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THE COORDINATED FEDERAL PROGRAM FOR THE APPLICATION

OF SPACE TECHNOLOGY TO

CRUSTAL DYNAMICS AND EARTHQUAKE RESEARCH

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TABLE OF CONTENTS

PREFACE

This document summarizes the Federal plan, involving our respective agencies, for the application of space technology to important geophysical problems relating to crustal dynamics and earthquake research.

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1. Introduction

During the past 15 years, the development of the plate tectonics model for large-scale geological processes has revolutionized the whole approach to the study of our planet's history. We are at the beginning of a new era of an understanding of the earth. It is reasonable now to expect the kind of progress in earth science that occurred in physics after the development of quantum mechanics and in chemistry after the discovery of the periodic table of the elements.

1.1 Review of Plate Tectonics

The plate tectonics hypothesis is that the surface of the earth is covered by about a dozen large and almost rigid blocks or "plates" in continual motion with respect to one another. The plates are moving away from rift zones, or spreading centers, where hot molten material from the underlying mantle rises and solidifies onto the edges of the receding plates. At present, the spreading is taking place at the worldwide ocean ridge system which forms an almost continuous girdle around the earth.

On the sides of the plates opposite the ocean ridges, the plates are colliding and being thrust under one another at convergent boundaries or "subduction zones." These are typically marked by deep ocean trenches, island arcs, and volcanism. This occurs, for example, in Japan, Indonesia, and the Aleutian Islands. The continents, however, are carried along on the plates like rafts, and tend to survive the subduction of plate material because continental rocks are light and not easily carried downward into the mantle.

Another type of plate boundary is one at which the plates are moving horizontally past one another. A typical example of such a transverse boundary is the San Andreas Fault in California, where the Pacific Plate is moving north with respect to the North American Plate.

The present rates of plate movement vary from almost zero up to about 18cm/year at the west coast of South America.

There the floor of the Pacific is being thrust under the South American Plate.

1.2 Relevance of Plate Tectonics to Earthquake Hazards and Natural Resources

By far the greatest number of the world's earthquakes occur at plate boundaries. The plates are moving as the result of driving mechanisms whose nature is largely unknown, and are constrained by frictional stresses at the boundaries. Eventually the crustal rocks near the plate boundaries are strained beyond their breaking point and ruptures occur, resulting in earthquakes. The general geographical distribution of earthquakes and the direction of their faulting motion can be predicted by the plate tectonics concept, but the actual prediction of the time, place, and magnitude of individual earthquakes cannot. This is one of the major unsolved problems of geophysics today. This problem is one of considerable economic and social importance, and it is one of the areas of research being conducted under a research program established by the Earthquake Hazard Reduction Act of 1976 and led by the U.S. Geological Survey.

The generation of mineral and petroleum deposits is much more complicated than earthquake processes. We are much further from understanding the geochemical and geological accidents responsible for emplacement of these vital resources. It is clear, however, that one of the keys to understanding the formation of mineral deposits lies in the plate tectonics approach to the history and evolution of the earth's crust.

1.3 The Basic Issues in Earth Science

Among the fundamental questions in earth science today are: (1) what is the combination of mechanisms that drives the plates? and (2) how do the plates move, deform, and change chemically in response to these driving forces?

Many lines of research are being pursued in this country and elsewhere to answer these questiors. The particular area of investigation that concerns us here is the observation of the present relative movement between plates and the internal deformation of the plates as they move. Such observations are of special importance, since our present knowledge of plate motion is based almost entirely on geological inference. We have a reasonable body of evidence about how the plates have been moving over the past few million years, but very little information on what they are doing at the present time. The feeling of geophysicists concerned with earthquake prediction is that detailed studies of crustal deformation are important to making progress in understanding earthquake processes.

A significant portion of the USGS earthquake prediction research program is being devoted to the study of crustal dynamics in fault zones. The objective is to measure the temporal variation of the strain field near fault systems in order to define the spatial and temporal requirements for strain measurements as an earthquake premonitor. Similar studies are being conducted in other countries where seismic risk is high; for example, in Japan, the USSR, and South America. In a later section we describe how space technology can be used to extend and complement these studies.

1.4 Program Needs

For a comprehensive study of plate movement and deformation, five areas of concentration are required:

1. Observation of the relative position of major plates, at an accuracy of at least 2-5cm, and changes in position and orientation of the plates.

