Solid Earth Science in the 1990s

Volume 2—Panel Reports

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FOREWORD

With the 1980's came the first widespread recognition that an understanding of the Earth requires a global perspective of the numerous interacting dynamical 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 of 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 at 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 (**Volume II**) was compiled from papers prepared by the Science and Program-related panels of a workshop held at Coolfont, WV in July 1989. **Volume I - Program Plan** - outlines a plan for solid Earth science research for the next decade. The plan is based on the discussions, results, and recommendations of the workshop and the position papers of the Coolfont Panels. **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.

To help develop this 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 Panels' 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.

The collective reports of the Science Panels and the International Panel are presented in **Sections II through XI**. The report of the International Panel is presented in **Section X**. A list of the more common abbreviations and acronyms used in those Reports is provided in **Appendix A**, and a list of the Coolfont Workshop participants and their affiliation is provided in **Appendix B**.

SECTION II.

REPORT OF THE PANEL ON

PLATE MOTION

AND DEFORMATION

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SECTION II.

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SUMMARY

GOALS AND OBJECTIVES

Our goal is to understand the motions of the plates, the deformation along their boundaries and within their interiors, and the processes that control these tectonic phenomena. In the broadest terms, we must strive to understand the relationships of regional and local deformation to flow in the upper mantle and the rheological, thermal and density structure of the lithosphere. The essential data sets which we require to reach our goal consist of maps of current strain rates at the Earth's surface and the distribution of integrated deformation through time as recorded in the geologic record. Our success will depend on the effective synthesis of crustal kinematics with a variety of other geological and geophysical data, within a quantitative theoretical framework describing processes in the Earth's interior. Only in this way can we relate the snapshot of current motions and Earth structure provided by geodetic and geophysical data with long-term processes operating on the time scales relevant to most geological processes.

The wide-spread use of space-based techniques, coupled with traditional geological and geophysical data, promises a revolution in our understanding of the kinematics and dynamics of plate motions over a broad range of spatial and temporal scales and in a variety of geologic settings. The space-based techniques that best address problems in plate motion and deformation are precise space-geodetic positioning —on land and on the seafloor— and satellite acquisition of detailed altimetric and remote sensing data in oceanic and continental areas.

Of the overall science objectives for the NASA Solid Earth Science plan for the 1990's, our interests are most relevant to Objective #4: "Understand the motion and deformation of the lithosphere within and across plate boundaries", and are also clearly pertinent to understanding the dynamics of the mantle, the structure and evolution of the lithosphere, and the landforms that result from local and regional deformation (Objectives #2 and #3).

In order to reach our goal of understanding plate-scale tectonics and kinematics, we have identified major objectives for the development and application of space technology in the context of a NASA program for the 1990's:

1. *Refine our knowledge of plate motions:*

    - Determine the variability of plate motion on time scales short compared with the averaging time of geological plate models;

    - Measure the vector motion between plates with poorly determined or questionable relative velocities;

    - Understand the driving mechanisms of plate tectonics.

2. *Study regional and local deformation:*

    - Determine the kinematics of deformation within plate margins and interiors;

    - Understand the dynamics of plate deformation along plate margins and in tectonically active intra-plate regions;

    - Evaluate the non-rigid large-scale behavior of plates.

3. *Contribute to the solution of important societal problems*

- Alleviate the risks associated with various natural hazards, such as seismic and volcanic activity, and contribute to the International Decade of Natural Hazard Reduction;

- Permit direct measurements of the pattern of vertical displacement of the crust, and thus remove ambiguities inherent to the problem of eustatic sea-level changes, a critical aspect of global warming issues;

- Contribute useful constraints to the search for mineral and hydrocarbon resources.

REQUIREMENTS

In addition to basic space-positioning measurements, the pursuit of these objectives will require the use of global and regional data sets obtained with space-based techniques. These include topographic and geoid data to help characterize the internal processes that shape the planet, gravity data to study the density structure at depth and help determine the driving mechanisms for plate tectonics, and satellite images to map lithology, structure and morphology. These requirements are summarized in the following table:

Measurements	Precision required	Spatial scale/resolution
Horizontal motions		
Variability of plate motion	1-10 mm/yr	10^4 km
Vector motion between plates	1-10 mm/yr	$10^2 - 10^3$ km
Nonrigid plate behavior	1 mm/yr	10^3 km
Regional and local deformation	1 mm/yr	$10^1 - 10^2$ km
Post-seismic deformation	10-100 mm over hours	$10^0 - 10^2$ km
Vertical motions		
Post-glacial rebound	1 - 4 mm/yr	$10^3 - 10^4$ km
Active vertical tectonics	0.1 - 1 mm/yr	$10^1 - 10^3$ km
Thermal & dynamical processes	0.01 - 0.1 mm/yr	$10^2 - 10^3$ km
Continental epeirogeny	0.03 mm/yr	10^3 km
Post-seismic deformation	10-100 mm over hours	$10^0 - 10^2$ km
Satellite images		
Regional studies	10 - 30 m multispectral	$10^2 - 10^3$ km
Local and neotectonic studies	1 m single band	$10^0 - 10^2$ km
Topography & altimetry		
Global continental topography	10 m vertical	1 km
Global oceanic bathymetry	10 m vertical	20 km
Local topography	1 m vertical	10 - 100 m
Gravity		
Regional tectonic studies	1 - 2 mgal	50 - 100 km
Local tectonic studies	0.1 - 1 mgal	10 km
Post-glacial rebound	1 μgal	1000 km
Magnetics		
Global crustal anomalies	1 nT	100 km
Local anomalies	1 nT	1 km

RECOMMENDATIONS

Basic Recommendations

Our panel has four specific recommendations:

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

This can be best accomplished by:

- deploying a world-wide network of dedicated, continuously monitoring GPS stations with 1000 km spacing and measuring relative positions to 1 cm over one day and to 1 mm over three months. Approximately 150 stations will be required on the continents with another 50 stations located on islands, for a total of about 200 stations;

- deploying a full constellation of GPS satellites to support this network.

- continuing a world-wide network of approximately 12 VLBI/SLR sites with at least one on each major plate and several distributed around the Pacific Ocean. These sites must maintain relative positions to 1 cm over one day and to 1 mm over three months to determine earth orientation and GPS fiducial coordinates;

- co-locating GPS receivers at other existing VLBI/SLR stations and ceasing to occupy these stations as soon as it can be done <u>without loss in precision and without offsets in the data series</u>.

- continuing a network of SLR stations with positions relative to the earth's center-of-mass determined with sufficient accuracy to provide adequate orbits for the GPS satellites. At such time as GPS (or some other system) demonstrates a capability of meeting center-of-mass requirements at the same level these SLR sites will no longer be required for this purpose;

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

- Some obvious scientific problems include: the kinematics of major plate convergence systems; the distribution and rate of post-glacial rebound; and the distribution of deformation within tectonically active areas, such as western North America, the Pacific Basin, and the Alpine-Himalayan collision zone. Specific experiments should be selected through a peer-review process to ensure the highest quality of science.

- We recommend that resources be allocated among three modes of operation as follows: continuously recording arrays—45%; mobile campaigns (GPS / GLRS)— 45%; Seafloor positioning campaigns—10%.

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

These requirements are defined as:

- Global, coherent topographic data with moderately high accuracy (10 m vertical and 1 km horizontal). High resolution capability (a few meters vertical and 10 m horizontal) applied in selected areas.

- High resolution satellite images (roughly 1 m pixel size, even if only at single spectral band) for identification of structural, neotectonic and other morphologic features from space. Lower resolution (10 m) needed over a wide range of spectral bands to distinguish different lithologies.

- Globally dense, coherent gravity data to a few mgal at resolution of 50-100 km and local high-resolution gravity data to a few mgal at resolution approaching km.

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

Indispensable technology includes:

- a new generation of systems capable of continuous mm to sub-mm horizontal and vertical positioning on 1 to 1000 km vectors; systems capable of sub-cm relative positioning of moving platforms; and inexpensive (< $10K), transportable (< 5 kg), and rugged instruments with minimal power requirements (~ 1 W);

- monumentation stable at the sub-millimeter level, and marks that can be installed rapidly and economically;

- seafloor mark positioning with a precision of better than 1 cm;

- more efficient and accurate processing techniques to reduce cost of analysis and delay in interpretation of large data sets;

- the creation and maintenance of a permanent geodetic archive for existing data sets and for those collected during the next decade, with common data formats and convenient access;

- effective, affordable, and practical means for exchange and dissemination of remote sensing data such as EosDIS or SESDIS. This effort should be coordinated with other agencies and countries.

A global fiducial network

The most important recommendation of our panel is for the implementation of a world-wide space-geodetic fiducial network to provide a systematic and uniform measure of global strain.   As outlined above, we recommend that this network consist of globally distributed GPS receivers tied to a number of strategically located VLBI/SLR stations. We further recommend that some stations be equipped with an expanded set of additional sensors to facilitate calibration of various space-based data sets. These may include

gravimeters, magnetometers, environmental sensors, and calibrated targets for various orbital instruments, such as those planned for Eos. In the long term, GLRS reflectors should be co-located with the VLBI/SLR and GPS stations.

Direct scientific benefits that will accrue from the proposed network include monitoring of :

Plate motions, especially important for plates with poorly determined vector velocities;

Short-term variations in rates of plate motion and deformation (days to years);

Non-rigid behavior of plate interiors (important for models of plate driving forces);

Rates of post-glacial rebound (constrains viscosity models for the mantle);

Rates of sea-level change (crucial for study of global warming and climate change).

Additional benefits identified by our panel include:

Determination of highly accurate orbits for GPS and other spacecraft;

Mission support and satellite tracking;

Calibration of globally coherent space-based topography, gravity and magnetic data;

Calibration of a global set of GLRS reflectors;

Establishment of an accurate fiducial network for local and regional space-geodesy;

Assessment of natural hazards (earthquakes and volcanoes).

The specifications listed above for the number, density and type of space-positioning stations are based on both scientific and technical considerations: we require at least three sites per major plate to resolve rigid plate motions; mapping of non-rigid behavior within the interiors of plates requires a denser distribution. For example, with a station spacing of 1000 km there will be approximately 30 sites in North America - enough to map the distribution of non-rigid behavior across the continental part of the plate. The cost of deploying this number of VLBI or SLR stations would be prohibitive. GPS provides a relatively inexpensive alternative using current technology. The required accuracy of the network is dictated by the rates of movement that we wish to determine, as described in Table 1.

In tectonically active areas where deformation is concentrated, we need geodetic stations with intersite spacing much smaller than the 1000 km provided by the permanent sites within the network. We therefore recommend a vigorous long-term program of monitoring regionally dense space-geodetic networks through periodic campaigns (every two or three years) using portable equipment. These regional networks will be intimately tied to the permanent geodetic stations. Taken together, these two components —the permanent sites and the regional densification networks— will allow us to create a global strain map of the planet. Furthermore, the permanent fiducial network will foster studies of local and regional deformation because it will provide a means of tying local observations to a global framework and will greatly simplify the computations required to do so.

One of the outstanding problems with existing topography data is their lack of global coherence. Under our proposal, we will have 200 sites distributed around the world with accurately determined absolute elevations. This will permit topographic data sets to be calibrated precisely at each of these sites and removal of any offsets in the data sets. Similarly, enhancement of a subset of the global sites with other devices (e.g. gravimeters, magnetometers, calibrated targets for orbital instruments) will provide superior calibration of a variety of other space-based observations of the earth.

In addition to its obvious scientific benefits, the proposed network will facilitate the quest for natural hazard reduction by permitting study of the phenomena that control seismic and volcanic activity. Comparisons between crustal kinematics, seismicity and other environmental data are crucial to achieve a quantitative understanding of these phenomena. Particularly noteworthy is the need to establish permanent geodetic, geophysical, and environmental facilities in areas of frequent volcanic or seismic activity, so as to acquire a continuous record of short-term behavior immediately before and after major eruptions and earthquakes and to aid in their prediction. Such facilities will also assist in the assessment of global warming through evaluation of absolute sea-level change and estimation of the rate of melting of polar ice-caps. Deployment of the proposed network in the 1990's will thus be timely in its response to the call for an increased emphasis over the next decade on the reduction of natural hazards and evaluation of man-made climate change.

Establishment and maintainance of a global network requires a long-term commitment and a global focus. While inter-agency and international participation is clearly critical to a successful deployment, it is imperative that a single agency take the initiative and the responsibility for the development and implementation. As a mission-oriented space agency with a global outlook, NASA is uniquely poised to lead this effort. As the prime developer of space geodesy, NASA is uniquely poised to tackle this technological challenge. Finally, NASA is perhaps the only agency in a position to make the necessary long-term commitment to this global program. In this light, we view deployment of a space-based geodetic network as an integral part of the *Mission to Planet Earth*.

1. INTRODUCTION

During the previous decade, the NASA program in Crustal Dynamics has been extremely successful in directly measuring instantaneous plate motions. Decadal changes in baselines over intercontinental distances using techniques such as VLBI and SLR match, in general, the values predicted from geologically-based rigid-plate motion models such as RM2 [*Minster and Jordan*, 1978] and NUVEL-1[*DeMets et al.*, 1990] which average tectonic movements over 10^6-yr time scales . This remarkable agreement between short-term motions between plates and those observed on geological time scales has motivated and justified the use of the latter as *a priori* information in the reduction and interpretation of space-geodetic data. In adopting this approach, one recognizes implicitly that the geodetic signals of interest are not plate motions in the classical sense, but the differences between geodetically-derived motions and the geologically-predicted ones. In this light, the primary impact of the NASA program for the 1990's on plate tectonics will be to permit quantitative measurements of departures from the classical geological description of horizontal and vertical motions of the major plates. Such departures fall into two major categories: 1) large scale and regional scale non-rigid behavior (plate deformation and plate boundary zones of deformation), and 2) Time-dependent motions, including post-seismic strains and aseismic deformations.

For example, in the plate tectonic hypothesis, the lithospheric plates are taken to be rigid, their speeds are assumed to remain steady for long periods of time, and their motions are described as rigid-body rotations along the surface of the Earth except at convergent and divergent plate boundaries [e.g., *Le Pichon et al.*, 1976]. However, we know that at some point these predictions must break down. Local and regional departures from rigid plate behavior occur along inter-plate boundaries and within domains of intra-plate deformation. Where deformation involves oceanic lithosphere, it is primarily localized along narrow, well-defined zones that form discrete boundaries between plates. Where plate boundary deformation involves continental lithosphere, it is commonly distributed over complex networks of faults and folds up to several thousand kilometers wide. On a geologic timescale, permanent deformation is commonly partitioned into zones of intense diastrophism along the margins of less deformed crustal fragments whose dimensions range from tens to hundreds of kilometers, and which experience different rates of horizontal and vertical motions. This spatial complexity is demonstrably tied to temporal variations in the pattern of motions. In contrast to global plate motions, the complex history of deformation within regions of plate boundary interaction and intra-plate deformation is known in most areas only at the crudest level of detail.

