INTERNATIONAL GLOBAL NETWORK OF FIDUCIAL STATIONS: SCIENTIFIC AND IMPLEMENTATION ISSUES

Panel on a Global Network of Fiducial Sites
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PANEL ON A GLOBAL NETWORK OF FIDUCIAL SITES

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PREFACE

The Panel on a Global Network of Fiducial Sites was formed by the Committee on Geodesy, National Research Council, with the encouragement of its supporting agencies, to address specific issues, including:

1. evaluation of the scientific importance of a proposed global network of fiducial sites, monitored very precisely, using a combination of surface and space-geodetic techniques;

2. examination of strategies for implementing and operating such a network, in light of the anticipated scientific return, building on existing capabilities whenever possible; and

3. assessment of whether such a network would provide a suitable global infrastructure for geodetic and other geophysical systems of the next century.

The charge to the Panel developed from the rapid growth of space-geodetic systems with a global distribution of stations, including the Satellite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI) network deployed in the 1980s; the French DORIS and the German PRARE systems; and the Global Positioning System (GPS) networks, such as the Cooperative International GPS Network (CIGNET), and the proposed Fiducial Laboratories for an International Natural science Network (FLINN). Thus, various countries and a number of national and international organizations have embarked on the development of global observing programs, with varied life spans and objectives. The scientific implications of such a collection of global networks transcend the objectives of any single organization or even any single country. The potential benefits to be derived from an international, multidisciplinary research effort with a well-defined infrastructure are sufficiently important to warrant global support and participation.

The scientific aim should be the establishment of a globally distributed network of fiducial stations that would include a core of ground-based observatories to study the Earth. The dual scientific goals of such a global geodetic and

geophysical fiducial network would be (1) to improve our understanding of geophysical and geological phenomena that operate on a global scale, and (2) to provide a reference framework and boundary conditions for analyzing the phenomena that operate on smaller scales.

Therefore, the Panel opted to broaden the initial concept and to consider how a mix of space-based geodetic techniques, expanded to include other geophysical techniques, would best contribute to the solution of fundamental geodetic and geophysical problems with a global scope. Such a broad approach is not only desirable but also essential if we are to realize the full potential of global networks for solid Earth research. The scope of the tasks imposes on the scientific community an obligation to consider how a global network of fiducial sites can be built on existing structures.

Coordination of space-geodetic global deployments with ongoing global activities in other disciplines, such as global seismology, geomagnetism, gravimetry, and absolute gravity, offers exciting possibilities for comprehensive studies of the Earth, although compatibility issues remain to be resolved. An initial complement of instruments, modified as needs are identified, should be proposed by the geophysical and geodetic science communities and a determination made as to which instruments should be installed at individual sites.

The Panel met four times during 1990. In 1991 it was recognized that a broader range of expertise was needed to deal with many of the issues raised by this study. Therefore, the Committee on Geodesy joined with the Panel in preparing the final report. The members of the Panel and the Committee represent users of various geodetic techniques and many geophysical sciences such as gravimetry, seismology, geomagnetism, tectonophysics, and oceanography. This combined Panel and Committee represent a cross section of the diverse technical and scientific interests considered in the report. In addition, the Panel especially appreciates the assistance of a number of scientists, particularly, Professor Richard J. O'Connell, Harvard University, for his early discussion on issues relevant to this report; Professor Michael Bevis, North Carolina State University, for his discussions on the issues of sea-, land-, and ice-level changes; and Drs. Oscar Colombo, Werner Gurtner, Ruth Neilan, and Stephen Lichten for their many discussions of various issues raised in this report. A substantial fraction of the material on the International GPS Geodynamics Service proposed to the International Association of Geodesy was prepared by members of this Panel; not surprisingly, this report incorporates much of the same material. The Panel also drew from the International Earth Rotation Service (IERS) annual reports and associated publications. However, responsibility for the final document rests exclusively with the Panel and the Committee.

The Panel expresses its appreciation to the staff of the Board on Earth Sciences and Resources, who provided support for its activities, and to the agencies that provided funding for this study.

J. Bernard Minster, *Chairman*
Panel on a Global Network of
Fiducial Sites

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OVERVIEW

Introduction

Geodesy, in the space age, has strived to steadily improve the precision of measurements to meet the ever more demanding metric needs of the Earth, ocean, and space sciences. These needs are most evident from the increasing number of gatherings of scientists at which the benefits of modern geodetic techniques are discussed and relied upon to help solve diverse problems in the Earth sciences (see Appendix A). Geodesy has always contributed to Earth studies on both local and continental scales. However, only since the advent of space-based geodetic techniques, the increased precision of these techniques, and the feasibility of obtaining data from a large number of sites have scientists been encouraged to apply these methods to existing global networks and to the solution of global problems. This has led naturally to the consideration of a worldwide network of interconnected fiducial stations where geodetic as well as other scientific measurements could be made. Such an international global network of fiducial stations is the theme of this report. To consider issues raised by the transition to such a network, the Panel on a Global Network of Fiducial Sites was formed by the Committee on Geodesy, National Research Council.

The Committee's supporting agencies suggested that the Panel address specific issues, including:

1. evaluation of the scientific importance of a global network of fiducial sites, monitored very precisely, using a combination of surface- and space-geodetic techniques;

2. examination of strategies for implementing and operating such a network, in light of the anticipated scientific return, building on existing capabilities whenever possible; and

3. the assessment of whether such a network would provide a suitable global infrastructure for geodetic and other geophysical systems of the next century.

To address these issues, the Panel defined (1) a *core network*, consisting of a relatively small number (about 30 or more) of very-high-performance stations, operating with a high degree of reliability, many (but not necessarily all) of which would be collocated with other global geodetic and geophysical instruments, thereby providing a common reference frame; (2) *fiducial sites*, which are defined as stations where geodetic and, if feasible, geophysical measurements are made, continuously or periodically, meeting standards and specifications established for highly precise data. The Panel believes that promising scientific potential exists in including geophysical activities, in addition to geodetic, at fiducial sites. The *global network* discussed in this report consists of the total of all fiducial sites, including the core network.

The Panel's conclusions on the three issues, briefly, are:

1. A global network of fiducial sites would provide an irreplaceable and vital tool for addressing several important global issues such as (1) sea-level change and postglacial rebound and (2) the monitoring of tectonic plate motion and deformation. The network also would play a critical role in providing a reference frame, monitoring Earth orientation, constraining fundamental rheological parameters of the Earth, validating models of ocean dynamics, determining Earth satellite orbits at a sustained and unprecedented level of precision, and providing essential spacecraft tracking support for scientific missions in low Earth orbit. Finally, a global network would offer a new level of support for local and regional geodetic and geophysical studies, through its reference frame and through the logistical simplification of orbit determination.

2. As the Global Positioning System (GPS) receiver costs decline and the ease of operation and precision of measurements improve, GPS systems are proliferating worldwide. Competing systems, such as the USSR Global Navigation Satellite System (GLONASS), do not provide similar precision at this time. Furthermore, the cost for deploying systems such as Satellite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI) at core and fiducial sites is likely to be prohibitive. Therefore, the Panel concluded that GPS is likely to play a major role in global geodesy over the next decade and complement effectively existing

techniques. The Panel therefore examined with particular care global deployment strategies explicitly using GPS. This choice of technology influences in turn the nature of the global network. A viable strategy for implementing and operating the network is to integrate existing global networks into a common reference frame and to establish a GPS core network of about 30 or more sites, which permits the definition and realization of the global reference frame and supports the precise determination of orbits and Earth orientation parameters. The GPS core network should therefore incorporate sites presently occupied by equipment devoted to space geodetic measurements via techniques such as VLBI, SLR, Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS), and Precise Range and Range-rate Equipment (PRARE). Growth of the network beyond the core stations can take place by progressive evolution of sites from a status of periodic reoccupation to a status of permanent occupation, with a higher density of sites in tectonically active areas and areas critical to the resolution of postglacial rebound problems. An analysis of the requirements for a global network capable of meeting these objectives indicates that the network should grow over time to about 200 fiducial sites including the core stations. In this respect the definition of the fiducial network adopted by the Panel is more ambitious than the one contemplated for the International GPS Geodynamics Service (IGS), which proposes that the stations in the fiducial network, other than the core stations, would be reoccupied at regular intervals and would not generally operate continuously, at least initially. The Panel's definition agrees with the concept proposed for the Fiducial Laboratories for an International Natural science Network (FLINN) (NASA, 1991).

3. Such a global network of fiducial sites will provide a suitable long-term infrastructure for geodetic and geophysical studies, especially if a special effort is made to foster coordination with other global deployments (e.g., seismological) and promote a multidisciplinary approach. Such fiducial sites would then evolve into terrestrial observatories, or laboratories, at which a variety of measurements would be made in concert to permit more comprehensive studies of the Earth. Even though many fiducial sites might be occupied only periodically in the early phase of the global network deployment, it is the Panel's view that, in the long term, the majority of sites would be permanently and continuously occupied and equipped with multidisciplinary batteries of instruments.

The Panel therefore views the concept of a global network of fiducial sites in a favorable light, provided that its implementation proceeds along the lines of international cooperation that have historically characterized geodesy. However,

with the much denser temporal and spatial sampling implied by the various global network concepts recently proposed (see Appendix A), data flow, data management, data processing, and data archiving loom as much larger problems than in the past. Although solutions exist in theory, they need to be implemented, tested, and evaluated in the context of realistic experiments. Ongoing and planned services and campaigns, such as the International Earth Rotation Service (IERS), the First GPS IERS and Geodynamics Experiment (GIG'91), or the International GPS Geodynamics Service (IGS) Epoch '92, will provide much of the data needed for such tests and evaluations.

This report first discusses the scientific rationale behind the concept of an extensive global network of fiducial sites. It defines the scientific goals that govern the design and operation of the network and identifies two classes of scientific objectives: (1) general geophysical objectives characterized by important scientific problems that cannot be solved without a global approach and (2) geodetic objectives that call for a global deployment of fiducial sites. These objectives are discussed in detail in Chapter 2.

Chapter 3 addresses operational considerations, which include a review of existing and emerging technology, issues raised by the inevitable transition to newer technologies, and items to consider in order to mitigate the complications introduced by such transitions. Data flow and data management issues are then raised, as well as operational concerns such as standards and data formats. In Chapter 4 a plan is proposed, including a hypothetical global network that could effectively address the scientific problems discussed in Chapter 2. Special attention is given to the benefits that would accrue from a deliberate effort to coordinate global deployment and operation of seismic, magnetic, atmospheric, and environmental networks.

The Committee on Earth Sciences (1989) of the White House Office of Science and Technology Policy recently published a report, *Our Changing Planet: The FY 1990 Research Plan*, that addresses research priorities in the U.S. Global Change Research Program and provides the framework for yearly updates in the program's definition. That report emphasizes global observation programs that tend naturally to be more efficiently conducted from space-based platforms. However, *in situ*, or ground-based, observations are accorded a rather prominent place as well, and the report notes that "there are many important parameters which we can't yet measure from space" (p. 16). The report also identifies seven "interdisciplinary scientific elements" (p. 104) that together constitute the backbone of the U.S. Global Change Research Program. They are, in order of assigned priority:

1. climate and hydrologic systems,
2. biogeochemical dynamics,
3. ecological systems and dynamics,
4. Earth system history,
5. human interactions,
6. solid Earth processes, and
7. solar influence.

All of these seven elements call for observational programs that are global, and all require a substantial ground-based component. *In situ* measurements play an even more important role in the report *Reducing Natural Hazards: A 10-Year Research and Applications Strategy* (Committee on Earth and Environmental Sciences, October 1990), in which the scientific elements deemed most important match elements 1, 3, and 6 above. This U.S. national program would be an important contribution to the International Decade for Natural Hazard Reduction, described in the report *Confronting Natural Disasters* (National Research Council, 1987b).

In 1988 the Task Group on Earth Sciences of the Space Science Board, National Research Council, produced a seminal report entitled *Mission to Planet Earth*. The primary theme of the report pertains to the study of the Earth as a system, to be explored by a variety of techniques, including in particular space-based techniques. The main recommendations are couched in terms of four Grand Themes, the first of which pertains to the "structure, evolution, and dynamics of the Earth's interior and crust," (p. 5) the space science orientation of the Task Group on Earth Sciences notwithstanding. To conduct the necessary research and to collect the required data, the Task Group recommended deployment of a Permanent Large Array of Terrestrial Observatories (PLATO) that would complement the Earth Observing System (EOS). The concept of a global network of terrestrial fiducial laboratories is, therefore, in tune with the main recommendations of *Mission to Planet Earth*. (The term *Mission to Planet Earth*, coined by the Task Group, has since been adopted by NASA to define a proposed set of orbital missions starting late in the next decade and extending into the next century. Although the Task Group's concept and the NASA proposal have many similarities, we shall use the term in this report in the sense defined by the Task Group and not as a description of a particular space mission.)

At several major workshops in the past three years, global issues in geophysics and geodesy held a prominent place. The first, an international workshop on The Interdisciplinary Role of Space Geodesy, was held in Erice, Sicily, in July 1988.

The resulting report (Mueller and Zerbini, 1989), hereafter referred to as the Erice report, contains 11 main recommendations, several of which concern issues that call for a global point of view. A number of these recommendations were reiterated and summarized in *Geodesy in the Year 2000* (National Research Council, 1990a). The second major workshop was held in July 1989 at Coolfont, West Virginia, with the specific purpose of developing a NASA program in solid earth science. From the point of view of global geodesy, this workshop recommended the deployment of a global network of permanently occupied sites, to be known as Fiducial Laboratories for an International Natural science Network (FLINN) (NASA, 1991). Finally, a workshop held in May 1990 at the Woods Hole Oceanographic Institution focused on issues associated with measuring changes in global sea level. The associated report, *Towards an Integrated System for Measuring Long Term Changes in Global Sea Level* (Joint Oceanographic Institutions, 1990), specifically treats the need for continued development of geodetic techniques on both global and local scales. The main recommendations from these various studies are summarized in Appendix A.

Scientific Priorities

Scientific priorities that clearly call for global *in situ* measurements are described in considerable detail in *Mission to Planet Earth* (National Research Council, 1988). A fundamental tenet of that report is that the extremely wide range of temporal and spatial scales of the phenomena that govern the state and evolution of the solid Earth, the atmosphere, and the oceans "require measurements by a variety of means, all requiring completeness, simultaneity, and continuity" (p. 11). Not surprisingly, geodetic measurements will play a fundamental role in the study of many of these phenomena. However, with the advent of space-geodetic techniques, this role has evolved and grown, because precise geodetic measurements at almost all scales are now capable of detecting signals, such as tectonic strains and sea-level changes, that had heretofore only been inferred from geological evidence. Geodesy is now a major contributor of quantitative data that help Earth scientists solve geological and geophysical problems. This contribution has been recognized explicitly by Lambeck (1988), who coined the term "geophysical geodesy."

Among the major topics in geophysical science that will benefit from a global network of fiducial stations, three have long been recognized as clear targets for a geodetic attack. They are (1) changes in global sea level, which are thought to be an important index of global climatic change and which require careful geodetic control to separate signals and noise sources of comparable amplitudes (e.g., Carter et al., 1989); see also Sea-Level Change (National Research Council, 1990b) and Towards an Integrated System for Measuring Long Term Changes in Global Sea Level (Joint Oceanographic Institutions, 1990); (2) postglacial rebound, a closely associated topic, which is also coupled to the viscosity structure and flow of material in the Earth's mantle; and (3) global and regional tectonic motions and deformation, which address directly the dynamic characteristics of the crust and mantle on short time scales never accessible until very recently.

These topics cannot be tackled, however, until other, more purely geodetic problems are solved. These include calculation of precise ephemerides for the satellites used by space-geodetic techniques, determination of Earth orientation and rotation parameters, and realization of a precise reference frame for global studies. Interestingly, we shall see that these geodetic objectives can be achieved with a much sparser network than the geophysical ones mentioned above. This has substantial implications for the design of a global network and the attendant logistical structures, such as systems for data collection and analysis.

A number of scientific missions in near-Earth orbit require very precise knowledge of the ephemerides of the spacecraft. This is particularly true of missions such as Aristoteles, ERS-1, and TOPEX/POSEIDON. It will be true of a number of missions in various stages of planning for the second half of the decade, including, in particular, GP-B and EOS. Geodetic support for such missions can be provided at the required level only if a global tracking network is available. At the same time, the availability of GPS receivers on low-orbit spacecraft would significantly strengthen a global GPS network by providing, in essence, additional network nodes at very high elevation. Mission support is therefore a clear motivation for the deployment and operation of global fiducial networks.

Finally, a powerful motivation for a global network derives from the support it can afford the geodetic community at large by providing important data products such as precise orbits, a global realization of a terrestrial reference frame, and regional fiducial points to which local and regional networks can easily be tied. Partly in recognition of such benefits, the International Association of Geodesy (IAG) sponsored a symposium, Permanent Satellite Tracking Networks for Geodesy and Geodynamics, at the meeting of the International Union of Geodesy

and Geophysics (IUGG) held in Vienna, Austria, in August 1991 and has issued a Call for Participation in an International GPS Geodynamics Service (see Appendix C). The notion of *service* is crucial in this respect. Such actions constitute a clear indication of the timeliness of these ideas.

Global Networks

Use of the word *global* when characterizing a fiducial network implies a certain distribution of stations. The actual coverage and intersite spacing will vary with the requirements of the users and with the signals that must be accounted for properly. For instance, relative plate motions in the definition of a terrestrial reference frame may be accounted for through a theoretical (geological) model or through a Tisserand condition (e.g., Boucher and Altamimi, 1989). (Tisserand axes are defined by minimizing the kinetic energy of the mobile plate system and are characterized by null linear and angular momenta.) Either approach can be made unambiguous by appropriate selection of conventions and analysis methods, but the second is rather more difficult to assess in a geophysical context without conducting a detailed analysis of how the network samples the plate mosaic.

It is natural for space geodesy to adopt a global perspective. This perspective has been held in the past and holds for many existing or planned techniques and networks, such as SLR, VLBI (including the Soviet QUASAR Project [Finkelstein and Yatskiv, 1989], the French DORIS system, the German PRARE system, the USSR GLONASS, and the GPS).

From the point of view of a global network of fiducial sites, it is clear that GPS will play a major role in achieving global geodetic coverage. Already, the Cooperative International GPS Network (CIGNET) (Schenewerk *et al.*, 1990; Neilan *et al.*, 1990) and other global GPS networks, such as the NASA Deep Space Network (DSN), offer 20 to 30 permanent stations with a global, if uneven, distribution of sites. The Panel, based on the scientific goals discussed in this report, concluded that a core network of about 30 or more stations would be appropriate. Global GPS campaigns have also been conducted successfully (e.g., GOTEX, IERS GIG'91). Embryonic permanent and continuously recording GPS networks are being deployed in Japan and California (e.g., Shimada *et al.*, 1990; Bock *et al.*, 1990).

In other disciplines, global has essentially the same meaning, although colored by the particular data products the network is supposed to support. For instance, for very-long-period seismology, a global broadband network can be quite sparse, but for the International Seismological Observing Period (ISOP) a very large number of stations will participate in an unprecedented coordinated experiment. In geomagnetism the INTERMAGNET program is aiming at a global distribution of nearly 70 sites in the next few years, with real-time data transmission via satellite.

Recently, E. H. Knickmeyer and C. Boucher, in an exchange of correspondence (Knickmeyer, 1990; Boucher, 1990) offered a rationale for a *Common, Global, Integrated, Fundamental Network*. The IERS, as well as a number of working groups of the IAG, would play a central role and provide the needed international umbrella. Knickmeyer and Boucher analyzed the implication of each qualifier in the following terms:

Common: Commonality to all data users and data producers requires an international scope and an international umbrella. International groups will therefore play a central role.

Global: The word is usually taken to mean uniform coverage, but the mean intersite spacing required depends on the application and on practical considerations, such as the distribution of geologically active zones. For these reasons, a slightly nonuniform distribution may be superior to a rigidly uniform one.

Integrated: This modifier has several connotations: (1) A global network using a specific technology should have enough sites collocated with sites equipped with other technologies to permit the realization of a common coordinate system. (2) Other measurements (such as cryogenic or absolute gravity) should be performed at the same sites—that is, in the same reference frame—which can affect the selection of global sites. (3) Individual sites should all adhere to a common set of standards and data formats to permit exchange and analysis of both local and global data.

Fundamental: The global network will be a primary network to which existing regional networks, or future densification networks, will be linked.

An ever-growing proportion of the Earth sciences community is taking a global view of the planet. The point is important because much can be gained by looking beyond the straightforward applications of instrumentation deployed by scientists in any given discipline and actively seeking to cross disciplinary boundaries. If the direct scientific benefits are not always necessarily obvious, the

practical benefits, in terms of economies of scale, technology transfer, and logistical simplifications, will quickly be realized if they exist.

State of the Art

The nature and distribution of existing global geodetic networks have been determined by the needs of particular techniques, political and funding realities, and many other considerations and constraints. Some networks have evolved from early experiments into an operational mode, while others have been able to build on existing technology into an almost immediately operational system.

Current space geodetic techniques can conveniently be classified into optical and radio systems. The most precise optical systems are based on the measurement of the time of flight for a laser pulse between source and detector. The most precise radio systems measure a similar time of flight in the 1- to 20-GHz microwave spectrum or the differential time delay of a signal received at two sites.

The laser ranging systems had their experimental foundations in the early 1960s and reached a significant milestone in 1969 with the successful ranging to reflectors placed on the moon by Apollo astronauts. These space-geodetic systems are referred to as the Lunar Laser Ranging (LLR) and the Satellite Laser Ranging (SLR) systems. The SLR network has evolved into an operational network that regularly tracks the dedicated LAGEOS (U.S.) satellite as well as several others, such as Starlette (France), Ajisai (Japan), and the Etalon satellites (USSR). SLR is the primary U.S. tracking system for the TOPEX/POSEIDON mission (U.S./France) to be launched in 1992 (DORIS being the primary French tracking system). The LAGEOS satellite series will be augmented with LAGEOS 2 to be launched in 1992 and LAGEOS 3 planned for launch in 1994. A spaceborne version of SLR will be the tracking system for the Geoscience Laser Ranging System (GLRS), which is slated for launch on the Earth Observing System. Current ground-based systems are characterized by an instrumental precision of better than 1 cm in a single range measurement, which can be corrected, in part, for tropospheric refraction if sufficiently precise measurements of temperature, pressure, and humidity are made or if two-color range measurements are made.

The radio systems can be classified according to the radio source used. The VLBI systems ordinarily use extragalactic radio sources and a differential mode of signal analysis that requires receivers at two or more sites. Other radio systems are based on satellite sources, in particular, the well-publicized and widely used GPS (U.S.) constellation of satellites and the USSR Global Navigation Satellite

System (GLONASS). More recent radio systems developed for space-geodetic applications include DORIS, which will be carried on TOPEX/POSEIDON, and PRARE, which will be carried on ERS-1, an Earth Resources Satellite of the European Space Agency. The VLBI systems have demonstrated millimeter-level precision for the lengths of transcontinental and intercontinental baselines (e.g., Herring, 1991). GPS systems have been shown to achieve comparable precision for shorter baselines. Radio measurements are influenced by both ionospheric and atmospheric effects, but the ionosphere's contribution can be largely removed with dual-frequency measurements, and the dry component of the atmosphere can be appropriately modeled. The wet component of the atmosphere can be handled by using water vapor radiometer measurements or by including appropriate estimation of atmospheric parameters (e.g., Herring *et al.*, 1990).

Direct comparisons of coordinates of 16 fiducial sites common to both SLR and VLBI networks have shown agreement at the 2-cm level (e.g., Ray *et al.*, 1991). The remaining 2 cm could be due to remaining systematic errors in either or both techniques (e.g., water vapor effects for VLBI, orbit errors for SLR, and local survey errors for all space-geodetic techniques). Insufficient data exist to gauge the effects of other geodetic parameters, such as the gravity field (static and time-dependent), since, in practice, the insensitivity of VLBI to those parameters precludes a determination. Future radio applications using, for example, a GPS receiver on a low-altitude satellite will permit independent determinations of the gravity field. Regardless of the technique, availability of a global fiducial network of stations is critical to the successful determination of such geodetic parameters. Existing and planned networks for the various techniques are described in Chapter 3 of this report. Some of the networks are based on long-standing international cooperation (e.g., SLR), while others have developed more rapidly (e.g., CIGNET). Still others have been deployed for particular missions (e.g., the DSN tracking of GPS). In many instances, special efforts were made to ensure that different networks included several common sites to eliminate the effects of unknown relative orientations.

The IERS is a prominent user of the existing SLR, LLR, and VLBI networks. Not only are the data generated by the networks used to determine Earth orientation, but the establishment of conventional reference frames for a variety of other applications is an important IERS product. The mission statement of the IERS is reproduced in Appendix B. It touches on many of the issues discussed in this report. IERS is a member of the Federation of Astronomical and Geophysical Data Analysis Services (FAGS) and cooperates with the Bureau International des Poids et Mesures (BIPM) in its activities concerning the UTC (Coordinated

Universal Time) time scale. The IAG's recent Call for Participation in a proposed International GPS Geodynamics Service (IGS) is also likely to increase the use of existing global network data through close coordination with IERS.

Recommendations

Six primary recommendations have been formulated from the discussions in this report. They outline a path that, it is believed, can be followed over the next decade or so to deploy an International Global Network of Fiducial Sites and, ultimately, build a network that conforms with concepts proposed for PLATO (National Research Council, 1988) or FLINN (NASA, 1991).

The premise of these recommendations is that GPS is most likely to be the technology around which the global network will be built, at least for the foreseeable future. The popularity of the technique, its affordability, and mounting evidence that it can provide the required accuracy of measurements all combine to make it an extremely attractive way to address the scientific objectives of the global network. The experience accrued worldwide over the past few years by Earth scientists using GPS to solve geological and geophysical problems provides ample proof that, as a global geodetic tool, this system effectively complements the global networks already in place, particularly the VLBI network. The Panel carefully considered the various issues raised by choosing GPS as the prime candidate technology for the global network. Some of these—such as reliable, accurate, and timely orbit determination, definition of a terrestrial reference frame; and monitoring of Earth orientation and rotation parameters—will be addressed by selecting well-conceived deployment strategies and creating the infrastructure necessary to facilitate global data flow, timely processing, and effective dissemination of data products.

Selection of GPS as the primary technique for the global network also raises a variety of nonscientific questions. In particular, GPS is designed, deployed, and operated by the U.S. Department of Defense (DoD). The DoD has a stated policy that access to the Precise Positioning System (PPS) will be restricted to authorized users, whereas the Standard Positioning System (SPS) will be generally accessible to civilian users. Usage of PPS has been restricted by a mechanism called Selective Availability (SA) since March 1990. The DoD also plans tests of the Antispoofing (AS) capability of the system, which involves encryption of the signals, when the system is fully operational. The Panel found from the geodetic community's (as yet limited) experience with SA that most geodetic applications

of GPS involve sufficient dwell time to permit averaging the effects of SA (e.g., clock dithering). Consequently, at present it appears that SA does not preclude the precise global applications of GPS contemplated for the global network. It will force network operators to do considerably more data processing work than they would have to do in the absence of SA, however, which entails a definite cost that is difficult to assess at present. From the point of view of the operation of a global network, access to the P-code would make a very significant difference in terms of the processing burden. If the P-code is not accessible, it is likely that, for a given level of available resources, a much smaller network can be analyzed, with a concomitant loss of scientific return. Certain applications, such as spacecraft orbit tracking using GPS, would benefit substantially from access to PPS. The Panel made no new explicit recommendation concerning these issues, which are the subject of ongoing discussions between the DoD and various user communities and of vigorous public debate among federal agencies, civilian users, and commercial equipment manufacturers.

Nevertheless, the Panel endorses the recommendation in *Towards an Integrated System for Measuring Long Term Changes in Global Sea Level* (Joint Oceanographic Institutions, 1990) that the DoD should remove selective availability during periods of normal international relationships.

The Panel's recommendations focus on strategies for the deployment of the global network, assuming GPS to be the most likely technique of choice. These strategies are examined in the light of overall scientific applications.

Recommendation 1: The Panel recommends (1) incorporating part or all of the existing global GPS networks into a core network of about 30 or more locations as the first priority in the deployment of a global network of fiducial sites, primarily to support the reliable determination of precise GPS orbits; (2) maintaining a sufficient level of collocation of different systems, particularly SLR, VLBI, and GPS, to permit realization at the required accuracy of a common reference frame; (3) maintaining a transportable capability for VLBI and SLR systems for occasional verification and validation of long baselines; and (4) planning for long-term reoccupation of sites after transition to a new technique, system, or monument. The network should then grow over time to 200 sites, all eventually equipped with permanent, continuously recording GPS or comparable tracking equipment.

