NASA Technical Memorandum 4256, Vol. 1

Solid Earth Science in the 1990s

Volume 1—Program Plan

FEBRUARY 1991

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NASA Office of Space Science and Applications
Washington, D.C.

NASA
National Aeronautics and
Space Administration
Office of Management
Scientific and Technical
Information Division
1991

FOREWORD

With the 1980's came the first widespread recognition that an understanding of the Earth requires a global perspective of the many interacting dynamic systems operating over a range of spatial and temporal scales. This has led to the recognition of the urgent need to understand the Earth as a planet and to assess the impact of both natural change and human interaction. From this has arisen the novel concept of the "Mission to Planet Earth".

In the 1990's, we can, for the first time, make major advances in achieving this global perspective of Earth system science, for three reasons:

1. Space offers the opportunity to make long-term synoptic observations of many diverse aspects of our planet, with appropriate control from surface, submarine, and interior measurements;

2. Procedures to manipulate and assimilate large data volumes are in hand or under development; and

3. A theoretical framework to integrate the various Earth dynamic systems can be anticipated.

The solid Earth is a crucial element in the global interplay of dynamic systems, and the NASA Solid Earth Science Program for the coming decade builds upon the new paradigm of Earth system science.

To help plan its Solid Earth Science Program for the 1990's, NASA sponsored a workshop at Coolfont, West Virginia, from July 22 to July 28, 1989. The workshop was attended by over 130 people from universities, research institutions, and government agencies in the United States and 13 countries.

In addition to addressing such major themes as the relationship of the solid Earth to the atmosphere, oceans, and climate, and the concept of the Earth as a system, the workshop identified the achievements of NASA Solid Earth Science in the previous decade and the outstanding questions now facing our science. We have made major advances in our ability to observe, analyze, and monitor the surface of the Earth, to measure the movement and deformation of the surface at scales and accuracies heretofore thought to be impossible, to discern incipient activities leading to catastrophic events, to monitor the dynamics of the Earth's rotation, and to model the Earth's gravity and magnetic fields and monitor their variations.

As a result of these accomplishments, we stand today on the verge of a new epoch, one in which these capabilities can be directed toward the understanding of the Earth both as a system and as a planet. While the technology and the motivation for this endeavor are manifest, much remains to be done. The study of the solid Earth is necessarily a multi-agency, multi-national effort. In the future, the scope of these joint activities is expected to expand and eventually to encompass most of the world's nations.

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SECTION I. INTRODUCTION

This report is contained in three volumes. **Volume I - Program Plan** - outlines a plan for solid Earth science research for the next decade. **Volume II - Panel Reports** - was compiled from papers prepared by the Science and Program-related panels of a workshop held at Coolfont, WV, in July 1989. **Volume III - Measurement Techniques and Technology** - was prepared to support the Science Panels.

The NASA Solid Earth Science (SES) Branch was formed in mid-1989 by placing two previously autonomous programs, Geology and Geodynamics, under one branch. The new Program includes the Crustal Dynamics Research, Earth Structure and Dynamics, and Geopotential Fields elements of the Geodynamics Program and the Land Surface, Volcanology, and Geopotential Fields elements of the Geology Program.

In anticipation of this reorganization, and of the completion in 1991 of the Crustal Dynamics Project (CDP) of the Geodynamics Branch, it was decided to develop a plan of research for the next decade which would integrate the Geology and Geodynamics Programs into a SES Program commensurate with the goals of Global Climate Change and "Mission to Planet Earth". As a first step in this planning, NASA supported the participation of U.S scientists in an international workshop held in Erice, Sicily, Italy, in July 1988[1].

To help develop the SES plan a workshop was organized and held at Coolfont, WV, during July 22 to July 28, 1989. The workshop involved over 130 scientists from the domestic and international academic community, the National Science Foundation (NSF), the U.S. Geological Survey (USGS), the National Oceanic and Atmospheric Administration (NOAA)/National Geodetic Survey (NGS), the U.S. Naval Observatory (USNO), and international agencies.

Preparation for the Coolfont Workshop began in late 1988. Seven Science Panels addressing different aspects of solid Earth science were formed largely from the existing research foci in NASA Geology and Geodynamics. The Science Panels addressed the following fields:

- *Plate Motion and Deformation*
- *Lithospheric Structure and Evolution*
- *Volcanology*
- *Land Surface: Processes of Change*
- *Earth Structure and Dynamics*
- *Earth Rotation and Reference Frames*
- *Geopotential Fields*

Panel members were tasked with assessing the salient scientific questions in their field, identifying those which NASA within its charter could help resolve, and recommending an approach by which NASA could address those questions. In addition, a Measurement

Techniques and Technology Panel was formed to assess the technological developments necessary to meet the Science Panel's requirements. In parallel with these panels, a Program Plan Panel met to integrate the science panels' requirements and supporting measurement technology into a program plan for research and technology development in the 1990's.

Because the NASA SES Program is intrinsically international and interagency in nature, two program-related panels were formed: the International Programs Panel, with representatives from 13 countries, and the Interagency Program Panel, representing four U.S. federal agencies. These Panels were charged with identifying those common programs and endeavors where the NASA SES Program could be an important contributor.

Section II outlines the general scope of the NASA SES Program in terms of some of the important scientific problems of the next decade.

In **Section III** the scientific goals and objectives of the NASA Geology and Geodynamics Programs have been reformulated into goals and objectives for the SES Program.

Section IV is a summary of the accomplishments and status of the original programs.

In the course of the Coolfont Workshop five new initiatives emerged as major new emphases for the 1990's. These new initiatives are introduced and discussed in **Section V.**

The NASA Program's relationships with other Federal agencies, with international groups, and with other groups within NASA are discussed in **Section VI.** Since portions of the SES Program requirements can best be met by joint activities involving other groups, the planned or expected benefits to the NASA Program resulting from joint activities and cooperative programs have been considered in the development of the SES Program implementation outlined in **Section VII.**

SECTION II. PROGRAM RATIONALE

Throughout the globe there is a heightened concern for the fate of our planet. The depletion of the ozone layer, the impact of deforestation and fossil fuel combustion on global climate, and the mitigation of such devastating natural disasters as severe storms, major earthquakes, and catastrophic volcanic eruptions are steady topics for our news media. Because of increasing evidence that human activities on the planet are leading to secular changes in our environment, the future of the Earth is a major political issue. Because addressing that issue calls for improved levels of understanding of how our planet works, significant new research in the Earth sciences is required.

Earth scientists have recently come to realize that our planet is governed by a complex interplay of processes whose origins range from the deep interior to the actions of the sun. As expressed by the NASA Earth Systems Sciences Committee (ESSC)[2]:

> *"Our new view of the Earth system...corresponds to the intuitive notion that all the components of the Earth must somehow function together. Interactions among the oceans and ice, land masses, the atmosphere, and the biological systems are both significant and complex. The transport of energy and material within and among these subsystems occurs on a global scale across a wide range of time scales. Crucial insights into global change will be obtained not only from studies of present processes but also from an examination of paleoclimate and the geological record, which reveal the changing balances among processes that have shaped the Earth throughout its history."*

Clearly any attempt to draw boundaries between parts of the Earth or among traditional scientific disciplines would be artificial. Just as clearly, the study of the solid Earth makes an essential contribution to our understanding of the processes that contribute to global change.

A few examples serve to illustrate some of the many ways that solid Earth processes affect or record changes in our environment on a variety of time scales. A highly visible current issue is global warming and the consequential changes in global ice volume and mean sea level. It is less well appreciated that the issue of sea level and the global volume of the oceans cannot be understood without accounting for a multitude of competing effects that cut across virtually all of the traditional disciplines of Earth science. As the relative volumes of ice and water change, the mantle deforms gradually in response to the changing location of the loads. The effects of unloading due to glacial melting and the consequent loading in the oceans as they receive the melt water have continued since the time of the last major ice age. These are superimposed upon changes which may be due to global warming induced by human activity. Thus, the problem of monitoring sea level changes and deducing their causes is clearly a multi-disciplinary task. To begin with, a stable and well-defined reference frame for describing sea level is an essential element of such studies which is best provided by space geodesy, and its attendant investigations into satellite orbit dynamics, and radio astrometry. Geodetic, geomorphic, archeological, geochemical, and geochronologic studies are required to document the ice load, melting, and uplift history since the last ice age. In addition, careful observations of Earth rotation variations, (especially polar motion) by space geodetic methods, provide powerful global constraints on mass redistribution due to water movement and resulting mantle deformation. Changes in the Earth's gravity field as detected from satellite orbit variations also provide important constraints on sea level and associated mantle deformation. Changes in the amount of water stored on land in various forms directly affect the sea level variation, and there are additional steric variations involving thermal expansion of the water column. Changes in ice distribution and water volumes may affect the climate and result in long-term changes in wind patterns, altering ocean currents which make a separate and large contribution to sea level changes. Tectonic uplift and subsidence near shorelines affect the interpretation of sea level data, and over longer time scales variations in global spreading rates affect the shape of the sea floor and the continental freeboard. Sea level data are strongly influenced as well by geological processes ranging from erosion and sedimentation to coastal evolution. An integrated approach to the topic of global ocean volume is clearly essential, and the development of comprehensive models of these interlinked processes will guide the proper selection of the types and locations of future measurements most needed to understand changes in the near term.

The plate tectonics revolution, several decades ago, permitted solid Earth scientists to place such diverse phenomena as earthquakes, volcanism, and mountain building within a globally consistent kinematic framework. Within the last few years, a major achievement of space geodesy has been the demonstration that the rates of relative motion of the Earth's plates on time scales of years are nearly the same as those on time scales of millions of years. The scientific challenge of the next decade is to understand the dynamics of plate motions and the underlying convective motions of the mantle and core. Achieving that goal for the lithosphere and mantle will require the measurement of horizontal and vertical crustal motions, concentrating particularly on the complex deformational zones near plate boundaries, and the global determination of gravity and topography over the range of length scales influenced by mantle and crustal dynamics. From a societal standpoint, an understanding of the dynamics of the Earth's interior is likely to be a prerequisite to predicting future crustal motions, including those that occur by catastrophic earthquakes.

To understand the dynamics of the core and its relationship to mantle flow, the first step is to obtain improved time-dependent global models of the Earth's main magnetic field. Mantle dynamics is intimately linked to the processes of generation and transport of magma and thus to the location and frequency of volcanic eruptions. Beyond their obvious roles as modifiers of the landscape and hazards to population, volcanoes are increasingly recognized as important influences on the chemistry of the oceans and atmosphere and, through the eruption of gases and particulates into the stratosphere, modulators of global climate. On time scales greater than millions of years, tests of our understanding of mantle dynamics will come from the geological record of the evolution of the continents, including time-variable global patterns of assembly and rifting of crustal blocks.

A final example of the fundamental contributions that the solid Earth sciences will make to the study of global change is in documenting paleoclimate. It is now widely recognized that the identification of past principal land surface changes and tests of global climate models come from the geological record. Data utilized as tests of models for Quaternary climate have typically included paleotemperature measurements from ice cores, deep sea sediment cores, lake levels, glacial boundaries, and pollen types on land. Additional important tests of climate models not currently utilized can potentially come from land remote sensing information, notably on landforms and on soil characteristics. Such landforms as dunes, shorelines, and fluvial features can be discerned from high-resolution images and topography and can be used to document changes in regional climate patterns. A systematic understanding of soil characteristics in different climatic and ecological settings, obtained from multispectral images and careful ground-based studies, can lead to improved quantitative measurements of past and current movements of desert margins and forested areas.

NASA is in a unique position to play a major role in the solid Earth sciences, and particularly in those aspects of solid Earth processes that impact global change. The Earth Observing System (EOS) in the late 1990's will provide crucial global remote sensing data which when integrated with conventional data will enhance the study of neotectonics, landforms, soil characterization, and the geological evolution of the continents: critical ground-based validation experiments can be conducted with airborne and available satellite data in the nearer term. Improvements in ground-based space geodetic instruments and globally coordinated measurement strategies will usher in a new era of increasingly accurate and systematic measurements of crustal deformation and variations in Earth rotation. In the EOS era, the Geoscience Laser Ranging System (GLRS) will significantly augment our space geodetic capability. The Earth Probes, a series of small and intermediate-size missions, will open a number of possibilities to make major advances in global Earth science through spacecraft dedicated to the measurement of the time-varying global magnetic field, the Earth's gravity field, the Earth's crustal magnetic field, and the Earth's topographic shape, and through the global monitoring of the Earth's volcanoes and their interactions with atmospheric chemistry and climate. Recognizing the opportunity afforded by this combination of technological readiness and scientific need, the Space Science Board has recommended[3]

> *"...that NASA develop and support a more comprehensive program in the solid Earth sciences within NASA self."*

Through the missions and supporting major thematic programs described herein, NASA will contribute not only to a fundamental improvement in our understanding of the Earth but also to the collection of crucial information that will be needed as the basis for critical political decisions affecting the future of our planet.

The nation's space program not only gives us spectacular pictures of the whole Earth, but also provides us the means for studying its myriad of complex intertwined parts. It is imperative to organize our resources now to attack these global problems. *We cannot afford to wait.* Fortunately, we have the technical means to further our understanding and treatment of these problems, and the infrastructure of scientists and engineers, as well as the means to train the next generation of experts. Strong cooperation among the various agencies of Federal government, academic institutions, and industry, along with counterparts in other nations will insure the highest probability of a successful outcome. Such an organized, concerted attack on common global problems should be an important part of promoting peace among nations through dedicated effort to preserve our common heritage, *the Earth*.

SECTION III. SCIENTIFIC REQUIREMENTS

A. *SES PROGRAM GOALS*

As part of the effort to develop the scientific basis for SES research over the next ten years, six scientific goals were identified. In order of decreasing Earth radius, these are to improve our understanding of:

- *The interactions of the Earth's surface and interior with the oceans and atmosphere on time scales of hours to millions of years;*
- *The evolving landscape as a record of tectonics, volcanism, and climate change during the last two million years;*
- *The motions and deformations of the lithosphere within the plates and across plate boundaries;*
- *The evolution of continents and the structure of the lithosphere;*
- *The dynamics of the mantle including the driving mechanisms of plate motion; and*
- *The dynamics of the core and the origin of the magnetic field.*

These goals have obvious connections with the broader themes of Earth system science in terms of the interaction of the solid and fluid portions of the Earth, of the role of volcanic and tectonic activity in climate change and in natural hazards, and the fundamental understanding of the basic Earth processes responsible for the continuing short term dynamic and long-term secular evolution of the planet. Implicit in the attainment of these objectives are studies of the Earth's gravity field, rotation, and reference frames.

