NASA Technical Memorandum 81978

NASA Geodynamics Program: Annual Report for 1979

Geodynamics Program Office

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Geodynamics Program Office
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I. Introduction

This document is the first annual report of the NASA Geodynamics Program. Its purpose is to inform interested agencies and individuals of the status, progress, and future plans of the program. The Geodynamics Program Office intends to publish similar reports in March of each year.

The first report contains background information which will not be included in subsequent reports, to bring the reader up to date since the beginning of the program as the National Geodetic Satellite Program in the early 1960's.

A. General Status and Highlights of 1979

1979 was a year characterized by detailed planning and organization. In August the Geodynamics Program Plan was published (NASA, 1979), and over 1500 copies distributed to interested individuals, government agencies, and scientific organizations around the world. The document contains the program plan and description for the time period 1979-86 (additional copies may be obtained from the US Government Printing Office).

Among the highlights of 1979 were the following.

1. The Crustal Dynamics Project was organized at Goddard Space Flight Center to manage the operational aspects of the program.

2. An informal inter-agency coordinating committee for space geodynamics was established in mid-1979, and working groups were formed to deal with immediate problems such as the selection of sites for the mobile laser ranging and VLBI facilities (NASA, 1978). The coordinating committee produced a draft agreement between the agencies involved (NASA, NGS, DMA, USGS, and NSF), which will be circulated for signature in March 1980. The MOU establishes a steering committee at management level, and formalizes the program-level interagency coordinating committee.

3. A formal agreement was concluded with the Government of Japan to undertake joint VLBI experiments with US-operated observatories (see section V. below).

4. Twenty-six domestic and foreign investigations were selected in response to Announcement of Opportunity for use of Lageos laser ranging data.

5. The Mark-III VLBI system became operational and was used to carry out a ten baseline experiment involving three stations in the US and two in Europe.

6. VLBI achieved 4 cm repeatability in the determination of transcontinental baseline lengths, and recovered earth rotation with a formal error of 0.01 arcseconds in the X component of the pole position, and 1 millisecond of time in universal time (UT1).

7. The responsibilities in laser network operations of the NASA Office of Space and Terrestrial Applications and the Office of Space Tracking and Data Systems were clarified in a memorandum of understanding signed by the Associate Administrators of the two Offices.

8. Sites for operation of mobile laser ranging and VLBI facilities to measure crustal deformation in tectonic areas were tentatively selected in a cooperative effort involving personnel of the Crustal Dynamics Project, the Geodynamics Program Office, NASA Advisory Subcommittee on Geology and Geodynamics, NAS/NRC Advisory Committees, an inter-agency working group, and representatives of the academic community.

9. A five-station VLBI-laser ranging intercomparison experiment was initiated.

10. The San Andreas Fault Experiment was repeated using both Lageos laser ranging and VLBI.

11. Measurements of crustal deformation were begun in Southern California using the 9-meter ARIES VLBI facility.

12. A VLBI experiment involving three US observatories and two observatories in Europe was conducted.

13. Thirty-two investigators were selected for participation in the Magsat Project.

14. The Magsat satellite was successfully launched and is operating normally. An initial magnetic field model has been produced.

15. The Transportable Laser Ranging Station (TLRS) was completed by the University of Texas at Austin, and should be operational in early 1980.

16. A contract was signed with the University of Texas at Austin to construct a dedicated lunar/satellite laser ranging facility at McDonald Observatory, to replace the present lunar laser ranging operations on the 107" astronomical telescope there.

17. Twenty-seven investigators were selected to participate in the Geodynamics Research Program.

B. Objectives and Scope of Program

The objectives of the program are stated and discussed in the Geodynamics Program Plan (NASA, 1979). The goal of the program is to apply space methods and technology to advance scientific understanding of the dynamics of the solid earth. These objectives are:

1. To support the ongoing national and international program of research in geodynamics.

2. To support the US national program in earthquake hazard reduction, by studying dynamic processes related to earthquakes.

To accomplish these objectives, the Geodynamics Program is establishing, in cooperation with other Federal agencies, a global network of laser ranging and VLBI observatories to monitor polar motion, earth rotation, tectonic plate motion, and large-scale plate deformation, as well as to serve as base stations for mobile station operations. The mobile laser ranging and VLBI facilities are being used to study crustal deformation in tectonically active regions. Funding is also being provided to develop highly mobile radio systems to use signals from the DOD Global Positioning System (GPS) satellites to monitor crustal movements on a local scale. These activities are described in more detail in the following sections.

C. Interagency Participation

Research in geodynamics covers several broad areas of solid-earth sciences. A variety of Federal agencies has been involved for a considerable time in both general and focussed research in these areas. Recognizing that space technology is only one of the possible tools for advancing our understanding of earth dynamics, NASA has established a close working relationship with the other relevant Federal agencies. This relationship is being formalized by the creation of a consortium of Federal agencies, including which are primarily users as well as those which are primarily technology innovators.

In mid-1979 an informal interagency coordinating committee was formed, consisting of program-level representatives of NASA, the US Geological Survey, the National Geodetic Survey, the National Science Foundation, and the Defense Mapping Agency. Members agreed that space technology had valuable contributions to make to geodetic and geophysical science, and that a method of coordinating related activities in different agencies should be established. A draft agreement was written and informally approved by the management of each of the participating agencies; the final interagency agreement will be circulated for signature of agency management representatives in April, 1980.

The agreement provides for the continuation of the working-level coordinating committee, as well for establishment of a policy-level Steering Committee which will review the program each year. The working groups established in 1979 by the informal coordinating committee will continue to attack specific problems (local site surveys, mobile station site selection, contingency plans for observations immediately following major earthquakes, etc.).

Another mechanism for interagency coordination has existed since 1964 - the Satellite Geodesy Applications Board (previously known as the Geodetic Satellite Policy Board), whose Chairman is the NASA Associate Administrator for Space and Terrestrial Applications, and which includes the Assistant Administrator for Oceanic and Atmospheric Services of NOAA (of which the National Geodetic Survey is a part) and the Deputy Director for Management and Technology of the Defense Mapping Agency. The function of the SGAB is somewhat different from that of the Steering Committee to be established by the agreement described above, and the SGAB will continue to function as before.

One of the major interagency efforts at the present time is the development of systems based on the DOD Global Positioning System (see section IV. below) and the formulation of federal planning for earth gravity field surveying from space.

D. Geodynamics Program Organization and Funding

The current NASA Geodynamics Program was established in 1979; its predecessor was the Earth Dynamics Monitoring and Forecasting Program. This program supported research and development of VLBI and laser ranging systems. The principal elements were a Tectonic Plate Motion Project (TPM), which included the San Andreas Fault Experiment (SAFE), the Pacific Plate Motion Experiment (PPME), Astronomical Radio Interferometric Earth Surveying (ARIES), the Laser Earth Dynamics Project (LED, which included processing and analysis of laser ranging data), lunar laser ranging (LLR), and a supporting research and technology effort. Development and operation of the satellite laser ranging station network (Moblas and SAO stations) was funded by the NASA Office of Space Tracking and Data Systems.

Beginning in early 1979, TPM, LED, and LLR were combined into a Crustal Dynamics Project at Goddard Space Flight Center, with support from the Jet Propulsion Laboratory. This project is planned to extend to 1986, and has responsibility for accomplishing the system development and execution of the measurement program, to achieve the initial objectives of the Geodynamics Program. Beginning in fiscal year 1980, additional funding was authorized by the Congress for this purpose.

The funding for FY1979, 1980, and 1981 for the Geodynamics Program (including Magsat), is outlined in Table 1.

Table 1

Current Funding for NASA Geodynamics Program

(in millions)

	FY1979	FY1980	FY1981
Tectonic Plate Motion	$2.1	--	--
LLR	1.0	*	*
LED	1.5	--	--
Crustal Dynamics Project	--	9.6	12.6
Magsat	3.9	1.6	0.5
GEOS-3	0.5	--	--
Applications Research and Data Analysis	2.8	3.0	3.2
Laser Network Operations	8.3	8.7	9.0
Total	$16.6	22.9	25.3

* Funded under Crustal Dynamics Project.

II. Summary of Achievements

A. Geodetic Measurment Systems

Since the late 1960's, NASA has pursued the development of methods for measurement of the vector separation of widely separated points on the earth: laser ranging to man-made satellites and to the moon, and very long baseline microwave interferometry (VLBI) using quasar sources.

Laser ranging methods, originally developed to improve the precision of orbital tracking of satellites, have been applied to the determination of station position, baseline lengths, polar motion and earth rotation, and to studies of solid earth tides. In the past fifteen years, about a dozen satellites equipped with corner cube retroreflectors have been launched by the US and other countries. Meanwhile, laser ranging precision has improved rapidly from the meter levels of the early 1970's to subdecimeter- level systems in 1979. The principal limitations on systematic error reduction has cycled between system technology and accuracy of the orbital ephemerides for reference satellites. With improved gravity field modeling and a satellite (Lageos; Figure 1) in a high-altitude stable orbit, the current limitation is once again laser system performance. However, ranging precisions of 1-2 cm are now being achieved by specially designed systems, and ultimately these will be available for almost all laser ranging facilities.

Laser systems for ranging to retroreflectors placed on the Moon by the US and the USSR were first used for operational ranging by McDonald Observatory of the University of Texas at Austin. The international system of lunar laser ranging stations envisioned in the late 1960's is just now coming into being. In the early 1980's, systems in Hawaii, West Germany, and Australia should be operational, with a precision of a few centimeters. Currently about thirteen fixed satellite laser systems are operating in seven countries.

Lunar laser ranging has provided new information for determining the orbit of the moon, lunar librations, constraints on the interior structure of the moon, evolution of the lunar orbit, and possible changes in the gravitational constant.

The first Mobile Laser station (Moblas; Figure 2) was built in 1967. Two others were added in 1971 and 1975, and five more were procured in 1977. In 1979, seven of the Moblas stations were deployed in the US, Australia, and the Pacific. The Moblas stations and the fixed laser stations form a global network of lasers used to maintain the accuracy of the Lageos orbital ephemeris, to monitor polar motion and earth rotation, and to begin studies of tectonic plate motion and plate stability.

For regional crustal deformation studies, laser ranging precisions of 1-2 cm and high system mobility are required. In 1976, the University of Texas at Austin, under contract to NASA, began the development of a highly mobile truck-mounted Transportable Laser Ranging System (TLRS; Figure 3). The initial design goals of ability to range both to Lageos and the Moon, while maintaining air transportability, were modified in 1977 to adhere to cost constraints, and to reflect new information on the stability of the Lageos orbit. Fabrication of the TLRS was completed in late 1979, and field testing initiated.

Advanced laser system development has continued, with several goals:

- to achieve improved mobility by reducing the size of the laser systems;
- to increase ranging precision to one centimeter or better;
- to reduce laser power requirements in order to improve field operability;
- to reduce system unit costs.

The development of VLBI methods has paralleled laser developments. Prior to 1969, VLBI was used principally in radio astronomy, but it became evident that this technique could be used for geodetic purposes: accurate measurement of baselines and earth orientation. In the early 19770's, VLBI methods were used to study the orbit of the moon, using microwave signals transmitted from the Apollo Lunar Science Experiment Packages (ALSEP's). It also became evident in the 1970's that interferometric techniques would be needed for tracking and navigation of deep space missions.

In the period 1970 to 1976, radio astronomy telescopes at Haystack Observatory in Massachusetts, the National Radio Astronomy Observatory in West Virginia (NRAO), the Deep Space Network facility at Goldstone, California, and the Onsala Space Observatory of the Chalmers University of Technology in Onsala, Sweden, carried out an extensive VLBI observing campaign under the auspices of the National Science Foundation, for the purpose of studying the structure of radio sources. In these experiments the Mark-I system was used for data acquisition. At the same time, VLBI experiments were being carried out using the Mark-II system with the Deep Space Network stations in California, Spain, and Australia. The purpose of this activity was to determine the applicability of the VLBI technique to problems of deep space navigation, principally to the problem of determining universal time and polar motion.

In 1974, the baseline length between Haystack Observatory in Massachusetts and the Goldstone 210-foot antenna was determined with a repeatability of 16 cm, and more recently a 4 cm repeatability on the baseline length between Haystack and the Owens Valley Radio Observatory (OVRO) in California. In 1979 the Mark-III VLBI data acquisition system became operational. This system was specifically designed for geodetic applications, and should produce vector baselines with an accuracy of a few centimeters. 1979 also saw the first successful use of the dual frequency observation technique (X and S band) to observe directly the effect of ionospheric refraction. Water vapor band microwave radiometers, developed at JPL, were installed at Haystack and OVRO to observe the water vapor content of the troposphere, in order to remove the effects of tropospheric refraaction from VLBI data with a level of accuracy never before achieved. Mark-III terminals were used on the Onsala telescope and the 100-meter antenna of the Max Planck Institute of Radio Astronomy at Effelsberg, West Germany. These observations established baselines between Europe and North America for later use in determining the spreading rate between the two plates.

The first mobile VLBI system (ARIES; Figure 4) was initiated in 1973 using a 9-meter erectable antenna and a surplus Nike antenna. This system, which is still in use, requires several weeks between site visits. The mobile VLBI system is designed to work with the larger fixed antennas. In 1977, measurements from Palos Verdes and Malibu (California) to Owens Valley and Goldstone were used to compute the distance across Santa Monica Bay. Comparison with NGS geodimeter data showed agreement within 6 cm, which is the accuracy of the geodimeter measurement.

To improve system mobility, work was started in 1978 on a 4-meter VLBI mobile station. This station, which will include a wide-band data system, a hydrogen maser, and a water vapor radiometer, is expected to reduce site transition time from two months to one week.

At present, the principal limitations in VLBI precision appear to be errors in modeling the effect of atmospheric water vapor content on the speed of signal propagation through the troposphere. This error is believed to be of the order of 2-3 cm in residual tropospheric refraction correction, but the use of water vapor radiometers is expected to reduce the error to about 1 cm. Other important error sources which affect VLBI results are: clock instabilities in the range of a few minutes to one day, errors in modeling the earth's nutation, radio source positions and structure, and errors in modeling the response of the solid earth to the combined effects of tides and ocean loading.

With the advent of the first of the Global Positioning System (GPS) satellites in 1978, the opportunity arose to use the strong GPS signals as a substitute for the quasar sources for short-baseline operations. Calculations have shown that interferometric analysis of GPS signals should provide precisions of ± 1 cm at distances of up to 100 km. In 1978, studies were initiated at JPL of a system of small highly mobile stations for this purpose (SERIES - Satellite Emission Radio Interferometric Earth Surveying; Figure 5).

Laser ranging systems are referenced to a geocentric coordinate system. This is also true for SERIES. However, VLBI systems which use quasar sources are referenced to an inertial coordinate system. Both systems may be subject to systematic errors which are undetectable unless independent methods exist by which measurement accuracy can be assessed. On scales of 20 km or less, such checks can be provided by conventional surveying techniques. On larger distance scales there are no systems which are comparable to laser ranging and VLBI. Fortunately, these systems are almost certainly independent in terms of sources of error and bias, and can be used to check each other.

In 1978, satellite laser ranging, VLBI, and doppler satellite measurements were made at OVRO, Haystack, and Goldstone, for the purpose of intercomparing the techniques. The results showed that the orientations of the recovered baseline vectors did not agree to better than 50 cm, although the baseline lengths consistently agreed to better than 10 cm. The Moblas stations will remain at Haystack, Goldstone, Fort Davis (Texas), and OVRO for further intercomarisons.