2. Measurement of regional deformation of plates within about 1000km of active boundaries, to an accuracy of at least one part in 10^7, two to three times per year.

3. Measurement of strain in the vicinity of fault systems, to an accuracy of at least one part in 10^7, at least three to four times per year and preferably weekly.

4. Development of highly mobile systems for measurement of vertical and horizontal movements, suitable for rapid deployment near the epicenters of major earthquakes or near places where major earthquakes are predicted.

5. Measurements of the earth's gravity field to detect gravity anomalies caused by variations in the distribution of masses inside the earth. This information is considered important to study mechanical properties of the plates and to study mantle convection, an important candidate among possible driving mechanisms. The requirements for accuracy and resolution are not as well defined as those for strain measurements. Our present capability will resolve 5 milligal anomalies over regions 200-500km across.

2. Requirements for Space Technology

Conventional surveying and leveling methods, although capable of high precision, are not able to meet all the needs of this program: first, they are limited to line-of-sight measurements so that surveying over long distances must be done in a series of steps. The inevitable errors of measurement accumulate at a rate that obscures the expected crustal movements over distances greater than 100-200km, and of course such observations cannot be made across oceans. In addition, geodetic surveying and leveling are expensive and time-consuming.

Over the past ten years, NASA has advanced the development of two space techniques for accurate position determination which complement and extend conventional geodetic methods. One uses laser ranging to satellites in known orbits to determine the position of the laser on the ground; the other uses radio noise from the distant quasars for very long baseline microwave interferometry (VLBI), a technique originated by radio astronomers. Much of the early VLBI activity was initiated by DOD in the mid-1960's. Both techniques appear capable of attaining the required positional accuracy of 2-5cm, and both can be conducted either from fixed observatories or from small mobile stations. NASA with the help of NOS is presently conducting validation and intercomparison studies of both methods. Prototype, fixed and mobile stations of each type are currently operational on research projects.

3. Program Elements

3.1 Polar Motion and Earth Rotation

In order to derive the location of points on the earth's surface from space data, it is necessary to know the orientation of the earth. This is specified by the instantaneous pole position and universal time (UT1), both of which vary with time.

To meet the requirements of a crustal dynamics program, these quantities must be determined during the same period of observation and to the same accuracy as the positioning methods. This can be most effectively accomplished by a dedicated polar motion and UT monitoring service utilizing space technology. The DOD-operated connected element interferometer (CEI) may approach centimeter accuracy with averaging times on the order of a few weeks; however, the VLBI technique will be needed to achieve the required accuracy during the same observation period as the crustal measurements. The new Polaris System under development by the National Ocean Survey (NOS) of NOAA will use fixed VLBI stations to determine polar motion and time parameters. The Polaris stations will be crucial to the geodynamics program in two ways. First, polar motion and earth rotation will be determined by the Polaris network to an accuracy of a few centimeters with averaging times of a few days or less. Second, the Polaris observatories will be used as reference stations for mobile VLBI operations.

3.2 Plate Stability and Relative Motion

It is planned to monitor the internal stability and relative motions of the North American, Pacific, and Australian plates. Plate motion and deformation measurements are particularly important around the circum-Pacific belt. Movements in these regions may affect the earthquake hazard in California and thus deserve special consideration within the program.

Observing stations on the Pacific plate will be located on Hawaii, Kwajalein, American Samoa, and possibly a few other islands. Position determinations will be made at mobile sites once per year.

For measurements of the gross deformation of the more stable central part of the North American Plate, a combination of fixed observing sites and a few mobile sites will be used.

The detection of the relatively rapid movement of Australia with respect to the Pacific plate will be one of the more interesting early results of the crustal dynamics program. It is therefore necessary to monitor the stability of the Australian plate. Models of relative plate motions derived from the space-technology measurements will be compared with those derived from historic geologic data, magnetic data, and other information to compare the contemporary and longer-term motion.

3.3 Regional Deformation

Regional deformation studies in the western part of North America along the San Andreas Fault are to be initiated in 1980. In 1981, studies will be extended to the Caribbean region. Later (1982-83), similar studies are planned for Alaska, New Zealand, and the western portion of South America. Both the San Andreas Fault and the Alpine in New Zealand are segments of transcurrent or strike-slip plate boundaries, while at the Aleutians and the west coast of South America are parts of subduction boundaries. A major question for earthquake prediction is the nature of the distribution of strain and strain changes within the plates.