Within the framework of these broad goals, the scientific objectives and requirements of the SES Program have been formulated based on the reports of the individual Coolfont Science Panels (Volume II). The individual panel inputs are summarized below and form the basis around which this plan is written.

B. *PLATE MOTION AND DEFORMATION*

The primary goal of plate motion and deformation studies within the next decade must be the documentation of crustal kinematics and deformation over length scales from global to local, and across a variety of different oceanic and continental plate boundaries. This must also include synthesis of crustal kinematics with a variety of other geological and geophysical data to produce a theoretical framework describing plate motion and deformation as the product of flow in the upper mantle and of the rheological, thermal and density structure of the lithosphere. The fundamental data used to constrain the driving forces for plate motion and deformation are crustal motions observed at the Earth's surface. Over the next decade, our success in understanding the dynamic processes that control plate motions and deformation will depend largely on our ability to map vertical and horizontal motions at the Earth's surface.

The scientific objectives are:

- *To refine our knowledge of present day plate motions, especially across poorly observed plate boundaries;*
- *To measure regional and local deformation within plates and across plate boundaries; and*
- *Through the above to contribute to the solution of important societal problems, such as mitigation of hazards.*

The crustal deformation patterns associated with the earthquake cycle can depend strongly on the rheological properties of sub-crustal material. The detailed description of the deformation pattern (specifically, the surface displacements, displacement rates, strains, and strain rates) depend on the structure and geometry of the material near the seismogenic zone. In recent years various viscoelastic models of deformation near major strike-slip faults have been proposed. These differ in their predictions of the temporal and spatial patterns of crustal deformation throughout the seismic cycle.

These objectives involve the acquisition and study of geodetic, geophysical, and geological data. The geodetic and geophysical data provide the snapshot of the present-day deformation and structure, while the geological data provide the context of past evolution.

Requirements include:

1. Development of a global strain and fiducial network of mixed space geodetic systems with average station spacing of 1000 km on land and a capability for measurements on the ocean floor;

2. Deployment of systems for detailed studies of regional scale tectonic motion and volcanic uplift;

3. Acquisition of high resolution (Thematic Mapper-TM or Satellite pour l'Observation de la Terre-SPOT) satellite images, high resolution topographic data, and moderate resolution gravity and crustal magnetic field data on a global basis; and

4. Geologic field studies and associated laboratory work.

Major components of this work are the continuation of the present plate tectonic, regional deformation, and associated Earth rotational measurements, but with improvements in the measurement capability to the 1-3 mm level of accuracy; expansion of the regional deformation measurements to many more areas; and the development of a geodetic capability.

C. LITHOSPHERE STRUCTURE AND EVOLUTION

The principal goal is to understand how the differences in the composition and thermal structure of continental- and oceanic-types of lithosphere have led to their very distinct geologic histories. The dynamic evolution of the Earth's lithosphere is determined by its rheology and density structure, both of which are controlled by temperature, pressure, and composition. In the effort to calibrate better the rheology and density of the Earth's crust and upper mantle, high priorities are to observe the pattern of horizontal and vertical crustal deformation occurring now and in the geologic past as revealed by geodetic measurements, geologic mapping, and potential field anomalies.

The scientific objectives are:

- *To determine how the lithosphere has evolved to its present state; and*
- *To test and directly calibrate models for the temperature, density structure, and rheology of continental and oceanic lithosphere.*

Improved knowledge of lithospheric evolution and rheology is critical for predicting the temporal and spatial patterns of crustal deformation throughout the seismic cycle, the vertical response of the coastlines and sea floor to increased water volume associated with global warming, and the magnitude of sea-water fluctuations likely to result from ongoing post-glacial rebound. Geodetic and potential field measurements are sensitive to the deformation patterns (specificially, the surface displacements, displacement rates, strains, and strain rates) resulting from these load redistributions, and thus can be inverted to yield the elastic and viscous properties of the crust and upper mantle.

Understanding the deformation of continental lithosphere clearly has an implicit element of natural hazards reduction (earth-quakes), and relates directly to the objectives of Plate Motion and Deformation.

Required to address both the current nature and past evolution of continental and oceanic lithosphere are:

1. High resolution (4 m vertical, 30 m horizontal) land topographic data for the entire globe;

2. Sea floor bathymetry (from satellite measurements of sea surface altimetry) with a track spacing of 10 km at the equator;

3. Medium resolution global gravity data (100 km or better surface resolution, at a few mgal accuracy);

4. Medium resolution global crustal magnetic anomaly data (100 km surface resolution, 1-2 nT accuracy);

5. Satellite data including: TM, SPOT, EOS, Large Format Camera (LFC)-like high resolution stereo-panchromatic imaging system;

6. An aircraft remote sensing capability that includes Airborne Visible and Infrared Imaging Spectrometer (AVIRIS), Thermal Infrared Multispectral Scanner (TIMS) and a multifrequency polarimetric Synthetic Aperture Radar (SAR), as well as gravity and magnetic gradiometers; and

7. A user-friendly data information system for integration of large data sets.

These requirements lead to the need for high resolution topographic and improved gravity and crustal magnetic field mapping missions, as well as for ancillary surface and laboratory data such as isotopic dating, rock magnetic properties, and chemical analyses.

D. VOLCANOLOGY

The major goals of volcanology are to understand the relationship between volcanoes and global habitability, long term climate and atmospheric evolution, as well as the relationship between crustal evolution and recycling and volcanic hazards.

The scientific objectives are:

- *To understand the eruption of lavas, gases and aerosols from volcanoes, the dispersal of these materials on the Earth's surface and through the atmosphere, and the effects of these eruptions on the climate and environment; and*

- *To understand the physical processes that lead to the initiation of volcanic activity, that influence the style of volcanic eruptions, and that dictate the morphology and evolution of volcanic landforms.*

The first objective is a major new effort directed at the volcano-climate connection, and includes the effects of particles and volcanic gases injected into the atmosphere. In order to study these phenomena and the details of the eruptive process and long-term evolution of volcanoes, the following are required:

1. Development of a dedicated satellite sensor to characterize and measure volcanogenic gases and aerosols;

2. Repetitive monitoring of a set of active volcanoes using:

    a. Satellite sensors, with special emphasis on the acquisition of high resolution multi-spectral images and SAR data;

    b. Airborne measurements and coordinated field deployments;

    c. Global Positioning System (GPS), GLRS, and/or other techniques for monitoring deformation;

    d. *In situ* monitoring systems for acquisition of seismic, thermal, and gaseous species data;

    e. High resolution topographic data;

    f. Low-cost techniques for relay of *in-situ* sensor data.

E. THE LAND SURFACE: PROCESSES OF CHANGE

The land surface has been modified throughout geologic history by climatic and tectonic processes. Today a third process, human activity, is significantly changing the Earth's surface. It is difficult to assess the current and future impact of human activities on the Earth system without knowing how the factors that cause changes interact with one another and the extent to which natural variation of the factors may extend. Essential steps are to study present processes and to develop models of rates and interactions over time. We must also understand the geologic record preserved in sea and lake sediments, ancient ice, soils and weathering rinds, eolian deposits and landforms. Since these processes impact large regions of the Earth, global-scale observations will be required.

The major goal is to understand the processes which lead to change in the surface of the Earth.

The scientific objectives are:

- o *To understand processes of soil development and degradation, erosion and redistribution, salinization and other chemical changes, and gas exchange and reservoir properties, and soil-related changes in vegetation and desertification, particularly as they reflect or affect the interaction of humans with the surface of the Earth;*

- o *To undertake integrated studies of long-term continental climate change, climate-tectonism interactions, and models for the prediction of change in the Earth's surface; and*

- o *To understand the nature of processes in transitional areas such as coastal zones, permafrost and glacial regions, the margins of arid regions, and the nature of tectonic processes and their changes through time.*

To meet this research challenge, land surface investigations in the SES Program should emphasize:

1. Studies of soil characterization, degradation, erosion, and redistribution, particularly as a result of human activity;

2. Studies focussing on transitional areas such as coastal zones or the margins of arid regions;

3. Integrated studies focussing on the spatial and temporal response of the land surface to climate change, and on interactions between the climate system and global tectonics.

Systematic, repetitive measurements of physical and chemical conditions on the Earth's surface at several spatial and temporal scales will be required for these investigations. Thus, coordinated field measurements and remote sensing observations from aircraft and Earth orbit must be key elements of the SES Program.

The major requirements are for the combined data sets expected to be available from EOS together with high resolution topography data and data from the TM and SPOT; the Advanced Very High Resolution Radiometer (AVHRR) data are also important. Multidisciplinary teams of investigators will be required to address the research challenges in this area.

F. EARTH STRUCTURE AND DYNAMICS

Earth Structure and Dynamics is concerned with the structure of the core, core-mantle interface, mantle rheology and dynamics, and the coupling between the lithosphere and asthenosphere.

The scientific objectives are:

- *To determine the nature of core dynamics and the origin of the magnetic field;*
- *To determine the nature of the driving mechanism for plate motion;*
- *To determine the relationship between post-glacial rebound and mantle rheology; and*
- *To determine the relationship of post-seismic rebound to lithospheric and asthenospheric rheology.*

These objectives require precise measurements of point positions and their time-dependent change (including both plate motions and rotational dynamics) with long term measurements of the magnetic and gravity fields.

The requirements include:

1. Continued monitoring of global plate motions and Earth rotational parameters, but with improvement in precision of measurement to the 1-3 mm level;

2. Campaigns to measure both regional deformation and post-glacial rebound, and other vertical motions to a precision of 1-3 mm per year;

3. Long term measurement of the secular variation of the magnetic field from high altitude satellites;

4. Repeated measurement at high accuracy of the long wavelength portion of the Earth's gravity field for temporal change, and improved measurement of the short wavelength portion of the gravity field on a global basis;

5. Improved digital maps of global topography referenced to a common datum;

6. Ground measurements of the magnetic field to remove external field effects, and of the local gravity field using cryogenic gravimeters; and

7. Laboratory measurements of rock properties under high temperature and pressure.

Additional requirements include access to super-minicomputers and the appropriate algorithms for study of seismic tomography, finite-element modeling, inversion of rotational dynamical data and other large scale modeling efforts.

G. EARTH ROTATION AND REFERENCE FRAMES

Rotational variations of the Earth are caused by external mechanisms (such as the interaction of the Earth with the sun, moon, and planets), as well as by internal effects normally considered to be part of the Earth, including the core, atmosphere, and oceans. Both types result in changes in the speed of rotation and the position of the rotation axis. The high-precision nutation observations that have become possible with the techniques of space geodesy have provided new information on the properties of the core and the core-mantle boundary: improved observations will provide a fuller understanding of the Earth's interior. Changes in the speed of rotation at periods less than a few years and longer than a few weeks are largely due to the exchange of angular momentum between the Earth and the atmosphere, but there is much to be learned about the causes at periods outside this range. The causes of change in the position of the rotation axis within the Earth, commonly called polar motion, are largely enigmatic. There remain significant discrepancies in explaining annual polar motion which must be forced by air and water at the Earth's surface. Polar motion at other than the annual period is certainly due in part to air and water redistribution as well, but unknown additional excitation sources arising perhaps in tectonic activity may also contribute.

The scientific objectives are:

- *To observe and understand the interactions of air and water (oceans, ground-water, ice) with the rotational dynamics of the Earth, and their contribution to the excitation of Earth rotation variations, over time scales of hours to centuries;*

- *To observe and understand the effects of the Earth's crust and mantle on the dynamics and excitation of Earth rotation variations over time scales of hours to centuries;*

- *To observe and understand the effects of the Earth's core on the rotational dynamics of the Earth and excitation of Earth rotation variations over time scales of a year and longer; and*

- *To establish, refine, and maintain terrestrial and celestial reference frames.*

These objectives reflect the unique strength of studying Earth rotation variations to provide an absolute reference frame for geodynamics; provide global measures of mass redistribution and deformation due to hydrologic and meteorologic variability, tectonic activity, mantle convection, glacial melting, sedimentation, and erosion; constrain the rheology of the lithosphere through observation of Earth rotation variations at the time of earthquake activity; study physical properties of and motions within the inaccessible core; and constrain magnitudes of viscous, magnetic, and pressure torques acting at the core-mantle boundary.

The requirements include:

1. Measurement of the rotation vector of the Earth, but with improved precision (at least 0.1 mas) and increased temporal resolution (nominally 4 times per day);

2. Improve analysis and modeling capabilities to a level commensurate with improved spatial and temporal resolution;

3. Geophysical, oceanographic and atmospheric data required for interpretation of the rotational data;

4. A reference frame that ties together the celestial and terrestrial coordinate systems at the 1-3 mm level; and

5. Plate motion measurements for at least three sites per major plate with auxiliary data such as surface gravity at key sites.

H. GEOPOTENTIAL FIELDS

Our present understanding of global gravity and magnetic fields at long wavelengths (>1000 km) is derived almost exclusively from Earth-orbiting satellites. Lateral inhomogeneities in the Earth's density structure cause perturbations to satellite orbits which are measured by ground tracking stations and used to map variations in the gravitational potential. Our current models of the viscosity structure of the mantle, how it convects, and how it is coupled to the core and lithospheric boundary layers are based on this space-derived gravity data, in combination with observations of lateral and vertical variability in seismic velocity structure and geomagnetic variations. In the past decade, orbiting radar altimeters have measured the height of the sea surface, which approximates the marine geoid, with accuracies of a few centimeters at wavelengths of 100 km, leading to extremely rapid progress in our understanding of the thermal structure and rheology of the oceanic lithosphere and the origin of features such as oceanic wells and plateaus. In the southern oceans, altimeter observations have been used to infer the locations of bathymetric features such as fracture zones and seamounts, thus furthering our knowledge of plate kinematics and dynamics. The magnetic field has been measured directly from space via orbiting scalar and vector magnetometers. These data constitute the most important constraints we have on the dynamics of the Earth's core and the origin of the geomagnetic field.

The requirements are described in two parts: gravity and magnetics. However, both areas have a need for:

- o Higher resolution global measurements in order to study the structure of the lithosphere and upper mantle; and
- o Time-dependent observations for the study of the dynamics of the mantle and core.