In deploying the global network of fiducial sites, it is essential to ensure continuity of existing geodetic time series and to tie measurements by different space geodetic techniques into a common reference frame. The development and deployment of the network should proceed as a natural extension of the activities of the past decade. In particular, it is critical whenever and wherever possible to continue the time series collected over the past few years without breaking continuity. The Panel believes that proper continuity can be maintained by building the network as a two-tiered system, comprising two main categories of sites:

1. A GPS core network, comprising about 30 or more globally distributed, very-high-quality sites with continuous, reliable operation of GPS and other equipment, and near-real-time data acquisition and transmission to processing centers. This network would contribute the data from which would be derived (1) precise orbits, including force model parameters; (2) GPS clock estimates; (3) Earth orientation information to be contributed to IERS; and (4) ties to the terrestrial reference frame through collocation at a sufficient number of sites with multiple techniques, specifically fixed and mobile VLBI and SLR equipment, DORIS, and PRARE.

Preliminary results from the GIG'91 campaign are very encouraging: A globally distributed network of about 15 GPS stations appears to yield precise orbits and polar motion estimates in good agreement with the VLBI solutions (G. Blewitt and S. Lichten, Jet Propulsion Laboratory, Pasadena, California, private communication, 1991). Care must be taken to provide adequate coverage in remote areas, particularly in the southern hemisphere. The Panel's recommended core network of 30 or more sites incorporates the notion of redundancy, which is the most straightforward way to guarantee that the quality of the data products will be robust with respect to equipment failure and similar disruptions.

2. A larger set of stations (perhaps on the order of 200) providing denser coverage of tectonic deformation zones, regions of postglacial rebound, and coastal areas near tide gauge networks. Such sites might be occupied initially at regular intervals (in particular during global campaigns) to determine secular geodetic signals, but many would be upgraded to continuous operation over time, thereby contributing data similar to those derived from the GPS core network. These stations would contribute to the solution of global geological and geophysical problems. Of special importance to this expanded network would be the capability of periodic visits with portable systems—particularly VLBI and SLR systems—especially to isolated locations tied to the rest of the network through fairly long baselines.

Distribution of the larger network of fiducial stations is likely to be controlled in large part by available resources and logistics constraints. The Panel's proposal of 200 sites results from arguments presented in Chapter 4. The Panel strongly recommends that some fiducial sites be located at or near tide gauges so as to elucidate some of the problems raised in Chapter 2 concerning the separation of sea-level changes, postglacial rebound, and tectonic signals. However, it is clearly premature to extend such a recommendation to all tide gauges participating in global sea-level monitoring. Instead, the Panel recommends that a manageable subset of these sites be targeted for focused, continuous measurements.

Existing permanent GPS, SLR, LLR, and VLBI stations, primarily from the CIGNET and DSN networks and from global VLBI and SLR networks, can be selected as an initial set of GPS core sites, with which the critical data flow issues can be examined now. A major advantage of such an approach stems from the existing infrastructure, which offers an opportunity for efficient use of existing resources. Continued growth should take advantage of advances in receiver technology, as well as data collection, processing, and distribution techniques. Implementation of the FLINN concept will require broad international participation and will proceed at different rates in different regions, depending on local logistical conditions and availability of reconnaissance surveys and on available resources.

Recommendation 2: The Panel recommends a concerted effort to continue the integration of existing global networks.

This recommendation recognizes that existing or planned global networks, including VLBI and QUASAR, SLR, LLR, DORIS, GPS/GLONASS, and PRARE have the potential to satisfy many of the scientific requirements of a global network of fiducial sites. The recommendation also entails strong support for the continued operation of enough sites for each technique, distributed globally and collocated with other techniques, at enough locations to permit the realization, at a sufficient level of accuracy, of a common reference system. This point raises not only the rather obvious issue that a mere collection of stations does not a network make, so that these stations must be melded into a network, but also brings up the thornier difficulty of integrating different technologies. IERS merges data sets from several sources to produce unified data products. The procedure involves development of an assortment of weighting schemes that acknowledge the relative reliability of these different sources. The variety of data sources generated by globally distributed networks will increase. In addition, some technologies will

become obsolete, and a transition to new technologies will prove necessary. Further, for a number of scientific purposes, the range of data products offered through IERS will have to be expanded—to include, for instance, full covariance information—and standards must be developed for these new products. If the global network is to realize the scientific promise it holds for its nongeodetic users and for the geodetic community at large, the path to the use of new technology must be charted in a predictable way. In the Panel's view, this recommendation requires that national and international organizations aggressively seek international cooperation and coordination of efforts conducted by many countries.

> *Recommendation 3: The Panel recommends development and implementation of (1) data standards, (2) communication paths, and (3) data processing and archiving techniques. One of the earliest priorities is to produce and disseminate standard geodetic data products, by operating coordinated data centers to ensure a smooth flow of data from the network operators to the user community, and to establish analysis centers to develop and test techniques and results that support part-per-billion three-dimensional geodesy. The creation and operation of these centers should begin concomitantly with the initiation of the GPS core network. The effectiveness of the international flow of global data should be tested and evaluated in the context of a series of global campaigns, including a mechanism for identifying and implementing necessary improvements.*

This recommendation is rooted in the recognition that no matter how many sites are installed in the field and irrespective of the quantity and quality of the observations, these sites cannot constitute a *network* unless an effective mechanism is in place to collect the data and distribute the data sets to the users along with products generated by the analysis centers. This function must include the unavoidable updates—some of which may be required after a substantial delay—of data sets already distributed, as well as the continued monitoring of data quality. The mechanisms are well known in principle, although fraught with practical difficulties in implementation. It is essential that these difficulties be identified explicitly and that solutions be developed and subjected to rigorous tests. The nature of such tests depends on the data sets and, therefore, on the discipline addressed by the network. This means that the issues associated with data flow should be addressed from the very outset of the deployment of a fiducial network. In other words, high priority should be given to the design and creation of international data centers, and the international community should initiate

operation of such centers, and analysis and evaluation centers, with the first data streams available—that is, with the GPS core network data.

In geodesy the time-honored approach to identifying and solving data flow problems is through the execution of campaigns. The several campaigns conducted in the recent past include the very successful MERIT campaign, which resulted in establishment of the MERIT standards and ultimately creation of the IERS. More recently, the GOTEX and the GIG'91 IERS campaigns have tested the collection, distribution, and analysis of data from large global GPS networks. In the future, global networks will be large, integration of multiple techniques will be required, and demands for rapid data access and rapid data processing and analysis techniques will increase. It is therefore essential that additional global campaigns, such as the proposed IGS Epoch'92 campaign, be executed to prepare for the deployment of a global network of fiducial sites.

Recommendation 4: The Panel recommends that the global network be completed in parallel with the initiation of regional densification to study local and regional geophysical problems. This process should be driven by scientific issues at both the global and regional levels.

By itself, the global network will not suffice to solve some of the crucial scientific problems. Work on geological or geophysical problems that would benefit immensely from the global network also requires a higher density of sites, on a regional or local scale, than the network can provide. Densification should therefore be considered an intrinsic aspect of the global deployment that should be driven by the scientific requirements of each application. The resolution of technical issues such as data flow and analysis can be developed in the context of the global network and applied or adapted immediately to the solution of local problems. In other words, the Panel sees substantial benefits in proceeding with local densification at the same time as the global network is being deployed, at both the technical and the scientific levels. In many instances global fiducial sites might often be selected from high-quality sites (i.e., well-monumented, geological-ly stable) in a regional network.

Recommendation 5: The Panel recommends that, whenever feasible, the deployment of fiducial sites in the global network be coordinated, in terms of site selection and network operation, with deployment of instruments used by scientific disciplines in addition to geodesy, to (1) facilitate data

*integration, (2) achieve economies of scale, and (3) realize the scientific
benefits of multidisciplinary studies of the Earth.*

It is clear that global geophysical networks are of great interest not only to
geodesy but also to other disciplines of the Earth sciences, including seismology,
geomagnetism, gravity, oceanography, and volcanology. There is of course no
reason that the list should stop here; other types of measurements that should be
considered include atmospheric, geochemical, meteorological, and environmental.
Partly in recognition of this situation, the concept of FLINN as a set of globally
distributed sites with a multidisciplinary vocation was proposed as a logical and
desirable generalization of the initial geodetic network concept. This is why
"Laboratories" is used in the acronym, which honors the late E. A. Flinn, who led
the NASA Crustal Dynamics Project and helped develop it into an international
collaboration. In this sense FLINN might really be thought of as the necessary
ground component of the *Mission to Planet Earth*—that is, the core of the
Permanent Large Array of Terrestrial Observatories (PLATO) originally proposed
as an integral element of the mission. Such a coordination, if effective, could have
a major positive impact on the *Mission to Planet Earth* and may in fact be the best
way that the ground segment of this mission can be developed to its full scientific
potential. Precise space-geodetic control is of course an essential ingredient of
FLINN and is the basis for the long-term goal the Panel set for the global network
of fiducial sites. But a coordinated program in telemetry and data management
without question could provide real economies of scale: As the seismological
community is developing adequate technological solutions to its part of the
problem, seismologists are likely to use the lion's share of available bandwidth.
Therefore, it seems probable that other disciplines will benefit from a multidisc-
iplinary approach.

*Recommendation 6: The Panel recommends (1) continuing the evaluation
of new observing techniques and investigation of the role of GPS in
complementing VLBI and SLR, (2) continuing VLBI and SLR observations
at key sites for the foreseeable future, (3) obtaining parallel data sets
where major changes in instrument systems are made at critical sites, (4)
continuing observations with no change in technique and no gap in data
or discontinuity in the time series or its first derivative where there are
discrepancies between existing systems, and (5) maintaining mobile
VLBI/SLR capability to allow reoccupation of VLBI/SLR sites.*

In this era of rapid technological development, observing systems that are more precise and more economical to operate inevitably will evolve. However, we must not lose sight of the value of geodetic time series in evaluating long-term change. It is therefore incumbent on system and network operators, to the extent possible, to minimize disruptions in these time series by changes in technology, observing techniques, and analysis procedures. Further, until it is demonstrated, within the limits of accuracy of the data, that a significant discontinuity in a time series or its derivative does not exist, the ability to collect additional data compatible with the conditions preceding the change remains very valuable and should not be abandoned. These considerations obviously apply to changes in the fundamental technology, such as the transition from VLBI to GPS monitoring at a site, as well as to the situation where a mundane change of monument takes place at a given location.

It must be noted that space-geodetic techniques involve many corrections, such as those for ionospheric and tropospheric effects, water vapor, clock corrections, relativistic terms, and, of course, survey ties to a ground monument. As experience is acquired with each system, geodesists' confidence in the results increases. Nevertheless, as demands for precision and accuracy continue to push the limits of every technique, new sources of errors, both random and systematic, must be carefully assessed. It is essential to continue the systematic comparison of results obtained by different techniques along the same baseline. This comparison will be critical to the integration of GPS with the existing networks, particularly VLBI and SLR, and is the principal method we have for recognizing and eventually eliminating sources of systematic errors.

Possible Network Configuration

After examining many existing global geodetic and geophysical networks (see Chapter 3), the Panel undertook to map a network configuration with two purposes: (1) to develop a general feeling for the magnitude of the task of establishing a network and gauge the extent to which existing sites might be used to start the deployment in the near future and (2) to obtain a general idea of the appearance of a global network of fiducial stations. This map (Figure 1) is intended to illustrate the type of network being considered by the Panel but not to

Tracking GPS "core" network (28 sites)
Global Fiducial Sites (about 170 sites)
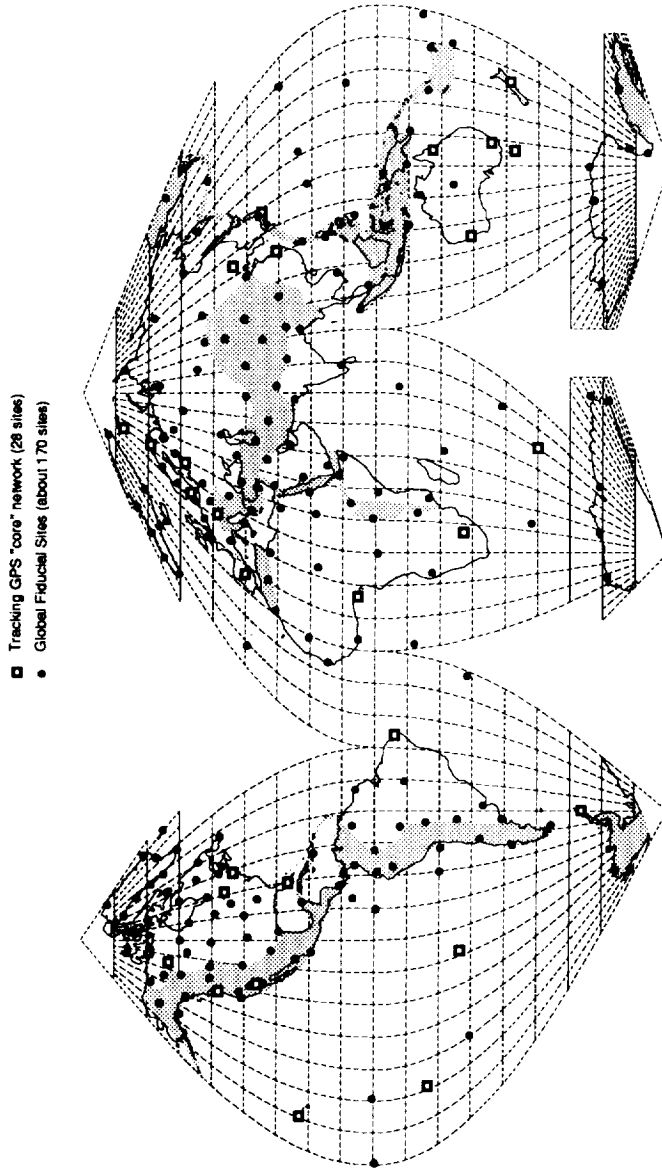
Example of Possible Global GPS Fiducial Network

FIGURE 1. Possible configuration of a global network of fiducial stations. Core sites are taken primarily from existing permanent sites; others are selected according to the arguments outlined in Chapter 4 of this report. Shaded areas indicate regions of recent or current tectonic activity.

depict a specific site selection process. The GPS core network is derived from existing CIGNET and DSN sites with a few additions in locations where other countries have said they intend to run permanent GPS stations (e.g., Tahiti, where the French intend to collocate GPS and DORIS equipment). The additional sites are drawn from existing and planned campaigns and from existing networks such as those discussed in Chapter 3. Sites shown in Siberia, Tibet, and Africa are purely imaginary and are distributed so as to meet the scientific goals mentioned above, as are a number of island sites. The criteria leading to this network configuration are discussed in some detail in Chapter 4.

This exercise highlighted the fact that existing and planned sites with a global flavor are already remarkably numerous. The robustness and reliability of GPS orbits determined from the core network in Figure 1 has yet to be fully quantified, so that it is not yet clear that coverage is adequate and robust in all areas. (It might be necessary to deploy redundant equipment at certain island sites to achieve the desired reliability.) Collocation of different geodetic techniques and of geodetic instruments with other scientific instruments makes considerable sense in areas where the density of existing deployments is low. This is the case in most of Africa, Antarctica, and large areas of Asia. In such instances, where any measurement would in essence break new scientific ground, the multidisciplinary site concept would offer extraordinary scientific benefits. Finally, in vast oceanic areas the global networks are unavoidably sparse. Many disciplines have been developing ocean bottom instrumentation and exploring ways to retrieve the data reliably and conveniently. This is also true of geodesy, and, as the technology becomes available over the next few years, it will become desirable and in some cases imperative to add sea bottom fiducial sites to the global network.

2
SCIENTIFIC RATIONALE FOR GLOBAL NETWORKS

Introduction

Geodesy as a scientific discipline is in the enviable position of marrying fast-developing technology with rapidly expanding scientific goals. In a sense it is valid to ask whether technology development drives the science to the same extent as scientific requirements drive the technological innovations. As high-precision space-geodetic techniques become more easily accessible to the scientific community, the range of problems that geodesists can attack in earnest expands to incorporate problems previously deemed too formidable to be treated successfully. Examples abound as described in detail in several recent reviews, such as the Erice and Coolfont workshop reports mentioned earlier, and several recent reports by the National Research Council's Committee on Geodesy (*Geodesy: A Look to the Future*, 1985; *Current Problems in Geodesy*, 1987a; *Geodesy in the Year 2000*, 1990a). These reports cover the opportunities offered by space-geodetic techniques and make specific recommendations concerning the areas in which to focus attention now and in the next decade or two. In this chapter we draw from these studies but adopt a somewhat more specialized point of view. Specifically, we endeavor to identify scientific problems that cannot be addressed properly in the absence of a global network, as well as applications of space geodesy that would benefit directly and substantially from such a network without requiring its existence. In addition, we recognize that precise global geodesy by itself is not a panacea that will produce the needed solutions, and we attempt to consider its contribution in the context of the broadly based, multidisciplinary environment advocated in *Mission to Planet Earth* (National Research Council, 1988).

Although space geodesy is a relatively young discipline, it tends by nature to adopt a global perspective. For instance, SLR and VLBI networks (including the QUASAR network) have a global scope, although they do not provide uniform

coverage. More recent deployments, such as the DORIS and PRARE networks, are both global and quite uniform by design. The rapidly growing CIGNET GPS network exhibits similar characteristics, especially when considered in conjunction with other stations such as the tracking sites currently being deployed by NASA. Temporary global GPS deployments have been conducted successfully (e.g., GOTEX), and a global international campaign (GIG'91) was conducted in early 1991 under the aegis of IERS. Although our focus is on geodetic networks, other disciplines dealing with solid Earth science are actively building global networks of their own. These include, for instance, seismic networks (e.g., GEOSCOPE, IRIS GSN) and magnetic observatories (INTERMAGNET). Largely in recognition of the value of multidisciplinary measurements, the concept of the Permanent Large Array of Terrestrial Observatories (PLATO) was originally proposed as one of the two major elements of the *Mission to Planet Earth*.

Scientific Goals

It is self-evident that the major purpose of global geophysical and geodetic networks is to permit the collection of observations capable of constraining models of the planet as a whole. The qualifier global takes on a dual connotation in this context. On the one hand, such data are needed to study phenomena that operate on a *global scale*—instead of continental, ocean basin, or any of a hierarchy of scales down to the dimensions of grains that form the rocks. On the other hand, even when the scales under consideration are much smaller than the radius of the planet, so that a regional or even local description may be adequate, *global coverage* is still desirable to help understand the underlying physical processes that shape the planet. Long-wavelength features are then used as a background to analyze short-wavelength components. The scientific goals of global networks should reflect this duality (see also International Association of Geodesy, 1991):

The dual scientific goals of global geophysical and geodetic networks are (1) to improve understanding of geophysical and geological phenomena that operate on global scales and (2) to provide a framework and boundary conditions to analyze phenomena that operate on smaller scales.

A simple illustration is the spherical harmonic expansions commonly used to describe global characteristics of the Earth. The geopotential and geomagnetic fields are classical examples, but this type of representation is also used for the

three-dimensional internal structure of the Earth determined by seismic tomography, in models of convection currents in the mantle, or even to describe the kinematic plate velocity field at the surface. In some instances, global coverage—at least at sufficiently long wavelengths—is provided by observations from satellites in low Earth orbit. This is true of potential fields. However, for small-scale features, and for all structural, kinematical, and dynamical models of the Earth that depend on surface observations, the resolution is limited by the coverage provided by surface observatories. For instance, the determination of radial and lateral inhomogeneities in seismic velocities requires a *global* distribution of both seismic stations and seismic sources. Because Earth is a dynamic planet, and because its surface is covered by highly mobile tectonic plates, even measuring the rotation parameters of the planet—a global characteristic *par excellence*—requires adequate *global* coverage by a network of space-geodetic observatories. For that matter, even defining an International Terrestrial Reference Frame, on a planet where every piece of real estate is in constant motion with respect to every other piece, is a challenge (e.g., Boucher and Altamimi, 1989), and current realizations depend on data collected at a set of *globally* distributed sites.

With geodetic precise positioning networks, these problems are sharpened by the lack of a natural and unambiguous way to interpolate observations. We do not enjoy the benefit of having potential fields or elastic waves to define a physical averaging of pointwise properties (such as density, velocity, and Poisson's ratio) of the Earth and, therefore, must resort to using a particular mechanical and rheological model of the Earth between sites to interpolate and interpret the data. This technique is often quite successful when the intersite distances are smaller than or comparable to scales of relevant inhomogeneities. However, for spatial scales that can be realistically sampled by global networks, this approach is fraught with danger, because large-scale crustal inhomogeneities are likely to invalidate smooth strain models between sites. Geodesists therefore have deployed a hierarchy of networks in which sparser regional networks serve as fiducial sites in the survey of denser local networks. With the advent of space geodesy, we can conceive of and actually implement a global high-precision network of sites that will serve as fiducial points tied to a common reference frame with uniformly high precision. The deployment of such a network will substantially influence the various uses of space-geodetic techniques. The first steps have already been taken toward a goal that is specific to geodetic global networks, namely (see also International Association of Geodesy, 1991):

Geodetic measurements with a precision of approximately 3 mm or better, in both horizontal and vertical components, should be made possible at any time, anywhere on the planet, on spatial scales ranging from a few kilometers to intercontinental distances, with an achievable temporal resolution of a day or better.

Millimeter-precision geodesy is now possible even on very long baselines using VLBI (e.g., Herring, 1991). In other words, the technological know-how exists to achieve this level of precision between properly upgraded VLBI sites. The problem raised by this goal is therefore not so much to achieve very precise measurements, but rather to make them affordable and logistically feasible at unprecedented temporal and spatial densities. The equivalent strains detectable with such a deployment would be about 10^{-6} on local scales and better than 10^{-9} on global scales, with a temporal resolution of 1 day or better. On local scales such a capability obviously would neither duplicate nor supplant existing techniques such as observatory strainmeters capable of detecting strains of a few parts in 10^{10} over times shorter than a day (Agnew, 1987). Instead, the capability should be viewed as complementary, designed to investigate spatial patterns of rather large strains and their variability with space and time, an aim not achieved by most existing geodetic monitoring networks primarily because of their low time sampling rates.

Although our goal introduces 3 mm as a target precision, it must be recognized that in many areas of the world significant scientific progress would result even from measurements made at a precision of 10 mm. This is true, for example, of areas where crustal motions are poorly known and where any geodetic constraint would help. As an illustration, crustal deformation in the India-Eurasia collision zone, which includes the large Tibetan Plateau, is a matter of considerable current debate among geologists and tectonophysicists (England and McKenzie, 1982; England and Houseman, 1989; Molnar and Tapponnier, 1975; Tapponnier *et al.*, 1982; Peltzer and Tapponnier, 1988). In that case, reconnaissance geodetic surveys would be most valuable to help select among the various deformation models proposed in the literature. In other instances a precision of 1 mm for daily measurements would be very desirable. This is true, for example, of areas already well instrumented, where important geological problems are likely to require analysis and interpretation of rather subtle geodetic signals. Examples include the detection and analysis of postseismic, interseismic, and possible preseismic strains within plate boundary deformation zones such as the western United States or intracontinental seismic zones such as the New Madrid area in the central United

States. Averaging observations over longer times will of course improve the detection of small signals with long time constants, but it must be borne in mind that systematic effects do not cancel in such a procedure and that the rule of thumb is that a signal-to-noise ratio improvement of a factor of three constitutes a practical limit. Furthermore, especially at the millimeter level, monumentation issues are important (e.g., Wyatt, 1982, 1989), and geological interpretation is chancier.

The goal stated above could be reached through a coordinated international effort by the middle of the decade and should be largely surpassed—in precision as well as spatial and temporal resolution—by the year 2000. As stated, it is compatible with several recommendations cited in Appendix A and incorporates some of the notions expressed in them. Although global networks are not discussed in detail in the Erice report, which focuses on geodesy, they are a centerpiece of the Coolfont report, which is permeated by the notion of global studies of the Earth. This includes not only global altimetric, geodetic, geological (e.g., soil and surface processes), and geophysical coverage (e.g., potential fields) but also studies of large-scale structures of the interior of the Earth, for which a multi-disciplinary approach is essential. As an example, a recommendation of the Coolfont Plate Motion and Deformation Panel states:

> *In order to study plate motion we need a global distribution of geodetic stations that measure relative positions to 1 cm over one day and to 1 mm over three months. In order to monitor regional and local deformation we need a terrestrial reference frame. Both of these objectives can be accomplished with a global distribution of space-geodetic observatories.*

Although this recommendation is couched in terms of a geodetic network, the concept that has been derived from it involves a set of globally distributed sites with a multidisciplinary vocation, described collectively as FLINN. As stated in the Coolfont recommendation, FLINN sites should also be tied to a geocentric reference frame with a precision of 1 mm averaged over 1 year and should serve as fiducial sites for dense regional networks (NASA, 1991).

Objectives

The primary scientific objective of a Global Network of Fiducial Sites is to provide an effective and economical means of acquiring, analyzing, and archiving the data required to solve global problems. The primary objectives are identified directly with research topics that cannot be pursued in any other way. In this category we place the study of complex multiscale problems such as global sea-level monitoring and postglacial rebound, for which global coverage is essential. A second category involves the precise measurement of tectonic motions, including plate deformation. The most interesting signals are departures from the motions predicted by the long-term geological models (e.g., Jordan and Minster, 1988a). Further, many signals of practical interest that take place on local and regional scales can only be interpreted properly if the large-scale motions are well understood. Such problems place very stringent demands on network operations and often require improved solutions to other problems with a global character, such as the determination of an improved geoid or the measurement of densely sampled, precise time series of Earth orientation and rotation parameters.

Other objectives, no less important, are more easily defined in terms of support of various scientific endeavors: examples include the calculation of precise orbits for a variety of Earth-orbiting spacecraft and the realization of a precise global reference frame. Applications that do not intrinsically require a global network but that would benefit directly from it cover a wide range of geological problems, such as relative motions across specific plate boundaries and plate boundary deformation zones, earthquake and volcanic cycles, and altimetric surveys. Finally, with the advent of inexpensive, and lightweight space-geodetic techniques such as GPS, a suitably dense, carefully maintained global set of fiducial points would have a significant impact on almost all aspects of geodesy, including practical surveying considerations.

For our present purposes, geological and geophysical objectives may be discussed from the point of view that they identify certain scientific users of global geodetic data, the scientific customers of the global network. Geological and geophysical objectives are primarily applications of the capability obtained through the global network. But most of these applications require some degree of densification of the network to achieve the spatial and temporal resolutions needed to make substantial contributions.

Two major global problems are used as examples to support and focus our discussion. These are:

- global sea-level change, response to surface loads, and postglacial rebound

and

- tectonic motions and intraplate deformation.

The rates of horizontal motions from these phenomena are comparable. The main distinction is that the regional vertical motions associated with the first are typically much greater than for the second. As a result, although each of the problems of eustatic (global) sea-level change, postglacial rebound, and intraplate deformation has its own intellectual focus, these problems are very tightly intertwined from an observational standpoint. Not one of them can be solved independently of the others. For example, present sea-level change cannot be inferred correctly from tide gauge records without first adjusting observations of relative sea level for postglacial rebound. Similarly, horizontal motions associated with postglacial rebound or surface loading caused by sea-level changes are comparable to those associated with departures from the predictions of rigid plate theory. The challenge is to separate the deformations associated with tectonics from those associated with surface loads.

In order to meet this challenge, we must first meet specific geodetic objectives, which must subsume those listed by Knickmeyer (1990). These include:

- determination of precise orbits for spacecraft used in geodesy and geophysics,
- precise determination of Earth rotation and orientation parameters,
- realization of a precise global terrestrial reference frame,
- support of scientific orbital missions, and
- support of local and regional studies.

The first four of these objectives might be identified with providers of information and data made available via the global network. The fifth objective pertains to end users of the global network. Because of the large community of professional users of the data products (such as GPS ephemerides) provided by the global network operation, the concept of a service is an important component of international organizations such as IERS or the proposed IGS. However, this concept affects primarily the issues of data processing, management, and distribution; it does not introduce new constraints on network design as high-quality orbits (covered by the first objective) would satisfy the vast majority of the needs of the professional community.

The global solid Earth scientific problems that can be addressed, at least in part, through a global geodetic network share one feature: they are characterized by a spectrum of spatial and temporal scales. As a result, one is strongly tempted to seek ever-improved resolution by densifying the network everywhere. One possible approach is to construct a large global network as an assemblage of properly connected regional networks, the operation of which must be carefully orchestrated and coordinated. This approach may well be viable in the long run, but it seems preferable first to discuss general global network design without introducing the complications of a practical implementation strategy. In the following discussion, several numbers will prove useful:

The area of the Earth's surface is 5.1×10^8 km^2, with a square root of 2.3×10^4 km. This means that a 25-station global network uniformly distributed on the surface of the Earth will have an average intersite spacing of $\sim 4,400$ km. This is a crude, but workable characterization of a GPS core network. A 100-station network would have an average intersite spacing of $\sim 2,200$ km, and more than 400 stations would be needed to achieve an average spacing approaching 1,000 km, assuming again a globally uniform distribution. Of course, such a geodetic network cannot be easily realized because of the presence of large oceanic areas without emerged lands.