Many earthquakes occur in plate interiors, with focal mechanisms implying both horizontal and vertical relative motions. The earthquake recurrence time itself imposes a time-dependence to the rate of motion, at least in the vicinity of the rupture: along plate boundaries, earthquakes can reflect a significant fraction of the total relative motion, which takes place episodically. By directly observing such transients as departures from the rigid-plate model predictions we can bound the state of stress in plate interiors, constrain the short-term rheology of the lithosphere and asthenosphere [e.g. *Elsasser* 1969; *Melosh*, 1976; 1977, 1983; *Cohen*, 1984; *Rundle and Jackson*, 1977; *Rundle*, 1988a,b], and test various models of plate-driving forces. On longer time scales, subsidence of basins on the foreland side of thrust belts is known to result from loading of flexurally strong lithosphere by nappe emplacement and by forces that originate at depth within the mantle [*Lyon-Caen and Molnar*, 1985; *Royden*, 1987]. Careful analysis of the timing and magnitude of deformation allow us to constrain ideas about the processes that drive it and about the long-term mechanical behavior of the lithosphere, but the details remain poorly understood.

While the attention of our panel is focused on plate motion and deformation, the details are likely to be of great importance in understanding the driving forces and the interaction between the Earth's crust and mantle. In this respect, the goals of our panel overlap strongly with those of the *"Earth Structure and Dynamics"* and the *"Lithospheric Structure and Evolution"* panels. Likewise, many landforms, from the very local, such as fault scarps, to the regional, such as topographically high mountains, are the direct result of deformation processes, and mandate close ties to the *"Landforms and Paleoclimate"* panel and to the *"Volcanism"* panel.

2. GOAL

Our goal is to understand the motions of the plates, the deformation along their boundaries and within their interiors, and the processes that control these tectonic phenomena. In the broadest terms, we must strive to understand the relationships of regional and local deformation to flow in the upper mantle and the rheological, thermal and density structure of the lithosphere. The essential data sets which we require to reach our goal consist of maps of current strain rates at the Earth's surface and the distribution of integrated deformation through time as recorded in the geologic record. Our success will depend on the effective synthesis of crustal kinematics with a variety of other geological and geophysical data, within a quantitative theoretical framework describing processes in the Earth's interior. Only in this way can we relate the snapshot of current motions and Earth structure provided by geodetic and geophysical data with long-term processes operating on the time scales relevant to most geological processes.

The wide-spread use of space-based techniques, coupled with traditional geological and geophysical data, promises a revolution in our understanding of the kinematics and dynamics of plate motions over a broad range of spatial and temporal scales and in a variety of geologic settings. The space-based techniques that best address problems in plate motion and deformation are precise space-geodetic positioning —on land and on the seafloor— and satellite acquisition of detailed altimetric and remote sensing data in oceanic and continental areas.

Of the overall science objectives for the NASA Solid Earth Science plan for the 1990's, our interests are most relevant to Objective #4: "Understand the motion and deformation of the lithosphere within and across plate boundaries", and are also clearly pertinent to understanding the dynamics of the mantle, the structure and evolution of the lithosphere, and the landforms that result from local and regional deformation (Objectives #2 and #3).

3. PANEL OBJECTIVES

In order to reach our goal of understanding plate-scale tectonics and kinematics, we have identified major objectives for the development and application of space technology in the context of a NASA program for the 1990's:

1. *Refine our knowledge of plate motions:*
    - Determine the variability of plate motion on time scales short compared with the averaging time of geological plate models;
    - Measure the vector motion between plates with poorly determined or questionable relative velocities;
    - Understand the driving mechanisms of plate tectonics.

2. *Study regional and local deformation:*

- Determine the kinematics of deformation within plate margins and interiors;
- Understand the dynamics of plate deformation along plate margins and in tectonically active intra-plate regions;
- Evaluate the non-rigid large-scale behavior of plates.

3. *Contribute to the solution of important societal problems*

- Alleviate the risks associated with various natural hazards, such as seismic and volcanic activity, and contribute to the International Decade of Natural Hazard Reduction;
- Permit direct measurements of the pattern of vertical displacement of the crust, and thus remove ambiguities inherent to the problem of eustatic sea-level changes, a critical aspect of global warming issues;
- Contribute useful constraints to the search for mineral and hydrocarbon resources.

In addition to basic space-positioning measurements, the pursuit of these objectives will require the use of global and regional data sets obtained with space-based techniques. These include topographic and geoid data to help characterize the internal processes that shape the planet, gravity data to study the density structure at depth and help determine the driving mechanisms for plate tectonics, and satellite images to map lithology, structure and morphology.

In the remainder of this section, we elaborate on these objectives, and examine the role of space-based techniques to achieve them, in light of the current state of the art. The associated scientific requirements, in terms of resolution, accuracy, and overall capabilities, will be discussed in Section 4. We base much of the discussion below on Chapter II [*Agnew et al.,* 1989] of the Workshop on *"The Interdisciplinary Role of Space Geodesy"*, held in Erice, Sicily in July, 1988 [*Mueller and Zerbini , eds,* 1989, hereafter referred to as the Erice report].

3.1 Plate motions

Current geological estimates of the relative velocities between the dozen or so major rigid plates are constrained by three basic types of data collected along mainly submerged plate boundaries: (1) spreading rates on mid-ocean ridges from magnetic anomalies, and directions of relative motion from (2) transform-fault azimuths and (3) earthquake slip vectors. The first self-consistent global models were synthesized soon after the formulation of plate tectonics [*Le Pichon,* 1968], and significant refinements have been made since [*Chase,* 1978; *Minster and Jordan,* 1978; *De Mets et al.,* 1989]. Seafloor magnetic anomalies used to constuct these rigid-plate motion models average rates over the last 2-3 million years. This interval is geologically brief, and the small plate displacements that take place during it are well described by infinitesimal (as opposed to finite) rotations. In these models, the formal uncertainties in the angular velocity components are quite small, corresponding to 1 or 2 mm/yr in the predicted rates of relative motions. More importantly, at this level the most recent model for plate motion (NUVEL-1) is consistent with the hypothesis that major plates behave rigidly over a million-year time scale.

There is now convincing evidence that the rates-of-change of geodetic baselines spanning plate boundaries are consistent with the geological estimates [e.g., *Herring et al.,* 1986], provided that the endpoints are located within stable plate interiors. This is

important as a check on the positioning techniques and corroborates the geophysical expectation that the instantaneous velocities between points in stable plate interiors are dominated by secular plate motions (Figures 1 and 2). This means that, for those plates whose motions are well constrained by geological observations, the improvement of existing models of present-day motion among the major plates requires that —for interplate baselines with endpoints located within stable plate interiors— the tangential components of relative velocities be resolved to an accuracy on the order of 1 mm/yr.

It is therefore clear that geologically-based global plate motion models provide a kinematic reference frame in which to analyze short-term geodetic observations, and the kinematic boundary conditions which must be satisfied by models of plate boundary deformation zones. The most important and interesting geodetic signals with characteristic time scales ranging from 0 to 100 years will be departures from predictions of million-year average rates based on geological rigid-plate models. The major types of such departures include non-rigid behavior within plates and along their boundaries and time-dependent (nonsteady) horizontal and vertical motions. Because they must be direct manifestations of detailed aspects of the underlying geodynamical physical processes, these are among the most exciting issues in plate tectonics to be addressed by space geodesy.

3.1.1 Recent changes in plate motions

Space-geodetic (VLBI and SLR) measurements of relative plate motions show that the geological predictions of the directions and rates of plate motion are generally well matched by direct measurements over short time scales. Any changes in plate velocities over a time span significantly shorter than the 10^6 yr would be difficult to detect and document using geological observations alone. Although space-geodetic data sets are still sparse along many baselines and show much more scatter than the geological observations used to construct the rigid-plate models, tantalizing evidence has been uncovered from VLBI that the North Atlantic —probably the best sampled boundary— may be opening at an instantaneous rate slower than predicted from the geology [e.g., *Herring*, 1988]. On the other hand, these observations may be contaminated by vertical drift at Wettzell, FRG, of as much as 10 mm/yr *T. Herring, CDP presentation, 1989*]. The same behavior is seen at the Wettsell SLR station (*Smith et al.*, 1989a). To decide whether we can truly detect changes in plate velocities by space geodesy, we must analyze many baselines crossing a variety of plate boundaries and continue to monitor a global space-geodetic network.

Given a set of interplate baselines connecting the major plates and monitored regularly over a sufficiently long period of time, we will acquire the necessary time series to begin to address the following first order questions, beyond the mere comparison between the geodetic and geologic rates (both globally and locally):

On what time scales are plate motions steady? Is there a global pattern to time dependence? How does this relate to what is occurring on the boundaries of those plates? Is there a correlation with "absolute" motions or hot spot activity?

How is the variability of motion along the strike of plate boundaries related to the variability across and away from the boundary? How does this impact our ideas concerning the physical mechanisms governing plate motions?

We must also note that such observations will affect the definition of global geodetic reference frames. In order to answer such questions, we must pursue a systematic and coordinated program to measure the relative motions of the interiors of major plates using space geodesy. This endeavor requires a global network, and care must be taken to insure continuity and uniformity of the data over decadal time spans, starting with the ongoing programs.
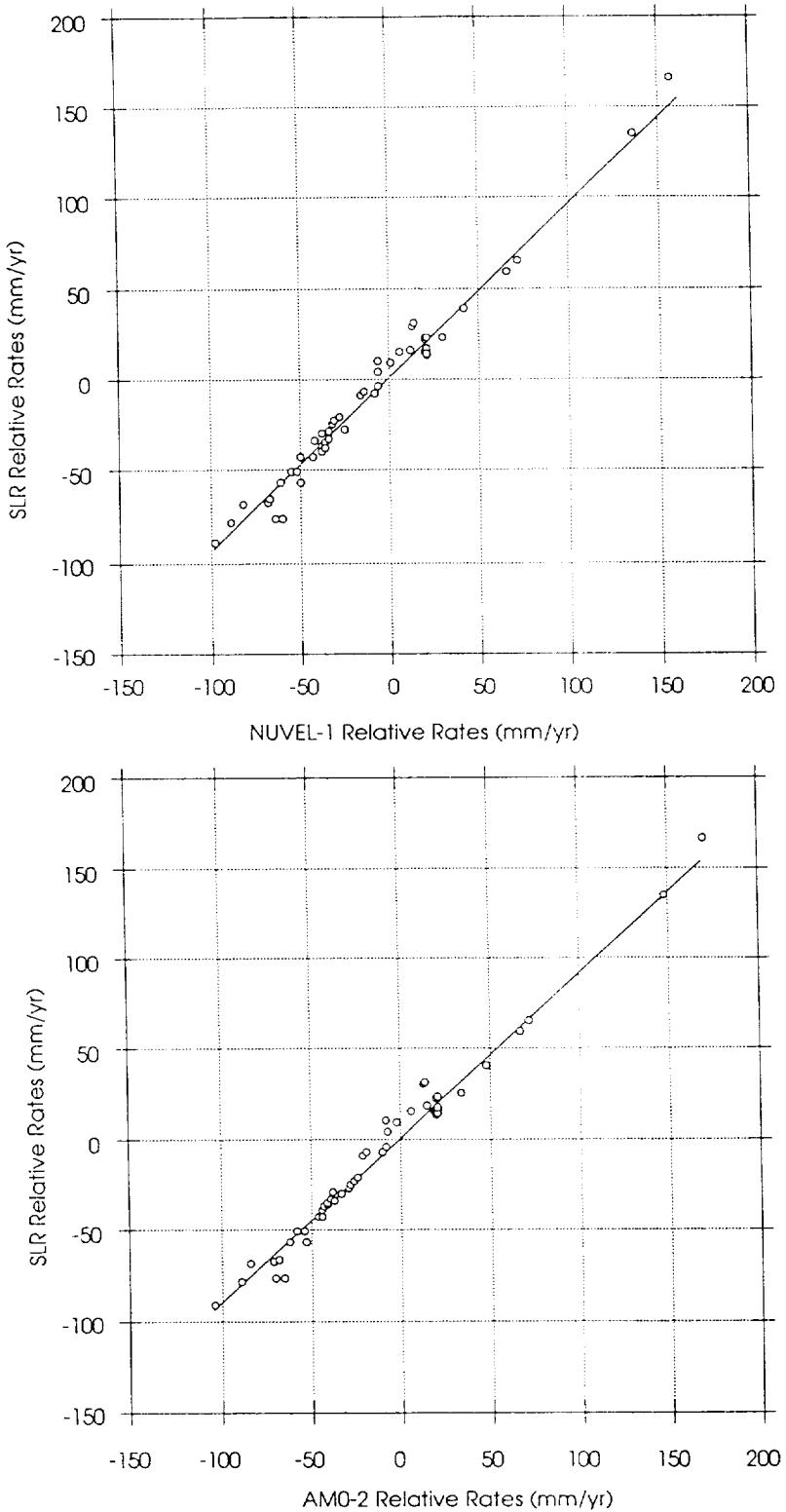
Figure 1. Comparison of observed instantaneous rates of plate motion from changes in baseline length monitored by satellite laser ranging (open circles) with those predicted by two geologic models: NUVEL-1 (upper panel) and AMO-2 (lower panel). In the top frame, the slope of the line is 0.949 ± 0.019, and in the bottom frame, it is 0.914 ± 0.017, indicating close agreement, although the space-geodetic rates are 3% to 7% slower than the geological estimates. (From *Smith et al* [1990]).
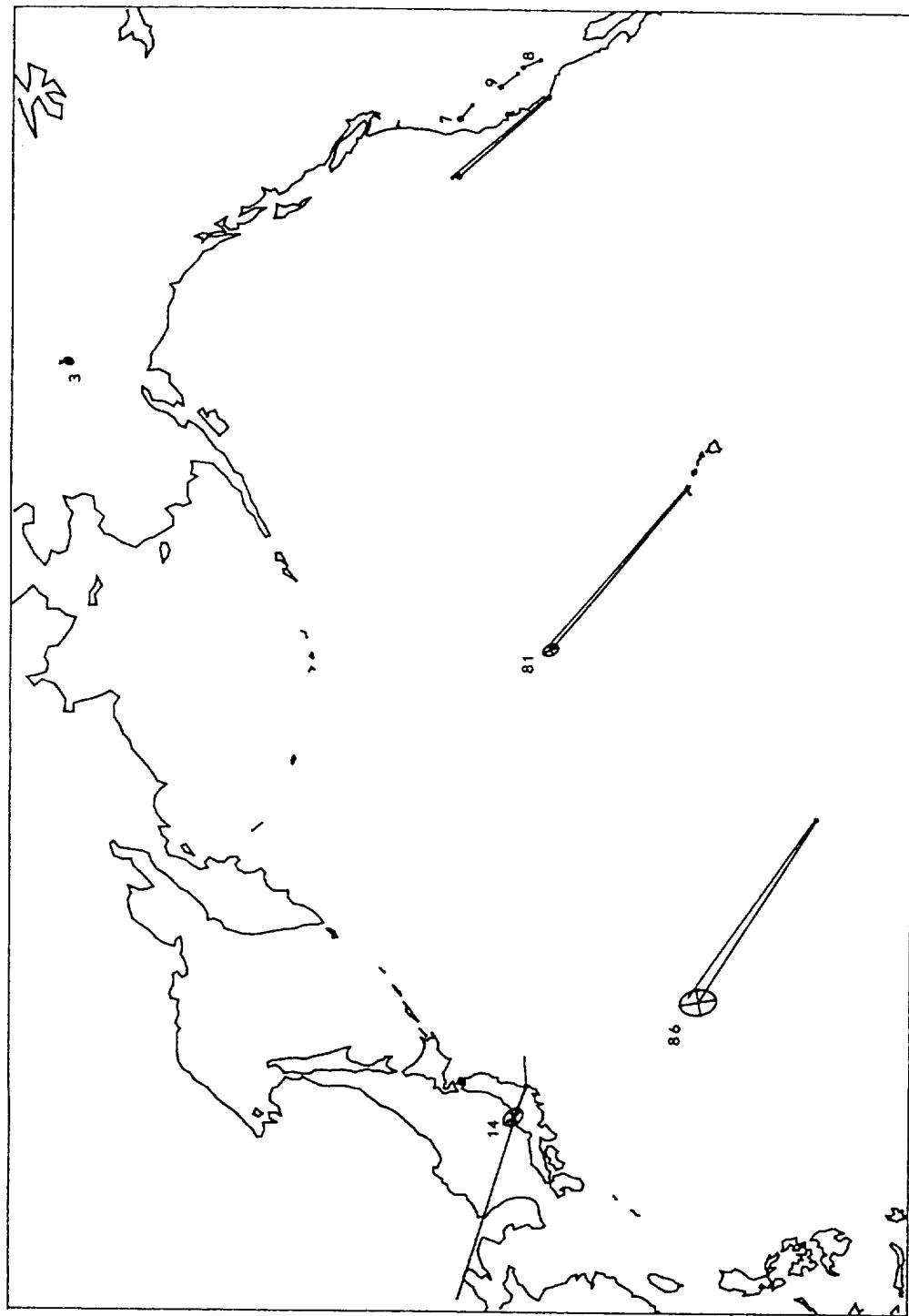
Figure 2. Comparison of vector rates and directions of absolute plate motions determined from geology with the observed instantaneous vector velocities from VLBI measurements (lines which terminate in uncertainty ellipses) for several sites on or bordering the Pacific plate. Note that in almost all cases, the observed vectors fall within the uncertainty ellipses determined from geologic observations. (T. Clark, 1990, personal communication.)

