *IGSN-71* gravity values are less than 10^{-6} m sec^{-2} (International Association of Geodesy, 1971).

An accuracy of 3×10^{-8} m sec^{-2} for transportable gravimeters, as proposed in Section 5.1.5, would provide a means of maintaining a network of master vertical control points to be used in connection with periodic releveling. It is essential that the gravity measurements be made at the same time as the leveling, as each system is sensitive to the mass distribution of the physical earth at the moment of measurement.

The problem of measuring gravity at sea is much more complex. It is impossible to correct for all the accelerations of the ship carrying the gravity measuring system. Vertical accelerations can be separated from variations in gravity only by temporal averaging. Horizontal accelerations of the ship act systematically to increase measured gravity over the ambient value. To eliminate this effect, the gravimeter is mounted on a gyrostabilized platform. Under good sea conditions, when accelerations are small, errors of up to 1 mgal may exist. Under very poor sea conditions when accelerations amount to 0.1 or 0.2 g, the errors may amount to several milligals. Through the continuing efforts of a few oceanographic institutions, remarkable progress has been made in measuring gravity at sea (Figure 4.3).

4.2 SPACE TECHNIQUES

For discussing applications of space techniques to geodesy and geodynamics, it is convenient to break the subject into six parts. Section 4.2.1 contains a review of results for the earth obtained up until quite recently and a discussion of the general techniques used in determining station positions and information on the earth's gravity field from satellite tracking data. The following four sections consider present and probable future applications of space techniques for studying the earth. The determination of the three-dimensional position of points separated by distances ranging from a couple of hundred kilometers to intercontinental distances is discussed in Section 4.2.2. The resulting reference points are expected to form an accurately known worldwide geodynamic and geodetic control network, to which measurements over shorter distances can be tied. Section 4.2.3 covers possible use of space techniques to make frequent measurements at large numbers of points in seismic zones or in other areas. Probable major improvements in global gravity measurements are discussed in Section 4.2.4, and the expected change to space techniques for determining the earth's rotation and polar motion is considered in Section 4.2.5. Finally, the use of geodetic techniques for studying the moon and other planets is discussed briefly in Section 4.2.6.

4.2.1 Status in 1978

The main use of space techniques in geodesy until recently has involved the tracking of artificial earth satellites from fixed ground stations. The methods used are traditionally categorized as geometric or dynamic. The geometric techniques take advantage of an artificial satellite or other extraterrestrial object being very high, and hence simultaneously visible, from widely separated points on earth. The data—directions and/or ranges from tracking stations to spacecraft—are analyzed as a purely geometric problem. The product is three-dimensional positions of tracking stations and spacecraft locations in an earth-fixed coordinate

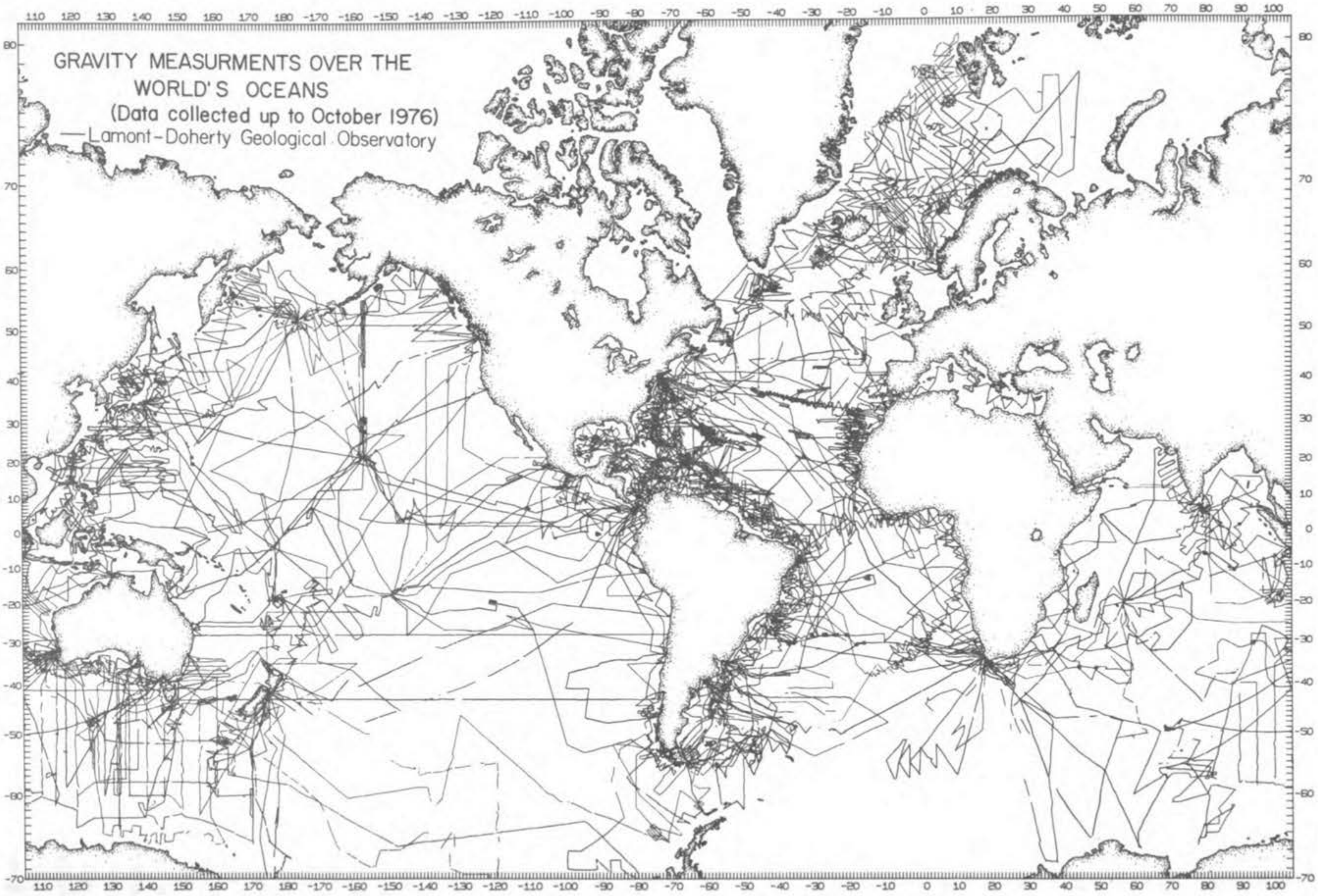

FIGURE 4.3 Gravity at sea obtained by Lamont-Doherty Geological Observatory through October 1976.

system of arbitrary origin. The main limitations are instrumental accuracy and environmental effects on the observations (Schmid, 1974; Mueller, 1974).

The dynamic techniques take advantage of an artificial satellite being in an orbit obeying Newton's laws and hence subject to perturbations due to irregularities in the earth's gravitational field and to other sources. The dynamical techniques, which require calculation and adjustment of orbits, also obtain geometric information, since the discrepancies of observations from *a priori* models are affected by tracking-station positions. In place of spacecraft coordinates, model parameters are the six constants of integration of each orbit plus variations of the natural environment that affect the orbits: air drag, radiation pressure, and the earth's gravity. Spatial variations of the gravity field are the most significant and are normally parameterized as spherical harmonic coefficients. The main limitations are model incompleteness and insufficient observations and orbits to eliminate ambiguities (Kaula, 1966).

With the evolution of tracking accuracy, orbit calculation precision, and spacecraft design, the application of the two techniques have become much less distinct. For satellites in moderately high-altitude orbits, the distinction is more between whether short arcs of data or long arcs are used in the solutions. The current principal "dynamic" satellite, LAGEOS, is a very dense, spherically symmetric satellite, deliberately placed in a high orbit. Hence air drag and radiation pressure effects are reduced so that its orbit is accurately calculable over many revolutions.

The original tracking techniques for geodetic purposes were cameras and radio Doppler tracking. Radio ranging was also developed for geodetic purposes in the early 1960's. These systems obtained global networks of positions with about 5-m accuracy by the early 1970's. The cameras had a fundamental limitation in that they depended on accurate positions of stars in the background of the satellite to obtain directions and are now superseded for geodetic purposes by laser ranging.

Doppler tracking of near-earth satellites has been utilized in geodetic research programs for over 17 years. Its all-weather tracking capability provides maximum satellite coverage for a given network of ground stations. Almost all of the results so far were obtained using the U.S. Navy Navigation Satellite System.

Current geopotential models derived from Doppler measurements are capable of modeling the motion of some near-earth satellites to 3 m rms (Anderle, 1974). Relative positions of fixed sites derived from Doppler measurements have been compared with a precise geodimeter traverse in the United States conducted by the National Geodetic Survey. This comparison yielded rms differences of 1 m in each position component for sites in the eastern half of the United States and 3 m for the western sites. Doppler-derived fixed-site positionings of 37 worldwide locations have also been compared with determinations based on BC-4 camera observations (Anderle, 1974). The BC-4-determined positions had an estimated accuracy of 5 m rms. An overall rms difference of 14 m (approximately 9 m in each component) was found in this comparison (Schmid, 1977).

Doppler tracking of near satellites also has been used routinely for some time to follow the motion of the poles (Anderle, 1973). The results that are being obtained agree with the IPMS and BIH results from conventional astronomical observations to better than 1 m (Guinot, 1973).

In the dynamical technique using artificial satellites, the limitation is not tracking inaccuracy so much as lack of orbital variety to separate different gravitational effects on the orbits and the massive computation required. Recent solutions for the earth's gravity field at the Smithsonian Astrophysical Observatory (SAO), NASA Goddard Space Flight Center (GSFC), and the U.S. Naval Surface Weapons Center (USNSWC) analyze about 400,000 observations of 25 different satellites from about 100 tracking stations to determine 300 gravity-field spherical harmonic coefficients and 300 station position coordinates (Gaposchkin, 1974; Smith *et al.*, 1976; Anderle, 1974). In determination of the gravity field from these solutions, using only satellite data, the effective resolution is about 1500 km. However, it is now normal practice to combine satellite data with surface measurements of gravity, so that the resolution is appreciably improved where the surface data are available. Figure 4.4 shows the most recent such solution in the form of a global geoid (Lerch *et al.*, 1977).

4.2.2 Worldwide Determination of Three-Dimensional Positions

We distinguish three types of position:

1. Fixed reference stations: a few points at which observations are made daily, mainly to monitor earth rotation and wobble. These are discussed in Section 4.2.5.
2. Global network stations: geologically stable sites at intervals of several hundred kilometers, which are reoccupied every year or two, to measure large-scale tectonic motions and to provide reference points for seismic zone networks. These are discussed in Section 4.2.2.
3. Seismic zone stations: points at intervals on the order of 30 km to map evolving strain patterns associated with regional creep and earthquakes. These are discussed in Section 4.2.3.

For determining geometric positions over intercontinental distances, space techniques are the only ones capable of achieving the accuracy helpful for studies of tectonic motions. As will be discussed in Sections 5.3.2 and 5.3.5, laser-range measurements to satellites like LAGEOS, or to the moon, and long-baseline radio interferometry (LBI)

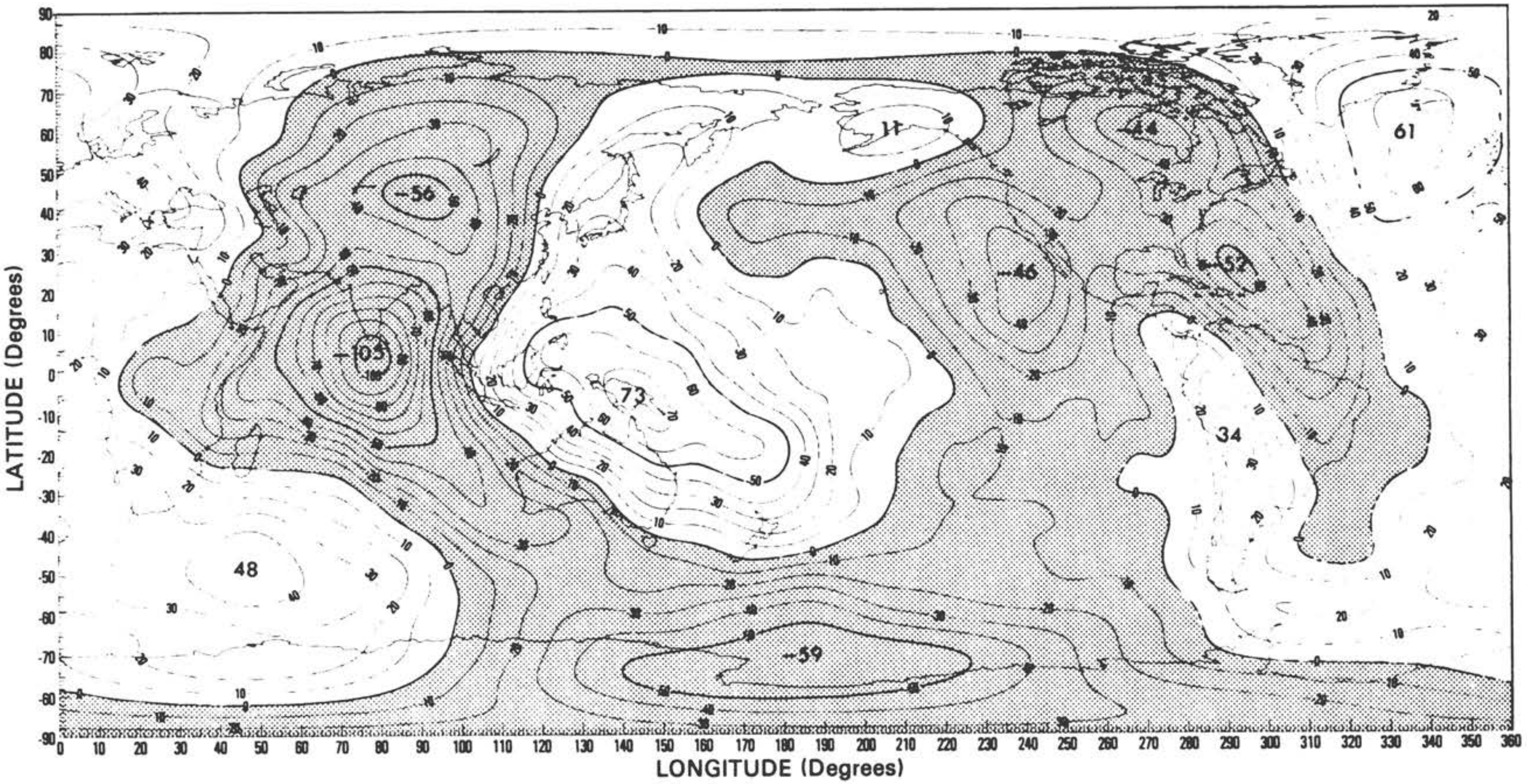

FIGURE 4.4 Geoid surface computed from the GEM 10 model (height in meters above the mean ellipsoid, $f = 1/298.255$).

measurements using signals from extragalactic radio sources appear capable of achieving accuracies of a few centimeters. For LBI measurements, very high accuracy has been demonstrated for very short baselines. Accurate extension to intercontinental distances is expected to become possible with the introduction of new instrumentation that is being tested and with improved determinations of radio-source positions and structure. For laser ranging to LAGEOS, some improvements in measurement accuracy and calibration procedures are needed, as are some further improvements in the gravity-field model used. For lunar ranging, the completion of several observing stations now under development is needed, as well as some improvements in measurement accuracy and in modeling the lunar motion.

In addition to estimating departures of present plate tectonic motion rates from the long-term averages inferred from remanent magnetism, it is hoped the space techniques will help to determine large-scale distortions within plates, as discussed in Section 3.2.1. Such a problem as large intraplate earthquakes might be addressed. Early in the program, the stability of each major plate segment believed to be stable on other grounds should be verified. This can probably be done to an accuracy of about 1 cm/year. This verification is necessary to interpret measurements of changes in the distance between two points on different plates.

The strategy for determining plate tectonic motions and large-scale distortions in plates will necessarily involve the use of a combination of fixed and mobile observing stations. Desirable for a geodynamic program would be the determination of locations for roughly a couple of hundred fairly widely spaced points throughout the world (Committee on Recent Crustal Movement, 1977; Bender, 1978). Mobile stations provide the only means for determining the locations of anywhere near this number of points without the investment of unreasonably large amounts of money in the construction and maintenance of many fixed stations. On the other hand, some fixed stations distributed around the world are needed in order to provide reference locations with respect to which the mobile stations can make their measurements and also to monitor changes in the earth's rotation and polar motion, which otherwise would degrade the accuracy of the results, as discussed in Section 4.2.5. It is expected that a sufficient number of fixed stations of various kinds will be operated in Europe and the United States during the 1980's for these purposes, but additional stations on other continents would be valuable to give better coverage.

A question of major importance for geodesy in the next decade is the time that will be required per site for a mobile station to determine its location accurately with respect to the worldwide set of fixed stations. Assuming that the distances between successive sites usually are to be a few hundred kilometers, estimates of the time required per site range from about two days to one month. Groups at the Jet Propulsion Laboratory and the University of Texas, which are building mobile LBI and LAGEOS ranging stations, respectively, are confident of achieving measurement time of one week or less per site (MacDoran, 1978; Bender *et al.*, 1978). These stations are intended only for rapid measurement of station positions and are designed specially for this purpose. If this measurement time per site can be achieved, it means that the cost of determining a couple of hundred sites and of repeat measurements at them every one to two years would be relatively low.

We recommend that two mobile stations using long-baseline interferometry and two using laser ranging to LAGEOS be developed and tested rapidly, with the goal being to demonstrate that both high accuracy and rapid measurements can be achieved by mobile stations that are optimized for position determination measurements.

One station of each kind would be insufficient to have a strong and timely impact on the understanding of plate tectonic motions and distortions.

The mobile stations approach discussed above also can be used to establish a framework of known reference points around and within seismic zones, with a spacing of perhaps 200 to 400 km between points. Over distances somewhere in this range, the accuracy of monitoring crustal movements by space techniques appears likely to become better than the accuracy achievable with improved ground measurement techniques.

The combination of reference points on various plates, for studies of plate tectonic motions and of large-scale distortions within plates, and of reference frameworks around a number of the world's seismic zones, can be thought of as constituting a worldwide geodynamics control network. We believe that a network of this kind will be of major value in evaluating present plate tectonic theories and in developing an improved understanding of strain buildup and of postseismic motions in the broad areas surrounding seismic zones. Such a network also would facilitate measurements of stress migration after large earthquakes by mobile stations. International discussions of the need for a worldwide geodynamics control network already have started (Commission on Recent Crustal Movements, 1977). In view of U.S. contributions so far to the development of space techniques and of our capabilities in this field, we believe that the United States should take the lead in helping to establish such a network.