Geophysical and Geological Objectives

Eustatic Sea-Level Change. Global sea-level change is one of the most easily imagined end results in the chain of effects hypothesized to come from man's interference in the global climate system (see, e.g., *Sea-Level Change*, National Research Council, 1990b; also *Towards an Integrated System for Measuring Long Term Changes in Global Sea Level*, Joint Oceanographic Institutions, 1990). Human agricultural activity and consumption of fossil fuels are causing a possibly unprecedented increase in carbon dioxide and other greenhouse gases in the atmosphere. This is expected to lead to increased retention of solar heat and thus to global warming. Two possible consequences are more rapid melting of polar ice caps and mountain glaciers and an increase in the volume of water in the oceans because of thermal expansion. Both would cause a worldwide (eustatic) sea-level rise. Such an event, even if it were not large enough to cause widespread inundation, would be disastrous for coastal regions if only because it would increase the rate of coastal erosion. On the other hand, the climate changes

associated with global warming might lead to increased precipitation over ice sheets, resulting in an increase in the amount of water trapped in polar ice caps and thus a decrease in eustatic sea level.

While those who attempt to model the complex interconnection of climatic processes have generated great controversy without much predictive success, other scientists attempting to measure directly the temperature or sea-level manifestations of the indisputable increases in atmospheric carbon dioxide are also facing great difficulties. Relative sea-level (RSL) change would seem to be a fundamental observable that should be obvious over the years at any coastal location. And in fact RSL has been monitored fairly precisely at many locations. Many good tide gauge records go back more than 100 years. The problem is that these observations depend on many factors in addition to changes in the mass of water in the oceans. Factors affecting RSL across the whole range of time scales include:

- changes in water volume caused by changes in temperature and salinity;
- changes in area and shape of the ocean basins;
- changes in volume and spatial distribution of ice;
- oceanographic signals such as basin-scale circulation, local currents, and tides;
- atmospheric or meteorological signals such as winds and barometric pressure changes;
- elastic and viscous response of the solid Earth, including postglacial rebound and tectonic motions;
- local ground effects such as compaction or changes in the water table;
- solid Earth tides and ocean loading tidal responses; and
- changes in the inertia tensor and Earth orientation/rotation parameters associated with changes in the Earth's center of figure relative to the center of mass.

These factors were the subject of an extensive review in *Sea-Level Change* (National Research Council, 1990b). Table 1 summarizes the factors contributing to relative sea-level changes at various time scales.

Problems at shorter time scales associated with extracting a reliable rate of eustatic sea-level change from tide gauge records are illustrated by Figure 2. First, as the figure shows, annual deviations from the secular trend can be fairly large—the mean annual sea level varies at the level of centimeters. This variation is due to atmospheric and oceanographic (short-term) influences on RSL.

TABLE 1. Some mechanisms of sea-level change (from National Research Council, 1990b).

	Time Scale (years)	Order of Magnitude of Change (mm)
Ocean steric (thermohaline) volume changes		
Shallow (0 to 500 m)	10^{-1} to 10^{2}	10^{0} to 10^{3}
Deep (500 to 4,000 m)	10^{1} to 10^{4}	10^{0} to 10^{4}
Glacial Accretion and Wastage		
Mountain Glaciers	10^{1} to 10^{2}	10^{1} to 10^{3}
Greenland Ice Sheet	10^{2} to 10^{5}	10^{1} to 10^{4}
East Antarctic Ice Sheet	10^{3} to 10^{5}	10^{4} to 10^{5}
West Antarctic Ice Sheet	10^{2} to 10^{4}	10^{3} to 10^{4}
Liquid Water on Land		
Groundwater Aquifers	10^{2} to 10^{5}	10^{2} to 10^{4}
Lakes and Reservoirs	10^{2} to 10^{3}	10^{0} to 10^{2}
Crustal Deformation		
Lithosphere Formation and Subduction	10^{5} to 10^{8}	10^{3} to 10^{5}
Glacial Isostatic Rebound	10^{2} to 10^{4}	10^{2} to 10^{4}
Continental Collision	10^{5} to 10^{8}	10^{4} to 10^{5}
Sea Floor and Continental Epeirogeny	10^{5} to 10^{8}	10^{4} to 10^{5}
Sedimentation	10^{4} to 10^{8}	10^{3} to 10^{5}
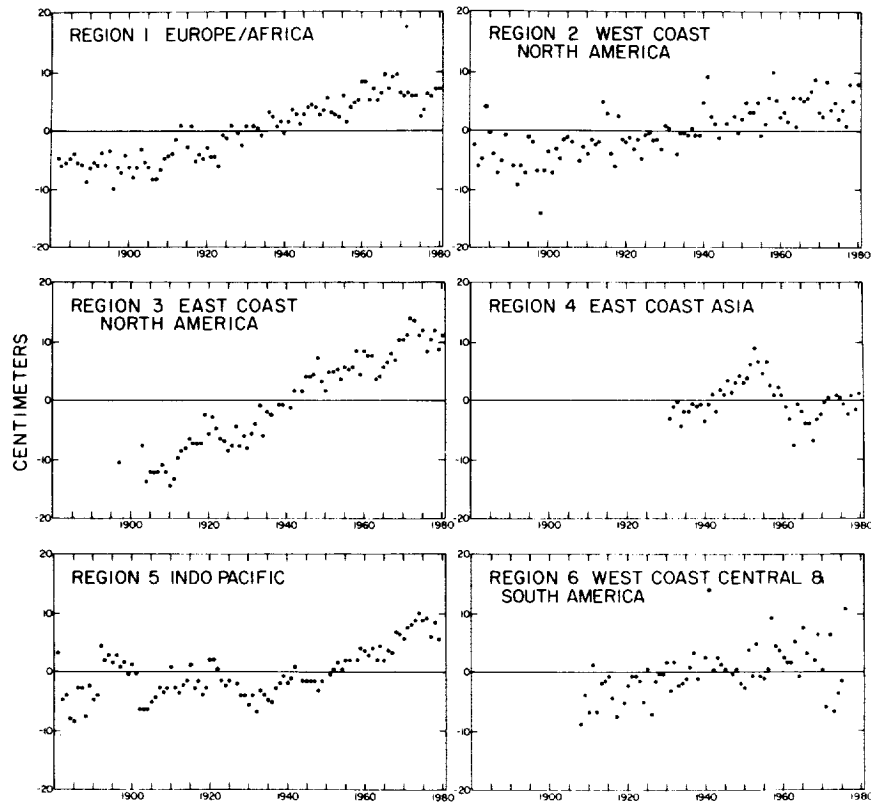
FIGURE 2. Regional averages of annual sea level anomaly (from Barnett, 1984; see also National Research Council, 1990b, p. 17).

Second, the secular trend varies with location, with differences between local trends comparable to the amplitude of the secular trend itself. This effect is due mainly to continued viscous relaxation, or postglacial rebound, following the Pleistocene deglaciation ~ 10,000 years ago, although tectonic motions and elastic response to loading of the crust also contribute, as we shall see.

Perhaps the best understood of the short-term effects is the inverse barometer effect: local sea level rises 1 cm for every 1-mbar decrease in barometric pressure. This effect is important in the midlatitudes, where large pressure fluctuations over

periods of a few days cause sea-level changes of 10 to 20 cm. On a monthly basis, a typical standard deviation of 4 mbar leads to a 4-cm variation in RSL, translating into a 1-cm standard deviation for annual RSL. While barometric changes probably have a very small variability on a decadal basis, century-scale barometric trends have been noted at individual sites. Another local and short-term contributor to RSL is wind forcing. It is particularly significant in shallow seas, where the wind effects may be larger than the barometric contributions.

Other complications contaminating the RSL record introduce variability on larger spatial and longer temporal scales. Larger regional effects are due to steady-state basin-scale flows and to oscillations on regional and global scales. Figure 3 is a world map of dynamic ocean topography derived from GEOSAT satellite altimetry. To determine dynamic ocean topography from satellite altimetry, the orbit must be determined very precisely using tracking stations (tied to the global fiducial network). Furthermore, atmospheric and ionospheric effects must be modeled, which requires knowledge of atmospheric variations, and the geoid must be removed, which again links the sea-level problem to solid Earth geophysics. Despite this need for a cascade of interdisciplinary data corrections, satellite altimetry has been very successful in observing sea surface topography over a fairly wide range of spatial and temporal scales. Data from the GEOSAT mission are still providing better insight into the basin-scale circulation (see Figure 3) and are helping to quantify regional effects such as the El Niño-Southern Oscillation (Douglas, 1991). However, resolving large-scale oscillations with periods of years to decades and correcting RSL estimates for such sources of contamination (basin-scale sloshing) will require longer observation periods (e.g., Sturges, 1987). Upcoming missions such as ERS-1, TOPEX/POSEIDON, and the Earth Observing System (EOS) will provide immense volumes of new data that will presumably help unravel the many oceanic, atmospheric, and solid Earth contributions to understanding global sea level.

To estimate eustatic sea-level changes, various corrections have been applied to correct the raw data for the many effects on tide gauge readings of RSL (e.g., Douglas, 1991). Gauges in tectonically active areas must at present be excluded from the analysis given the current lack of independent measurements of the motion of the land. Modeled tide gauge motions caused by postglacial rebound have been removed to obtain better long-term secular variations in eustatic sea level (see, e.g., Peltier, 1990) (although, for reasons discussed below, the corrections made include substantial uncertainties, with differences among models of ~1 mm/yr). These studies of corrected tide gauge records indicate a global eustatic sea-level rise of about 2 mm/yr over the past 50 to 100 years. Only about

34
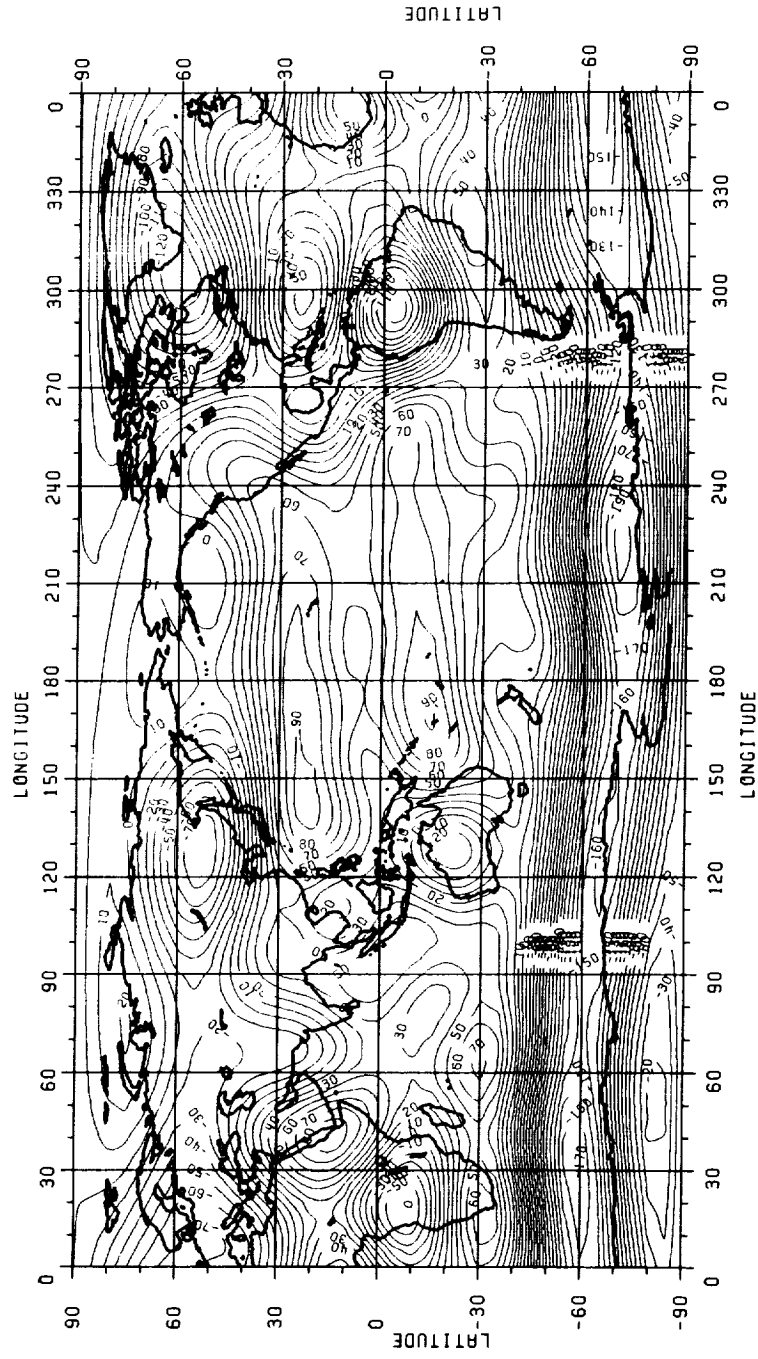
FIGURE 3. Dynamic sea surface topography caused by global ocean circulation derived from 1 year of GEOSAT Exact Repeat Mission altimeter data. Contour interval is 10 cm (from Denker and Rapp, 1990).

10% of this rise can be accounted for by thermal expansion of the oceans, so a substantial input of water into the oceans is needed to account for the rest. Lakes, groundwater, and mountain glaciers seem to account for only about a 0.7 mm/yr increase in sea level (e.g., Meier, 1990); hence, about 1 mm/yr is unaccounted for. The only sources that have been proposed to explain this discrepancy are Greenland and Antarctica, although published—albeit controversial—estimates of mass balance for these ice sheets indicate growth rather than decay (e.g., Zwally, 1989; Zwally et al., 1989; Meier, 1990). It is apparent from the variability of estimates in the literature that we do not know either the magnitude or sometimes even the sign of specific contributions of various sources to variations in sea level. As recognized by the Committee on Earth Sciences of the White House Office of Science and Technology Policy (1989, p. 32):

> Our most glaring deficiency in knowledge of the cryosphere is whether Antarctica and Greenland are gaining or losing ice because, with 99.3% of the combined volume of the world's ice, changes in their volumes have the greatest potential impact on sea level.

Careful monitoring of snow accumulation (possibly aided by satellite missions to profile ice sheet topography) combined with field surveys of ice sheet flux and satellite monitoring of iceberg calving is one approach to this problem (Thomas, 1991). However, a direct approach, using the elastic properties of the crust as a spring balance for detecting changes in the ice sheet mass, has the advantage of providing a spatially integrated response (Hager, 1991). For a uniform disk of ice with a radius of 1,000 km, the vertical displacement of the Earth's crust at the edge would be about 10% of the total change in ice thickness, with the crust springing upward in response to ice wastage and sagging in response to accumulation. Rela-tive horizontal displacements are up to two-thirds of the vertical displacements, with the edges springing outward in response to a decrease in ice sheet mass. (These motions are elastic responses to very recent loads, not long-term visco-elastic behavior such as postglacial rebound.) Thus, one important reason for deploying an accurate geodetic network in polar regions is to assess changes in ice sheets in order to constrain the net water input to or removal from the ocean basins.

In addition to this regional elastic response, redistribution of mass caused by ice sheet melting or growth will affect the Terrestrial Reference Frame. Redistribution of surface loads by the melting of ice sheets and resulting transfer of mass to the oceans leads to a change in the center of figure (CF) of the Earth relative

to the center of mass (CM), whose trajectory in inertial space is, of course, unaffected by this redistribution of mass, since no external forces are involved. Measuring this offset provides a powerful means of monitoring these large-scale changes. For example, melting of an average of 1 m of ice from the Antarctic ice sheet (sufficient to change sea level by 40 mm) would lead to a shift of the CM relative to Earth's surface of 15 mm. Table 2 lists recent estimates of ice sheet evolution and the corresponding effects on sea level, expected elastic displacements of the crust, and CF shifts. This set of simple conclusions is given primarily for illustration purposes. More extensive modeling is needed to account for all possible effects, including combinations of various sources of possible CF shifts. One important criterion of a global network of fiducial sites is that the positions of these sites should be known in a center-of-mass reference frame to a precision sufficient to support the scientific questions raised by mass redistribution. These changes in surface load also change the moment of inertia tensor, leading to polar motion (e.g., Douglas *et al.*, 1990).

The surface loads resulting from changes in short-term nonsteric loads such as shown in Figure 3 will also cause significant elastic displacements of the crust that will be detectable by a global geodetic network. Thus, oceanographic, meteorological, and solid Earth processes are closely coupled.

To summarize the present understanding of global sea-level changes, we note that many processes acting on different spatial and temporal scales are contributing. Observations of many different quantities are necessary to unravel the interfering effects. Meteorological parameters (rainfall, surface winds, surface pressure) are relevant not only for their own direct climatological sakes but also for their indirect effect on sea-level measurements and surface displacements at the shorter time scales. If we can understand the effects of these factors within the frequency band in which they are dominant, we will be able to remove their effects over longer time periods. And if we can monitor these effects continuously, we will reduce the contamination of our results by spatially and temporally localized effects.

Postglacial Rebound. Intimately related to RSL change is postglacial rebound; this classic problem in geophysics is gaining renewed importance for both scientific and societal reasons. Aside from the relationship to global climate change by way of the rebound signal's strong presence in most available tide gauge and geological observations of relative sea level, today the problem is of increasing interest because it can provide crucial constraints for understanding the dynamics of

TABLE 2. Proposed rates of change in average thickness of the Greenland and Antarctic ice sheets, with the predicted concomitant change in relative sea level, vertical displacement rate, u (positive downward), and shift of the center of figure (CF).

Ice Sheet	Radius (km)	Δ Ice (cm/yr)	Δ RSL (mm/yr)	u (mm/yr)	CF Shift (mm/yr)
Greenland (1978-1986) (Zwally, 1989)	465	21	−0.4	10	0.1
Greenland (1990-2050) (Meier, 1990)	465	−60	1.2	30	0.3
Antarctic (recent) (C. Bentley, private communication, 1991)	2,100	2	−0.8	4	0.3
Antarctic (1990-2050) (Meier, 1990)	2,100	13	−5	27	1.7

mantle convection and the driving mechanism of plate tectonics (e.g., Peltier, 1989). Several recent investigations of mantle viscosity as probed both by changes in surface loads (associated with deglaciation) and by the geoid signal from interior loads (plate tectonic slabs) have suggested that the radial and lateral variations of viscosity have more structure than had previously been believed. Constraining the variation of mantle strength with depth is crucial for understanding the dynamics of mantle convection and the driving mechanism of plate motions.

More importantly from a societal perspective, in order to measure the changes in ocean mass and volume associated with global change, it is crucial to separate out this "noise" from deformation of the solid Earth in order to recover the "signal" of global sea-level change. The fundamental observations used in modeling postglacial rebound are surveys of the relative heights of geomorphological features such as raised beach terraces that can be dated reasonably well over the past few hundred to few thousand years. The rheological models that fit these observations generally predict present local vertical changes (either upward or downward, depending on location relative to the historic ice load) on the order of 0.5 to 10 mm/yr. Horizontal velocities are comparable. This means that postglacial rebound, like the elastic displacement of the Earth in response to changes in

surface loads, has large geodetic signatures that must be understood and modeled thoroughly if we wish to study sources of motion such as those from continental epeirogeny or intraplate deformation. Models derived by different investigators vary greatly in their predictions of present motions. The reasons include the following serious problems:

- The geometry of the ice load is not known in detail.
- The melt history is not known in detail.
- Different *a priori* assumptions are made by different investigators.
- Rebound models do not yield very good resolution of mantle structure.
- Lateral variations in mantle rheology are likely.

These factors trade off against the details of the resulting rheological models that fit postglacial rebound—a reflection of the nonuniqueness of the inverse problem. Some of these problems can be reduced by considering viscosity constraints inferred from the geoid response to interior loads (such as descending slabs), constraints associated with the dynamics of plate motion, and constraints derived from observations of Earth rotation and nutation. Among the scientific questions driving research in the general area of postglacial rebound, mantle rheology, and changing sea level are the following:

- What are the lateral variations in mantle rheology? Different estimates of mantle rheology have come out of studies focused on different regions. There is a systematic trend in these estimates of upper-mantle viscosity as a function of tectonic age. We can rank them in order of decreasing inferred upper-mantle viscosity, as follows: (1) Laurentian (predominantly shield); (2) Fennoscandia (shield plus Paleozoic fold belt, close to ocean); (3) Australia (shield and Paleozoic fold belt, close to ocean); and (4) Pacific Islands (ocean basin).
- What has been the amount of melting of the Antarctic ice sheet in the past 6,000 years? There is a substantial trade-off between mantle-inferred viscosity structure and ice load history. Models that assume no recent melting yield estimates with higher upper-mantle viscosities and smaller lower-mantle viscosities than those that assume recent melting. These models differ in their predictions about the current rate of collapse of peripheral bulges surrounding various ice sheets, as well as on the tilting of continental margins caused by the load from increased melt water in the ocean basins.

Consideration of postglacial rebound will influence the optimum geometry of a global network of fiducial sites, and its contribution must be fully understood before other problems can be solved. In terms of network design, these points lead to the following general considerations:

• Network design is a multiscale problem. The density of sites must vary as a function of distance from the center of the ice sheet, and good azimuthal coverage is needed.

• Global coverage would help to unravel the complexities of the problem. However, at large distances from the ice sheets, the signals are small (0.5 mm/yr vertical, compared to 5 to 10 mm/yr vertical close to the ice sheets, based on disk load approximations). The problem may be best addressed with a combination of global and regional sites.

• Sampling rates, including continuous recording, are not mandated by the postglacial rebound signal itself: if the signal were large, the time scales involved could be sampled through occasional campaigns. However, high sampling rates are desirable to reduce noise in the rate estimate, to avoid temporal aliasing, and to improve noise modeling, particularly since fundamental questions about mantle viscosity will require resolution of rather subtle characteristics in the data.

• Horizontal as well as vertical motions are useful for discriminating among models of mantle rheology (e.g., James and Morgan, 1990).

Changes in the ice mass will also trigger secular motions of the pole. The centroid of the annual and Chandler (14-month) motions shifts in response to long-term redistribution of mass within and on the surface of the Earth. Historically, the pole has been shifting by approximately 3 milliarc-seconds per year toward Hudson Bay, Canada. This rate is in good agreement with the rate expected from glacial rebound. Since the motion depends on all changes in mass distribution, it cannot be ascribed to any specific cause, such as ice buildup on Greenland, but it can be used to place constraints on mass relocation and thus help test the consistency of putative changes (Douglas *et al.*, 1990).

Tectonic Motions and Deformation. A major conclusion from the NASA Crustal Dynamics Project is that the space-geodetic estimates of relative plate motions over the very short time of 10 years or so are in very good agreement with the million-year averages provided by geological data. Such an agreement over five orders of magnitude in time scales is of great interest to scientists who construct numerical models of mantle convection and plate tectonics. That this agreement

holds for essentially all the plates sampled by space-geodetic sites is illustrated by Figure 4, where the relative motions between sites on stable plate interiors, estimated by satellite laser ranging to LAGEOS, are shown to be extremely close to and well correlated with the NUVEL-1 (DeMets *et al.*, 1990) geological estimates.

This agreement may be an indication that the motions of the interiors of the plates are steady, implying that the present plate geometry is the product of continuous motions over millions of years. However, as discussed by Smith *et al.* (1990) (Figure 4), the difference in the average NUVEL-1 and SLR geodesic rates is small but statistically significant and requires an explanation. They discuss three main possibilities, namely (1) plate acceleration, (2) bias in the geological time scale, and (3) geographical bias in the SLR network. Differences between the geological predictions and VLBI results also seem significant for the baseline from Westford Massachusetts to Wettzell (Germany), for which the NUVEL rate is 18.8 ± 0.5 mm/yr, while the 1985-90 VLBI rate is 14.9 ± 0.4 mm/yr, although the effect of local deformation remains an unresolved issue (T. Herring, Massachusetts Institute of Technology, private communication, 1991; see also the section on Spatial and Temporal Sampling and Figure 6 on page 58).

Space-geodetic techniques are already contributing valuable estimates of plate motions in areas where geological evidence is weak. These include relative plate motions across trench boundaries, where the lack of geological rate information leads to substantially poorer estimates (DeMets *et al.*, 1990), and in regions where geological data are too sparse to permit reliable solutions (e.g., around the Philippine plate). Also included are areas where the ideal rigid–plate model does not adequately describe tectonic interactions, especially within the continents and along their margins. Examples include the Mediterranean (WEGENER-MEDLAS Project; Wilson, 1987) and the western United States (e.g., Minster and Jordan, 1987; Jordan and Minster, 1988b; Ward, 1990; Argus and Gordon, 1990; Smith *et al.*, 1990; Humphreys *et al.*, 1990). Although we do not yet enjoy the benefit of long time series, it is clear that the combination of permanent space-geodetic systems, incorporating all existing techniques (such as SLR, VLBI, GPS, DORIS, and PRARE), will help refine plate motion models in several such areas.

To eliminate the trade-off between horizontal and vertical motions that exists for isolated long baselines or sparse networks, this analysis should be done on a global basis, and the network geometry should reflect plate geometry. Furthermore, with the Westford-Wettzell baseline mentioned above, if we decimate the original data set to one point every 90 days, the rate estimate becomes 16.5 ± 1.4
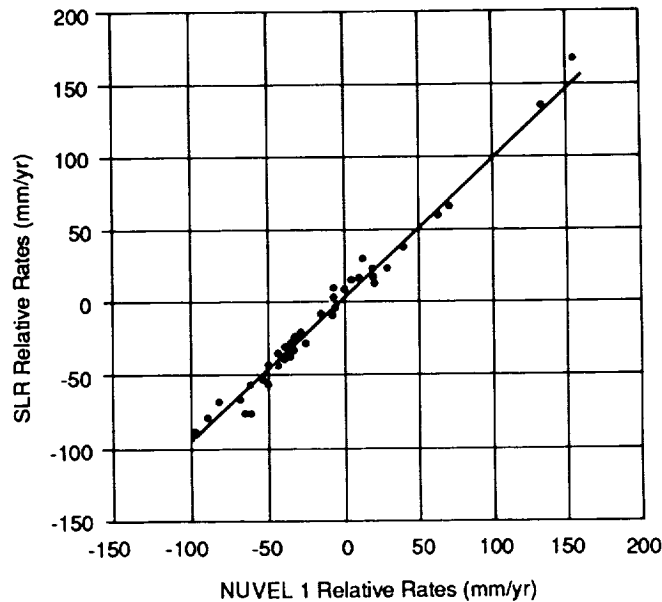
FIGURE 4. Comparison of SLR-determined geodesic rates with those predicted by NUVEL-1 for 54 baselines with end points well within the interiors of five plates. The slope of the line is 0.949 ± 0.019 (from Smith *et al.*, 1990).

mm/yr, which is not distinguishable from NUVEL-1 at any comfortable confidence level. This indicates that comparison of geodetic and geological estimates at the level where we look for temporal dependence of tectonic rates requires smaller errors. Furthermore, frequent sampling is required to elucidate the temporal character of the errors and to determine the noise spectrum. In addition, redundancy—through the survey of a geodetic footprint surrounding fiducial sites and analysis of a complete network—is needed to detect contamination by local effects (e.g., subsidence and monumentation), which may mask interesting geological signals or, worse, masquerade as such signals.

Only a few geodetic data sets have been published that involve measurements frequent enough to warrant time series analysis. Many consist of terrestrial measurements, but some baselines (e.g., Westford-Wettzell) have been measured

frequently enough over the past decade or so to provide estimates of the noise processes and the detectable signals. Another example, shown by Figure 5, is the time series representing the length of the Westford (Massachusetts) to Ft. Davis (Texas) baseline as a function of time. This particular baseline has been the subject of considerable debate during the Crustal Dynamics Project, since the eye-detectable excursion apparent during the approximate 1984-88 period could not easily be explained in terms of geologically plausible causes. The last data points in the series suggest that the long-period (5-year) transient may have ended recently, but the details of this recovery are missing, because of the data gap in 1989-90. The other point well illustrated in Figure 5 is that both the error bars on individual data points and the overall scatter show large variations as well as an overall decrease with time. With the global network of fiducial sites, such complications will presumably be rare, at least for a substantial subset of sites, but they cannot always be avoided in practice, so that the network design should attempt to compensate for them, in particular, by choosing a strong network geometry.

From a geophysical standpoint, even if the nominal design requirement for the global network is for reliable positioning of sites at ~3,000-km spacing, strong arguments can be made that closer spacing (~1,000 km) is highly desirable. Again, Figure 5 is a case in point. This time series shows apparent time-variable motion at the 10 mm/yr level, a surprising result for a baseline spanning a stable plate interior. It is clear that frequent measurements of intermediate locations (i.e., a denser network) would greatly aid the interpretation of this behavior.