3.1.2 Vector motion between plates with poorly determined velocities

Velocity estimates across all consuming plate boundaries such as trenches and active mountain belts are determined mainly by geometrical inference, assuming the plates to be rigid on geological time scales. The primary geological indicators of the direction of relative motion across such boundaries consist of earthquake slip vectors, which are typically much more uncertain than other direction indicators such as transform fault azimuths, and can be contaminated by local conditions affecting the details of earthquake rupture [e.g. *Minster and Jordan*, 1978; *DeMets et al.*, 1990]. For plates with no spreading boundary, such as the Philippine plate, no reliable rates are available and slip vectors are the only indicators of the direction of motion, so that geological estimates of the motions of such plates are at best extremely uncertain, and quite possibly wrong. In some areas (e.g., SE Asia), the rigid plate model cannot be used even if it is applicable, because the plate geometry is so poorly determined.

Global space-geodetic networks, judiciously densified in such areas, and monitored over a sufficiently long period of time offer the only practical means of addressing these problems by providing direct, quantitative measurements of tectonic motions. However, it is essential to recognize from the outset that, unless we are prepared to wait for a time period long compared to the earthquake cycle, such a geodetic program must be supported by a concomitant effort aimed at improving our understanding of the recent geological and geophysical history of the region. This is a critical point, which is raised again in the context of regional and local deformations: without the supporting field and modeling studies, the interpretation of space-geodetic data in terms of long term geological phenomena will remain doubtful.

The primary focus of such applications of space geodesy in the next decade would be on plate pairs separated by trenches, such as in the western Pacific and along the Pacific coast of the Americas. In such cases, space geodesy can help refine the rigid-plate models locally and permit tests of assumptions, such as plate rigidity. In places where the geological record is difficult to obtain or interpret, such as the Philippine plate and much of the southeastern portion of Asia, space geodesy is the only technique that will provide quantitative constraints on both directions and rates of relative motions.

Some trench boundaries are conveniently characterized by islands on the subducting plate, at relatively short distance from the trench axis. These islands would make it relatively easy to establish and monitor fairly short baselines spanning the trench with which to determine the local convergence vector. This is unfortunately not always the case; without emerged land seaward of the trench at a reasonably short distance, we may have to rely on long baselines tying points far removed from the trench axis, and it becomes difficult to unravel the tradeoff that exists between apparent relative plate motion and plate deformation. In such instances, the emerging technology of precise sea-floor positioning provides an exciting alternative, particularly when even cm/yr observations are sufficient to test or even improve significantly our models.

3.1.3 Driving Mechanisms

Because the relative motions between plates constitute the known boundary conditions that any successful model of mantle circulation must satisfy, solutions to the kinematic problems described above will have a direct bearing on studies of the driving mechanism(s) of plate motion. Detailed discussion of plate driving mechanisms and mantle dynamics can be found in the contributions of other panels, notably the *"Earth Structure and Dynamics"* panel. The problem of mantle viscosity as constrained by rates of post-glacial rebound is discussed by the panel on *"Lithospheric Structure and Evolution"*.

3.2.Regional and local deformation

Our understanding of the nature of and processes responsible for regional deformation varies greatly as a function of tectonic setting, age of deformation, seismic activity, surface exposure and physical accessibility. Our specific objectives for the next decade will thus vary greatly from one region to another, and must be individually tailored by a realistic assessment of existing knowledge of each individual area, physical accessiblility, cost, and the needs of society.

3.2.1 Kinematics of deformation

Over the next decade, documentation of crustal kinematics and deformation must be the most basic goal of studies in regional and local deformation. Without kinematic data, informed development of theory describing crustal motion as the result of Earth processes and properties will not be possible. The time scales of interest in regional and local deformation span at least 13 orders of magnitude (see Figure 3) and include:

- Instantaneous motions, from seconds to hours
- Active motions of crustal fragments, averaged over years to tens of years
- Motions over recent earthquake cycles (10's to 1,000's of years)
- Holocene deformation
- Quaternary and older deformation in currently active systems

The length scales of interest span at least 9 orders of magnitude and include:

- Strain accumulation within crustal fragments (mm to cm)
- Displacement on and strain adjacent to individual fault (zones) (meters to 10's of km)
- Motions and internal deformation of coherent crustal fragments (10's to 100's of km)
- Net deformation across zones of plate boundary activity (100's to 1,000's of km)

Within a given tectonic system, motions and deformation occur over this entire spectrum and result in spatially and temporally complex patterns of superposed deformation. Of course deformation of the lithosphere involves not only horizontal and vertical motions at the Earth's surface and the development of surficial structures, but also affects the lower crust and the mantle. While subsurface deformation is generally not amenable to direct measurement, a large number of geological and geophysical data are sensitive to the way in which deformation is distributed with depth. In particular, gravity and topography data, which together are widely used to constrain the density structure of the Earth at depth, have proven a powerful tool for relating vertical and horizontal motions at the surface to subsurface deformation and to thermal and dynamic processes operating at depth.

An excellent example of the spatial complexity found in zones of plate boundary deformation occur within the Mediterranean region (Figure 4). At the largest scale this region comprises a zone of continental convergence and collision between the slowly moving European and African continents. At every smaller scale, tectonic systems within this broad region exhibit convergent, divergent and strike-slip motions in a large number of different directions. It is not uncommon for very different types of crustal motion and deformation to exist adjacent to one another, such as occurs in the Aegean-Hellenic subduction system in the Eastern Mediterranean where an area of active "back-arc" subsidence beneath the Aegean Sea exists adjacent to a zone of shortening and convergence along the Hellenic trench [eg. McKenzie, 1972, 1978a; Mercier, 1977]. At least enough is known about the kinematics of this system to relate subsidence of the Aegean sea floor to stretching and thinning of the underlying lithosphere, while subsidence of basins on the
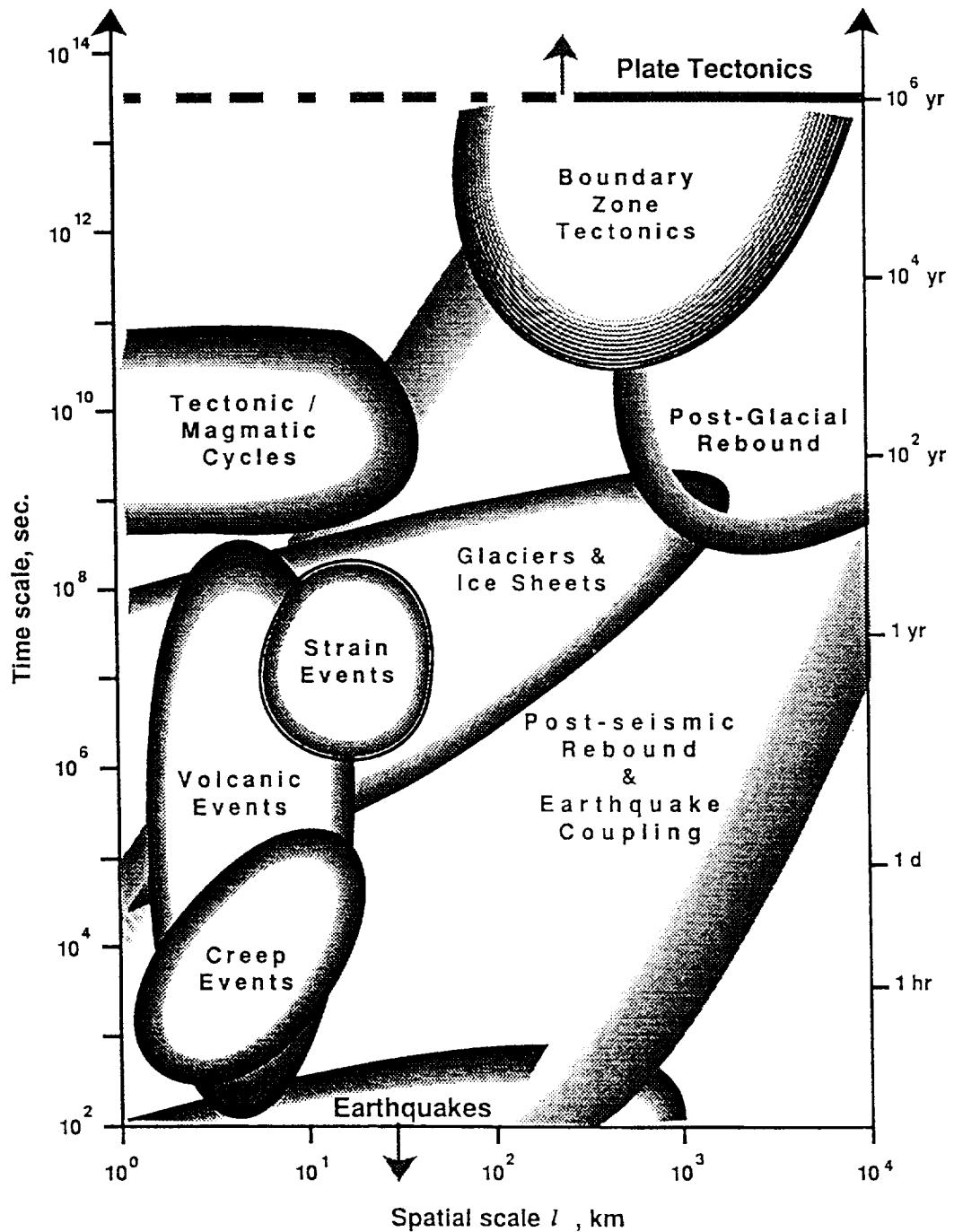
Figure 3. Spatial and temporal domains characteristic of various geological phenomena. The lower left portion of the diagram, at small spatial and temporal scales, is the domain of earthquake seismology, while the upper right is that of quaternary geology and plate tectonics. Most of the area covered represents the domains occupied by phenomena which must be studied through a combination of geodetic techniques, field geology, and tectonic interpretation. Except for the leftmost portion of the diagram, space geodesy is the only approach that yields the required quantitative measurements with sufficient spatial coverage and accuracy.

II-18
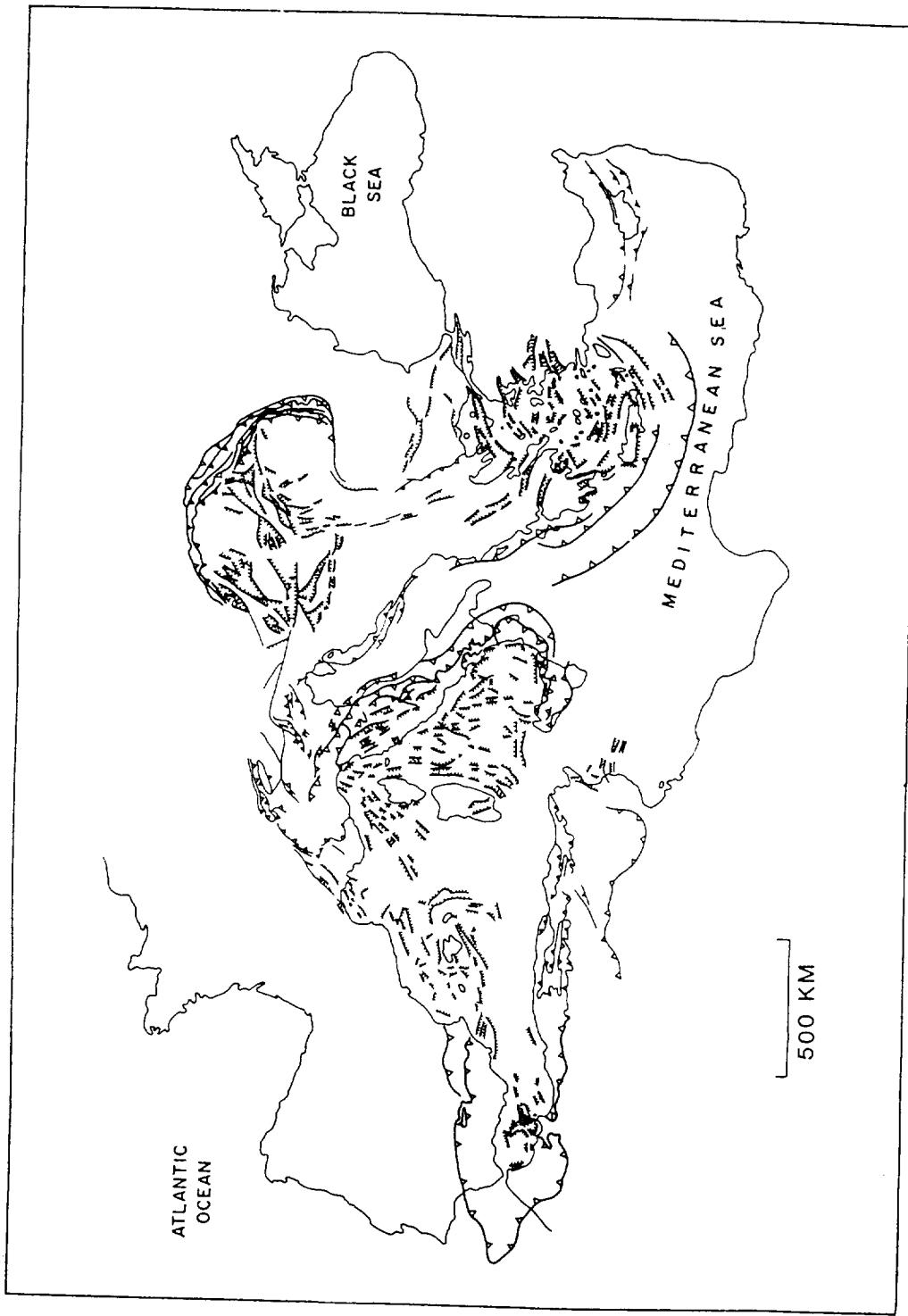
Figure 4. Late Cenozoic examples of thrust belts (with heavy barbed lines indicating thrust faults) associated with coeval back arc extensional systems (with heavy ticked lines indicating normal faults) in the Mediterranean region (from *Royden, 1988*). From east to west the thrust belt-basin pairs are (1) the Aegean-Hellenic system; (2) the Pannonian-Carpathian system; and (3) the Tyrrhenian-Apennine-Calabrian system.