We recommend that the United States take an active role in the early establishment of a worldwide geodynamics control network. We further recommend that, in so far as possible, U.S. contributions to establishing such a network should utilize mobile stations requiring short measurement times per site.

ADDITIONAL REFERENCES

A complete report on the National Geodetic Satellite Program is given in a publication of the National Aeronautics and Space Administration (1977). An introduction to satellite geodesy can be found in Mueller (1964), and an early discussion of geodetic uses of artificial satellites is given in Veis (1960).

4.2.3 Position Measurements at Many Points

The direct application of geodetic positions to the problems discussed in Chapter 3 entails an appreciable variety of accuracies, station spacings, and repetition rates. For these purposes, space and terrestrial (see Section 4.1) techniques should be compared on the basis of other factors in addition to accuracy, such as cost and responsiveness to changing circumstances. Space techniques in support of surveying and mapping where economy is of primary importance are discussed in Section 4.1.3. Here we emphasize more the use of space techniques for time-varying positions, where accuracy and rapidity of response are paramount, particularly in seismic zones. This discussion is in continuation of that in Section 4.1.4.

Three candidates among the space techniques that have been suggested so far for frequent monitoring of many points in and around seismic zones are (1) satellite-generated radio signals, (2) satellite-to-ground laser ranging, and (3) ground-to-satellite laser ranging.

The first suggested approach is to use the signals from the Global Positioning System (GPS) satellites (see Section 5.3.3). This system is intended primarily for navigational purposes–moderate accuracies in real time–rather than geodetic purposes–high accuracies through subsequent analyses. Hence, special observing and analysis procedures designed for high accuracy are needed. Four satellites in different directions in the sky would be observed simultaneously. Whether this approach is successful for crustal movement monitoring or not, it still is likely to be valuable for general applications to geodesy. The three modes of operation that have been discussed for differential measurements from two stations are use of the Doppler information, as is done with the present Navy Navigation Satellite System (NNSS) transmission; use of the coded train of timing pulses to determine range; and use of the signals in the LBI mode. The differential approach would greatly reduce the effects of satellite orbit and satellite clock uncertainties. As an example, the signals available in the LBI mode would be much stronger than those from extragalactic radio sources, and a very much narrower bandwidth could be recorded. The required observing time would be considerably reduced. Careful comparisons of the different modes of operation have not yet been carried out, but the prospects appear good for at least one of the modes of operation to be accurate enough for use in crustal movement measurements.

We recommend that support be provided for the development and refinement of the Global Positioning System with the aim of achieving at least geodetic accuracy and we hope also the accuracy needed for crustal movement measurements.

The NNSS will also continue to be useful. As discussed in Section 4.1, space data are being employed systematically for the first time to control a terrestrial survey through the use of portable Doppler receiver data as constraints on the adjustment of the North American Datum. This adjustment will produce geocentric positions accurate to about 0.5 m, which is sufficient for many surveying and mapping requirements. The GPS, scheduled to replace the NNSS, will require new receiving equipment. The GPS is scheduled to become operational in 1985, and present plans are for the NNSS to be maintained until 1990.

We recommend that, for continuity in ongoing geodetic programs, the operation of the present Navy Navigation Satellite System be continued so that there is a significant overlap with operation of the forthcoming DOD Global Positioning System.

A second approach that is being studied is the Spaceborne Ranging System, in which the most complicated and expensive technology required would be centralized in the spacecraft. As conceived at present, a pulsed laser-ranging system would be located in the spacecraft and would range to a number of retroreflectors on the ground (Mueller *et al.*, 1975; Kumar, 1976; Vonbun *et al.*, 1977b). The ranging can be done either sequentially to different retroreflectors or simultaneously. The relative locations of the other retroreflectors can be determined without accurate knowledge of the spacecraft orbit from other information.

It has been proposed that a system of this kind be flown several times on Shuttle missions and then flown on a free-flying satellite if successful. With sufficient development, an accuracy of about 1 cm may be feasible. It appears necessary that there be requirements for monitoring large numbers of points frequently in order to make the cost of this approach attractive. However, sufficient requirements could be present if large-scale monitoring of crustal movements in a number of other countries were undertaken also or if other substantial needs developed for accurate positioning by the Spaceborne Ranging System. The use of the Spaceborne Ranging System for the lower-accuracy applications discussed in Section 4.1.3 should also be considered. Where dense control or appreciable detail is required, a supplementary or competitive technique is satellite photogrammetry (National Research Council, 1969; Doyle, 1977.)

The third approach, laser ranging to satellites, could in principle use the LAGEOS satellite discussed in Section 4.2.2. However, much greater mobility could be attained by simpler laser systems capable of ranging to satellites at only 1000-km altitudes, such as STARLETTE. To avoid error from orbit calculation, differential laser ranging from two or more ground stations has been suggested recently (Wilson *et al.*, 1978). The more low-altitude satellites (besides STARLETTE) equipped with laser retroreflectors, the more rapidly can differences in station positions be determined during clear weather periods. Therefore,

We recommend that optical corner reflectors be placed on any satellites for which accurate orbits are being determined in order to utilize the laser tracking that is currently state of the art.

4.2.4 Global Gravity Measurements

The use of accurate laser range data for satellite-orbit determination already has made an important impact on the determination of the earth's gravity field. The GEM 10 model field was shown in Figure 4.4. With the number of accurate tracking stations in operation expected to increase substantially during the SEASAT-A tracking period, further gravity-field improvements are likely to be obtained from accurate tracking of medium- and high-altitude satellites with low area-to-mass ratios such as STARLETTE and LAGEOS. However, satelliteborne radar altimetry has already improved our knowledge of the gravity field significantly. Further improvement will come from satellite-to-satellite tracking—particularly the extension to land areas—and possibly gravity gradiometry (Section 5.1.6).

Although an altimeter was flown successfully on the SKYLAB mission, the first major new contributions to the determination of the gravity field have come from the GEOS-3 radar altimeter. This instrument senses directly variations in the absolute height of the sea surface with respect to the orbit and thus obtains a good approximation to the height of the geoid. Effects due to wave shapes and tides have to be subtracted, and the resulting surface is expected to deviate from the geoid by the order of a meter or less. Such deviations are generated by currents in the oceans, by wind-shear effects, and possibly by other effects. It is hoped that the ocean currents can be mapped in the future by improved altimetry data, provided that sufficiently accurate information on the geoid undulations at the necessary wavelengths can be obtained from other approaches.

The present GEOS-3 altimeter accuracy is about 0.5 m (the accuracy of the resulting radial coordinate is a few meters because of imperfect orbit determination). This accuracy, plus the frequency with which the observations are made, has improved the resolution for gravity-field variations to about 200 km, where data are available (Figures 4.5–4.7). The main remaining limitations on GEOS-3 data for improvements in the geoid height are the power supply and the inability to store data onboard the spacecraft, so the coverage is incomplete. These defects of coverage will be eliminated on SEASAT-A, launched in June 1978. In addition, the accuracy of the SEASAT altimeter will be an improvement, to around 10 cm. Hence the main limitation is anticipated to be the accuracy of orbit determination, for which new 5-cm laser-ranging instrumentation is being built. New measurements of the complex oceantide patterns and their amplitudes as a function of time also are expected from the altimetry data.

Perhaps the most promising new technique for obtaining much improved information on the gravity field is satellite-to-satellite tracking. This method overcomes the inadequacies inherent in tracking from a limited number of surface tracking stations: incomplete tracking coverage, coupled with the aliasing effect of the stations revolving (with respect to an inertial frame) at the same rate as the gravity field. The method also obtains gravity variations over the land, which cannot be measured by altimetry. Satellite-to-satellite tracking has been, or is being, carried out between 24-hour satellites and several spacecraft, such as NIMBUS, ASTP, and GEOS-3 (see e.g., Vonbun, 1977c; Vonbun *et al.*, 1977a). However, most of these satellites are too high for the Doppler measurements to detect accelerations of the orbit by the shorter-wavelength features of the gravity field, which are the current area of interest (Section 3.2.3). The optimum information will probably require dedicated satellites with drag compensation, orbited at as low an altitude as can be maintained long enough to obtain global coverage, probably about 200 km.

An alternative to high-low satellite range-rate measurements at microwave frequencies that has been suggested is laser range-rate measurements between two low satellites (Roucher *et al.*, 1977; Rummel *et al.*, 1978). Test measurements between SPACELAB and a subsatellite have been proposed. The most favorable geometry would be to have one satellite above the other. An extension of this idea might be to use laser range-rate measurements between two satellites in coplanar polar orbits, with one at low altitude and the other at intermediate altitude. An alternate technique that has been suggested is ranging between two low satellites in counterrevolving near-polar orbits. This experiment is designed primarily to test relativistic effects but could also obtain refined determinations of some components of the earth's gravity field (Van Patten and Everitt, 1976).

The accuracy of satellite-to-satellite microwave tracking estimated as achievable is approximately 0.3 mm/sec (Argentiero and Lowrey, 1978). It has recently been suggested that significant further improvement in accuracy could be attained by use of a two-way coherent signal.

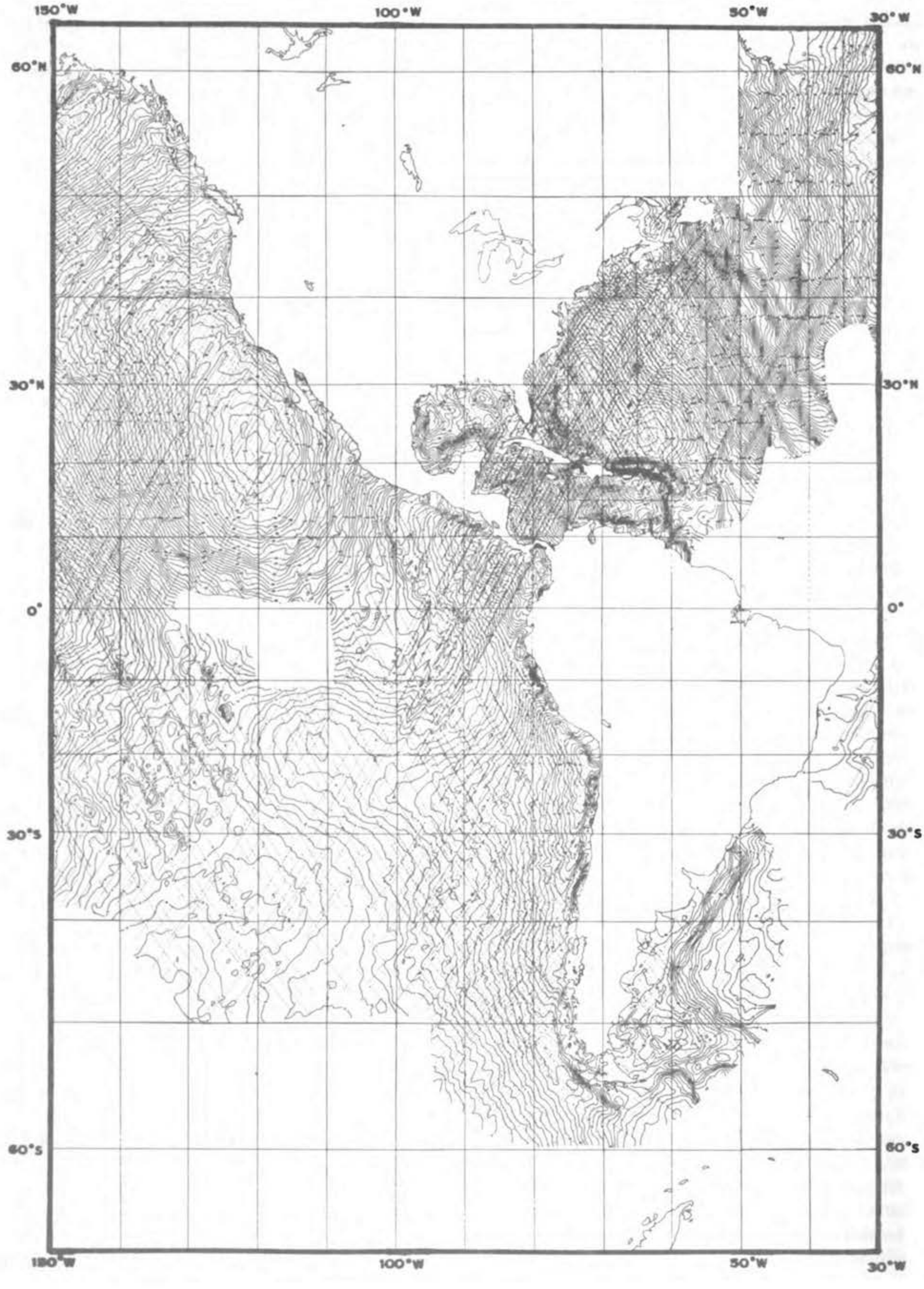

FIGURE 4.5 Preliminary DOD GEOS-3 geoid (Oct. 1977, Units = Meters).

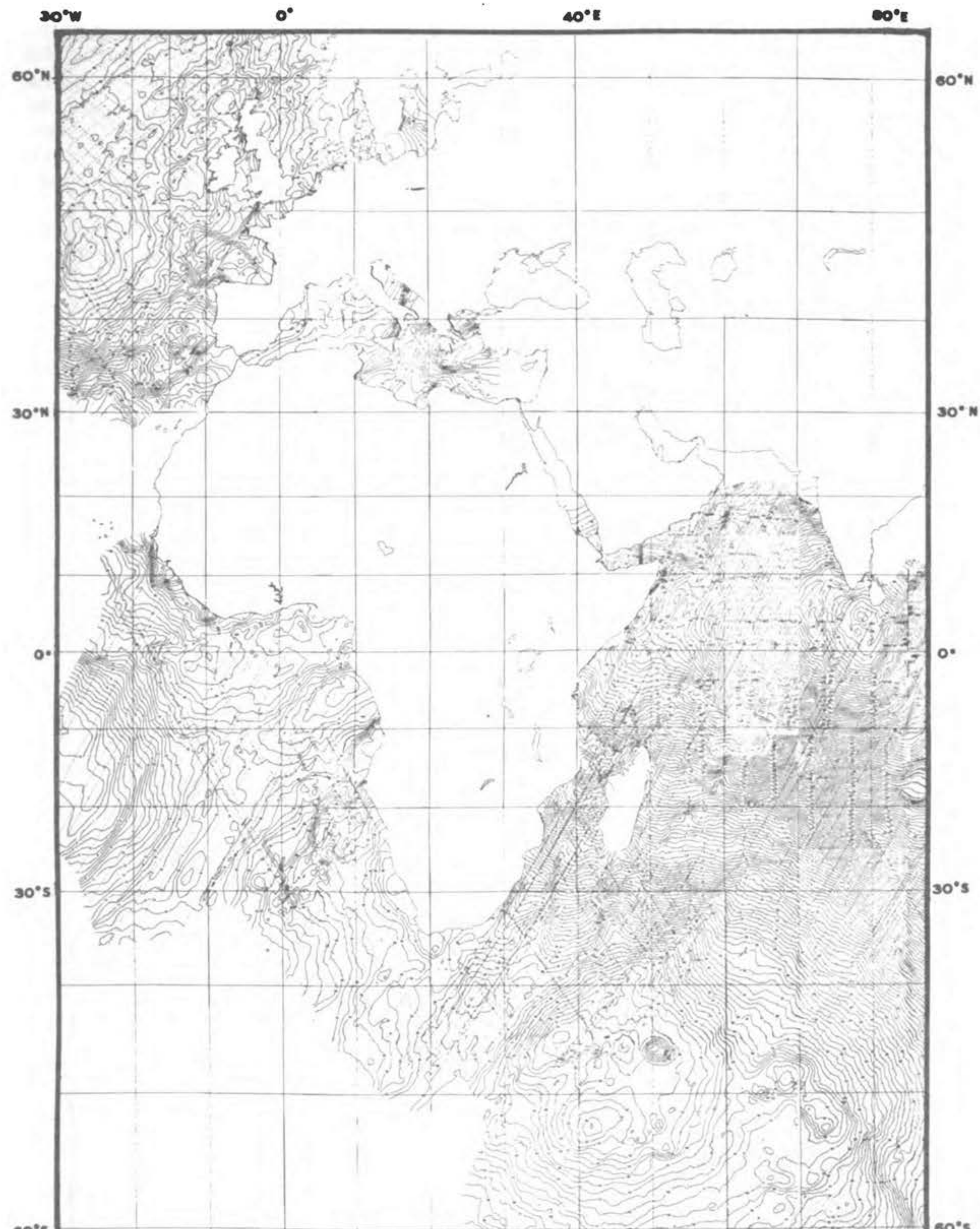

FIGURE 4.6 Preliminary DOD GEOS-3 geoid (Oct. 1977, Units = Meters).

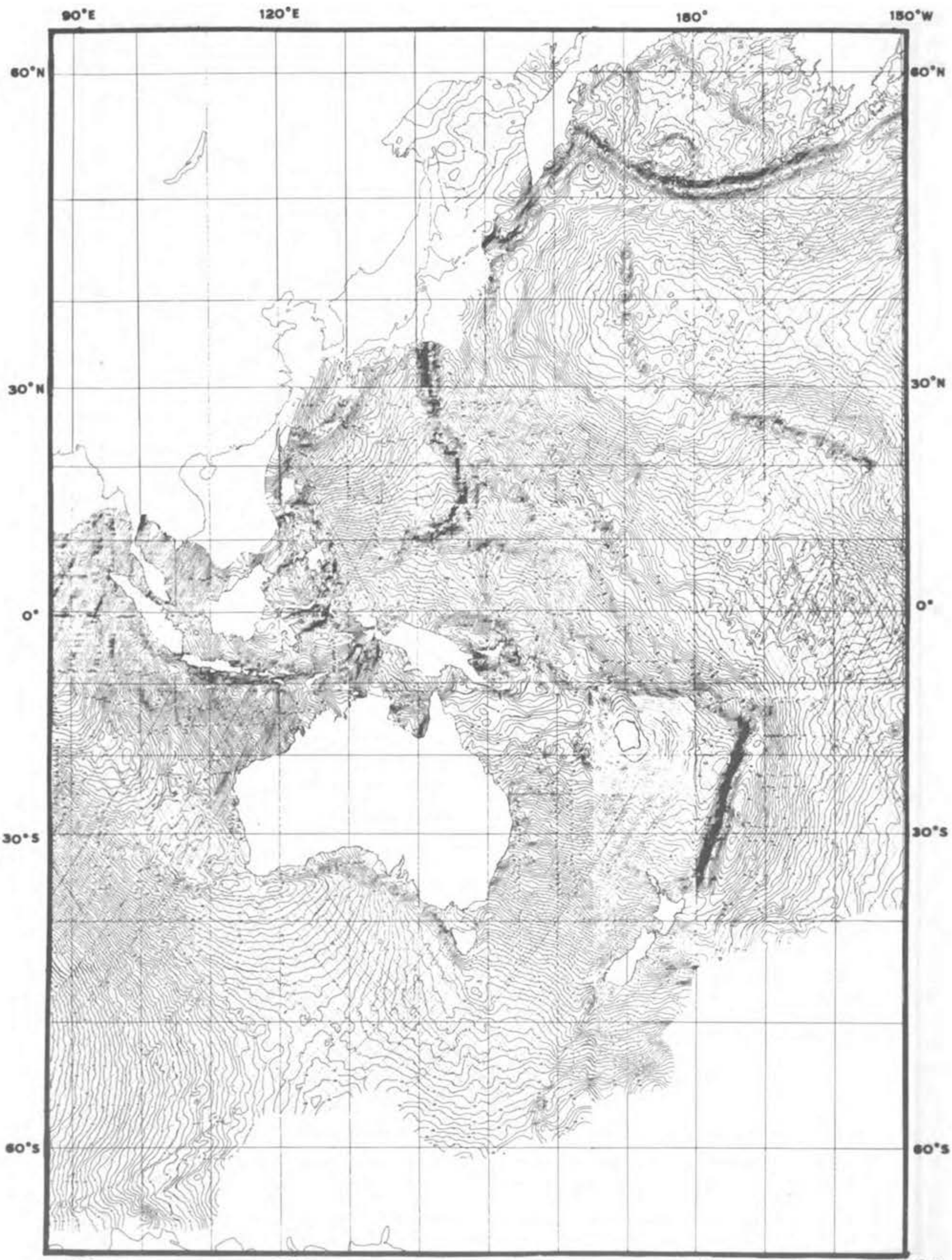

FIGURE 4.7 Preliminary DOD GEOS-3 geoid (Oct. 1977, Units = Meters).