Plate boundary zones are characterized by seismic and volcanic activity, two hazards that space geodesy may help mitigate. The spatial scales involved in earthquake and volcano monitoring are small, and these problems are properly addressed in the context of regional densification. But local and regional space-geodetic networks would benefit considerably from a global fiducial network. Since frequent, or even continuous, monitoring is increasingly the norm for this type of work, the global network also should function in this mode. This requirement is extended not only to stations used primarily for orbit determination but to others as well, since these other stations will often be used as regional fiducial sites for precise relative positioning within local networks. This is not to say that the fiducial stations alone could not collect data directly relevant to earthquakes or volcanic eruptions. For example, in the great (M_w 9.5) Chilean earthquake of 1960, the Chile trench ruptured over an area of 10^3 km, so that even a coarse geodetic network would have had a fair chance of including a site within the region of strong deformation. With continuous operation, such a station would
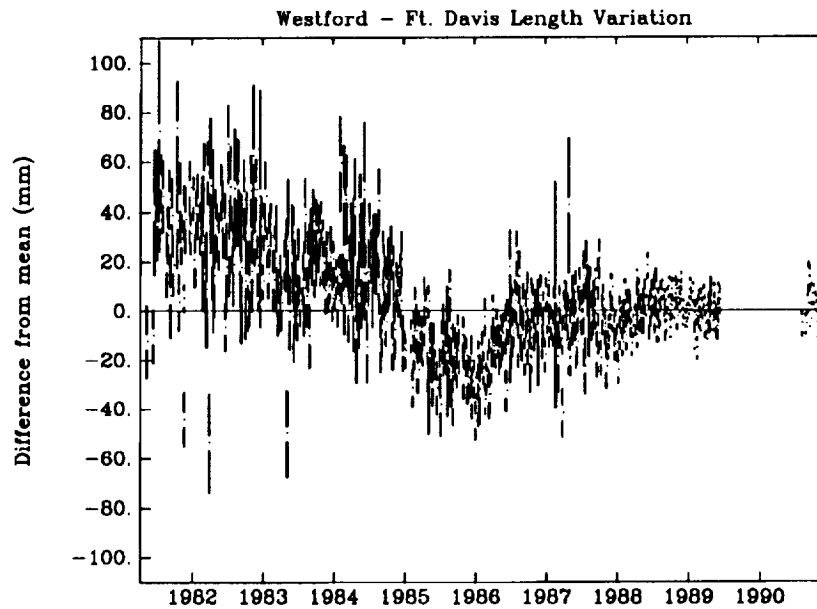
FIGURE 5. Time series for the Westford (Massachusetts)-Ft. Davis (Texas) VLBI baseline (courtesy of W. Carter, NOAA and T. Herring, MIT, private communication, 1991).

contribute extremely valuable information. Such events are quite rare, however, and the chances of catching an earthquake with a global network are far from overwhelming.

Finally, in plate boundary deformation zones, the spatial distribution of deformation is a critical question. It must be resolved to reach an improved understanding of the mechanics of deformation, particularly in large regions of the world such as Tibet, where even reconnaissance surveys are still lacking. In such instances, the global network would play an important supporting role by simplifying logistical issues of reconnaissance surveys and by providing the necessary reference frame.

Geodetic Objectives and Applications

The scientific objectives discussed above will not be achieved unless the geodetic problems they raise are solved with sufficient accuracy and reliability. The existing fiducial networks formed by VLBI, SLR, and LLR are insufficiently dense to satisfy the scientific objectives stated previously; the most cost-effective technology now available for such densification is GPS. As stated previously, a global fiducial network supports interdisciplinary science, but it should serve specific geodetic objectives as well. Below we discuss these geodetic objectives and the concomitant design considerations for a global fiducial network.

Determination of Precise GPS Orbits. One of the important data products generated by the global network is a set of precise ephemerides for the various spacecraft involved, in particular the GPS (and GLONASS) constellation. To support high-accuracy geophysical studies, the orbits should be globally accurate at the 10- to 20- cm level to allow relative baseline accuracy at the level of a few parts in 10^9. For a variety of geophysical applications (e.g., earthquake or volcano monitoring), solutions should be available within a few days after data acquisition. This does not mean that solutions could not be produced within a shorter time. However, the trade-off between the solution delay (relative to real time) and the robustness and accuracy of the orbits so obtained remains to be explored. GPS is the only current cost-effective technology with the potential for meeting the array of scientific objectives described in the previous sections. An important element of a global fiducial network is fundamental support for determination of precise GPS ephemerides (and possibly GLONASS ephemerides at some future time), which are required for precise positioning.

Under the proposed International GPS Geodynamics Service (IGS), ephemerides for support of high-accuracy scientific applications would be transmitted in a timely fashion to geodetic users, thereby simplifying the data processing task of the user community. The Department of Defense (DoD) maintains the satellites and produces ephemerides broadcast by the satellites, but these ephemerides permit only part-per-million (ppm) geodesy, rather than the required part-per-billion (ppb) precision. The ppb need is evident from the fact that, at this level of precision, a 2,000-km spacing of fiducial sites translates into about a 2-mm baseline error, a desired level based on the preceding discussion of scientific requirements. More importantly, this level is required for all three components of the baseline. By far the most effective mechanism to satisfy this need would be for

DoD to broadcast more precise ephemerides. The civilian community should continue a dialogue with DoD to explore this possibility.

From the geodetic standpoint, the ephemerides should be fully traceable. That is, accepted standards should be used (e.g., McCarthy, D. D., ed., 1989) and the techniques, procedures, and constants fully documented. The information should contain not only ephemerides (positions and velocities) but also parameters derived during the orbit determination process leading to the ephemerides. Furthermore, special information about the status and health of the satellites should be available.

The geodetic objective for the generation of GPS ephemerides should be orbits of the highest precision to support high-accuracy positioning anywhere in the world. Such a determination requires a fiducial network, but as discussed by Lichten and Neilan (1990), the spacing does not need to be 2,000 km. In fact, about 20 to 30 stations will more than suffice; larger numbers would enhance the network and, through redundancy, provide a check on the data and ensure that a minimum number of stations are on-line at any one time. This set of stations, referred to as the "GPS Core Network" or "GPS Core Stations," should be selected for worldwide coverage and for collocation with VLBI and SLR stations at a sufficient number of sites to satisfy reference frame requirements but should be dedicated to continuous GPS tracking. The global distribution of stations is required to ensure high-accuracy geodesy everywhere in the world, as well as to support such geodetic applications as determination of Earth rotation and establishment and maintenance of a GPS reference frame.

To facilitate the timely generation of ephemerides, a standard GPS receiver and antenna is required for the GPS core stations to eliminate potential problems arising from mixing dissimilar instrumentation. Other problems, such as multipath effects, should be minimized by adopting a set of appropriate uniform standards for the deployment and operation of the GPS core network.

The GPS stations may be augmented to provide redundancy, to enhance geographical coverage, or to meet other needs, such as enhancing ambiguity resolution using a clustering of sites (e.g., Lichten and Neilan, 1990). Further, network operation should not be significantly affected by the temporary outage of one, two, or even several core sites. Simulations should provide a quantitative evaluation of the expected network performance for any given selection of sites and help decide whether adequate redundancy is available, particularly in remote oceanic areas where coverage is more difficult to achieve.

Precise Earth Rotation and Orientation Parameters. The determination of Earth rotation parameters (pole position, length of day) and orientation parameters (precession, nutation, and UT1) by the IERS is based on VLBI, LLR, and SLR. However, GPS is affected by somewhat different error sources than are these techniques, which could aid in the separation of geophysical errors from other systematic errors. Nevertheless, GPS Earth rotation and reference frame applications have not yet matured to a level comparable to that of baseline determinations. As a consequence, a campaign was conducted from Jan. 22 to Feb. 13, 1991—the First GPS IERS and Geodynamics Experiment (GIG'91)—with the goal of collecting data for investigating these applications, particularly the monitoring of short-term fluctuations in the length of the day. This relatively short campaign limits the extent of the assessment, but future campaigns proposed by the IAG (e.g., EPOCH'92) will permit a more complete evaluation. Such experiments will also help identify optimum ways to use GPS data in the IERS technology mix.

As noted in the Coolfont report (NASA, 1991), the goal for determination of pole position is 0.25 mas (milliarcseconds) with temporal resolution of 6 hr and the goal for the length of day or UT1 rate is 0.1 msec/day, every 6 hr. These values correspond to subcentimeter accuracy in determination of Earth orientation. It is expected that the GPS core network, as a by-product of the GPS precise orbit determination process, can support the determination of Earth rotation parameters. To what extent the Coolfont goal can be attained remains to be investigated and is one of the challenges of the global network.

Realization of a Precise Global Terrestrial Reference Frame. The requirements for a terrestrial reference frame have been specified by IAG Special Study Group SSG 5.123. The intention is to permit realizations of this reference frame at the millimeter level at the Earth's surface (or 10^{-10}) without ambiguities. In this respect the deployment and operation of a global network of fiducial sites would result in a major advance. Several points deserve mention.

This objective requires, at the core network level, integration of several techniques, particularly VLBI, SLR, and GPS, but also other techniques used on either local or global scales (e.g., DORIS, PRARE), so that all measurements are reduced to the same reference frame. This also holds for a variety of other types of geodetic or geophysical measurements, in particular gravity. SLR is needed to achieve center-of-mass reference (GPS also uses a center-of-mass reference), while VLBI is needed to provide a tie to an inertial frame of reference.

The IERS has tackled the problem of realizing a terrestrial reference frame by incorporating a very large number of space-geodetic sites in its solutions. However, because of the large variations in the nature of sites, in the history of site occupancy, and in the equipment at each location, characterization of the reference frame depends on the weighting scheme used in combining the data sets, which is itself somewhat subjective. The incorporation of GPS data in the context of the global network will require reexamination of these points. However, as data quality becomes more uniformly high, it can be anticipated that the realizations of the reference frame will improve as well.

Defining a suitable reference frame has been so important over the years that current and/or planned deployments pay considerable attention to it. As a result, there is already substantial collocation of sites equipped with different technologies, including GPS. Current plans for the southern hemisphere, coordinated primarily through U.S. agencies such as the National Geodetic Survey and NASA, will lead to a substantially improved situation in the next few years. In this respect the need for transportable VLBI and SLR systems endures, since the permanent VLBI and SLR networks are rather sparse, and GPS accuracies for long baselines are still questionable.

Support of Scientific Orbital Missions

An important application of the global network is to support scientific missions in low Earth orbit. A comprehensive discussion is given by Melbourne (1990). The most visible advantage in the short term is the determination of an accurate orbit independent of the usual ground tracking techniques. The benefits of a global distribution of ground stations for orbitographic systems have been demonstrated with the DORIS system and will be further illustrated with the PRARE system. Given that several orbitographic systems are now deployed, there is again a need to maintain accurate ties, through collocation between the GPS global network and these other networks (SLR, DORIS, PRARE). Data from the global network can greatly simplify the implementation of precise differential GPS orbit determination of low-altitude satellites with onboard receivers and thereby contribute substantially to a variety of scientific goals of such missions (e.g., aeronomy and gravity studies). Without global network data, the operators of such satellites must set up

and maintain costly ground stations of their own, so that significant cost benefits would accrue from a cooperative global network.

In return, this particular class of applications entails a possibly significant mission-dependent operational impact on the network, particularly in terms of data availability, data rates, and telemetry. This impact may be felt at only a subset of the global network, which for present purposes can be identified with the GPS core network introduced above. In addition, mission support requires faster reactions and usually has a much smaller time constant (defined by the mission lifetime) than most other applications of the global network. For practical purposes, a global network of fiducial sites that satisfies the requirements listed earlier will be capable of providing the data required for mission support, provided that quality control is effective.

Low Earth orbiters, such as TOPEX/POSEIDON, Aristoteles, GP-B, or the EOS platforms, equipped with an onboard receiver to track the GPS constellation at the same time as the global network, can provide additional data of considerable value to the operation of this network:

- The orbiter is capable of simultaneously tracking GPS satellites that are only visible separately from the ends of extremely long baselines on the ground. In this fashion the orbiter may act as a temporary bridge and expand the range of distances over which differential techniques can be used. From the point of view of network design, this makes it possible in principle to determine the precise locations of stations on remote islands using differential positioning.

- The rapid change in geometry resulting from the motion of the orbiter will strengthen the solution of all terrestrial baselines, regardless of whether a bridge is needed. Alternatively, the observation time required to achieve a specific accuracy may be shortened.

- If we consider the orbiter a flying station that is part of the global network, the overall network will incorporate Earth-to-space baselines with large vertical (radial) components. This will improve the accuracy of the estimated vertical coordinates (typically the worst-determined ones) and help correct for tropospheric refraction, which affects ground-based data but does not corrupt the orbiter's data. Use of orbiter data will also increase the accuracy of the GPS ephemerides as part of the operation of the global network. Simulations described by Yunck and Melbourne (1990) suggest a possible doubling in accuracy for both horizontal and vertical station coordinates, with subcentimeter results for baselines up to

4,000 km long, after inclusion of data from each of the EOS platforms. Ephemeris accuracy could triple in all three directions (radial, along orbit, and across orbit).

A number of Earth observing missions require precise global tracking to accurately recover the trajectory and orientation of the satellite. For example, satellite altimeters require radial orbit accuracies of 20 to 40 mm to monitor slow variations in sea level; these accuracies must be maintained for at least 10 years. Satellite gradiometers, and other geodetic satellites in low Earth orbit, are used to measure the Earth's gravity field on regional (100 to 1,000 km) and global (1,000 to 10,000 km) scales. The accuracy and resolution of the recovered gravity field depend primarily on the accuracy, coverage, and duration of operation of a global tracking network. Finally, high-resolution imaging systems require global tracking to provide real-time control on the location of the spacecraft and to register the images precisely during postprocessing. Thus, many planned and proposed missions depend on the implementation and maintenance of global tracking networks.

At least two types of global tracking networks have been developed. Satellite-to-satellite tracking, using the GPS system, can provide global coverage at relatively low cost to NASA since the DoD maintains the GPS system. In this configuration the high-altitude (20,000-km) GPS satellites have orbits that are relatively insensitive to the poorly known higher harmonics of the Earth's gravity field. Satellites in lower orbits (~ 1,000 km) can be tracked continuously by the GPS constellation. As few as a dozen well-distributed GPS ground sites would suffice in principle to give orbital accuracy that meets or exceeds that currently available with the best ground-based laser tracking systems. For redundancy to protect against station outage, about 30 stations would be prudent. Given the coverage that can be physically achieved in areas mostly covered by oceans, and given the fixed ground tracks of GPS satellites, an optimal network geometry is unlikely to be achieved. As a result, a somewhat greater number of stations might be required in areas where network geometry is not flexible (as in the South Pacific). Concomitantly, a detailed analysis of each proposed network geometry should be conducted, and the need for redundant equipment at the more isolated sites should be assessed with care.

Ground-based tracking systems also used in orbitography include TRANET (TRAnsit NETwork), DORIS, SLR, and PRARE. The most accurate range measurements (~ 10 mm) are made with SLR, using ground-based laser telescopes and a laser retroreflector on the spacecraft. However, since SLR sites are expensive to maintain, the global network is relatively sparse. Nevertheless, the

high-accuracy range measurements from SLR sites are required for precise tracking of geodetic satellites such as Starlette, LAGEOS I and II, and Stella.

Satellite Altimeters

Satellite altimeters provide topographic data for a number of important scientific applications. Precise measurements of ocean topography reveal the fine-scale marine gravity field ($\sim$ 10 km horizontal resolution) as well as the dynamic topography associated with mesoscale and basin-scale ocean circulation. Repeat measurements of ice topography can be used to monitor the mass balance of the major ice sheets. Over land altimeters can be used to measure topography at high spatial resolution on a global basis. In each application the topography of the surface is the difference between the altitude of the spacecraft above the closest surface (water, ice, or land) and the height of the satellite above the reference ellipsoid. For the ocean and ice applications, the altimeter can achieve an accuracy of 20 to 40 mm. Depending on the application, the radial position of the satellite must be tracked with an accuracy of 40 to 200 mm. The most stringent tracking requirements come from the World Ocean Circulation Experiment (Chelton, 1988).

Many satellite altimeter missions are planned for the next decade. ERS-1 (launched July 17, 1991) and ERS-2 (1994) will measure the marine gravity field at high spatial resolution and monitor changes in ocean dynamic topography (i.e., geostrophic surface currents) for about 6 years. PRARE and SLR will be used for tracking the ERS spacecraft. The TOPEX/POSEIDON mission (mid-1992 launch) has the most stringent requirement for radial orbit accuracy ($\sim$ 100 mm); it will be tracked using a combination of SLR, GPS, and DORIS systems. The Earth Observing System (EOS) satellites (launches in 1998 and 2001) will carry radar altimeters for oceanographic and geodetic applications. In addition, the second EOS mission is slated to carry a Geoscience Laser Ranging System (GLRS), which will be used for precise positioning of ground-based laser retroreflectors as well as for laser altimetry over land, ice, and water. The EOS platforms will be tracked using multiple GPS receivers as well as ground-based systems such as DORIS and SLR.

A topographic mapping mission is anticipated (1999 launch) to map the topography of the land and ice at high spatial resolution ($\sim$ 100 m) and high vertical accuracy ($\sim$ 3 m). While the type of instrumentation (e.g., laser, radar,

or stereo-optical) has not yet been chosen, the positions and orientations of these spacecraft must be tracked quite accurately on a global basis. A discussion of imaging altimeters appears in the section titled High-Resolution Imaging Systems.

Aristoteles, Gravity Probe-B, and Other Gravity Field Missions

A number of planned or proposed gravimetric satellite missions require accurate tracking on a global basis. The first is the GPS experiment to be demonstrated on-board the TOPEX/POSEIDON spacecraft (mid-1992 launch). Although the primary mission of TOPEX is to monitor global ocean circulation, it will be used as a secondary experiment for gravity model improvement. The TOPEX/POSEIDON spacecraft will carry a GPS receiver to monitor its own position and trajectory with respect to the higher GPS constellation. The ground-based part of the experiment will include at least six GPS receivers (Wu and Yunck, 1991) distributed around the globe for tracking the GPS constellation. It is anticipated that the ground receivers will be positioned to an accuracy of about 50 mm. This experiment should yield continuous position estimates for TOPEX/POSEIDON that are accurate in the radial direction to better than 100 mm. These position estimates can be used in turn to improve the global gravity field dramatically at long wavelengths (up to spherical harmonic degree 35; Schrama, 1990). Knowledge of gravity field variations at wavelengths shorter than the spacecraft's elevation (1,330 km) will not be significantly improved.

This same concept for gravity field improvement has been advanced for two satellites in low-altitude orbits, Aristoteles and GP-B. Aristoteles is a gravity gradient satellite proposed by the European Space Agency (ESA) for launch in 1996-98. The onboard gradiometer is expected to provide great improvements in the short to intermediate (150 to 500 km) wavelengths of the Earth's gravity field, whereas the precise tracking system should improve gravity models significantly at wavelengths longer than 450 km (Schrama, 1990). Although the high-precision tracking system may be a GPS instrument similar to the demonstration experiment on TOPEX/POSEIDON, it is likely that accuracy requirements for gravimetric missions will be more stringent. The global network of precisely positioned fiducial stations proposed here may contribute in a large way to the success of Aristoteles. This would be particularly true if a direct ground tracking system such as PRARE or DORIS were used in lieu of (or in combination with) the more indirect GPS approach. Moreover a direct tracking system for a low orbiter such as Aristoteles would include several hundred accurately positioned (~ 10 mm)

ground stations. Another low-orbit spacecraft that may carry GPS or other precise tracking equipment for global gravity field mapping is Gravity Probe-B (GP-B). GP-B, planned for the mid-1990s, will fly at a 600-km altitude and will conduct, as its primary mission, the Stanford relativity gyroscope experiment.

Regardless of which high-precision system is used—GPS, PRARE, or DORIS—these upcoming or proposed satellite missions to map the global gravity field will be enhanced by a global network of fiducial stations.

High-Resolution Imaging Systems

Space-based imaging systems such as NASA's Landsat Thematic Mapper and France's Satellite pour l'Observation de la Terre (SPOT) satellite are having a major impact on scientific applications of remote sensing technology. This impact reflects the increasing spatial and spectral resolution of these instruments, increasing ease of data acquisition coupled with decreasing costs, improvements in computer technology and image processing algorithms that permit ever more sophisticated and rapid analyses, and improved models and understanding in the scientific community.

Closely related to these changes is increased demand for more sophisticated data products. One example is the need for image data with better geometric fidelity and more accurate location knowledge. This implies the need for improvements in the areas of spacecraft *location* and *orientation* (pointing). Spacecraft designers usually distinguish between *control* and *knowledge* for both location and orientation. Control requirements are generally less stringent than knowledge requirements, the latter being computed after the fact with the benefit of accurate models and additional data. However, control is required in real time, which often makes this aspect more challenging. Earth observation missions with the most stringent location and orientation requirements can be divided into two classes: high-resolution spectral imaging systems and imaging altimeters. In the first application we require geometric fidelity such that a picture element, or pixel, will be accurately associated with a given spot on the ground. Pixel location knowledge currently planned for imaging sensors in the civilian areas implies that we need to be able to locate pixels to an accuracy of 3 m. Actual performance at present—for locating 20- to 30-m pixels from sensors with high spectral resolution—is considerably worse. Location knowledge is usually improved during postprocessing and image analysis, as the image itself allows location to be

determined by reference to ground tie points. Nevertheless, because it is desirable to reduce processing and analysis time, accurate *a priori* location knowledge would be very useful for automating the analysis.

Imaging altimeters may actually have more stringent requirements; we will therefore use them to illustrate potential tracking system applications. An imaging altimeter is a high spatial resolution instrument for height measurement over continents and ice caps. The oceanographic counterpart estimates height from time-of-flight measurements of a simple radar pulse with a spherical wavefront, the echo of which can be assumed to arrive at the spacecraft from the exact nadir point. The imaging altimeter, in contrast, uses some sort of scanning or imaging system, such as a scanning laser or synthetic aperture radar imaging system. With this approach, location and pointing knowledge (and to a lesser extent control) are critical to accurate height estimation. Spacecraft location knowledge in the radial component must be better than 0.5 m. Three-dimensional location accuracy, including along-track and cross-track components, can be slightly worse but should not exceed several meters. The required pointing knowledge depends on spacecraft altitude, surface slope, and desired accuracy; for a spacecraft altitude of 500 km, surface slope of 25 degrees, and desired height precision of 1 m, pointing knowledge should be accurate to about 1 arcsec.

Most current spacecraft designs for high-precision Earth imaging rely on a combination of sophisticated star trackers or star cameras, which can be supplemented with (inertial) gyroscopes for accurate orientation information (both control and knowledge). They also use relatively crude ground tracking information and/or orbit modeling for real-time location data and more sophisticated orbit modeling for improved location knowledge. Clearly, one of the applications of a global tracking network based, for example, on GPS would be to improve the quality of spacecraft location data, in terms of both control and knowledge. Moreover, this approach is relatively cheap in comparison to existing high-precision tracking techniques, which rely on numerous ground-based lasers (constrained by limitations on satellite visibility from the ground stations) and extensive after-the-fact modeling. The GPS approach has additional advantages where near-real-time location accuracy is required because GPS tracking is essentially geometric, in the sense that range is measured between the orbiter, whose position may be poorly known initially, and several GPS satellites whose positions are well known. Extensive orbit modeling is not required in this geometric approach, implying that high orbit accuracy could be available in near real time.

The situation is somewhat different with orientation data. Current star trackers are capable of delivering approximately 1-arcsec performance. Although star tracker technology is mature, the instrumentation can be expensive. Can three GPS antennae be used to establish both the location and orientation of a spacecraft in a cost-effective manner, thus eliminating the need for expensive star trackers? Consider first two GPS antennae (separated by a baseline that might range from 1 to 10 m in length for a typical spacecraft), feeding their signals to a common receiver. The lowest achievable standard error in position estimates from GPS data in the absence of ionospheric and atmospheric errors is about 0.1 mm (based on zero-length baseline tests with advanced digital receivers). We conclude that even with a 10-m baseline, the best possible GPS orientation performance (~ 2 arcsec) is not quite competitive with star tracker technology. However, a case can be made that if high-precision tracking with GPS is required on a given spacecraft for other reasons, a GPS-based orientation system might be attractive to provide redundancy with star tracker orientation systems. This might be appropriate once space-based tracking with GPS becomes routine and the cost of a space-qualified GPS receiver falls. The core network described above for location information would similarly be adequate for orientation applications.

Support of Local and Regional Studies

Although support of local and regional studies is perhaps the primary objective when defining the need for a service, such as the International GPS Geodynamics Service initiated by the IAG, it probably has only a relatively minor impact on the design of a global fiducial network. On the other hand, applications of the global network data are many, and the following are merely possible examples:

• *Tie local and regional nets to the global network*: The main application of the global network is to provide a precise and reliable reference frame. However, for a number of applications, having two or three global sites within 10^3 km of the survey area will simplify processing and logistics and often result in higher accuracy. In general, however, the existence of globally accurate orbits is likely to have the greatest impact, if only in the form of much simpler and more streamlined processing of local survey data.

• *Precise local geodetic and geophysical surveys*: The number of local and regional networks monitored precisely for geophysical purposes (e.g., earthquake

and volcano studies) is increasing. The support afforded by a globally operated network cannot be overstated. Local dense networks would typically be operated independently of the global network, although a small number of sites could well be incorporated into the global operations, thus providing an automatic high-quality tie. Note that a *single* global site on Kilauea would permit reliable prediction of rift events! Finally, it should be noted that current efforts toward developing ocean bottom geodetic systems depend critically on the availability of kinematic GPS techniques when tying seafloor monuments to land-based networks.

• *Other applications:* For most surveying applications (e.g., cadastral, highways), the global network and associated services (e.g., IGS) would contribute primarily orbit information, in addition to providing a global set of very-well-located primary sites. The data processing could then be streamlined, although questions arise about the timeliness of orbit solutions and data accessibility. In addition, civilian services broadcasting regional corrections to Selective Availability (SA) would clearly benefit from the global network.

A global network of fiducial sites would not only benefit the global sciences but would also have positive effects on local and regional surveying operations and thus contribute to other scientific and engineering operations. In many countries points with accurately determined coordinates in a global coordinate system (typically longitude/latitude) are rare but are necessary for many surveying operations. Surveying and cartography are therefore hindered by the lack of accurately determined points in a global network. Errors in the control used are usually noticed when maps from two countries are joined or when engineering projects extend beyond national boundaries. The inaccuracies in the control surveys are detected in such projects because modern surveying instruments are very precise compared to those used in the control surveys. Typically, it is impossible to correct the flaws discovered, so that good new data are forced to fit the existing low-precision control. More very precise control points must be established using GPS, which would be useful for new cartographic or Geographic Information System (GIS) data collections. Locations determined with GPS technology often do not fit easily into the existing network because of the errors it contains. One may argue that the precision proposed in this report is not relevant for surveying (clearly millimeter precision is not necessary for boundary location). But the justification for keeping high precision in boundary surveys and other day-to-day surveying operations is the need for long-term maintenance. Property surveys must be maintained over long periods, so that new measurements must be merged with old ones. Imprecision hinders this process and leads to costly fudging.

Finally, current GIS technology relies heavily on coordinate values, which in practice are often determined very imprecisely. An accurate global network could provide the control for securing national geodetic networks and tying them to an international standard, thus helping to make data from different sources more compatible—for example, for the study of phenomena on a continental scale. A detailed review of many of these matters, including the requirements for precise control, is provided in the report *Spatial Data Needs: The Future of the National Mapping Program* (National Research Council, 1990c).

In view of these general considerations, progressive densification of the global network beyond the GPS core network is required in the medium to long term. An expanded network, compatible with and tied to the core network, would consist of many more sites, possibly numbering in the hundreds, but not all of them would have to be monitored continuously.

Spatial and Temporal Sampling

The scientific matters—sea-level change, postglacial rebound, tectonic motions—that the global fiducial network is designed to address call for highly accurate determinations of radial and horizontal velocities (~ 0.1 mm/yr over $\sim 1,000$ km). Redundancy of measurements is crucial, both to reduce noise and to help eliminate systematic errors through recognition and editing of data that are suspect for either geodetic (e.g., instrument malfunction) or geophysical (e.g., site instability) reasons. On the other hand, financial resources are finite, so it is important to recognize the point of diminishing returns. We discuss below a rationale for determining optimal sampling strategy, both in time and in space.

Because the forces acting on GPS satellites are much more difficult to model than those acting on a simpler satellite such as LAGEOS, continuous operation is necessary for GPS orbit determination. This means that the GPS core network must be operating continuously with high reliability. The core network also can adequately handle the determination of polar motion and Earth orientation, including high temporal resolution objectives.