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opposite (foreland) side of the convergent zone is known to result from loading of flexurally strong foreland lithosphere by thrust sheets [*McKenzie*, 1978b; *Moretti and Royden*, 1988]. Careful constraints on the timing and magnitude of basin subsidence and thrusting show that there is a close connection between thrusting and extension in space and time, but the detailed kinematic and dynamic relationships between thrusting, extension and subduction remain poorly understood phenomena. It is only through documentation of the interaction between extension and convergence that the disparate types of deformation within this tectonic system can be understood as part of a single dynamic system that is related to flow within the upper mantle.

A substantial long term multi-national effort, the *Wegener-Medlas Project*, has been undertaken in 1984 to refine the kinematic picture of the Mediterranean region, and has begun to yield SLR data capable of placing useful constraints on the geological models (ie *Wilson*, 1987). The continuation of this project on a regional scale, and the densification of the network in critical areas (using, for example, GPS campaigns) will remain an important component of tectonic studies of the region in the coming years. These geodetic studies need to be augmented by careful geological observations and quantitative modelling of dynamic processes. In this area where overall kinematics and some processes are relatively well known, models of deformation and deformation processes will be much better constained than in areas such as Tibet, and models developed to describe specific sets of observations are likely to prove fruitful.

Advancement of basic scientific knowledge requires study of a wide variety of processes in many different tectonic settings including detailed studies in areas where the over-all deformation history is known and reconnaisance studies in regions where the deformation history is poorly known. Specific objectives for the next decade will thus vary greatly from one region to another, but some of the universal issues that must be addressed through these studies can be illustrated through the following list of questions:

> How much of the overall strain is internal to crustal fragments, and how does it vary with distance from active faults?
>
> What are the short-term strains before and after major earthquakes and volcanic eruptions, and what are the controlling mechanisms?
>
> How do strain measurements from geodetic experiments compare to either seismic estimates or long-term geological estimates?
>
> How is displacement transferred from one set of faults to another, and what is the time scale for the reorganization of motions?
>
> What is the role of pre-existing structures within the crust for localizing deformation?

Some of these questions may be answered through analysis of geodetic data, but answers to most of them will rely on the combination of geodetic data with traditional geological field studies to examine the relationship between current and past deformation within a single tectonic or dynamic system. The combination of geodetic and traditional geologic data has the potential to provide insight into the nature of deformation that go far beyond those that can be provided from analysis of either type of data in isolation. We must begin now to establish basic constraints on active, historical and geological rates of fragment motions, including vertical and horizontal movement, and on the rates and style of regional deformation.

3.2.2 Dynamics of deformation

As we collect and refine our basic kinematic maps, we must continue to pose questions about the dynamic phenomena underlying the surface deformation. Over the entire spectrum of time scales for deformation, the relative roles of stress transmitted across the boundaries of crustal blocks and stress transmitted to the base of blocks by flow in the upper mantle remain major unanswered questions. Eventually we must address the

difficult questions pertaining to the dynamic mantle phenomena underlying the near-surface deformation in regions which are very active today. At present, techniques for measuring flow within the mantle on a regional scale are not yet available, but recent work that combines crustal kinematics, gravity data, velocity structure, and theoretical models for fluid convection show promise for the future [Hager and Clayton, 1989]. The implications for our understanding of mantle dynamics are enormous. This can be illustrated briefly by considering the deformation history of Tibet.

A number of studies suggest that deformation within Tibet involves movement of crustal fragments, with dimensions of tens to hundreds of kilometers, in directions oblique or even orthogonal to the overall direction of convergence between India and Asia (Figure 5) [Molnar and Tapponnier, 1975, 1978; Tapponnier et al., 1982, 1986]. Preliminary data from northeastern Tibet show that, on a length scale of tens of kilometers, major deformation has switched from one system of faults to another and from one type of deformation to another over time intervals of less than a million years (Zhang, 1987). If mantle flow beneath Tibet can be linked spatially to the active movements of sizable crustal fragments, then the spatial variability of mantle flow must correspond to the motions of individual crustal fragments (which can be measured using space-positioning techniques), while the temporal variability of mantle flow must occur over the same time scale as changes in the direction and rate of movements within the crust (which can be dated using traditional geological techniques and remote sensing data). Alternatively, if mantle flow can be shown to be related to crustal motion only at the scale of the entire plate boundary, then one might suspect that the temporal variability of flow in the mantle corresponds to that of the entire plate boundary zone (10^7-10^8 yr, e.g. England et al., 1985).

The processes that control earthquake and volcanic cycles also require considerable attention and comparisons between crustal kinematics, seismicity and other geophysical data are crucial to achieving a quantitative understanding of these phenomena. Crustal deformation patterns associated with the earthquake cycle, particularly surface displacement, displacement rates, strain, and strain rates, depend strongly on the rheological properties of crustal and subcrustal material near the seismogenic zone [Cohen and Kramer, 1984]. Over the past 15 years a number of viscoelastic models of deformation near major strike-slip faults have been proposed; these models differ in their predictions concerning the temporal and spatial patterns of crustal deformation throughout the seismic cycle [Nur and Makvo, 1974; Turcotte and Spence, 1974; Rundle, 1978; Prescott and Nur, 1981; Yang and Toksöz, 1981; Thatcher, 1983; Cohen and Kramer, 1984; Thatcher and Rundle, 1984; Li and Rice, 1987].

Ideally, we would like to be able to combine large scale geodetic or geologic information about relative plate motion, rheologic properties of the crust and upper mantle near the boundary, and the geometry of the plate boundary to understand how deformation is distributed through time, where faults develop, what their slip rates are, and how fault patterns evolve with time. Of particular note 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. Several regions where large earthquakes or volcanoes are predicted to occur in the 'near' future should be selected and measurements begun, so that we can will begin to accumulate complete sets of observations spanning all parts of the seismic cycle, in a variety of tectonic environments. Such studies will require densely monumented geodetic networks and a rich environment of supplementary studies, including geologic and seismologic investigations. For example in California, the large number of densely spaced seismic stations, extensive geologic mapping of quaternary and holocene structures and detailed maps of gravity and heat flow, in combination with horizontal and vertical geodetic observations on scales from a few meters (creepmeters and strainmeters) to hundreds of kilometers has resulted in one of the best understood plate boundaries in the world. Yet even with the rich panoply of
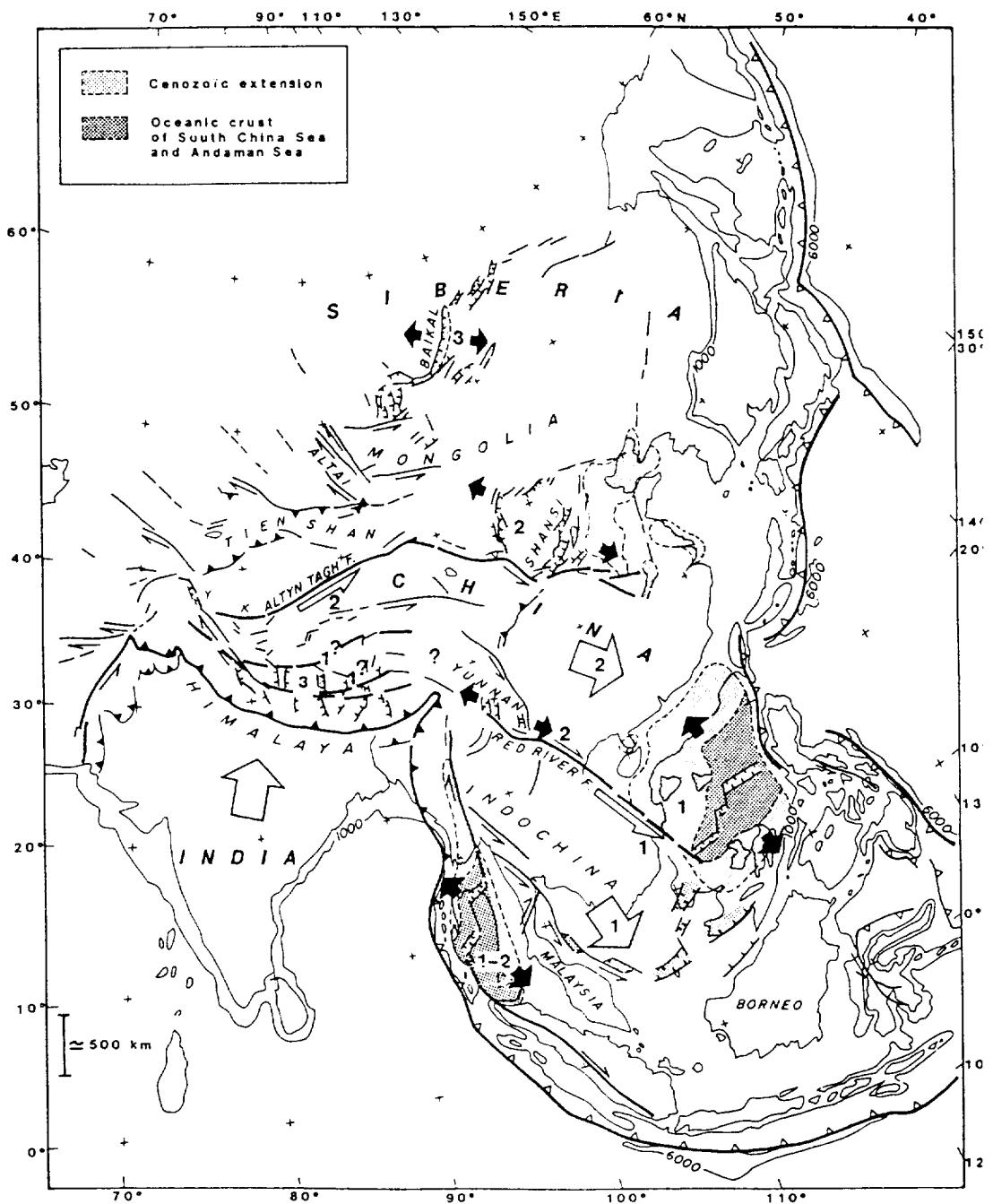
Figure 5. Schematic map of Cenozoic tectonics and large faults in eastern Asia (from *Tapponnier et al.*, 1982). Heavy lines are major faults of fault boundaries, thin lines are less important faults. Open barbs indicate subduction, solid barbs indicate intracontinental thrust faults.

observations available in California we are far from a comprehensive understanding of how deformation occurs during earthquakes and over the earthquake cycle.

3.2.3 Internal deformation of large plates

There is convincing geological evidence that some plates are deforming on million year time scales and suggestive evidence that deformation of oceanic plates may be occurring on even the short time scales spanned by space-geodetic techniques. Questions that can be effectively addressed by space geodesy include:

Does diffuse deformation occur in zones much smaller than typical plate dimensions or over the plate as a whole?

Do diffuse deformation zones tend to evolve into simpler, narrower boundaries?

Even though most plates may behave rigidly to a good approximation over 10^6 year time scales, what happens over short and intermediate time scales?

Can we detect, by space-geodetic techniques, differences between the behavior of continental and oceanic areas?

For regions that are largely inaccessible to direct geologic mapping due to water (Pacific plate) or ice (Antarctic plate), space geodesy appears to be the only means of resolving internal deformation of these plates. For example, within the Indian plate deformation of sedimentary cover into east-west-trending ridges south of the Bay of Bengal and associated gravity anomalies and intraplate earthquakes suggest that the Indian plate is buckling in response to the collision with Asia (Figure 6). This interpretation is supported by observations of the relative motions of plates adjacent to the Indo-Australian plate, which have motions inconsistent with a completely rigid Indian/Australian plate [e.g., *Gordon et al.*, 1988]. Baseline geodetic measurements from India to Australia will provide a powerful and definitive test of this hypothesis.

Another example of possible nonrigid plate behavior is suggested by very preliminary TLRS results collected over the past 6 years: Huahini, an atoll near Tahiti, is moving away from Hawaii at the rate of 6±5 mm/yr [*Smith et al.*, 1989b]. In the absence of a sufficiently dense geodetic network linking Huahini to neighboring islands, the areal extent and meaning of this deformation are unknown, but if confirmed, it might be linked to the origin of large scale depth, geoid, and seismic velocity anomalies in French Polynesia [*McNutt and Fischer*, 1987]. However, we must examine carefully possible tradeoffs between apparent horizontal and vertical motions.

There is a need to relate the geodetic observations to the geology if we are to draw geologically valid inferences from any evidence of deformation. Since regional geological history may be difficult to establish directly in some cases, present-day rates derived from space geodesy must then be compared to other geophysical observations such as intraplate seismicity, volcanism, seismic velocity anomalies, small-scale gravity features, etc., to investigate the causes and consequences of intraplate deformation.

Figure 6. "Intraplate" earthquakes, gravity anomalies [*Haxby*, 1987], and predicted stresses from the model of *Cloetingh and Wortel* [1985] in the northeast Indian Ocean. Note that the orientation of the gravity highs corresponding to the buckled oceanic lithosphere agrees with the orientation predicted by the compressional stress field. The undulations are not observed far south of the predicted transition from compressional to tensional stresses. The undulation patterns at 3°S, 83°E are distorted by the Afanasy Nitikin seamounts. The Chagos-Laccadive Ridge is outlined by its 3.5-km contour. The seamounts and Ninetyeast Ridge are shown by 2.5-km and 4.0-km contours. From *Stein, Cloetingh, and Wortel* [1989].