However, the attenuation with altitude of shorter-wavelength features in the gravity field means that even with a 200-km-altitude satellite, the resolution would not be better than 100 km. The alternative technique of gravity gradiometry, discussed in Section 5.1.6, should be continued in consideration, but it is also affected by attenuation. In any case,

We recommend a dedicated gravity satellite, maintained at as low an altitude as possible with satellite-to-satellite tracking, subject to further analysis of accuracy requirements and feasibilities.

It is important that such a mission be designed to achieve the geoid accuracy needed for ocean-current determinations if possible.

4.2.5 Earth Rotation, Polar Motion, and Tidal Dissipation

The international services for determining universal time (UT1) and polar motion (PM) were described in Section 4.1.5. Data from Doppler satellite measurements are now being included, as well as those from about 80 classical observing instruments for time and/or latitude. However, the accuracy being attained is an order of magnitude worse than that which appears achievable by *either* laser ranging or long-baseline radio interferometry (see Sections 5.3.2 and 5.3.5). In addition, the accuracy of the results given at present by the international services is insufficient for use in studies of worldwide plate tectonic motions and large-scale distortions within plates with mobile stations, which are expected to start soon.

Fortunately, the prospects now appear good for being able to switch over to primary reliance on the new techniques in the near future. However, it is important that this be done in such a way as to maintain international confidence in the reliability and accuracy of the results that are obtained. For this reason, it is highly desirable that a new international observing program be set up, which includes *both* laser ranging and long-baseline radio interferometry for at least the next decade. This would permit comparisons to be made between the completely independent laser and interferometry results and would show up any unsuspected systematic errors that might otherwise escape detection. LAGEOS ranging data alone would not give information on all UT1 variations, thus lunar ranging data also are needed in order to allow comparisons of laser results with long-baseline interferometry results for both UT1 and PM at all periods.

It is expected that about 15 stations capable of laser ranging to SEASAT-A with 5- to 10-cm accuracy will be in operation by early 1979 (Vonbun, 1977b, 1977c; Bender, 1978). A majority of these are likely to range to LAGEOS as well often enough for determinations of PM to be made. It appears that about 10 LAGEOS ranging stations at favorable sites plus a few lunar ranging stations will be sufficient to give reliable results for UT1 and PM, which very rarely are interfered with by weather. In view of the number of U.S. laser ranging stations that exist at present and the value of their continued operation for other purposes also, we believe that the United States should support about half of the stations necessary for an interim international network during the 1980's. This is the basis for our recommendation in Section 3.2.4 that the United States support ". . . three long-baseline radio interferometry stations and approximately six laser ranging stations . . ." on a continuing basis.

For long-baseline microwave interferometry, the first international programs of high-accuracy observations are expected to start in 1979. One program involves the Haystack, Greenbank, and Owens Valley Observatories in the United States; the Onsala Observatory in Sweden, and the Effelserg Observatory in Germany. Wideband Mark III recording systems will be used at each site, as well as dual frequencies to correct for the ionosphere. Another program utilizes the 64-m antennas of the JPL Deep Space Network (DSN) at Goldstone, Madrid, and Canberra. This system will also have dual frequencies. In addition, the NGS has proposed initiating a continuing program of accurate *daily* measurements from three stations in the United States. A minimum of three stations is necessary in order to be able to observe changes in UT1 and PM at all frequencies. It is hoped that measurements with antennas at Westford, Massachusetts, and Ft. Davis, Texas, can be started by the end of 1979. Because of strong U.S. capabilities in this field, we believe that three stations making daily observations should be supported by the United States, as stated in our recommendation in Section 3.2.4. It is expected that such support by the United States will encourage the participation of a similar number of non-U.S. stations in a continuing international program. Additional stations may be needed to support tectonic motion measurements in the southern hemisphere.

As part of recent international discussions on the future of UT1/PM determinations, strong concerns have been voiced by many geodesists and astronomers that the work of the International Latitude Service (ILS) Stations in determining secular polar motion since 1895 not be lost. For this reason, an extended period of overlap with observations by the new techniques has been recommended. We agree that a substantial overlap period is desirable, both for the ILS stations and for a few of the best stations making time observations by the classical techniques. During this period the actual UT1/PM values will be known well enough from the new techniques so that the deviations observed by individual classical instruments can be studied carefully to determine the causes of the nonrandom components of the errors. To the extent that the earlier instruments are still in use, this will allow estimates to be made of the accuracy of the early polar-motion determinations.

An entirely different respect in which space techniques contribute to our knowledge of long-term changes in the earth's rotation comes through the measurement and analysis of tidal effects on the orbits of artificial satellites and the moon (Lambeck, 1977). Amplitude and phase lags of the combined ocean and solid-earth tides have been estimated from satellite orbit perturbations (Cazenave *et al.*, 1977; Goad and Douglas, 1977), while the secular acceleration of the moon arising from the tidal torque has been estimated by analysis of lunar laser ranging (Calame and Mulholland, 1978; Williams *et al.*, 1978). Another area of significant recent improvement is the analysis of ancient and medieval eclipse observations (Muller, 1976). In addition to the tidal deceleration of the earth's rotation, these data yield the nontidal acceleration of the rotation due to internal mass shifts, such as the postglacial isostatic backsurge.

4.2.6 Lunar and Planetary Geodesy

Geodetic measurements of the moon and planets suffer from remoteness but have the compensating virtue of looking at the planet from the outside, so the atmospheric and geometric constraints ("aliasing") of earth-oriented space techniques do not apply. An exception to this rule is the moon. The synchronous rotation of the moon has lead to its farside gravity field being much more poorly determined than its nearside gravity field. With existing data from the Apollo, Lunar Orbiter, and Explorer satellites, this determination is a complex process of indirect inference from long-term perturbations of the orbit. It is therefore proposed to have a small relay satellite at a high lunar altitude in conjunction with the Lunar Polar Orbiter to track the orbiter when it is hidden from the earth.

The tracking accuracy of the JPL Deep Space Network (DSN) required for navigation of distant probes with ill-conditioned geometry is sufficient for planetary geodesy. The main constraint is the deboost capability necessary to place spacecraft in low-altitude polar orbits about distant planets where the approach velocity is several kilometers/second. As mentioned in Section 3.4, the information about the Martian gravity field obtained by Mariner 9 and the Viking orbiters is quite nonuniform in quality because of orbits with high eccentricities, long periods, and inclinations appreciably less than polar. The data anticipated about the Venerean gravity field and topography by Pioneer Venus Orbiter, launched in May 1978, will be even more constrained.

Valuable information about the topographic variation of planets is obtained by the great radars at Arecibo (Puerto Rico) and Goldstone (California). These data can be located on the planetary surface by a combination of the time delay in signal return with the Doppler effect arising from planetary rotation. However, the accuracy degrades rapidly away from the planetary equator. Hence altimeters are always sought for planetary orbiters such as the Venus Orbiting Imaging Radar (VOIR) proposed for 1983 launch.

4.3 THEORETICAL PROBLEMS

The diversity of research in theoretical geodesy is evidenced by the fact that the International Association of Geodesy maintains active Special Study Groups in 23 areas (see Section 6.3), which according to the By-Laws of the organization were formed to "study specific scientific problems," and whose duration is limited to the four years between two General Assemblies to avoid staleness. Indicative is also the fact that of the 309 symposia and scientific meetings organized by the IUGG, its Associations and Commissions, or other bodies during the period between the XV and XVI General Assemblies of the Union (1971-1975), 58 had direct geodetic implications and input (Melchoir, 1976). The U.S. National Report to the same Assembly lists over 1000 bibliographic entries in geodesy (Bell, 1975). Most of these activities have been aimed at improvement of the gravity field and the knowledge of the geoid (i.e., the solution of the geodetic boundary-value problem); establishment of geodesy as a three-dimensional technique, which, in the dynamic sense, overlaps that of geoid definition; refinement of the geodetic reference frame, taking into accord geodynamic effects and requirements; and. extension and improvement of statistical theory.

4.3.1 Geodetic Boundary-Value Problem

The development of artificial satellite theory and the solution of the geodetic boundary-value problem are aimed at the description of the earth's surface and its gravity field (though from entirely different types of observations). Historically, the classical problem of boundaries reaches back over centuries; but in geodesy the problem of determining the earth's surface from gravity observations is a nonlinear free solution of Laplace's differential equation, and it has a much shorter history. The term "free" implies that the unknown solution must agree with observed data on the boundary which itself is unknown. Thus, part of the problem is to find the geometry of the boundary. This is a much more difficult problem than the solution of the classical boundary-value problem, for which the solution agrees with postulated values on a given boundary. In addition to being free, the geodetic problem is of the "oblique" type, because it is formulated along the direction of gravity, which is oblique with respect to the normal to the surface. So far, great progress has been made in understanding the problem and in estimating the mathematical significance of the various necessary (e.g., linear) approximations involved in the solution. Work on the nonlinear problem involves appreciable technical difficulties, and the final solution is not yet in sight. However, the accuracy of existing solutions is considerably better than required for the currently available gravity data.

It was especially in connection with the above investigations of potential theory, the geodetic boundary-value problem, and other problems that conventional theoretical and computational methods were seen in the context of the very elegant and powerful theory of functional analysis (Hilbert spaces, Banach spaces) (Brosowski and Martensen, 1975).

The application of topographical and geological data that are correlated to the earth gravity field has been studied with the objective of providing a meaningful solution for high-order terms of the potential. A general model of analysis still needs to be developed in which the various data types will complement each other. An integrated solution will help to remove inherent biases and weaknesses in the individual data types and should result ultimately in a consistent stable and reliable solution of the earth gravity field.

4.3.2 Three-Dimensional and Differential Geodesy

The development of the theory of artificial earth satellites occurred almost entirely during the last quarter century, though its roots again reach back a century or so to the classical theories pertaining to natural satellites, particularly the moon. The circumstances surrounding an artificial geodetic earth satellite are different from those of a natural satellite mainly because it moves much nearer to its primary. Hence, medium- and short-wavelength gravitational effects also perturb its orbit, the nonlinear effects arise more from planetary oblateness than from third-body effects, and atmospheric drag may be significant. These main effects, and other smaller factors (radiation pressure, for example), give artificial satellite theory a character of its own (Kaula, 1966). An additional difficulty peculiar to earth satellites is that observations of satellite motion are made from stations of uncertain location fixed on the same planet that is generating the perturbations of the orbit. Hence, aliasing effects arise from both nonuniform station distribution and truncation of the harmonic representation of the gravity field. Satellite theory can be stated to be complete enough today; the deficiencies in orbit determination are due mainly to inaccurate values of geometric and physical parameters. The most recent improvements in theory–e.g., the application of Lie transformation theory to the Poisson operator–are of value more for economy of computer time than for improvement of insight or closer matching of observations more accurately (Kinoshita, 1977).

Another interesting three-dimensional development is the geodetic utilization of gyroscopic systems. Such a system under the influence of gravity and the rotation of the earth is oriented with respect to the horizontal plane and the astronomical north (south). This "inertial surveyor" installed on a moving platform, after an initial orientation, provides continuous information on relative three-dimensional coordinates and the gravity potential (anomalies and deflections) (Sections 5.1.7 and 4.1.3). Theoretical work has been oriented toward the reduction of systematic errors and noise affecting the survey performance via filtering and coupling the inertial surveyor with a gradiometer (Canadian Institute of Surveying, 1977). The concept of this system is an elegant example of the interrelationships among three-dimensional geodesy, the geodetic boundary-value problem, reference frames, and statistical filtering. Further research is needed to include investigations of the factors affecting or limiting the accuracy of the gradiometer-aided inertial survey system; study of system performance, in particular, the extent to which the system can be used without outside information; and derivation of error models designed to compensate for varying gravity disturbances and to eliminate the necessity of measuring in a nonmotion state.

There are reasons for expecting that three-dimensional geodesy will develop much further in the 1980's and may fundamentally alter the role of the geodetic boundary-value problem in geodesy. Accurate laser range measurements to a high altitude and dense satellite such as LAGEOS, which is only moderately affected by the earth's gravity field or by radiation pressure, can give very strong three-dimensional position determinations. The same is true for LBI and for lunar laser ranging. The position accuracies are expected to be in the range of a few centimeters with all three techniques, and the use of high-mobility stations for laser ranging or LBI probably make the cost per point relatively low. Thus hundreds or even larger numbers of points around the world are likely to be determined and to form a three-dimensional network of accurately known geometry to which gravity field measurements, leveling data, and satellite orbits can be tied. If its accuracy potential is realized, the Global Positioning System should play an important role.

One must also note the gaining recognition of the importance of differential geodesy, utilizing differential geometric techniques, especially for the determination of unique space and time coordinates of points on the earth's surface (Italian Geodetic Commission, 1976; Hotine, 1969). The main task is the conversion of measurements of directions, distances, and gravity–which are referred to local coordinate frames, such as the local vertical, astro-north, and east–to obtain coordinates of points in a uniquely defined global reference frame. Thus the problem is the development of rigorous transformations and conditions between the local "moving" frames and the unique global reference frame. Most problems involved have been solved theoretically in a number of different ways, and now a generalization process is taking place, together with formulation beyond conceptualization, which could lead to practical application once the necessary observational data become (globally) available and the adjustment method is clarified.

4.3.3 Reference Frames

The problem of reference frames for both geodesy and geodynamics has received considerable international attention recently and was the subject of the International Astronomical Union Colloquium No. 26 in 1974 (Kolaczek and Weiffenbach, 1975).

If we neglect secular or irregular distortions of the earth's crust, the three-dimensional network discussed above can be used in a rational way to define an earth-fixed reference frame. The rotation and tilting of this frame with respect to celestial ("inertial") reference frames then defines what we mean by polar motion, earth rotation, nutation, and precession. The center of mass of the earth will be connected by the LAGEOS or lunar laser-ranging measurements to the network, so the earth-fixed frame can be closely geocentric. The main question to be decided would be how many of the points to use in defining the reference frame in order to make it as "robust" as possible versus how many points to regard as measured with respect to the defined reference system.

For the real earth, the problem of defining a reference frame that rotates with the earth in some reasonable sense is more difficult but still feasible. It has been suggested that such a frame, once it has been internationally agreed on, be called "the conventional terrestrial system" (Fedorov, 1978). If the currently known long-term relative tectonic plate motion rates are assumed to apply to the present time, the measured station positions can be corrected for the expected relative motions by referring them to a common epoch. The conventional terrestrial system is then defined conceptually, except for a possible common rotation of all the plates with respect to the bulk of the mantle. Fortunately, quite different assumptions about what types of tectonic features are likely to remain nearly fixed with respect to the bulk of the mantle give quite similar results for the common rotation, and thus they would give definitions of the conventional terrestrial system, which differed by a rotation rate of only about 1 cm/year. As better geophysical information on the plate motions and on intraplate distortions are obtained, an improved conventional system can be adopted.

The celestial reference frame used in geodesy in the past has been a frame implicitly defined by a fundamental star catalog, such as the present FK-4 or the nearly completed FK-5. Such reference frames will continue to be important in geodesy for uses such as determining astronomical positions and orientation. However, two other frames are likely to be used for polar motion, nutation, precession, and earth-rotation measurements. One is a new "extragalactic radio source frame" determined by LBI observations. The second is the "planetary dynamical frame" determined by the motion of the planets and the moon. The angular motions of the conventional terrestrial system with respect to these two celestial reference frames are expected to be measured by LBI and lunar laser ranging, respectively, with the observations themselves determining the relative orientation of the frames. Both frames are expected to be nonrotating (rotationally inertial) to very high accuracy. Laser range measurements to LAGEOS or to similar satellites also are expected to be very important for determining polar motion and possibly certain variations in the earth's rotation, as discussed in Section 3.2.4.

Additional problems of concern to geodesists related to referencing include the values of the parameters of a mean earth, an equipotential (level) ellipsoid which most closely approximates the geoid—the product of the gravitational constant and its mass, GM; the semimajor axis, a; the flattening, f, or the corresponding oblateness term J_2; the rate of rotation of the earth, ω—and the definition of mean sea level and its relationship to the geoid.

In connection with the last problem, research in two areas is needed: (1) the separation between the sea-surface topography (to which satellite altimeter measurements refer) and the geoid needs to be investigated; and (2) the current reference for heights, the mean sea level, as determined from geodetic and oceanic leveling techniques shows a discrepancy, which needs to be resolved by independent technologies.

4.3.4 Statistical Problems

In geodesy, problems associated with incomplete or inaccurate observations generally come under the heading of *adjustment theory*. In adjustment theory probably the most important single objective is to clarify the mathematical and probabilistic background of standard linear estimation techniques used in geodesy and to reveal their interrelationships. The pursuit of this objective led to the increased role of linear algebra (matrix algebra) in adjustment theory (especially generalized inverse theory—a special geodetic concern); to the increased use of statistics (beyond the "theory of errors"); and to the increased presence of functional and numerical analysis. A note must be made on the spreading use of *collocation* (in general, viewed as a prediction technique) as a unification and extension of adjustment technique, mostly in connection with the determination of the gravity field (Brosowski and Martenson, 1975). Collocation theory has some similarities to the inversion theory developed by seismologists since 1967 but appreciable differences in emphasis; most notably, collocation theory is concerned with obtaining an optimum solution from incomplete data on a natural variable that is accessible—such as the earth's gravity field—while inversion theory is concerned with the resolution with which an inherently inaccessible variable—such as the internal density of the earth—can be inferred.