B. National Geodetic Satellite Program (NGSP)

Among the earliest scientific results to be obtained from space were those related to the shape of the earth. Revisions to the accepted value of the flattening of the earth that were obtained from analysis of tracking data from these early satellites established that the earth was not in hydrostatic equilibrium and that its internal strength was greater than had been thought. It was discovered that the earth was not radially symmetric about its axis of rotation.

It was soon realized that these same tracking data could be used to connect local geodetic datums together; the relative position of some of these datums was known only to several hundred meters.

These results and additional national geodetic requirements led to the establishment of the US National Geodetic Satellite Program (NGSP). The multi-agency program involved NASA, DOD, and DOC; it was established under NASA management in 1964. Two active geodetic explorer satellites (GEOS-1 and GEOS-2) and a passive geodetic explorer (PAGEOS) were launched between 1965 and 1968. These spacecraft were especially equipped for various kinds of radio, radar, optical, and laser tracking.

The objectives of the program were threefold: first, to establish a unified world datum with an accuracy of 10 m in center-of mass coordinates. Second, to define the structure of the earth's gravitational field to five parts in 10^8, and refine the locations and magnitude of large gravity anomalies (since the customary representation of the gravity field is in terms of spherical harmonics, this amounts to an accurate representation of the field with coefficients up to degree and order fifteen). The third objective was to intercompare and correlate the results obtained with the various types of tracking in order to remove bias and systematic errors in the tracking systems.

C. Gravity Field Modeling

Improvement of the quality and resolution of gravity field models over those generated during the NGSP has been due to several factors. The main satellite observation data in the NGSP models (up to about 1972) was from cameras, primarily from the Baker-Nunn network. The observational accuracy of the precision reduced Baker-Nunn data was 30 meters in right ascension and declination. Recent improvements in the gravity field have been the result of the availability of three significant new sources of satellite data in reasonable quantity. First, more and better satellite laser ranging systems have been deployed, and more satellites equipped with laser cube corner retroreflectors (and with varying orbital parameters) have been placed into orbit. The result is that now there are about a dozen satellites and about a dozen laser tracking facilities able to track them with accuracies of typically 10 cm, at repetition rates of about one per second.

The second major development was the advent of satellite-to-satellite tracking. Tracking of Nimbus G, GEOS-3, and the Apollo CSM during the ASTP mission by the geosynchronous ATS-F satellite, provided continuous range-rate data of 0.003 cm/sec quality for durations as long as half an orbit.

The third major advance was the beginning of satellite altimetry from Skylab, GEOS-3, and Seasat-A. These missions provided altimetric data over the oceans with accuracies of 1-2 m, 20-50 cm, and 10-20 cm respectively, the variability depending on knowledge of orbital position, ability to model sea-state corrections, and characteristics related to the return pulse. This data source has provided a significant increase in information about short-wavelength components in the gravity field. In addition, throughout the period from the end of the NGSP to the present, there has been a considerable increase in the quantity and knowledge of the quality of surface gravity data; this data has been used in gravity field solutions. As a result, we now are able to construct gravity models complete to degree and order 36 (compared to 15 for NGSP) that represent components of the field down to wavelengths of 500 km (compared to 1200 km for NGSP) with an accuracy of at least 10 milligal, the longer wavelengths being known more accurately. Further significant improvement will have to await a dedicated gravity field mission.

D. Geodynamics Experimental Ocean Satellite (GEOS-3)

GEOS-3 was implemented as an interim step between the National Geodetic Satellite Program and the emerging NASA Earth and Ocean Dynamics Applications Program, EODAP; EODAP subsequently was split into two programs, the Geodynamics Program and the Ocean Processes Program.

The GEOS-3 spacecraft (Figure 7) was launched from the Western Test Range on April 9, 1975, into an 843 km orbit with an inclination of 115 degrees. All functions of the satellite performed successfully, and all objectives were accomplished during the first nine months of the planned two-year lifetime. Early in the project, it was determined that the altimeter was performing well beyond its planned performance level, and new investigations were established to use the unexpectedly increased capability.

Four years after launch, operation of the GEOS-3 altimeter was terminated on July 1, 1979. Functional use of GEOS-3 for calibration of DOD C-band ground radar tracking systems continued on a cost-reimbursable basis through February 1980.

Computer modifications being implemented by the STDN will make it impossible for NASA to continue to provide monitoring and control services for GEOS-3 beyond the spring of 1980. To continue C-band radar calibration, DOD has initiated action to develop this capability itself, and it is expected that DOD will assume spacecraft monitoring and control functions in April 1980.

Prior to the phaseover of this responsibility to DOD, GEOS-3 will be used for simulation tests of shuttle entry and landing tracking. The purpose of these tests is to calibrate and validate the operational readiness of the shuttle tracking network (which includes both NASA and DOD C-band and S-band radars) for the initial shuttle flight.

The decision to terminate GEOS-3 altimetry observations was based on serious degradation of the high-intensity mode, which occurred in late 1978. This mode, which was used almost exclusively during the mission, provided a spatial resolution of 3.6 km. Operations were continued in 1979 using the global mode (14.3 km resolution) to complete joint NOAA and US Navy investigations on monitoring sea state and ice boundaries. While all other GEOS-3 systems continue to perform satisfactorily, the resolution available with the global mode has limited application, and it was decided that continued data acquisition was not warranted.

Final processing of the GEOS-3 mission data (from launch through October 31, 1978) was completed in early 1980. These data are being archived by the Satellite Data Services Division of the NOAA Environmental Data and Information Service (EDIS) in Suitland, Maryland. During the three and one-half years of normal operations, the GEOS-3 altimeter provided the most complete set of geodetic and geophysical data ever collected over the oceans: more than from all previous shipboard measurements.

In each of the thirteen designated areas of investigation, the GEOS-3 data were successfully used to further scientific knowledge, and to demonstrate practical applications of remotely sensed data. The altimeter, the first extensively operated in space, has paved the way for future operational radar altimeter satellites. The GEOS-3 contributions to understanding and application of microwave altimetery as a source of ocean, ice, and land surface topography measurements, and as a means of sensing a variety of geodynamic and oceanic parameters, have been invaluable. A special issue of the Journal of Geophysical Research (July 30, 1979) was devoted to the publication of thirty-eight papers reporting results by GEOS-3 investigators.

E. Laser Geodynamics Satellite (Lageos)

Lageos was the first NASA satellite dedicated exclusively to laser ranging. It was launched May 4, 1976, into a nearly circular orbit at an altitude of 5900 km and an inclination of 110 degrees. The satellite is an aluminum sphere with a brass core, 60 cm in diameter, weighing 411 kilograms. The surface of the satellite is covered with 426 uniformly distributed optical cube corner retroreflectors.

The initial phase of the Lageos mission was devoted to determination of the precise satellite ephemeris and to development of the laser tracking systems. In the current phase, Lageos is being tracked by ground-based laser systems at several locations around the world. By accurately measuring the time for a laser pulse to travel to the satellite and return, the position of the laser system can be determined to a precision of 10 cm or better (the current capability of laser systems). By observing from several locations, the relative distance between locations can be determined.

Lageos ranging data are being acquired with mobile laser systems (Moblas) located on Kwajalein Island and American Samoa in the Pacific; Geraldton, north of Perth, Western Australia; Owens Valley, California; Goldstone, California; Fort Davis, Texas; and Haystack Observatory in Massacusetts. Fixed laser observatories are also acquiring data: Goddard Space Flight Center (Stalas); the LURE Observatory on Haleakala, Maui, Hawaii; a US Air Force laser station at Patrick Air Force Base, Florida (Ramlas); and laser stations operated by SAO at Natal, Brazil; Arequipa, Peru; and Orroral Valley, Australia. Another SAO-operated laser is being relocated from Mount Hopkins, Arizona, to Nanital, India, where it will become operational in late 1980.

Lageos data are also being acquired by several foreign lasers in Europe. Data from a Transportable Laser Ranging System (TLRS), will be available later in 1980. This truck-mounted highly mobile system will support scientific investigations in the western United States during its first year of operations.

An Announcement of Opportunity for scientific investigations using Lageos data was released in September 1978. Twenty-six investigations were selected, covering four general topics: plate tectonics measurements; polar motion and earth rotation; the earth's gravity field and elastic properties; and orbital analysis. The investigations selected are listed in Appendix 1.

Eighteen of the investigations were submitted through US institutions, and the remaining eight came from foreign countries: France, West Germany, Italy, The Netherlands, and the United Kingdom. All principal investigators are members of the Lageos Working Group. The first meeting was held at GSFC in August, 1979, and the second in February, 1980. The analysis and publication of the results portion of the investigations are generally planned for a period of three years, and are to be completed by July 1982.

F. Magnetic Field Satellite (Magsat)

The third Applications Explorer Mission (AEM-C), the Magnetic Field Satellite (Magsat; Figure 8), was launched October 30, 1979, from the Western Test Range at Vandenberg Air Force Base, on a Scout launch vehicle. Although the expected lifetime was about five months, current predictions based upon present solar activity imply a lifetime of about eight months before re-entry. Magsat's mission is to map the magnetic field of the earth for the 1980 epoch and to obtain a global crustal anomaly distribution with a horizontal resolution of 350 km. Using Magsat data and airborne and ground survey data, the earth's main field will be modeled by a spherical harmonic expansion of degree and order fourteen. This will be the first global vector measurement of the near-earth field. An initial field model, based on three days of data, is shown in Figure 9. Scalar data from the polar Orbiting Geophysical Observatory satellites (OGO-2, 4, and 6) in the late 1960's has been used to construct field models for that epoch and to develop crustal anomaly maps of coarse resolution.

Magsat is a cooperative effort between NASA and the US Geological Survey. The USGS plans to use the Magsat observations and models to update regional and global magnetic charts and maps, which are published by the USGS.

Magsat instruments consist of a scalar and a vector magnetometer: the scalar instrument is a dual lamp cesium vapor magnetometer, and the vector instrument is a three-axis fluxgate magnetometer. When uncertainties associated with orbit position, spacecraft attitude, and attitude transfer between the sensor platform and the spacecraft are taken into account, the expected accuracy for the scalar measurement is 3 gamma in total field, and 6 gamma in each component for the vector measurement. The spacecraft is in a 350 by 550 km sun-synchronous orbit with an inclination of 97 degrees.

Thirty-two investigations were selected in response to an Announcement of Opportunity issued September 1, 1978. These included thirteen foreign investigations, from Australia, Brazil, Canada, France, India, Italy, Japan, and the United Kingdom. The six general categories of research are geophysics, geology, magnetic field modeling, marine studies, magnetosphere and ionosphere, and core/mantle studies (see Appendix 2). Data distribution is through the National Space Science Data Center (NSSDC).

III. Measurements

A. San Andreas Fault Experiment (SAFE)

The San Andreas Fault Experiment is being conducted to demonstrate the feasibility of measuring plate motion along the San Andreas Fault, the transform boundary between the Pacific and North American plates connecting the East Pacific Rise in the Gulf of California to the Mendocino Triple Junction off the coast of Northern California.

Initially, two laser ranging stations were set up on opposite sides of the fault, far enough away from it to be free of the influence of local effects. These stations (Moblas) were located on Otay Mountain just east of San Diego (on the Pacific plate) and at Quincy in the Plumas National Forest in the northern Sierra Nevada (on the North American plate). Later, a station was added at Bear Lake, Utah, in order to measure crustal extension across the Basin and Range Province.

The first measurement period began on September 12, 1972, and lasted for three months. Similar campaigns have been conducted approximately every two years up to the present time. Data analysis to date indicate a relative plate motion of about 9 ± 2 cm/year (Figure 10), approximately twice the relative motion anticipated on the basis of geological and geophysical evidence. This result may imply greater strain changes in the area than expected.

B. Southern California Measurements

Frequent measurements of the length of the baseline between JPL and Goldstone, and between JPL and OVRO, have been made since 1974. In August 1979, remeasurement of these baselines indicated that the position of JPL had shifted about twenty cm to the northwest since the previous measurement in January 1979. During this same interval, several unusual anomalies were observed in Central and Southern California - changes in the radon content of water wells, gravity changes, changes in creep rate on the San Andreas Fault near Parkfield, and changes in the strain observed near the San Andreas Fault by ground surveys. As part of an intensified geophysical study of the area, measurements of the JPL - Goldstone - OVRO baselines were made in November and December, 1979, and January 1980, and further measurements are planned for March and June 1980. The ARIES station will also occupy a site at Pearblossom, California (east of the San Andreas Fault, near Palmdale) during the first half of 1980. If the TLRS successfully passes its acceptance tests in early 1980, it will move to Southern California in order to measure these and other baselines in the area, working with the Moblas units at OVRO and Goldstone.

Preliminary analysis of the JPL - Goldstone - OVRO measurements made in late 1979 indicate that JPL has moved in different directions about a decimeter between each observing period, and that its position is now back to what it was in 1978. The validity of these observations is not completely established, and these results must be regarded as tentative, pending review of the VLBI analysis procedures, the ARIES electronics system behavior at the time, and simultaneous measurement of one or more of the baselines by ARIES and TLRS. However, if the ARIES results are valid, they are of considerable geophysical importance, since they indicate that large-scale crustal movements may be occurring in Southern California on an unexpectedly short time scale. Not enough is known about crustal movements across an area this large to be able to assess the possible significance of the ARIES results (if valid) in terms of the likelihood of a large earthquake occurring in the region in the near future. NASA and the USGS are continuing intensive studies in the area.

If the ARIES results are confirmed, the GPS-based systems will probably assume a higher level of importance in the program, since more frequency surveys of areas that behave like Southern California will be necessary.

C. North America - Europe Baselines

In August and November 1979 observations were made between VLBI systems at Haystack, OVRO, NRAO, Onsala, and Bonn, using Mark-III systems. The data has been used to determine the baseline length between Haystack and the west coast stations, with a repeability of about 4 cm. The X-component of pole position and UT1 have been determined in these experiments with accuracies of about 0.01 arcseconds and 1 millisecond in time.

These measurements are important as a demonstration of intercontinental observations using Mark-III systems, and as an initial-epoch determination of baseline lengths to begin to measure the spreading rate across the boundary between the North American and Eurasian plates.

IV. System Development Plans

A. Fixed VLBI

NASA and the NGS plan to complete the Fort Davis (Texas) station in 1980. Fort Davis and the Westford (Massachusetts) station, to be completed by the NGS in early 1981, will be joined by a station in Richmond, Florida in 1982 to form the operational NGS polar motion monitoring network in 1983. All these stations and the existing observatories at Haystack, Owens Valley, and NRAO, will have full Mark-III capability. DSS-13 at Goldstone, California, has a narrow-band (4 MHz) data system, and is limited to S-band reception. Upgrade to a wide-band system (120 MHz) and expansion to include X-band reception, is planned for 1983.

In the early 1980's, VLBI systems are expected to become operational in Germany, Italy, and Japan.

For measurements of plate motion, a global VLBI system (Figure 11) is needed; however, permanent stations are not required, since observations every one or two years are sufficient. Almost any radio observatory antenna can be converted to a VLBI system. This has been demonstrated with portable Mark-III VLBI systems deployed last year at Onsala (Sweden) and Bonn (West Germany). In 1980, work will begin on fabrication of two portable Mark-III systems for the Crustal Dynamics Project. These systems are intended for use in Hawaii and Alaska (to work with the Japanese, US, and Australian stations) in 1983, and for use in South America and possibly Africa.