The primary objectives of regional-scale measurements where the strike-slip movement is taking place at plate boundaries are: (1) to determine the rate of regional fault motions; (2) to determine whether that motion is constant or episodic in time; and (3) to measure how the strain field and its rate of change are distributed on a regional basis. The long-term motion along the San Andreas fault in California is predominantly strike-slip, with regions of the fault temporarily locked. Over long periods of time strain is steadily accumulated and at a given position is released when the stresses reach a level sufficient to initiate rupture. The strain released can be measured in terms of the slip that occurs during the earthquake and, in general, will vary along the fault rupture depending on local geological conditions.

In order to support ground-based position measurements being undertaken by the USGS and NOS, and to extend the crustal deformation measurement across the Basin and Range Province and into the Pacific Northwest, a network of mobile sites will be occupied by NASA laser ranging and VLBI stations. The spacing of sites is about 500 km in the eastern portion of the network, and decreases to 50km or less near the San Andreas Fault. Fixed observatories will contribute to the strain monitoring program. Stations in northwestern Mexico will measure the rate of crustal deformation across the East Pacific Rise in the Gulf of California.

Other regions deserve special attention. The Caribbean area is extremely important, but poorly understood in the global tectonics model. A number of small plates are colliding in this region, resulting in an intense zone of seismicity and volcanism that stretches over 2000 km from Mexico to Panama. Alaska is another geologically complex region of high seismic activity. In this area, the Pacific plate is being thrust under the North American plate along the Aleutian archipelago at an average rate along the Aleutian Trench of about 5 cm/yr.

South America is an unusually well-defined plate. The eastern boundary is the Mid-Atlantic Ridge, and the western boundary is the subduction zone where the Nazca Plate plunges under the Andes. This subduction zone is the site of many very large earthquakes, presumably resulting from the rapid relative movement of the two plates in this area.

New Zealand, Turkey, and Western North America are among the few places where a transcurrent plate boundary is well exposed for study on land. The geological setting of New Zealand may be less complex than the Western part of North America, and it could afford an opportunity to study the same type of plate boundary in a different geological context, thus avoiding the possible obscuration of general features by local peculiarities.

The logical observational program for studying all of these regions consists of combinations of fixed and mobile VLBI and laser ranging measurements with the mobile stations visiting selected sites 2-3 times per year. The locations will be chosen to complement ground-based surveys at the small scale and to extend across tectonically active regions where strain changes are taking place. These large-scale networks will be tied in with the sites used to observe plate-wide deformation. The observing program for the mobile stations must be flexible so that when large earthquakes occur in the regions under study, the mobile stations can be diverted to locations suitable for delineating crustal movements following the earthquakes. Such observations will provide important information on earthquake mechanism and the rheology of the crust and upper mantle.

3.4 Local Strain

The objectives of the local strain measurements are:

1. To monitor local crustal deformation and strain rate in seismically active regions.

2. To monitor local land movement in the years immediately following a major earthquake.

3. If a major earthquake is predicted, to monitor land movement near the predicted epicenter before the earthquake occurs.

A thorough understanding of these phenomena can only be obtained from more frequent and more densely-spaced measurements than those contemplated for a program using a few mobile laser ranging and VLBI stations.

Alternative methods to those above include a spaceborne laser system ranging to retroreflectors on the ground, the use of Global Positioning System (GPS) satellites as radio sources for the VLBI and related techniques, and improved conventional geodimeters. Each of these methods appears capable of monitoring relative local movements over distances of 20 to 100 km with 2-3 cm accuracy.

4. Agency Plans

The application of space technology to earthquake research and crustal dynamics by Federal agencies in the 1980-85 time period is projected to consist of three broad activities. These are:

- Fixed VLBI observatory operation,
- Mobile laser ranging and VLBI station operations,
- Study of improved local geodetic methods.

The fixed VLBI observatory operations are needed to obtain polar motion and earth rotation data and to act as components of a network of VLBI stations for determination of crustal movement, deformation, and strain. The lead agencies for the fixed VLBI observatory operations are NASA and NOAA. NASA will develop and validate the technology and transfer it to the National Ocean Survey, which has the responsibility for monitoring polar motion. The VLBI-related activities of the other agencies are shown in Table 4.1.