Further developments are needed in optimization and planning, including economic factors. In the planning of geodetic measurement systems, the optimization process plays a most important role. Two aspects can be recognized: (1) Economy—the cost factor should be minimized; (2) Geometry—the precision and reliability should be optimized. These aspects, which are often counteractive (i.e., the more reliable, the more expensive), have to be subjected to a decision theory. The latter should yield criteria to serve as the quantitative basis for making the decisions. Such criteria must be based on the careful evaluation of social motives and subsequent translation into a cost analysis of the scientific realization and on the careful evaluation of the mostly nongeodetic requirements (e.g., from geophysics) and their subsequent translation into geodetic requirements.

Other areas for research should include search for greater diversity of adjustment techniques, i.e., other than least-squares adjustments, other norms, and linear and nonlinear programming. Different optimality criteria in adjustment theory and their applicability to geodetic problems need to be investigated. These methods should be compared, and specific criteria for the choice of the optimum method for all major problems in geodesy and geodynamics need to be selected. Estimable quantities that can be derived from a specific kind of observation need identification.

Also needed is a unique best and practical solution to the problem of the generalization of the (random effects and mixed) analysis of variance. Statistical methods for variance analysis and comparison of numerical results from applications in geodetic problems need to be studied. Parameters of each problem for which variance analysis will give meaningful results need identification. The ability of each method to detect systematic errors in the model should be determined.

Additional investigations should be made on specific topics such as the employment of refined methods of spectral analysis (e.g., the maximum entropy method) in order to extract signals from noise more efficiently; the discovery of a deterministic, as opposed to empirical, method for assigning weights in solutions with heterogeneous data; and numerical analysis for the expeditious handling of sparse matrices.

5 Advanced Instrumentation

In geodesy the position of topographical features on the earth's surface are determined by measurement. The vertical is used as a reference in these measurements; therefore, gravity and geometry are involved.

The classical instruments of the surveyor and geodesist have not changed appreciably in recent years in terms of accuracy or use and are described in Section 4.1. They include the theodolite, zenith telescope, spirit levels, and rods. Electronic distance measuring and laser distance measuring have become standard in the last 20 years. As a result, traverse is frequently preferred to triangulation (Bomford, 1971). The instruments described in this chapter are those that are relatively new in their contributions to geodesy or are instruments or measurement techniques that have changed appreciably in recent years and therefore have new implications in the measurement process.

The most significant change in instrumentation has resulted from the utilization of satellites. Worldwide coverage and a common reference are available for the first time, and future systems may provide an accuracy known only in local surveys heretofore.

The specification of performance depends on the type of instrument under discussion. In this chapter, we are concerned about the instrumentation and the natural environment in which it must necessarily operate to make well-defined measurements, such as those of distances, angles, and accelerations. Examples of natural environmental effects are atmospheric refraction effects on distance-measuring devices and ocean-wave effects on radar altimetry reflections. In other chapters—particularly Chapter 4—we are also concerned about effects on the end results of a system of measurements, which may entail geometrical configurations and their adjustment, orbit determinations, and observing programs to infer temporal changes. The performance terminology used throughout takes into account these different levels and is given herewith.

Bias is an unknown error that persists with the same sign for a series of measurements by the same instrument or at the same site; it may be constant or slowly varying, and it may arise from either the instrument or the environment.

Random error is an error that fluctuates from one measurement to the next; it may arise from the environment as well as from the instrument, and in the long run averages zero.

Precision is the repeatability, or difference between successive measurements, of the same quantity by the same instrument; it is part of the random error and is closely related to *jitter*, the high-frequency part of the random error.

Round-off error is dependent solely on the number of digits to which an instrument can be read; it is part of the precision.

Uncertainty as used in this text means the root-mean-square value, or sigma, of the combined bias and random error of the instrument plus environment. If either contribution is specified, they are called instrumental uncertainty or environmental uncertainty as appropriate. If possible, instruments are utilized in such a manner that the uncertainty is largely determined by the bias. Occasionally the 90 percent, or two sigma, error may be given.

System uncertainty is the sigma estimated for a quantity inferred from a system of measurements plus computations, such as a rate of motion inferred from distance measurements between two points at different times or a sea-level height inferred from a calculated orbit position plus a satellite height measured by an altimeter.

Resolution as used in this text means the minimum wavelength of a spatially varying quantity, such as the gravity field, which can be discriminated with about 50 percent uncertainty by a given system, i.e., a combination of instruments, environment, and configuration of measurements. This resolution in turn entails an estimate of the spectrum of the spatially varying quantity. (This use of resolution differs from that normally used for instrumentation, where typically it means the smallest interval or angle at which two standard features can be discriminated.)

Instrumentation has usually been supported by a mission needing new or more accurate measurement. In some cases, principal users cannot support instrument development—at least alone—or do not have the competence to direct it. Some agencies having the responsibility to generate and collect data are particularly conservative in entertaining new instrument types when existing instruments appear to be adequate and are widely accepted. This has led to the development of some instrumentation by the nongeodetic community, as noted in Chapter 2, without benefit of geodetic requirements.

We recommend that the development of geodetic instrumentation be supported in its own right to satisfy geodetic requirements.

The advances in instrumentation have been dramatic in the past 20 years. There is no reason to expect that this has stopped or significantly slowed down. It is important to prepare plans for what can be done with improved accuracy; reduced cost, volume, and power; and extended, *in situ*, operating capability, for example, in the deep oceans. Many of these improvements will occur in any event, but they are likely to develop more rapidly if the potential applications have been made clear. This is true for mathematical models of instruments and propagation and also of the physical phenomena that are being examined by the measurement process. Geodesists are most likely to take advantage of the broad development of instrument technology that is very likely to continue for the next few decades, if they communicate their needs to the engineers and scientists involved as Bossler (1977b) has done in establishing the needs of the National Geodetic Survey.

5.1 TERRESTRIAL INSTRUMENTATION

5.1.1 Electronic Distance Measuring (EDM) Instruments

Principle

Electromagnetic waves are transmitted from one instrument to a reflector and back to the instrument; the distance between stations is determined by measuring the transit time of the signal between stations. The instruments are usually categorized according to the emission source: microwave, infrared, and laser.

Status

There are about 30 electronic distance measuring (EDM) instruments on the market today. Some are designed for geodetic measurements and are very accurate, long range (to 150 km), rapid measuring, and have convenient presentation of data. Other instruments are designed for ordinary surveying and are lightweight, sufficiently accurate, and have automatic readout and a range from 0 to 40 km.

EDM instruments have been combined with angular measurement or direction instruments to provide multifunction surveying instruments for static applications. Two or more distance measuring instruments have been combined in a single package for determination of position in dynamic situations.

The wide range of EDM instruments and a price range from $3500 to $100,000 have virtually eliminated taping operations for distances of more than 300 m.

Performance

The performance of EDM instruments is satisfactory for most surveying operations. The accuracy of the better instruments is 1 mm ± 1 ppm. The greatest source of error in EDM instruments is the uncertainty of propagation through the atmosphere.

For applications requiring higher accuracy, such as monitoring of crustal movements in seismic zones, special precautions are needed. An accuracy of 2 mm ± 0.3 ppm has been reported by Savage and Prescott (1973) for routine laser distance measurements over distances of up to 35 km in California. The approach used is to fly a helicopter or light aircraft along the line of sight to measure the atmospheric properties. Very high accuracy, without the use of aircraft measurements, has been reported by Parm (1976) for determining a 900-km baseline in Finland. The terrain was quite level, and great care was used to make sure that the measurements of atmospheric properties represented a good average of the values along the path.

Recently, several investigations have been made with EDM instruments where both a red and a blue laser are used and the beams are modulated at a microwave frequency. The difference in the measured distances for the two colors is used to calculate the integrated effect of the atmosphere along the path. Slater and Huggett (1976) have included a microwave wavelength to sense the average water-vapor density along the path and have reported achieving a stability approaching 0.1 ppm for paths of up to 10 km. Their instrument also has been used for monitoring creep along the San Andreas fault near Hollister, California, by repeated measurements from the main site to a number of optical reflectors in the area (Slater and Burford, 1978).

Future Performance

Only modest improvements can be expected in the accuracy of EDM instruments for use in most applications. Some reduction in size and power requirements may be realized. EDM instruments will be combined with other measuring devices, and more automatic recording of data on tape or other devices will eliminate some of the visual readouts.

For higher accuracy applications, substantial room for improvements appear to exist. Commercial availability of three-wavelength instruments appears likely in a few years. Also, an attempt is being made to develop an instrument capable of 0.05 ppm accuracy over 50-km paths under normal atmospheric conditions (Moody and Levine, 1978). The approach is to use an active demodulator at the far end of the path rather than sending the light back to the origin by means of a retroreflector.

We recommend that the range capability of the developing three-wavelength electronic distance measurement equipment be improved to 50 km with 5×10^{-8} accuracy.

Additional References

EDM instruments are discussed in Downing (1973), Savage and Prescott (1973), Tomlinson and Burger (1977), and Romaniello (1977).

5.1.2 Strainmeters

Principle

Strainmeters can be constructed using either a material standard or the wavelength of light to define the reference length against which strain in the earth is measured. A number of continuously recording instruments using either fused-silica tubes (Benioff, 1959) or invar wires under constant tension (King and Bilham, 1976) have been constructed. A few laser interferometer strainmeters with lengths of 30 m to 1 km have been operated, with an evacuated path provided between the end mirrors in order to remove atmospheric effects (Berger, 1973; Levine, 1977; Beavan and Goulty, 1977).

Status

No commercial instruments are available. Fused-silica tube or invar-wire strainmeters can be constructed quite cheaply and can be temperature compensated or corrected to reduce the effects of temperature changes. Laser interferometer strainmeters are more expensive, with a substantial part of the cost for longer instruments being that of the vacuum path.

Performance

Fused-silica tube instruments are limited mainly by spurious length changes due to water adsorption on the tube and to variations in temperature gradients along the instrument. Invar-wire instruments show some effects of creep in the wire, as well as residual thermal sensitivity. Laser interferometer strainmeters in which feedback into the laser is reduced sufficiently and the laser is well stabilized are limited mainly by the stability of the piers on which the end mirrors are mounted. However, stabilities of the order of one part in 10^7 over a year have been observed recently by Berger and Levine. (See Berger and Wyatt, 1973; Berger and Levine, 1974, for earlier results.)

Future Performance

The ultimate limitations are the effects of local motion at the ends of the path being monitored. Efforts to develop improved methods for maintaining stable reference points are needed. Progress in improving the performance of fused-silica tube or invar-wire strainmeters and in reducing the cost of laser-interferometer strainmeters appears possible. The main alternative is the use of frequent remeasurements with a multiple-wavelength EDM instrument, as discussed in the preceding section. Longer baselines can be used, so that reference point stability is less of a limitation.

5.1.3 Tiltmeters

Principle

Pendulum tiltmeters mounted in boreholes are commonly used for measurements of irregular and secular tilt rates. Servo-controlled bubble instruments also have been developed. Long-baseline liquid tiltmeters provide measurements of tilt averaged over larger distances and are less sensitive to local effects due to rainfall, frost heaving, or nonuniform ground heating. They consist of a reservoir at each end connected by a liquid-filled tube. The difference in apparent liquid level at the two ends usually is the quantity recorded.

Status

Recent interest in continuous measurement of tilt for earthquake prediction research has led to the deployment of a large number of borehole tiltmeters in seismic zones. The relatively low cost of the instruments and of installing them in shallow boreholes has been an important consideration. However, results from such installations indicate that local effects may be a serious limitation (McHugh and Johnston, 1976, 1977).

Performance

For pendulum tiltmeters, the method of installation and the effects of local ground motions, rather than the inherent instrumental stability, frequently limit the performance. It is thus difficult to give useful performance information at present. Long-baseline liquid tiltmeters have been limited in the past by the effects of temperature-induced density differences along the connecting tube and by other systematic effects. Such effects can be reduced in instruments where the connecting tube is straight (Beavan and Bilham, 1977). However, the cost of achieving this in many locations is substantial.

Future Performance

Borehole pendulum devices in which the points of support of the case against the borehole wall are separated by a relatively large vertical distance are being installed and tested at depths of about 100 m. Long-baseline liquid tiltmeters of several new types are being developed. In one type, two liquids with different temperature coefficients of density are used in parallel, connecting tubes to correct for temperature variations (Huggett *et al.*, 1976). Another approach being followed is to servo control the temperature along the path (Berger and Wyatt, 1978). As for high-accuracy strainmeters, the ultimate limitation on using the new types of long-baseline tiltmeters for detecting tectonic crustal movements is likely to be local motions of the end piers. Experiments to compare the new types of long-baseline tiltmeters with each other and with straight tube devices, as well as comparisons with borehole instruments at different depths, would be valuable.

5.1.4 Optical-Angle Measurement Instruments

Principle

Many instruments such as transits, theodolites, zenith telescopes, and astrolabes are used in surveying and in geodetic astronomy. The principles employed are well known.

Status

A wide range of instruments are available for triangulation, for measurement of elevation angles, and for determining astronomical azimuth, astronomical latitude and longitude, the direction of the local vertical, the earth's rotation, and polar motion.

Performance

The performance for high-quality instruments is limited mainly by atmospheric effects. Scintillations are important for short-period measurements, and continuing deviations from simple atmospheric models give systematic offsets even over quite long periods. Measurements near the zenith are least affected, but ray bending due to persistent horizontal gradients in the integrated atmospheric index of refraction (wedge effect) still sometimes is as large as 0.1 second of arc. Elevation-angle measurements are the most affected because of the steep vertical gradients in the atmospheric density due to temperature gradients.

Future Performance

It appears possible to improve the performance of optical-angle measurement instruments by making use of the dispersion in the refraction angle with wavelength. The principle is similar to that for multiwavelength electronic distance measurement instruments. Since the angle differences to be measured are small, techniques such as interferometry, multiple slit interference, or modulated-slit-type readout are used. The development of instruments to correct for refraction effects in elevation-angle measurements and possibly for horizontal angles is being carried out by Tengström (1977) at Uppsala University in Sweden and by Williams (1977) at the National Physical Laboratory in England. A device for correcting stellar observations is being developed by Currie (1977) at the University of Maryland.

We recommend that increased emphasis be put on the development of improved optical-angle measurement instruments using the two-wavelength method to correct for the atmospheric index of refraction.

5.1.5 Gravity Measurements

Principle

Two methods are currently used for gravity measurement: free fall and force rebalance. The free-fall method determines *absolute* gravity by measuring accurately the time versus distance of a proof mass carefully dropped in a vacuum (Sakuma, 1971; Hammond and Faller, 1971). Force balance instruments, like gravimeters and conventional accelerometers, measure the force necessary to support a proof mass in the gravity field. Because of the necessity of converting current or support geometry to force, these instruments measure *relative gravity*. The instrument may develop part or all of the force, the effect of the force, or a small deflection as gravity changes. Most gravimeters employ a mechanical spring in bending or torsion, but in one cryogenic instrument a superconducting ball is supported in a magnetic field produced by persistent current coils (Prothero and Goodkind, 1968).

Survey gravimeters are frequently corrected for drift by measurements at standard gravity stations. A small number of these stations have been calibrated by absolute gravity measurements using the free-fall method.

Status

The free-fall instruments are relatively new but have improved the state of the art of absolute gravity measurement by two to three orders of magnitude in the last 20 years. One laboratory instrument has been operated in Paris since 1969 (Sakuma, 1971). Transportable instruments now exist (Hammond and Faller, 1971; Sakuma, 1974), and the feasibility of routine use has been demonstrated.

The instruments used for most survey work in the United States are the LaCoste and Romberg, Worden, and Geodynamics gravimeters. An instrument intended for more stable measurements of gravity differences over a range of up to 200 mgal has been introduced recently by LaCoste and Romberg. Careful studies of the repeatability of gravity survey measurements have been made (Kiviniemi, 1974; Lambert and Beaumont, 1977). Instruments have been operated on an inertial platform on board a moving vehicle for 10 years and more (see Section 4.1.6).

Continuous measurements of gravity changes at fixed sites are made with tidal gravimeters. Classical instruments of particularly stable designs have been used, but the cryogenic design appears to have more potential because of its stability and low noise. These characteristics are suitable for studies of secular variations in gravity, normal modes of the earth's oscillations that have periods longer than 1000 sec, as well as tidal effects (Goodkind, 1978; Warburton and Goodkind, 1978).

The main limitation in determining solid-earth tides comes from the indirect and direct effects of ocean tides. The ocean-floor loading by the ocean tides causes changes in the elevation and vertical density distribution at tidal gravity sites, which add to the direct attraction of the proof mass by the water. Since present models of the ocean tides that have been fitted to tide-gauge data are not accurate enough to calculate the tidal gravity corrections, efforts now are being made to invert the tidal gravity data in order to obtain improved ocean-tide models. The existence of important tidal frequency components with beat periods of as long as a year means that long data records are needed. However, recent evidence against the existence of ocean-tide resonance within either the diurnal or semidiurnal tidal bands indicates that simpler models of ocean loading effects may be possible.

Performance

Absolute gravity measurements have been performed by Sakuma (1971, 1974) to an accuracy approaching 10^{-8} m sec^{-2}. An accuracy of 1×10^{-7} to 2×10^{-7} m sec^{-2} has been reported for transportable instruments.

A survey gravimeter repeatability of 1.3×10^{-7} m sec^{-2} has been reported after car transport over 200 km under carefully selected conditions (Kiviniemi, 1974). Even better repeatability has been achieved over shorter distances (Lambert and Beaumont, 1977). However, errors in the screw used to rebalance the instrument may introduce considerably larger uncertainties unless sites with almost identical gravity values are being compared.

A study of measurement limitations for cryogenic gravimeters has been carried out (Warburton and Goodkind, 1978). For a one cycle per year bandwidth and a two-year record length, the observed noise level in the tidal band is of the order 1×10^{-10} m sec^{-2}. The observed changes in proof mass attraction by the atmosphere due to atmospheric density changes are quite significant.

Future Performance

Easily transportable free-fall instruments capable of 1×10^{-8} or 2×10^{-8} m sec^{-2} repeatability with an hour or two of measurements appear feasible (Faller *et al.*, 1978). If so, such devices might be used for routine survey measurements in the future. To make use of both improved repeatability and a short measurement time per site, an accurate knowledge of the tidal gravity correction at the site will be needed. It is hoped that the absolute accuracy for easily transportable instruments also will approach 1×10^{-8} m sec^{-2} (10^{-9} *g*).

We recommend that easily transportable gravimeters be developed, which have 3×10^{-8} m sec^{-2} (3×10^{-9} g) accuracy for determining the difference in gravitational acceleration between different points based on measurement times of 1 or 2 hours at each site.