1. Gravity Field

The principal requirements, with highest emphasis on improved resolution at short wavelengths, are:

a. High resolution, low-altitude gravity mapping from space, first by supplementing planned missions but later with an advanced technology capability;

b. Airborne gravity measurements for very high resolution mapping in local or regional areas;

c. Global topographic maps;

d. Oceanic altimeter data with a track spacing of 10 km at the equator; and

e. Measurements of the temporal variation of the gravity field.

2. Magnetic Field

The primary requirements are the measurement of the time-variation in the main magnetic field and improved knowledge of the crustal field. Specifically these include:

a. Initiation of a multi-decade, nearly continuous observation of the Earth's main magnetic field to measure secular variation;

b. Low-altitude mission to measure the crustal magnetic anomaly field at 1 nT accuracy and 100 km resolution;

c. Theoretical studies of the physics of the sources of magnetic fields;

d. New and improved ground observatories, particularly in areas where current coverage is poor and including the ocean floor; and

e. Continued laboratory studies of rock magnetic, electrical conductivity, and paleomagnetic data.

SECTION IV. STATUS OF CURRENT RESEARCH

The focus of this document is on the NASA plan for solid Earth science research in the next decade. These plans build on the accomplishments of past and current research of the Geology and Geodynamics Program.

A. *GEOLOGY PROGRAM*

1. Background

The NASA Geology Program was established in the late 1960's to exploit the use of remote sensing data acquired by aircraft and satellites. Initially the objectives of the Program were to develop and demonstrate the use of remotely sensed data for application to the detection and assessment of natural resources. From the early 1980's, the Program's emphasis has been on basic research involving the analysis and interpretation of remotely sensed spatial, spectral and temporal data in the pursuit of geologic studies. In this role, the Program occupies a unique place among geological research agencies.

2. Program Goals

The goals of the NASA Geology Program have been:

- *To contribute to the understanding of the history and evolution of the Earth's crust from early formation and deformation through presently active accretionary, depositional, tectonic, and deformational processes; and*

- *To investigate Quaternary geologic history and geomorphic, neotectonic, and volcanic processes for a better understanding of the evolution of land surfaces and climate from several million years to the present.*

The Program uses remotely sensed data, field work, and laboratory analysis to address the research objectives outlined above. The uses and advantages of spaceborne data accrue from the regional coverage obtained with a data set of uniform quality, as well as the capability of the sensors to measure intrinsically different physical properties of the surface. These properties relate to rock mineralogy; electric, magnetic and thermal response; soil composition and weathering products; topography; and centimeter to decameter-scale surface roughness. Recently sensors operating at visible wavelengths have demonstrated the great utility of high spatial resolution (i.e., 10 m or better) for geomorphic and structural studies, especially where stereo data can be obtained for topographic mapping in regions measuring tens of thousands of square kilometers.

Microwave sensors currently in use for geological remote sensing include SAR imaging systems and microwave altimeters. The returned radar signal is strongly affected by the average slope of the surface, making it a useful tool for detecting subtle geomorphic features. Scattering of the radar signal depends upon surface roughness (near the scale of the radar wavelength), providing a method for distinguishing surfaces through its sensitivity to outcrop morphology and weathering characteristics. Newly available multifrequency, multipolarization radar data have also shown that the scattering matrix of the returned signal can be interpreted in terms of the structure of the surface or vegetation canopy. In hyper-arid environments, ground penetration of one or two meters yielding information on near-surface structures has been observed.

Crustal magnetic data have been used in a variety of studies including: nature and origin of submarine plateaus; variation in crustal structure within continents; nature of continent-ocean boundaries at passive margins and in major continental rift zones; thermal structures in subduction zones and large hotspot regions; nature of the long wavelength component of sea floor spreading anomalies; demagnetization of the oceanic crust by temperature effects caused by burial under thick sediments; and composition of volcanic structures and major ore-bearing regions. The Magnetic Field Satellite (Magsat) provided a view of the Earth's crustal magnetic field (at a spatial resolution of about 150 km from an altitude of approximately 350 km) suitable for study of regional scale problems of crustal evolution. Also, because Magsat data represent the entire crustal thickness, they provide information on the structure and composition of Earth's deep crust and possibly the upper mantle boundary. The Geology Program has perceived a need for magnetic field data obtained at lower altitude with greater spatial resolution.

High quality topographic data are important in the monitoring of land surface changes due to erosion; in the study of volcanism, flooding, subsidence, glaciation, neotectonics; and the interpretation of gravity data. Other fields such as hydrology, vegetation studies, ice sheet glaciology also require high quality topographic data in certain applications. Local microtopography can be obtained by means of laser altimeter instruments which have sub-meter scale geodetic location and permit quantification of 0.1-10 m scale features of landforms. Such data are necessary for characterizing terrain properties that influence land surface processes. Acquisition of a single, coherent set of global topographic data has been an important objective of the Geology Program.

3. Accomplishments

Some of the major accomplishments of the Geology Program are listed below:

a. The Joint NASA/GEOSAT Test Case Project, involving NASA geologists and researchers from the exploration industry, produced the most comprehensive evaluation of the use of optical and radar remote sensing data from satellite and aircraft for geological mapping and copper, uranium, oil and gas exploration. The Project results established the geological and geobotanical utility of TM data.

b. The Sedimentary Basins Study involved approximately 30 scientists from 14 institutions, including seven universities. The Wind River Basin, Wyoming, was selected as the site of the study because of the excellent field exposures of sedimentary rocks and the paleontological significance of fossil-bearing strata in the area. In addition, the Wind River Basin is important as a petroleum exploration site: an extensive data base of geophysical measurements (seismic, gravity, drill-core) allowed the remote sensing results to be checked against existing information. A workshop summarizing regional geologic interpretation and technologic accomplishments was held in May 1989. Because the technology developed for this project can be broadly applied to many geologic studies, particularly in sedimentary basins, the International Union of Geological Sciences (IUGS) arranged a special session on these techniques in the IUGS meeting in January 1990.

c. Discoveries by Geology Program investigators have suggested that a major Tertiary river system once flowed across much of North Africa from the Red Sea to the Atlantic coast in Nigeria. This model was proposed following the reconstruction of flow directions of buried river channels first identified from the Shuttle Imaging Radar-A (SIR-A) images. Subsequently, observations from Landsat and SIR-B images, as well as known geological events such as the desiccation of the Mediterranean Sea during the Miocene were incorporated into the geological investigation of the paleodrainage of North Africa. This analysis has identified many new areas of paleolithic man and has fostered considerable collaboration between the archeological and geological communities working in this area.

d. A number of research efforts have focussed on northeastern Africa and Arabia, including use of remote sensing, field, and laboratory data to explore in detail the assembly and subsequent deformation of the late Proterozoic Arabian Nubian Shield. Maps depicting major rock types have been generated and used to pinpoint detailed mapping efforts. Results include identification of ancient crustal components in younger granites and detailed analyses of transcurrent faulting. The transcurrent faulting is associated with the largest pre-Mesozoic system known and may be comparable, because of extensive erosion, to structures approximately 10 km below the surface of the San Andreas Fault System.

e. Magsat observations have been used for regional geologic analysis. Radially polarized anomalies of a reconstructed Gondwanaland during the early Cambrian era show remarkable correlation across present continental boundaries. This shows that a principal source of the anomalies are pre-rift terrains which acquired their magnetic characteristics during Precambrian tectonic and thermal events. Discrepancies in correlation across rifted margins reflect rift or post-rift modification of the magnetic characteristics of the crust or difficulties in reconstruction of the ancient configuration of the continents.

f. A variety of new remote sensing approaches have been applied to some outstanding volcanological problems. This work has involved newly available sensors, particularly in the thermal infrared, deployed on aircraft and from a variety of orbital platforms. From orbit, analyses were carried out on the characteristics of eruption plumes and stratospheric and tropospheric SO_2 transport. The mapping of recently active features in the Andes revealed a far more volcanically active post-glacial history than expected. The energy characteristics of lava lakes and fumaroles were determined from Landsat TM data and the radar signatures of lava flows and other volcanic features were obtained from SIR flights.

g. Aircraft observations of the thermal budgets of volcanoes use TIMS, the Thematic Mapper Simulator, and the Airborne Imaging Scanner (AIS), which together provide radiance data representing a temperature range from ambient through nearly magmatic. New data include surface temperature maps of Campl Flegrei (Italy) during the recent volcanic crisis, thermal energy maps of several active lava flows on the Kilauea Shield (Hawaii) and on Mt. Etna (Italy), and a map of an active lava tube system and associated offshore water plum (Hawaii). In addition, stereo-photogrammetric models from SPOT image data have been fashioned into simulated aircraft flybys of the Kluchevskoy volcanic shield in Kamchatka (USSR). Finally, detailed mapping of flow units at a variety of volcanoes using TIMS has demonstrated a startling ability to discriminate between flows of slightly differing ages, providing a powerful synoptic tool for field volcanology.

4. Activities

Considerable emphasis has been placed on the development of a broader NASA geological community and on program planning. Program-wide planning meetings were held at Lincoln City, Oregon, (July 1985), St Louis, MO, (April 1986), and Washington, DC, (August 1987). Geology Workshops in 1988 and 1989 have provided more specific directions for the accomplishment of goals in the areas of volcanology, paleoclimatology, and sedimentary basins.

The Topographic Science Working Group (TSWG) organized by the Geology Program recommended[4] that NASA begin a program to acquire a topographic data set with a vertical resolution of 1 m and horizontal resolution of 50 m, augmented in selected areas with higher resolution. The TSWG concluded that the technology exists in the form of narrow beam radar altimetry, although a large subset of that group has since revised that conclusion to recommend radar interferometry as the appropriate technology. It also suggested that the required high resolution data could be obtained using the LFC and SPOT stere-photogrammetry. The TSWG recommended that the global, regional and local topographic data sets be stored in a common, easily interpreted format on video disk or similar medium to facilitate widespread distribution and analysis.

The Geology Program also participates in the Land Processes Aircraft Science Management and Operations Working Group which was formed to advise on the coordination of aircraft planning activities, particularly in the case of major deployments, such as overseas or multi-temporal experiments. In addition to long-term planning, the group considers short-term issues, program balance, current program effectiveness and data handling. Emphasis is placed on broadening access to the aircraft sensors for a wider range of users, including the university community.

The Geologic Remote Sensing Field Experiment was held in the Fall of 1989 in the southwestern United States. This was the first attempt to study several geologic processes using multiple remote sensing data sets, and to build quantitative physical models for data interpretation. Emphasis was placed on the interpretation of eolian erosion and deposition landforms, the weathering of lava flows and alluvial fans, and the ability to define geomorphic phenomena using multispectral, radar, and altimetric data. The experiment was conducted with the NASA Planetary Geology Program in order to prepare for comparable types of data that will be collected for Mars, Venus, and the moons of Jupiter over the next decade.

A new laser profiler has been developed to fly on NASA's P-3 aircraft. Using differential GPS measurements, geodetically-controlled profiles with less than 10 cm vertical accuracy have been collected for a number of volcanic, glacial, and coastal sites, located in Iceland, Arizona, Washington State, and the coast of New England.

The NASA/JPL Aircraft SAR system development was supported by the Geology Program. This system, which operates at C-band (5530 Mhz), L-band (1250 Mhz), and P-band (440 Mhz), flies on the NASA DC-8 aircraft and is capable of producing fully polarimetric data from all three frequencies simultaneously; yielding 12 coherent, co-registered radar images of any scene with approximately 10 m resolution. In early 1988, the radar system was flown over the Goldstone calibration site in California. In early 1989, data were acquired in Alaska and over the Mojave Desert, CA.

B. *GEODYNAMICS PROGRAM*

1. Background

In 1969 the Williamstown, MA, Conference[5] recommended that NASA focus on the use of:

- Space techniques such as Satellite Laser Ranging (SLR), Very Long Baseline Interferometry (VLBI), and Lunar Laser Ranging (LLR) to measure plate motion and deformation, and Earth orientation;

- Satellite geodesy to measure the Earth's gravity field; and

- Ocean altimetry for physical oceanography and studies of the rheology of the oceanic lithosphere.

These recommendations were incorporated into a NASA plan[6] which led to the establishment in 1972 of the Earth and Ocean Dynamics Applications Program. This Program was responsible for the fabrication of several SLR facilities and the initiation of the development of geodetic VLBI. The SLR stations operated in California to measure displacements across the San Andreas Fault System, performing laser ranging to several early satellites equipped with CCRs. The program successfully launched the GEOS-3 altimetry satellite in 1975, the Laser Geodynamics Satellite (Lageos-I) in 1976, Seasat in 1978, and Magsat-A in 1979.

In 1978, physical oceanography was separated from geodesy and geodynamics, and solid Earth geophysics was made into a new program: the Geodynamics Program. The objectives and content of this Program were decided upon after consultation with other Federal agencies, as well as with individuals and organizations in the U.S. and many other countries. A Memorandum of Understanding involving five agencies was signed in 1980, formalizing the ways in which they would cooperate in the application of space technology to geodesy and geodynamics, and a Geodynamics Program Plan was published[7]. The program it described comprised three major elements:

- Geopotential field studies;

- Studies of the dynamics of the Earth's deep interior; and

- Studies of the movement and deformation of the lithosphere.

The last was implemented in 1979 through the Crustal Dynamics Project (CDP) at the Goddard Space Flight Center (GSFC). LLR, which had been carried out independently since 1969, was brought into the CDP and was concentrated at the University of Texas at Austin, the University of Hawaii, and the Jet Propulsion Laboratory (JPL). In 1982 development of improved ground receiver instruments and analysis techniques making use of the radio signals from GPS was assigned to JPL. Along with technology development, this task involved GPS demonstration campaigns in southern California, the Caribbean and Central America.

2. Goals

The goals of the NASA Geodynamics Program have been:

- *To contribute to the understanding of the dynamics and evolution of the solid Earth and in particular, the processes that result in movement and deformation of the tectonic plates; and*

- *To obtain measurements of the Earth's rotational dynamics and its gravity and magnetic fields in order to understand the internal dynamics of the Earth.*

The Geodynamics Program has been subdivided into three research areas: *Earth Dynamics, Crustal Motion,* and *Geopotential Research.*

The objectives of *Earth Dynamics* have been to develop models of polar motion and Earth rotation and to relate studies of global plate motion to the dynamics of the Earth's interior. This is expected to lead to an increased understanding of the global structure of the Earth and the evolution of the crust and lithosphere. The research includes studies of the dynamic interaction between different regions of the Earth's tectonic features as well as the interactions between the solid Earth and the atmosphere and oceans. A significant portion of this includes activities performed under the CDP through highly accurate measurements of Earth rotation and polar motion.