For most of the other scientific problems we have talked about, the geophysical processes are expected to occur on time scales of years to decades. The frequency of observations should be determined by the trade-off between geodetic accuracy and economic/logistic considerations. The more frequent the measurements, the

more accurate the (averaged) values, up to some point. For example, several measurements per year clearly give more reliable determinations of crustal motion over decades than do yearly measurements, but it is not clear that daily measurements give more reliable determinations than weekly measurements. On the other hand, the more frequently measurements are made, the more financially attractive continuous monitoring becomes. For example, weekly measurements could be extracted more economically from continuously operating stations than from field campaigns, but it is not obvious that the same is true of quarterly measurements. Similar comparisons can be made with spatial sampling: if most of the resources are spent traveling between sites, a permanent instrument equipped with a data transmission system (telephone or telemetry) may be more attractive. Finally, leaving a permanent installation in the field largely eliminates certain sources of error or noise associated with installation and removal of geodetic equipment.

Assuming that high accuracy is the overriding consideration, how often should measurements be taken for optimum operation? Although our experience is still relatively limited, some relevant data are available from VLBI experiments. For example, Figure 6 shows the history of length determinations on the trans-Atlantic baseline from Westford, Massachusetts, to Wettzell, Germany, from 1984 to 1991. Individual length determinations scatter by up to ~ 50 mm from the best-fitting line (14.9 $\pm$ 0.4 mm/yr), even though the outliers otherwise appear to be "good" experiments from the point of view of their residuals. An unfortunate choice of individual measurement points could obscure the entire linear trend, which has a change of ~ 80 mm over the time shown. Averaging over 90-day windows reduces the scatter by an order of magnitude, but there is still nearly 5 mm of scatter.

Examination of Figure 6 also reveals evidence of systematic variations at the noise level (~ 10 mm) in the original data, some of which survive the 90-day averaging and some of which do not. These variations are as yet poorly understood, although recent solutions indicate the presence of seasonal/annual effects. In addition, if the noise in the data averages followed the classical $\sqrt{N}$ law, the 90-day averages shown would have had a root mean square (rms) scatter of 2.7 mm instead of the 3.2 mm shown. Furthermore, if we decimate the original data set to one point every 90 days (taking the closest raw data points to the middle of the 90-day windows), the VLBI rate estimate becomes 16.5 $\pm$ 1.4 mm/yr, which is not resolvable from NUVEL-1. Thus, frequent measurements offer a clear benefit, primarily in the ability to apply statistical techniques and time series analysis to the data. On the other hand, the errors from atmospheric effects are
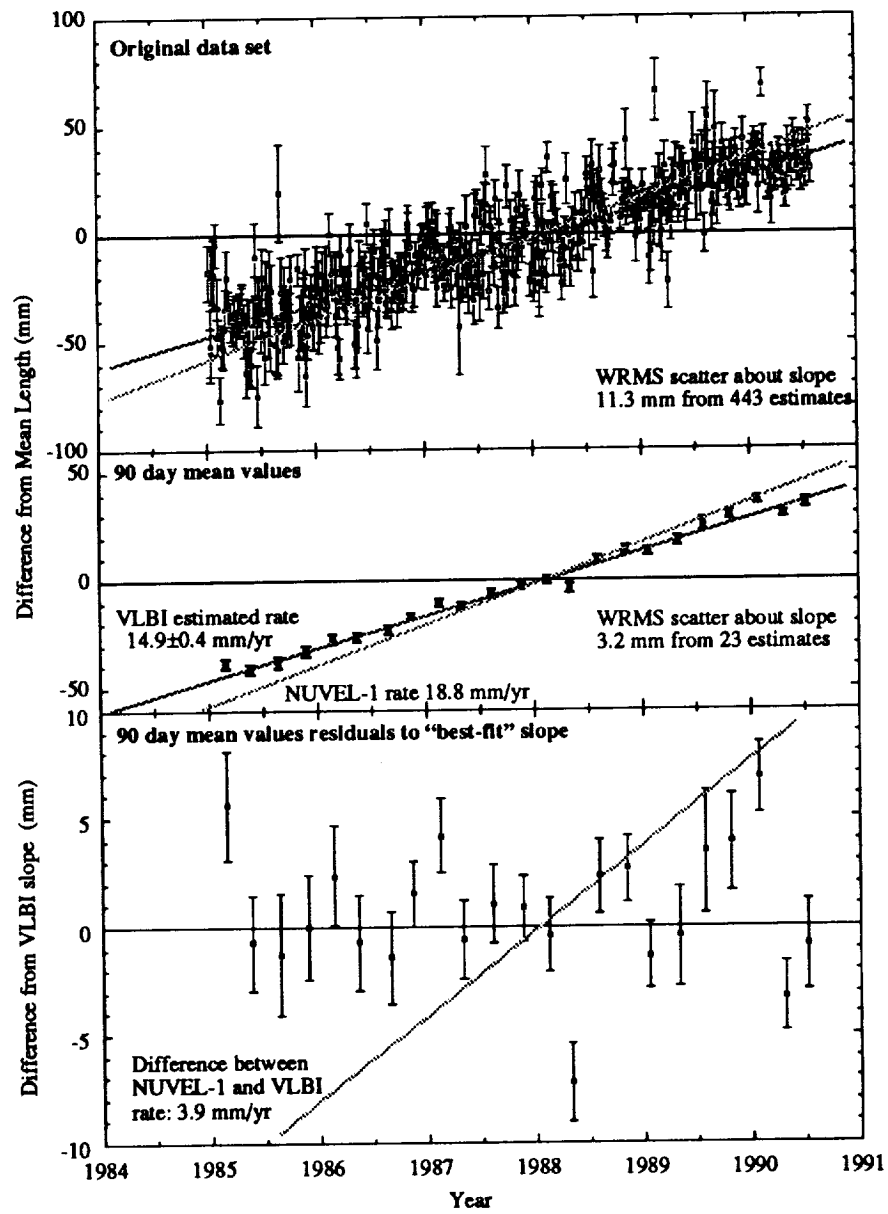
FIGURE 6. Evolution of the Westford-Wettzell VLBI baseline length, 1984-1991 (courtesy of T. Herring, Massachusetts Institute of Technology, 1991).

probably correlated on time scales of 2 to 5 days, so little might be gained by computing solutions more frequently than about weekly.

Another example of the potential benefits of dense temporal sampling are the 8 year records along three baselines in the San Francisco Bay area shown by
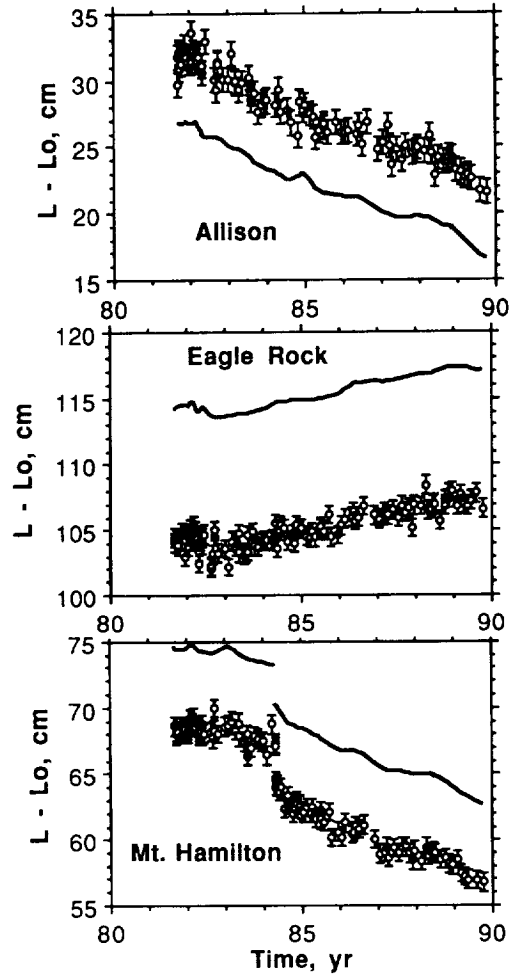
FIGURE 7. Lengths for three geodolite lines in the San Francisco Bay area, showing possible anomalies precursory to Loma Prieta about 1 year before the event. The break in the plots in mid-1984 corresponds to the coseismic offset for the Morgan Hill earthquake. The solid line is simply a smoothed version of the data (from Lisowski et al., 1990).

NW—SE Strain   —   Piñon Flat Observatory

Vertical Motion at PFO
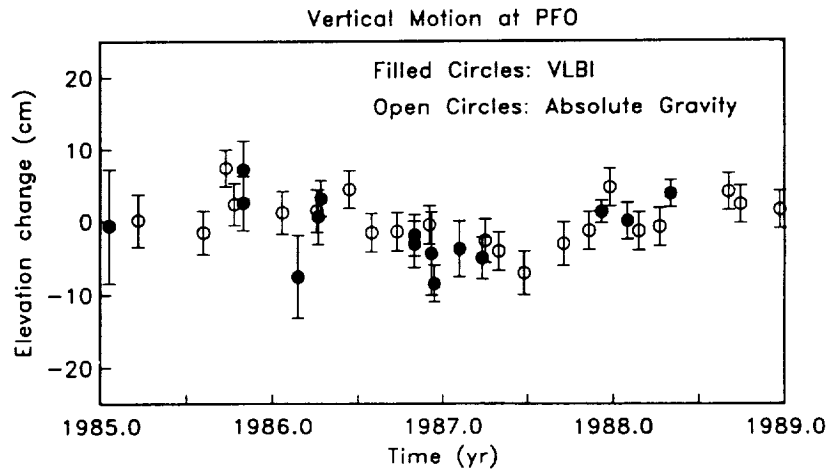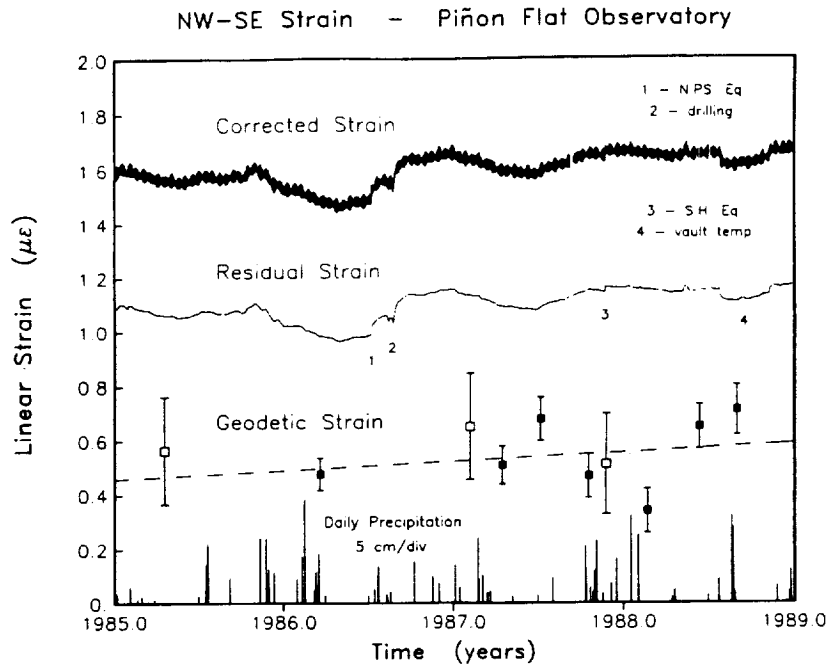
FIGURE 8. *Top panel*: Laser strain record from Piñon Flat Geophysical Observatory, compared with Geodolite (open squares; courtesy of W. Prescott, J. C. Savage, and M. Lisowski, U.S. Geological Survey) and 2-color EDM (solid squares; courtesy of J. Langbein, U.S. Geological Survey) measurements of geodetic arrays near PFO. Geodolite array dimension is 15 km, 2-color EDM baselines are 4 km, and laser strainmeter length is 0.732 km. The dashed line gives the long-term strain rate found from the Geodolite network over 15 years (0.03 ± 0.013 $\mu\epsilon$/yr), in good agreement with the NW-SE strainmeter rate (0.03 $\mu\epsilon$/yr). The residual strain record highlights abrupt changes due to earthquakes and locally induced deformation. This series is formed by removing Earth tides from the monument- and laser-frequency-corrected strain record. The zero level for all series is arbitrary. *Bottom panel*: Comparison of absolute gravity (converted to elevation changes) and VLBI. An interesting correlation is evident in 1987, but since there is no anomaly in the PFO strain or tilt data, this may be a coincidence of instrumental effects (courtesy of D. Agnew, H. Johnson, F. Wyatt, and M. Zumberge, University of California, San Diego).

Lisowski *et al.* (1990) to contain signals possibly precursory to the 1989 Loma Prieta earthquake. Lisowski *et al.* document what they label a "marginally convincing" strain anomaly approximately 1 year before the event, over spatial scales of 30 to 50 km. The time series in this study are shown in Figure 7. It seems believable that there is more to these time series than just random noise superposed on a steady trend, and it seems clear that, without the dense set of points shown, the possible anomalies would certainly be missed.

Figure 8 shows a comparison of strains recorded continuously at the Cecil and Ida Green Piñon Flat Geophysical Observatory, California, with several types of geodetic measurements by both ground-based and space-geodetic techniques. Although the various trends agree reasonably well, it is abundantly clear that occasional geodetic occupations will not tell the whole story. But given the apparent scatter in the geodetic solutions, increasing the frequency of occupations to the point of continuous presence may not be scientifically justified.

The other side of this issue is, of course, the economics. The economics of continuously operating stations versus occupation by field campaigns depends on the number of campaigns per year, the number of days per campaign, the cost of collecting data continuously, and the cost of returning data to the central archive (Appendix D). For the cost estimates in Appendix D, it was assumed that 20% of

the expense of maintaining dedicated laboratories can be attributed to the global network; the break-even point is about six campaigns per year, or bimonthly occupations. As discussed by Melbourne (1990), the cost of GPS receivers is decreasing rapidly and the newer generations of receivers are very likely to require much less maintenance in the field than earlier instruments. The result is that the cost of running the global network will be dominated by data processing and communications costs.

In this respect, participants in the development of the global network will face the choice of either occupying network sites during temporary campaigns or equipping such sites with permanently installed receivers with a telemetered data stream. Both modes can be scientifically valuable, although we have argued that, at least in some cases, very frequent sampling should be a design constraint.

Clearly, the choice of operation mode must depend in part on the characteristics of the site (e.g., availability of power, communications, personnel). However, with a substantial drop in the price of the equipment itself, labor-free, unattended operations with permanently installed equipment will become more and more economical at many sites. The obvious trade-off with the desired sampling rate yields a crossover point where permanent occupation is more cost effective than a temporary campaign that is rapidly shifting such that even fairly infrequent measurements might justify a permanent installation. On the other hand, from the point of view of site selection, the requirements for sustaining data logging and telemetry become correspondingly more important. Considerable economies could result from coordination with other activities with a global perspective, as we shall argue.

Spatial sampling requirements are governed primarily by the scientific goals of the network. A number of the objectives we have set forward can be met with a GPS core network of approximately 30 sites, but other objectives, such as the identification of deformation patterns, require a mean intersite spacing small enough to avoid spatial aliasing. The answer is problem and region dependent, but, again, economic considerations rapidly become the main issue, since the number of sites is a quadratic function of the wavelengths to be resolved.

3
OPERATIONAL CONSIDERATIONS

Technology

Space-geodetic networks have existed from the early days of space activities. These networks have evolved in their scope, precision, and technologies used since the late 1950s. Mentioned in previous chapters are several global networks using different technologies that were deployed to meet different objectives. In this section, we shall delve into technological aspects in slightly greater detail, examine the geographical distribution of existing sites, and compare briefly the contributions of various techniques. This discussion focuses on techniques used now or expected to be used in the coming years for the very highest precision geodetic applications.

Very Long Baseline Interferometry (VLBI)

In the VLBI technique, two or more radio antennae simultaneously measure the difference in time of arrival of extragalactic radio sources. In some cases other radio sources, such as satellites, are observed. The difference in arrival time is the fundamental observation from which the geodetic quantities are determined. The extraction of these time differences of arrival usually utilizes recordings of the received signal on high-density media at the various sites over several hours. The data recorded at the various sites are compared pairwise on a correlator, and the differences in arrival time delay are estimated. The primary operational limitation is the mutual visibility of a radio source between a pair of sites. The global fixed VLBI sites in 1990 are shown in Figure 9.

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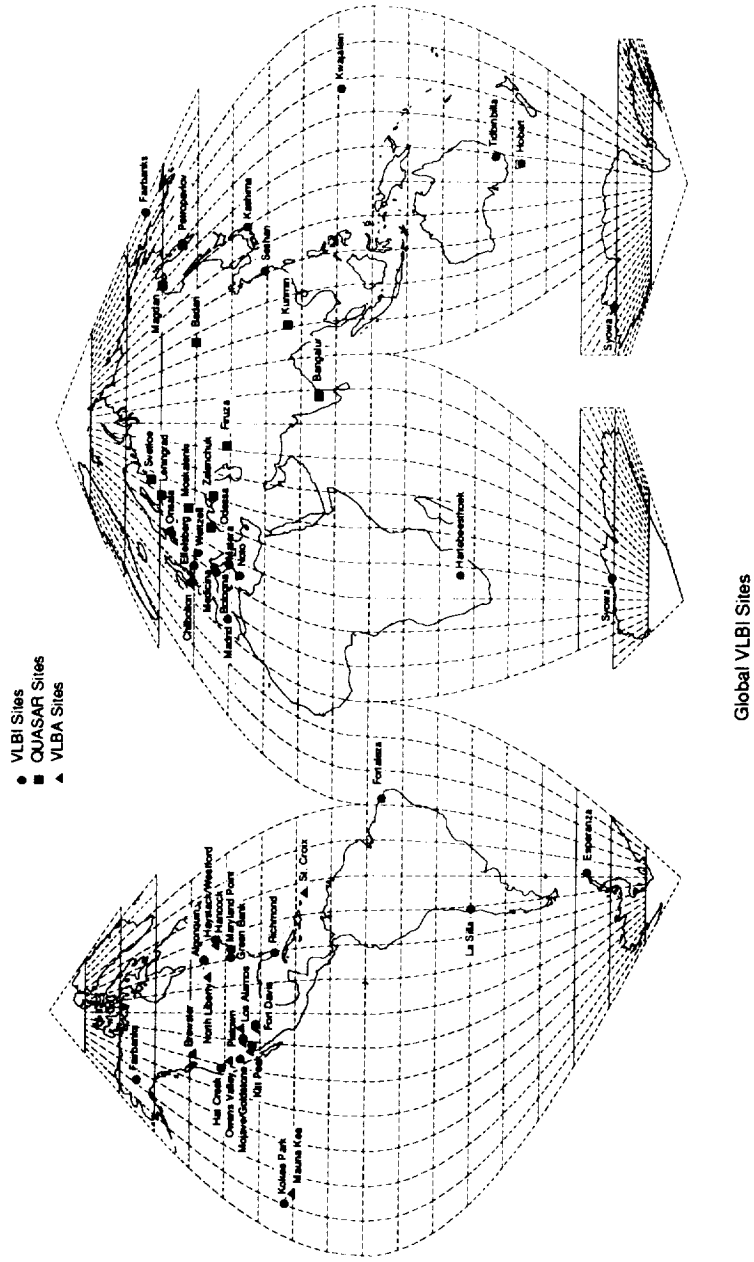
FIGURE 9. Map of global fixed VLBI sites. This includes newly installed sites in the southern hemisphere and sites of the QUASAR (USSR) network (from Crustal Dynamics Data Information System (CDDIS) of the NASA Crustal Dynamics Project).

When the radio sources used in VLBI are quasars, the technique has no sensitivity or tie to the Earth's center of mass. If the radio source is a satellite, the satellite's dynamics must be introduced through the adoption or determination of an ephemeris; the center of mass is, therefore, an inherent element of the solution for such cases.

The demonstrated sensitivity of VLBI to geodetic parameters is as follows:

- *Relative site coordinates*

The technique requires the adoption of a constraint, such as the selection of one site in a network as the reference; the coordinates of the other sites are determined with respect to the reference (i.e., the baseline vectors).

- *Earth orientation*

The technique is sensitive to the direction and magnitude of the Earth's angular velocity vector with respect to the reference frame defined by the adopted reference site coordinates (polar motion). Furthermore, the technique is sensitive to variations in the magnitude of the angular velocity vector (exhibited by length of day and UT1). Finally, because of the observation of extragalactic radio sources in normal VLBI operation, the technique is dependent on phenomena influencing the orientation of the Earth's reference frame relative to the quasar reference frame (i.e., the precession and nutation angles). Figure 10 shows a high-resolution determination of UT1 using VLBI (Herring, 1991).

- *Reference frame*

In the common mode of operation in which compact extragalactic radio sources are observed, VLBI is used to establish an extraterrestrial reference frame. In essence, this reference frame is nonrotating.

Since the radio signals pass through the ionosphere, delays of the signals due to both the ionosphere and the atmosphere are important. The ionospheric effect is greatly diminished by measuring group delays at two frequencies (typically S- and X-band). The atmospheric delays depend on both wet and dry components of the neutral atmosphere; the wet component correction may be inferred from water vapor radiometer data. The dry component can be modeled with site measurements of atmospheric pressure, temperature, and humidity. The geodetic estimation using VLBI time delay data usually includes the determination of a set of parameters representing corrections to the models of atmospheric propagation effects.
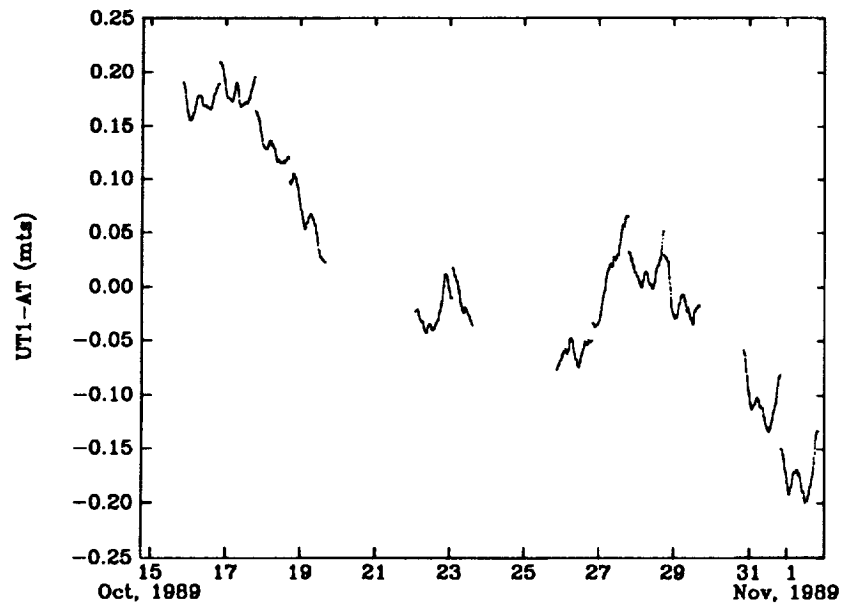
FIGURE 10. Example of high-resolution determination of UT1 variations using VLBI (from Herring, 1991).

Laser Ranging (SLR, LLR, and GLRS)

The laser ranging technique is characterized by transmission of a short pulse of laser-emitted energy (usually visible as green light) to a retroreflector (corner cube) target and the detection of photons reflected back to the transmitter by the target. The fundamental measurement is the roundtrip travel time of the pulse. When the target is an artificial satellite and the transmitter is a ground-based instrument, the technique is called Satellite Laser Ranging (SLR). If the target is a retroreflector on the moon, the technique is Lunar Laser Ranging (LLR). Planned for the Earth Observing System in the late 1990s is the Geoscience Laser Ranging System (GLRS), in which the laser is in a satellite and the reflectors are at ground sites. Global SLR sites in 1990 are shown in Figure 11. Both SLR and LLR are used by the IERS to determine components of Earth orientation.
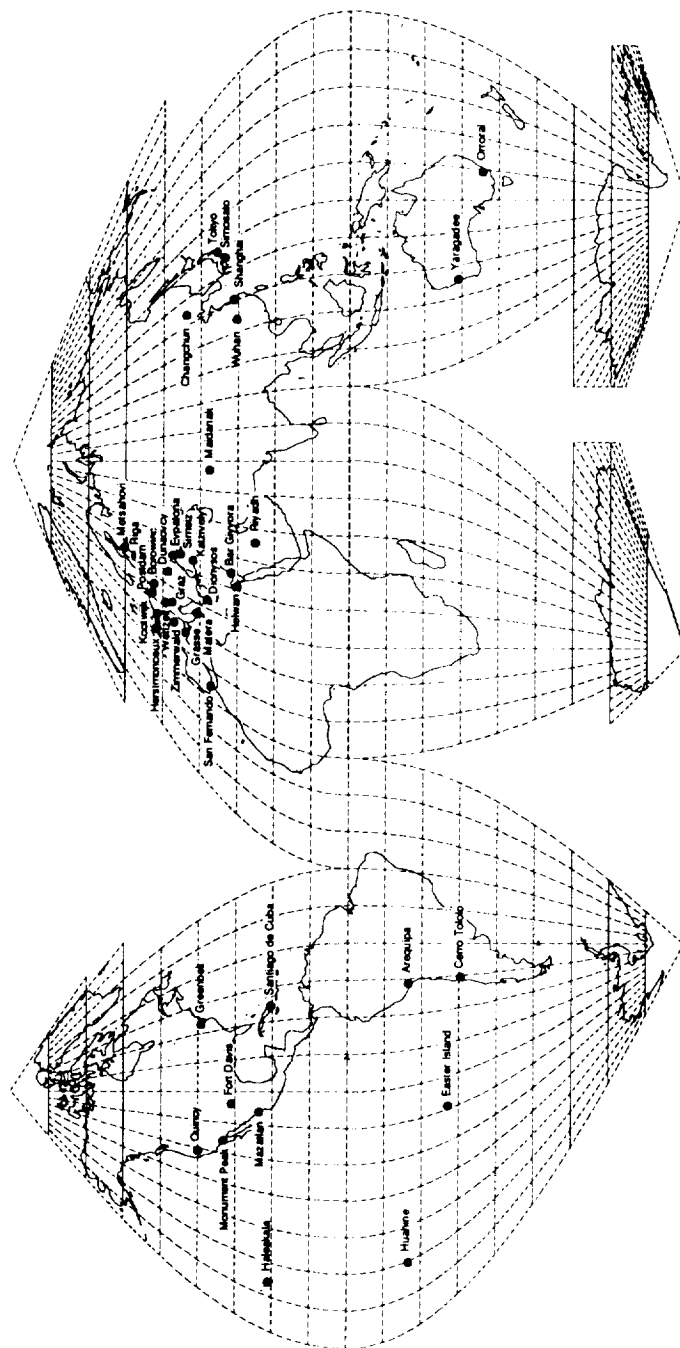
Global SLR Sites

FIGURE 11. Map of the global Satellite Laser Ranging network. This includes sites to be used to track the TOPEX/POSEIDON spacecraft (from Crustal Dynamics Data Information System [CDDIS]).

Since the dynamics of a satellite directly affect laser ranging results, the measurements reflect an inherent sensitivity to the location of the center of mass. (Depending on how these measurements are used, however, this sensitivity can be diminished.) Common targets for SLR are given in Table 3 and future targets in Table 4.

Numerous other satellites have been tracked by SLR—the GEOS series, SEASAT, and BE-C, to name a few. These satellites were tracked for various purposes, including precise orbit determination and gravity field applications. Other current targets include GEO-1K, a candidate for gravity field applications, at a 1,500-km altitude.

As illustrated by Tables 3 and 4, no single satellite target meets the complete range of geodetic needs from reference frame to gravity field, even though laser ranging measurements are sensitive at some level to all of them. Because gravity decreases with altitude, the lower-altitude satellites are more sensitive to field variations and have therefore made the greatest contributions to our knowledge of the gravity field. Thus, in general, the lower-altitude satellites are used for gravity

TABLE 3. Current SLR targets.

Satellite	Altitude (km)	Application and Comments
Starlette	800	Primary application is gravity field, including temporal variations. Spherical satellite.
Ajisai	1,300	Primary application is gravity field. Spherical satellite.
GEO-1K	1,500	Gravity field applications.
LAGEOS-I	5,900	Adopted satellite for reference frame, crustal motions, Earth rotation, and gravity field (including temporal variations). Spherical satellite.
Etalon-1	20,000	Primary applications are reference frame and Earth rotation. Spherical satellite.
Etalon-2	20,000	Primary applications are reference frame and Earth rotation. Spherical satellite.

TABLE 4. Future SLR Targets. (Other satellites have been proposed—e.g., Lageos-III and ACRE—but are not yet completely funded.)