It is not clear whether further substantial improvements in tidal gravimeter performance during the next decade are probable. However, improved knowledge of the frequency dependence of the ocean tidal admittance, careful mapping of the ocean loading and direct attraction effects, and further understanding of atmospheric effects are likely to lead to much better knowledge of tidal gravity variations.

5.1.6 Gravity Gradiometers

Principle

The gravity gradient implies a gravity difference between two nearby locations. Gravity gradiometers measure this small difference by a variety of techniques and infer an average gradient. Each instrument determines one or two measurements of the five independent elements of the gradient tensor. A group of at least five single-axis or three double-axis instruments are used together for a complete determination.

Status

Static gradiometers have been used in survey work since the nineteenth century. Gradiometers capable of working in a moving base are under development at Hughes Research Laboratories, the Draper Laboratory, and the Bell Aerospace Company (Bell *et al.*, 1970; Metzger and Jircitano, 1974; Trageser, 1975). Hughes and Bell use instrument rotation to separate spectrally the gravity gradient information from low-frequency instrumental noise. The Hughes design avoids damping so as to use resonance to amplify further the signal prior to its detection. The Draper Laboratory spherical instrument is not rotated to avoid dynamic error sources. The Hughes and Draper devices are new sensors, developed for this specific purpose. They each operate by letting the gravity difference produce a torque on a dumbbell to avoid the dynamic range problem of measuring to the order of 10^{-10} m sec^{-2} in a 9.8 m sec^{-2} field. The Draper Laboratory instrument is floated in an inviscid fluid, which provides some passive isolation from high-frequency rotational jitter. By contrast, the Bell approach uses a modified accelerometer of proven design and a feedback technique to match the gains of two pairs of these instruments in a cruciform arrangement. Additional feedbacks are used in what is a systems information handling and control development to achieve the result with existing sensors. Similar instruments have been proposed for orbital use, but because of the attenuation of gravity variations with altitude, the advantage of a benign environment is offset by increased required accuracy.

Performance

Static instruments measure to 1 E (1 Eötvös unit is equivalent to a gravitational gradient of 10^{-9} m sec^{-2}/m).

The moving base instruments are under development. There are no field data yet. Design goals are 1 E with a 10-sec moving window average in an aircraft, ship, or ground vehicle. All three techniques have been demonstrated under laboratory conditions to have resolution in the 1- to 10-E range with varying amounts of stable bias. Field data are still a few years away.

Future Performance

Instrumental errors and noise due to Brownian motion are current limitations. The Brownian noise is understood, and its predicted values have been verified. Improved Brownian noise performance can be obtained at the expense of size within limits. The instrument errors are under study. Some but not all mechanisms for errors produced by thermal, magnetic, and kinematic environment are understood, and manufacturing and balancing techniques are being developed. Compensation has been developed at Bell for several corrections and is planned for jitter compensation of the Draper Laboratory instrument. Analysis of the Hughes instrument has established the feasibility of compensation for the kinematic environment by on-line balancing by moving masses on the dumbbells.

We recommend that support be maintained for development of a practical moving base gravity gradiometer with 1-E accuracy in a 10-sec moving window averaging time.

5.1.7 Inertial Navigation Systems (INS)

Principle

Changes in position are determined by the second integral of acceleration. Accelerometers measure specific force, which is the combined effect of acceleration and gravity; therefore, gravity must be calculated and compensated for to obtain acceleration. The orientation of the specific force is determined by gyroscopes. A variety of mechanizations are employed that depend on the orientation of the instruments; these include inertially fixed, body-mounted (strapped down to the vehicle), locally level wander azimuth, and locally level north pointing. The gyroscopes in each case provide information about the angular velocity of the instruments. A computer keeps track of the orientation with respect to the reference of interest and provides the calculation of gravity and integration in the appropriate reference coordinates.

The curvature of the earth and gravity cause a natural behavior of the errors in an Inertial Navigation System (INS) that have a Schuler period (84 min). The earth rotation introduces additional 24-h periods in the system errors.

An INS can be used as a precision relative-distance measuring unit for short times. Because of the integrations, accelerometer errors grow with time squared (t^2) and a gyro drift (which causes an accelerometer to pick up an unmodeled component of g which increases linearly with time) produces an error dependent on time cubed (t^3). This is true for short periods of time compared with the Schuler period, which bounds the constant accelerometer error growth for, say $t < 10$ min. If a vehicle can be stopped, the computer can reset the velocity to zero removing all the velocity errors contributed by the instruments to that time. Since the position error growth is a high power of time, in principle the position errors can be kept arbitrarily small by stopping frequently enough.

Inertial instruments have been developed to have very stable characteristics so that they can be accurately modeled. Any velocity or position information can be used through appropriate modeling and filtering to estimate the model parameters and correct for errors in future operation. All INS depend on this to obtain their performance—some use more complicated models than others to achieve superior accuracy.

Some INS are so accurate that unmodeled gravity anomalies are the limitation in their performance.

Litton has used frequent velocity updates by stopping a carrier vehicle every 3 to 4 min (Huddle, 1977). The Draper Laboratory Aerial Profiling of Terrain System (APT) has analyzed an airborne system that would use position fixes with an on-board laser tracking and ranging from three corner reflectors placed around the region to be surveyed. In each case, the velocity or position updates calibrate the inertial system (fit the parameters in the model of the instruments), as well as provide initial conditions for the navigator.

In addition, the gyros can provide a stable mount for a gravimeter or gravity gradiometers.

Status

The art is mature but still marked by change as new instruments are developed. Most recent changes have been to reduce cost and improve reliability as adequate accuracy is available for most navigation missions.

Performance

The Litton system provides 1-m accuracy for ranges up to approximately 50 km. Its performance is currently limited by a combination of accelerometer scale-factor errors and instrument noise.

Future Performance

Modest improvements could be achieved with the velocity update system with improved instruments that are still within the state of the art. The APT proposal would give 3:1 improved horizontal position. In the vertical axis, with the addition of a laser altimeter, accuracy of ±0.15 m (±0.5 ft) is predicted over a local survey area of 3 x 30 km (2 x 20 miles).

5.2 OCEAN INSTRUMENTATION

5.2.1 Direct Gravity Measurements at Sea

Principle

Gravity measurements at sea require the overcoming of two environmental problems: (1) vertical accelerations of the ship, which can be considered high-frequency noise for the gravity sensor, and (2) rotations and horizontal accelerations of the platform. The problem of the vertical acceleration (most gravity systems are designed to cope with accelerations of up to 1 to 2 m $\sec^{-2}$ in a period range of 6 to 20 sec) is handled by adequate filtering. In spring instruments (Graf Askania and LaCoste and Romberg) a part of the filtering is provided by damping of the gravimeter beam. In force rebalance (Bell) and vibrating string instruments (Bosch Arma) the filtering is provided almost entirely external to the basic sensor by using appropriate low-pass filters. The problem of rotations and horizontal accelerations is handled by employing gyro-stabilized platforms. Most platforms are utilized only with respect to the vertical (no azimuth stabilization). The gyroscopes are slaved to primary vertical references (so that gyroscope drift is inconsequential). The primary vertical references are short-period pendulums (horizontal accelerometers). In order that the primary vertical references respond to tilt but not to accelerations, a filtering network is interposed between the reference and the gyroscope, which filters out the short-period horizontal accelerations.

Since the Eötvös acceleration (the vertical component of the Coriolis acceleration) due to the east-west velocity V (km/h) at a latitude ϕ of the ship contributes an acceleration signal of approximately $4V \cos \phi$ mgal, a determination of ship velocity to 0.25 km/h is necessary in order to obtain the Eötvös correction to 1 mgal at the equator.

Status

Shipboard gravimeters and stable platforms are routinely available (Graf Askania, LaCoste and Romberg, VSA, and Bell) for normal shipboard gravity work. Adequate stable platforms are supplied by LaCoste and Romberg, Bell, and Aeroflex Company.

Cost

Approximately $150,000 for gravimeter and approximately $150,000 for stable platform.

Performance

Since gravity measuring errors due to ship accelerations are nonlinear, the performance is highly dependent on sea conditions. Under good sea conditions (accelerations less than 0.5 m $\sec^{-2}$) measurements to an accuracy of 1 mgal can be obtained. Often the larger uncertainties arise from navigation, which leads to errors in the calculation of the Eötvös acceleration.

We recommend that developments be undertaken to improve moving platform gravimetry cost and reliability.

Additional Reference

A comprehensive review of gravimetry at sea is given by Talwani (1970).

5.2.2 Tide Gauges

Principle

Tide gauges are maintained at coastal tidal stations by the National Ocean Survey, NOAA, in the United States and by other agencies in other countries. They consist of a float or an automatically recording pressure gauge in a vertical tube or box called a stilling well, whose purpose is to dampen the effect of wind-driven waves. The gauges are routinely resurveyed into adjacent benchmarks of the U.S. National Vertical Control Network. Pressure gauges have been temporarily deployed in offshore shelf water for periods of up to a year to obtain the tides on the shelf. They are not tied to the U.S. National Vertical Control Network.

Status

Primary tidal stations are maintained over an extended period of time to provide a long series of continuous observations. There are 30 such stations on the Atlantic Coast, 8 on the Gulf Coast, 15 on the Pacific Coast, and 8 in Alaska. Measurements over shorter periods are made on the coast and shelf with pressure gauges that can vary in cost from $500 up to $20,000, depending on the depth, pressure expected, and duration of time that pressure is to be recorded.

Performance

Ocean surface heights are monitored to a precision of better than 1 cm in tidal stations and in the shelf waters. The shelf gauges suffer from a small drift of a centimeter over a year presumably because of gas absorption in the bellows.

Future Performance

Oceanographically ruggedized recorders will permit more and longer observations away from the primary stations. Laser ranging has made absolute leveling offshore feasible.

Additional References

Works on tidal measurements are Marmer (1951), Swanson (1974), and Beardsley *et al.* (1977).

5.2.3 Oceanic Pressure Measurements

Principle

Vibrating Crystal Transducer. The frequency of oscillation of a quartz crystal changes with pressure. Accompanying temperature sensors with sensitivities of 10^{-5} C are used to correct for temperature effects on the transducer. Pressure variations rather than absolute pressure is measured.

Bourdon Tube. A curved tube bent in an arc straightens when its internal pressure increases relative to the external pressure. The displacement is measured as the indication of pressure difference. A sealed, evacuated case makes the instrument an absolute pressure gauge.

Status

The crystal transducers have been in use since 1972. With them, fluctuations in pressure may be recorded at the bottom of the deep seas for months. Units can be constructed for $6000 that are suitable for use in the deep sea or on the continental shelf. A Bourdon tube made of metal was first used to measure absolute pressures in the ocean in 1971. A quartz device was used in a differential configuration in the MODE experiment (Baker, 1973) and more recently in the ISOS FDRAKE experiments for durations of one year. Units can be constructed for $45,000 that are suitable for use in the deep sea or on the continental shelf.

Performance

Sensitivities of 0.01 mbar (corresponding to approximately 0.1 mm of sea-surface height) with duration of operation up to two months are now available. There is considerable long-term drift in the instruments of 10 mm per month (1 mbar/month), and thermal and other noise appears to lead to a meaningful sensitivity of 0.1 mbar. Deep-sea tides can be observed routinely with these gauges. Sensitivities of 0.1 mbar are obtainable with Bourdon tubes as differential gauges, but drift has been a limitation in either differential or absolute operation. The 1976 ISOS instrument had a drift of less than 2 mbar/month. The quartz construction, however, is fragile for deep-sea use.

Future Performance

Drift may be reduced in either instrument with the use of new materials and geometry. Recording times up to two years should be possible.

We recommend that there be developed deep-ocean pressure gauges with drift of less than 0.5 mbar/year.

Additional References

Ocean-bottom pressure gauges are discussed by Snodgrass *et al.* (1974) and Filloux (1971).

5.2.4 Bathymetry

Principle

An array of high-frequency narrow-beam sonar devices take bathymetric soundings from stable and quiet platforms by measuring the time of propagation to the ocean floor and return. Corrections are made for changes in the speed of sound through the ocean column.

Status

Much of the high-quality work has been done on the continental shelf or slope areas. In the deep basins, such surveys are not routinely done. The best bathymetry is about an order of magnitude better in horizontal resolution and a factor of about 4 better in vertical precision than routine scientific bathymetry. Effectiveness depends on the size of the array and the sophistication of the data reducing, so the best arrays can exceed $1 million in cost.

Performance

On continental shelves, features of the order of 1 m in breadth can be resolved, and depths (floor to transducer) on the order of 10 cm can be obtained. In the deep seas, contour maps good to 2 fathoms (approximately 4 m) at 4000 m can be obtained with a beam width of 1 degree.

Future Performance

The sonar techniques have received a lot of development in the past, and developments will occur in the future with more extensive arrays and data-reducing systems. Acoustically and photographically active submersibles or towed sleds may be refined to the point of producing the best bathymetry in the future.

Additional Reference

An example of scientific application of bathymetry is the work by Maley *et al.* (1974).

5.2.5 Positioning on Deep-Ocean Floor

Principle

To position ships or submersibles, three or more deep-sea transponders are deployed 5 to 10 km apart, each transponder set to emit a pulse of given frequency when it receives an appropriate signal. A shipboard pinger periodically activates these transponders in sequence, and shipboard receivers measure the time duration between the activation pulse and the transponder response. Computer solutions of sonar paths through the water column can then be used to determine the distance from the ship transponder to the pingers and to other devices with transponders.

Status

Shipboard computers in the 1970's enabled computation of sufficient sophistication to be done to make the procedure possible. Hardware is available at approximately $10,000 per transponder and $20,000 for the shipboard pinger activator, timers, and other instruments, exclusive of computer.

Performance

Rough topography or unusual sonar propagation paths can give echo problems. Under good conditions and calm sea state relative positions to 1 m can be obtained.

Future Performance

Refinement to decimeter accuracy for specialized applications appears to be possible. Requirements for knowledge of the time-varying temperature and salinity profiles along the acoustic paths can be reduced by operating the ship near the center of the array. Then only the horizontal gradients in the sound speed across the array will cause inaccuracies in the horizontal components of position. Procedures to fix the transponders and to avoid the effect of ship motion would be required, as well as more refined calculations of acoustic propagation. One use of decimeter ship-positioning accuracy with respect to transponder arrays would be to combine it with measurements by extraterrestrial techniques of the ship's position with respect to points on land on the other side of a subduction zone or to another ship on the other side of a midocean ridge or rise. By reoccupation of positions above arrays at intervals of several years, the motions of the ocean floor could be determined.

We recommend the development of an ocean-bottom ship-positioning system with a reproducibility of 10 cm over very long time intervals and the investigation of other possible uses of high-accuracy acoustic distance measurements in oceanography.

One other possible use is for direct distance measurements between acoustic devices near the ocean floor for determining movements across transform faults or across central rifts in ridge-rise systems. Another is for determining vertical motions of transponders on the ocean floor. The accuracy achievable in such measurements with the use of subsidiary temperature and salinity measurements should be investigated.

5.3 SPACE INSTRUMENTATION

5.3.1 Radio Doppler

Principle

The change in frequency (i.e., Doppler shift) of a transmitted radio signal is proportional to the time derivative of the range of the transmitter and receiver. If the relative range is decreasing with time, then the receiver frequency will be higher and vice versa.

In practice, with satelliteborne transmitters, the usual procedure is to count a fixed number of cycles of the Doppler frequency and record the time interval required. This procedure is continuously repeated while the satellite is above the ground station's horizon.

Similar techniques are used for the tracking of one satellite by another.

Status

As discussed in Section 4.2, Doppler tracking of near-earth satellites from ground stations has been applied to geodetic purposes for nearly 20 years, using as many as 37 worldwide locations. Satellite-to-satellite tracking has been applied for about 5 years.

Performance

The Navy Navigation Satellite System (NNSS) transmits the frequency pair 150–400 MHz. The measurement errors associated with a single pass of this Doppler system has been estimated at less than 5 m (Black *et al.*, 1975). This estimate assumes (1) two-frequency ionospheric refraction correction; (2) existing (Hopfield, 1969) tropospheric refraction model; (3) 50-μsec ground clock accuracy; and (4) satellite oscillator stability ($\Delta f/f$) of 10^{-11} rms. For geodetic accuracies approaching 0.5 m, many satellite passes are required.

The NASA Goddard Space Flight Center satellite-to-satellite tracking system uses a single frequency of 2000 MHz. It is estimated to have a bias of 0.2 cm $\sec^{-1}$ and a noise of 0.04 cm $\sec^{-1}$ with 10-sec averaging (Bryan and Lynn, 1973). This system also obtains range. Several satellites have been tracked by the geosynchronous satellite ATS-6, but the only one of low enough elevation to be sensitive to regional gravity variations was Apollo-Soyuz (Vonbun, 1975).

Future Performance

The technology currently exists to make significant improvements in the present Doppler systems. By transmitting higher frequency pairs (in the gigahertz range), ionospheric refraction errors could be reduced to the centimeter level. Also, by using rubidium atomic reference oscillators, frequency stabilities ($\Delta f/f$) of 5×10^{-13} rms would be available.

For positioning, the NNSS Doppler is already scheduled to be superseded by the Global Positioning System (GPS) (see Section 5.3.3). Further development of Doppler techniques is desirable, however, to measure the gravity field by satellite-to-satellite tracking, which escapes much of the ionospheric refraction effects. The above-stated frequency stability should obtain range rates of 0.15 mm $\sec^{-1}$, and those using 200-km altitude satellites, a resolution better than 100 km of gravity field features.

5.3.2 Satellite Laser Ranging

Principle

Short pulses from a laser are sent up from the ground station to retroreflectors on an artificial satellite or on the moon. The roundtrip travel time up to the satellite and back is measured electronically. Corrections are made for the time delay due to the atmosphere, which is roughly 7 m at sea level for a 20° elevation angle. Calibration measurements are used to correct for any time delay differences in the electronics or photodetectors between the transmitted and received pulses.

Status

Roughly 15 "second-generation" laser ranging systems have been constructed. The laser pulse length generally is a few nanoseconds, and the largest source of uncertainty usually is associated with the electronic circuitry used to pick out the center of gravity of the returned pulse. Many of these systems are mobile, so that they can be moved from site to site (Smith *et al.*, 1977, 1978). Three "third-generation" systems with pulse lengths of the order of 0.2 nsec and energies per pulse of about 200 mJ are in operation.

Performance

The "second-generation" laser ranging systems have accuracies of 5 to 10 cm (Smith *et al.*, 1977, 1978; Vonbun, 1977a). With these systems, the main present limitations for most satellites are errors in the satellite orbits due to the gravity field uncertainties, radiation pressure effects, and atmospheric drag. For determining station positions, polar motion, and short-period variations in the earth's rotation with the Laser Geodynamics Satellite (LAGEOS), the range measurement accuracy and gravity-field uncertainty are the main limitations at present.