B. Mobile VLBI

By mid-1981, upgrade and refurbishment of the existing 9-meter (NASA-1) and 4-meter (NASA-2) VLBI stations will be completed. These stations will be equipped with wideband data systems, hydrogen masers, and water vapor radiometers. Mobile VLBI measurements of crustal deformation in the western United States, initiated in Southern California in 1979, will be continued and extended in 1980.

Procurement of a third ARIES station (NASA-3) is planned to start in mid-1980 for delivery in early 1982. NASA-3 will be the first of an operational class of mobile VLBI stations, and the prototype for future systems acquisitions by NASA, other Federal agencies, and other countries.

C. GPS-Based VLBI

Engineering prototypes of transportable Satellite Emission Radio Interferometric Earth Surveying (SERIES) receivers will be fabricated by September 1980. The first SERIES pair will be used later in 1980 in conjunction with GPS receivers built by the NSWC to intercompare measurement accuracies for two different GPS receiver concepts. Although both methods use interferometric techniques, SERIES is designed to use the PRN-modulated L-band transmissions, treating the signals in the same way as those received from quasars in classical VLBI. The NSWC receiver, which is patterned along a phase difference approach being developed jointly by NGS, USGS, MIT, AFGL, NSWC, and DMA, uses the PRN code to reconstruct the carrier waveform. For purposes of initial tests, a SERIES and a NSWC receiver will be positioned at each end of the OVRO-Goldstone baseline, which has been measured both by laser ranging and quasar-based VLBI. Use will be made of water vapor radiometers at these sites to test the sensitivity of the GPS receivers to the presence of water vapor in the atmosphere.

The SERIES units will be upgraded to fieldable systems in 1981. Later, probably in mid-1982, more extensive intercomparison of the performance, mobility, operability, and costs of the two approaches will be evaluated using a regional test area in Southern California to monitor changes at 20 to 30 sites.

Coordination of interagency plans for the development of geodetic applications of GPS is being directed through a panel of the Satellite Geodesy Applications Board. This GPS panel is chaired by NOAA, and includes representatives from DMA, NASA, and USGS. In 1979 a draft plan was prepared by the panel and reviewed by the GPS Panel of the NAS/NRC Committee on Geodesy. The plan is currently being revised, and is expected to be published in mid-1980.

D. Laser Ranging Systems

Improvements in laser ranging system performance are outlined in a Laser Development Plan prepared by GSFC and scheduled for completion in April 1980. This planning activity is considering both improvements to existing global systems, such as Moblas and the SAO lasers (Figure 12), and advanced laser systems which are sufficiently compact to be readily transported between sites. Ranging errors introduced by uncertainties in atmospheric modeling are, as for VLBI, becoming an important limitation for higher-accuracy systems. In the Laser Development Plan, work is proposed to assess the adequacy of current models and to undertake improved model development.

1. Moblas

Lageos normal point precision (average of 100 single shots) for Moblas-4 through Moblas-8 appears to be 5-8 cm, while the single-shot ranging precision is 10-15 cm. By comparison, the normal point precision for the Stalas system at GSFC is 1-2 cm. Moblas 4-8 use a green laser (Nd:YAG) and a mode-lock technique for output wave amplification. Laboratory tests in 1979 established that the far-field laser beam was corrupted by variations in pulse waveform, giving rise to a situation where range uncertainty was related to the position of the satellite in the laser beam. These tests also showed that using cavity dump techniques, which are employed with a ruby laser in Moblas 1, 2, and 3, substantially reduces this problem. In late 1979, the prototype of a cavity dump modification for Moblas 4-8 was delivered to GSFC for tests. After completion of laboratory tests, this prototype will be installed and checked out in Moblas 4 at GSFC prior to field retrofit of operational Moblas units. This retrofit (referred to as Phase I) is scheduled to be completed in 1980, and is expected to improve normal point precision to at least 3-5 cm.

In 1980, Moblas-4 will also be used to test a new short-pulse laser system and to evaluate modifications for low-energy (single-photon) operations. With either of these modifications (referred to as Phase II), it should be possible to achieve range precision of 1-2 cm or better. However, the possibility also exists that the cavity dump modification, along with optimization of other system components, could achieve these accuracies without the large financial requirements of Phase II.

2. TLRS

TLRS-1 is to begin field operations in Southern California in the spring of 1980. In 1979, work was begun at GSFC on a prototype laser system for TLRS-2. This prototype, which includes advances in laser transmitting and receiving systems, will be completed and tested in 1980. TLRS-2 specifications include normal point accuracies of 1-2 cm and the use of commercially available transport vehicles. The complete laser system is contained in a one-meter cube, and could be off-mounted from the carrier and left at a site. Initial operations with TLRS-2 could begin in 1981.

E. Smithsonian Astrophysical Observatory

SAO operates lasers for NASA at locations in the US, Brazil, Peru, and Australia. These laser systems were reconfigured in 1979 by additions of a pulse chopper and modification of the receiver system to detect single-photon returns. Currently the single-shot range precision to Lageos is 10 cm.

In 1980, the US laser located at Mt. Hopkins, Arizona, will be relocated in India. The other SAO lasers will continue to operate at the present sites: Natal, Arequipa, and Orroral Valley.

Studies are under way for upgrading the SAO lasers, probably in 1982-83, to the same capabilities as planned for the rest of the laser network.

F. Combined Lunar/Satellite Laser Ranging Systems

In late 1979, a contract was implemented with the University of Texas at Austin for fabrication of the McDonald Laser Ranging Station (MLRS). This station, to be permanently located at McDonald Observatory in Fort Davis, Texas, will be capable of ranging to the moon and to Lageos with a normal point precision of 3 cm. The MLRS is partially derived from equipment developed for, but not used in, the TLRS. The MLRS will be operational in late 1981. At that time, lunar laser ranging using the 107" astronomical telescope at McDonald Observatory will be terminated. These plans are consistent with a NASA understanding with the astronomical community that laser ranging using the large telescope would cease prior to 1983.

Lunar laser ranging at the Haleakala Observatory (Hawaii) over the past several years has been only partially successful. In 1979 the laser and the 16" transmitting telescope system were reconfigured for satellite laser ranging, and Haleakala is currently ranging to Lageos and other satellites on a routine basis. Testing of the Lurescope receiving telescope has continued, but there still appear to be problems in bringing this instrument to operational status. Consequently, alternatives are being studied for upgrading the satellite ranging in a manner which will also provide for lunar ranging.

The National Mapping Division in Australia is reponsible for operation of the Australian lunar laser ranging facility at Orroral Valley. NASA and Natmap have under discussion a joint program for upgrading this facility and to include capability for satellite laser ranging. These plans will be finalized and implemented in 1980, and operations would begin in 1982.

V. Crustal Dynamics Measurement Plans

Measurement plans for the fixed laser ranging observatories are simply to operate the maximum number of shifts and observe the maximum number of passes of the moon, Lageos, and lower-altitude satellites, consistent with funding limitations. Similarly, for fixed VLBI observatories, the maximum number of observations will be undertaken, subject to funding limitations and available time at the radio astronomy facilities that are used for purposes other than geodetic VLBI.

Planning measurement operations for the mobile VLBI and laser ranging stations is very much more complex. Much of the Geodynamics Program Plan (NASA, 1979) is devoted to discussion of possible operations with mobile stations in tectonically active regions, and these activities occupy a major part of the planning activities of the Crustal Dynamics Project.

There are many tectonic areas in the world where measurement of crustal deformation would yield useful and potentially important information about dynamic processes in the earth - so many that it is necessary to prioritize the possible activities of the mobile VLBI and laser ranging stations. NASA Program and Project personnel have consulted with a very broad range of expert opinion of what these priorities should be - the NASA Advisory Subcommittee on Geology and Geodynamics, NAS/NRC advisory committees and panels, experts in other agencies such as USGS and NGS, the Lageos Principal Investigators, and scientific organizations in other countries.

The result of these discussions is described in the Crustal Dynamics Project Plan (to be distributed in early 1980). The observational priorities outlined in the plan are: first, the Western United States; second, the Nazca Plate and its interaction with the South American and Pacific Plates; third, South America. Lower-priority areas include the Caribbean, New Zealand, Australia, Alaska, and tectonic regions in the northwestern Pacific. All foreign operations are, of course, subject to agreement on the part of scientific organizations in other countries, and formalization of joint agreements between NASA and the appropriate government organizations in those countries.

The schedule for development of the TLRS and the 4-meter ARIES VLBI station call for them to begin operations in mid-1980 at the latest. A plan for deployment of these mobile stations during the remainder of 1980 and 1981 is in the final stages of definition. Like the priorities, this plan is the result of extensive discussion with other Federal agencies and with outside scientific groups and individuals. Figure 13 shows sites in North America; Figure 14 is an expansion showing sites in California. In every case there is a scientific rationale for selecting the particular site shown. Lists of the sites and a discussion of the selection rationale are given in the Project Plan.

A working group of the informal inter-agency coordinating committee is now studying the localities shown on these maps to pin down the exact location at which the mobile stations should make observations, and to help NASA prioritize the site occupation schedule. Geology, logistics, and proximity to geodetic benchmarks are among the considerations being taken into account. The result of these studies will be a field operating schedule for the mobile stations.

It is quite probable that unforeseen circumstances will arise which will make it scientifically desirable to depart from the present schedule. An example of what is likely to happen is the discovery of geophysical anomalies in Southern California last year. The near-term plans for the NASA mobile stations as a result of these discoveries is described in section III.B above.

Similarly, the occurrence of a large earthquake in North America in 1980 or 1981 will lead to re-assessment of the program priorities, and the probable redirection of the mobile station activities. Another working group of the inter-agency coordinating committee is studying possible contingency plans that can be activated immediately following a large earthquake.

As pointed out in the Program Plan, it is almost certain that within a few years of the start of the measurement program the present site locations and priorities will be completely revised as a result of what the measurements show about dynamic processes. For example, in areas where crustal movements are unexpectedly small, the observation frequency can be reduced, and vice versa.

At the present time, no formal agreements have been reached with other countries regarding NASA mobile station operations outside the United States. Plans are being formulated in several countries (for example, Australia, New Zealand, Venezuela, Peru, Chile, and Canada), and it is expected that negotiations on joint agreements will begin in mid-1980. In each case, the proposed cooperative program will be prioritized by the Project, and a schedule for initiation of the measurements will be worked out. At present it appears that the earliest foreign operations will take place in 1983.

VI. Polar Motion and Earth Rotation

For the past decade, NASA-sponsored programs have been involved in the measurement of polar motion and earth rotation, using laser ranging and VLBI. Lunar laser ranging from McDonald Observatory has been useful in determining UT0. These results have been reported in the literature, and compare favorably with UT derived by BIH as well as with estimates from VLBI and satellite doppler methods.

The first satellite laser observations of polar motion were obtained by the SAO stations, using low-altitude satellites. Laser polar motion data have been acquired routinely since the launch of Lageos in 1976. The accuracy of the Lageos polar motion information derived from five to six laser sites compares favorably with the BIH information derived from global observations. With the global deployment of Moblas units in 1979, about 20 laser sites are operational, and the accuracy of the data is expected to improve.

VLBI observations in the US over the past two years have also provided polar motion and earth rotation data. As reported at several scientific meetings, these are in general agreement with satellite doppler data. However, comparison of these data with BIH data clearly show an annual variation unaccounted for in the BIH derivation.

The NASA Deep Space Network maintains large radio tracking antennas at Goldstone (California), Madrid (Spain), and Orroral Valley (Australia). To assist in the tracking and navigation of interplanetary missions, these stations are equipped with VLBI instrumentation, but DSN requirements for polar motion monitoring are less stringent than geodetic VLBI (50 cm vs. 2-3 cm), although data are needed nearly in real time. Beginning in 1980, the DSN plans to provide five-day polar motion averages to the BIH, every two weeks.

For the past several years, NASA has been assisting the NGS to develop an operational VLBI-based polar motion and earth rotation monitoring network under the NGS Polaris Project. This network is to consist of stations located in Westford, Massachusetts, Fort Davis, Texas, and Richmond, Florida, and is to be operational in 1983. The goals are to provide twelve-hour estimates of polar motion accurate to 10 cm, and earth rotation accurate to one hundred microseconds. The Fort Davis station is being jointly equipped by NASA and NGS, and is to be operational in April 1980. The Westford station is being developed by NGS, and is to be operational in early 1981. NGS expects to obtain funding for the Richmond station in FY 1982. When the Polaris network is operational, NASA plans to use the polar motion and earth rotation data acquired by NGS in the analysis of crustal movement and deformation measurements.

In 1979, the IAU established Project MERIT (Measurement of Earth Rotation and Intercomparison of Techniques) to evaluate the several methods of measuring polar motion and earth rotation, preparatory to recommending to IAU in 1985 the adoption of one or more of these techniques as a new basis for the international program. Project MERIT, which was endorsed by IUGG in 1979, includes a preliminary observation period in August-October 1980, and a more extensive one-year campaign in 1983. NASA has agreed to participate in Project MERIT, and is developing plans for coordinating observations in 1980 using VLBI, satellite laser ranging, and lunar laser ranging. Working with the NGS, a US network of three sites (Westford, Fort Davis, and OVRO) will acquire data for two seven-day periods in September and October. These observations will also be coordinated with DSN measurements. Raw data will be processed both by NASA and by designated analysis centers.

VII. Investigations Programs

One of the major objectives of the NASA Geodynamics Program is to support high-quality scientific research in relevant fields. There are three ways in which scientific research is supported by the Geodynamics Program Office:

1. Yearly requests are made of NASA Centers to submit Research and Technology Operating Plans (RTOP's) for the following year.

2. A yearly Applications Notice (AN) is issued to inform the scientific community of the areas of research that are being emphasized in any given year, together with methods by which investigators outside NASA can participate in the program.

3. As new programs (usually flight programs) are approved, an Announcement of Opportunity (AO) is distributed, which is a formal solicitation for proposals pertaining to the specific opportunity. Recent solicitations of this kind were made for the Lageos and Magsat programs.

Most of the work supported under the first of these methods is in-house effort, but with some limited involvement of of the academic community when joint efforts are proposed. For the last two methods of supporting research, most of the work is done outside NASA by industry, academic researchers, and foreign investigators. All proposals and RTOP's are reviewed by peer groups except for certain RTOP's that involve programmatically necessary work that must be done within NASA; examples include study of future space flight missions or generation of complex software systems for using space data.

Lists of investigations being conducted as a result of the Lageos AO, the Magsat AO, and the Geodynamics AN for 1979 are given in Appendices 1, 2, and 3, respectively.

VIII. Advanced Studies

A. Time Transfer

Current methods for time synchronization between the US and other countries are good to about 100 nanoseconds to Europe and one microsecond to the Far East. The universal time standard is established internationally by averaging time maintained by atomic clocks at half a dozen time centers distributed around the world, half of which are in the US.

Operational time systems such as the Omega and Loran systems routinely provide accuracies of 100 nanoseconds. In special cases, primarily involving distances of 20-100 km, accuracies of 10 nanoseconds have been achieved. Experiments using VLBI have demonstrated time transfer between antenna sites to one nanosecond. However, time transfer using the VLBI technique is limited by the location of radio antennas and the special equipment required. By the late 1980's, the Global Positioning System will be operational and global time synchronization at the 10 nanosecond level should become routine.