NORTHEASTERN INDIAN OCEAN

400 MPa

SEASAT
GRAVITY

MGAL

> 45

30 45

15 30

0 15

-15 0

-30 -15

-45 -30

< -45

compression
tension

separates
compression
and tension

earthquake magnitude
> 6.9
5.5 - 6.9
< 5.5
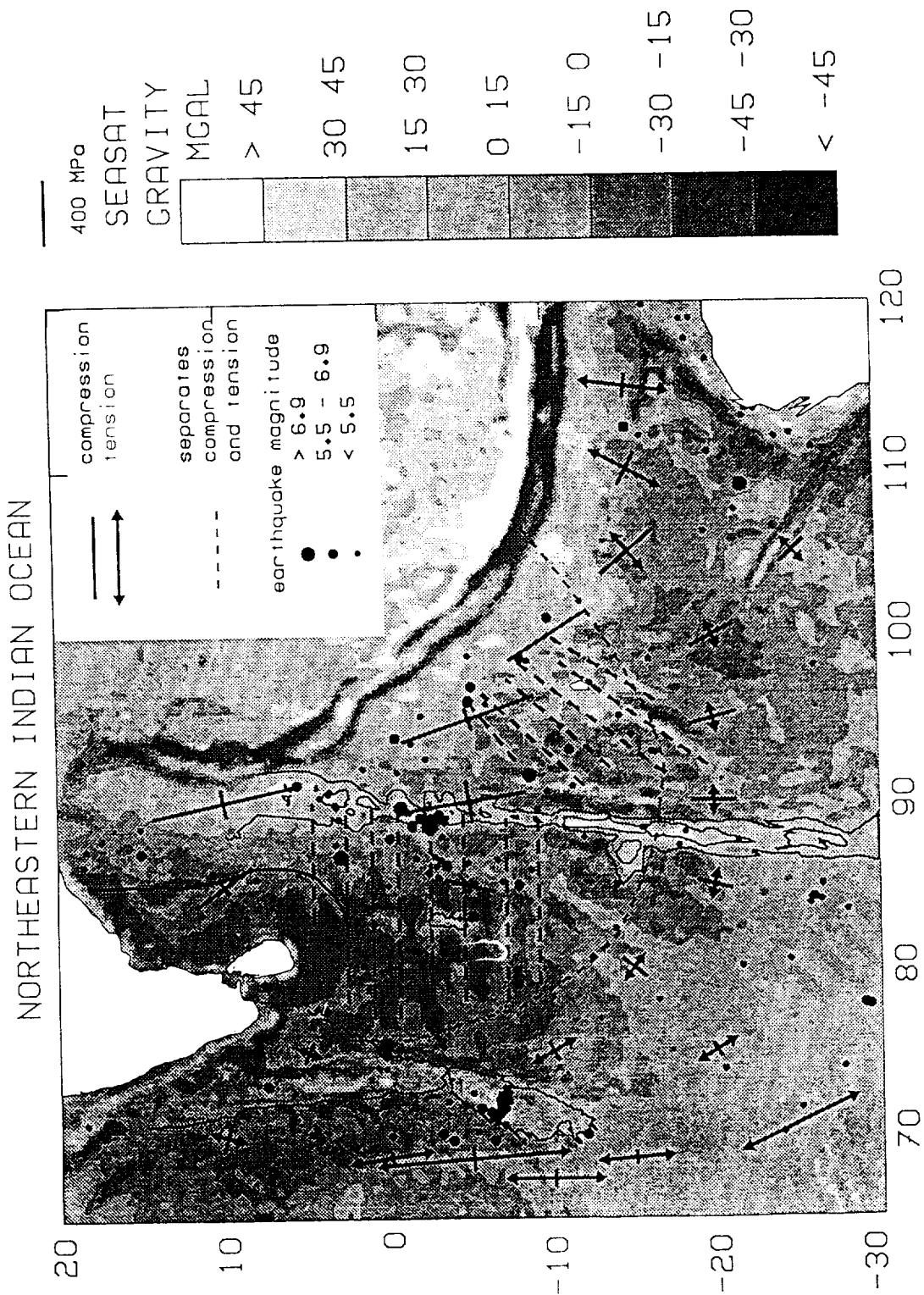
3.3 Societal impact

Study of plate motions and deformation is not motivated solely by a quest for knowledge but also as a means to achieve a reduction in natural hazards, particularly in the prediction of earthquakes and volcanic eruptions, and in the assessment of global warming and climate change. Comparisons between crustal kinematics, seismicity and other geophysical data are crucial to achieve a quantitative understanding of seismic and volcanic phenomena. Several historical examples serve to illustrate the incredible damage and loss of life that may accompany seismic and volcanic disasters. In 1556 AD an earthquake occurred in a tectonically active region near Shensi, China with a probable magnitude greater than eight. It killed more than 800,000 people. This is the largest loss of life recorded from any one earthquake, but is not unique in China's history. More recently the Haiyuan earthquake in 1920 and the Tangshan earthquake in 1976 each killed more than 200,000 people. In approximately 1200 BC an explosive volcanic eruption roughly 15 times larger than that of Krakatoa occurred on the island of Santorini in the Aegean Sea. This eruption is thought to have been responsible for the destruction of the Minoan civilization. The potential for a similar eruptions in the western US underlines the need to understand and eventually predict these natural phenomena.

A comprehensive discussion of applications to the mitigation of volcanic hazards is given in the report by the panel on volcanic problems. Similarly, continued national and international effort toward a better assessment and understanding of seismic hazards will benefit directly from the investigations mentioned in the preceeding sections, and from improved geodetic measurement techniques. In this sense, the study of plate motion and deformation can make a significant contribution to multi-agency, multi-national and multi-disciplinary programs aimed at making progress in this area.

Perhaps even more important is the need to monitor global warming by measuring sea-level rise to evaluate the rate of melting of the polar ice-caps. This will require significant improvement in plate deformation measurements, including determination of reliable measurements of surface vertical movements on regional and global scales. More substantial discussions can be found in companion reports, such as those prepared by the *"Earth Structure and Dynamics"* and *"Lithospheric Structure and Evolution"* panels.

4. REQUIREMENTS

The next frontier in global plate kinematics and dynamics clearly lies in resolving small, departures from the standard models. In this section, we shall summarize the precision requirements needed not merely to detect plate motion and deformation, but also to test and refine existing models. In addition to the measurement accuracies needed from space technology, general requirements of any program to model plate motion and plate deformation in the 1990's will include ongoing efforts to develop new models, compare instantaneous rates with geologically-inferred ones, and interpret motions within the geodynamic context through integration with other geophysical data.

4.1 Horizontal Motions

4.1.1 Plate Motions

It is difficult to estimate the measurement accuracy required to resolve time-dependence in plate motions. We have no firm basis for predicting the amplitude or the characteristic time scale of such motions on a plate-wide basis. A few plate thicknesses away from plate boundaries, we can expect transients following large earthquakes, but these will not propagate with large amplitude into the plate interiors if current rheological models are correct. Nevertheless, it is not unreasonable, as an initial hypothesis, to suppose that

accelerations in plate motion would be either caused by, or the cause of, time-dependent behavior along plate boundaries, such as earthquakes, creep events, rapid pre- or post-seismic motions, etc. Therefore, any program to measure variability in plate motions should be coordinated with deformation measurements on the corresponding plate boundaries.

The most important measurement requirement when trying to detect and document time dependent motions is that we avoid temporal aliasing by frequent surveys. The finite nature of resources then demand that this kind of monitoring be restricted to a rather coarse network until such time as an "interesting signal" is detected. Of course, if such a signal is indeed detected, we will have to respond with a coordinated investigation involving densification of the network around the sites of interest. Another important consideration is that we must consider this type of monitoring to be a long-term endeavor. Thus, detecting variations in plate speeds over decadal time scales cannot be achieved without a long term commitment to the acquisition of long time series of high-quality data. Even with the present technology we should be able to detect time-dependent plate motions at the sub-millimeter level provided we patiently accumulate continuous time series over several decades.

To refine significantly models of plate motions in regions where they are most uncertain (i.e. have an reliability on the order of 10 mm/yr), would require monitoring a number of well-selected baselines with an accuracy of 1-4 mm/yr (although even 10 mm/yr can be of great value in certain areas such as Southeast Asia). The requirements in terms of accuracy are similar, 1-5 mm/yr, for the problem of determining plate geometry in regions where the location and nature of plate boundaries is uncertain. A fiducial network will not have the dense coverage necessary to locate plate boundaries and determine the rate of relative motion across them. Repeated surveys at 10^2 to 10^3 km spacing using techniques such as GPS, GLRS, or mobile VLBI and SLR, should meet the accuracy and resolution requirements, provided the regional survey is tied to a high-quality fiducial net.

4.1.2 Regional and local deformation

Application of space geodesy to regional deformation will require a precision in horizontal positioning considerably greater than that needed to merely detect the movements of large plates on a global scale. Ideally, one would like to resolve horizontal motions within zones of plate boundary activity to better than 5 to 10% of the rates of motion between the adjacent plates. Rates of relative motion between the large plates fall into the general range of about 10 to 100 mm/yr, so that resolution of motions at rates of 0.5 to 5 mm/yr are needed to document the partitioning of strain within plate boundary zones. If significant results are to be obtained within a reasonable period of time - perhaps five years - measurement accuracy of about 1 mm in horizontal positioning will be needed. There will be a large payoff in the improvement of horizontal positioning techniques in the range between 1 and 10 mm. With a horizontal resolution of 10 mm, even rudimentary partitioning of strain can be obtained only within the more rapidly deforming regions, while partitioning of strain within more slowly deforming areas will be difficult to obtain without experiments that run for many decades. Improvement in accuracy to a few mm/yr will be sufficient to resolve the partitioning of active deformation in the more rapidly deforming regions on a relatively fine scale, as well as the basic features of strain fields in more slowly deforming regions.

Logistical considerations will be crucial in determining the practicality of applying space positioning techniques to problems in regional deformation, particularly in remote areas. Except in the most densely populated regions, geodetic surveys will depend upon the repeated occupation of geodetic sites using portable instruments rather than on the maintainance of permanent facilities. Instruments need to be sufficiently lightweight to be carried on foot for short distances (1 km or so), and yet sturdy enough to stand up to transportation by air and by truck over bad roads. The need to carry out geodetic surveys

in a reasonable time period requires that the instruments must be capable of obtaining the desired level of accuracy in a time period of no more than about two days, preferably less. For example, a typical network might consist of 10 to 15 sites. If two instruments are moved continuously while one or two other instruments remain fixed, a complete survey of the network may be completed in roughly four to six weeks, assuming 2 days for measurement at each station and 2-3 days for transport between stations.

Different logistical problems exist in densely populated areas where frequent or intense seismic or volcanic activity poses a hazard to large numbers of people. In such regions it will be necessary to maintain a dense network of continuously monitoring geodetic facilities, so as to maintain a record of pre- and post-seismic deformation. It may make sense to deploy seismic and geodetic instruments together as part of a single network. The cost per instrument and the man power required to maintain the intruments will become crucial if a large number of stations are to be established, with inter-site spacing from perhaps 3 to 30 km. If pre- and post-seismic deformation are to be measured, then it will be necessary to obtain the desired levels of accuracy in the shortest time possible - roughly hours to days. The large spatial density and high rate of sampling in these networks will make it possible to treat crustal deformation in the same way as digital seismic network data, using standard techniques of digital data processing to eliminate spatial and temporal aliasing effect, to stack the data in various ways in order to bring out particular strain patterns, etc. This has generally not been possible with crustal deformation data before.

A global network of fiducial stations will be needed for all regional and local surveys, to tie local and regional deformation patterns to global motions of the major plates, and to separate local effects from large-scale plate deformation. Our requirement for global coverage with a sufficiently dense, high precision fiducial network is the basis for our main recommendation for the next decade.

4.1.3 Non-rigid plate behavior

The overall success of the rigid-plate motion models indicates that non-rigid behavior of plates is limited to rates of less than a few mm/yr over million-year time spans. Over shorter time intervals, lack of data prevents us from making trustworthy predictions. We have an overriding requirement, namely that it will be critical to distinguish between broadly distributed non-rigid plate behavior and localized tectonic deformation. Any signal suspected to be caused by the breakdown of the rigid plate assumption detected with the fiducial network must be followed up with densification campaigns 1) to ascertain whether the signal is indeed due to a regional effect instead of to the motion of a single site, and 2) to measure the area over which the effect is detectable because data interpretation will depend critically on the spatial scales encountered.

4.2 Vertical Motions

Except for vertical motions induced by post-glacial rebound —typically 10 mm/yr— most vertical motions are at least an order of magnitude slower than horizontal motions. Only in tectonically active areas with very rapid erosion or tectonic denudation (and in areas subject to post-glacial rebound) do rates of vertical motion reach as much as 1 mm/yr. Because vertical motion is dominated by post-glacial rebound at large spatial scales (Figure 7), we must document and understand post-glacial rebound before other contributions to the vertical signal can be isolated. These requirements are described by the panel on "Lithospheric Structure and Evolution".

Uplift rates related to dynamic stresses or heating and cooling of the lithosphere are typically a few tenths of a mm or less. For example, geobarometry on metamorphic rocks from central Nepal indicate that 20 km of uplift and erosion has occurred in the last 20 Ma, giving an average uplift rate of 1 mm/yr. While it is not known is how uplift has been partitioned through time, although it is generally thought that uplift rates in mountain belts
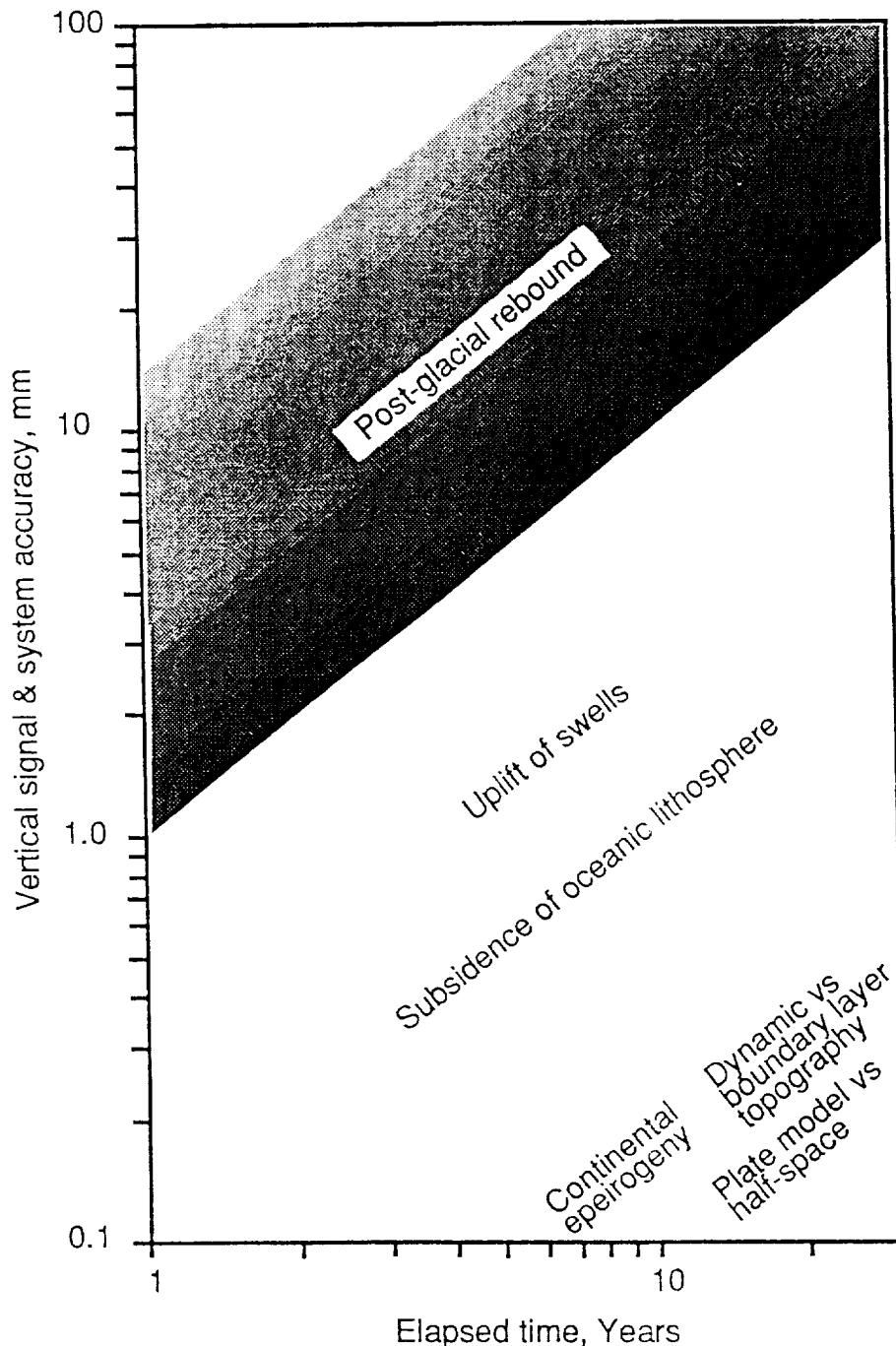
Figure 7. Vertical geodetic signals which can be treated as steady-state over decadal time spans are characterized by much slower rates than horizontal signals, except for post-glacial rebound. Even if a very long term program is initiated to measure directly these signals, the interpretation of the data will require first that the post-glacial rebound contribution be thoroughly understood and modeled before other, much smaller contributions can be interpreted reliably.

seldom exceed a couple of mm/yr. In regions of extensional tectonics, such as in the Basin and Range Province, uplift of footwall rocks beneath low angle detachment faults by about 15 to 20 km is thought to occur over a time period of a few million years, yielding an average uplift rate of a few mm/yr and comparable to uplift rates inferred for rapidly eroding mountain belts. Because these are the maximum rates of long-term uplift or subsidence that are likely to be observed, vertical positioning with accuracies of one or two mm are critical. Higher rates of vertical movement may occur as short-term phenomenon near active faults and volcanoes (some numbers), so that monitoring of vertical movements in these regions at the cm level of accuracy may be rewarding. Except as regards study of short-term, local deformation near active faults and volcanoes, and study of post-glacial rebound, vertical positioning with accuracies poorer than one or two mm will be useless.