Future Performance

Improvements in the lower-degree terms of the gravity field in the next couple of years plus the expected accuracy of 1 to 3 cm with several minute averaging times for the "third-generation" stations ranging to LAGEOS are likely to give 3 cm or better accuracy for station positions, polar motion, and short-period variations in the earth's rotation. Laser ranging to the moon is likely to give accurate checks on the above quantities, and also on nutations and long-period variations in the earth's rotation (Stolz *et al.*, 1976). The use of the single photoelectron detection method for satellite ranging to LAGEOS or STARLETTE should reduce the laser energy required per pulse and the receiving aperture sufficiently so that simplified stations combining high mobility and high accuracy can be built (Silverberg, 1974; Bender *et al.*, 1978; Wilson *et al.*, 1978).

5.3.3 Global Positioning System

Principle

A coded train of pulses emitted simultaneously from four satellites determine the position of a receiver by the relative time of arrival. This will be the primary method of using Global Positioning System (GPS) transmissions for navigation. The GPS signals also can be used in the Doppler or long-baseline interferometry modes if special receivers are built to utilize them.

Status

Clocks of sufficient accuracy are available in a cesium or rubidium standard. Six satellites are planned for launch in 1979 into two orbit planes to verify the system concept. The operational system will have 24 satellites equally spaced in three orbit planes to provide continuous coverage. It will eventually replace the current NNSS.

Performance

The accuracy anticipated from a set of 24 satellites is approximately 10 to 15 m navigation accuracy and reading times of less than 1 sec. It is a goal that inexpensive user equipment will cost $10,000 to $15,000.

Future Performance

With the design of special ground stations, it appears possible to achieve accuracies for differential measurements over a few hundred kilometers that are comparable with those expected for long-baseline interferometry (see Section 5.3.5). The time required per site may be as short as a few hours.

We recommend that special receivers that utilize the Global Positioning System signals in the ranging, long-baseline interferometry, or Doppler mode be developed specifically for geodynamic and geodetic applications.

Additional References

Description of the GPS can be found in the reports of the Space and Missile Systems Organization (1977) and the Institute of Navigation (1977).

5.3.4 Drag-Free Satellite Technology

Principle

A drag-free control system permits a spacecraft trajectory to be free of nongravitational forces. To be made drag-free, a spacecraft contains an unsupported proof mass, which it is forced to follow. Thrusters are operated by a control system, which measures the relative position of the spacecraft with respect to the proof mass. The proof mass is shielded by the satellite and therefore is free of disturbances due to surface forces such as radiation pressure and atmospheric drag. Thus the spacecraft has the same drag-free orbit as the proof mass (Lange, 1964). When operated drag-free, the motion does not contain acceleration errors due to nongravitational forces.

Status

Development work has been done primarily at Stanford University, the ONERA (Office National d'Etudes et de Recherches Aerospatiales), and the Applied Physics Laboratory of Johns Hopkins University (JHU/APL, 1974). The first flight was in September 1972 on a transit Navigation Satellite. It was entirely successful. Two subsequent satellites with single-axis controllers operating on the same principle have been launched and are being evaluated.

Performance

Performançe is limited by the forces between the spacecraft and the proof mass because of mass attraction, residual gases, electrostatic charge, and other small forces. The flight in 1972 has experimentally demonstrated $<10^{-10}$ m sec^{-2} average disturbance over three-day periods. Calculated disturbances due to internal force gradients should have comparable rms values near 100-sec periods because of the relative motion of the satellite with respect to the proof mass permitted by the control-system limit cycle.

Future Performance

Spinning the spacecraft averages the body-fixed forces in the plane of spin. Performance of 10^{-12} m sec^{-2} is predicted, based on careful analysis. The technology is available and has been demonstrated with a laboratory simulator. Additional flights must be made to demonstrate this improved accuracy in space. Large proof-mass cavities can be employed to minimize the interactive force. Practical sizes suggest a limit in the plane of spin of approximately 10^{-13} m sec^{-2}, and 10^{-11} m sec^{-2} along the spin axis.

5.3.5 Long-Baseline Microwave Interferometry

Principle

Random microwave signals emitted by each of several extragalactic sources are received at two widely separated antennas and beat against monochromatic signals generated locally from high-stability frequency standards (clocks). The beat signals are recorded on wide-band magnetic tape for later processing. If the frequency standards were synchronized, the beat signals at the two antennas would be the same if they were offset by a time τ equal to the extra travel time for the signal to reach the more distant antenna. For nonsynchronized frequency standards, a computer search is carried out using data from sources in different directions in the sky to find the baseline length, its orientation at a particular epoch, and the epoch and rate differences of the clocks (Counselman, 1976).

Status

A substantial number of long-baseline interferometry (LBI) measurements for geodetic purposes have been carried out using various antennas, including ones at the Haystack, Green Bank, and Owens Valley Observatories; at Fairbanks, Alaska; at Onsala, Sweden; and at the NASA Deep Space Network stations. Repeated measurements of the 3900-km baseline between the Haystack Observatory and the Goldstone DSN station have been made since 1972 (for early results, see Shapiro *et al.*, 1974). Some recent measurements have made use of both S-band and X-band signals to correct for the ionospheric electron density, plus water-vapor radiometers looking along the paths to measure the integrated water-vapor density. The ultra-wide-band Mark III recording system is expected to come into operation in 1979 at a number of stations.

A transportable LBI station with a 9-m-diameter antenna has been constructed by the Jet Propulsion Laboratory (JPL) and operated at various sites in California (Niell *et al.*, 1978). In addition, a mobile station using a 4-m-diameter antenna and position measurements at a number of sites per month are planned to begin in 1978. The 4-m system is intended to be as accurate as, but less expensive than, the 9-m system.

Current Performance

The random measurement noise in some cases has been reduced to a level of a few millimeters, and improved calibration procedures for time delays in the system are now being used. Subcentimeter reproducibility in all components over a 16-month period has been demonstrated for a short baseline (Rogers *et al.*, 1978). A reproducibility of about 10 cm over the 3900-km Haystack–Goldstone baseline was obtained in the earlier measurements (Shapiro *et al.*, 1974). Analysis of more recent observations is expected to give accuracies of about 3 cm when an improved source catalog is used. The water-vapor distribution in the atmosphere has been found to be quite uniform at most times. The accuracy achieved by the transportable station for measurements over 380-km baselines from Malibu and Palos Verdes to Owens Valley is better than 10 cm.

Anticipated Performance

For fixed stations with large antennas, the corrections for both the wet and the dry parts of the atmosphere are expected to be among the main limitations. However, recent studies of methods for correcting for the water vapor have been quite encouraging (Moran and Penfield, 1976; Winn *et al.* 1976). With a network of stations, accuracies for crustal movements, polar motion, the earth's rotation, and nutation are expected to be about 3 cm. High-mobility stations taking roughly two days per site to determine their locations appear to be feasible.

5.3.6 Satellite Altimetry

Principle

A short burst of electromagnetic waves is directed downward from the satellite, and the return signal is monitored by a fast-response instrument. The time of return is determined by a number of such pulses, and the results are added together. The resulting signal's delay time and shape are then used to determine the vertical distance from the wave source to the ocean surface and back to the detector. Meanwhile, the satellite's orbit is monitored to a few meters.

Status

Altimeters with a sensitivity of approximately 1 m have flown on GEOS-3 and in Skylab. An improved altimeter with 10-cm sensitivity is scheduled to fly in SEASAT-A (Dunne, 1976). The cost of the altimeter is approximately $5 million.

Performance

A number of corrections must be made for atmospheric temperature and humidity, ionospheric activity, and ocean sea state. Best results from GEOS and Skylab indicate that these corrections can be made properly to the published sensitivites up to sea-state 7 (gale). Cross-track intercomparison studies of GEOS data indicate that an accuracy of 50 cm is attainable with proper analysis, which is somewhat better than the original design specifications. Below 50-cm resolution, the cross-track analysis is made difficult by bias that is due to oceanic tides and ocean eddies.

Future Performance

There are no atmospheric corrections or instrument noise problems that prohibit improving the sensitivity to below 1 cm, although sea-state corrections may present minor problems. The absolute accuracy at present cannot be obtained to better than a few meters because of uncertainty in the orbit, although the global positioning system can change that picture. The true scientific utility of the altimeter will become more apparent as the SEASAT program progresses.

6 People and Organizations

The geodetic applications and procedures discussed in the foregoing chapters require, of course, people to carry out these activities, and these people must somehow be educated and organized. In this chapter we examine who is doing geodesy (as defined in Chapter 2), the educational programs related to geodesy, scientific communication in geodesy through societies and journals, the organization of geodetic operations and research and development, and the international implications of these activities.

As with most environmentally related activities of nationwide character, the federal government plays a dominant role. Probably the most important document relevant to this chapter is the study by the Federal Mapping Task Force on Mapping, Charting, Geodesy and Surveying (1973).

6.1 OCCUPATIONAL DISTRIBUTION

Statistics on the occupational distribution of geodesists in the United States are not readily available, apparently because of its appreciable overlap with other occupational categories, such as surveyor, geophysicist, mathematician, and various subdivisions thereof. It is easier to get some estimates for the manpower in surveying and mapping activities. Brandenberger (1976) estimates that there are about one million surveying and mapping personnel in the whole world. About 60 percent of these people work in government agencies and 40 percent in commercial enterprises. They include about 100,000 professionals, 300,000 technicians, and 600,000 auxiliary personnel. These categories are defined mainly by the educational level required: college, technical school, and general, respectively.

Brandenberger (1977) estimated that $3.5 billion per year is currently spent in the world's surveying and mapping activity, subdivided as shown in Table 6.1.

Table 6.2 gives the distribution of effort within the federal government (for 1972), in terms of percentages of a total of 17,400 man-years. The corresponding budget total is $447 million, as discussed in Section 6.4. Although most of the research activity in the industry and in the universities are government funded, the corresponding manpower is not reflected in Table 6.2. Also not included are private property surveys and mapping and surveying activities sponsored by state and local governments. The Education Committee of the American Congress on Surveying and Mapping (Weeden, 1978; Irish, 1977) estimates that there are about 21,000-25,000 surveyors in the United States, of which 2000-2500 are geodesists, 3000-3500 are cartographers, and the remainder are land surveyors. The number of licensed surveyors is somewhat larger—36,000—but probably a fair number who hold a license are not active.

The best estimate for the ratios between the number of professionals, technicians, and supporting personnel in the United States is a survey conducted by Hychko (1974), who received 394 returns to a questionnaire sent to employers. If it is assumed that holders of a B.S. or higher degree are professionals, while those having less education are technicians, the ratio of professionals to technicians and

TABLE 6.1 Annual Expenditures and Manpower for Various Surveying and Mapping Works[a]

Type of Work	Annual Expenditures, %	Manpower, %
Geodetic and control work	15	15
Photogrammetric and related work	20	15
Various kinds of surveying	30	30
Cartography, reproduction	25	25
Administration and other work	10	15
TOTAL	100	100

[a] Source of data: Brandenberger (1977).

TABLE 6.2 Percentage Breakdown of Federal Manpower in Surveying, Mapping, and Related Activities for 1972[a]

Land Surveys	
Engineering	11.9%
Control	7.4%
Cadastral	4.5%
Geophysical	0.8%
TOTAL LAND SURVEYS	24.6%
Marine Surveys	
Scientific and Engineering	5.9%
Oceanographic	14.6%
TOTAL MARINE SURVEYS	20.5%
Mapping and Charting	
Multipurpose land mapping	11.7%
Thematic land mapping	5.9%
Aeronautical charting	2.2%
Marine Mapping	9.5%
TOTAL MAPPING AND CHARTING	29.3%
Technical Services	
Cartography	14.5%
Others (imagery collection and processing, printing and distribution, data and information systems, research and development)	11.1%
TOTAL TECHNICAL SERVICES	25.6%

[a] Source of data: Federal Mapping Task Force (1973).

TABLE 6.3 Population Sampled by Occupational and Educational Questionnaire

	Questionnaires	
Group	Sent	Returned
1. Attendees at Geodesy/Solid Earth and Ocean Physics (GEOP) Conferences, Ohio State University, 1972-1974	400	121
2. Members of Geodesy Section, American Geophysical Union (AGU)	50	23
3. Members of Other Sections, AGU	50	13
4. Members of Control Surveys Divisions, American Congress on Surveying and Mapping (ACSM)	50	23
5. Members of American Society of Photogrammetry (ASP)	50	14
6. Members of American Institute of Aeronautics and Astronautics (AIAA)	50	8

auxiliary personnel is 1:3:4. Brandenberger (1977) proposed the ratios 1:3:6 for the whole world. A lower ratio of support personnel in the United States seems plausible, so we estimate there are about 30,000 professionals, 100,000 technicians, and 150,000 supporting personnel engaged in surveying and mapping activities in the United States.

This committee conducted a limited survey of professionals in geodesy and in related fields. A questionnaire was sent to six categories of personnel, as given in Table 6.3. Groups 1 and 3 include professions in a wide range of disciplines; the remaining groups represent specialized interests.

The responses to the questionnaire varied appreciably among these populations. Also the surveyed population, and, even more, the respondents therein, are more engaged in research than is representative of all geodesists and related professionals. We report the responses to questions under three headings; those who consider themselves geodesists, those who consider themselves geophysicists, and all others. To estimate the trend into and out of various activities, we also report the number and percentages of individuals under age 40 and those 40 and older for each category. Table 6.4 indicates the occupational distribution of the respondents in terms of licenses held, professional activities, and employers.

The small percentages of professional licensees in Table 6.4 indicate that the population identifiable as active in research and development by membership in the groups listed in Table 6.3 has little overlap with the 30,000 surveyors mentioned earlier as constituting the economic bulk of practitioners active in geodesy and related activities. Hence, Table 6.4 is more of interest relevant to predominately federal, or federally supported, programs.

An evident inference from Table 6.4 is that a lot of work in geodesy, particularly in the areas of research and development, is done by people who do not consider themselves geodesists. Opinion within the committee is divided as to whether this blurring of the identity of geodesy is good, as indicative of an alive and interactive discipline, or bad, as obscuring the contribution of geodesy to modern research and making it more difficult to obtain support for geodetic research or education *per se.*

On the applicatory aspects, the portion of people trained and identified as surveyors and mappers in the United States is much less than in other advanced countries, such as the Soviet Union and Germany. It is difficult to verify whether and how the United States is affected economically by this difference in emphasis. Contributory to this difficulty is the circumstance that, for most applications, the requirement of geodesy is not so much accuracy as reliability, the absence of outright mistakes. The manner by which this reliability is attained is to meet standards of accuracy that are quantifiable; the same work habits that attain accuracy also bring the reliability. Studies of some aspects of the economic benefits of geodesy have been carried out by Johnson (1972) and Spencer (1976). However,

This committee recommends that further operations research or economic cost-benefit analyses be pursued to ascertain the benefits of geodesy and surveying, and thence how these activities should be modified.

More specific problems arising from the obscuration of the identity of geodesy are that geodetic personnel are often utilized inefficiently or that nongeodesists are used for geodetic work because better qualified personnel are not sought and found. These problems often result from inadequacies of government occupational classification systems and their application. Therefore,

We also recommend that federal and state agencies reexamine their classification policies that place geodesists under other categories and take corrective action.

6.2 EDUCATION

Although maps based on surveys were produced as long ago as 4000 BC, formal university-level educational programs started about the beginning of the nineteenth century with programs at such institutions as the Ecole Polytechnique in Paris and the Polytechnical School in Karlsruhe, Germany (Draheim, 1974). Usually the academic programs in surveying were developed in Civil Engineering Departments. Civil engineers felt that they should know something about surveying, but the trend was that they wanted to be civil engineers with some knowledge of surveying and not surveyors with some knowledge of civil engineering. Surveyors in central and eastern Europe considered this attitude detrimental to the vigorous evolution of the profession of surveying and mapping. Therefore, around 1920 they broke away from civil engineers to establish independent surveying and mapping departments at many universities. In North America, such developments have not flourished to anywhere near the same extent. A Department of Geodesy and Surveying existed at the University of Michigan from 1921 to 1941. The Institute of Geodesy, Photogrammetry, and Cartography was established in 1951 at The Ohio State University, which remains the principal center of geodetic education in the United States. This differing history probably arises from the counter trend toward greater breadth and generality in U.S. engineering curricula in recent decades.

Surveying and mapping is taught at three educational levels: university level, technician level, and supporting personnel level. At present, there are about 10 autonomous higher educational surveying and mapping institutions in the entire world, none of them in the United States. Furthermore, it has been estimated (Brandenberger, 1976) that there are altogether 250 departments at various higher educational institutions specializing in surveying and mapping throughout the world, but only one in the United States. There are not available worldwide figures regarding enrollment and annual graduations at various educational levels. The total enrollment of students in surveying and mapping at higher educational institutions in the Soviet Union in 1974 was approximately 7500, which is more than 0.3 percent of the enrollment of all university level

TABLE 6.4 Current Activities of Sampled Geodesists and Related Professionals

Category	Total	Geodesists	Geophysicists	Others	Age over 40	Age under 40
Number of Responses:	202	43	27	132	110	92
	Percentages[a]					
Current Activity						
Surveying[b]	8.8	20.4	2.5	6.4	7.2	10.7
Space Techniques	14.9	22.9	8.8	13.5	12.5	17.6
Geophysics	16.4	16.1	23.7	14.8	16.5	16.3
Marine	8.2	3.0	6.8	10.3	8.6	7.8
Photogrammetry and Cartography	9.2	13.8	0.6	9.4	12.3	5.4
Remote Sensing	4.2	2.6	1.0	5.3	3.9	4.5
Data Processing	7.3	9.7	6.4	6.7	4.9	10.1
Education	9.0	3.9	14.8	9.4	8.5	9.7
Other	21.8	7.4	35.0	24.0	25.5	17.7
Professional Licenses						
Land Survey Only	5.0	11.6	0.0	3.8	3.2	6.4
Engineer Only	8.4	11.6	0.0	9.1	6.5	10.0
Both Land Survey and Engineer	4.0	2.3	0.0	5.3	4.4	3.6
Institutions						
Federal	48.8	67.4	37.0	45.0	54.1	42.4
State	36.3	20.9	44.4	39.7	32.1	41.3
Commercial	11.4	11.6	11.1	11.4	8.3	15.2
International	0.5	0.0	0.0	0.8	0.9	0.0
Other	1.0	0.0	3.7	0.8	1.8	0.0

[a] Percentages do not total 100.0 because of round-off and nonresponses.

[b] About 1/2 Control, 1/4 Engineering, and 1/4 Land Surveying.

institutions in that country. The corresponding figure for the United States is 0.01 percent (Brandenberger 1977).