Field measurements and modeling studies of crustal deformation in various tectonic settings are the primary focus of the *Crustal Motion* research. These activities provide measurements, analyses, and models which describe the accumulation and release of crustal strain and the crustal motion between and within the tectonic plates, particularly the North American, Pacific, Eurasian, South American, Nazca, African, and Australian plates. Activities include development of quantitative descriptions of geophysical and geological constraints on the motions of measurement sites through refinement of global plate motion models and tectonic models of the western U.S.

Geopotential Research uses space and ground measurements to construct gravity and magnetic field models. Investigations of data analysis techniques and software systems are also part of this activity. Studies of the Lageos-I orbit and the orbits of near-Earth satellites contribute to gravity field studies. Other data used in constructing the models include gravity field data derived from satellite altimetry; satellite-to-satellite tracking and gravity gradiometry; magnetic field data from satellite magnetometers; and ancillary data.

3. Crustal Dynamics Project

The scientific objectives and plans of the CDP were derived from the Geodynamics Program Plan[7]. These are to improve knowledge and understanding of:

- *Regional deformation and strain accumulation related to large earthquakes in plate boundary regions in western North America;*

- *The present relative motions of the North American, Pacific, South American, Nazca, Eurasian, and Australian Plates;*

- *Internal deformation of continental and oceanic lithospheric plates, with particular emphasis on North America and the Pacific;*

- *Rotational dynamics of the Earth and their possible correlation with earthquakes, plate motion, and other geophysical phenomena; and*

- *Regional deformation in other areas of high earthquake activity.*

The CDP is responsible for furthering the development of SLR, LLR, and VLBI systems; and for the acquisition, processing and archiving of geodetic baseline, Earth rotation, and polar motion data. As part of its data management, the CDP designed and implemented a centralized Crustal Dynamics Data Information System (CDDIS), which has been fully operational since September 1982.

A significant part of the success of the Project is attributable to the extensive participation of over one hundred scientists from NASA Centers, universities in the U. S. and abroad, other Federal agencies, and agencies or organizations in other countries. Approximately 30 countries are participating with the CDP in measurements of Earth dynamics and lithospheric deformation. Several other countries have developed or are now developing mobile SLR facilities and VLBI observatories which will contribute further to global and regional deformation measurements in cooperative campaigns.

The CDP Principal Investigator's Working Group, (CDP/IWG), which meets semi-annually, has been an effective forum for the discussion of investigator results, for the review of the CDP status and progress, and for recommending redirections for CDP measurement campaigns.

While helping to build and deploy SLR, LLR, and VLBI facilities worldwide, the CDP has also developed technology to improve the accuracy and reliability of the field measurements. Most of the systems which form the world-wide network are now capable of determining the motion of any one site with respect to another at a level of better than 1 cm/yr: some are capable of 1 mm/yr. This has resulted, for the first time, in the direct measurement of the motion of most of the major tectonic plates and of large-scale crustal deformation in the western United States, Alaska, and the Mediterranean. The history of the development of the SLR, VLBI, and LLR techniques and the global networks that currently exist are described in a summary report on the Geodynamics Program[8].

Through the CDP, NASA is a member of the Mediterranean Laser Project (Medlas) which was organized in 1981 under the Working group of European Geo-scientists for Establishment of Networks for Earthquake Research (WEGENER). This Project is committed to the measurement of crustal deformation in the Mediterranean area, and now involves 12 countries. In 1986 and 1989, mobile SLR stations from three countries obtained measurements at sites in Turkey, Greece, and Italy. In 1988, a European mobile laser participated with U.S. lasers in measurements at VLBI sites in the U. S. in support of studies of terrestrial reference frames. The next Medlas campaign is planned for Europe in 1992. Meanwhile, WEGENER is developing plans for the extensive use of GPS to densify measurements in the Mediterranean Basin, and is exploring the possibility of extending SLR studies to areas other than the Mediterranean. The results of the Medlas Campaigns have been presented at several meetings of the CDP/IWG, and at WEGENER symposiums held in Italy in 1987[9] and The Netherlands in 1989[10].

While the CDP is scheduled to finish its activities at the end of 1991, the current measurement program will be continued through 1991, with some changes to reflect the emerging GPS techniques and the recommendations of the Coolfont Workshop. In addition, the NASA SES Branch is committed to providing SLR tracking for the European Space Agency (ESA) Earth Remote Sensing-1 (ERS-1) satellite to be launched in 1990 and the Ocean Topography Experiment (TOPEX) to be launched in 1992.

Beyond 1991, NASA has chosen to continue and improve on the work of the CDP by establishing a new program whose objectives will be very similar to those of the CDP.

4. Accomplishments

Some of the major accomplishments of the Geodynamics Program are listed below:

a. Contemporary relative motions of several of the major tectonic plates were measured and were found to be generally consistent with long-term average velocities derived from geophysical and geological data.

b. Extensive measurements and studies of regional crustal motion were carried out in the continental United States, Alaska, Canada, Mexico, the Caribbean, and the Mediterranean.

c. Measurements were obtained of the crustal deformation associated with recent earthquakes in California and Alaska.

d. Earth rotation and orientation values were produced which are one to two orders of magnitude more accurate than previously obtained.

e. Mass movements in the atmosphere were established as the primary cause of short period variations in Earth rotation.

f. More accurate gravity field models (a factor of 2 in gravity and an order of magnitude for the geoid) were derived using both laser ranging to Lageos-I and altimeter data from GEOS-3 and Seasat.

g. For the first time, temporal variations in the Earth's gravity field were detected in the analysis of satellite orbit perturbations.

h. Major improvements were achieved in the modeling of the Earth's main magnetic field (a factor of 5 in the minimum wavelength resolved) and in identification of magnetic crustal anomalies associated with tectonic features.

5. Activities

The first and second generation GPS receivers developed in the early 1980's made it possible to use facilities for measuring crustal deformation which are highly mobile. GPS measurements have already been carried out, in cooperation with other countries, in Mexico, the Caribbean, and Andean South America. Detailed planning is now in progress for similar campaigns in other regions, such as the southwestern Pacific, the Himalayas, and eastern Asia.

A major step was taken in the early 1980's by the formation of the Commission for coordination of Space Techniques for geodesy and Geodynamics (CSTG), a joint commission of the International Association of Geodesy (IAG), the International Astronomical Union, and the Committee on Space Research (Cospar) of the International Council of Scientific Unions (ICSU). The CSTG organized several international observation campaigns in the period of 1980 to 1984 (MERIT-Monitoring Earth Rotation and Intercomparison of Techniques), and subsequently established the International Earth Rotation Service (IERS) based on the Project MERIT results. Global networks of stations, and international analysis centers, are now operating to gather, archive, and distribute data, and to carry out and distribute analysis of the SLR, LLR, and VLBI data from all countries. The IERS centers were formally established in January 1988 and are now functioning well.

Development and planning activities are underway for:

- the launch of Lageos-II (a cooperative program with the Italian Space Agency - ASI);
- the GLRS (funded under EOS) which will range to CCRs on the ground for studies of crustal motion;
- a joint NASA/ESA mission (ARISTOTELES- Application and Research Involving Space Techniques Observing The Earth's field from Low Earth orbiting Satellite) which will measure the gradient of the gravity field and the crustal magnetic field at low altitude for 6-8 months and the main magnetic field at high altitude for 3 years;
- development of VLBI techniques for millimeter determination of vertical position;
- two-color SLR systems for determining the atmospheric delay corrections;
- a Superconducting Gravity Gradiometer (SGG) which can be used to obtain a global map of the Earth's gravity field to unprecedented accuracy and resolution;
- an inexpensive high-accuracy geodetic GPS receiver; and
- sea floor geodetic technology involving GPS receivers and sea floor transponder coupling.

Programmatic reports include: a scientific rationale[11] and spacecraft conceptual studies[12] for the Geopotential Research Mission; studies of gravity gradiometers[13]; conceptual studies of the Superconducting Gravity Gradiometer Mission (SGGM)[14 & 15]; Phase A and B studies for the Magnetic Field Explorer (MFE)/Magnolia mission[16&17]; and studies of the geophysical and geodetic requirements for global gravity field measurements in the next decade[18].

Annual reports on the Geodynamics Program were issued in 1979, 1980, 1981, 1982, and 1983[19-23]. A Program Overview was published in 1983[8] , and in 1987 a report was published which summarized Program accomplishments from 1979 to 1987[24].

Previous long-range planning workshops were held in 1982[25] and 1985. The 1985 workshop was sponsored by the Geophysics Panel of the ESSC, and the results of that workshop were incorporated in the report of the ESSC[2].

Other program-related publications include special issues of the Journal of Geophysical Research on the results of the Lageos-I mission[26] and the Magsat mission[27]; and an IEEE special issue on satellite geodynamics[28].

SECTION V. MAJOR NEW EMPHASES IN THE 1990's

While most of the current activities of the SES Program are consistent with the science objectives and measurement requirements outlined in Section III, five areas have been identified which are sufficiently important to the Program's goals and objectives to warrant new emphases in the 1990's. These emphases are meant to enhance and complement on-going work in the NASA SES Program. These new emphases include: global monitoring of lithospheric deformation; global characterization of soils and soil-modifying processes; acquisition of global topographic data; elucidation and monitoring of volcano-climate interaction; and measurement of gravity and magnetic fields and their long term secular variations.

A. *GLOBAL GEOPHYSICAL NETWORKS*

As outlined in the reports of the Coolfont Science Panels (Volume II) a principal priority for the 1990's is the establishment of Global Geophysical Networks (GGNs) for integrated, comprehensive measurements of many geophysical parameters. The GGNs take the form of:

- <u>Fiducial Laboratories for an International Natural science Network (FLINN)</u> - a global network of space geodetic stations with approximately 1000 km spacing which integrate GPS, VLBI, SLR, and LLR technology to monitor plate motion and deformation, to monitor Earth rotation, and to define and maintain a terrestrial reference frame.

- <u>Densely Spaced Geodetic Systems (DSGS)</u> - regional and local monitoring networks deployed across tectonically active regions to measure and analyze motion and deformation over a broad range of spatial and temporal scales.

1. <u>FLINN</u>

a. *Basis*

Deformation of the Earth's lithosphere covers a broad spectrum of temporal and spatial scales, from seconds to eons and from mineral grains to planetary dimensions. At the largest scale, the concept of rigid plate tectonics has been spectacularly successful in explaining the relative motions of the dozen or so lithosphere plates that together comprise most of the Earth's surface. Earth science has progressed to the point where we must look beyond the simple descriptions of classic plate tectonic theory towards an understanding of the driving mechanisms of global plate motion and towards quantitive descriptions of the kinematics and dynamics of those areas where rigid plate tectonics do not apply. We now know departures from classic plate tectonics occur as time-dependent deformation within tectonically active plate boundaries, and we strongly suspect that departures also occur as non-rigid behavior within the interior of plates and as time-dependent motion of the plates themselves.

Precise monitoring of positions is required not only to understand the long term behavior of the solid Earth but also to understand global change on time scales of decades or less. For example, large parts of the surface of the solid Earth are undergoing vertical motions (from a few mm/yr up to 10 mm/year) in response to Pleistocene deglaciation. These motions lead to changes in volumes of ocean basins and the height of shorelines at rates comparable to those from melting ice and temperature changes in the oceans. Understanding the "signal" of global change in sea level requires understanding the "noise" from the solid Earth.

The study of plate motions and deformation is also motivated by a need to discern methods leading to achievement of reductions in natural hazards, particularly earthquakes and volcanic eruptions. Comparisons between crustal motion, seismicity and other geophysical data are crucial to a quantitative understanding of seismic and volcanic phenomena.

The full model of the dynamics of the Earth includes the effects of mass redistributions both internal and external to the Earth. The motions of the "fluid" parts of the Earth (atmosphere, oceans, and the fluid core) produce observable effects on the rotation of the Earth. The clear correlation between atmosphere angular momentum and variations in the rotation rate of the Earth for periods less than a couple of years is well established, as is the impact of the fluid core oh the diurnal variations of the direction of the Earth's rotation axis. By monitoring Earth rotation, FLINN will provide an essential set of measurements which will be used to address the coupling mechanisms between the solid Earth, atmosphere, and the oceans.

b. Approach

The development of space geodetic positioning techniques capable of achieving accuracies of a cm or better has been one of the most exciting developments in crustal kinematics over the last two decades. The agreement between short-term plate motion (years to decades) as determined from space geodetic data and long-term average motions (millions of years) as determined from geologic observations is of great importance in the study of local and regional deformation. For the first time, we have the capability to observe the relative displacements and internal deformation of crustal fragments within plate boundary zones and, on a shorter time scale, to document the accumulation and release of strain energy within zones of active faulting and to identify patterns of crustal strain that precede earthquakes. The widespread application of space geodesy to precise documentation of crustal motions promises a revolution in our understanding of the kinematics of active crustal deformation and of the physical processes that control that deformation.

The study of the dynamics of the Earth requires an understanding of the changes of the Earth's gravity field. The only means currently available for globally studying the Earth's gravity field is through the analysis of satellite orbit perturbations. Thus a component of the global fiducial network will be stations that are able to track Earth orbiting satellites and acquire the data necessary to monitor variations in the gravity field over time.

c. Measurement Requirements

What is needed is a systematic approach to measuring global strain. Two basic requirements are:

1. In order to study absolute plate motion, we need a global distribution of space geodetic stations which can provide accurate measurements of relative motion between points on the Earth and can maintain a terrestrial reference frame; and

2. In order to monitor regional and local deformation we need to tie densely distributed regional geodetic networks to an accurate terrestrial reference frame. These requirements can be met with a globally distributed system of GPS receivers augmented by strategically located VLBI and SLR stations. Such networks can also serve a variety of other purposes, including extremely accurate determinations of satellite orbits and calibration points for space-based gravity, magnetic, topography, and remote sensing data.