Rates of subsidence from cooling of the lithosphere are about an order of magnitude less than those resulting from active deformation. For example, in sedimentary basins that form by extension, basement subsidence of 5 km in a couple of million years is not uncommon, yielding subsidence rates of perhaps 2 mm/yr. In contrast, during the thermal cooling portion of the basin subsidence, rates of about 1 km in 10 my are the largest observed, or 0.1 mm/yr. Rates of uplift or subsidence from dynamic processes are likely to be similar or larger by a factor of two to three. For example, the Hawaiian island chain has been uplifted by roughly 2.5 km in 8 my, yielding rates of roughly 0.3 mm/yr. Thus geodetic measurement of vertical motions resulting from dynamic and thermal effects in the Earth's interior require the resolution of motions of 0.1 to 0.3 mm/yr. Clearly this level of accuracy is beyond our reach within the next decade. With precision of about 1 mm/yr, it may be possible to resolve these rates with experiments that last several decades, but it is futile to begin such studies until we have the capability of vertical positioning to at least 1 mm.

The logistical requirements for vertical positioning are rather different from those required for horizontal postitioning. Accuracy is much more important than speed in obtaining measurements, and the feasibility of continuous monitoring should be considered for carefully selected sites in which rates of uplift or subsidence are key in constaining the nature of thermally, dynamically or tectonically driven processes in the Earth's interior.

4.3 Satellite Images

Satellite images have revolutionized our ability to map neotectonic structures on a regional scale and have proven to be an indispensable tool for geological mapping. Landsat 4 and 5, carrying Thematic Mapper (TM) with 7 spectral bands and a higher spectral resolution than the older Landsats, provides excellent data at 30 m resolution. While the current resolution of these images is sufficient for many purposes, improvement beyond the 10-30 m range will enable geologists to map structures and neotectonic features at a level of detail not now possible. For study of landforms resulting from local deformation and faulting, an improvement to 1 m resolution, even at a single spectral band, will allow geologists to map fault offsets resulting from even a single earthquake. A more general discussion is given by the panel on *"Landforms and Paleoclimate"*.

A significant impediment to using current high resolution satellite data for regional studies is the high cost of the data ($3,000 to $4,000 per 180 km square for TM and about four times more for SPOT). This is unfortunate because large remote regions, requiring numerous scenes for adequate coverage, are precisely the areas where this data is most sorely needed. Therefore, a high priority for satellite imagery in the next decade should be to provide systems whereby data comparable to Landsat 4 and 5 for all continental regions, and higher resolution images for selected areas, are readily available at moderate cost. Emphasis should also be placed on developing a system that can distinguish between various lithologies on the ground, thus improving the ability to extend local field mapping studies to more regional scale using satellite images. For these reasons, we anticipate that a

number of facility instruments planned for the Eos mission (e.g. MODIS, HIRIS), together with the associated data information system (EosDIS) will have a very favorable impact on our understanding of regional deformation and related geological phenomena.

4.4 Topography

A global, coherent data set with moderately high accuracy (10 m vertical and 1 km horizontal) is needed to support interpretation of satellite-derived gravitational and magnetic data aquired over continental areas. The target sensitivity of the next generation gravitational satellite will be on the order of 2.5 mgal surface gravity at 100 km horizontal resolution. At these wavelengths, an error in topography of 1 m will cause an equivalent error in the gravity anomaly measured by the satellite (at 160 km orbit) of about 0.1 mgal. Thus a maximum of 10 m uncertainty in the height measurement will ensure that topographic variance is not a limiting noise source for gravity measurements. The requirements for interpretation of magnetic data are less stringent.

Identification of structural and features as a clue to neotectonic activity clearly requires very fine resolution of topography, perhaps 1 m vertical and 10 m horizontal would be ideal for most purposes (equivalent to about 1:50,000 topographic sheets). This higher resolution topographic data set need only be acquired once for most problems in regional and local deformation. What is needed is a moderately high resolution data set (10 m vertical and 1 km horizontal) for all continental areas, with higher resolution data in selected areas - particularly those tectonically active areas with rugged topographic relief. For studies of dynamic morphology, the evolution of topography as a function of time becomes paramount, so repeated precise topographic surveys will be needed. An extended discussion of these issues is provided by the panel on *"Landforms and Paleoclimate"*.

4.5 Gravity

The Earth's gravity field, together with its topography, is a direct reflection of subsurface processes that produce horizontal and vertical motions at the Earth's surface and within its interior. As discussed by the panel on *"Lithospheric Structure and Evolution"*, gravity data are crucial in assessing the strength of the lithosphere in a variety of tectonic settings and the spatial and genetic relationships between applied loads and vertical deflection at the Earth's surface. Gravity data will also be critical in determining the role of mantle flow beneath actively deforming regions, because convective patterns within the mantle, whether driven by thermal or compositional buoyancy, produce dynamically maintained topography at the Earth's surface, at the core-mantle boundary, and at other internal density interfaces. Because zones of regional deformation at the surface of the Earth consist of interactions along crustal fragment boundaries typically a few tens to a few hundreds of km in width, most applications of gravity data to problems in regional deformation require accuracy of 1 to 2 mgals at a spatial resolution of 20 to 200 km. Since the lower limit on spatial resolution for satellite gravity data is roughly 50 km, some problems in regional deformation and dynamics cannot be addressed directly through satellite gravity data and must rely on airborne and surface measurements. However, collection of such observations over much of the Earth's land surface is an onerous task, and satellite gravity data is at present the only available source of adequate gravity coverage in many regions, and will remain so for some time to come.

For many problems in regional deformation and dynamics, a 100 km spatial resolution seems to mark a critical divide: at better resolutions a wide range of important problems can be addressed, including many aspects of the thermal structure of the continental lithosphere and driving forces for continental tectonics. At poorer spatial resolution, few problems in regional deformation can be constrained by gravity data. Therefore development of the capability for obtaining satellite gravity data accurate to 1-2 mgal or better at 50-100 km spatial resolution during the next decade must be a high priority.

4.6 Magnetics

Oceanic and continental swells that are suspected to be thermal in origin, such as beneath Bermuda, Hawaii and East Africa, are typically 500 to 1500 km in diameter. If magnetic data are to be used to infer the thermal structure beneath these regions, a desirable spatial resolution for magnetic data would be perhaps 100 kilometers. Similar spatial resolutions would be required for the Tibetan plateau and many sedimentary basins. An accuracy of a few nT should suffice for reconnaissance work. However, at the present time, little research has been conducted on the use of magnetic signatures in regional deformation problems. This may well change in the next 10 years as we obtain better maps of the crustal field. An accuracy of 1 nT with a horizontal resolution of 100 km is a suitable goal for global coverage, although local resolutions of 1 km or better will be needed to evaluate the existence and usefulness of signatures associated with local deformation. As in the case of gravity, these requirements call for a combination of satellite, aircraft, and ground observations.

4.7 Modeling and Data Synthesis

A reasonable understanding of regional deformation cannot be developed using only one type of observation. The need to consider a phenomenon from several observational aspects is an integral part of the scientific method - without it we cannot hope to obtain the insights we seek. Emphasis must be placed on the thoughtful integration of geodetic, topographic, gravity and magnetic data, and space images, with one another and with ground-based geophysical and geologic observations. For example, geodesy may ultimately provide detailed velocity maps for much of the Earth's surface - without doubt a significant achievement in its own right. Yet even at a high level of detail, regional strain nets can at best resolve present day rates of motion between various parts of a broad plate boundary. In isolation, regional strain nets cannot provide answers to fundamental questions about how strain is accommodated, in what ways and how quickly the spatial distribution of long-term deformation may change with time in a geologic system, and how mechanical and dynamical connections unify disparate types of deformation into a single coherent tectonic picture. Only by combining geodetic information with geological and geophysical data and with theoretical geodynamic models can we hope to understand fully the motions at the Earth's surface and to relate them to processes within its interior.

Similarly, without the use of geologic field data, geodetic and geophysical techniques provide only a snapshot of the present state of complex regional dynamic systems. Because regional deformation and the motions of lithospheric and crustal fragments must be understood in light of time dependent flow within the mantle, crustal dynamics will ultimately depend on geologic field data to establish temporal constraints on crustal motions and on mantle flow beneath active plate boundary regions. In order to progress in our understanding of the physics of crust-mantle interaction and mantle flow, we must turn to a joint interpretation of geodetic observations, geophysical data, and geologic reconstructions of crustal motions.

Acquisition of data to constrain regional deformation must proceed hand in hand with the development of theoretical models that link surface deformation and motions to flow in the Earth's interior and to the thermal and mechanical structure of the lithosphere. Ultimately, we must develop models that provide a genetic link between different types of phenomena, and that can be tested through analysis of existing data or of data to be collected during future operations. Theoretical models are essential to any well-founded program of observations, in that they can help to direct future acquisition of data towards areas that will most efficiently test the dynamic framework within which we view Earth processes. Conversely, these models must be continuously reviewed and modified to incorporate new data and concepts. In this way both theory and observations play important and complementary roles in the formulation and testing of geological hypotheses.

4.8 Summary of Requirements

Table 1 summarizes the requirements discussed above. It must be borne in mind that these requirements are those placed by scientific problems related to plate motion and deformation, and are therefore not necessarily adequate to address other geophysical and geological problems discussed by other panels.Of these requirements, those listed for vertical motions are clearly the most demanding ones; except for the measurement of vertical motions due to post-glacial rebound, they are by and large inaccessible to current technology. Consequently, the focus of our efforts to measure vertical motions should remain on issues related to post-glacial rebound for the moment, for this term will mask the other signals, until such time as the technology improves significantly.

Finally, it must be noted that even more stringent requirements of horizontal resolution of field and topographic data may exist locally, but not globally. This means that special attention needs to be paid to the merging of space-geodetic data sets with the results of ground or air-borne techniques in these areas.

Table 1. Measurement requirements

Measurements	Precision required	Spatial scale/resolution
Horizontal motions Variability of plate motion Vector motion between plates Nonrigid plate behavior Regional and local deformation Post-seismic deformation	1-10 mm/yr 1-10 mm/yr 1 mm/yr 1 mm/yr 10-100 mm over hours	10^4 km 10^2 - 10^3 km 10^3 km 10^1 - 10^2 km 10^0 - 10^2 km
Vertical motions Post-glacial rebound Active vertical tectonics Thermal & dynamical processes Continental epeirogeny Post-seismic deformation	1 - 4 mm/yr 0.1 - 1 mm/yr 0.01 - 0.1 mm/yr 0.03 mm/yr 10-100 mm over hours	10^3- 10^4 km 10^1 - 10^3 km 10^2 - 10^3 km 10^3 km 10^0 - 10^2 km
Satellite images Regional studies Local and neotectonic studies	10 - 30 m multispectral 1 m single band	10^2 - 10^3 km 10^0 - 10^2 km
Topography & altimetry Global continental topography Global oceanic bathymetry Local topography	10 m vertical 10 m vertical 1 m vertical	1 km 20 km 10 - 100 m
Gravity Regional tectonic studies Local tectonic studies Post-glacial rebound	1 - 2 mgal 0.1 - 1 mgal 1 µgal	50 - 100 km 10 km 1000 km
Magnetics Global crustal anomalies Local anomalies	1 nT 1 nT	100 km 1 km

5. RECOMMENDATIONS

5.1 Basic Recommendations

Our panel has four specific recommendations:

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

This can be best accomplished by:

- deploying a world-wide network of dedicated, continuously monitoring GPS stations with 1000 km spacing and measuring relative positions to 1 cm over one day and to 1 mm over three months. Approximately 150 stations will be required on the continents with another 50 stations located on islands, for a total of about 200 stations;

- deploying a full constellation of GPS satellites to support this network.

- continuing a world-wide network of approximately 12 VLBI/SLR sites with at least one on each major plate and several distributed around the Pacific Ocean. These sites must maintain relative positions to 1 cm over one day and to 1 mm over three months to determine Earth orientation and GPS fiducial coordinates;

- co-locating GPS receivers at other existing VLBI/SLR stations and ceasing to occupy these stations as soon as it can be done <u>without loss in precision and without offsets in the data series</u>.

- continuing a network of SLR stations with positions relative to the Earth's center-of-mass determined with sufficient accuracy to provide adequate orbits for the GPS satellites. At such time as GPS (or some other system) demonstrates a capability of meeting center-of-mass requirements at the same level these SLR sites will no longer be required for this purpose;

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

- Some obvious scientific problems include: the kinematics of major plate convergence systems; the distribution and rate of post-glacial rebound; and the distribution of deformation within tectonically active areas, such as western North America, the Pacific Basin, and the Alpine-Himalayan collision zone. Specific experiments should be selected through a peer-review process to ensure the highest quality of science.

- We recommend that resources be allocated among three modes of operation as follows: continuously recording arrays—45%; mobile campaigns (GPS / GLRS)—45%; Seafloor positioning campaigns—10%.

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

These requirements are defined as:

- Global, coherent topographic data with moderately high accuracy (10 m vertical and 1 km horizontal). High resolution capability (a few meters vertical and 10 m horizontal) applied in selected areas.

- High resolution satellite images (roughly 1 m pixel size, even if only at single spectral band) for identification of structural, neotectonic and other morphologic features from space. Lower resolution (10 m) needed over a wide range of spectral bands to distinguish different lithologies.

- Globally dense, coherent gravity data to a few mgal at resolution of 50-100 km and local high-resolution gravity data to a few mgal at resolution approaching km.

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

Indispensable technology includes:

- a new generation of systems capable of continuous mm to sub-mm horizontal and vertical positioning on 1 to 1000 km vectors; systems capable of sub-cm relative positioning of moving platforms; and inexpensive (< $10K), transportable (< 5 kg), and rugged instruments with minimal power requirements (~ 1 W);

- monumentation stable at the sub-millimeter level, and marks that can be installed rapidly and economically.

- seafloor mark positioning with a precision of better than 1 cm.