Advances to the one nanosecond level, while technically feasible, have not been demonstrated, and suffer from the lack of a well-defined need. Nevertheless, future applications to communications, astronomical and earth science studies, and military needs warrant experimentation to establish that global time transfer at the one nanosecond level is readily achievable.

In 1981, Goddard Space Flight Center will participate with the USNO, NBS, and the University of Maryland in the LASSO experiment to be conducted by ESA. In this experiment, laser systems at GSFC and in Europe will range to SIRIO-2, an ESA communications satellite in geosynchronous orbit. The satellite will store the time of detected laser pulses for later comparison with laser transmit times controlled by clocks on the ground. In this manner it is expected to detect clock differences between the US and Europe to one nanosecond.

The US LASSO participants and Marshall Space Flight Center are studying the next phase - global time transfer at one nanosecond or better and frequency comparison to one part in 10^{14}. In this experiment a hydrogen maser would be flown on the Space Shuttle in the 1984-85 time period, and synchronization at sites around the world would be accomplished using both laser and microwave transmissions.

B. Gravity Gradiometry

In 1979 a contract was issued by Marshall Space Flight Center to the University of Maryland, for design and development of a three-axis super-conducting gravity gradiometer. The concept is based on detecting the differential motion of suspended masses. Movement of the mass, which is fabricated from niobium, is detected by changes in the magnetic field generated by persistent loop currents. The superconductivity provides shielding of the sensor from external magnetic fields. Sensitivities of 0.001 Eötvös unit (1 EU = 10^{-9} sec^{-2}) appear to be readily achievable with mass separations of 10 cm. Improvements in sensitivity can be obtained by increasing the separation distance.

A single-axis unit will be built in 1980, and a three-axis vector gradiometer will be available in 1981. Development work is expected to continue for several years, and may possibly include a shuttle test flight prior to a decision in 1984 for use of a gravity gradiometer as the primary sensor for a Gravsat-B mission.

C. Water Vapor Radiometer

The accuracy of VLBI measurements is limited by uncertainties in propagation through the atmosphere, particularly those caused by the presence of water vapor. The effect varies markedly with season and site location. Surface meterological monitoring can reduce this effect to 10 cm on a typical 200 km baseline. Water vapor radiometers are expected to reduce the uncertainty further, to about 2 cm, which is still a significant component in an overall estimated present error budget of 5 cm. Field tests of radiometers in 1980 should provide the information needed to verify these accuracies.

Simulations have shown that it should be possible to reduce this error to one centimeter, an attainment which is critical in establishing the overall system accuracy goal of 2 cm.

D. Gravity Field Mapping Mission (Gravsat)

Although significant improvements in our knowledge of the gravity field have been made over the last two decades using satellite data, important problems in solid earth geophysics, oceanography, and resource assessment require improved accuracies at certain horizontal wavelength resolutions. Surface gravity data and altimetry have provided data on short wavelength components, and "conventional" satellite geodesy has been used to obtain long wavelength information. The general objective of the Gravsat mission will be to contribute to the solution of fundamental problems in mantle convection, lithospheric structure, ocean circulation, and the formation and subsidence of sedimentary basins. The measurement objectives of Gravsat are a resolution of a few milligals in a 1° square, and a geoid undulation difference accuracy of 10 centimeters for distances from 100 kilometers to 3000 kilometers. These measurements will be obtained from analysis of the changes in range-rate in the relative motion of two satellites caused by gravity anomalies.

Because the Earth's gravity field reflects the distribution of mass within the Earth, it can be used to explore the existence, form, and scale of convection in the mantle. Mantle convection is thought to play a major role in the movement of the tectonic plates, and the question of how and why the plates move is a fundamental but unsolved question in geophysics, with important implications for understanding the occurrence of earthquakes. Gravity can also be used to study continental and oceanic lithospheric features, such as mountains and ocean trenches, caused by collision of plates, and to study the mechanical properties of the plates themselves. Further, the gravity field can be used to construct a model of the geoid (the equipotential surface which would coincide with sea level on a static Earth). In combination with the geoid, satellite altimetry (which can provide the instantaneous height of the ocean surface) can be used to study global ocean circulation, is an important factor in meteorological and climatological research.

A better understanding of the formation and subsidence of sedimentary basins, the type of geological formation where many of the world's major oil fields are found, is important in assessing earth resources. Since gravity data are sensitive to the overall thickness of sedimentary rocks in a basin, as well as the configuration of the basement, it provides useful information on the regional geological structure, which in turn is necessary in order to enable the resources of a region to be assessed accurately.

E. Spaceborne Laser Ranging

Studies of a system for rapid measurement of position over distances of a few tens of kilometers, in which the laser is carried on a spacecraft and the passive retroflectors are on the ground, were conducted during 1976-79. Results of these studies, and the applicability of this system, were reported in the proceedings of a workshop held in November 1978 (Tapley and Smith, 1979). The studies indicate that accuracies of the order of 2 cm in all components can be attained with existing equipment, and that the system may be cost-effective if the relative position of a sufficient number of ground targets are required. These studies were discontinued in 1980, pending the outcome of studies and prototype development of the GPS-based radio systems (for example, SERIES), and a decision point in 1982 or 1983 on which system should be further developed.

However, funding is being provided in 1981 for further studies of local surveying by laser, since the possibility of placing the laser in an aircraft instead of in a spacecraft appears to be economically attractive and technically feasible.

IX. Investigation Results

During the week of February 4, 1980, a Geodynamics Program review was held at Goddard Space Flight Center, at which forty-six of the current Geodynamics Program investigators presented papers related to their research. In subsequent publications of this Annual Report, it is intended to include a synopsis or abstract for each current investigator. For this first report, however, only a general discussion of the types of problems being studied under each of the four areas of research is presented.

The four areas of Geodynamics Program research are global earth structure and dynamics, regional crustal deformation modeling, geopotential field models, and advanced geodynamics studies.

1. Global Earth Structure and Dynamics. The objective is to improve our understanding of the dynamics of the earth, by development of models of polar motion and earth rotation, global plate motion, mantle convection and other possible plate-driving mechanisms, and the dynamics of the core; and to improve our understanding of the global structure of the earth, including its crustal magnetization, gravity field, and the evolution of the crust and lithosphere. Formulation of a standard dynamic earth model will be attempted under this program element.

In this area, studies are being made of the use of short-wavelength geoid data to derive mechanical properties of the crust, and the use of long-wavelength geoid data (along with residual topography anomalies) to derive information about mantle convection in oceanic regions. At the February 1980 review, the magnitude of long-wavelength geoid variations was functionally related to the dip of subducted slabs. Corrections for conductive cooling were made by using the relationship between lithosphere age and ocean depth, and age and geoid height. Studies were made of elastic and anelastic properties of the earth, using ocean tide parameters.

2. Regional Crustal Deformation Modeling. The objective of this program element is to conduct modeling studies of crustal deformation in various tectonic settings, relevant to the analysis and interpretation of geodetic data obtained by the Crustal Dynamics Project. The modeling studies are needed to determine what measurements are required, and to provide a proper perspective for the data analysis. The major types of models are ground deformation around active faults, earthquake focal mechanism, intraplate stress, strain, strain propagation, and vertical crustal motion.

Investigations in this program element were conducted using surface creep measurements and laboratory rheology studies; these indicate that non-Newtonian relaxation occurs after earthquakes, with a strain rate dependence on stress that has a power-law relationship depending on the material. Post-seismic relaxation using a layered anelastic earth indicated that stress recovery on a fault due to lithospheric relaxation is sufficient to cause aftershocks and aseismic slip. Numerical models of continent - continent collisions using heat flow, gravity, and topography data were obtained, and the tectonic consequences studied.

3. Geopotential Field Models. The objective of this element of the program is to develop gravity and magnetic field models, data analysis techniques, and software systems, and to support the previous two program elements as well as the Non-Renewable Resources Program. Emphasis is placed on using satellite altimetry for gravity field modeling, and determining the maximum resolution that can be achieved in the gravity field with existing data sources. Magnetic field models, including secular variations, are being developed. A data base is being established for auxiliary information required for geodynamics investigations (gravity anomalies, topography, and bathymetry).

Gravity and magnetic field modeling studies were reported. Improved $1^{o} \times 1^{o}$ terrestrial gravity anomalies, and improved methods of using gravity for geoid undulation computations, were discussed. Interpretations were made of the gravity anomalies obtained from satellite-to-satellite tracking data. Local ground gravity survey data were correlated with recent measurements of crustal movements in Southern California. A review of the magnetic field and secular variation was presented. Gravity and magnetic anomalies, along with heat flow, were used to study mechanical properties of continental crust in certain regions.

4. Advanced Geodynamic Studies. These studies support the development of new methods for geodynamics measurements, including improved accuracy, higher mobility, and minimum observing times. Advanced space missions such as Gravsat-A and Magsat-B are also included. Currently, studies of new methods for high-mobility VLBI systems are being conducted.

A number of supporting studies and advanced systems studies were described at the February 1980 program review. Progress on the highly mobile SERIES VLBI station (discussed earlier in this report) was noted. Plans to conduct a time transfer experiment using the Space Shuttle were reviewed. Progress was reported on development of a supercooled gravity gradiometer capable of making measurements to 0.001 EU or better. Definition of the proper geodetic reference frame in which to place crustal motion measurements was discussed, along with the problems associated with understanding the relationship between such a reference system and an inertial reference system.

X. Program Planning and Coordination

The Geodynamics Program interacts with the scientific community, both international and domestic, and with related activities in other Federal agencies, through a variety of mechanisms.

A. Advisory Committees

The NASA Advisory Council's Space and Terrestrial Applications Advisory Committee (STAAC) has an Advisory Subcommittee on Geology and Geodynamics, which meets several times a year to review progress and plans in both the Geodynamics Branch and the Non-Renewable Resources Branch of the OSTA Resource Observations Division. The present Chairman is Dr. Michael A. Chinnery of MIT Lincoln Laboratory; members involved with geodynamics include Dr. Charles L. Drake (Dartmouth), Dr. Don L. Anderson (Caltech), and Dr. William M. Kaula (UCLA). The STAAC advisory committees make comments and recommendations to NASA management through the NASA Advisory Council.

Several committees and panels of the National Academy of Sciences - National Research Council have cognizance over geodynamics. These include the Committee on Geodesy (Dr. I. I. Mueller, Ohio State University, Chairman), the Committee on Seismology (Dr. K. Aki, MIT, Chairman), the US National Committee for the International Geodynamics Project (Dr. John Maxwell, University of Texas at Austin, Chairman), the Geophysics Research Board (Dr. Phillip Abelson, Carnegie Institution of Washington, Chairman), the Panel on Crustal Movements Measurements (Dr. A. Dziewonski, Harvard, Chairman), and the Committee on Earth Sciences of the Space Science Board (Dr. S. Solomon, MIT, Chairman). NASA has liaison representation on these committees.

B. International Bodies

NASA Geodynamics personnel are involved in several international committees and study groups. These include the International Association of Geodesy's Commission on International Coordination of Application of Space Technology to Geodesy and Geodynamics, the IAG Special Study Groups on Lunar

Laser Ranging, Satellite Laser Ranging, and VLBI, and the Committee on Mathematical Geophysics of the International Union of Geodesy and Geophysics. These organizations promote the exchange of information, and sponsor meetings and symposia.

Bilateral discussions have been held between NASA Geodynamics personnel and scientific representatives of over twenty foreign countries, to explore possibilities of establishing mutually beneficial cooperative research projects in geodynamics. A formal agreement has been concluded between NASA and the Government of Japan on a joint VLBI experiment.

C. Federal Government Coordination

An inter-agency agreement is being circulated for signature between five Federal agencies involved in the application of space technology to geodynamics: NASA, NSF, USGS, NGS, and DMA. The agreement establishes an Interagency Coordinating Committee at the working level, which will coordinate activities in the various agencies. Several Working Groups have already been established to deal with high-priority items such as selection of sites for the NASA mobile facilities, GPS development, and local surveys near the mobile station sites.

Appendix 1

LAGEOS INVESTIGATIONS

Plate Tectonics

Aardoom, L., Delft University of Technology, The Netherlands: Precision and Reliability of Station Determination in Selected Areas with a View of Investigating the Potentiality to Detect Relative Station Displacements.

Bender, P. L., National Bureau of Standards: Determination of Worldwide Mobile Station Positions and Geodynamics Reference System.

Dorman, H. J., University of Texas at Galveston: Earth Strain Measurements with the Transportable Laser Ranging System.

Morgan, W. J., Princeton University, Princeton, New Jersey: Lageos Study of Polar Motion, Plate Rigidity, and Plate Motion.

Smith, D. E., Goddard Space Flight Center: Measurement of Fault Motion in the Western United States.

Polar Motion and Earth Rotation

Fliegel, H. F., Jet Propulsion Laboratory: Earth Rotation Parameters from Lageos and Lunar Laser Ranging Data.

Lelgemann, D., Institut für Angewandte Geodäsie, Frankfurt, West Germany: Lageos and Starlette Orbit Investigations, Accurate Station Position, and Polar Motion Determination from Satellite and Lunar Laser Ranging Data.

Nouel, F., Groupe de Recherches de Geodesie Spatiale, Toulouse, France: Comparative Studies of Polar Motion by Laser and Doppler Techniques.

Mueller, I. I., Ohio State University: Utilization of Range and Range Difference Observations in Geodynamics.

McCarthy, D., US Naval Observatory: Comparison of Earth Rotation Parameters Derived by Satellite Laser Ranging and Radio Interferometric Techniques.

Rosen, R. D., Environmental Research and Technology, Inc., Concord, Massachusetts: Earth-Atmosphere Momentum Exchange and Lageos-Determined Rotation Rates.

Shapiro, I. I., Massachusetts Institute of Technology: Validation, Intercomparison, and Use of Laser Ranging and Radio Interferometric Data for the Determination of Geophysical Parameters.

Smith, D. E., Goddard Space Flight Center: Determination of Polar Motion and Earth Rotation from Lageos Data.

Smith, M. L., Cooperative Institute for Research in Environmental Sciences, University of Colorado: Nutation and Polar Motion of the Earth.

Tapley, B. D., University of Texas at Austin: Solid Earth Dynamics Using Lageos Range Observations.

Earth Gravity Field and Elastic Properties

Cazenave, A., Groupe de Recherches de Geodesie Spatiale, Toulouse, France: Use of Artifical Satellite Laser Data for Tidal Studies.

Goad, C. C., National Geodetic Survey, Rockville, Maryland: The Value of Q at Tidal Frequencies Obtained from Laser Tracking of Lageos and Other Geodetic Satellites.

Wells, W. T., EG&G/Washington Analytical Services, Inc., Rockville, Maryland: Gravity Model Improvement Using Laser Data.

Williamson, R. G., EG&G/Washington Analytical Services, Inc., Rockville, Maryland: Tracking Station Coordinate Determination and Lithospheric Plate Motion Investigation.

Orbit Analysis

Barlier, F., Groupe de Recherches de Geodesie Spatiale, Grasse, France: Investigation of Lageos Laser Data at GRGS/Grasse.

Caputo, M., University of Bologna, Italy: Determination of Lageos Orbital Perturbations Caused by Solar Radiation Pressure and the Determination, by Scalar Translocation, of Interstation Baselines.