The required accuracy of the location determination of the geodetic sites is dictated by the rates of movement that we wish to observe. Relative rates of horizontal motion between the major plates fall mainly between 1 and 10 cm/yr. In order to measure these rates to 5 to 10% accuracy on a yearly basis it is necessary to measure relative positions precise to 1 mm over at most one year and preferably over one month. Equally important, in order to be used as a terrestrial reference frame for more detailed space geodetic studies of inter- and intra-plate deformation, the global network must be more accurate than the regional networks. Motion in these zones of intense deformation is several cm/yr down to 0.1 mm/yr or less; therefore, at least 1 mm accuracy over long time periods is needed to support local and regional networks. Except for post-glacial rebound, most large scale vertical motions are at least an order of magnitude slower than horizontal motions and only in tectonically very active areas do rates exceed 1 mm/yr, while thermal and dynamic processes are typically a few tenths of a mm or less. Therefore, 1 mm accuracy in the vertical is crucial if we are to use space positioning data to address phenomena that result in vertical motions at the Earth's surface.

The number, spacing, and type of space geodetic stations required for FLINN are based on both scientific and technical considerations. At least three sites per major plate are required to resolve plate motions, but mapping of non-rigid behavior within the interiors of plates requires a denser distribution of stations. With a station spacing of 1000 km there would be approximately 30 FLINN sites in North America, enough to map the distribution of non-rigid behavior across the subaerial part of the plate.

The geometrical strength of the GPS measurements will increase as the constellation reaches its full complement and the global tracking network becomes well-distributed geographically. The additional fiducial constraints provided by independent colocated space geodetic techniques, such as VLBI and SLR, further improves the quality of the GPS measurements and permits geodetic data of all types to be expressed in a unified celestrial/terrestrial reference frame.

Approximately 150 such stations will be required on the continents, with another 50 stations located on islands. There is also a requirement for precise sea floor geodetic positioning which is currently under development at NASA. The location of these stations should be chosen to provide a good sampling of the major plates. GPS receivers can be installed between and at the existing worldwide network of VLBI and SLR sites with at least one colocated station on each major plate and several distributed around the Pacific Basin. The VLBI stations must also measure relative positions to less than 1 cm over one day and to 1 mm over three months and thus will monitor deformations and provide a tie of the FLINN coordinate system to an inertial coordinate system. A ground network of SLR stations and GPS receivers, many of which are colocated, will be required to support tracking of Earth orbiting satellites. When GLRS is deployed, 200 GLRS reflectors should be colocated with the VLBI, SLR, and GPS fiducial stations for the purpose of precise EOS orbit definition, calibration, and provision of a common reference frame for all space geodetic techniques.

Some of these geodetic stations will be augmented with other types of instruments to permit calibration of various space-based data sets. Installation of globally distributed gravimeters and magnetometers at some of the FLINN sites will provide useful ancillary data in support of spaceborne or airborne gravity and magnetic measurements, as well as for spaceborne or airborne topography, and complement the ground-based programs of U.S. and international agencies. One of the main problems in existing topography data sets is the difficulty in obtaining globally coherent data. FLINN will provide 200 sites distributed around the world with very accurately determined elevations. Magnetic data suffer from a different problem in that large variations in the Earth's magnetic field occur on a daily to hourly basis. These effects must be removed if we are to study processes within the Earth using magnetic data. Deploying magnetometers at globally distributed FLINN sites will permit continuous monitoring of the time-varying, long-wavelength part of the magnetic field and allow the separation of ionospheric and telluric contributions to spacebased magnetic measurements. Deploying superconducting gravimeters at the VLBI/SLR sites will permit accurate measurement of Earth tides at these stations. In locations with suspected long period (months to years) height variations, absolute gravimeters would also be deployed.

FLINN will be instrumental in encouraging studies of local and regional deformation because it will provide a means of tying local observations into global reference frames. Comparisons between crustal kinematics, seismicity and other geophysical data are crucial to achieve a quantitative understanding of the processes controlling earthquake and volcanic eruptions. Particularly noteworthy is the need to establish permanent networks of geodetic instruments in areas of frequent volcanic or seismic activity, so as to maintain a continuous record of short-term ground motions immediately before and after major eruptions and earthquakes and to aid in their prediction. Siting of these geodetic networks within a fiducial reference frame will be greatly facilitated by FLINN. FLINN will also be of great use in the assessment of global warming by permitting local measurements of sea level change to be calibrated and combined into a global data set to evaluate the rate of volume change of the oceans and the rate of melting of the polar ice caps. The basic data that we must have to achieve this goal is a set of globally distributed measurements of vertical motions at the Earth's surface as will be provided by FLINN.

2. DSGS

a. Basis

In the effort to understand the kinematic and dynamic evolution of the Earth's crust, the first goal of regional geodesy over the next decade is to document crustal kinematics and deformation surrounding different types of inter- and intra-plate boundaries and over a great range of length and time scales.

The crustal deformation patterns associated with the earthquake cycle can depend strongly on the rheological properties of subcrustal material. The detailed description of the deformation pattern (specifically, the surface displacements, displacement rates, strains, and strain rates) depend on the structure and geometry of the material near the seismogenic zone. In recent years various visco-elastic models of deformation near major strike-slip faults have been proposed. These differ in their predictions of the temporal and spatial patterns of crustal deformation throughout the seismic cycle.

Until recently, the ability to observe the deformation associated with the relative motion of adjoining plates was restricted to a few countries having the necessary advanced geodetic technology. Much of the work to date has focused on either transform fault environments like the western U.S. and New Zealand or in subduction environments like Japan. With the much larger community that will soon be able to carry out field observations, and with the added flexibility and portability of GPS and GLRS geodetic systems, we can now develop a kinematic understanding of deformation in all regions and tectonic environments. By extending our data set to include both more varied tectonic settings and new examples similar to those already studied, we will advance our understanding of the mechanisms by which plate motion proceeds.

b. Approach

The 200-station FLINN network will span the globe at a fairly coarse scale to provide, among other things, a picture of large scale plate motion and deformation. Supplemental measurement systems deployed at much higher densities will be needed to study the complex activity at plate margins and other active regions. Array spacings of 10 km or less will be required in a number of areas. Deformation within many of these regions will be best measured by a long-term program of DSGS networks. These DSGS networks will be intimately tied to FLINN and constitute one of the major advantages to be gained by implementation of FLINN.

The DSGS will combine two complementary elements: permanent regional geodetic arrays deployed in regions of high priority and accessibility, and mobile systems for use in scheduled campaigns and for rapid temporary densification. As technology and economics permit, the trend should be toward increasing the number and extent of automated permanent arrays and minimizing reliance on manpower-intensive and logistically complex mobile operations. There will always be a need, however, for selected campaigns and directed densification in response to events, even in regions well covered with permanent sites. Areas of particular interest include:

1. Regional and local deformation in North America and along the North American-Pacific Plate boundary;

2. Major plate convergence systems including subduction zones around the Pacific Basin and the Alpine-Himalayan collision;

3. Regional deformation in the Mediterranean, southeastern Asia and elsewhere; and

4. Post-glacial rebound in North America and Eurasia.

Three or four regions where large earthquakes are predicted to occur in the relatively near future should be selected and high density measurements begun so that we may begin to accumulate complete sets of observations spanning the seismic cycle. Since VLBI and GPS measurements are already being made there, continued intensive work along the North American-Pacific Plate boundary in Alaska and California should be a high priority.

The first permanent regional array for GPS geodesy will be deployed in southern California in 1990. This will be a pilot network serving as both an operating scientific instrument and a test bed for array technology as it is refined in the coming years. A typical array might eventually include 50 observing sites. Arrays should be fully automated, editing and compressing data within the receivers in real time and telemetering them to a processing center for continuous reduction. Automated permanent arrays will operate much like seismic networks today, extending the regime of observability to periods ranging from minutes to years.

Late in the 1990's, in the era of GLRS, inexpensive laser retroreflectors will be deployed in large numbers as permanent arrays at selected locations around the world. Because they will not provide continuous coverage, GLRS arrays will not actually replace all GPS systems, but will complement them by providing a means to further densify space geodetic measurements, particularly in remote areas and areas that offer little logistical support.

As receiver and operations costs drop, the role of permanent arrays will grow. Mobile densification will be a feature of every permanent array, and selected mobile campaigns, with costs dominated by manpower and logistics, will likely continue at a steady rate. To develop as we have described it, both FLINN and DSGS will require a broad base of interagency and international collaboration.

c. Measurement Requirements

Typical studies will require observing sites separated by 10 or 20 km in both dimensions over the area of interest. Depending on the deformation rates involved, observing periods of 5 to 10 years may be required to clearly reveal tectonic signals. Measurement frequency will range from continuous to once every 2 to 3 years, depending on the region.

B. SOILS AND SURFACE PROCESSES

1. Basis

During the past century both the area affected and the rate of change of the Earth's surface due to human activities has increased, so that anthropogenic changes now have a significant influence on the global system. The most obvious change has been deforestation and even devegetation in the most severely affected regions. Water impoundment and diversion projects are so widespread that few major river systems on the planet remain unmodified. Soil degradation, erosion, and transport are increasingly serious global problems. Soil degradation in some areas is now occurring so rapidly that its progress is difficult to measure using conventional ground-based mapping techniques. Soil degradation includes eolian and fluvial erosion and transport, waterlogging, and changes in chemical composition including salinization and acidification. It is both a cause and result of changes in the type and amount of vegetation. While the role of soil as a reservoir, a sink, or a source of CO_2 is not clear, the great magnitude of soil degradation and erosion has implications for atmospheric chemistry. Each process impacts the chemistry, soil texture, and morphology of the Earth's surface. Eroded soil is ultimately redistributed as wind-blown dust, as silt in reservoirs, increased sedimentation in estuaries, deltas, and other coastal environments, and as alluvium in flood plains.

Changes in the rate of fluvial erosion, transport, and deposition of sediment can have profound effects on human facilities and natural systems. Remote sensing is uniquely capable of assisting ground-based programs to measure soil degradation and redistribution globally and on a repetitive basis.

Transitional zones are regions that are environmentally sensitive to modification in response to changing climatic conditions. Many such areas are particularly sensitive because they are located within present climatic zones that are subject to shifting boundaries. The surfaces of transitional regions tend to be in rather tenuous equilibrium with the present-day climate, and they typically exhibit evidence of past changes in response to multiple climatic variations. These regions include, but are not limited to, the margins of the deserts and polar regions, alpine glacial and periglacial terrains, and the shorelines of lakes and coastal areas.

Process studies of the land surface using remote-sensing data in conjunction with field and laboratory observations are needed to study changes in all of these transitional environments. A multidisciplinary effort is needed to gather and interpret data on such factors as vegetation cover, soil characteristics, and hydrology, in addition to the standard stratigraphic and topographic studies. Especially important are measurements that will add to the presently inadequate geochronology of geologic surficial units and landforms. Both radiometric and relative dating are needed to improve definition of sequences of events and establish the rates of processes that operated under past climatic conditions.

The continental climate history has been impressed on the land surface of the Earth as landforms and as chemical and physical weathering products, including soils and rock coatings. Regional distributions of landforms chart paleoclimatic zones; the degree and type of chemical weathering can be used to infer paleoenvironmental conditions, including precipitation and temperature regimes. Remote sensing is well suited to morphometric measurements, and multispectral images have been shown useful in determination of soil type and development. Remote sensing is especially valuable because the extensive coverage and closely spaced measurements permit the reliable distinction of different units and the detection of subtle or diffuse gradients. Coupled with age data for different surfaces, this remotely sensed information can be used to help reconstruct a continental climatic history on longer time scales than has been accessible through most other studies. Because geologic surfaces dating from times throughout the previous glacial cycle (the last ~130,000 years) are still well preserved, even if widely scattered, regional studies of soils and landforms are expected to yield information on the spatial variability of climatic history on a scale sufficient to test paleoclimate reconstructions made using General Circulation Models.

Climate-tectonic interactions are most evident where tectonic processes create landforms that interfere with the global atmospheric or oceanic circulation. These include major uplifted areas, such as the Sierra Nevada, Andes, and the Tibetan Plateau. In these areas, we must understand the spatial and temporal distribution of the processes that have been involved, including constructional (e.g., uplift, volcanism) and erosional (physical and chemical weathering, fluvial, glacial) processes and the linkages between them. Using this understanding, we can then model the interacting system in space and time, with special attention to feedbacks and sensitivity of the system to variations in individual processes. The models can then be used in reconstructions of the history of global climate as well as of entire mountain ranges. Critical problems which can be addressed very powerfully by satellite observations are the spatial patterns of surface deformation and the redistribution of mass by erosion, transport and deposition. An adequate continental topographic database combined with plans for new visible-near infrared, TIR, and radar data, linked to climate and climate history, will provide new insights into the role of denudation rates in the tectonic evolution of mountain ranges, the role of sedimentary budgets in defining the characteristics of sedimentary basins and the potential feedbacks between topographic evolution and global atmospheric circulation patterns.

2. Approach

Physical characteristics important to land surface processes include surface roughness; geometry and distribution of landforms; soil moisture; thickness of eolian mantles; particle-size distribution; density; vegetation type and density; and development of hard pans and caliche. Chemical conditions of interest include rock type, weathering products, rock coatings and soil composition. Most of these qualities may be derived from remote sensing data. Visible-near infrared data are sensitive to composition of surficial materials such as rock type and weathering products and to vegetation; thermal infrared sensors are sensitive to rock type as well as bulk properties; and radar can be used to derive surface roughness, bulk properties, and potential subsurface horizons.

The spatial scales covered by surface-process investigations range from small intensively studied "anchor sites" to global. High-resolution, very frequent measurements are required in the smaller areas and lower resolution coverage is required less often for continental-scale regions. Ground data will be required at intervals ranging from seasonal (for vegetation cover, glaciers, and snowpack) to daily (for stream discharge and sedimentation); to hourly or less for soil moisture and temperature gradients; to a few minutes for wind speed and direction, peak gusts, precipitation, eolian flux (sand and dust in transit), and solar radiation.

3. Measurement Requirements

The major requirements are for the combined data sets expected to be available from EOS together with high resolution topography, and data from TM, SPOT, and TIR. NASA's aircraft sensors will provide important EOS-type data in the interim before launch of EOS.

Measurements from aircraft and satellite sensor systems are needed to obtain both high-resolution spatial and spectral data. Panchromatic stereo and multispectral images with a pixel resolution of 5 m and 20 m, respectively, are desirable. SAR systems of at least 30 m resolution are essential for mapping surface roughness related to physical weathering processes and for imaging shallow subsurface topography and geologic structures in arid regions obscured by wind-blown sand.