- more efficient and accurate processing techniques to reduce cost of analysis and delay in interpretation of large data sets;

- the creation and maintenance of a permanent geodetic archive for existing data sets and for those collected during the next decade, with common data formats and convenient access.

- effective, affordable, and practical means for exchange and dissemination of remote sensing data such as EosDIS or SESDIS. This effort should be coordinated with other agencies and countries.

5.2 A Global Fiducial Network

The most important recommendation of our panel is for the implementation of a world-wide space-geodetic fiducial network to provide a systematic and uniform measure of global strain. As outlined above, we recommend that this network consist of globally

distributed GPS receivers tied to a number of strategically located VLBI/SLR stations. We further recommend that some stations be equipped with an expanded set of additional sensors to facilitate calibration of various space-based data sets. These may include gravimeters, magnetometers, environmental sensors, and calibrated targets for various orbital instruments, such as those planned for Eos. In the long term, GLRS reflectors should be co-located with the VLBI/SLR and GPS stations.

Direct scientific benefits that will accrue from the proposed network include monitoring of :

Plate motions, especially important for plates with poorly determined vector velocities;

Short-term variations in rates of plate motion and deformation (days to years);

Non-rigid behavior of plate interiors (important for models of plate driving forces);

Rates of post-glacial rebound (constrains viscosity models for the mantle);

Rates of sea-level change (crucial for study of global warming and climate change).

Additional benefits identified by our panel include:

Determination of highly accurate orbits for GPS and other spacecraft;

Mission support and satellite tracking;

Calibration of globally coherent space-based topography, gravity and magnetic data;

Calibration of a global set of GLRS reflectors;

Establishment of an accurate fiducial network for local and regional space-geodesy;

Assessment of natural hazards (earthquakes and volcanoes).

The specifications listed above for the number, density and type of space-positioning stations are based on both scientific and technical considerations: we require at least three sites per major plate to resolve rigid plate motions; mapping of non-rigid behavior within the interiors of plates requires a denser distribution. For example, with a station spacing of 1000 km there will be approximately 30 sites in North America - enough to map the distribution of non-rigid behavior across the continental part of the plate. The cost of deploying this number of VLBI or SLR stations would be prohibitive. GPS provides a relatively inexpensive alternative using current technology. The required accuracy of the network is dictated by the rates of movement that we wish to determine, as described in Table 1.

In tectonically active areas where deformation is concentrated, we need geodetic stations with intersite spacing much smaller than the 1000 km provided by the permanent sites within the network. We therefore recommend a vigorous long-term program of monitoring regionally dense space-geodetic networks through periodic campaigns (every two or three years) using portable equipment. These regional networks will be intimately tied to the permanent geodetic stations. Taken together, these two components —the permanent sites and the regional densification networks— will allow us to create a global strain map of the planet. Furthermore, the permanent fiducial network will foster studies of local and regional deformation because it will provide a means of tying local observations to a global framework and will greatly simplify the computations required to do so.

One of the outstanding problems with existing topography data is their lack of global coherence. Under our proposal, we will have 200 sites distributed around the world with accurately determined absolute elevations. This will permit topographic data sets to be calibrated precisely at each of these sites and removal of any offsets in the data sets. Similarly, enhancement of a subset of the global sites with other devices (e.g. gravimeters,

magnetometers, calibrated targets for orbital instruments) will provide superior calibration of a variety of other space-based observations of the Earth.

In addition to its obvious scientific benefits, the proposed network will facilitate the quest for natural hazard reduction by permitting study of the phenomena that control seismic and volcanic activity. Comparisons between crustal kinematics, seismicity and other environmental data are crucial to achieve a proposal understanding of these phenomena. Particularly noteworthy is the need to establish permanent geodetic, geophysical, and environmental facilities in areas of frequent volcanic or seismic activity, so as to acquire a continuous record of short-term behavior immediately before and after major eruptions and earthquakes and to aid in their prediction. Such facilities will also assist in the assessment of global warming through evaluation of absolute sea-level change and estimation of the rate of melting of polar ice-caps. Deployment of the proposed network in the 1990's will thus be timely in its response to the call for an increased emphasis over the next decade on the reduction of natural hazards and evaluation of man-made climate change.

Establishment and maintainance of a global network requires a long-term commitment and a global focus. While inter-agency and international participation is clearly critical to a successful deployment, it is imperative that a single agency take the initiative and the responsibility for the development and implementation. As a mission-oriented space agency with a global outlook, NASA is uniquely poised to lead this effort. As the prime developer of space geodesy, NASA is uniquely poised to tackle this technological challenge. Finally, NASA is perhaps the only agency in a position to make the necessary long-term commitment to this global program. In this light, we view deployment of a space-based geodetic network as an integral part of the *Mission to Planet Earth.*

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7. APPENDIX
- MEASUREMENT SYSTEMS -

The following space-dependent instrument systems are likely to contribute to plate motion and deformation studies during the next decade: Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Global Positioning System (GPS), Geoscience Laser Ranging System (GLRS), and Sub-Marine Positioning (SMP). This section highlights the aspects of these techniques that lend them most direct effectiveness.

7.1 VLBI, SLR

The key roles of VLBI/SLR in crustal deformation studies will be in supplementing other more flexible observing systems like GPS or GLRS. In particular, VLBI/SLR will play a critical role in maintaining a reference frame for GPS satellites, will provide independent observations for validation of longer range GPS or GLRS observations, and will provide boundary condition information for studies using GPS or GLRS to study local deformation.

During the next decade, it seems clear that the principal tool in investigating problems in crustal deformation will be the Global Positioning System (GPS). The principal applications of VLBI and SLR to regional and local deformation will be in several critical support roles: 1) maintaining a fiducial network tied to the center of mass of the Earth; 2) providing Earth orientation; 3) providing calibration and validation; and 4) providing boundary condition constraints. For many of the larger scale problems such as global plate motion the role of VLBI and SLR will be much more direct, but these are covered by other panel reports. At local and regional scales, GPS is a much more cost effective and flexible tool. Current results make it clear that for lines shorter than about 500 km GPS precision competes with VLBI.

One of the key roles of VLBI/SLR in crustal deformation studies will be in maintaining relative positions of a network of about 20 globally distributed sites. These sites must have collocated VLBI and SLR observations at least annually and continuous GPS observations. The position of these sites relative to each other and to the center of the Earth must be known and maintained at the 1 cm level. The position of the various antennas and marks within each site must be known and maintained at the 1 millimeter level. The necessity for these sites is discussed in the GPS section.

VLBI and SLR are the key components of the polar motion and UT1 series published by the International Earth Rotation Service (IERS). These series are an essential requirement for processing high precision GPS vectors.

A few vectors throughout the world should be chosen as collocation sites where VLBI and GPS observations are made simultaneously for the purposes of comparison of the two systems. Ideally these vectors would be about 500 km long: long enough for scale differences to be apparent, but short enough to be clearly in the useful range of GPS. All current studies indicate that the systems agree at the level of a few parts in 10^8, but the current data is sparse and does not cover a very long time span. Vectors between the fiducial network stations will probably be too long for this purpose in general.

Last, but not least, VLBI and SLR must provide boundary condition information for use in interpreting the local and regional studies. This process is already occurring in the western coterminous U.S. and in Alaska, where global plate motion rates from VLBI supplement more detailed studies of the distribution of relative motion across the Pacific-North America boundary.

7.2 GPS

During the next decade, GPS will likely be the primary source of observational data for local deformation studies. The key challenge is to improve precision while making receivers more portable and easy to use and software less time-consuming. This will be even more challenging than it may appear because several forces are acting to degrade the precision. These forces are: potential military corruption of the signals; new receivers with less than full wavelength data on L_2; and mixtures of different antennas in experiments.

The advent of GPS has already caused a revolution in the measurement of crustal deformation. Prior to GPS, programs designed to systematically measure crustal deformation on a large scale were the exclusive province of government agencies both in the United States and in other countries. The availability of GPS has produced to a dramatic increase in the number of groups making these kinds of measurements. It is clear from several recent papers (Dong and Bock, 1989, Prescott et al., 1989, Tralli and Dixon, 1988) that under proper conditions GPS produces precision of a few mm on short lines and a few parts in 10^8 on long lines. The "proper conditions" are an essential part of the demonstrated precision. All of the experiments obtaining high precision on vectors over 10 km in length have used extended observation sessions (5 to 9 hours of tracking per day and often several days of tracking at each site), dual band receivers with full wavelength data on both frequencies, and orbit improvement using data from tracking stations distributed over a continent-sized area. They have required person-months of processing time for each experiment. And the experiments have been carried out during the relatively quiet part of the solar cycle. It is not yet clear what precision will be obtained when these conditions are modified, and the conditions are being modified. Because of Department of Defense statements regarding access to GPS, most of the new receivers on the market do not provide full wavelength data on the second frequency. The sunspot number is increasing and with it the ionospheric activity. Fiducial stations necessary for orbit improvement do not exist yet except in a rudimentary and marginally useful form. During the next decade we must put effort into advancing GPS technology.

7.2.1 World-wide tracking network. We must develop a world-wide network of continuously tracking GPS receivers with relative position and velocities between sites determined by VLBI to the 1 cm and 1 cm/year level. At each site the relative positions should be maintained at the 1 mm level between the various instruments and through changes in instrumentation. Experience with existing prototype fiducial networks has made it clear that much work needs to be done to develop reliable receivers, software, and distribution mechanisms.

7.2.2 Development of new receivers. We need to continue to develop a next generation of field receivers which will be characterized by precise phase and pseudorange, low power consumption, compact size and light weight. There is also a need for a new generation of fixed-site receivers. These receivers need to operate reliably with minimal maintenance and operator attention, and produce very low noise pseudo-range and phase data. Issues such as weather resistance, power consumption, and weight are of less concern at fixed sites.

7.2.3 Validation of new receivers. There needs to be a methodical demonstration of the precision of new receivers and of the results when vectors are formed between different types of receivers. Current Federal Geodetic Control Committee testing is aimed more at a demonstration of functionality than at an exhaustive test. Networks will be observed with mixtures of receiver types or reobserved with different receivers than the original observations. We need to know what affect this will have on the results.

7.2.4 Algorithm development and improvement. Processing GPS data for high precision with today's receivers and software is very time consuming. Part of this time is the result of cycle slips and bad data with today's receivers and part of it is the result of the extent of human interaction required in selecting double difference combinations, lengths and number of parameters for orbit arcs, or fixing bias. The procedures used vary greatly from one processing system to another, but all systems require a great deal of time.

7.2.5 DoD cooperation. The civilian community should use all possible means to influence on the Department of Defense to make the system as useful as possible to the measurement of crustal deformation. The current broadcast orbits are precise enough to provide a starting orbit for preliminary processing with all vectors. For vectors less than about 10 km in length, the current broadcast orbits are precise enough for final processing. This is very convenient, and would allow implementation of near-real-time monitoring fairly conveniently. If these orbits are degraded significantly (e.g. under Selective Availability), we may need to think about replacing these orbits with some other near-real-time highly accessible source of orbits. Currently there are other sources of orbits (Naval Surface Weapon Center, Dahlgren, VA; University of Texas, Austin, TX; National Geodetic Survey, Rockville, MD) but they are available weeks after the observations. For some applications (monitoring volcanos and faults, post seismic studies, e.g. Japanese Tokai net) there is a need to operate GPS in real-time or near-real-time. The requirements of the geophysical community for high precision GPS are in the national interest whether the research is for hazard reduction or less directly applied. The Department of Defense must be made aware of our requirements.

7.2.6 Monumentation. Even with the current precision of GPS we are pushing the limits of the techniques used to tie the location of the observing instruments to a point on the ground. Better GPS can only aggravate this problem. We need investigations into the source of the signals seen in frequent high precision measurements (Langbein et al., 1987) and we need monumenting techniques to eliminate them if they are indeed noise.

7.2.7 Continuously operating GPS networks. In order to study the complete spectrum of geodetic signals, from periods of hours to decades, networks of continuously operating GPS receivers should be deployed in a few key areas. Using GPS, it is possible to obtain essentially continuous records of deformation. This will produce an entirely new geodetic data set. When combined with the records from shorter strainmeter-type instruments, these data will provide a powerful tool for investigating strain events such as pre- and post-earthquake deformation. These observations will provide data from a nearly unexplored part of the spatial and temporal deformation spectrum (period less than 1 week and scale greater than 1 km). With every new observation type there is an opportunity for quantum jump in our understanding.

7.3 GLRS

NASA is currently considering flying an altimetric and ranging laser on one of the polar Earth Observation System (EOS) platforms. GLRS will operate in two modes: a nadir-looking-altimetric-mode with a principal applications to ice sheet topography and cloud height; and a steerable ranging mode with a principal application in determining relative positions of ground sites. GLRS would greatly simplify the users side of positioning. The field sites would consist of corner cube reflectors with no requirements for on-site power, data processing capability, or data storage. GLRS will only begin to impact deformation studies during the next decade (it will be launched in 1996 or 1997). However, continued development of GLRS is essential to provide a complimentary system to existing GPS and ground-based geodetic techniques and to explore techniques for cheaper, easier and more precise measurements in the future.

7.4 SMP

Many important problems in crustal deformation will only be addressed when there exists a way of making precise observations to sub-marine points. Since two-thirds of the Earth's surface is water covered, it is not surprising that many areas of interest in deformation problems are wholly or partially under water. The percentage of plate boundaries that are sub-marine is even higher because of the non-random distribution of plate boundaries. Most plate boundaries occur either in the middle of the oceans or at the edges. There are relatively few plate boundaries that occur entirely on land.

These facts of geography suggest that the ability to position points on the bottom of the ocean would be a very useful in studying crustal deformation. Because of environmental factors, one can divide the problems and opportunities into three categories on the basis of distance: less than 1 km, 1-10 km, and greater than 10 km (Spiess, 1989). At distances shorter than 1 km, sub-aerial techniques can be adapted to use of the ocean bottom. Strainmeters and tiltmeters can be adapted to the oceanic environment, and visible light will propagate up to about a kilometer allowing ranging or angle measurements in a manner similar to land based observations. From 1 to 10 km it becomes necessary to use acoustic techniques. Knowledge of the effective speed of sound limits these techniques to about 1 part in 10^5 under the best conditions at present, with possible improvement to 1 part in 10^6 at best. Thus the range must be limited to 10 km in order to even approach 1 cm precision with purely acoustic techniques. Beyond 10 km, it is necessary to use composite systems with acoustic techniques locating a floating platform relative to the ocean bottom and space geodetic techniques, probably GPS, locating the platform relative to a distance mark, either another floating platform or a sub-aerial mark.

The current level of precision in the techniques, $\sigma = 10$ cm, suggests that it may be premature to consider widespread deployment, but the potential value of making measurements to sub-marine sites is great. Consequently, we recommend continuing a development effort in this technology with test applications until the precision reaches a level where the measurements can be expected to provide favorable signal-to-noise ratios with a few years of observations.

Table 2: Number of years required to detect tectonic motion as a function of the precision in the measuring system and the rate of motion. The motion is detectable when the change during the specified time period exceeds twice the standard deviation in the difference of the observations ($= 2*\sqrt{2}*\sigma$).

Tectonic rate	σ 10 cm	σ 1 cm
1 cm/yr	30 years	3 years
10 cm/yr	3 years	0.3 years

If the precision of sub-marine positioning is 10 cm/yr, it will be of value for measuring vectors between the fastest moving plates. As the precision increases the number of applications does also. We recommend continuing a development effort in this technology with only test applications until the precision reaches a level where the measurements can be expected to provide favorable signal-to-noise ratios in a few years.