Dunn, P. J., EG&G/Washington Analytical Services, Inc., Rockville, Maryland: Studies of Atmospheric Refraction Effects on Laser Data.

Gaposchkin, E. M., Smithsonian Astrophysical Observatory, Cambridge, Massachusetts: Analysis of Satellite Tracking Data for Study of Satellite Ephemerides, Solid-Earth and Ocean Tides, and Laser System Performance.

Lefebvre, M., Groupe de Recherches de Geodesie Spatiale, Toulouse, France: Tentative Determination of General Relativity Beta Coefficient Using Secular Variations of the Perigee of Laser Satellites.

Martin, C. F., EG&G/Washington Analytical Services, Inc., Rockville, Maryland: Study of Relativistic Effects on Lageos Orbit Determination and Parameter Estimations.

Meadows, A. J., University of Leicester, United Kingdom: Development of a new British Orbital Analysis Program.

Appendix 2

MAGSAT INVESTIGATIONS

Core/Mantle

Benton, E. R., University of Colorado: Geomagnetic Field Forecasting and Fluid Dynamics of the Core.

Hermance, J. F., Brown University: Electromagnetic Deep Probing (100-1000 km) of the Earth's Interior from Artificial Satellites: Constraints on the Regional Emplacement of Crustal Resources.

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Stern, D. P., Goddard Space Flight Center: Study of Enhanced Errors and of the Secular Magnetic Variation Using Magsat Models and Those Derived in POGO Surveys.

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Appendix 3

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Geopotential Fields

Marsh, B. D., Johns Hopkins University: Interpretation and Delineation of the Earth's Gravity Field.

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Haxby, W. F., Lamont-Doherty Geological Observatory: The Effect of Subduction Zones on the Low-Order Harmonics of the Geoid.

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Phillips, R. J., Jet Propulsion Laboratory: Satellite Local Gravity Field Subsurface Modeling and Interpretation.

Turcotte, D. L., Cornell University: Finite Element Studies of the Surface Strain Field Adjacent to the San Andreas Fault.

Watts, A. B., Lamont-Doherty Geological Observatory: The Relationship Between Gravity and Bathymetry in the Pacific Ocean.

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Regional Crustal Deformation Modeling

Alexander, S. S., Pennsylvania State University: Combined Use of Remote Sensing and Seismic Observations to Infer Geologically Recent Crustal Deformation, Active Faulting, and Stress Fields.

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Berger, J., University of California at San Diego: Improvements in Benchmark Stability for Precision Tilt Measurements of Crustal Dynamics.

Dewey, J. F., State University of New York at Albany: Structural and Tectonic Evolution of the North Anatolian Fault: A Pilot Study in Synthetic Integration of Field Investigations and Landsat Interpretation in the Evolution of Intracontinental Plate Boundaries.

Molnar, P., MIT, Seismicity and Active Tectonics of the Andes and the Origin of the Altiplano.

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Oliver, J., Cornell University: Precise Leveling, Space Geodesy and Geodynamics.

Solomon, S. C., MIT, Application of Laser Ranging and VLBI Data to a Study of Plate Tectonic Driving Forces.

Toksöz, M. N., MIT: Geophysical Study of the Structure and Processes of the Continental Convergence Zones Alpine - Himalayan Belt.

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Gaposchkin, E. M., Smithsonian Astrophysical Observatory: Feasibility of Satellite-to-Satellite Doppler Tracking for Mapping of the Earth's Gravity Field Suitable for Geophysics and Oceanography.

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Schenkel, F. W., Applied Physics Laboratory, Johns Hopkins University: Proposed Inquiry on an Improved Precision Measurement of DISCOS Proof-Mass Velocity Relative to Gravsat.

Appendix 4

Glossary of Acronyms

AEM-C	Third Applications Explorer Mission (Magsat)
AFGL	Air Force Geophysical Laboratory
ALSEP	Apollo Lunar Surface Experiment Package
AN	Applications Notice
AO	Announcement of Opportunity
ARIES	Astronomical Radio Interferometric Earth Surveying
ASTP	Apollo-Soyuz Test Project
ATS	Applications Technology Satellite
BIH	Bureau International de l'Heure
CIRES	Cooperative Institute for Research in Environmental Sciences (University of Colorado)
CSM	Command and Service Module
DMA	Defense Mapping Agency
DOC	Department of Commerce
DOD	Department of Defense
DSN	Deep Space Network
EDIS	Environmental Data Information Service
ESA	European Space Agency
GEOS	Geodynamic Experimental Ocean Satellite
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
HO	Haystack Observatory
IAG	International Association of Geodesy
IAU	International Astronomical Union
IUGG	International Union of Geodesy and Geophysics
JPL	Jet Propulsion Laboratory
Lageos	Laser Geodynamics Satellite
LASSO	Laser Synchronization (of atomic clocks) from Synchronous Orbit
LED	Laser Earth Dynamics
LLR	Lunar laser ranging
LURE	Lunar Ranging Experiment
Magsat	Magnetic Field Mapping Satellite
Mark-III	Advanced VLBI data system
MERIT	Monitoring Earth Rotation and Intercomparison of Techniques
MIT	Massachusetts Institute of Technology
MLRS	McDonald Laser Ranging System
Moblas	Mobile Laser System
NAS/NRC	National Academy of Sciences - National Research Council
Natmap	Division of National Mapping (Australia)
NBS	National Bureau of Standards

NGS	National Geodetic Survey
NEROC	Northeastern Radio Observatory Corporation
NGSP	National Geodetic Satellite Program
NOAA	National Oceanic and Atmospheric Administration
NRAO	National Radio Astronomy Observatory
NSF	National Science Foundation
NSSDC	National Space Science Data Center
NSWC	Naval Surface Weapons Center
OGO-2	Orbiting Geophysical Observatory (2)
OSTA	Office of Space and Terrestrial Applications
OVRO	Owens Valley Radio Observatory
Pageos	Passive Earth-Orbiting Geodetic Satellite
Polaris	Polar Motion Analysis by Radio Interferometric Systems
PPME	Pacific Plate Motion Experiment
PRN	Pseudo-random noise
RTOP	Research and Technology Operating Plan
SAFE	San Andreas Fault Experiment
SAO	Smithsonian Astrophysical Observatory
SERIES	Satellite Emission Radio Interferometric Earth Surveying
SGAB	Satellite Geodesy Applications Board
STAAC	Space and Terrestrial Applications Advisory Committee
Stalas	Stationary Laser System
STDN	Space Tracking and Data Network
TLRS	Transportable Laser Ranging System
TPM	Tectonic Plate Motion
USGS	United States Geological Survey
USNO	United States Naval Observatory
VLBI	Very long baseline interferometry

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Figure Captions

1. Laser Geodynamics Satellite (Lageos).
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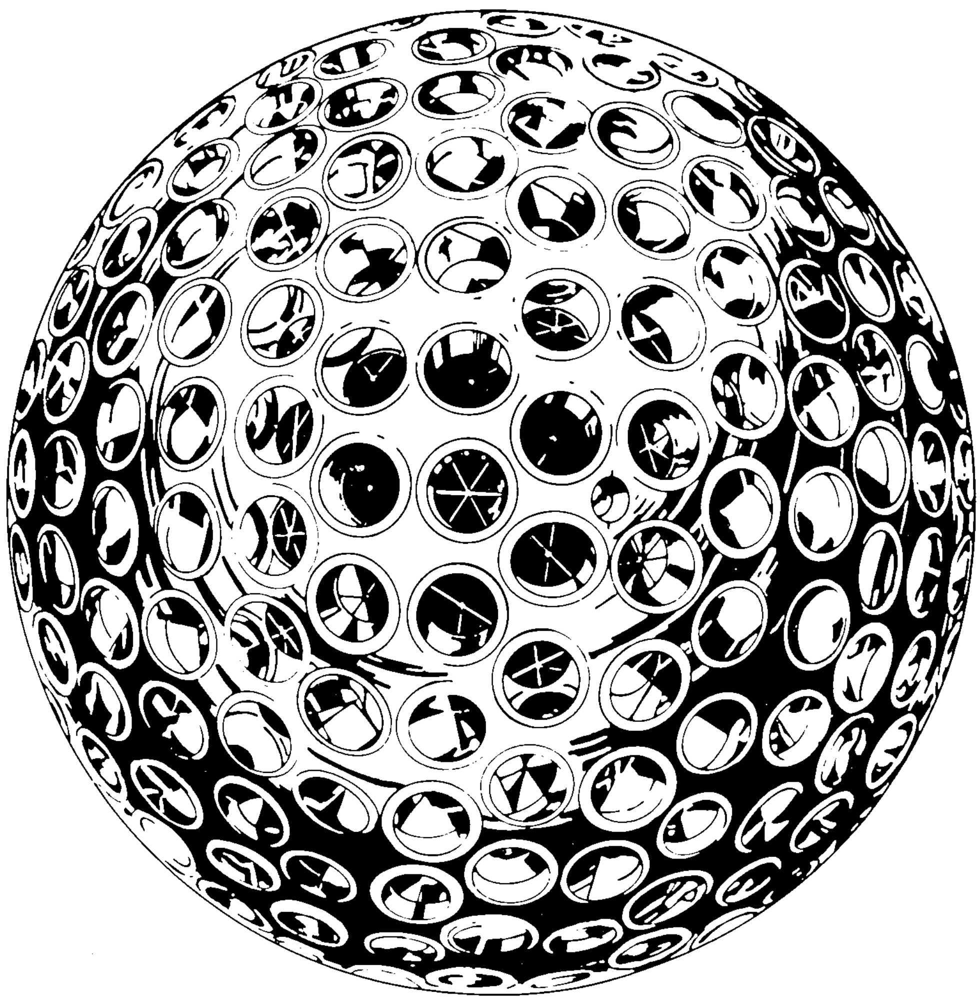
3. Transportable Laser Ranging Station (TLRS).
4. Transportable VLBI stations (ARIES).
5. SERIES system schematic.
6. Detailed gravimetric geoid, Goddard Space Flight Center Model GEM-10B.
7. GEOS-3 spacecraft.
8. Magnetic Field Satellite (Magsat).
9. Initial Magsat magnetic field model.
10. San Andreas Fault Experiment: results showing change in baseline length, Quincy to Otay Mountain, 1972-1978.
11. Global network of VLBI observatories.
12. Global network of laser ranging observatories.
13. North America: observatory and proposed mobile station sites for the Crustal Dynamics Project.
14. California: observatory and proposed mobile station sites for the Crustal Dynamics Project.



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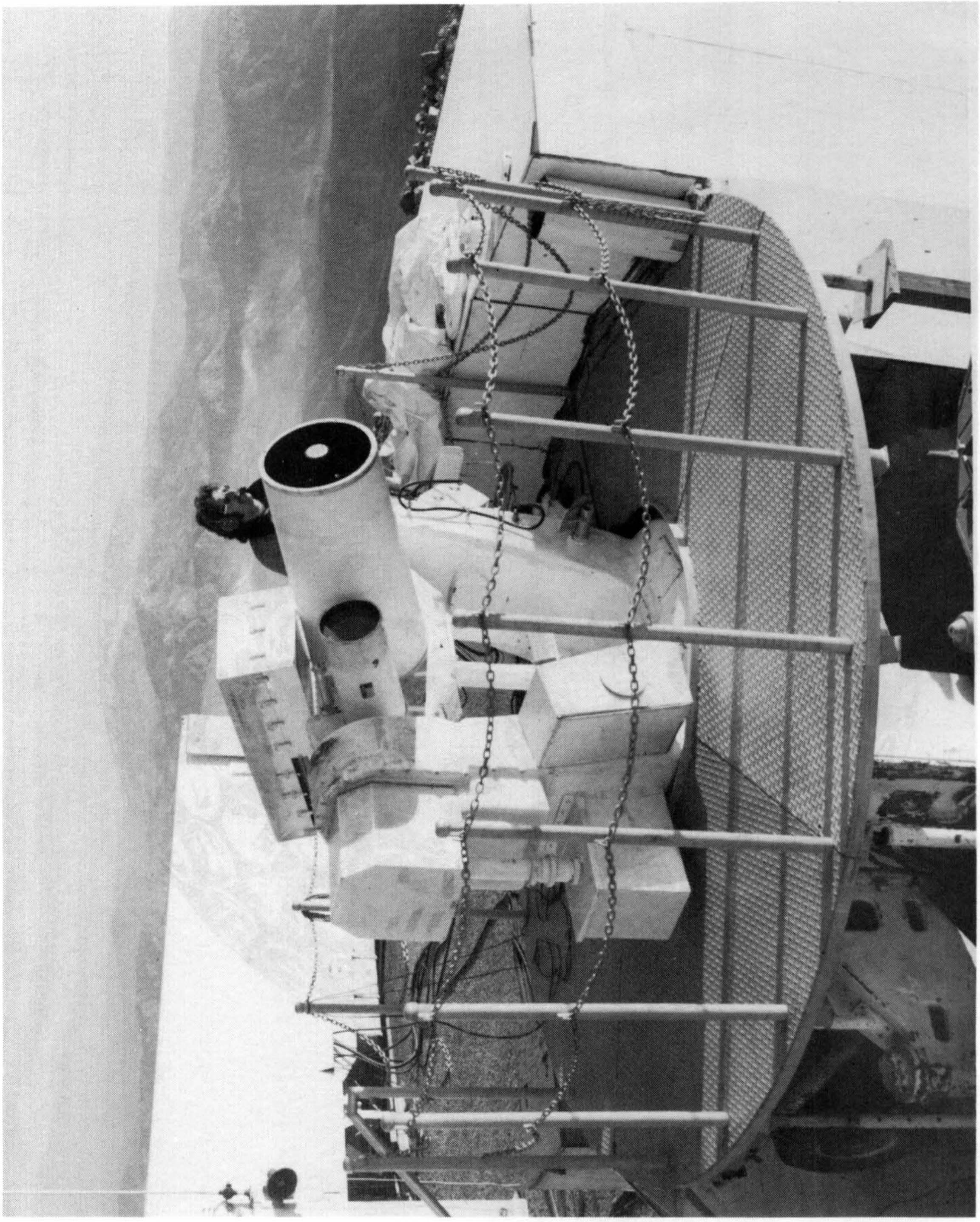