In the area of mobile laser ranging and VLBI station operations, the lead agencies are NASA, NOS, and the USGS. As shown in Table 4.2, NASA has the primary responsibility for validation of the performance and use of these systems for the acquisition of geophysically meaningful data, and for transfer of the new techniques to NOS and the USGS. NOS will begin domestic operations with the NASA-developed mobile VLBI stations in 1983 and will provide supporting gravity and geodetic surveys and data analysis. NOS operations will provide for monitoring of North America plate stability and regional deformation in the Western United States. Later (1985) NOS will assume responsibility for regional deformation measurements in Alaska, to be initiated by NASA in 1982.

The USGS will play a critical role in these operations in the key areas of site selection and scheduling, in addition to data analysis and basic research activities. The North American/Pacific Plate Motion observation program will be assumed by the NOS in 1986. NSF will support basic research using the data acquired by the mobile station operations. NASA will take the lead in establishing joint measurement programs in other areas with foreign countries and the international science community. It is expected that by 1986, international organizations will be capable of assimilating the new technology and of continuing these measurements without U.S. assistance.

In the study of improved local geodetic methods, all agencies will play a complementary role (Table 4.3). A joint study program will be established to evaluate the performance and cost effectiveness of the several methods proposed. DMA, NASA, and NOS will coordinate the design, test, and evaluation of advanced doppler and VLBI systems using GPS signals. The USGS and NOS will support studies and development of advanced geodimeters. NASA will study applications of a spaceborne laser ranging system. These activities will be jointly monitored and the progress of technical developments and field operations will be redefined as required. To this end, the NOS will organize periodic interagency/academic/commercial sector workshops to review and analyze progress. The reports of these workshops will provide the larger user community with the necessary data to evaluate the total program for their own needs.

5. Implementation

To accomplish the inter-agency contact and cooperation required for the success of this program, an interagency coordination committee made up of representatives from each agency will be established. The committee membership will consist of the lead scientists and engineers in each agency. Means for higher management review and direction already exist, but could be expanded if necessary.

The functions of this Committee will be:

1. To review agency plans to assure that the various agencies' activities are properly coordinated.

2. To review appropriateness and adequacy of joint programs with other countries.

3. To assess progress and evaluate the readiness of the operational agencies to undertake routine observations with the new technologies.

4. To recommend actions for implementation by management of the various agencies.

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NASA Office of Space and Terrestrial Applications: Interagency Coordination Plan for Development and Applications of Astronomic Radio Interferometry for Geophysical Sciences, Washington, DC., October 1978

TABLE 4.1

Agency Activities in Fixed VLBI Observatory Operations

NASA	1.	Development of advanced systems.
	2.	Transfer of technology to NOS for Polaris.
	3.	Use of Polaris data in geodynamics program.
NOS	1.	Equipping of Polaris stations.
	2.	Comparison and evaluation of Polaris results.
	3.	Provide Polaris polar motion and earth rotation data for use by outside investigators.
USGS	1.	Support of VLBI wideband data collection development at MIT.
	2.	Support of geophysical research.
NSF	1.	Support for Fort Davis radio antenna.
	2.	Support of portable advanced data equipment (Mark III) for Onsala, Sweden.
	3.	Support of geophysical research.
DOD	1.	Logistical support for Polaris operations at Richmond, Florida.
	2.	Support of VLBI equipment for Onsala, Sweden.
	3.	Continue publication of Earth rotation parameters and provide CEI results for VLBI comparison.

TABLE 4.2

Agency Activities in Mobile Laser Ranging and VLBI Station Operations

NASA	1.	Completion and testing of mobile laser systems.
	2.	Construction and testing of mobile VLBI stations.
	3.	Feasibility and design studies of a micro-mobile station concept.
	4.	Initiation of measurements at North American sites, expanding to Caribbean and eleswhere.
NOS	1.	Mobile VLBI station operations (beginning in 1983).
	2.	Local gravity and surveying operations to support mobile sites.
USGS	1.	Site selection.
	2.	Recommend diversion of facilities to study post-seismic crustal movements.
	3.	Support of geophysical research.
NSF	1.	Support of geophysical research.

TABLE 4.3

Agency Activities in Support of Improved Local Geodetic Methods

NASA	1.	Concept and design studies of spaceborne laser ranging, and VLBI using the Global Positioning System satellites as sources (GPS/VLBI).
NOS	1.	Studies of doppler and GPS systems.
	2.	Definition of requirements for geodetic surveying.
USGS	1.	Definition of requirements for crustal motion monitoring.
NSF	1.	Basic research; definition of requirements.
DOD	1.	Concept and design studies of GPS/VLBI and doppler.
	2.	Responsible for GPS; approval of system modifications.