Satellite	Altitude (km)	Launch	Purpose
ERS-1	800	1991	SLR will be used as one of the primary orbit determination systems. Oceanographic satellite with altimeter. Nonspherical satellite.
Stella	800	1992	A duplicate of Starlette, but different orbit inclination. Applications to the gravity field, including temporal variations. Spherical satellite.
TOPEX/ POSEIDON	1,300	1992	SLR will be used as the primary orbit determination system. Oceanographic satellite with altimeter. Nonspherical satellite.
LAGEOS-II	5,900	1992	A duplicate of LAGEOS-I, but different orbit inclination. Applications to reference frame, crustal motions, Earth rotation, and gravity field. Spherical satellite.

field applications (including temporal variations associated with tides, postglacial rebound, etc.), while the higher-altitude satellites are used for reference frame and Earth rotation applications. While it is theoretically possible to use one satellite to determine the gravity field, experience has shown that highly correlated coefficients and geographical distribution of stations will adversely influence such determinations.

In summary, the demonstrated sensitivity of laser ranging techniques to geodetic parameters is as follows:

• *Site coordinates*

The coordinates of sites can be established in a reference frame whose origin coincides with the center of mass and in which the longitude of one site has been adopted as reference.

• *Earth orientation*

The technique is sensitive to the direction and magnitude of the Earth's angular velocity vector with respect to the adopted or determined reference frame. However, the ability to separate variations in the angular velocity vector (e.g., UT1) and precession/nutation from other characteristics depends on the satellite used. For example, LAGEOS is used to determine UT1 variations with periods less than about 60 days, but because of similar signals associated with tides it is limited in its application at longer periods and for nutation studies. Ranging to the moon, on the other hand, is sensitive to the full range of Earth orientation parameters.

• *Inertial orientation*

Only high satellite ranging, especially LLR, is adequately sensitive to an inertial frame defined by the orbital characteristics of the Earth about the sun. There is no direct sensitivity to the quasar reference frame, only an indirect link through common terrestrial sites of laser ranging and VLBI.

As with other space-geodetic techniques, laser ranging signals pass through the atmosphere and propagation effects occur. The spread of laser pulses is essentially independent of ionospheric effects, but the influence of the dry component of the atmosphere is important. At present, the propagation delay due to the atmosphere is usually modeled using measurements of temperature, pressure, and relative humidity at the laser station. Experiments are under way to make two-color laser range measurements to permit correction of the atmospheric delay (analogous to the ionospheric correction at microwave frequencies).

Global Positioning System (GPS)

The U.S. Department of Defense is establishing a constellation of 21 to 24 navigation satellites called the Global Positioning System (GPS). While the primary purpose of these satellites is to support military applications, it has been clearly demonstrated that GPS signals can be used for various civilian applications without access to classified codes and information. The GPS system has become

immensely popular with the geophysics and geodesy communities in recent years and probably will be the space-geodetic technique of choice for the foreseeable future.

Figure 12 shows the permanent GPS stations currently in operation, including in particular the sites of the CIGNET and DSN networks. For precise geodetic applications it is essential to use dual-frequency receivers (1,200 and 1,600 MHz) to correct for ionospheric effects. Ionospheric and atmospheric effects parallel in every essential respect those previously discussed for VLBI, and the corrections follow very similar procedures. The network is growing explosively at the moment, and the recent IERS GIG'91 campaign involved more than 100 sites distributed globally. The proposed International GPS Geodynamics Service, to function under the aegis of IAG, has met with very positive response worldwide. Finally, the NASA-sponsored FLINN network will use GPS as its base technology.

GPS is the only space-geodetic technique available today that is fully commercialized. Its application to precise navigation, and the resulting large market, have brought substantial industry-led advances in miniaturization and decreases in equipment costs, to the point that equipment costs are expected to cease to dominate field budgets in the near future. Advanced applications to orbitography using onboard GPS receivers, discussed in Chapter 2, promise to dramatically alter the role of orbit errors as a dominant error source for many geophysical applications.

The main concern about GPS for commercial and precise scientific applications is the DoD's explicit policy of denying precise real-time positioning to general civilian users through implementation of Selective Availability (SA) (since March 1990) and its plans to test Antispoofing (AS) as soon as the system is declared fully operational (end of 1992). Provided that sufficient dwell time is allowed at each site—that is, long enough to average the dithering effects of SA—selective availability is not expected to impede significantly most geodetic applications, which involve site occupations of several hours. It is not yet known whether shorter deployments, typical of rapid static or even kinematic GPS surveys (see papers in GPS'90 Symposium Proceedings, Ottawa, Canada, 1990), will be affected enough to limit their geophysical usefulness. AS, which involves encryption of the code broadcast by the satellites, potentially could negatively affect a variety of precise civilian applications, in particular the mission support uses of GPS discussed earlier.

72
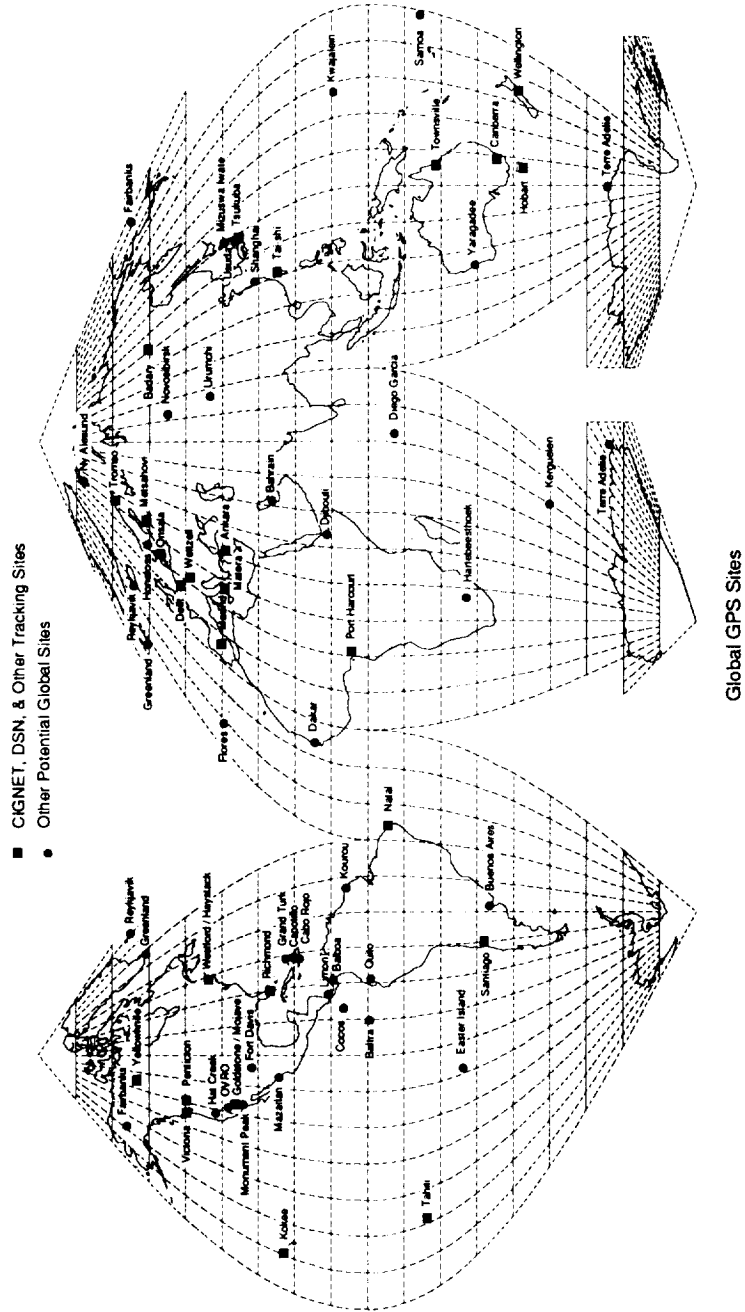
FIGURE 12. Map of existing and potential permanent global GPS sites. This map becomes obsolete very rapidly because of the rapid growth of the networks. (from Crustal Dynamics Data Information System [CDDIS], CIGNET Project, and GIG'91 IERS project).

Doppler Orbitography and Radiopositioning Integrated by Satellite

DORIS—Doppler Orbitography and Radiopositioning Integrated by Satellite—
is a ground-based tracking system developed in France mainly for orbit
determination, but it can be used for precise positioning as well. DORIS and the
older TRANET (TRAnsit NETwork) systems use Doppler shifts of radio waves
traveling between ground station and satellite to determine the line-of-sight
velocity or range rate of the satellite. In TRANET the transmitter is on the
satellite, and up to 40 globally distributed ground stations record the Doppler
shifts. In DORIS the receiver is on the spacecraft, and the signals are transmitted
by nearly 50 globally distributed radio beacons (Figure 13).

DORIS is a dual-frequency system (401 and 2036 MHz). The first DORIS
receiver was launched successfully by the European carrier Ariane in January
1990 as a payload of the SPOT-2 satellite, and the ground network is fully
operational. Willis *et al.* (1990) report encouraging initial results, with month-to-
month repeatability of absolute positioning solutions between 0.23 and 0.40 m.

Precise Range and Range-rate Equipment

The German PRARE—Precise Range and Range-rate Equipment—is a space-
borne, two-way, two-frequency (S/X band: 2,200 and 8,500 MHz) range and
range-rate measuring system (Flechtner *et al.*, 1990). PRARE is self-contained,
with two-way transmission of all relevant data between the satellite and the ground
stations on the tracking loop. The space segment has sufficient memory to store
tracking data and corrective data transmitted from the global network stations for
transmission to a master ground station during overflights. Through the master
station, commands and broadcast data are transmitted into the onboard memory
and disseminated from there to the ground stations.

The ground stations operate as regenerative coherent transponders, deployed
as a global network (Figure 14). They are of low weight, are highly mobile, and
can operate unattended. They comprise an antenna unit (0.6-m-diameter steerable
parabolic dish), an electronics box, and a weather unit. S- and X-band signals
modulated with a PRN (pseudorandom noise) code are sent to the Earth from the
satellite, and the time delay in the reception of the two simultaneously emitted
signals is measured on the ground and retransmitted to the onboard memory for
later ionospheric correction of the data. In the ground station the received X-band
signal is translated to 7.2 GHz, coherently modulated with the regenerated PRN
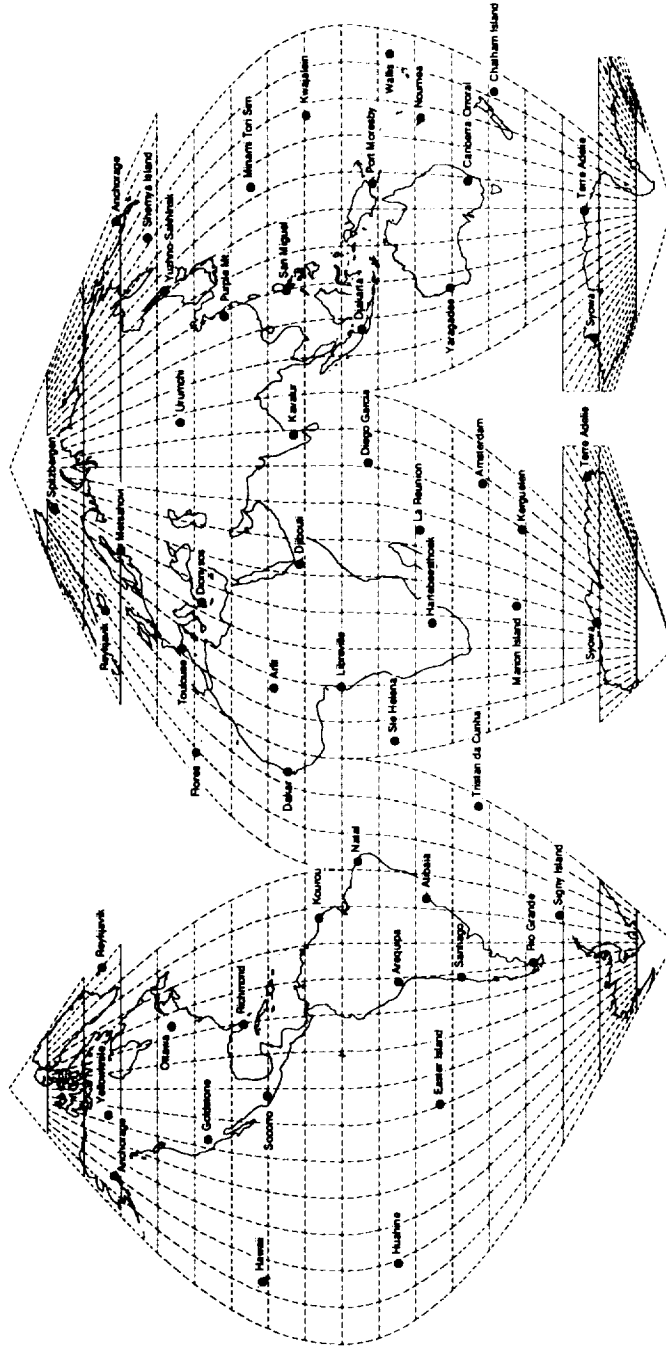
DORIS Ground Network

FIGURE 13. Map of the global DORIS (France) network. The DORIS system is now operational (from Willis *et al.*, 1990).
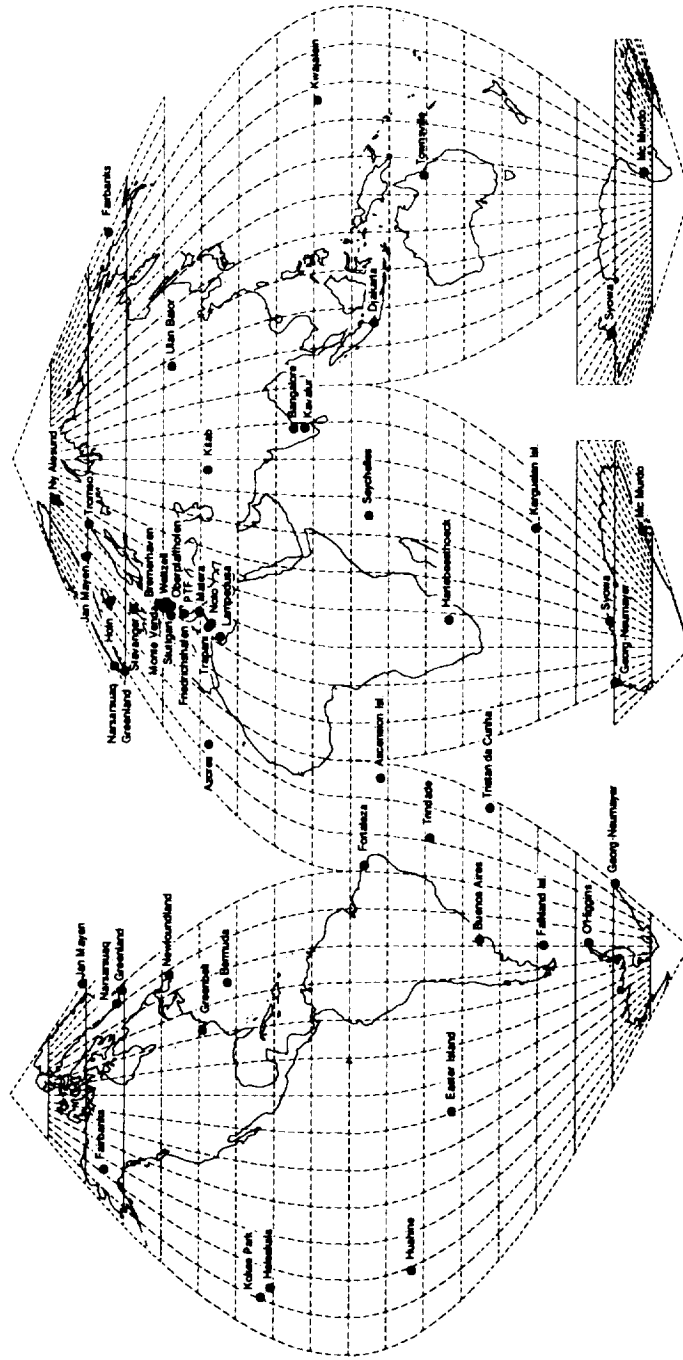
PRARE Ground Network

FIGURE 14. Map of the global PRARE (Germany) network. The overall system is expected to be operational at the end of 1991 (from Flechtner *et al.*, 1990).

code, and retransmitted to the space segment, where the PRN code is fed into a correlator to determine, onboard, the two-way signal delay, which is a measure of the two-way slant range between satellite and ground station. In addition, the received carrier frequency is evaluated in a Doppler counter to derive the velocity of the spacecraft relative to the ground station. Four independent ground correlators and four Doppler counters allow simultaneous measurement with four ground stations in code multiplex.

The measurement accuracy of PRARE is estimated to be 0.1 mm/s for X-band Doppler (integration interval 30 sec) and 3 to 7 cm for X-band ranging (one measurement per second); the main error source is the atmospheric refraction (2 to 5 cm). The two-way unbiased range measurements provided by this system will make it less sensitive than other microwave systems to modeling errors resulting from atmospheric delay. The planned addition of two optical uplinks to the PRARE system may further reduce the atmospheric refraction limitation. With this upgraded equipment it will be possible to determine the atmospheric correction to better than 5 mm, so the resulting range accuracy will be better than 1 cm. The upgraded version, called PRAREE (i.e., PRARE Extended version), is planned for missions later in the decade.

Future Systems: GeoBeacon, Geoscience Laser Ranging Systems

Among future space-geodetic systems that might contribute significantly to a global network of fiducial sites are the GeoBeacon concept and the Geoscience Laser Ranging System (GLRS), mentioned earlier. Both systems could be deployed at global fiducial sites.

GeoBeacon is a proposed microwave system with multiple inexpensive ground transmitters, multiple inexpensive relay satellites, and one complex ground receiver station per region (e.g., Cangahuala, 1989). The ground stations would transmit signals in a number of narrow bandwidth channels (the exact sequence has not been fixed yet, but it could start as low as tens of megahertz and increase to several gigahertz). These signals would be received by all visible satellites and relayed to the ground station (after some onboard signal rejection to stop abuse of the system). A pseudorandom noise code would be incorporated into the signal structure to allow transmissions from different ground stations to be separated. In the ground station the signals would be correlated with replicas of the PRN codes, with tracking of higher frequencies being guided by the lower-frequency signals. This latter technique will allow low-power transmission in the higher frequencies. The observables from this system will be (doubly differenced) carrier-phase

measurements in each of the channels transmitted. Linear combinations of these carrier phases will allow the dispersive delay caused by the Earth's ionosphere to be estimated. Since the satellites will most likely be in low Earth orbit, and some of the transmitters will be at known positions, the data from these stations will be used to determine the satellite orbits. The accuracy of this system is expected to be similar to that of GPS. However, since the satellites probably will have no data storage facilities (and therefore data must be downlinked while both the transmitters and ground station are visible), the system may best be used to survey regional networks of small area (several hundred kilometers on a side).

GLRS is planned for launch on the EOS-B platform in 2001. The key features of GLRS are a dual-color laser ranging system and the ability to conduct both laser ranging to passive retroreflector targets and altimetry to natural surfaces. As currently planned, the laser transmitter consists of a Nd:YAG laser that will be pumped by a long-lived laser diode array. Its output frequency is doubled and tripled to produce pulses at 1064 (infrared), 532 (visible), and 355 (ultraviolet) nm. The visible and ultraviolet pulses are to be used for laser ranging, and the infrared pulse is to be transmitted at nadir for altimetry. The dual-color ranges will be used to correct in large measure the atmospheric propagation delay. The system is expected to provide (1 to 2 sec) normal points with subcentimeter accuracy. These range measurements combined with accurate GPS tracking of the EOS-B platform, are expected to yield station position estimates with a precision of a few millimeters within regional networks that are several hundred kilometers in extent. Data will need to be collected over 5 to 16 days from multiple EOS-B orbits to obtain accurate station position estimates. Since this system operates at optical wavelengths, it will provide a valuable complement to the microwave systems operating at the time.

Implementation Issues

A global geodetic network will have two independent parts: an organizational structure and a collection of stations. It is perhaps not immediately obvious that the organization will be fully as important as the stations in meeting the desired goals. During the next decade, local, regional, and national requirements will dictate the deployment of hundreds of continuously operated geodetic stations. This deployment will occur independently of any effort on the part of the community to produce an integrated global network. The effect is apparent from the proliferation of various networks such as CIGNET, PGGA, PRARE, and DORIS. These

stations, to be most useful, must be *integrated* into a single global network with consistent policies governing sites, receivers, and data. The organizational structure that provides this integration is the part of a global network that will require the most attention during the next few years. In the next two sections we discuss the organizational and physical implementation of an international global network of fiducial stations.

Organizational Implementation

The global nature of the geodetic network envisioned demands that an international entity be designated as the responsible governing body. This entity will need to derive its mandate from an international organization (e.g., the International Union of Geodesy and Geophysics, IUGG). To achieve an integrated network, channels of communication and responsibility must be simple and straightforward. This suggests a hierarchical structure with each observatory or data center taking direction from only one agency. In fact, however, the observatories and data centers will be parts of various national or subnational organizations. They will be established to meet goals other than those of the global fiducial network and will be funded from other sources. Funding agencies will allow these data centers and observatories to participate in the global network only when they clearly perceive a benefit to themselves. It will be a delicate task to negotiate a command and control structure that produces a consistent, reliable, and perhaps homogeneous network without infringing on the rights of the local, regional, or national organizations that support the observatories or data centers.

An example of such a structure can be found in the International Earth Rotation Service (IERS). The IERS was established in 1987 by the International Astronomical Union and IUGG. IERS is responsible for defining and maintaining conventional terrestrial and celestial reference systems, for determining Earth orientation and for organizing operational activities such as observation and data analysis, collecting and archiving appropriate data and results, and disseminating the results (see Appendix B). IERS consists of a Central Bureau and Coordination Centers for each of the principal observing techniques. The Central Bureau combines the various types of data collected by the service and disseminates to the user community the appropriate information on Earth orientation and the terrestrial and celestial reference systems. The Directing Board is composed of representatives of the International Astronomical Union, the International Association of Geodesy/International Union of Geodesy and Geophysics, the Federation of Astronomical and Geophysical Data Analysis Services, the Central

Bureau, and each of the Coordinating Centers. The Directing Board exercises general control over the activities of the service, including modifications of the organization and participation that would be appropriate to maintain efficiency and reliability, while taking full advantage of advances in technology and theory.

The organization of the global fiducial geodetic network may need to differ somewhat from IERS. The hardware required at each observatory is smaller and less expensive than the VLBI, SLR, and LLR stations that contribute to the IERS. Consequently, it is likely that many more smaller organizations will contribute to future global fiducial networks. For example, many states in the United States are establishing or have established regional GPS networks. It will probably be valuable to include some of these stations in a global network. However, this will mean including stations funded and operated by many different organizations with many different objectives and standards. The challenge facing us is to learn how to integrate these diverse stations into a single network that can meet the demands of all users, including those who may require great consistency and continuity across the network.

Physical Implementation

Users of global geodetic networks will fall into several categories, ranging from those who require raw data to those whose interest is in derived products, such as GPS satellite orbits or Earth orientation information. All users, however, depend directly or indirectly on three critical aspects of the network:

- The coordinates of the stations must be known to the required accuracy in a consistent and fully documented reference frame.
- The stations must be reliable, and specific care should be taken in implementing changes in the global network.
- Data must be easily accessible to users and flow efficiently through the system.

Station Coordinates. For many of the applications of global networks, users will need to know the coordinates of all the stations in a common global reference frame. Several such reference frames are in use in the world today. At present the only observations with sufficient precision and coverage to provide such a reference frame are the VLBI and SLR data sets. All of the current high-precision

reference frames used by GPS are defined by a set of station coordinates derived
from VLBI and SLR observations, such as those of the IERS Terrestrial Reference
Frame (Boucher and Altamimi, 1989, 1990). To obtain the coordinates of a GPS
station in the adopted reference frame, it is necessary to determine its position
relative to some station with known coordinates. Such a determination is only the
first step, however. The determination must be carried all the way through to the
appropriate reference point for the particular instrument at the station. For
example, the appropriate reference points for GPS receivers are the phase centers
of the antennae. At the levels of precision that are routinely attained today,
knowledge of the coordinate vector at one epoch is not adequate. It is also
necessary to know how this vector evolves as a function of time. The position of
a station varies with time in response to many factors. A short list of factors
influencing the location of station reference points would include:

- solid Earth tides;
- plate motion;
- polar motion/ UT1 series (essential for determining site motions);
- regional deformation (e.g., fault slip, strain accumulation, volcanic
inflation/deflation);
- local site deformation (e.g., landslides);
- meteorological effects (e.g., rainfall, desiccation, thermal cycling,
freeze/thaw cycling);
- monument instability;
- relocation of antenna;
- changes in antenna type; and
- changes in surface loads and water table changes.

The actual time history imposed by some of these factors may be quite
complex. At current levels of precision many can be approximated by either a
linear change with time (plate motion, regional deformation, local site
deformation); a quasi-periodic change with time (solid Earth tides, meteorological
effects); or a series of step functions (changes in antenna position, changes in
antenna type). To maintain knowledge of the position of the station reference point
at all times, we must account for all of these factors. Solid Earth tides can be
predicted with adequate precision. Plate motions—averaged over periods that are
long compared to geodetic time series—can be estimated from other types of
observations (e.g., geological) and should therefore be incorporated in the
definition of the reference frame.

At some sites regional deformation may not contribute significantly to the station's position, while at other sites a regionally distributed network (10- to 30-km spacing) of ancillary sites may be required to understand the motion of the central site. A few regionally distributed sites (5- to 10-km spacing) will also be very useful in ascertaining the existence of local site deformation in those cases where this is a concern. Monument stability can be improved by careful attention to the techniques used in installing the monument and then monitoring its location with a few reference stations around the central station (10 to 100 m). In all these cases it is only necessary to occupy the ancillary station occasionally; continuous occupation will not generally be required. Apparent changes in position introduced by changes in antenna position or type cannot be eliminated unless they are determined by special calibration observations at the reference stations and recorded in a log of station history. There will be many reasons for changes in position; some are discussed below.

To maintain knowledge of the station's location it is critical that changes be carefully documented and made known to all users of the network. Meteorological effects on monument location are perhaps the least understood of all the effects on the list, but some of the techniques discussed for other effects will mitigate them. For example, reference stations occupied frequently enough may provide some insight into desiccation cracking or expansive soil swelling in wet conditions. Some meteorological effects can be identified by their periodicity; temperature variations can produce diurnal and annual signals. One of the complicating factors with meteorological influences on the actual station position is that meteorology can also affect the data obtained and thus produce apparent changes in station location (e.g., Wyatt, 1982, 1989). It may not be easy to separate these two effects.

With a possible fiducial sites spacing on the order of 10^3 km, the question of establishing the coordinates of sites that are not collocated with VLBI or SLR becomes important in implementation. It is clearly infeasible, financially and operationally, to operate mobile VLBI or SLR equipment at all sites. As a consequence, determining the GPS orbits to support part-per-billion accuracy will be essential to the implementation. Only with such accuracy will it be possible to obtain meaningful ties to the global reference frame for fiducial sites that have not been occupied by VLBI or SLR. The essential aspect of such orbit precision is the ability to support three-dimensional geodesy at the level of 1 ppb.

Station Reliability. Users of the network must be able to make observations at any time with certain knowledge that the required network products will be available. Our goal should be network integrity 100% of the time. At critical stations this may require onsite service personnel, adequate spare hardware, and ongoing evaluation of data quality so as to recognize problems immediately. This does not necessarily imply that every station in the network will have to be operational 100% of the time. For some purposes it may be adequate to have sufficient redundancy in the network so that the loss of some stations some of the time can be tolerated. It may be enough to have 90% of the stations operational 90% of the time. However, many kinds of applications will be much better off with 100% reliability or as close to that as we can achieve. A local scientist depending on the data from a network station at Mojave as part of some southern California observations will not be satisfied if the network operators report that, while Mojave was not operating during the campaign, Ft. Davis, Texas, was operating, and from a network perspective they are equivalent stations. For example, to someone looking for subtle changes in a vector as a function of time, a change in the set of stations used to produce an ephemeris may be one more potential noise source. If isolated from the details of the network operation, the user may have no (easily determined) knowledge of what network stations contributed to the ephemeris disseminated by the agency operating the global network.

One of our principal tools for improving reliability and performance is to upgrade or replace both hardware and software components of the system with newer and better ones. The evolution of technology makes changes in sites, instrumentation, and monumentation inevitable over the lifetime of a global geodetic network. Such change is desirable, but it does have a significant disadvantage. Changes in the networks greatly complicate the solution of problems in that artificially induced changes must be separated from changes in the phenomena under study.