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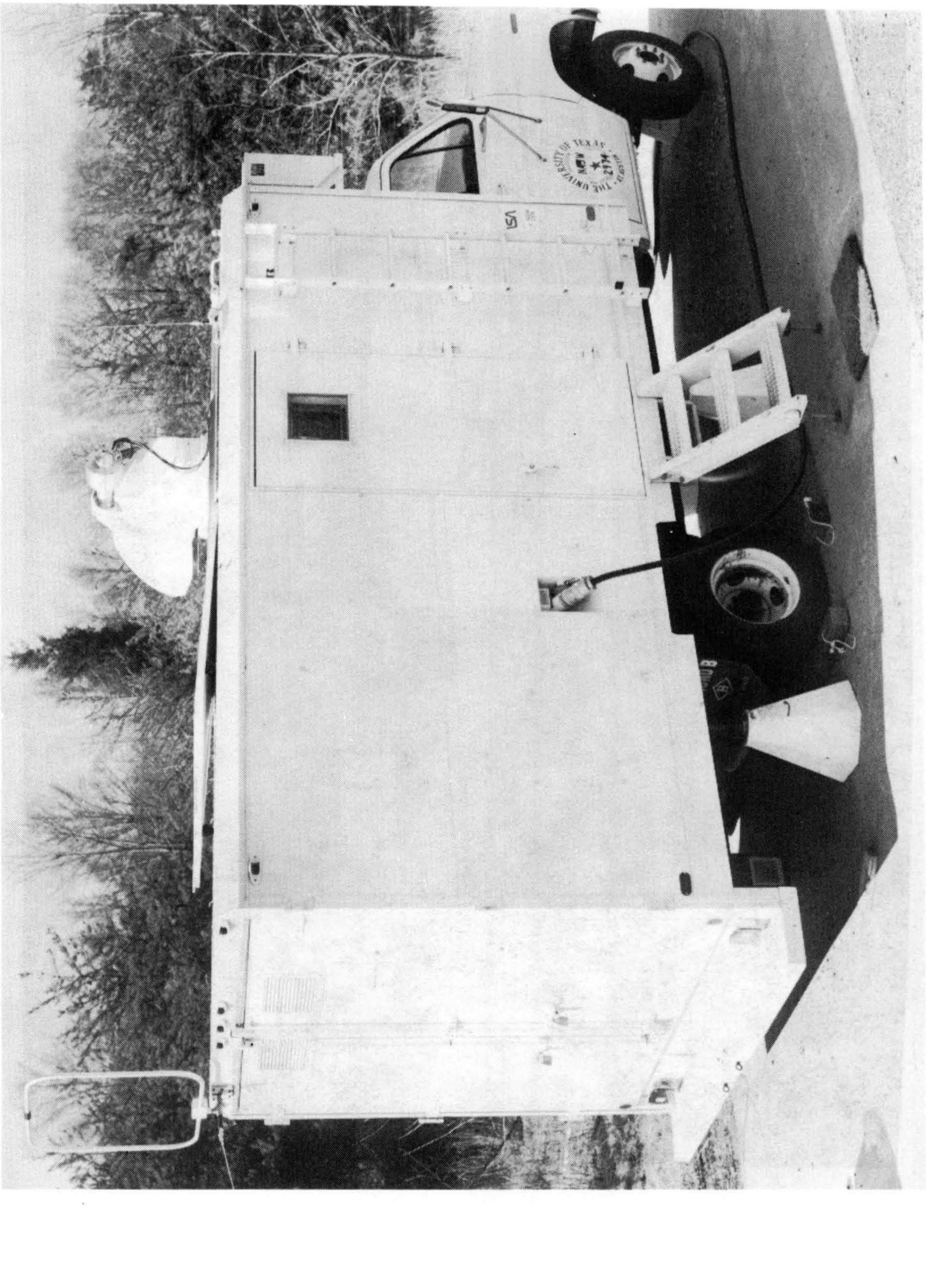

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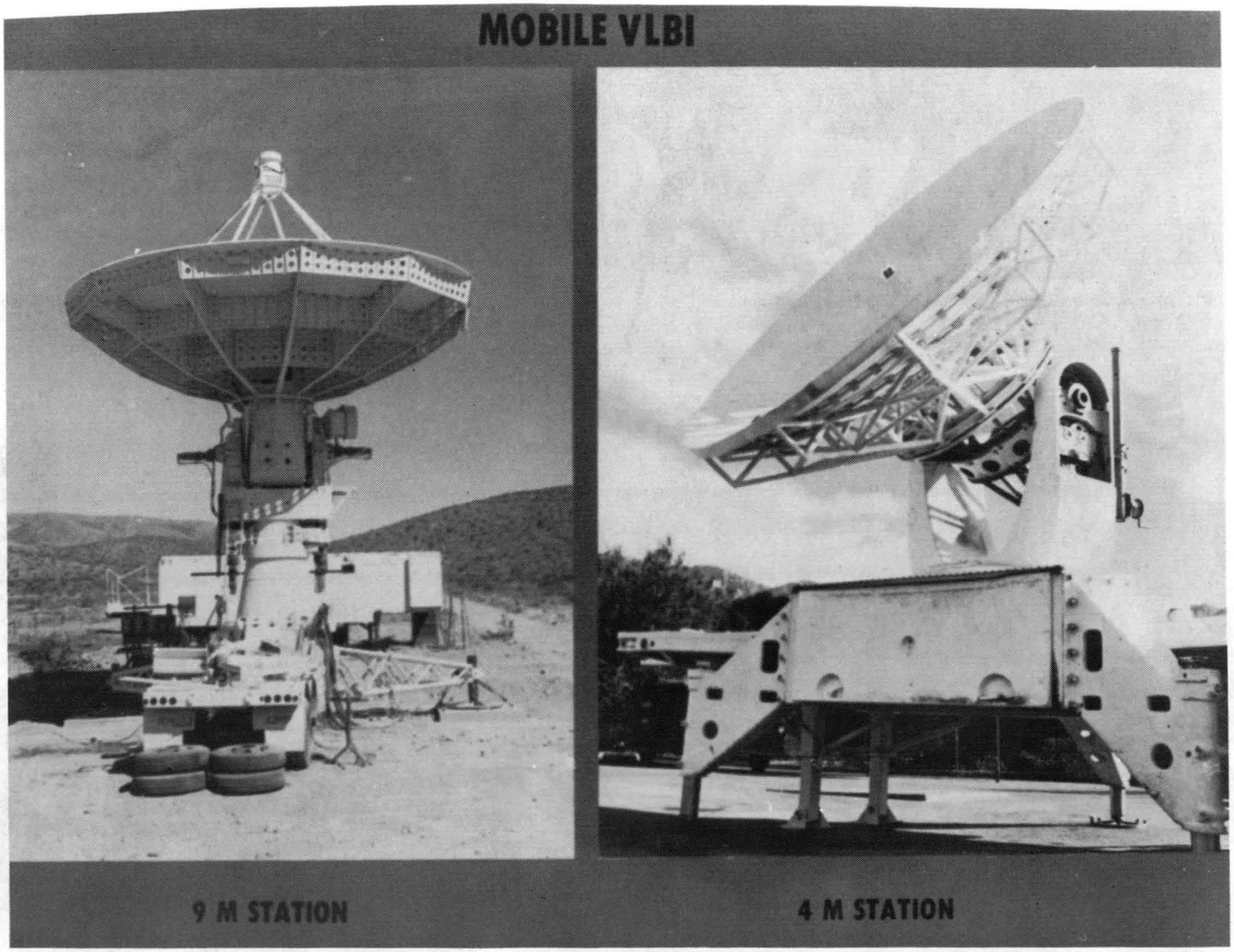
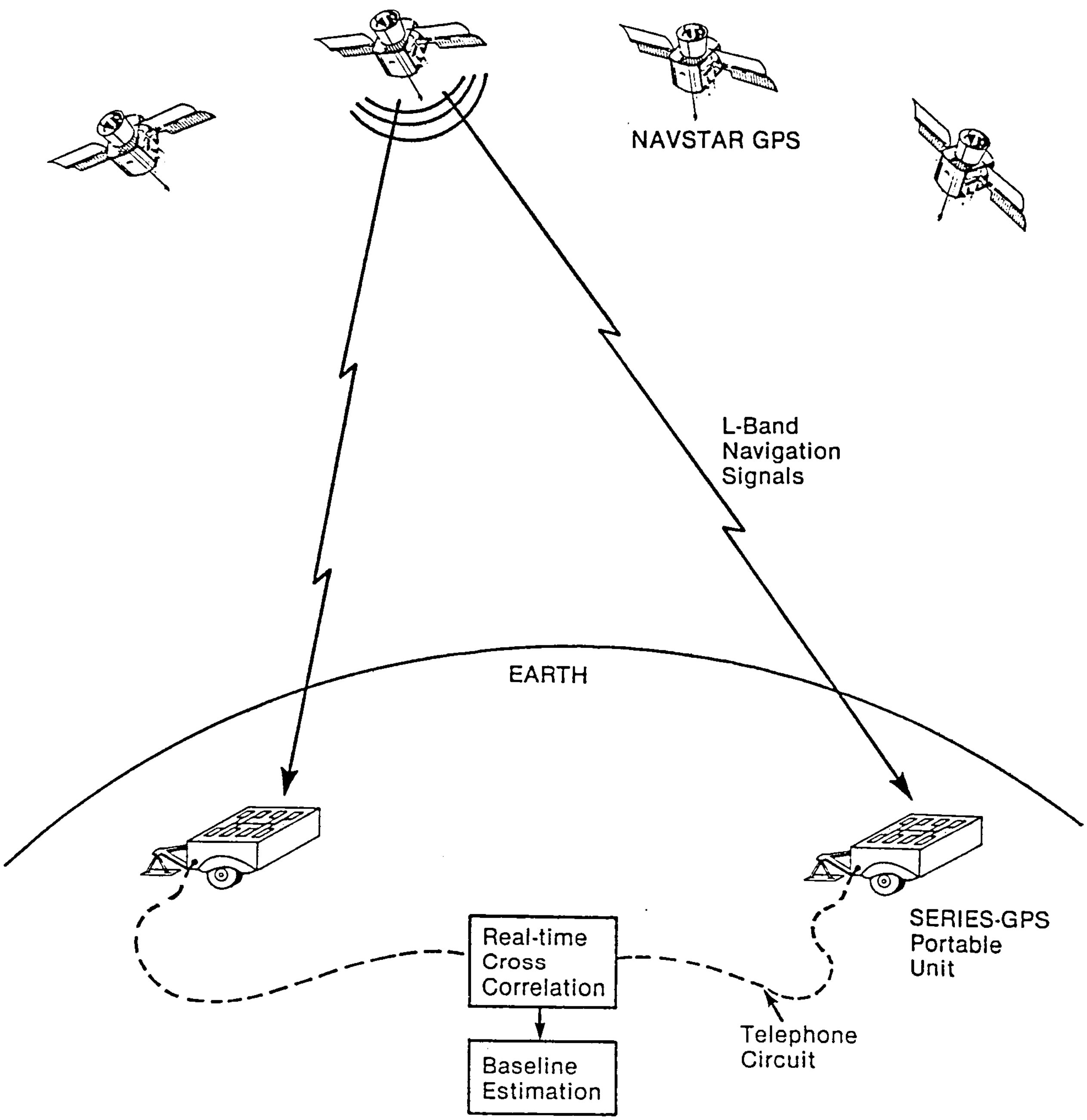


Figure 4

SATELLITE EMISSION RADIO INTERFEROMETRIC EARTH SURVEYING (SERIES) CONCEPT



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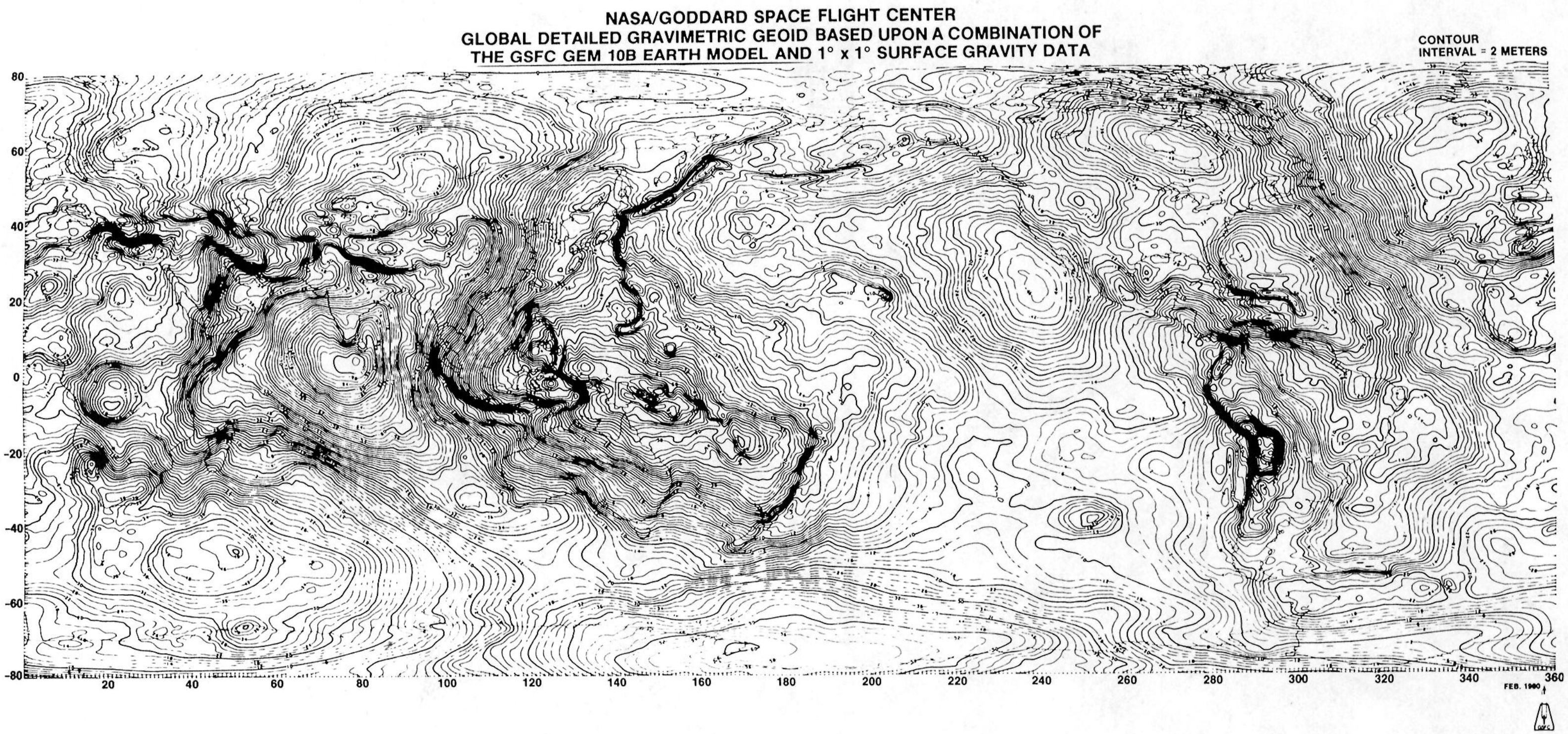
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INTERVAL = 2 METERS
FEB. 1980