The measurements needed are similar to those required to address questions pertaining to the tectonic evolution of the continental lithosphere. In fact, it is expected that projects in continental lithosphere evolution, and soils and soils processes, will provide a suite of data extraction procedures needed to generate quantitative maps of surface properties. Such maps, augmented with field and laboratory observations, will be critical components in understanding both surface and interior processes that have affected the Earth's continents.

C. GLOBAL TOPOGRAPHIC MAPPING

1. Basis

Topographic information is vital for most geologic and geophysical investigations and was deemed a requirement by the majority of Science Panels at Coolfont. For example, topography combined with gravitational information provides an important constraint on the structure and rheological properties of the lithosphere. In addition, detailed topographic data can be used to map geological structure and thus reveal the effects of tectonic deformation.

Topography is also an important element in regional and global geomorphic studies because it reflects the interplay between erosion and the tectonic and volcanic processes of formation. It also plays an important role in soil formation and has a strong influence on such properties as soil depth, pH, soluble salt content, and potential for erosion or accumulation.

2. Approach

For many parts of the world topographic data are limited, inaccurate, or nonexistent. Mountain belts, deserts, tropical rain forests, and polar areas, all critical environments for Earth science research, suffer from topographic coverage that is totally inadequate mainly because of difficulties in physical access. Even where topographic maps exist, they may have been generated in such a way as to limit their usefulness. For example, the distribution of horizontal and vertical control points across a map is usually uneven, and this results in variable accuracy. Even maps that are internally consistent can rarely be assembled to generate good regional coverage. Lack of uniformity in reference levels compromises the integrity of topographic data over large regions and limits the scope of any regional or global study where precise topography is important.

Topographic data in digital form are even more limited. Digital topography showing about the same level of detail as a topographic map at a scale of 1:250,000 or better exist only for the U.S., Australia, and western Europe. The best global coverage for the continents is limited to several km horizontal resolution in large areas. Moreover, digital elevation data are usually generated by digitizing contour maps produced in conventional ways, and suffer from any problems that afflict the original data set, particularly in spatial integrity over long distances.

Because of the importance of topography to the majority of the SES research objectives, high priorities for the Program are:

a. To acquire a globally consistent topographic data base at moderate resolution, and

b. To provide access to high resolution topographic data for regional and local areas.

Several technological approaches now exist for the space-based acquisition of global topographic data at resolutions of order 100 m horizontal and 1 m vertical[4]. High resolution topographic data can be acquired in selected areas using satellite sensors such as the LFC and SPOT and airborne laser systems. However, there is not a clear path for acquisition of intermediate resolution data (30-50 m horizontal, 1 m vertical) in a globally-consistent manner, mainly because of cloud-cover, and data handling problems. Among possible options is the use of SAR in an interferometric mode.

The SES Program proposes to establish an interagency working group to develop an implementation plan for acquisition of topographic data that will satisfy a variety of needs. In addition to interfacing with an engineering team on technology-related issues, this group will also address problems related to access to existing data which may be limited because of cost or military classification.

3. Measurement Requirements

Different applications of topographic data have different resolution requirements. Many geomorphologic applications require very high resolution (1-10 m horizontal, 0.1 m or better vertical) topographic data in selected areas. Other applications require intermediate resolution (30-50 m horizontal, 1 m or better vertical) coverage of large regions and would benefit from a globally coherent data base. Finally, many geophysical applications have much less stringent resolution requirements (100-1000 m horizontal, 10 m vertical), but they require spatially coherent data on a global basis.

D. GEOPOTENTIAL FIELDS

1. Basis

Higher resolution gravity and magnetic field studies which would permit investigations of the structure and evolution of the continental lithosphere, improve our understanding of the marine magnetic field, and provide a true gravimetric geoid for oceanographic investigations, have been a high priority within the Earth science community for the past two decades.

Gravity and magnetic fields are two of only a very few ways for viewing the physical state of the Earth beneath its surface and its variation with time. In the next 10 years the opportunity exists to provide the Earth science community with precise, global observations of the gravity and magnetic fields and their rates of change in order to address an array of scientific problems spanning all regions of the Earth from its surface to its core and time scales from years to billions of years.

The feasibility of measuring secular variation of the Earth's gravity field has only recently been demonstrated using Lageos-I and Starlette data, but it is a problem that is best addressed with space technology. The secular change in gravity is dominated at the longest wavelengths by the signal from post-glacial rebound, with smaller signals at higher wavenumbers predicted from mass redistribution associated with melting of glaciers, changes in groundwater, earthquakes, volcanic eruptions, and tides. Secular variations in gravity at the shorter wavelengths thus provide a measure of the mass changes caused by atmospheric warming, sea level rise, and the associated response of the solid Earth that complement other means of monitoring global change, such as sea surface temperature and tide gauge measurements.

2. Approach

The 1990's time period offers exciting opportunities for extremely rapid advancement in terrestrial potential field studies. A number of geopotential missions have been proposed by NASA and the space agencies of other nations that would ultimately achieve the scientific requirements for high-resolution global gravity and magnetic fields, as well as make significant progress in resolving the temporal variations in these fields.

The first opportunity in the 1990's to demonstrate the feasibility of directly measuring gravity in low-Earth orbit using gradiometry is ARISTOTELES. NASA is continuing to study ways to enhance the mission, such as by contributing magnetometers to measure the crustal magnetic field and subsequently in a high altitude phase to measure the Earth's main magnetic field, and by contributing GPS receivers to improve satellite tracking.

As a follow-on to ARISTOTELES, NASA should also continue its support for instrument development and Phase A/B studies for a lower altitude, more sensitive SGGM, which will achieve the scientific requirements of 1-2 mgal accuracy at less than 100 km resolution.

Gravity Probe-B (GP-B), a mission from the physics community to measure the relativistic Lense-Thirring effect, should be extremely sensitive to the intermediate to longer wavelengths of the gravity field. These data would be very useful if the SES Program were to provide modest support for adding a GPS receiver to GP-B for more precise tracking by FLINN stations.

The resolution of the marine gravity field via radar altimetry will be improved by ESA's ERS-1 mission. Currently, NASA has a formal agreement with ESA to track the ERS-1 satellite with its

SLR network. The ERS-1 altimetric data will be of more use to the SES community if the mission is flown with a long repeat time to acquire dense track spacing.

Still in the feasibility stage of planning are generic studies of missions to measure temporal changes in gravity ("delta g"), perhaps by a number of small Lageos-type satellites tracked by lasers at FLINN stations, as well as other mission designs for obtaining high-resolution gravity, such as using lasers to measure the changes in range between two satellites tracking each other in low orbit.

Converting space observations to equivalent gravity anomalies observed at the Earth's surface and combining the results for many different kinds of missions is a major undertaking which requires continued commitment of NASA to gravity modeling studies in order to realize the potential from any of these missions.

In addition to NASA's efforts to add magnetometers to the ARISTOTELES mission in order to obtain an accurate crustal field, a very high priority in the Earth science community is the high altitude, long-duration MFE/Magnolia mission, a candidate for a NASA Earth Probe mission. NASA should also continue studies of other methods of monitoring the core field, such as deploying tethered magnetometers from the EOS, and development of better instrumentation. As with gravity, in order for the data from these missions to be of use to the scientific community, there must be ongoing efforts to accurately and efficiently reduce, combine, and represent the magnetic field measurements.

There is also a need for airborne flights of gravity field and magnetic field sensors to meet requirements for the higher spatial resolutions. This need requires coordination with other agencies currently utilizing airborne gravity and magnetic gradiometers and may lead to the development of high resolution gravity and magnetic gradiometers suitable for use in aircraft. Airborne missions will also require precise aircraft positioning (especially in the vertical) in a controlled reference frame, both of which can be provided by the fiducial GPS stations working in parallel with an airborne GPS receiver in a differential mode.

3. Measurement Requirements

The signals of interest for mapping gravity and magnetic anomalies from sources in the crust and lithosphere require accuracies of a few mgals and nT, respectively, with spatial resolution of 100 km or less. Geopotential field data at this accuracy and resolution acquired by field parties and aircraft flights are available for less than one quarter of the Earth's land area, with political and geographical barriers preventing further data collection by conventional geophysical exploration methods.

In the case of magnetic field observations, it is difficult to combine local surveys from different epoches to make regional maps of the crustal field due to unmodeled secular variation of the core field. Knowledge of the secular variation of the magnetic field is important not only for properly isolating the crustal magnetic field, but also for constraining models of the core dynamo. Such information is inadequately sampled by sparse ground observatories but easily measured from space via either long-lived missions (>5 years) or repeated missions (~1/decade).

E. VOLCANISM AND ITS EFFECTS ON CLIMATE

1. Basis

That large-scale volcanic eruptions can have observable effects on the Earth's climate is widely recognized. Such observations date back over two hundred years when Benjamin Franklin correlated the decrease in temperatures in western Europe with the 1783 eruption of the Laki volcano on Iceland. A new term, "Volcanic Winter"[29], has been coined to describe the effects of large eruptions on hemispheric temperature and climate, and it is evident that both explosive and lava-producing eruptions can have major impacts on climate and the biosphere. Essential questions still remain, however, concerning the bounds of these effects in terms of degree, duration and spatial extent.

In broad terms, it is known that the climatic effects of volcanism are due to the emission of sulfur dioxide (SO_2) (because it results in absorption of solar radiation), aerosols, and possibly other gases such as chlorine (Cl) and fluorine (F) (because of their effects on the ozone layer). The injection of these gases and particles into the stratosphere during very explosive eruptions (such as Tambora in 1815, Krakatau in 1883, and El Chichon in 1982) warrants particular attention, and is an interdisciplinary investigation that NASA should address. The study of these effects can be considered in three phases linked to the history of the gases:

a. The first phase concerns characterization of the flux of the SO_2, Cl_2, F_2, as a function of factors such as the type of magma and the tectonic setting of the volcano. This knowledge will permit the extrapolation of data from one type of volcanic/tectonic setting to the general population of volcanoes and geologic environments around the Earth.

b. Gases and particles injected into the stratosphere can be transported around the Earth, and can have residence times of months to a few years. The dispersal of these materials is almost impossible to monitor without spaceborne techniques, due to the scale and high altitude of the phenomena. Modeling the reaction of SO_2 to H_2SO_4 (the aerosols that attenuate solar radiation) is very important in order to study changes in atmospheric chemistry and climate.

c. Modeling climate effects of these constituents comprises the third phase of this effort. It will be important to study the global dispersal of volcanic gases, model the hemispheric and global changes in atmospheric chemistry, and correlate these observations with data on atmospheric temperature, sea surface temperature, vegetation productivity and annual rainfall.

Major drops in temperature have been observed for several years after the largest volcanic eruptions, and it is likely that rainfall patterns and, hence, biological productivity, will also be affected. In this manner, data on volcanic eruptions provide a direct input into other aspects of Earth system science.

2. Approach

Three new sensor systems will be needed for thorough study of volcano effects on climate. The first is an advanced Total Ozone Mapping Spectrometer (TOMS) instrument with improved spectral bands which will provide more sensitive and precise SO_2 determinations and may permit the analysis of tropospheric eruption plumes.

The second development will involve the use of ground-based remote sensing systems to provide ground truth and calibration for orbital systems. Data to be collected from these ground systems will include seismicity, tilt, temperature and gas emissions.

A third possibility would be the capability offered by a proposed Orbiting Volcanological Observatory (OVO), a satellite dedicated to volcanological research. A major feature of this system would be the frequency of observations (perhaps as often as once/day) at a high (a few 10's of meters) spatial resolution. The system will be designed to measure the abundances of volcanic gases and to determine thermal emissions from volcanoes. Such a system would undoubtedly have many other uses outside volcanology, including the analysis of transient phenomena such as forest fires, industrial pollution and coastal flooding.

In order to develop the OVO, studies on the requirements for the gas sensor are needed in the near future. This should be followed by Phase A and B studies. The system should be ready for launch as an Earth Probe mission some time in the second half of the decade.

3. Measurement Requirements

The observational measurements required are the following:

a. Observations of newly-erupted volcanoes using existing airborne and spaceborne instruments (e.g., TM, SPOT, TOMS, TIMS, SAR, AVIRIS, and AVHRR) and instruments incorporated on the EOS spacecraft;

b. Automated field monitoring of volcanoes using data collection platforms to monitor gas emissions, seismicity, temperature, and tilt; and

c. Monitoring volcano dome inflation/deflation using GPS and GLRS.

In addition to these measurements, an appropriate number of scientific investigations should be supported in order to interpret the results, construct the models, and develop the parameters for future sensor systems.

SECTION VI. INTERAGENCY AND INTERNATIONAL PARTICIPATION

The NASA SES Program Plan is predicated on the continuation and expansion of the strong interagency and international cooperation in solid Earth sciences which has existed in the NASA Geology and Geodynamics Programs. This Section outlines those areas of activity to be pursued in the 1990's which are anticipated to be of interest to other U.S. federal agencies and international groups.

A. *GLOBAL GEOPHYSICAL NETWORKS*

By their distributed global nature, the measurement networks within FLINN depend greatly upon interagency and international cooperation.

This follows in a tradition from past programs where NASA developed technology has been furnished to other U.S. and international groups for implementation and operation, and data are shared by scientists working at both common and individual approaches to problems in Earth science. In some cases these groups carry out comprehensive programs on their own, but in other cases, the technical and management assistance from NASA has brought a new group with new ideas and energetic approaches into participation.

FLINN will be coordinated with the mandated responsibilities and programs being carried out by other agencies including: monitoring polar motion (NGS), measuring changes in global sea level (NGS), monitoring of time (USNO), monitoring of polar motion variability (USNO), and maintenance of star catalogs (USNO).

Of the approximately 40 VLBI stations now in operation or planned for operation in the 1990's that would support FLINN measurements, all are operated collaboratively by U.S. agencies and international groups. Currently, VLBI data reduction is also an interagency and international venture, with the costs of the U.S. VLBI correlators at Haystack, MA, and Washington, DC, shared by NASA, NOAA, USNO, NSF, and the Naval Research Laboratory (NRL).

There are approximately 40 SLR stations in operation (or planned) around the world that support measurements in crustal motion, Earth rotation, gravity field determination, and precision orbit determination. Within the global SLR network, NASA operates or funds the operation of 11 systems. This number is expected to decrease by at least 2-3 in the 1990's as other countries expand their tracking role and GPS assumes more of the responsibility for intracontinental baseline measurements.