6.2.1 University Programs in the United States

The Education Committee of the American Congress on Surveying and Mapping (Education Committee, 1978) has been collecting the data on surveying and mapping education in the United States, with 217 schools offering nine or more credits in surveying and mapping. The degree programs offered by various schools are summarized in the report as follows:

One-Year Certificate Programs	9
Two-Year Technology Programs—"Surveying"	35
Four-Year Technology Programs—"Surveying"	3
Four-Year Bachelor of Science—"Surveying"	10
Four-Year Bachelor of Science—"Geodetic Science"	3
Master's Degree Programs in Surveying	8
Ph.D. Programs in Surveying and/or Geodesy	6
Two-Year Associate Degree in Cartography	1
Four-Year Bachelor of Arts in Cartography	4
Master's Degree in Cartography	14
Ph.D. Degree in Cartography	11

The six universities offering graduate-level programs leading to the Doctor of Philosophy Degrees in Surveying and/or Geodesy are the University of California, Berkeley; the University of Hawaii; The Ohio State University; Purdue University; the University of Washington; and the University of Wisconsin.

The most extensive organized courses in geodesy are offered at The Ohio State University, Purdue University, and Iowa State University (which grants the MS only); the other programs emphasize either surveying or geophysics. A dozen universities, not having a program in surveying or geodesy, offer graduate-level courses in geodesy or in related areas such as Orbital Dynamics, Satellite Geodesy, Inertial Guidance and Navigation, Space Mechanics, Planetary Structure, Physical Geodesy, and the Gravity Field and Its Interpretation. The more scientific courses are in Departments of Astronomy, Physics, Geophysics, or Geology; the more applicatory courses are in Departments of Civil, Mechanical, or Aerospace Engineering.

6.2.2 Number of Graduates

The most recent estimates for surveying graduates is by McDonnell (1974), who gave for the mean annual rates 1972-1974: 9 PhD's, 41 MS's, 92 BS's, and 281 Associates. In the area of geodesy, there are approximately 4 PhD's, 20 Master's, and 20 Bachelor graduates every year. Given the estimate of 30,000 professionals in surveying and mapping made in Section 6.1, a rate of BS production of 1000 per year—more than ten times as much—seems more appropriate. Evidently a large portion of surveying professionals earn their degrees in more general areas, such as civil engineering. This difference of educational background is certainly true for the nontypical population sampled by the committee, as shown in Table 6.5.

TABLE 6.5 Educational Majors of Sampled Geodesists and Related Professionals

Major	BS	MS	PhD
Geodesy and/or Photogrammetry	5	15	10
Civil Engineering	25	6	
Other Engineering	30	15	6
Geophysics (including Oceanography)	8	27	35
Geology (or Earth Science)	26	17	13
Physics or Astronomy	50	25	25
Mathematics	35	11	2
Other	13	7	16
TOTALS	192	123	107

The production of graduates in mapping and surveying in proportion to the total population in the Soviet Union is 30 times that in the United States. Apparently this difference reflects the greater emphasis on breadth, rather than technical specialization, in the U.S. education. To determine whether this distribution of education effort is inefficient would require a fairly thorough user survey. In any case, the United States should not blindly imitate the Soviet Union.

6.2.3 Curriculum

The contents of the degree programs in surveying and geodesy reported in Section 6.2.1 are quite varied. For comparison, Table 6.6 gives the numbers of courses in geodesy

TABLE 6.6 Course Offerings in Geodesy and Related Subjects

	Institution						
	Hawaii		Purdue		Ohio State		
Course	Undergraduate Only	Undergraduate and Graduate	Undergraduate Only	Undergraduate and Graduate	Undergraduate Only	Undergraduate and Graduate	Graduate Only
Surveying	2		7	3	7	2	
Geodesy	1	4		4		10	9
Photogrammetry		1		3		6	7
Cartography						4	3
Other[a]	3	2		2		4	1

[a] Data adjustment, geophysics, mathematical methods, navigation, remote sensing, terrain analysis.

and related subjects offered by the Department of Geology and Geophysics at the University of Hawaii; the School of Civil Engineering at Purdue University; and the Department of Geodetic Science at The Ohio State University. The program at Hawaii is strongly oriented toward geophysics, and that at Purdue toward engineering applications, while the most complete curriculum in geodesy is offered by the Department of Geodetic Science of The Ohio State University.

The department at The Ohio State University has a faculty of twelve, four of them joint and one of them adjunct. The bachelor's program includes lower division mathematics and physics given outside the department, but the graduate program is entirely within the department. While this degree of specialization is not unique among U.S. graduate departments, it is the feeling of the nongeodesist members of the committee that only one such center within the United States is appropriate.

Given one center of geodetic specialization, questions arise as to its support, since it is primarily a national functional though located in a state university. The fortunes of such a center of excellence are heavily dependent on federal policy, since the major part of challenging geodetic work is by, or for, the federal government. One frustration in educating geodesists for the federal government is that the civil service hiring system rates a candidate only by his grades and not by the strength of the program he took. Discussions oriented more toward surveying education are given by Lyon (1968) and McDonnell (1974).

The committee recommends that examination be given to the effects of federal policies on education in geodesy. This examination might be incorporated in a general study of spcialized departments whose graduates largely go to federal, or federally supported, work.

TABLE 6.7 Importance of Skills to the Geodesist (Opinion Survey of Sample Summarized in Table 6.3)

	Geodesists			Geophysicists			Others		
Skill	Essential	Contributory	Unnecessary	Essential	Contributory	Unnecessary	Essential	Contributory	Unnecessary
Land Surveying R&D		✓			✓			✓	
Engineering Surveying									
Techniques		✓				✓		✓	
Theory and Computation	✓				✓		✓		
Control Surveying									
Observation		✓				✓		✓	
Theory and Computation	✓			✓			✓		
Artificial Satellites									
Observation		✓				✓		✓	
Theory and Computation	✓			✓			✓		
VLBI and LLR									
Observation		✓				✓			✓
Theory and Computation	✓				✓			✓	
Gravity									
Observation		✓			✓			✓	
Reduction and Interpretation	✓			✓			✓		
Tectonic Motions									
Local Measurements		✓			✓			✓	
Regional Measurements	✓				✓			✓	
Computation and Interpretation	✓			✓			✓		
Tide and Mean Sea Level		✓		✓			✓		
Hydrography			✓			✓			✓
Photogrammetry	✓				✓		✓		
Cartography	✓				✓			✓	
Remote Sensing		✓				✓		✓	
Data Processing	✓				✓		✓		

The survey of geodesists and related professions described in Section 6.1 also included several questions related to education, mostly in the form of the importance of certain skills to the geodesist. The results of this part of the questionnaire are summarized in Table 6.7.

As anticipated, the surveyors related control surveys as most important, while the geophysicists emphasized more the reduction and interpretation of the gravity field and tectonic motion measurements.

In response to another question as to where geodesy should be taught, the predominant responses were geophysics and engineering departments.

Finally the committee's questionnaire asked those surveyed how they were educated or trained for their current geodetic work. As expected, more of those who called themselves "geodesists" considered themselves well prepared by formal education than members of any other subpopulation. There was not much variation among subpopulations as to what had contributed most to their geodetic capability: 29% formal education, 13% continued education, 25% on-job training, 30% self study, and 3% other.

In conclusion, it must be emphasized that the majority opinions as to education and skills required for geodesists obtained from responses to this committee's questionnaire reflect the predominantly scientific or geophysical interests of the sampled population. Of all possible subgroups, that which had the lowest correlation with other subgroups were members of the American Society of Photogrammetry (ASP), indicating their primarily engineering or mapping interests.

6.3 SCIENTIFIC COMMUNICATION

6.3.1 Scientific Societies

The most important national societies in the United States related to geodesy are the American Geophysical Union (AGU), the American Congress on Surveying and Mapping (ACSM), the American Society of Photogrammetry (ASP), the American Society of Civil Engineering (ASCE), and the Marine Technology Society (MTS). Most of these societies hold two meetings per year and have their own journals.

The most important international organization related to geodesy is the International Association of Geodesy (IAG), one of seven within the International Union of Geodesy and Geophysics (IUGG). The Union holds a General Assembly every fourth year, last meeting in 1975. The IAG normally holds its meetings at the same time but is considering meeting at an intermediate year in 1981. The IAG is divided into five sections: Control Surveys; Satellite Techniques; Gravimetry; Theory and Evaluation; and Physical Interpretation. In addition, there are currently seven interassociation commissions within the IAG and 23 special study groups within the sections.

Other international societies of interest to geodesists include, in approximate order of importance, the International Federation of Surveyors, the International Geographical Union, the International Astronomical Union, the International Society of Photogrammetry, the International Association for Mining Surveying, and the Pan American Institute of Geography and History (governmental organization).

6.3.2 Scientific Communication

The principal meetings in geodesy are those of the societies listed above. An important series of interdisciplinary symposia involving geodesy were the GEOP conferences, eight meetings in 1972-1974 run by The Ohio State University under AGU sponsorship.

As in other fields, the number of journals is awesome, but significant new work appears in relatively few. Within the United States there is no exclusive journal of geodetic science; the principal outlet for scientific geodesy is the AGU's *Journal of Geophysical Research*, of whose content about 10 percent is geodetic. The principal national journal for surveyors is the *ACSM Surveying and Mapping.* The most important journal devoted totally to scientific geodesy is the IAG's *Bulletin Géodésique*, which totals about 400 pages per year.

Papers of geodetic interest also appear occasionally in journals of other disciplines, such as the *AIAA Journal, Celestial Mechanics, Geophysics, Navigation, Photogrammetry Engineering and Remote Sensing*, and *Tectonophysics.* Foreign nations have journals devoted solely to geodesy, such as the *Survey Review of the British Commonwealth* and the *Zeitschrift für Vermessungswesen.* Within the United States, this role is filled more by institutional publications such as the report series of The Ohio State University, Department of Geodetic Science; the National Geodetic Survey; the Air Force Geophysics Laboratory (formerly AFCRL); the Research Institute of the U.S. Army Engineer Topographic Laboratory; the Naval Surface Weapons Center (Dahlgren); the NASA Goddard Space Flight Center; and the Smithsonian Institution Astrophysical Observatory.

An important summary of U.S. geodetic activities is given in the Quadrennial Report to the IUGG, currently published as part of the *Review of Geophysics and Space Physics* (Bell, 1975).

6.4 OPERATIONS

Economically significant geodetic activities are carried out by all levels of government–federal, state, and local–and by industry. The principal activities supported by geodesy

TABLE 6.8 Federal Fiscal Year 1972 Expenditures for Land Surveys by Agency[a]

Agency	$ Millions	Man-Years, Thousands
Department of Defense		
Defense Mapping Agency (DMA)	4.1	0.34
Corps of Engineers (CE)	11.9	0.77
Others	1.4	0.09
Department of the Interior		
Geological Survey (GS)	6.4	0.34
Bureau of Land Management (BLM)	8.6	0.43
Bureau of Reclamation (BR)	5.2	0.41
Bureau of Indian Affairs (BIA)	3.2	0.27
Others	2.6	0.13
Department of Agriculture		
Forest Service (FS)	6.8	0.45
Others	0.6	0.06
Department of Commerce		
National Oceanic and Atmospheric Administration (NOAA)	8.7	0.40
Others	0.8	0.06
Department of Transportation		
Federal Highway Administration (FHWA)	3.2	0.28
Department of Housing and Urban Development (HUD)	3.4	–
Independent Agencies		
National Aeronautics and Space Administration (NASA)	2.9	0.08
Smithsonian Astrophysical Observatory (SAO)	2.4	0.09
Others	2.5	0.11
TOTAL	74.7	4.31

[a]Source of data: Federal Mapping Task Force (1973).

(in approximate order of magnitude of geodetic costs) are highway and street construction, mapping and charting (both civil and military), other construction, oil and mineral exploration, property surveys, defense weapons systems, navigation and communication, civil space systems, water resources and flood control, urban planning, and earthquake studies. The bulk of general-purpose or multipurpose geodetic activities are carried out by the federal government. State, local, and industrial geodetic surveys are almost entirely special purpose, such as the control surveys by the California Water Resources Division or the gravimetric surveys by geophysical exploration companies. The geodetic activity is thus usually incorporated in the same organizational elements as the activity that it supports or is done on a fee-for-service basis, as discussed in Section 3.1.

Hence this section will concentrate on the organization of geodesy in the federal government. A comprehensive study thereof was performed by the Federal Mapping Task Force (1973) in a report to the Office of Management and Budget (OMB). This section will therefore first review this OMB report, before discussing subsequent developments and commenting on those aspects most closely related to the charge and competence of the committee.

6.4.1 Report to Office of Management and Budget, 1973

This report identified $75 million of fiscal year 1972 federal budgeting for "land surveys," distributed among 27 agencies, as summarized in Table 6.8. This land survey effort includes geodetic, engineering, and cadastral survey (referred to as land survey in Section 3.1); probably about 30 percent is geodetic, as defined by Chapter 2. Table 6.9 summarizes the breakdown by purpose, as given by the OMB report.

The designations in Table 6.9, taken over from the OMB report, are to some extent arbitrary (e.g., "Earth Physics" as distinguished from "Geophysics") and unclear as to the extent the surveys involved are "geodetic" in the sense of entailing measurements of high accuracy or considerations as to the natural environment such as the gravity field and atmospheric refraction. In any case, Table 6.9 serves to emphasize that the bulk of survey effort is for applicatory purposes, with little relevance to scientific research.

In addition, the OMB report lists federal fiscal year 1972 expenditures of $117 million for "Marine Mapping, Charting, and Surveying" by 14 agencies, of which perhaps 10 percent is control surveys and gravimetry, and hence classifiable as geodetic. Finally, not included in the OMB report

TABLE 6.9 Federal Fiscal Year 1972 Expenditures for Land Survey by Purpose[a]

Purpose	$ Millions	Man-Years, Thousands	Principal Agencies
Geodesy	9.1	0.50	NOAA, FHWA, CE
Earth physics	7.3	0.25	NASA, NOAA, NSF
Geophysics	3.2	0.14	DMA, GS
Mapping control	10.7	0.52	GS, CE, other DOD
Cadastral	14.1	0.79	BLM, CE
Construction and Facility	30.3	2.07	CE, FS, BR, BIA, DMA, FHWA
	74.7	4.28	

[a]Source of Data: Federal Mapping Task Force (1973).

are some geodetic surveys by military personnel, most of which are apparently considered as training, and geodetic by-products of NASA space projects (moon and planets, as well as earth), appropriately considered as research and development.

The total federal effort in geodesy for fiscal year 1972 was thus on the order of $50 million. Of this effort, about 85 percent was operational, and 15 percent was research and development.

The principal recommendation of the OMB report was that federal mapping, charting, and geodesy activities should be largely combined into a single agency, to reduce waste and duplication of effort and to respond to national needs more efficiently. This agency was recommended to include five principal centers, of which one would be a National Survey Center responsible for the bulk of federal civil geodetic and cadastral surveys. The agency would preferably be in a Department of Natural Resources (or Energy and Natural Resources) with other technical and scientific agencies (e.g., USGS and NOAA), but its organization should not be delayed until such a department was formed. More detailed recommendations of relevance to geodesy were:

1. Expansion of the National Geodetic Base to include selective control of less than second-order accuracy;
2. Continuation of NGS programs cooperative with other federal agencies and state and local governments only as long as a coherent national geodetic program is advanced;
3. Improvement of the nationwide horizontal control system, with emphasis on densification of control in urban areas;
4. Readjustment of the national horizontal control network;
5. Doubling of the national vertical control program;
6. Concentration of responsibility for civil scientific geodetic programs in NGS;
7. Release of classified gravimetry by DOD, where feasible;
8. Implementation of a combined geodetic and cadastral program in Alaska;
9. Development of civil aerotriangulation techniques;
10. Review and coordination by the central agency of all federal surveys of more than a rather minimal size; and
11. Consolidation of civil R&D activities, to facilitate application of DOD developments, as well as to further an independent civil capability.

6.4.2 Developments since 1973

Since fiscal year 1972, the largest federal initiative in geodesy for civil purposes has been the Earth and Ocean Dynamics Applications Program of the Office of Applications, NASA. This program has risen from a level of $7.5 million for fiscal year 1973 (of which $4.5 million was for GEOS-3) to $18.5 million for fiscal year 1978 (of which $10.5 million is for MAGSAT). NASA considers this budget as about equally divided between earth dynamics and ocean dynamics; this committee estimates a third of the earth-dynamics part can in turn be considered as "geodetic," even though NASA's main rationale is earthquake prediction. Another major federal initiative is the earthquake hazard reduction program, which started with $56 million in fiscal year 1978. Of this fiscal year 1978 total, $14 million is the USGS earthquake prediction effort. From this budget, plus lesser supplements, $3 million is being expended for geodetic surveys to measure ground motion. Both the NASA and USGS efforts are research and development. A more operational effort is the DOD NAVSTAR Global Positioning System, for which fiscal year 1977 costs were $74 million. While its intent is navigational, it is hoped to have some geodetic by-products, as discussed in Section 4.2

The approximately $40 million estimated for federal geodetic operations in fiscal year 1972 probably has received a partial compensation for inflation, like most ongoing federal programs, and hence has had about a 15 percent increase in dollar amount but a 15 percent shrinkage in real support from fiscal year 1972 to fiscal year 1977. The most purely geodetic part of the budget, the National Geodetic Survey, has had a dollar increase from $8 million to $12 million. This increase reflects new programs in leveling and North American Horizontal and Vertical Network Adjustments as discussed in Section 4.1.

The major recommendation of the 1973 OMB report—concentration of federal civil mapping, charting, and geodesy in one agency—has not been carried out. However, progress has been made on some of the "subsidiary" recommendations in Section 6.4.1, in particular, Nos. 1, 4, 8, and 9. Most of these were implementable by single agency initiatives. An exception is No. 8, joint geodetic and cadastral survey of Alaska, which is being carried out by NGS and BLM.

6.4.3 Prospects and Recommendations

The principal current stimuli for new directions in federal geodetic activity are the continued development of space techniques and the improved understanding in the behavior of the solid earth. Meanwhile, the bulk of federal geodetic effort is devoted to more practical engineering purposes, as summarized in Table 6.9. The federal agencies principally associated with each of these three main stimuli are in different departments (NASA, DOI, DOD). Hence there are strong program-oriented pressures to maintain the fragmentation deplored by the 1973 OMB report as discussed in Section 6.4.1. Such organization may be the most effective in the larger sense; it is conceivable that it is not any more appropriate to unify the technical activity of geodesy than that, for example, of computers.