Figure 6

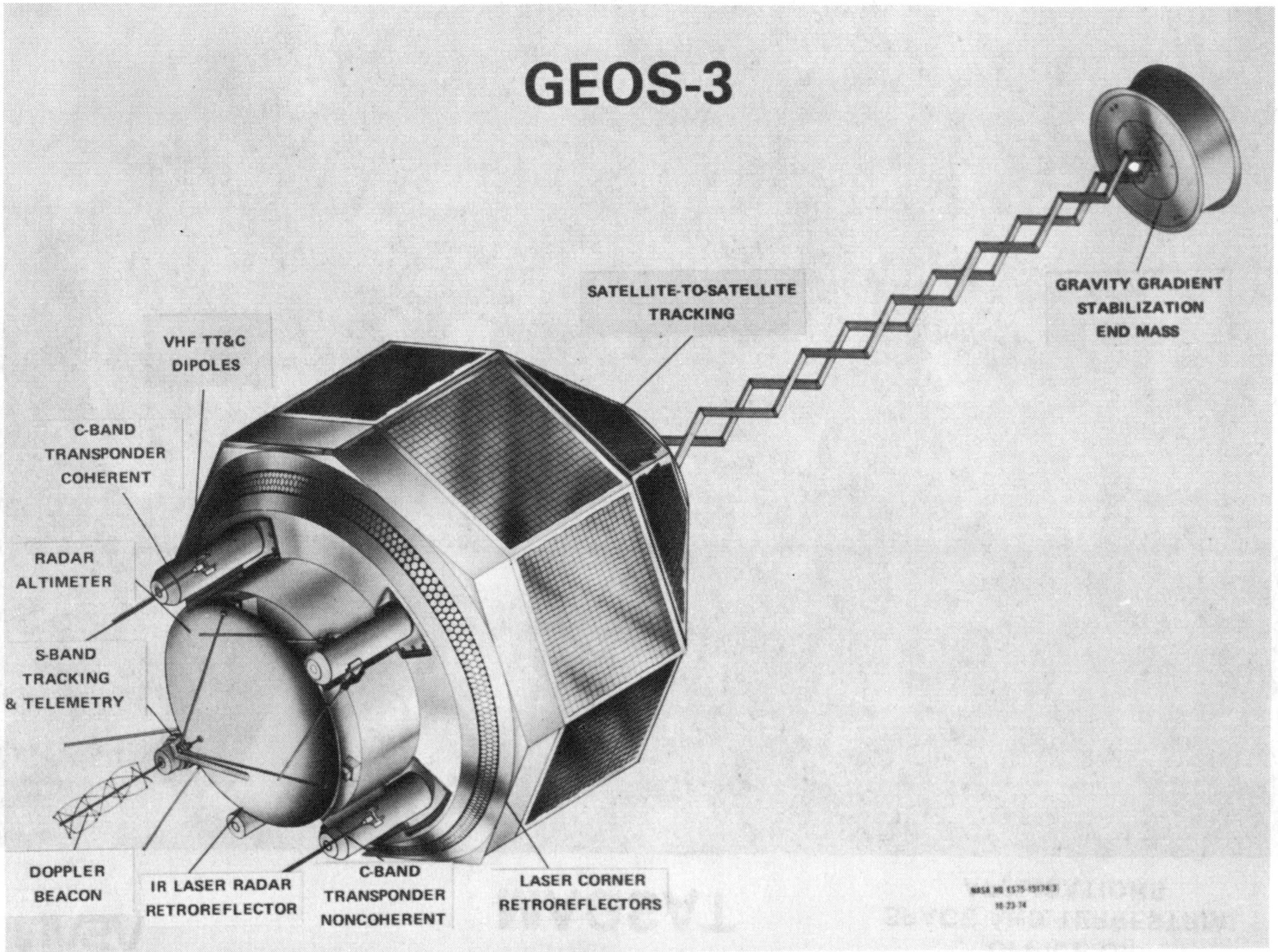
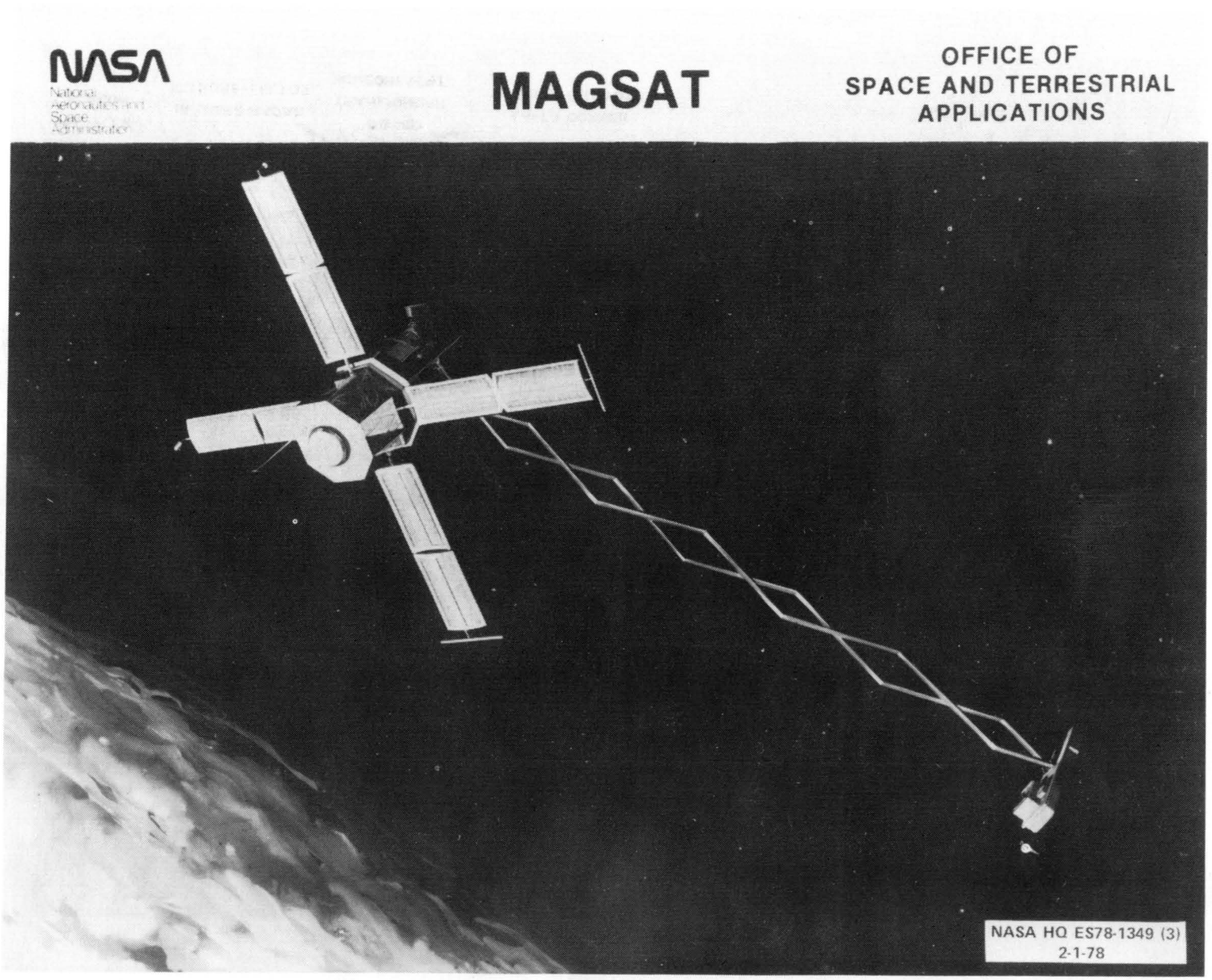

GEOS-3
SATELLITE-TO-SATELLITE TRACKING
GRAVITY GRADIENT STABILIZATION END MASS
VHF TT&C DIPOLES
C-BAND TRANSPONDER COHERENT
RADAR ALTIMETER
S-BAND TRACKING & TELEMETRY
DOPPLER BEACON
IR LASER RADAR RETROREFLECTOR
C-BAND TRANSPONDER NONCOHERENT
LASER CORNER RETROREFLECTORS

Figure 7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OFFICE OF
SPACE AND TERRESTRIAL
APPLICATIONS
NASA HQ ES78-1349 (3)
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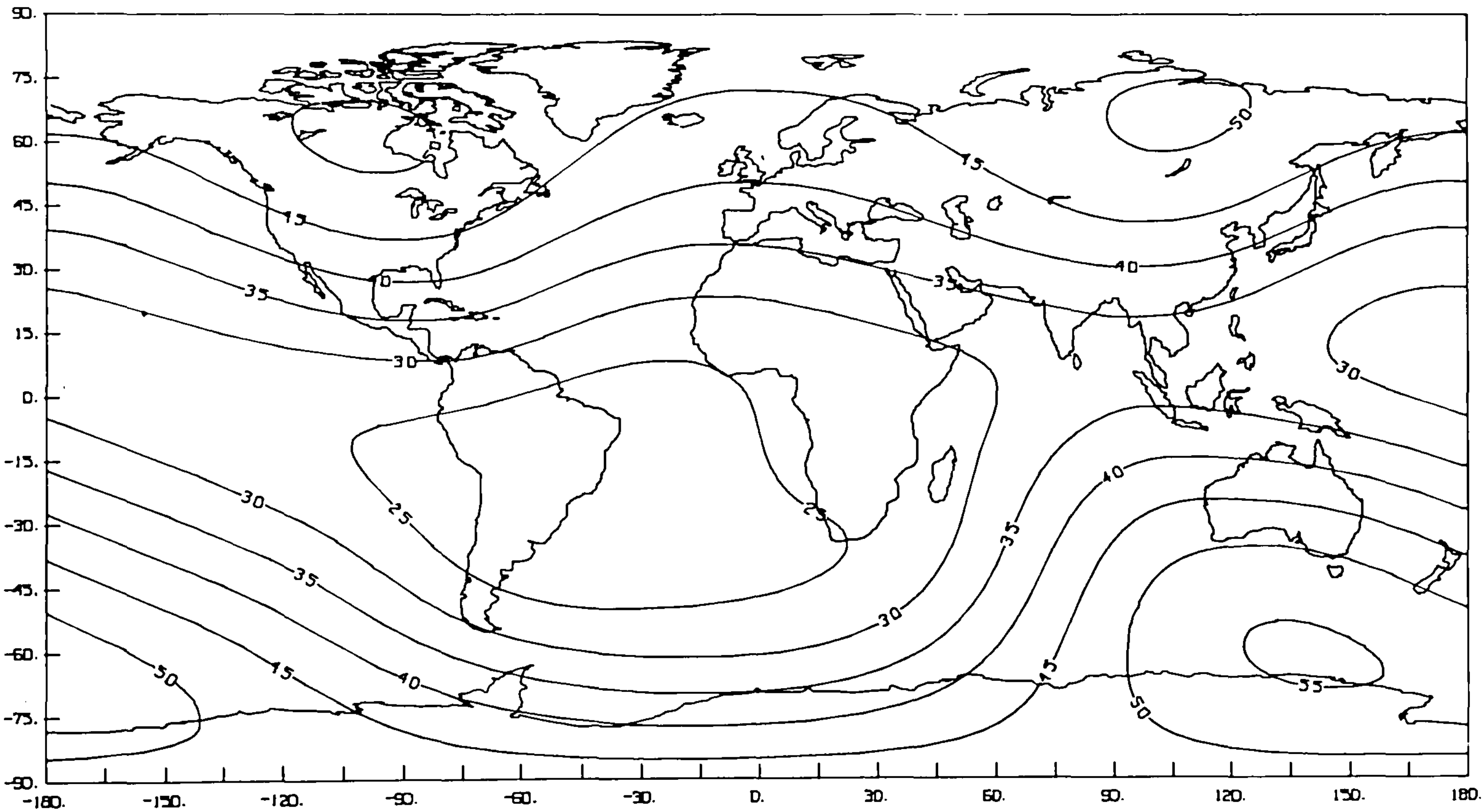
Figure 8

Figure 9

FIRST PRELIMINARY MAGSAT MAGNETIC FIELD MODEL



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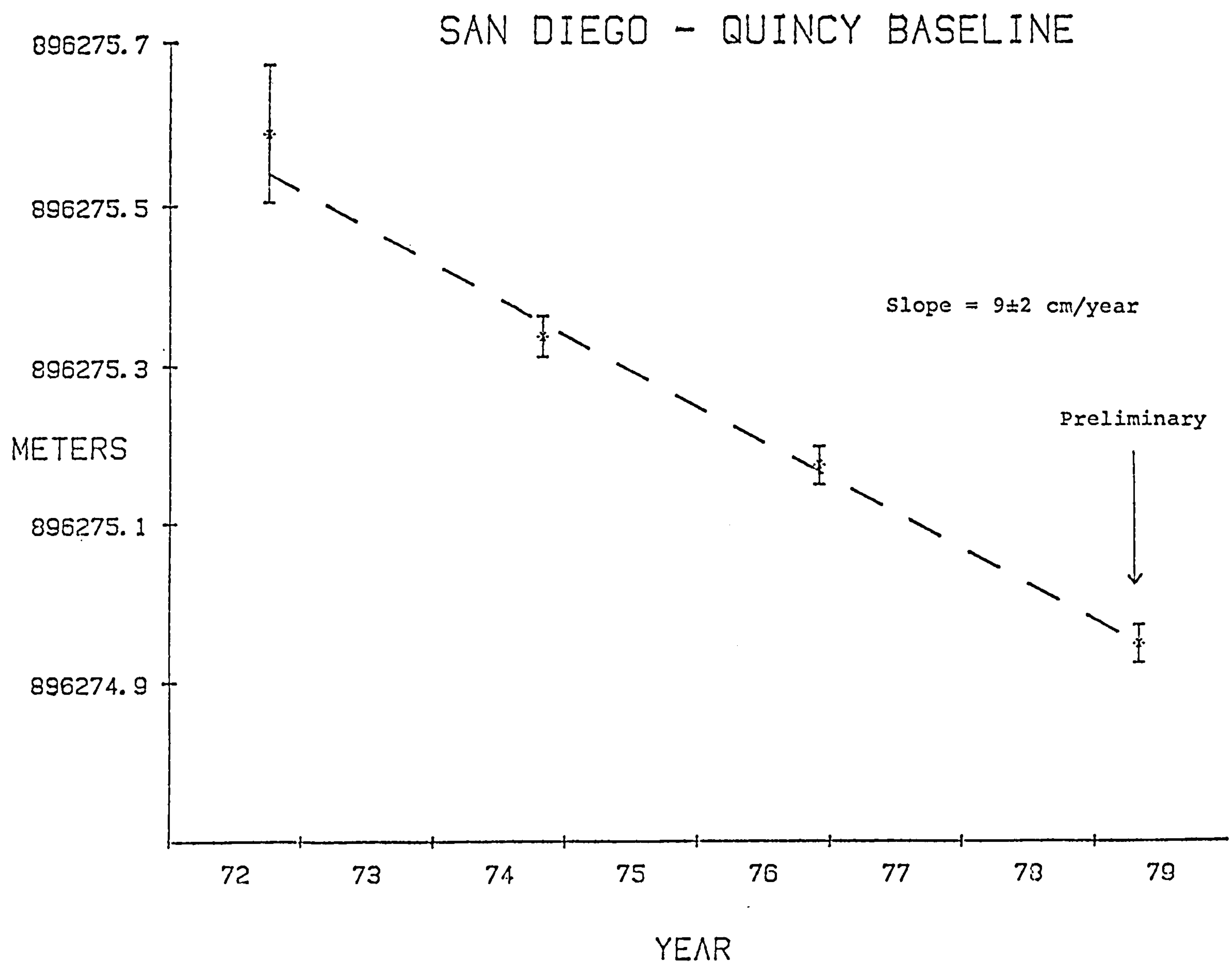
SAN DIEGO - QUINCY BASELINE
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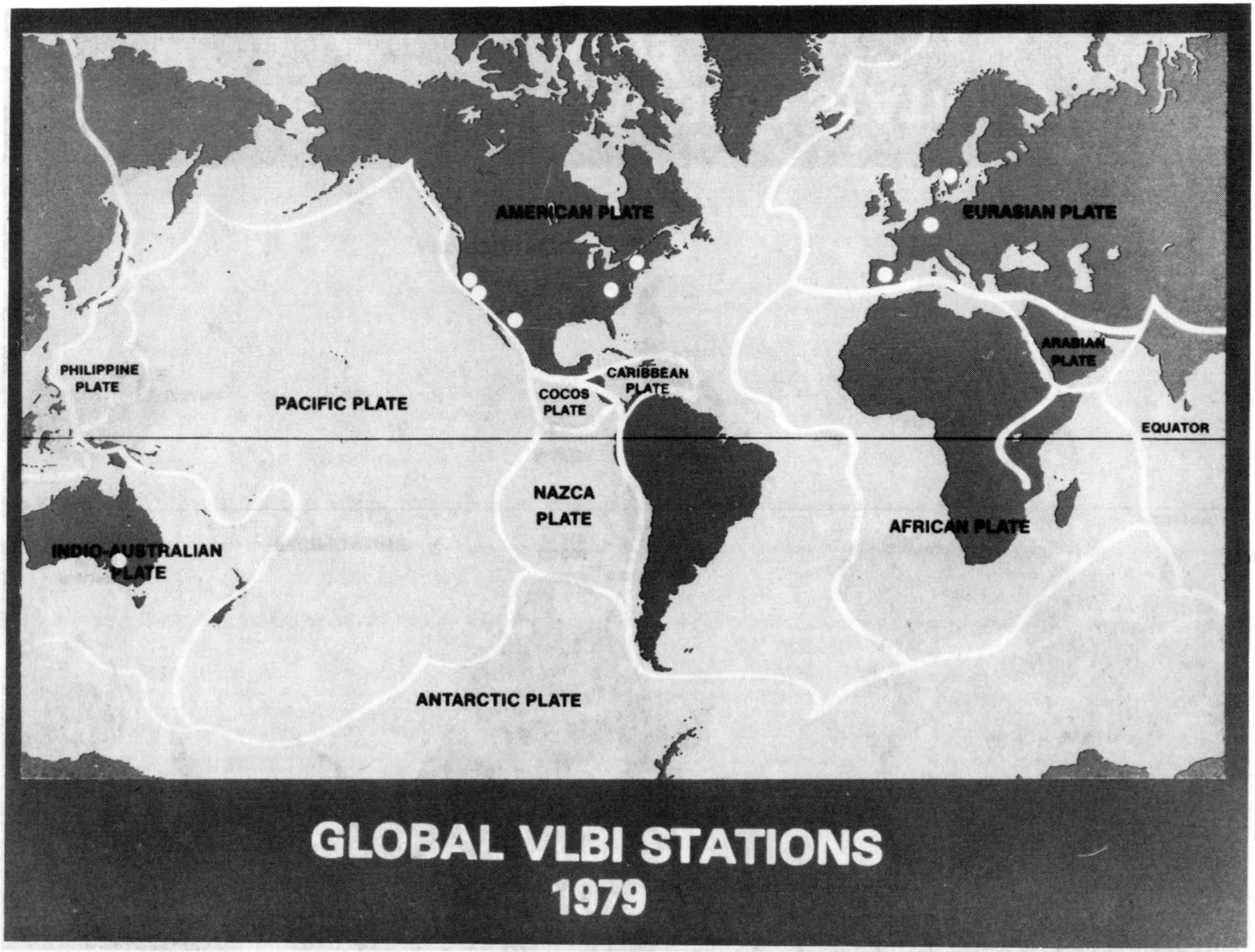
Figure 10