Several nations have launched satellites equipped with CCRs and intended for tracking by SLR systems. The more recent satellites include Ajisai (Japan), Etalon-1 and -2 (U.S.S.R.). Stella, a French satellite, is expected to be launched in 1995.

In the case of SLR, all of the cooperating partners of the NASA laser network are international organizations. For the most part, each of these organizations forwards its data to NASA for processing and to the CDDIS for archiving and distribution.

FLINN will be far more extensive than the existing VLBI and SLR Networks. Like the VLBI and SLR activity, the FLINN activity will build on interagency and international cooperation. It is anticipated that NGS and USNO will participate with NASA in the establishment of additional U.S. sites. Agreements with other countries will be used as the basis for FLINN sites, with equipment and operation costs shared by the participating countries, as appropriate.

Since the FLINN sites are natural nodes for the location of other measurement and monitoring devices, it is anticipated that other U.S. programs and agencies and international organizations will be interested in using the mature development of these sites for the implacement of magnetometers, gravimeters, seismometers, weather monitoring devices, or other instrumentation such as DORIS (France) and PRARE (Germany) ground stations.

The requirements and configurations of the permanent and mobile DSGS networks will be developed with the participation of NOAA, NSF, and USGS, and the active international organizations that have GPS programs in progress or under development.

Since the GPS receivers are becoming inexpensive and highly automated, the threshold for participation is low, and it is anticipated that a large number of groups will participate in the network operation. It may develop that it would be advantageous to make the receivers available on long-term loan to local university groups in exchange for their operating the unit and furnishing the data.

B. AIRBORNE GEOPOTENTIAL FIELD MEASUREMENTS

The SES program has a need for the capability to make high resolution airborne measurements of land topography and surveys of gravity and magnetic fields. Since other agencies and several countries have similar needs and some capabilities for these measurements, NASA plans to work with these groups to develop the procedures and costing arrangements for acquisition of these data. In cases where science requirements cannot be met with existing instrumentation NASA would consider development or co-development of the required instrumentation with another agency or country. The data acquired by the airborne activities would be shared by the participants and generally available to the scientific community.

C. REMOTE SENSING

NASA anticipates much common interest with other U.S. and international agencies in pursuit of Solid Earth Science goals within the broader context of the U.S. Global Change Research Program, the International Geosphere-Biosphere Program, and the International Decade of the Natural Hazard Reduction. Collaborative efforts among investigators utilizing NASA remote sensing data and *in situ* data collected by collaborating agencies are encouraged.

Many of the diverse requirements for remote sensing technology beyond that currently in existence will be met by the planned complement of EOS polar orbiting platforms of NASA, ESA and Japan. For example, the HIRIS and its aircraft prototype the AVIRIS provide high spectral resolution remote sensing information in the visible-infrared portion of the electro-magnetic spectrum, the Japanese ITIR and its NASA aircraft prototypes (TIMS and TIIS) provide information in the thermal infrared portion of the spectrum. A team of NASA scientists is working with the Japanese to define the features of ITIR and develop an improved capability to produce quantitative stereo images with a spatial resolution of 15 m. The NASA/X-SAR consortium (consisting of the German Aerospace Agency and ASI is developing an X-Band SAR sensor for EOSSAR which will have the same multiple-wavelength, -incidence angle, and -polarimetry capability as SIR-C/X-SAR and NASA's prototype aircraft AIRSAR.

An international policy needs to be established whereby existing and future remotely sensed data would be processed to a common reference base and made available at minimal cost to all program-funded investigators. The EOS Data Information System (EOSDIS) is currently pursuing this goal together with NASA's interagency, international, and academic partners in EOS.

D. TOPOGRAPHIC MEASUREMENTS

The NASA Earth Science and Applications Division recognizes the need for a global topographic data set which would support the science investigations in a diversity of disciplines, and has assigned the SES Branch the role of coordinating NASA activities in this area. NASA is currently working with ASI to develop an aircraft prototype of a possible Earth Probe class radar interferometer (see Section G.1.c.) as part of the NASA-ASI Topographic Science Working Group's effort to evaluate the science requirements and possible technological means of acquiring a global topographic data set. In addition, NASA is evaluating stereo-optical techniques using satellite and aircraft data and laser altimetry techniques using an airborne laser altimeter.

E. *VOLCANISM AND ITS EFFECTS ON CLIMATE*

Several U.S. agencies (USGS and NOAA) have strong interests in the monitoring of volcanic activity, particularly as part of the International Decade for Natural Hazard Reduction. NASA proposes to work with these agencies, and with other countries having similar interests, to develop joint programs for implementation.

F. *FIELD AND LABORATORY RESEARCH*

Several of the NASA emphasis areas require field and laboratory work. Since this effort is similar to that conducted by several agencies, it is proposed that these activities be coordinated among the agencies and that the costs be shared where possible.

G. *SPACE MISSIONS*

International cooperation in the development and operation of the space segment of the SES Program is an essential element both in terms of the affordability of these missions and the beneficial effects of scientific collaboration.

1. Earth Probes

Opportunities for international collaboration include the following Earth Probe mission candidates:

a. The ESA ARISTOTELES mission under consideration as a joint activity with NASA.

b. The MFE/Magnolia planned as a joint activity with CNES.

c. Joint NASA/ASI conceptual and definition studies for the development of a mission for the mapping of high resolution global topography.

d. Studies of small Lageos-type satellites for measurement of the secular variations of the gravity field.

NASA plans to encourage the participation of other countries in the missions which may follow from these studies.

2. SGGM

This will be a major mission and will require funding at a level of about $300M. Several prospects for international cooperation should be explored. These include joint development with ESA as a follow-up to the ARISTOTELES mission and/or direct cooperation with another country.

3. Lageos-II and III

Lageos-II, a joint mission between ASI and NASA, is expected to be launched in mid 1992 and will significantly enhance the accuracy and efficiency of the global laser network.

Lageos-III, a possible NASA/ASI mission, is primarily intended to be paired with Lageos-I as a test of general relativity. However, the Lageos-I, III combination provides an unparalleled opportunity to study tidal effects, the influences of non-gravitational forces (such as variations in Earth albedo, spacecraft thermal imbalances, and proton drag), and to test the predicted Lense-Thirring effects of general relativity.

SECTION VII. PROGRAM IMPLEMENTATION PLAN

In this Section, the long-range plan for the SES Program is developed. This plan which incorporates the recommendations of the Coolfont Workshop builds on the on-going activities of the Geodynamic and Geology Programs. It assumes that in the near term the funding level for the SES Program will be continued at the level of the combined Geology and Geodynamics programs with some moderate increases in future years. The Program Plan schedule for some of the major milestones is shown in Figure 1.

A. *SPACE GEODESY*

1. FLINN

The primary emphasis in Space Geodesy for the next decade will be the implementation and operation of FLINN and DSGS. As defined, FLINN will be a global network of some 200 sites with station precision of a few millimeters; an average station spacing of 1000 km; and at least three sites on each major plate. FLINN will also support the high-accuracy tracking needs of satellites such as ERS-1, TOPEX, EOS, ARISTOTELES, and GP-B; will provide the global tracking needed for GPS orbit determination and geometric rigidity; and will support the DSGS.

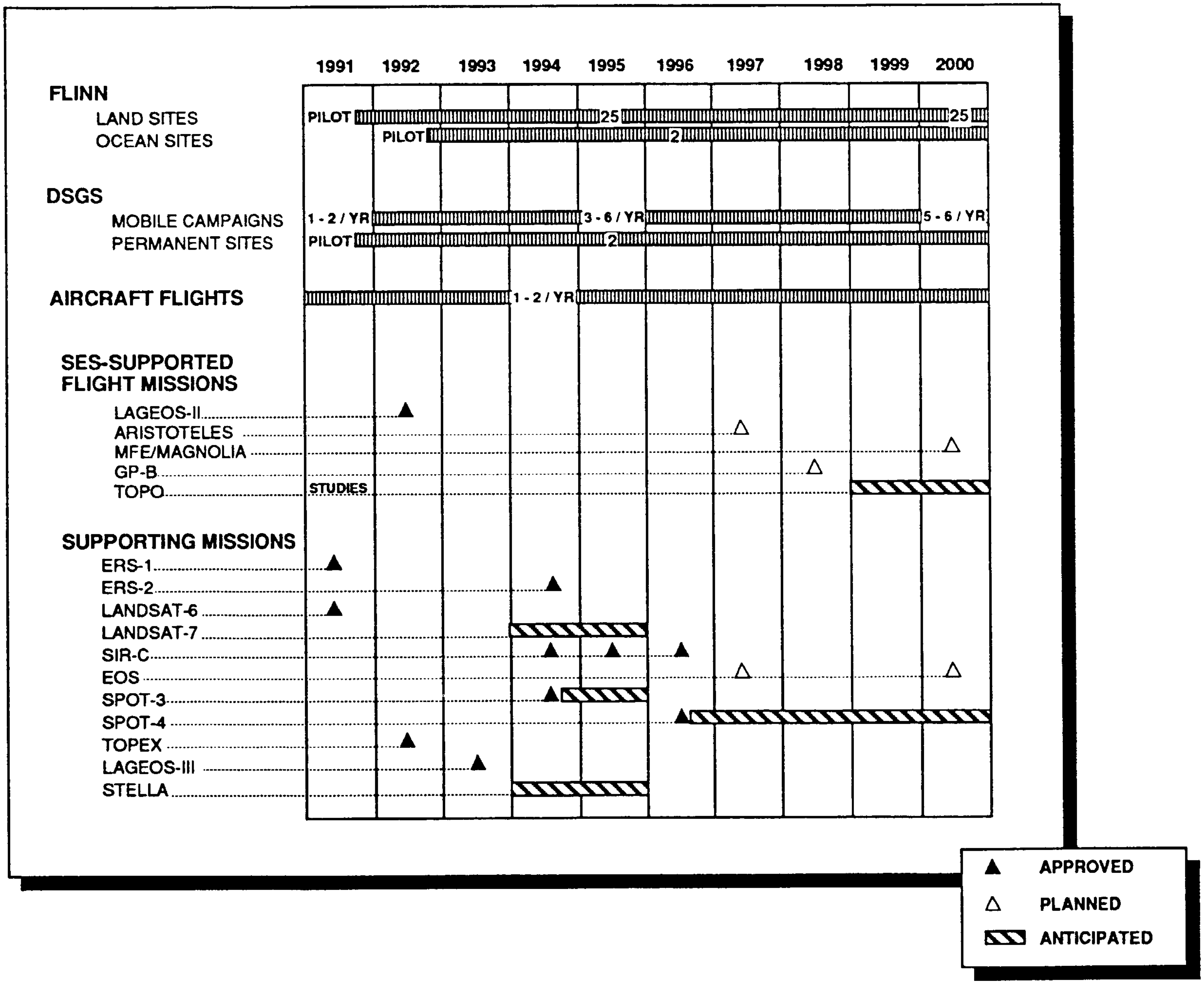
Establishment of a global network of this magnitude will be a major undertaking and will necessitate the involvement of U.S. federal agencies and many of the countries of the world.

The NASA portion of FLINN will build on the networks of VLBI, SLR, and GPS sites that exist as part of the CDP and related programs. Currently, NASA funds the operation of 11 fixed and mobile SLR stations and 3 fixed and one mobile VLBI station. Beginning in 1992, almost all of the NASA mobile stations will be assigned to permanent locations selected on the basis of a study to be completed in early 1991.

There are approximately 80 VLBI/SLR sites owned and operated or planned by other agencies and other countries. Together these sites form a basic global network with highly variable station spacing. North America and Europe are particularly well covered, but most other plates have few if any stations on them at present. The southern hemisphere requires the most attention and is likely to be the beneficiary of any relocated NASA stations. The remainder of the 200 FLINN sites will most likely be permanent GPS-only stations.

At present, most of the permanent space geodetic stations in North America and Europe are either SLR or VLBI systems, a few stations include both. The process of colocating NASA, NGS, and some foreign VLBI stations with GPS receivers has begun and is expected to be completed in a few years. The location of geodetic GPS receivers at SLR sites has lagged somewhat, but because of

FIGURE-1 SES PROGRAM PLAN



the low cost of implementing a receiver at an existing site (essentially the costs of the receiver only), this too should be completed for NASA stations in a few years. The colocation of GPS receivers with VLBI and SLR will provide for the maintenance of the terrestrial reference frame including important checks on the difference in reference frame for the different techniques, and the needed overlapping histories if a later decision is made to replace the VLBI or SLR system. The colocation of SLR and GPS also supports the development and verification of spaceborne GPS precise navigation techniques such as planned for the TOPEX mission.

As soon as the availability of less expensive high-accuracy, GPS systems make it possible, probably 1992, the gradual densification of FLINN can begin with NASA's assumption of the development and operation of some 25 additional globally-distributed sites. The first pilot sites should be in place in 1991. The rest will follow according to a schedule which has all 25 in operation by 1995.

In order to measure plate motion across Earth's many submerged plate boundaries, it will be necessary to develop a reliable, accurate sea floor positioning system. These studies have been underway for several years and are planned to continue with a pilot test of the system in the early 1990's. Assuming these tests demonstrate that sea floor measurements with centimeter (or better) precisions are achievable, the first ocean sites will be established in 1996.

To implement FLINN it will be necessary to re-negotiate NASA's cooperative agreements to incorporate the existing U.S. and foreign stations into an integral network. These discussions will also extend to the development of agreements with countries in those portions of the world where coverage does not exist or where it is still sparse.

The scientific objectives which FLINN will support also require a significant improvement in measurement precision. The development of the technology to achieve precisions of a few millimeter for VLBI measurements is well underway. Upgrading of the five NASA and NOAA stations to this precision is expected to be completed by 1992. The goal of 1 mm is more elusive, but should be achievable by 1995. The demonstration of 3 mm precision for the NASA SLR stations will require several more years, probably to 1992. However, since there are more SLR stations to upgrade and since a significant interruption of the SLR network would impact the laser tracking needs of a number of missions, it is planned that only two stations would be upgraded each year. This is expected to be completed by 1997. At the present time it appears that further improvements in the accuracy of laser ranging is only achievable by major modification or replacement of the existing systems, at considerable cost. Therefore, the SES Program Plan does not include a 1 mm SLR capability.