Global networks have been and will be implemented to contribute to the solutions of specific scientific problems (and through them to the solutions of societal problems). Solving these problems will often require signal-to-noise ratios that are very near the limits of the technology. For example, relative plate motion rates are typically a few millimeters per year for most plates and range up to about 100 mm/yr for the fastest-moving plates. The size of the major tectonic plates requires that their relative motion be observed over vectors thousands of kilometers long. The resolution of a relative plate motion rate of 50 mm/yr (e.g., Pacific-North America) in a few years over 5,000-km vectors requires an accuracy of 50 mm/5,000 km = 0.01 ppm. Even more challenging is the problem of resolving changes in plate rates or distinguishing between various models that may

predict slight differences in plate rates. Other scientific problems to be addressed with global networks are similar; they all require the highest precision obtainable from global networks.

Not only do the problems to be tackled require the highest accuracy possible from each measurement, but they also require that measurements be continuous. Producing adequate signal-to-noise ratios for many problems will require making measurements over periods of years. In the past, decades have often been required to obtain useful signal-to-noise ratios. To apply data collected over extended periods to geophysical problems, it will be necessary to maintain high accuracy over these same periods. Otherwise we will be unable to distinguish apparent changes from changes in the geophysical phenomena under study, be it plate motion, global sea level, ice sheet mass balance, or others. The quest for accuracy forces us to look continually for new and better ways to make our measurements. The instrumentation deployed to make the observations, the techniques used in making the measurements, and the models used in deriving Earth science from the data are subject to continual evolution, and occasionally revolution, in attempts to improve precision. The challenge facing us is to implement changes in such a way that we do not lose continuity. At the same time that we are upgrading our networks to take advantage of the most recent improvements, we must maintain a careful tie to the older observations so that we do not destroy valuable time series. Occasionally, it may be impossible to reconcile these two conflicting goals; often it will be difficult and perhaps expensive.

The first and most important step in accommodating change is maintaining a complete and accurate record of the changes that take place, particularly those changes over which control can be exercised, such as changes in equipment, position, and antenna. This record should document all changes that potentially could affect the accuracy or continuity of the parameters of interest. A second important step is to maintain continuity in the position of the stations that make up the global network. It is essential that the relative position of an existing station and its replacement station be known to 1 mm in all three coordinates. This positional continuity must be maintained through changes in antenna type or antenna location. Whenever a change is required, the positional continuity must be verified through extended experiments. New instruments should be run in parallel with the old ones for extended periods. The overlap time should be long enough to allow an overlapping data set to be collected and analyzed. Problems usually are not discovered until someone sits down and carefully looks at the data. In light of the long delay between data collection and data processing, an extended overlap period will often be required. When new models are used to interpret data,

an attempt should be made to understand the impact of the differences in the models. Where possible it is recommended that the continuity of time series derivatives be protected as well as the continuity of the time series themselves. Protecting the continuity of even the first derivative will require considerable commitment of resources, but the Panel believes that this commitment is essential at critical sites. The Panel discussed how best to accommodate technological progress without losing continuity in the geodetic time series. For implementing change in global geodetic networks, especially the core network, the following recommendations are made:

1. Continue VLBI observations at key sites for the foreseeable future to provide the long vector precision required by many applications and to provide a reference system for comparison of newer techniques.

2. Continue SLR observations at key sites for the foreseeable future to provide a tie to the center of mass of the Earth and to provide an independent system with which to compare VLBI.

3. Investigate the role of GPS in complementing the roles currently filled by VLBI and SLR—for example, reference coordinate system, Earth orientation, and plate motion monitoring over all length scales.

4. Continue to evaluate new techniques, such as GeoBeacon and GLRS, for potential contributions to solutions of problems using global networks.

5. When major changes in instrument systems are made at critical sites (e.g., the conversion of monitoring at Vandenberg Air Force Base from VLBI to GPS), obtain and analyze several years of parallel data before removing the old systems altogether.

6. Where there are significant discrepancies in existing systems (e.g., Ft. Davis, Texas), assign high priority to continuing observations with no change in technique, no gap in data, and no discontinuity in the time series or its first derivative.

7. Maintain mobile VLBI/SLR capability to allow reoccupation of VLBI/SLR sites and evaluation of the long-term behavior determined under item 5 above when new techniques indicate differences between new and old observations.

Data Flow, Processing, and Archive Issues. The tracking stations of the global fiducial network will generate a substantial volume of data that must be easily moved from the tracking sites to the analysis centers and to other users. Experience in geodesy and with other types of global geophysical data (e.g., seismic) suggests that these data should be managed though a number of Data

Centers, organized and designed according to the kind of tracking data they manage, the volume of data that passes through them, and various geographical considerations.

Some of the factors influencing data management include:

• The network concept described herein includes a core network of 30 or more GPS stations. These are treated as primary stations, which should be operated continuously, and collocated, insofar as possible, with VLBI or SLR observatories or sites regularly visited by transportable or mobile VLBI or SLR systems. They define the GPS reference frame consistent with the other space-based geodetic techniques. Data collected by the GPS core stations are used for generating precise ephemerides and for solving for Earth orientation and rotation parameters.

• The network should be organized into regional clusters of stations that can be used (1) to monitor regional or local crustal deformation or relative plate motions and (2) to supplement the core network, providing redundancy and therefore enhanced orbit control by serving as additional fiducial stations. Although such stations may be occupied intermittently at first, many will eventually move to continuous operation, as the technology for data acquisition improves and as efficient data transfer and data processing algorithms are developed.

• The data centers will most likely have direct links to tracking receivers. This requires detailed local knowledge of receiver types and data transmission options. Although all data ideally should be available to all users, in practice certain sites will have restricted data access, for a variety of reasons, depending on the operator and possibly involving security issues. It is important that the data centers establish working protocols with the appropriate agencies to obtain access to data on a case-by-case basis.

Estimates of raw data volumes depend on operating characteristics of the stations, sampling frequency, and so on. Data compression schemes can be devised to reduce the burden of data transmission and storage. A rule of thumb is that tracking stations may generate about 1 Mbyte per day of raw data. Therefore, a fully deployed fiducial network may generate several hundred Mbytes daily. Consequently, large-capacity mass storage systems (e.g., optical) will be required to make all data conveniently accessible. Specific details and requirements for archival storage remain to be completely established. It must be kept in mind, however, that such a volume of data is characteristic of current global seismic

networks, so that many technological solutions adopted to deal with the data flow generated by such networks could be adapted for geodetic data. (A substantial difference exists, however, as the bulk of seismic data is processed through a relatively simple detection processor, and more complex processing is restricted to seismic event recordings, whereas essentially all geodetic data must be fully processed.)

The potential data products that an appropriately organized service could provide using data from the global fiducial network include the following:

- *GPS Ephemerides*: A wide range of ephemeris accuracies are required by the user community. Some applications can be satisfied with an ephemeris accurate to 10 m, while others require centimeter accuracy. Further, the time delay in the ephemeris availability varies from perhaps a few days to several weeks. The potential user community includes, for example, regional survey institutions with accuracy requirements of one part in 10^6, while crustal motion applications have requirements of a few parts in 10^9. In all cases it is expected that the community requires ephemerides that are essentially free of Selective Availability or other degrading effects. Some applications may benefit from predicted ephemerides, provided they exceed the quality of the broadcast information. Both regional and global ephemerides will need to be produced, with the former being available within a few days and the latter within a few weeks or less. In addition, global ephemerides based on the GPS core network could be computed within a few days with the goal of providing Earth orientation data to the IERS. Accuracy estimates should be provided together with the orbits as a matter of policy.

- *Clock Information*: Since field operations with GPS typically rely on internal receiver clocks/oscillators, information about the satellite clock performance is important to establish the correct receiver time. For the highest-accuracy applications, satellite and fiducial clock information of sufficient quality for the support of the desired accuracy will be required.

- *Atmospheric and Ancillary Data*: With an appropriately distributed network of stations, the dual-frequency data collected can be used to infer ionosphere parameters and possibly aid in the improvement of ionospheric models. In addition, properly instrumented stations could record meteorological data for use in estimating the atmospheric-delay correction to GPS data. One possible product could be the development of atmosphere models that could be readily applied to data from sites in the vicinity of the respective fiducial stations, although the scale length of water vapor variation may be too short for such applications in most areas.

C 2

* *Satellite and Station Status*: Information about the satellite and station status, including anomaly determination made as a result of data analysis, would assist field and postprocessing operations. These status reports should reflect a different level of status assessment than that available from the satellite control center and from individual stations. Additional information that could be useful includes the historical set of satellite force parameters, such as the y-bias and radiation pressure scale factors, as well as orbit change parameters (delta-V).

* *Verification and Data Quality Assessment*: The statistics associated with the estimates of satellite states and other parameters, coupled with regular monitoring, are vital in assessing the overall quality of the estimates and the quality of the tracking data provided by the fiducial sites. Comparison of overlapping fits could be used as a preliminary indication of ephemeris quality. The globally derived ephemerides will be distributed to the regional analysis centers for further evaluation. A source of concern in this respect is that the time scale over which problems continue to be discovered in any given data set is occasionally quite long (years), so that even the best solutions may have to be updated long after they were first obtained. This raises the fundamental issue of updating all user data bases and keeping them synchronized.

* *Earth Rotation/Reference Frame*: It is expected that GPS will become a regular contributor to the IERS, although a complete demonstration is still lacking. Since baselines determined from GPS observations are affected by error sources that are somewhat different from those affecting other techniques, it offers an opportunity to separate technique-dependent systematic effects from geophysical phenomena. In addition, GPS will continue to provide geodetic ties between nearly collocated different systems, as well as the temporal variations in these ties. The potential for GPS to establish its own reference frame exists, but the technical requirements or limitations, if any, remain to be determined. At least for the Earth rotation applications, high-accuracy ephemerides are expected implicitly to be generated concomitantly with the Earth rotation parameters. For other applications, however, Earth rotation parameters obtained from IERS may be used in calculating GPS ephemerides.

* *Edited Tracking Data*: The edited tracking data from the fiducial sites used in the ephemeris estimation process can be made available along with appropriate quality indicators. However, as indicated above, a mechanism for dealing with data problems discovered later must be devised and implemented.

* *Point Positioning/Baselines*: Finally, the service could disseminate regular determinations of site coordinates, including their time variation, for the sites in

the global network. This could provide a check on the quality of regional surveys and on the accuracy of data products.

It should be noted that all these data products are at least partially available at present. The specific needs of the user community are not completely clear, however, and will have to be developed concomitantly with the progressive installation of the network. As has been the case with the MERIT project, much can be learned from focused campaigns of global scope. By and large, the data flow requirements for the data products mentioned are less demanding than those attached to the flow of the raw data. The establishment of archive centers with catalogs describing available data and their location is an essential element of the global network. Use of electronic networks should permit a user to browse the holdings of an archive, as well as determine the data holdings for raw and higher-level data products stored at any other archive worldwide.

At the same time, most of the subtle problems cannot be detected until a fairly high-level (sometimes even very advanced) analysis is performed. Consequently, in parallel with data centers, it is imperative that a number of analysis centers be established and adequately funded, with a clear mission to keep up with the data flow and provide reliable feedback to network operations. As with most other disciplines, this is the only mechanism that will maintain the level of quality control required by the scientific objectives discussed in the previous chapter.

4
A PROPOSED PLAN

Introduction

In this chapter we propose a plan for the creation of a global network of fiducial stations over the next 5 to 10 years. The viewpoint that fiducial sites should be collocated with sites equipped with a variety of geophysical instruments is adopted implicitly, so that the global network of fiducial sites is equated here, for practical purposes, with the proposed FLINN concept (NASA, 1991).

FLINN is conceived as a network of stations that will provide diverse and precise data to aid in the solution of geophysical and oceanographic problems on both local and global scales. It is anticipated that many of the existing stations can be incorporated into the network; however, it will be expected that the data obtained will meet established and agreed upon standards and specifications. Although collocation of observing systems is a highly desirable feature of the network, stations that operate a limited number of systems will also provide useful information. Hence, many of the core stations considered necessary for the success of FLINN can be considered to exist, although for various scientific and operational reasons some of them will have to be upgraded. Moreover, as a consequence of the number of stations visualized in the network and the amount of data that will be generated, efficient and economic techniques for data transmission, analysis, and distribution need to be established.

The local and global studies to be supported by data from the network range from those that can be addressed by one or two individuals to those that require the attention of large groups of scientists throughout the world. Hence, individual scientists and students should have ample opportunity to contribute to the

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advancement of geophysical and oceanographic sciences. The nature of the problems will determine the minimum number and maximum effective distribution of observing stations and the suite of instruments required at each.

Certain key stations may require extensive suites of instruments, whereas at other sites the configuration may not need to be as elaborate. In this regard the cooperation of the host country or group of countries will be essential if the endeavor is to succeed. Each host country will need to maintain and support its existing observing station or stations and establish additional stations where necessary. Some areas conceivably may have a redundant number of stations. In such areas the network might accept all of the data, within the processing capacity of the data centers, or it might elect to accept only those data of the highest quality. In any event, as many of the existing stations as possible should be incorporated into the network.

It will be necessary to provide data links between the observing sites and data and analysis centers, as well as a central service center where the data would be evaluated and prepared for dissemination to scientists throughout the world. Essential functions of the service center will be to provide for quality control and prepare summary reports on data availability. Because of the anticipated quantity of data to be generated and the burden that it would place on a single center, it will probably be necessary to establish regional processing service centers in each region. It will then be necessary to develop data links among these centers, thereby ensuring a truly international and global system. Early in the deployment the data centers should agree on standard formats for archiving and disseminating data and on quality control standards. A comprehensive study to determine the most effective, yet economical, solutions to data problems should be undertaken jointly under the aegis of an international organization. It is essential that the data be available to all scientists for, at most, the costs of data copying and transmission. Essentially, FLINN will require on a global basis the type of data management program already envisioned for the U.S. Global Change Research Program (National Research Council, 1991).

The FLINN program will have to be coordinated on an international scale. The cooperation of the international scientific organizations and the international networks of discipline-oriented observing stations will be essential. The International Union of Geodesy and Geophysics, in conjunction with the various international scientific organizations, might provide this coordinating function.

Strategy

A simple initial strategy for building FLINN is clearly to begin where the very successful programs of the 1980s (in particular the NASA Crustal Dynamics Project) left off. In particular, the existing VLBI and SLR global networks are in place, with well-established standards and well-defined data flow. The IERS, as a result of the MERIT experience, is operating according to a set of agreed upon standards with very extensive international cooperation. By building on existing structures, adding to the existing networks, and adapting the existing infrastructure to the expanded needs associated with the FLINN concept, we can achieve a gradual and flexible implementation and learn along the way what the best strategy should be.

The maps of existing global networks shown in the previous chapter, including in particular the rapidly growing GPS network, show clearly that the ingredients for establishing the GPS core network are nearly all in place. However, a network is much more than a collection of stations. The infrastructure for a smooth and effective flow of raw data, timely processing of these data, and wide dissemination of the data products to the end users is still lacking. As mentioned earlier, the true needs of the end users are still relatively ill defined. Setting up such an infrastructure will require a coordinated national and international effort and the allocation of substantial resources if the full potential of the data is to be realized.

To achieve this goal, the Panel proposes the following strategy:

- Begin the operation of FLINN immediately, using existing data sources. FLINN is a very ambitious long-term program, and it is not clear that we know how to implement it from our experience to date. *It is important to begin to process the data generated by existing stations as the embryonic global network, with emphasis on the processing of data from core stations and production of the relevant data products.* We should not expend a large fraction of available resources on deploying new stations and augmenting the network until we have identified effective ways to collect, process, archive, and disseminate the data in a manner that is timely and satisfactory to the user community. This also means that we should explore now the role of international organizations, particularly the IUGG and its member associations. Finally, it means that participating countries should make commitments to allocate the necessary resources to the collective endeavor.

• Experiment with the collection and processing of large data sets in the framework of time-limited tests or campaigns. This time-honored way to explore multinational, multiagency endeavors has been extremely successful in the past. The MERIT campaign, the GIG'91 experiment, and the proposed EPOCH'92 campaign fall into this category. Each campaign should have explicitly stated goals, whether to test processing capability, appropriateness of data standards, data transmission technology, or administrative structures. The lessons learned from each campaign should result in improved operations for the next one. In addition, such campaigns provide useful epoch measurements for many sites that might be incorporated into the permanent network at some future time. Existing global networks, in particular the CIGNET GPS network, should play a critical role in such campaigns in view of the many participants already involved and the associated infrastructure already in place.

• Whenever possible, learn from the experience developed in other disciplines. This is particularly true of digital data transmission technology, data archiving techniques and technology, and organizational architecture.

A Network Design Proposal

This section discusses a network design proposal that would satisfy the scientific objectives discussed in Chapter 2. It leads to a proposed network, combining existing resources with long-term wishes, which appears to be realizable, although the task of actually building and operating it will be a major challenge for the next decade.

Core Network

As stated earlier, the GPS core stations should number about 30 or more and should be collocated with equipment using other techniques. Using existing and planned CIGNET and DSN stations, supplemented with a handful of stations that might be collocated with DORIS and PRARE sites, would allow us to meet the GPS core network requirements in the very near future. In fact, enough infrastructure is already in place internationally to begin testing GPS core network operations (orbits, Earth orientation, data flow), provided that the resources are allocated to do it.

Sea-Level Change and Postglacial Rebound

A program of tying high-quality tide gauges to a global reference frame has been initiated within the National Oceanic and Atmospheric Administration. Although relatively few of these ties will be performed with high temporal sampling initially, this program could easily grow to take advantage of new technology and data acquisition, transmission, and processing techniques.

To address all the postglacial rebound issues with a space-geodetic network, we suggest a long-term goal of approximately 100 sites distributed as described below. Of course, many of these sites will also serve other scientific goals, so the number of sites earmarked specifically for postglacial rebound studies would be smaller.

• Antarctica—to constrain recent current melting and to discriminate among the various types of peripheral bulge behavior predicted by competing models: 10 sites, including 2 sites in the Trans-Antarctic Mountains and 2 sites on the Palmer Peninsula. The behavior of Cape Adare in Victoria Land is important in discriminating among models. Sites on Macquarie Island and/or Campbell Island would be useful, if geologically suitable. Table 5 lists potential Antarctic sites that might be considered for incorporation in the global network.

• Greenland—to constrain recent current melting and to discriminate among the peripheral bulge behaviors predicted by competing models: at least 6 sites. Table 6 lists possible candidates.

• North America—to constrain the behavior of the peripheral bulge, particularly in relation to tectonic provinces: 40 sites at ~500-km spacing, paying particular attention to the transition from precambrian shield and platform to fold belts in U.S. (Appalachian) and Canadian Arctic (Innuitian). The Canadian GPS network shown in Figure 15 (Delikaraoglou *et al.*, 1990) represents a system that is currently being deployed and is a major step toward this goal.

• Fennoscandia—to constrain the behavior of the peripheral bulge, particularly in relation to tectonic provinces: 20 sites at ~400-km spacing, paying particular attention to the transition from precambrian shield and platform to fold belt/margin.

TABLE 5. Potential Antarctic sites.

Site Name	Latitude	Longitude
Beardmore	−85.5	165.
McMurdo	−77.9	166.7
Terra Nova	−75.	165
Russkaya	−75.	225
O'Higgins	−63.3	302.1
UK	−68.	292
Maud	−71.	357.
Syowa	−68.	40.
Davis	−68.5	78.
D'Urville	−67.	140.
Wilkes	−67.	111.

• Far-field sites—to constrain the rate of tilting of continental margins caused by loading from the oceans: 20 sites—deployed in 5 networks of 4 sites each at ~400-km spacing in geologically stable environments far from regions where ice melted or is melting.

• Mountain glaciers—at least one global network site at each of the top 10 proposed contributors to global sea-level rise. Densification (up to ~5 sites/region at about 200-km intervals) could be considered part of the global network, or not, on a case-by-case basis. Expected rates of motion are ~0.5 to 5 mm/yr. The regions, taken from the list of Nakiboglu and Lambeck (1991), are shown in Table 7.

TABLE 6. Potential Greenland sites.

Site Name	Latitude	Longitude
Thule	77.	−68.
Narssarssuaq	61.5	−45.5
Godthab	64.	−52.
Christianshab	68.	−52.
Upernavik	73.	−56.
Scoresbysund	71.	−22.
Angmagssalik	66.	−38.
Frobisher Bay	63.5	−68.
Hofn	64.	−15.
Ny-Alesund	79.	16.

Tectonic Motions and Deformation

A global GPS network will greatly enhance our ability to detect and monitor tectonic signals associated with plate motions and deformation over short times. For convenience in the discussion, we can separate the various types of motions by geological types, although from a geodetic point of view the differences are immaterial.

To monitor rigid relative motions of the major plates, we require a minimum of three global network sites per plate. Taken at face value, this requirement translates into a globally distributed network of approximately 40 sites, which could include the GPS core network discussed above.

On the other hand, to study large-scale nonrigid behavior of the plates, we need an intersite spacing smaller than about one-third of the plate dimensions. This argues for a global coverage with mean intersite spacing of 2,000 km or so, which results in a 100-site network, with fairly uniform distribution. Continuous
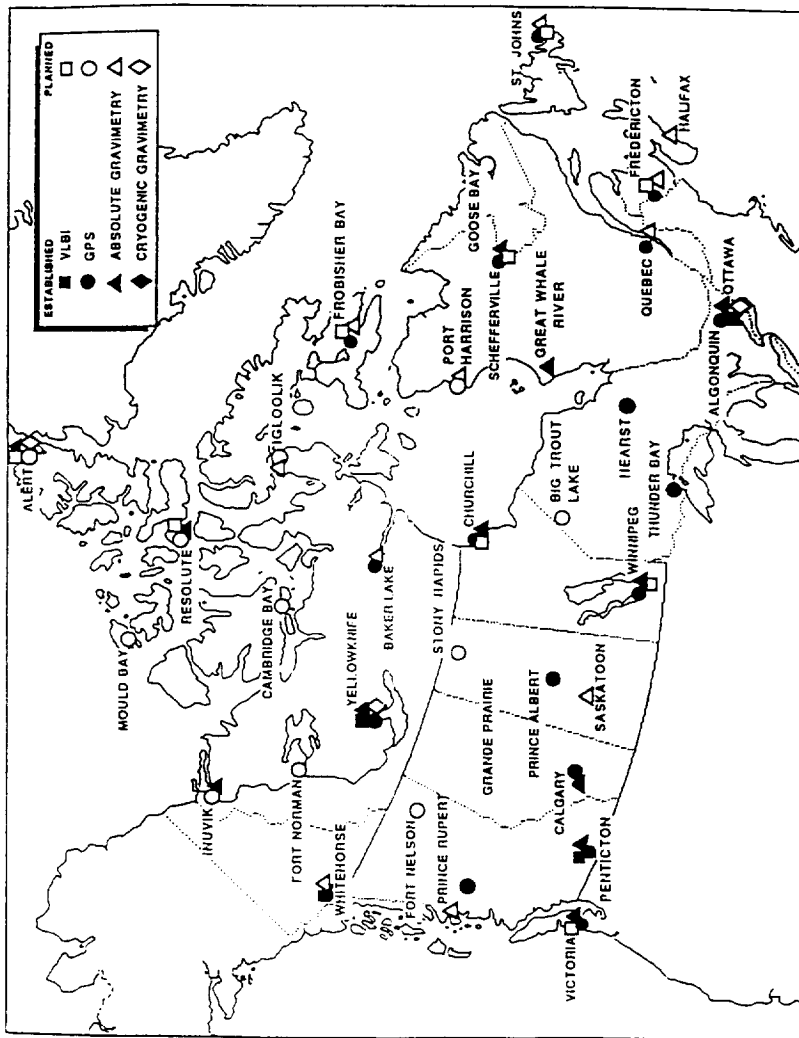
FIGURE 15. Canadian GPS active control system (from Delikaraoglou *et al.*, 1990).

TABLE 7. Contributions of glaciers to eustatic sea-level change.

Region	Characteristic Radius (km)	Eustatic Contribution (mm/yr)
Kenai Peninsula	176	0.109
Central Asia	196	0.091
South Andes	104	0.051
Cascades, Olympics	70	0.031
Alaska Range	72	0.025
Svalbard	116	0.022
Iceland	63	0.022
Canadian Arctic	195	0.020
Novaya Zemlya	119	0.017
Baffin, Labrador	121	0.012

operation is highly desirable, at least at a substantial fraction of the sites, as illustrated by existing transatlantic VLBI baseline data sets. At present, the full range of spatial and temporal scales at which plate deformation may (or may not) occur is not known. A strategy must be developed to avoid difficulties associated with spatial aliasing. For practical purposes it seems that detailed studies (with higher site densities) of a small number of plates of particular geological interest may be warranted. At high latitudes, especially in North America and Europe, this can be done at least in part by taking advantage of sites distributed for postglacial rebound studies.

It must be noted that long baselines cannot be avoided in most oceanic areas. Until such time as GPS transoceanic baselines have been shown to be reliably accurate, it is essential to continue the operation of existing techniques (VLBI/SLR) for long baselines; hence, a collocation requirement exists for this objective.

A 100-site network will achieve a 2,200-km average intersite distance if the distribution of sites is globally uniform. However, it is clear from geology that tectonic deformation is mostly concentrated in relatively narrow (< 1,000 km) zones. Figure 16 shows that the regions that are currently (or that have recently been) active tectonically cover approximately 9 % of the surface of the Earth. This conclusion is based primarily on geological indicators, as well as heat flow and seismicity. Densifying the global network in these areas to 1,000-km spacing would add 30 to 40 stations. Densifying the network to 500-km spacing would add about 150 stations.

In a number of areas, reconnaissance deployments would be invaluable, and probably a reasonable approach, before selecting permanent global sites. This is certainly the case in regions such as Tibet, where very little is known of the present-day patterns and rates of deformation. It should also be noted that, even if resources may not be available immediately to densify a global network with permanently occupied sites everywhere we should wish to do so, science would still be served by temporary occupations. In fact, the sooner potential sites are occupied for an epoch measurement, the better. These data will be used to make a more cogent selection of permanent sites. In this respect the proposed Epoch '92 campaign should be invaluable.

Possible Network Configuration

By collecting the information discussed above, and starting from the existing networks, the Panel devised a hypothetical network configuration to obtain a rough idea of the appearance of a possible FLINN deployment. It is shown in Figure 16 (see also Figure 1). The GPS core network is derived from existing CIGNET and DSN sites, with a few additions in locations where interested parties have stated their intention to operate a permanent GPS station (e.g., Tahiti, where the French intend to collocate GPS and DORIS sites). The selection of additional sites draws from existing and planned campaigns and from existing regional networks such as the one shown in Figure 15. Sites in Siberia, Tibet, or Africa represent fond wishes and are distributed so as to try to meet the criteria listed above. So are a number of island sites. No effort was made to incorporate ocean bottom sites.

Tracking GPS "core" network (28 sites)
Global Fiducial Sites (about 170 sites)
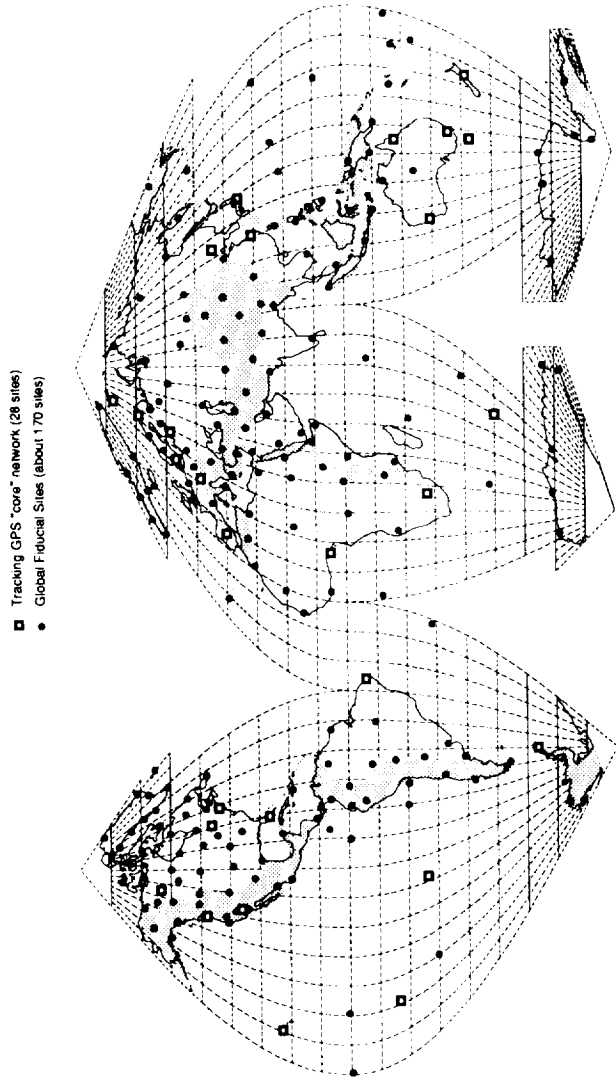
Example of Possible Global GPS Fiducial Network

FIGURE 16. Possible configuration of a GPS global network of fiducial stations. Core sites are taken from existing CIGNET, DSN, and other permanent tracking sites. Other sites are taken from existing campaign deployments; no such information was used for such areas as Tibet and Africa. Densification in areas of postglacial rebound and in shaded areas of current tectonic activity follows more or less the guidelines discussed in the text. Collocation with existing stations equipped with other systems (VLBI/SLR/DORIS/PRARE) can be achieved at a large number of sites. The shaded area covers approximately 9% of the total area of the Earth.