The one federal agency that is primarily geodetic—the National Geodetic Survey (NGS)—lies deeply imbedded in yet another department, the DOC, where it is a component of the National Ocean Survey (NOS) under the National Oceanic and Atmospheric Administration (NOAA)—an ocean-oriented environment. The present location of the NGS is a heritage of when geodetic survey activities were primarily oriented toward the coasts and hydrography. The agency was formed in 1807 as the Survey of the Coast, and from 1878 to 1965 was named the United States Coast and Geodetic Survey (USC&GS), with its Director answering directly to the Secretary of Commerce. It is a tribute to the NGS, NOS, and NOAA leadership that classical geodesy has been, in fact, pursued with considerable vitality. Both highly necessary and long overdue, an eight-year program to overhaul the national horizontal control network is in full swing since 1975, and a seven-year program to overhaul the national vertical control has just been funded (fiscal year 1978). Attempts to pursue new directions in geodesy, however, have not fared so well. A budget initiative for fiscal year 1977 to obtain funding and staffing for a national geodetic data bank has not succeeded, the status of a national cadastre is uncertain at present, and the POLARIS project has failed for fiscal year 1979. Given the organizational reality, it is of germane concern to this committee that new initiatives put forth by the NGS, either to take advantage of advanced technology or to fill a forecasted need, may not be adequately supported in the present austere budgetary environment of the federal government and that its modest resources may be eroded.

Detrimental effects of fragmentation of geodetic effort have occurred in other civil agencies. The NASA applications program in earth and ocean dynamics, as well as its predecessor, the geodetic satellite program, has suffered from lack of in-house geodetic expertise. The National Center for Earthquake Research (NCER) does not have the detailed picture of crustal motions in California and Alaska in recent decades desirable for its task, perhaps in part because of organizational separation between geodetic technology and the problems to which it applies. It is true that these deficiencies in NASA and USGS may result largely from there simply not being enough geodesists educated, as discussed in Section 6.2, rather than from organizational matters.

From the viewpoint of this committee, it is desirable that the federal geodetic effort be organizationally placed closer to other elements concerned with space instrumentation and with solid-earth problems, in order to have more empathetic managerial context, enhanced stimulation over mutual concerns, and quicker response to new developments. These reasons are in addition to those of efficiency, elimination of duplication, and responsiveness to user needs cited in the 1973 OMB report. Both the geophysical and mapping improvements could be achieved by placing NOAA in the same department as the USGS.

We recommend that the 1973 OMB Report of the Federal Task Force on Mapping, Charting, Geodesy, and Surveying, as it relates to geodesy, be re-examined and updated, with special emphasis on the new developments in earthquake prediction and space techniques.

6.5 RESEARCH AND DEVELOPMENT

The bulk of geodetic research and development is carried out by the Department of Defense. The justification for this work is support of navigation, reconnaissance, and weapons systems. In character, most of it is development of new instrumentation to obtain positions, azimuths, and gravity, primarily with greater rapidity and ease, secondarily with finer accuracy. Some of the research is toward recording and understanding the natural environment, such as work on mapping and analyzing the gravity field. The developmental work is executed, or contracted, by four research centers. In addition, data compilation and analysis of scientific interest is done by the three operational centers.

Although justified on military grounds, the instrumental developments are often of great value for civil geodetic purposes, while the data compilations are of scientific interest for geophysical purposes. Hence it is desirable that instrumentation developed by DOD of civil application—such as the inertial navigation system—be given broad dissemination; that civil applications be taken into account in designing DOD geodetic systems, such as the GPS satellites; and that data be made available where feasible. It is the observation of this committee that DOD has been quite cooperative in these matters but that on occasion there has not been as good interaction with potential user communities outside the federal government as there has been with civil federal agencies and that sometimes budgetary difficulties have led to failure to realize civil potentials of DOD systems. Hence, to assure realization of DOD instrumentation developments for civil applications, it is desirable to establish more systematic organizational arrangements for technology transfer.

The largest budget for geodetic research and development among civil agencies is NASA's. Within NASA, this work is carried out as part of the "Applications" program. Hence there is an emphasis on the practical goals of geodetic, or geodynamic, satellite programs despite the scientific problems that they address being comparable in complexity with those of the planetary exploration, astronomic, and other programs of NASA.

The civil agencies with geodetic missions, NOAA and USGS, have relatively modest geodetic research and development budgets. In part, this circumstance results from much of the actual research being done by what is designated as an "operational" rather than an "R&D" element of the agency, as is necessary for any work interacting closely with the environment. Nonetheless, this compartmentalization tends to make it more difficult to get funding for new developments.

The civil agency with the greatest capability for instrumentation development of geodetic application, outside NASA, is the National Bureau of Standards (NBS), which has been responsible for several innovations in mensuration. However, geodesy is not within NBS's charter, so that the progress of instrumental developments applicable thereto has been slow and halting and usually dependent on the enthusiasm of individual scientists.

In summary, the imbalance between space and terrestrial research budgets, the separation of instrumental and geophysical research, and the inability to transfer funds in accord with scientific sense has resulted in some severe distortions of emphasis.

We recommend that communication be improved between federal agencies, and, most important, transfer of funds be facilitated to bring about the efficient application of some agencies' technical capabilities to the missions of geophysical agencies.

A significant effort in scientific geodesy is supported by NSF and ONR through their oceanographic programs, since oceanographic research vessels normally carry gravimeters and depth meters. The major such efforts are carried out by the Woods Hole Oceanographic Institution and the Lamont-Doherty Geological Observatory of Columbia University.

A minor part of geodetic research and development is carried on outside the federal government, most of it federally supported. Aside from oceanographic work, the principal supporters of geodetic research in universities have been NASA and the DOD, the latter mainly through the Air Force Geophysics Laboratory in Bedford, Massachusetts. The lack of widespread academic interest in geodesy within the United States, in comparison with other areas of earth sciences or physical sciences, has led to greater development of scientific geodesy within the government.

6.6 INTERNATIONAL RELATIONS

The most extensive interactions have been developed by DOD, which has made a series of bilateral arrangements with other nations for cooperative surveys, tracking station establishment, data exchange, and technical assistance. While many of the data obtained are not publicly available, this work has had appreciable civil benefit in some areas. Most outstanding is the Inter-American Geodetic Survey, by which the United States has fostered the survey of most of Latin America.

The Agency for International Development (AID) also has assisted geodetic work in developing countries, most of which require mapping programs in order to develop and exploit their resources. Because of these needs, in most such countries geodesy is relatively more significant among the geophysical disciplines than it is to the United States. Probably the most effective use of AID funds for geodetic purposes is in the areas of education and training.

NASA is involved in international relations because of its need to place tracking stations around the world to maintain contact with spacecraft. This need is keenest for satellite geodesy because of the "aliasing" effects discussed in Section 4.2. The Smithsonian Astrophysical Observatory (SAO) also has contributed significantly to international collaboration in satellite geodesy. In addition, the development of economical Doppler receivers has led to the DOD Doppler satellites becoming the most effective means of establishing locations in some remote areas. Any modification of these satellite navigation systems should consider the needs of these users, since helping to meet some of these needs for the developing countries is a significant good-will by-product for the United States.

The fostering of international relationships is important to scientific geodesy in order to be able to obtain data or to have access to measurements. The study of certain phenomena, such as gravity variations, requires global surveys or surveys in regions of tectonic character lacking within the United States. International relations for the purpose of scientific geodesy are normally initiated within scientific associations—foremost the IAG—as discussed in Section 6.3, but the wherewithal to support surveys and other geodetic activities must come from governments, and governmental attitudes largely determine what gets done and how conveniently it is done. A continual need in geodesy, as in other geophysical disciplines, is to persuade other nations that it is to their benefit to allow freedom of inquiry and access to geographic regions for scientific purposes.

7 Conclusions

7.1 MAIN THEMES OF THIS REPORT

Geodesy has, to a large extent, shared in the explosive growth of the physical sciences and engineering over the last 30 or 40 years: great improvements in the measurement of distance and acceleration; much more elaborate calculations and adjustments, through use of the computer; and more extensive and accurate knowledge of earth dimensions, the geoid, and intercontinental positioning through space techniques. Much of this growth has occurred in ways that would not have been predicted 40 years ago and has cut across the lines of traditional geodesy. Furthermore, the growth has been only partial: terrestrial techniques for measuring angles, differences in level, and the direction of gravity have had but slight evolution; scientific geodesy has not been marked by conceptual revolutions such as plate tectonics; and, on the engineering side, instrumental improvements in electronic distance measurement and photogrammetry have lessened the dependence of the land surveyor and mapper on the geodetic specialist.

This recent history has, understandably, made some geodesists feel that their role has been pre-empted. In a sense, geodesy matured somewhat earlier than the other geophysical sciences and has marked time while other disciplines caught up. Gravity variations have not contributed as much as hoped to understanding the earth's interior because of the rheological and fluid-dynamical problems in defining the causes of lateral irregularities; measurements of position near fault zones have only recently become appreciated as contributing to understanding of earthquake mechanism, because of the difficulty of developing meaningful strain models. In the practical applications of geodesy, there has not been as marked an evolution toward the European tradition of thorough and precise survey as might have been expected from the rate of urbanization and the concomitant construction and rise in land values.

A consequence of the aforedescribed evolution (or lack thereof) is that the organization of geodetic activities is rather fragmented. The one element of the federal government primarily concerned with geodesy, the National Geodetic Survey, is located in a different department than those elements that have most fostered the new techniques—DOD and NASA—as well as those elements that have the most challenging geophysical problems to which geodesy should apply—USGS and NSF. The leading graduate center for geodetic science is located in a university that is not a known leader in solid-earth geophysics, The Ohio State University. The interactions between the Section of Geodesy of the American Geophysical Union and the Control Surveys Division of the American Congress on Surveying and Mapping have been low. Some of this fragmentation is proper: geodesy is a technique-oriented discipline, and the organizational evolution of a scientifically and technologically rich society is toward problem orientation.

Nonetheless, this mainly geophysical committee sees important problems to the solution of which geodesy could make major contributions. First and foremost, as discussed in Section 3.2, the most promising measurable precursors of earthquake activity are now believed to be surface deformations over distances of kilometers, and hence best measured by geodetic techniques. Point geometric measurements for detecting strain and tilt are excessively affected by localized phenomena, while indirect indicators of strain accumulation at depth—such as seismicity, seismic velocities, magnetopiezic effects, and radon emissions—are too uncertain in their interpretation. Other more purely scientific problems to which modern ultraprecise geodetic measurements apply include mantle convection, through the constraints of gravity field and plate tectonic motions; postglacial rebound (the principal independent indicator of mantle flow properties), through leveling; meteorological, tectonic, core motion, and tidal friction phenomena, through their effects on polar wobble and rotational variations; and ocean dynamical effects on sea level, through tidal measurements and leveling. More economically significant developments of geodesy that appear feasible are in the areas of geodetic support to land survey, mapping, and geophysical exploration.

To realize the potentials stated in the foregoing paragraph, the principal need seen by the committee is the fostering of improved instrumentation, not only by additional funding but also by better organizational arrangements within the federal government. Foremost is the need for more rapid and economical leveling techniques. This requirement is primarily for the earthquake-prediction problem, but its solution would also have economic payoff for some of the practical applications. Other valuable areas of instrumental development (discussed in Chapter 5) would be satellite techniques to determine positions, ocean-bottom devices, and moving-platform gravity gradiometers. To utilize current technical capabilities toward these goals, there are needed either transfers or developments of research elements to geodetic agencies of the federal government or more flexible arrangements to transfer funds or otherwise apply agencies' facilities to each other's problems. Improved transfer of instrumental developments to nonfederal surveyors is also needed, particularly of those achieved by DOD.

Another area in which interagency coordination is needed is to apply geodetic techniques more effectively to geophysical and mapping problems. It is difficult to see how this coordination can be accomplished short of placing NOAA and USGS in the same department.

The committee endorses the efforts of the National Geodetic Survey to systematize, update, and adjust the national horizontal and vertical control networks. Despite the development of more accurate techniques, these data will constitute a valuable framework for decades to come. We also endorse the development by NGS of better services for the land surveyor, such as standardized and centralized procedures for computing and recording geodetic control.

It is the committee's impression that the geodetic programs of the DOD and NASA are efficiently run. However, the NASA effort in the Office of Applications appears in need of more guidance as to the scientific aspects of its goals. Hence this committee was disturbed by the abrupt termination of the Earth Dynamics Advisory Subcommittee in April 1977.

In geodetic education, we do not see any major change to recommend; one graduate center of geodetic specialization seems appropraite. Probably it is desirable to enhance the interaction of geodetic and geophysical education. Geodesy is also one of those disciplines in which the influence of the federal government on education should be examined more carefully. Upgrading of land surveyor professional requirements is another area where significant educational progress seems feasible.

7.2 FUTURE COMMITTEE ACTIVITIES

There are several questions on which more useful recommendations could be made after more detailed technical study, which the committee felt it lacked either the time or the competence to pursue. It is proposed that these questions be examined by *ad hoc* panels, whose membership should be drawn partly from the committee but largely from elsewhere. Questions recommended for panel consideration are listed herewith. The order reflects some consensus among the members as to importance and feasibility, but the actual sequence of implementation would, of course, depend on other factors such as supporting-agency priorities.

1. *What geodetic instrumentation and observing programs are required for geodynamics purposes, in particular, to improve understanding of tectonic motions and to enhance earthquake prediction capability?* How should these programs be organized? What should be the priority of measurements, considering the somewhat conflicting emphases of practical concern versus scientific insight, terrestrial versus space techniques, and theoretical modeling versus empirical data compilation? This study would help implement recommendations made in Sections 3.2 and 4.1.4 and summarized in Section 1.2 for improved observations in fault zones. Capabilities on the committee should include geodesists knowledgeable of precise measurements of both positions and gravity, plus seismologists knowledgeable of seismic instrumentation in the fault zone as well as of models of tectonic deformation and earthquake occurrences. Acquaintanceship with the several agencies involved in the earthquake-prediction program would be helpful. This problem area is also of interest to the NRC Committee on Seismology.

2. *How should the DOD Global Positioning System be utilized for geodesy and surveying?* This study is in furtherance of the recommendation made in Section 4.2.3 and summarized in Section 1.3. The by-product use of this navigation satellite system is obviously desirable. However, there are a host of subsidiary questions. What is the positional accuracy attainable by using optimized definitive ephemerides with data from standard navigational receivers? To attain accuracies adequate for mapping control (say, 1 m), is some adaptation of navigational receivers required? Can geodetic accuracies (say, 5 cm) be attained by specialized improved receivers, using the navigational Doppler transmitter? Is any modification of the transmitter for geodetic purposes feasible? Is it feasible or desirable to equip some or all of the GPS satellites with laser retroreflectors? What arrangements need to be made to get definitive ephemerides? In view of incompatibility of receivers, how long is it desirable to continue the superseded Navy Navigation Satellite System? Are there problems in transfer of NASA as well as DOD instrumentation? Are the problems solely of transfer to state, local, and commercial surveyors,

or do they also involve transfer to federal civil agencies? Since the initial experimental satellites have been launched and since the system is planned to become operational in 1985, time is of the essence, and it is desirable to get a consensus from a panel with sensitivities that include the accuracy needs of geodynamicists, the economic circumstances of land surveyors, the techniques of definitive orbit determination, satellite, and radio Doppler technology, and DOD and NASA procedures.

3. *What should be the role of federal geodetic and mapping agencies in working with the states to establish a multipurpose cadastre?* What is the appropriate division of responsibility between the federal, state, and local governments? Among federal agencies? Should the federal government establish state-level surveying and mapping offices to facilitate uniformatization? Should control specifications be modified or extended? What pilot studies should be undertaken? Recommendations were made in Section 3.1 and summarized in Section 1.1 concerning the role of federal geodetic agencies in providing guidance and support to the land surveyor. Since a significant, perhaps major, part of the land surveyor's function is to provide the locational framework for land use, it would seem desirable for the geodetic agencies to be acquainted with state land registry systems and to coordinate their efforts with those of other federal agencies seeking to systematize cadastral procedures. Aside from control and property surveying, the panel should include competences in the law, data processing, and various aspects of land use, such as industrial and agricultural. Although the cadastre is primarily a legal device, the concerns of this panel would have some relation to those of NRC committees dealing with problems strongly affected by the pattern of land use, such as environmental quality and energy conservation.

4. *What are the applications of the gravity field, and what observations are required to satisfy these applications?* Recommendations relevant to the applications are made in Section 3.2 and to the techniques in Sections 4.2 and 5.1. Areas of application include physical geodesy, orbit determination, inertial navigation, oceanography, and tectonophysics. Current improvements in measuring gravity—satellite altimetry, satellite-to-satellite range rate, free-fall devices—are yielding a much better coverage and resolution of the gravity field over a wide range of circumstances. However, a variety of questions remain as to how these systems are to be utilized and what complementary measurements are required to help solve outstanding problems. For example: What surface gravimetry is needed in combination with satellite altimetry to distinguish sea level from the geoid for ocean-dynamics studies? What systems are needed to obtain the gravity field over inaccessible land areas of tectonic interest (How unique are the Himalayas? What is the effective resolution of their modeling?)? How should satellite-to-satellite tracking be implemented? What can precise gravimetry in addition to other data resolve about the nature of earthquake premonitory phenomena? The panel evidently should consist of a combination of those concerned about the applications and those expert in the various gravimetric techniques.

5. *What are the applications of the satellite altimetry data, and what needs to be done to assure their effectiveness?* This problem area overlaps No. 4 but is more limited in its scope. Aside from being limited to the oceans, it relates to the near-term question of implementation of satellite SEASAT-B, which is also of concern to the NRC Ocean Sciences Board. Probably most urgent is the question of gravity-field determination by other means, both to improve the accuracy of the SEASAT orbit and to discriminate the sea level from the geoid.

6. *How can existing and planned geodetic technology be most effectively transferred to users?* Instrumentation developed by DOD or NASA of interest to both federal and nonfederal users may often be expensive because it is designed to be more rugged or more reliable or more accurate than required for civil purposes. Mensuration techniques of geodetic potential invented in NBS laboratories may require appreciable further development for field application. In the case of nongovernmental surveyors, there may be an informational gap that could be bridged. All of these questions are somewhat procedural as well as substantive, so an effective panel should include members acquainted with the relevant federal agencies as well as the instruments and their applications.

7. *What is the economic benefit of geodesy?* A recommendation bearing thereon appears in Sections 6.1 and 1.5. Because the contribution of surveying and mapping, and thence of most geodesy, to economic activities is auxiliary—planning and avoidance of mistakes and accidents—and because this contribution is spread in a rather thin layer across the economy, this question is difficult to answer. Particular questions include: What industries are supported, and how? How is geodesy allocated among them? What measures of costs and benefits might be developed? What techniques of analysis might be borrowed from other areas? Should any questionnaires be developed? The committee feels least sure about recommending this panel, partly because of the intangibility of the problem and partly because some federal agencies have attempted to answer it as far as their own activities are concerned. In any case, the matter seems worth pursuing with economists specializing in land use, civil engineers, land surveyors, and operations research specialists.

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