While there are indications based on isolated results of the achievement of comparable accuracies (at the few centimeter level) for long baseline (few thousand kilometer) GPS and VLBI measurements, it is clear that a substantially larger data set is needed. This is expected to occur as a natural consequence of the acquisition of GPS data at the global VLBI sites, and by 1992 it should be possible to make a definitive assessment of the relative accuracies. Until this has been accomplished, it is not possible to project what further improvements in GPS technology are needed to realize accuracies of a few millimeter for long baselines.

The VLBI/SLR/GPS technology developed by NASA will be made available to other interested countries. Besides encouraging these countries to upgrade existing systems or to procure new systems if upgrades are not feasible, NASA will provide technical support for these upgrades.

The addition of other instrumentation at FLINN sites is an essential part of the overall concept of FLINN. However, this is expected to be accomplished as part of the activities of other elements of NASA, other U.S. agencies, or other countries. The SES Program plans to encourage such activities. In addition, the SES Program plan provides for the procurement of a sufficient number of GLRS CCRs to locate at least one at each FLINN site.

2. <u>DSGS</u>

The DSGS deployments will take several forms: the first consists of sites where GPS receivers will be deployed approximately once per year and the same receivers will be used to service sites in many regions; the second consists of regions with a large number of permanently installed receivers; and the third type consists of permanent regions that will be visited on an infrequent basis by other receivers to further densify the measurements. Most of the designated permanent regions will be initiated using mobile receivers.

It has been assumed that the entire global application of DSGS will involve measurement networks in some 25 regions. For some of these regions networks have already been established or are planned in the next few years. These include the NASA-supported measurements in Central And South America (CASA); the pilot permanent array in southern California; arrays in Greece and Italy established by several groups; and arrays in Japan, Tibet, and Turkey.

The SES Program will support the establishment and operation of arrays in ten, yet to be defined, regions: including the CASA Network and the California permanent array. Regional campaigns using GPS systems will be gradually increased from the 1-2 per year now operated by NASA to about 3-6 per year in the early 1990's. In addition, it is assumed that NASA will contribute to campaigns of other agencies or groups through the sharing of receivers, analysis of data, and global tracking support. During the decade, four of these regions will be assigned permanent arrays.

Significant progress in the development of real-time data handling and analysis capability will be required before large numbers of continuously operating GPS array are feasible. Experience with large volumes of data from permanent systems will be provided in the early 1990's through the California pilot. By the second half of the decade, a dozen such arrays might be operating in conjunction with other federal agencies in active tectonic regions. Late in the 1990's, GLRS densification of selected areas will begin, further increasing the number and frequency of site measurements in active areas.

B. REMOTE SENSING

A primary new emphasis in remote sensing in the 1990's will be the studies of land surface (emphasizing soils). Emphasis will also be placed on continuing the study of processes of change associated with climate, volcanology, and tectonics. This research depends greatly on the availability of high spatial and spectral resolution data from existing and planned sensors carried on space platforms. This includes data from the Landsat TM; stereoscopic data from SPOT; data from AVHRR, HIRIS, TIMS, ITIR, and SAR instruments; and data from topographic scanners and others. The acquisition and initial processing of these data will be provided by other NASA program elements. The SES Program will support the analyses of these data and the continued acquisition of airborne data.

Use will also be made of data to be acquired by ERS-1 and SIR-C. Effort is also expected to continue on the development of algorithms for the processing of data.

As part of the new soil emphasis, it is planned that a pilot program will be initiated in fiscal year 1991 using four regions as foci for the development of algorithms to characterize soil composition. Ultimately, a global soils distribution map will be produced, and several means of periodic updating for erosion and degradation will be utilized. Support is also planned for the continuation of field and laboratory work, mostly as a cooperative effort with other agencies.

1. Instrumentation Development

The instrumentation currently on board space missions or planned for flight on EOS were developed from the early 1970's to the late 1980's. Further advances in sensor technology now makes possible the development of a next generation of instrumentation which is optimized for the spectral frequency and resolution required for soils research. The specific requirements are outlined in the report of the Measurement Techniques and Technology Panel (Volume-III).

2. Topographic Mapping Mission

In 1991, Phase A studies will be initiated to evaluate the several techniques available for mapping the Earth's topography. Additional studies (Phase B) will be supported a few years prior to the initiation of the mission as a new start under the Earth Probe budget line.

3. Airborne Systems

Airborne systems will be used to test sensor concepts and to provide high resolution data for select areas. These flights are expected to continue after the space segment is in place both to provide calibrated areas for verification of the space data and to continue acquisition of specialized data sets.

C. GEOPOTENTIAL FIELDS

The development of gravity and magnetic field models of the Earth is expected to increase with the acquisition of new data. Gravity data of higher spatial and spectal resolution are needed to support the objectives of the SES Program. Similarly, measurements of the main magnetic field for an extended period of several decades and higher resolution measurement of the crustal magnetic field have been identified as high priorities.

As discussed in earlier Sections, plans exist for several space missions which will contribute to the formulation of improved models and hence to the research which these models support.

1. APPLICATIONS and RESEARCH INVOLVING SPACE TECHNIQUES OBSERVING The EARTH'S fIELD from LOW EARTH orbiting SATELLITE (ARISTOTELES)

ESA anticipates that ARISTOTELES will probably be launched in 1997. The current mission scenario is for the spacecraft to be placed into a medium altitude orbit by an expendable launch vehicle. During the subsequent three-month period the spacecraft will descend to 225 km for the gravity field and crustal magnetic field measurements. Following an approximate six-month period at low orbit, the orbit will be raised to 600 km where the mission will continue for about three years for the measurement of the Earth's main magnetic field.

It is planned that NASA participate in this mission in several ways:

a. By funding the development of boom-mounted magnetometers for measurements of both the crustal field and the main field;

b. By providing a launch vehicle, and

c. By providing an on-board GPS receiver to improve the quality of the gravity field data.

An ESA decision on initiation of Phase B studies (equivalent to a new start) is expected in early 1991. These studies should be completed in late 1991, and fabrication of the spacecraft would probably start in late 1992. ESA's current baseline scenario includes NASA's proposed participation. In 1990 studies will be conducted to define the subsystem design for the magnetometers and receiver. In addition, studies are planned to assess the effects of spacecraft and mission parameters on the accuracy and resolution of the gravity measurements.

2. Magnetic Field Explorer (MFE)/Magnolia

The NASA/CNES Joint Phase A and B studies for this mission were completed in 1988 and 1989, respectively.

Currently MFE/Magnolia is a candidate for an Earth Probe Mission.

3. Gravity Probe (GP)-B

GP-B is planned to verify portions of general relativity. However, studies indicate that the unique features of the mission augmented with a GPS receiver and laser CCRs would make it particularly useful for measurement of the intermediate wavelength gravity field. A mission new start is expected in 1995, with a launch near the end of the decade. In preparation for a possible new start, the SES Program plans to initiate a small study of the integration of the equipment needed for the gravity field measurements.

4. Time-varying Gravity Fields

The concept is to develop a system of satellites that will provide information on the variable component of the Earth's gravity field. Studies are planned to define the requirements and to explore various methods for implementation. A candidate approach is the launch of a series of small satellites with laser CCRs (Mini-Lageos).

5. Superconducting Gravity Gradiometer Mission (SGGM)

This is a dedicated mission planned for the acquisition of gravity field data of very high accuracy (few mgals) and spatial resolution (50 km). Sensor development has been underway for the past decade and is planned for completion in 1992. An interagency study team has prepared a pre-Phase A report on spacecraft concepts. A review team has been established to evaluate the current state of development and to provide an assessment of the long-term prospects for development of a flight instrument.

D. VOLCANIC EFFECTS ON CLIMATE

This activity will concentrate initially on volcanoes in Hawaii (Kilauea and Mauna Loa) and Alaska (Mt. St. Augustine) and will be extended to eventually include about 20 volcanoes.

Data will be acquired using aircraft missions at intervals of 1-2 years; implanted sensor packages; and space missions and experiments such as ERS-1, EOS and SIR-C.

E. SCIENTIFIC INTERPRETATION

The scientific interpretation of SES data currently is supported at a level of about 20% of the total budget. In the 1990's, this support is planned to increase both in terms of the number of investigator teams and the funding level. With the advent of new data sources, particularly the data volumes expected from the EOS, careful consideration must be given to the processing, archiving, and retrieval of data. The Geology Program currently uses the Pilot Land Data System (PLDS), an interactive data system in the archiving of remote sensing and ground data, and the CDDIS serves the Geodynamics Program. It is anticipated that both of these systems will be integrated into the EOSDIS by the mid-1990's.

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APPENDIX

GLOSSARY OF ACRONYMS AND ABBREVIATIONS

AIS	Airborne Imaging Scanner
AIRSAR	Airborne Synthetic Aperture Radar
Ajiasi	Passive laser satellite (Japan)
ARISTOTELES	Applications and Research Involving Space Techniques Observing The Earth's field from Low Earth orbiting Satellite
ASI	Agenzia Spaziale Italiana
AVHRR	Advanced Very High Resolution Radiometer
AVIRIS	Airborne Visible and Infrared Imaging Spectrometer
BMTF	Bundesministerium fur Forschung uad Technologic (FRG)
CCRs	Corner Cube Retroreflectors
CDP	Crustal Dynamics Project
CDDIS	Crustal Dynamics Data Information System
cm	Centimeter
CNES	Centre Nationale d'Etudes Spatiales (France)
Cospar	Committee on Space Research (UN)
CSTG	Commission for coordination of Space Techniques for geodesy and Geodynamics
DORIS	Doppler Orbitography and Radio positioning Integrated by Satellite (France)
DSGS	Densely Spaced Geodetic Systems
E	Eotvos Unit (10^{-9} sec^{-2})
EOS	Earth Observing System
EOSDIS	Earth Observing System Data Information System
EOSSAR	EOS Synthetic Aperture Radar
ERS-1	Earth Remote Sensing satellite (ESA)
ESA	European Space Agency
ESSC	Earth Science System Committee
Etalon	Passive satellite with CCRs (U.S.S.R.)
FLINN	Fiducial Laboratory for an International Natural science Network
FRG	Federal Republic of Germany
GEOS	Geodynamic Experimental Ocean Satellite
GGN	Global Geophysical Networks
GP-B	Gravity Probe-B
GPS	Global Positioning System
GSFC	Goddard Space Flight Center
GLRS	Geoscience Laser Ranging System
HIRIS	High Resolution Imaging Spectrometer
Hz	Hertz (frequency - cycles per second)
IAG	International Association of Geodesy
IAU	International Astronomical Union
ICSU	International Council of Scientific Unions
IERS	International Earth Rotation Service
ITIR	Intermediate Thermal Infrared Radiometer
IUGG	International Union for Geodesy and Geodynamics
IUGS	International Union of Geological Sciences
IWG	Investigator's Working Group
JPL	Jet Propulsion Laboratory
km	Kilometer

Lageos-I	Laser Geodynamics Satellite (U.S.)
Lageos-II	Laser Geodynamics Satellite (Italy)
Lageos-III	Laser Geodynamics Satellite (Italy)
Landsat	Land monitoring satellite
LFC	Large Format Camera
LLR	Lunar Laser Ranging
m	Meter
Magnolia	Magnetic field satellite (France)
Magsat	Magnetic field satellite (U.S.)
mas	Milliarcsecond
Medlas	Mediterranean laser project (WEGENER)
MERIT	Monitoring Earth Rotation and Intercomparison of Techniques
MFE	Magnetic Field Explorer (U.S.)
mgal	Milligal (10^{-3} cm sec^{-2}, approximately 10^{-6} g)
MLRS	McDonald Laser Ranging Station
mm	Millimeter
MODIS	Moderate Resolution Imaging Spectrometer
ms	Millisecond
mr	Milliradian
MSFC	Marshall Space Flight Center
NASA	National Aeronautics and Space Administration
NGS	National Geodetic Survey
NOAA	National Oceanic and Atmospheric Administration
nm	Nanometer
NRL	Naval Research Laboratory
ns	Nanosecond
NSF	National Science Foundation
nT	NanoTesla
OSSA	Office of Space Science and Applications (NASA)
OVO	Orbiting Volcanological Observatory
PLDS	Pilot Land Data System
PRARE	Precise Range And Range rate Equipment (Germany)
pps	Pulses per second
SAR	Synthetic Aperture Radar
Seasat	Ocean dynamics monitoring satellite
SES	Solid Earth Science
SGG	Superconducting Gravity Gradiometer
SGGM	Superconducting Gravity Gradiometer Mission
SLR	Satellite Laser Ranging
SPOT	Satellite pour l'Observation de la Terre
Starlette	Passive laser satellite (France)
Stella	Passive laser satellite (France)
TIMS	Thermal Infrared Multispectral Scanner
TIIS	Thermal Infrared Imaging Spectrometer
TIR	Thermal Infrared
TM	Thematic Mapper
TOPEX	Ocean topography experiment
TOMS	Total Ozone Mapping Spectrometer
TSWG	Topographic Science Working Group
USGS	United States Geological Survey
USNO	United States Naval Observatory
VLBI	Very Long Baseline Interferometry
WEGENER	Working group of European Geo-scientists for the Establishment of Networks for Earthquake Research

Report Documentation Page

NASA
National Aeronautics and Space Administration

1. Report No. NASA TM-4256, Vol. 1	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Solid Earth Science in the 1990s *Volume 1—Program Plan*		5. Report Date February 1991
		6. Performing Organization Code SEG
7. Author(s)		8. Performing Organization Report No.
		10. Work Unit No.
9. Performing Organization Name and Address NASA Office of Space Science and Applications Earth Science and Applications Division Solid Earth Science Branch		11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546		13. Type of Report and Period Covered Technical Memorandum
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

This report is contained in three volumes. Volume 1, Program Plan, outlines a plan for solid earth science research for the next decade. Volume 2, Panel Reports, was compiled from papers prepared by the science and program-related panels of a workshop held at Coolfont, W.V., in July 1989. Volume 3, Measurement Techniques and Technology, was prepared to support the science panels.

17. Key Words (Suggested by Author(s)) solid earth science, geodynamics, geology, tectonics, lithosphere, volcanology, land surface, remote sensing, space missions, space techniques	18. Distribution Statement Unclassified - Unlimited Subject Category 42

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price
Unclassified	Unclassified	68	A08

NASA FORM 1626 OCT 86

For sale by the National Technical Information Service, Springfield, VA 22161-2171

NASA-Langley, 1991