Integration with Other Geophysical Networks

Although this report naturally focuses on geodetic networks, other disciplines dealing with solid Earth science are actively deploying global networks of their own. The Panel encourages such groups to consider collocating these observations at fiducial sites along with other geophysical instruments in the expectation that such deployments will encourage a multidisciplinary approach to the study of the Earth. The detailed rationale for the deployment of geophysical networks should be considered both on a disciplinary and a multidisciplinary basis by the appropriate scientific communities. The geodetic community is of course familiar with relative and absolute gravimetric networks mentioned earlier, but coordination with other classes of measurements are also of fundamental interest. Selected global deployments of seismic stations and magnetic observatories are described briefly below.

Several countries are now deploying seismic networks. The two most active deployments are the U.S. IRIS/GSN (Incorporated Research Institutions for Seismology, Global Seismic Network) and the International Deployment of Accelero-meters (IDA), which together will ultimately consist of about 100-high quality stations worldwide. The deployment is under way; the 25 to 30 stations already installed include 6 in the USSR, which will grow to 10 in the near future, and several stations are being installed in the People's Republic of China. In parallel, the French Project GEOSCOPE has already deployed about 20 long-period broadband seismic stations worldwide.

The Group of Scientific Experts (GSE) of the Committee on Disarmament of the United Nations is conducting several Technical Tests (which would be called campaigns in geodesy) involving a global distribution of seismic stations and extensive near-real-time data exchange exercises among 27 participating countries. These tests involve an elaborate network of National Data Centers and three International Data Centers connected by high-bandwidth digital data links. In addition to these global deployments, a variety of modern digital seismic networks are being installed by a variety of countries on either a national or regional scale (e.g., the European ORPHEUS network). These activities are coordinated internationally through the Federation of Digital Broad-Band Seismic Networks. Coordination involves siting plans, data formats, data centers, and mechanisms for data exchange.

Figure 17 shows the current worldwide distribution of high-quality, broad-band, high-dynamic range, digital seismic stations of the IRIS Global Seismic Network, including the IDA stations. Note the similarity of site distribution and site density between this map and several geodetic network maps shown earlier.

Another global geophysical network of interest will result from the INTERMAGNET program. INTERMAGNET is an international geomagnetic observatory network now managed by the U.S. Geological Survey, the British Geological Survey, the Institut de Physique du Globe de Paris, and the Geological Survey of Canada. The network is expected to grow to about 70 sites in the next few years. It calls for real-time data acquisition from state-of-the-art instruments and therefore presents a challenging communications problem, to be solved initially by using geostationary satellites with multiple downlink points in various regions of the globe. The data collected by such a network will be of immense value to both the solid Earth and space physics scientific communities. Figure 18 shows the planned INTERMAGNET network and also shows that collocation of FLINN and INTERMAGNET sites when appropriate would not visibly compromise the overall distribution of sites.

An important addendum to these brief descriptions is the rapidly growing interest in sea bottom instrumentation. A promising approach, both for seismic and geomagnetic observations, is the scientific use of undersea cables. Several workshops have explored this possibility, with broad participation. Such undersea instrumentation would also be an important element of the Global Ocean Observing System (GOOS), a concept currently being discussed and refined by the oceanographic community. Another major program with a global vocation, which would involve permanent ocean bottom observatories, is the RIDGE program (Ridge Inter-Disciplinary Global Experiments). Finally, to return to geodesy, it must be noted that sea bottom geodetic systems are the object of a vigorous technological development effort and that we should expect to see geophysically interesting results emerge before the middle of the decade (e.g., Spiess, 1990).

These few examples make clear that global geophysical networks are of great interest not only to the IAG but also to other member associations of the IUGG, such as IASPEI, IAGA, and IAPSO. There is of course no reason why the list should stop here, and other types of measurements should be considered as well, such as atmospheric, chemical, meteorological, and environmental. FLINN sites may thus serve as collection facilities for data gathered by local arrays of instruments (e.g., atmospheric and geophysical sensors deployed around a volcano) and provide a common infrastructure for transmitting the composite data stream to one of the global data centers.
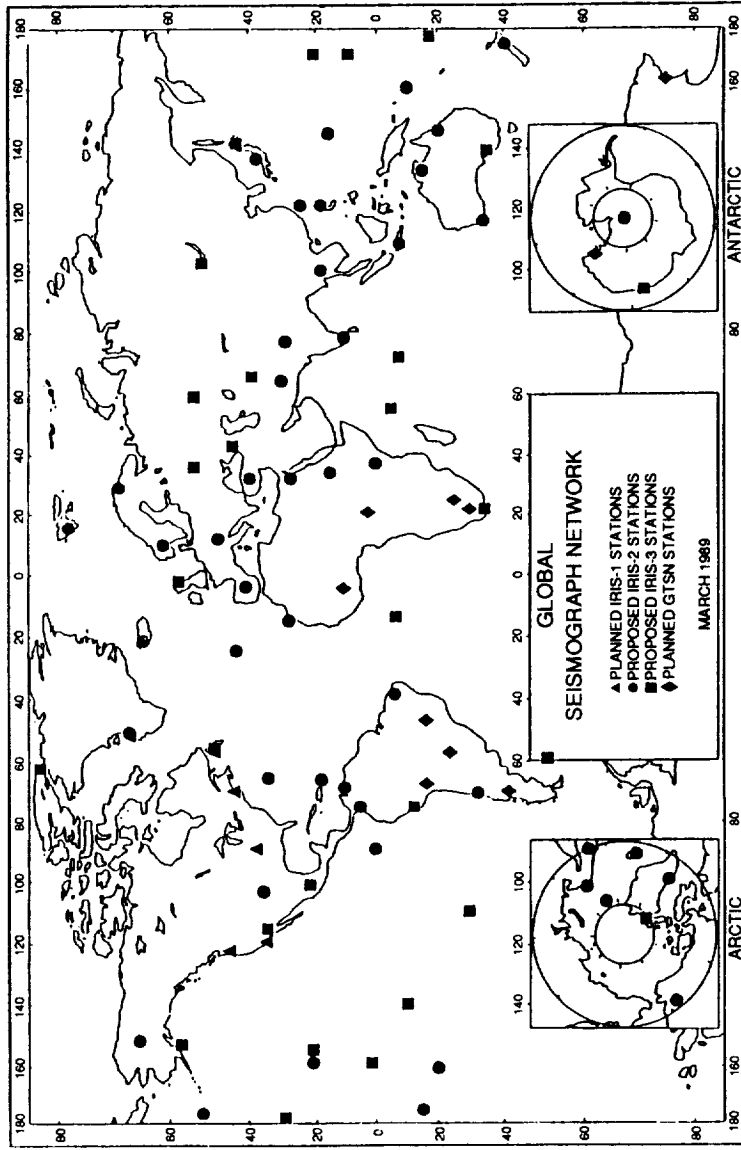
FIGURE 17. Map of existing and planned high-quality digital stations of the Global Seismic Network (GSN) of the Incorporated Research Institutions for Seismology (IRIS), including the International Deployment of Accelerometers (IDA) Network.
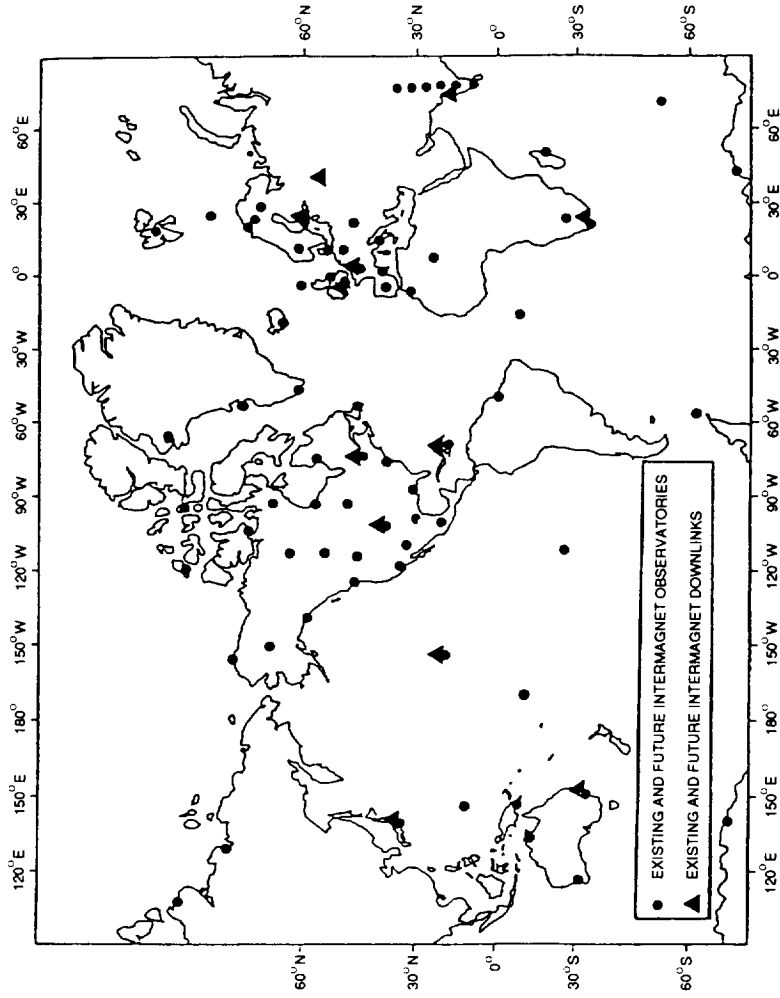
FIGURE 18. Map of existing and future observatories of the INTERMAGNET program. Also shown are planned data collection (downlink) sites.

The concept of FLINN as a set of globally distributed sites with a multidisciplinary vocation is therefore a logical and desirable generalization of the basic geodetic network concept. FLINN really should provide the necessary ground component of the *Mission to Planet Earth*, that is, the core of the Permanent Large Array of Terrestrial Observatories (PLATO) originally proposed as an integral component of the mission. Precise space-geodetic control is of course the essential ingredient of FLINN, but a coordinated program in telemetry and data management unquestionably could provide real economic and scientific advantages. Insofar as other disciplinary communities are developing advanced technological solutions to specific aspects of the problem, it seems highly probable that sister disciplines will benefit from a multidisciplinary approach.

Finally, to return to the suggestions made recently by Knickmeyer (1990) and Boucher (1990), in an exchange of correspondence published in the *Bulletin Géodésique,* the rationale for a "common, global, integrated, fundamental network" includes making various measurements at the same stations, *simultaneously.* For instance, this network would be coordinated with the International Absolute Gravity Base Station Network (IABGN), under study by the IAG Commission III. Collocation of a sufficient number of sites equipped with a variety of technologies and measurement techniques would be needed to permit the realization of a common coordinate system. A similar theme was developed in *Mission to Planet Earth*, based on the wide spectrum of spatial and temporal scales one faces when trying to understand the processes of change on the Earth: "This great welter of causative effects with different time scales requires measurements by a variety of means, all requiring completeness, simultaneity, and continuity" (p. 7).

In this respect we must recognize that the scientific objectives of the global network will not be achieved through a single national program, even if such a program intrinsically has a global perspective. Nor will these goals be achieved completely under the umbrella of a single disciplinary international association such as the IAG and its affiliated bodies (e.g., IERS). Instead, the full benefit can be achieved only through coordination of multidisciplinary efforts by several international bodies. This viewpoint was expressed in the report of the Committee on Earth Sciences of the Office of Science and Technology Policy (1989), which lists a variety of such bodies, including the International Union of Geodesy and Geophysics (IUGG) and its seven member associations (IAG, IASPEI, IAVCEI, IAGA, IAMAP, IAHS, and IAPSO), but also:

- the World Climate Research Program (WCRP);
- the International Council of Scientific Unions (ICSU);
- the World Meteorological Organization (WMO);
- UNESCO and its subsidiary bodies, such as the Intergovernmental Oceanographic Commission (IOC); and
- the United Nations Environment Program (UNEP).

This list is clearly incomplete. Nevertheless, it serves to illustrate an important point, namely that the path to a more effective network of laboratories used to study the Earth is through international participation. It is also the path for future growth of the global network of fiducial sites, especially as the scientific community focuses its attention on very demanding and difficult environments, such as the bottom of the oceans.

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ACRONYMS

ACRE	Advanced Clock and Range Experiment
ARISTOTELES	Gravity Gradient Satellite of the European Space Agency
AS	Antispoofing (of GPS satellite signal)
BE-C	NASA "Beason-C" Satellite Mission
BIPM	Bureau International des Poids et Mesures
CDDIS	Crustal Dynamics Data Information System (NASA Crustal Dynamics Project)
CDP	Crustal Dynamics Project, NASA
CF	Center of figure
CIGNET	Cooperative International GPS Network
CM	Center of mass
DORIS	Doppler Orbitography and Radiopositioning Integrated by Satellite
DSN	Deep Space Network
ESA	European Space Agency
EDM	Electronic Distance Measurement
EOS	Earth Observing Satellite
ERDE	Extended Research and Development Experiment
ERS-1	Earth Resources Satellite of the European Space Agency
FAGS	Federation of Astronomical and Geophysical Data Analysis Services
FLINN	Fiducial Laboratories for an International Natural science Network
GEO-1K	Geodetic Earth Orbiting (low-altitude satellite at 1.5 km)
GEOS	Geodynamics Experimental Ocean Satellite
GEOSAT	Geodetic Earth Orbiting Satellite
GEOSCOPE	French Global Long-Period Seismometers Network

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GIG'91	First GPS IERS and Geodynamics Experiment
GIS	Geographic Information System
GLONASS	USSR Global Navigation Satellite System
GLRS	Geoscience Laser Ranging System
GOOS	Global Ocean Observing System
GOTEX	GPS Orbit Tracking Experiment
GP-B	Gravity Probe-B
GPS	Global Positioning System
GSE	The Group of Scientific Experts
GSN	Global Seismic Network
IABGN	International Absolute Gravity Base Station Network
IAG	International Association of Geodesy
IAGA	International Association of Geomagnetism and Aeronomy
IAHS	International Association of Hydrological Sciences
IAMAP	International Association of Meteorology and Atmospheric Physics
IAPSO	International Association for the Physical Sciences of the Ocean
IASPEI	International Association of Seismology and Physics of the Earth's Interior
IAVCEI	International Association of Volcanology and Chemistry of the Earth's Interior
IDA	International Deployment of Accelerometers Network
IERS	International Earth Rotation Service
IGS	International GPS Geodynamics Service
INTERMAGNET	INTERnational real-time geoMAGnetic observatory NETwork
IPMS	International Polar Motion Service
IRIS	Incorporated Research Institutions for Seismology
ISOP	International Seismological Observing Period
IUGG	International Union of Geodesy and Geophysics
LAGEOS	Laser Geodynamics Satellite
LLR	Lunar Laser Ranging

MERIT	(An international program to) Monitor the Earth's Rotation and Intercompare the Techniques of observation
NEOS	National Earth Orientation Service
PGGA	Permanent GPS Geodetic Array
PLATO	Permanent Large Array of Terrestrial Observatories
PPS	Precise Positioning System
PRARE	Precise Range and Range-rate Experiment (German)
PRAREE	PRARE Extended Version
QUASAR	USSR Very Long Baseline Interferometric Network of radio telescopes
RSL	Relative Sea Level
SA	Selective Availability (of GPS satellite signal)
SEASAT	Sea Satellite
SLR	Satellite Laser Ranging
SPOT	Satellite pour l'Observation de la Terre
SPS	Standard Positioning System
TOPEX/ POSEIDON	USA/French system to measure sea surface topography for determination of global ocean circulation and to improve the Earth's gravity model
TRANET	TRAnsit NETwork
TRF	Terrestrial Reference Frame
UT1	A version of Universal Time based upon time observations at a number of observatories
UTC	Coordinated Universal Time, based on an atomic standard of time
VLBI	Very Long Baseline Interferometry

APPENDIXES

APPENDIX A
REVIEW OF RECENT STUDIES

This appendix reproduces recommendations made earlier, which are relevant to the global fiducial network. The recommendations made in the present report are essentially consistent with the results of these previous studies.

Mission to Planet Earth

In 1988 the Task Group on Earth Sciences of the Space Science Board, National Research Council, produced a seminal report entitled *Mission to Planet Earth*. The primary research objectives of this mission are addressed in terms of four "Grand Themes," which are:

1. *To determine the composition, structure, and dynamics of the Earth's interior and crust, and to understand the processes by which the Earth evolved to its present state.*

2. *To establish and understand the structure, dynamics, and chemistry of the oceans, atmosphere, and cryosphere and their interactions with the solid Earth, including the global hydrological cycle, weather, and climate.*

3. *To characterize the interactions of living organisms among themselves and with the physical environment, including their effects on the composition, dynamics, and evolution of the oceans, atmosphere, and crust.*

4. *To monitor and understand the interaction of human activities with the natural environment.*

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To address these four grand themes, the Task Group proposed a long-term program based on four classes of systems:

1. *The Task Group recommends that the centerpiece of the global observing system be a network of satellites and platforms in the following arrangement:*
   - *a set of five geostationary satellites,*
   - *a set of two to six polar-orbiting platforms, and*
   - *a series of special missions.*

2. *The Task Group recommends the development, deployment, and long-term operation of a system of in situ measuring devices—the Permanent Large Array of Terrestrial Observatories (PLATO)— to provide complementary data to the space network. Wherever applicable, the data should be transmitted in real time and integrated with observations from space.*

3. *The Task Group recommends that state-of-the-art computing technology be utilized for data analysis and theoretical modeling of Earth processes.*

4. *The Task Group recommends that a full and coordinated data system, which both archives and disseminates data, be established.*

Erice and Coolfont Workshops

In recent years two major workshops were conducted at which global issues in geophysics and geodesy held a prominent place. The first, an international workshop on The Interdisciplinary Role of Space Geodesy, was held in Erice, Sicily, in July 1988. The resulting report (Mueller and Zerbini, 1989) contains 11 main recommendations, of which at least five address issues that call for a global point of view. These include, of course, determination and analysis of the geopotential fields, but also (Agnew *et al.*, 1988):

Over the next 20 years, major efforts in applying precise positioning techniques should be aimed primarily at:

1. Continued large-scale reconnaissance surveys with station spacing on the order of 10^2 km, to improve our understanding of the kinematic evolution of extensive, largely unexplored zones of continental deformation.

2. Sustained, repeated measurements of dense networks at centimeter-level accuracy, to determine the time dependence and spatial distribution of deformation within and across zones of intense tectonic activity. Measurement frequencies

should range from daily to annually over a decade or more, with station spacing from 3 to 30 km and network dimensions from 10 to 1,000 km. In regions of complex deformation, geodetic measurements should be complemented by comprehensive tectonic and structural studies and careful estimates of displacements and displacement rates on geologic time scales.

3. Continued improvement of capabilities, to achieve:

• millimeter-level accuracy in both horizontal and vertical components for detailed subaerial studies, system calibration, and ultimately, low-cost, routine deployment.

• centimeter-level accuracy in both horizontal and vertical components for sea-bottom systems.

In July 1989 a planning workshop was convened by NASA at Coolfont, West Virginia, with the purpose of identifing major scientific and programmatic areas for NASA activities in solid earth science for the next 10 years. The final report, *Major Emphasis Areas for Solid Earth Science in the 1990s* (NASA, 1991), describes five primary research areas that emerged from the workshop discussions. They are:

1. a global geophysical network (GGN),
2. global topographic mapping,
3. soils and surface processes,
4. geopotential fields, and
5. volcanic effects on climate.

The Panel on Plate Motion and Deformation formulated four recommendations. The first two pertain (1) to the deployment of a global distribution of fiducial sites whose positions are to be maintained to 1 cm over 1 day and to 1 mm over 3 months and (2) to the establishment of a capability for beginning dense, frequent geodetic surveys in areas of tectonic interest. These are summarized as follows:

1. In order to study plate motion we need a global distribution of geodetic stations that measure relative positions to 1 cm over 1 day and to 1 mm over 3 months. In order to monitor regional and local deformation we need a terrestrial reference frame. Both of these objectives can be accomplished with a global distribution of space-geodetic observatories.

2. In order to monitor deformation in tectonically active areas where deformation is concentrated, we need a finer spacing of geodetic sites. We recommend the initiation of a vigorous long-term program of monitoring regionally dense networks deployed across tectonically active regions, to measure and analyze motion and deformation over a broad range of spatial and temporal scales.

3. We need globally coherent topography, geoid, and gravity coverage, and we need high-resolution satellite imagery and topography and gravity coverage in local areas.

4. We require technological development to permit a number of applications of space-based geodesy that are not possible with current capabilities.

Woods Hole Workshop

During May 2-4, 1990, the Global Programs office of the National Oceanic and Atmospheric Administration (NOAA) together with the Division of Ocean Sciences of the National Science Foundation (NSF) sponsored a workshop on sea level that was organized and led by the Joint Oceanographic Institutions (JOI) of Washington, D.C., and held at the Woods Hole Oceanographic Institution. The proceedings of this workshop, summarized in *Towards an Integrated System for Measuring Long Term Changes in Global Sea Level* (Joint Oceanographic Institutions, 1990), include a series of recommendations, grouped around the following topics:

- toward an integrated system,
- improving tide gauge networks,
- developing sea-level indices,
- continuing satellite measurements,
- developing the use of geodetic techniques,
- long-term *in situ* measurements,
- ice sheet measurements, and
- developing appropriate models.

For present purposes, the detailed recommendations pertaining to the use of geodetic techniques are reproduced:

With respect to geodetic aids and techniques, we recommend that:

• A Terrestrial Reference Frame (TRF) accurate to millimeter level and stable on time scales of decades is an essential component of a global change/sea-level monitoring system. The International Earth Rotation Service (IERS) and National Earth Orientation Service (NEOS) provide such a reference frame.

Applications include:

• Survey of tide gauges on a regional basis.
• Satellite orbits in a common reference frame.
• GPS orbits.
• Kinematic GPS fiducial stations.
• U.S. agencies should continue to refine VLBI/SLR/GPS technologies and share advances with other nations.

• U.S. agencies should vigorously participate in the IERS to improve accuracy and global coverage at a minimal cost.

• New technologies, such as the super-fluid gyroscope, should be explored.

• GPS promises to be a "cost-effective" technology for many applications, such as airborne mapping of ice masses, and surveys of tide gauges. Agencies should provide resources to advance GPS technology as rapidly as possible.

• DoD should remove Selective Availability (SA) during periods of normal international relationships. SA can be defeated by double-differencing techniques, but imposition would increase resource requirements and waste funds.

• Absolute gravity technology should continue to be developed and tested as an alternative method (less costly) to map and monitor vertical crustal motions.

• Kinematic GPS techniques and airborne altimeters should be developed and deployed to measure ice masses, starting with Greenland, as soon as possible.

APPENDIX B
IERS CHARGE/MISSION

General Information

Terms of Reference

The International Earth Rotation Service (IERS) was established in 1987 by IAU and IUGG, and it started operation on Jan. 1, 1988. It replaces the International Polar Motion Service (IPMS) and the earth rotation section of the Bureau International de l'Heure (BIH); the activities of BIH on time are continued at Bureau International des Poids et Mesures (BIPM). IERS is a member of the Federation of Astronomical and Geophysical Data Analysis Services (FAGS).

IERS should provide the information necessary to define a Conventional Terrestrial Reference System and a Conventional Celestial Reference System and relate them as well as their frames to each other and to other reference systems used in the determination of the earth orientation parameters.

IERS is responsible for:

• defining and maintaining a conventional terrestrial reference system based on observing stations that use the high-precision techniques in space geodesy;

• defining and maintaining a conventional celestial reference system based on extragalactic radio sources and relating it to other celestial reference systems;

• determining the earth orientation parameters connecting these systems, the terrestrial and celestial coordinates of the pole, and universal time; and

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- organizing operational activities for observation and data analysis, collecting and archiving appropriate data and results, and disseminating the results to meet the needs of users.

IERS consists of a Central Bureau and Coordinating Centers for each of the principal observing techniques, and it is supported by many other organizations that contribute to the tasks of observation and data processing.

The Coordinating Centers are responsible for developing and organizing the activities in each technique to meet the objectives of the service. The Central Bureau combines the various types of data collected by the service and disseminates to the user community the appropriate information on earth orientation and the terrestrial and celestial reference systems. It can include subbureaus for the accomplishment of specific tasks. The Central Bureau decides and disseminates the announcements of leap seconds in UTC and values of DUT1 to be transmitted with time signals.

The Directing Board is composed of representatives of:

- the International Astronomical Union,
- the International Association of Geodesy/International Union of Geodesy and Geophysics,
  - the Federation of Astronomical and Geophysical Data Analysis Services,
  - the Central Bureau, and
  - each of the Coordinating Centers.

The chairperson is a member of the Directing Board, elected by the board for a term of 4 years, with the possibility of reelection for one additional term. He/she coordinates the activity of the Directing Board and is the official representative of the service at meetings of the IAU, IAG/IUGG, FAGS, and other outside organizations.

The Directing Board exercises general control over the activities of the service, including modifications to the organization and participation that would be appropriate to maintain efficiency and reliability, while taking full advantage of advances in technology and theory. Most decisions are expected to be made by consensus or by a simple majority vote. Changes in the structure, membership, and chairmanship of the Directing Board can be made at any time by a two-thirds majority.

The secretariat of the board is provided by the Central Bureau. The function includes distribution of papers and compilation of the annual administrative and financial reports.

The board shall meet annually and at other times considered appropriate by the chairperson or at the request of two members.

APPENDIX C
IGS CALL FOR PARTICIPATION

February 1, 1991

Dear Colleague:

This IAG Call for Participation solicits support in the establishment of a permanent international service under IAG auspices for the purpose of providing precision ephemerides and associated products derived from observations of the Global Positioning System (GPS). These products are considered fundamental for the proper use of GPS in global and regional geodesy and in geodynamics during the next decade and may contribute to other areas of geophysical research.

Participation in this International GPS Geodynamics Service—IGS—is open to government agencies, educational institutions and other organizations whose financial resources allow a firm commitment to be made in support of the service. Proposals may be submitted at any time during the period ending May 31, 1991.

Based on the proposals received, a plan will be submitted to the IUGG General Assembly in Vienna in August, 1991, for endorsement and approval. This plan will be for a test campaign to be conducted during the International Space Year in 1992, followed by the establishment of the Service in 1993, provided all goes well.

The enclosed document provides program information on the IGS, outlining its roles, responsibilities, and functional areas for which proposals are sought. Proposals may address any aspect of IGS activity for which the proposing organization has the capability and capacity to support.

Those organizations interested in participating in the IGS should submit a letter of intent by March 29, 1991, expressing their interest in the Service. Those organizations which respond will receive a second document providing additional details on the Service such as the standards to be followed and proposal submission information. For this reason an early letter of intent may be advisable.

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The IAG is aware of already existing successful global international GPS scientific efforts such as CIGNET for orbit determination or GIG '91 for Earth rotation monitoring. IGS will offer full cooperation to these groups and thus enhance their effectiveness. For this reason, participants in these current activities are strongly encouraged to respond to this solicitation.

Your interest and cooperation in participating in this international effort are welcomed and appreciated. Please feel free to contact any member of the Steering Committee with questions or comments regarding the IGS.

Sincerely yours,

Ivan I. Mueller, President
International Association of Geodesy

APPENDIX D
ECONOMICS OF
CAMPAIGN VS. OBSERVATORY MODE

It is assumed that monumentation costs are the same, whether observatory or field campaign operations are employed. Only operational expenses are considered.

For fixed observatories the annual operational cost, O, includes the amortized instrument cost, I, the fraction of the cost for running the observatory, $f(M + B)$, where M is the manpower budget and B includes building rental, and the data transfer cost, D, or:

$$O = I + D + f(M + B)$$

For campaign mode costs, C, we assume N campaigns per site per year, each of m days. Instrument and manpower costs are shared among sites with efficiency e. Travel to the site is T, and per diem expenses are P. Then

$$C = N \{T + m [P + (I + M)/(365 \, e)]\}$$

Assuming the numbers given in the table below, $O = \$28,000$ and $C \sim \$19,000$.

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Quantity	Value	Notes
I	$15,000	Trimble, 3 years
D	$ 2,000	
f	0.2	
M	$50,000	
B	$ 5,000	
N	4	
T	$ 1,000	
m	5	
P	$ 150	Includes vehicle
e	0.3	