Figure 11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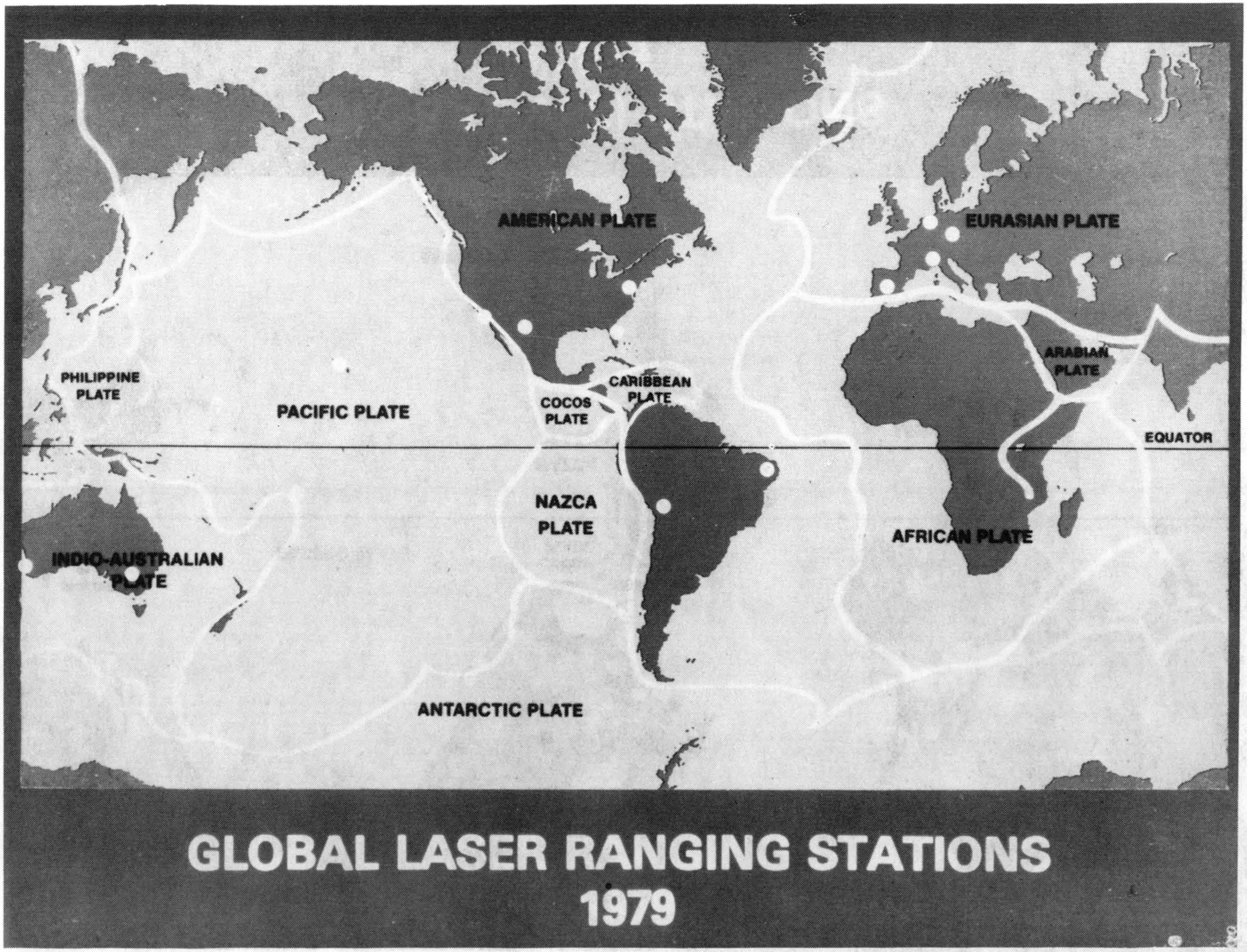
INDIO-AUSTRALIAN PLATE
ANTARCTIC PLATE
GLOBAL VLBI STATIONS
1979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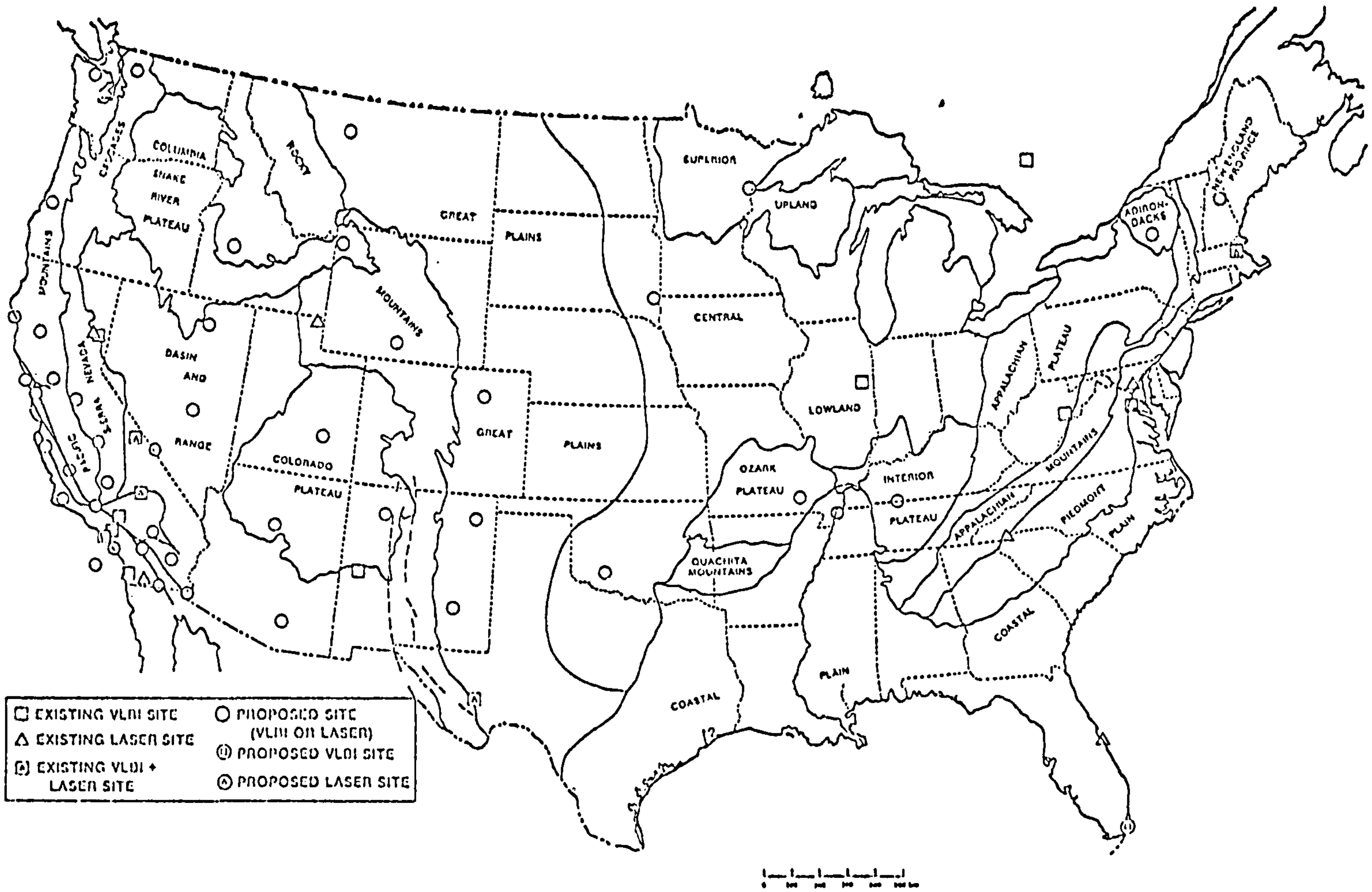
GLOBAL LASER RANGING STATIONS
1979

Figure 12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PROPOSED VLBI SITE
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SNAKE
RIVER
PLATEAU
ROCKY
MOUNTAINS
GREAT
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SUPERIOR
UPLAND
CENTRAL
LOWLAND
BASIN
AND
RANGE
SIERRA
NEVADA
PACIFIC
MOUNTAINS
COLORADO
PLATEAU
OZARK
PLATEAU
QUACHITA
MOUNTAINS
INTERIOR
PLATEAU
APPALACHIAN
PLATEAU
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NEW ENGLAND
PROVINCE

Figure 13

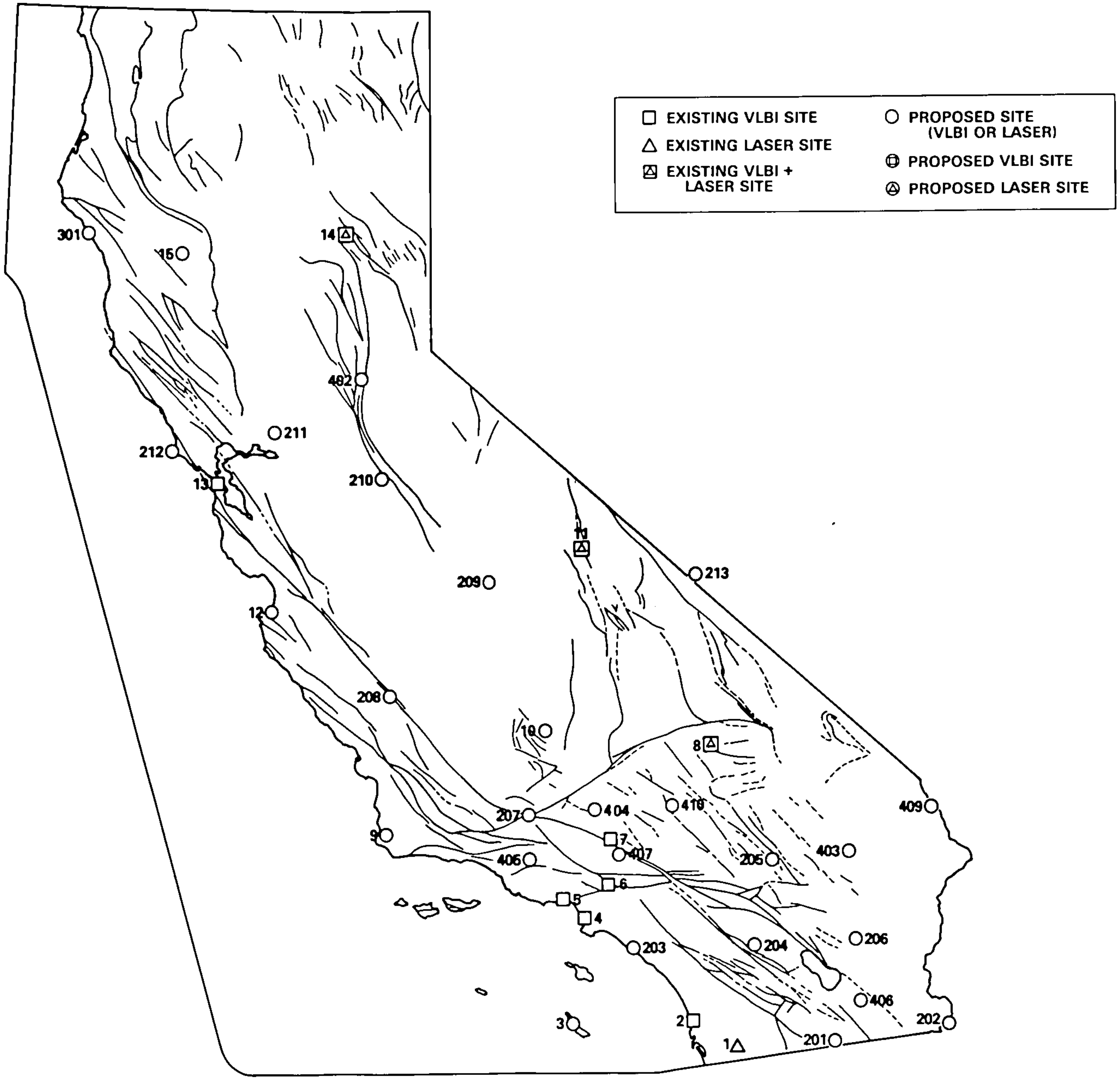
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Figure 14

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16. Abstract

This is the first annual report of activities of the NASA Geodynamics Program. The history and development of the program are described, in addition to accomplishments in 1979 and plans for future year activities. Extramural grant titles are listed for general research, Lageos investigations, and Magsat investigations.

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