SECTION III.

REPORT OF THE PANEL ON

LITHOSPHERIC STRUCTURE

AND EVOLUTION

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SECTION III.

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SUMMARY

As the twenty-first century approaches, better knowledge of the physical and chemical structure of the solid Earth's upper few hundred kilometers and how it has evolved over the past several billion years becomes increasing important for solving the basic problems which face human society, such as dwindling natural resources, deterioration of the environment, and loss of life and property through natural disasters. For example, the Earth's lithosphere contains the coal, petroleum, and uranium we rely upon for fuel, as well as the metals used in construction, communications, and industry. Through an improved understanding of the Earth's geologic history, we can more efficiently discover the untapped resources we need until alternatives to the limited natural resources can be found. In addition, the scientific community has become increasingly aware that the problem of global change can not be addressed solely through studies of the Earth's atmosphere, hydrosphere, and biosphere. The lithosphere contains the only record of global change before the influence of industrial society, which allows us to distinguish the anthropogenic signals from natural cycles. Finally, monitoring of volcanic eruptions and lithospheric plate motions by seismic and strain networks must be accompanied by broad-based geologic and geophysical studies of the lithosphere's physical properties and how it has been deformed in order to obtain the fundamental knowledge needed to predict exactly where and when lithospheric plate motions will lead to earthquakes and volcanic eruptions.

Many of the most basic questions concerning the lithosphere's structure and evolution can be addressed through space-based observations that NASA is capable of providing. These include:

1. What is the deep thermal and chemical structure of continental versus oceanic lithosphere? Can we explain why the oceanic lithosphere appears to reach an equilibrium thickness of 125 km in only 200 Ma while continental lithosphere continues to thicken to values 2 to 4 times greater?

2. How has the lithosphere formed and aged over the history of the Earth? Is the paradigm of plate tectonics, so clearly demonstrated to be correct for the modern Earth, appropriate for the young Earth? Alternatively, did the lithosphere evolve in a different fashion in the past dictated by its higher temperature and lower degree of differentiation? If so, can we recognize and reconstruct pre-plate teconic styles of lithospheric evolution?

3. What are the processes of rifting and extension in continental versus oceanic lithosphere? Uniform stretching models have proven extremely useful in describing rifting in the oceans, whereas recent studies of continental rifting have emphasized the role of subhorizontal detachment systems in accommodating extension. Are these differences real, and if so, what controls them? Progress in understanding the difference relies on deeper knowledge of the structure and dynamics of both kinds of rifts and the rheology of both types of lithosphere.

4. What areas of the continents are currently undergoing epeirogenic uplift and subsidence? Can we link these vertical movements to thermal and dynamic processes inferred from seismology and gravity to understand the formation of intracontinental basins and arches? How does eustatic sea level change relate to continental tectonics and sedimentation throughout the Phanerozoic? What is the present-day rate of eustatic sea level rise, and can it be distinguished from post-glacial rebound? Can we use geologic information to distinguish sedimentary, thermal, flexural, eustatic, and tectonic components of subsidence in order to address problems ranging from petroleum exploration to rheology of the lithosphere?

5. What is the thermal and chemical structure of midplate plateaus, swells, and super-swells? How do they relate to mantle plumes and continental rifting and convergence? How rapidly do midplate swells rise and fall? Are the rates consistent with conductive transfer of heat in the oceanic lithosphere, or is dynamic flow required? How much heat is liberated from the mantle by midplate volcanism and swell formation?

6. What is the rheology of the lithosphere and how does it interact with the asthenosphere at oceanic trenches and continental collision zones? What stresses act on the downgoing plate from its own negative buoyancy, surface and subsurface loads, and resistance to penetration through a viscous mantle?

Progress in solving these problems is dependent upon availability of several key data sets which NASA could effectively acquire using space technology, such as altimetry, potential field data, remote sensing imagery, and absolute vertical positioning. The following prioritization assumes that the remote sensing instruments now in operation, TM and SPOT satellite systems and the ASAS, TIMS, AVIRIS, NS-001, SAR, SIR-C, and photographic aircraft systems, will continue to provide data throughout the program life. We also assume that planned EOS systems or equivalent including SAR, TIMS-class ITIR, and HIRIS be in operation as scheduled, and that better altimetric coverage over the oceans is best achieved through the efforts of foreign space agencies due to classification issues. With these assumptions we prioritize our needs as follows:

1. **Digital topography over the continents (30 m horizontal, 4 m vertical).** These data are essential to all scientific objectives.

2. **Gravity measurements (<100 km horizontal, 2 mGal).** One approach to acquire these data is for NASA to contribute the GPS receiver and a drag-free system to ensure the success of the ESA Aristoteles mission, which would be an important first step in obtaining high resolution, global gravity data and for the purpose of demonstrating the feasibility of gravity gradiometry from space. However, it is unlikely that this mission will provide the accuracy and resolution we require. Therefore, NASA should pursue plans for a follow-on low-altitude gravity mission, such as the Superconducting Gravity Gradiometer Mission.

3. **Magnetic measurements.** Given the expense of flying missions in low-Earth orbit, we recommend that magnetic field measurements be included with both (Aristoteles and SGGM) gravity missions. A higher orbit, MFE-type mission is also important for isolating the core field from the lithospheric field.

4. **High spatial (approximately 5 m) resolution stereo panchromatic data.** One approach would be to use the Large Format Camera. This high spatial resolution stereo system fills an important void in planned remote sensing missions. The instrument or equivalent should routinely be flown on the Shuttle and/or on some other platform until global stereo coverage of the continents is obtained.

5. **Vertical Positioning.** The exciting prospect of directly measuring the vertical motions associated with the evolution of the lithosphere is still a decade or more away, but it will continue to be an elusive goal unless we begin now to improve the accuracy of absolute vertical positioning and start acquiring baseline measurements of signals that can be resolved a decade or more later.

In addition to providing the basic global data sets described above, NASA is in a key position to

- **foster cooperation among the space agencies of the world to address major scientific and environmental problems, with a philosophy of maximizing data exchange and the development of complementary missions; and**

- **realize the scientific potential of this data by funding data analysis as well as acquisition.** Selection of specific investigations and geographic sites for study should be based on the results from peer review process.

INTRODUCTION

The importance of the lithosphere can hardly be overemphasized from either a scientific or a societal perspective. From a purely scientific standpoint, the lithosphere preserves the only record of the Earth's geologic, biologic, and climatic history. From a societal standpoint, the lithosphere is the dynamic layer responsible for both natural hazards and resources, as well as the surface upon which we live.

Because of its importance, many U.S. and foreign agencies are devoted to the study of the lithosphere, but their efforts are fragmented by shorelines, political boundaries, and specific agency missions. From a space-based perspective, NASA can bridge these gaps by providing uniquely global data to constrain models of lithospheric structure and evolution via remote sensing, geopotential fields, altimetric measurements, and precise positioning.

Our present understanding of lithospheric processes is based on the concept of plate tectonics developed from observations in the ocean basins. We know that continental lithosphere is not mechanically equivalent to oceanic lithosphere because continental nuclei are more than 3 Ga old, whereas the ocean floor does not exceed 200 Ma in age. One of the major unsolved problems in Earth sciences is the question of whether this difference in the plate-tectonic recycling history of continental versus oceanic lithosphere can be explained solely by the difference in composition and thickness of continental *crust*, or whether it requires fundamental differences in the thermal and chemical structure of the subcrustal upper mantle.

To address this question, it is crucial that we develop a refined understanding of the compositional, structural, and thermal differences between oceanic and continental lithosphere. These three basic properties provide the keys to determining the magmatic, metamorphic, and sedimentary processes that have led to the differentiation and modification of the lithospheric chemical and thermal boundary layer, as well as the rheological laws which govern its deformation in response to applied stress. NASA can contribute to this understanding via a vigorous program in solid Earth science with the following objectives:

1. **Determine the most fundamental geophysical property of the planet: the detailed shape of the surface of the lithosphere (i.e., the topography) to a vertical accuracy of a few meters with a horizontal resolution of a few tens of meters;**
2. **Determine the global gravity field to an accuracy of a few milliGals at wavelengths of 100 km or less;**
3. **Determine the global lithospheric magnetic field to a few nanoTeslas at a wavelength of 100 km;**
4. **Determine how the lithosphere has evolved to its present state via acquiring geologic remote sensing data over all the continents.**

The topographic, potential field, and remote sensing signals of interest for studies of the long-term evolution of the lithosphere change extremely slowly on human time scales. Even if they can be accurately measured only once in the next decade, we can make substantial progress in inferring their time dependence by studying similar features in different stages of development. However, a exciting prospect for the next century is the possibility of directly detecting vertical motions at the Earth's surface predicted by isostatic adjustment to changes in surface loads (e.g., ice sheets), the temperature or composition of the lithosphere, and dynamic forces at its base. Therefore, we list as a longer-term objective of NASA's program for studying the evolution of the lithosphere:

5. **Improve the accuracies of vertical positioning to the sub-millimeter level and gravimetry to the sub-microGal level to test and directly calibrate models for the temperature, density structure, and rheology of continental and oceanic lithosphere.**

TOPOGRAPHY

Topography is one of the most basic geophysical characteristics of the planet Earth. Topographic data are vital for lithospheric research, with application to geological and geophysical studies. Geologists devote the entire field of *geomorphology* to the study of land forms for the purpose of understanding the dynamic, volcanic, and tectonic processes which build relief, as well as surficial processes such as weathering and erosion which wear it down. From a geophysical perspective, variations in elevation balance buried density anomalies arising from thermal and chemical inhomogeneities to bring about isostatic equilibrium. In addition, surface relief causes major perturbations to the gravity field, magnetic field, and seismic travel times for which we must correct before geophysical data can be used to probe structures within the Earth's interior. High priority goals of the SES should be:

- **aquiring a global digital continental topographic data set with at least 30-m horizontal resolution and 4-m vertical resolution;**
- **encouraging altimetric missions (e.g., ESA's ERS-1) to map the marine gravity field to an accuracy of 1 mGal with a resolution of 10 km for the purpose of predicting bathymetry in the 10 to 100-km wavelength band.**

The present status of our knowledge of the Earth topography and the scientific requirements which we discuss below are summarized in Figure 1.
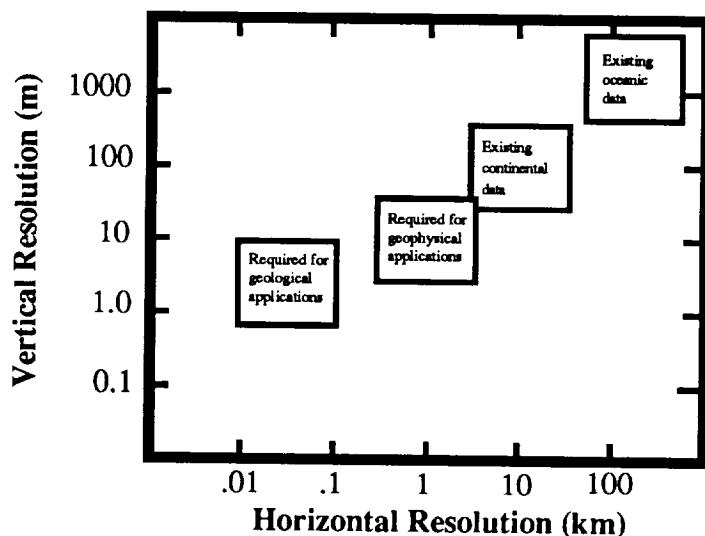
Figure 1. Scales (extent) of desirable global topographic coverage and appropriate resolution required for studies of lithospheric structure and evolution. For comparison, the best presently available global continental and marine data are shown.

Continental Topography

The continental surface has developed over millions to billions of years in reponse to volcanism, earthquakes, glaciation, and the effects of wind and surface water. The relief of a province alone can provide a good estimate of its age and the processes to which it has been subjected. In addition to the geologic and geophysical applications, topographic data over the continents are essential for atmospheric and slope corrections of image data acquired at wavelengths ranging from visible to microwave.

Present Status. Today, topographic data mostly consist of contours drawn around unevenly distributed spot height measurements [*Topographic Science Working Group*, 1988]. Available digital data are limited areally and for the most part derived from the same information used to create the contour maps. The best available global digital coverage for the continents has only about 5-km horizontal resolution, of little value for geological or gravity modeling of the continents. These data additionally suffer from the fact that 18 separate reference datums (horizontal control surfaces) are in use by different countries to measure local elevation. **A long term commitment by SES to utilize NASA satellite technology to create a digital topographic data set with a common global datum would contribute substantially to research related to lithospheric evolution.** Resolution requirements for the proposed data set are defined based on geological and gravity modeling requirements.

Geological Requirements. Topographic information is not only used as a base for geological mapping but also enables geologists to use surface mapping results to constrain the three-dimensional geometry of rock units and geological structures. This information in turn, constrains sedimentological and tectonic models describing the environmental and deformational history of continental crust.

The resolution of topographic data required for stratigraphic and structural studies is defined by mapping scale, local relief, and the attitude and thickness of mapping units. A standard maximum mapping scale used in such studies is 1:24,000. Based on National Mapping Accuracy Standards and geological mapping experience as described by *Lang et al.* [1987] and in the Remote Sensing section of this document, this mapping scale requires at least 30-m horizontal resolution and 4-m vertical resolution topographic data. This horizontal resolution is also appropriate because it is compatible with Thematic Mapper data, a standard remote sensing data set for lithologic and structural mapping of the continents.

Gravity Modeling Requirements. Accurate topographic data are required to correct gravity measurements used to model density distribution and infer structure of both continental crust and oceanic lithosphere. The requirements for topographic data in support of gravity studies as described by the *Topographic Science Working Group* [1988] and in the Gravity section of this report is 1-km horizontal and 10-m vertical resolution.

Suggested Approach. Minimal acceptable resolution requirements are most tightly constrained by geological research needs. Present space technology limitations indicate that acquisition of the 30-m horizontal and 4-m vertical resolution data set requires a phased/iterative approach. An initial digital topographic data base could be obtained with a radar altimeter, creating the first global digital topographic data set with a single datum. Horizontal resolution of such a data set would probably not exceed 100 m [*Topographic Science Working Group*, 1988]. Already available 30-m resolution digital data would then be incorporated. Finally, new data, acquired from aircraft or satellite using photogrammetric analysis of optical stereo images as well as laser altimetry would be iteratively incorporated. Appropriate GPS measurements could be used to adjust these elevations to the same datum as that used for the radar altimeter base. The process would continue until a global digital topographic data set with 30-m horizontal and 4-m vertical resolution was obtained.

Sea Floor Topography (Bathymetry)

Bathymetry is primarily an expression of volcanic and tectonic processes because seafloor erosion rates are low compared to the continents. Large-scale variations in seafloor topography (from shallow ridge crests, 2-5 km, to deep ocean basins, 5-6 km) are due to cooling and contraction of oceanic lithosphere as it moves away from a spreading

axis. Departures from the normal depth-age relationship reveal areas where lithosphere has been reheated and/or crustal thickness varies. While these basin-scale variations are well described, the fine-scale bathymetry is not. Global knowledge of bathymetry at 10-km scale would allow us to:

- Refine models of the generation of oceanic lithosphere by mapping ridge morphology;
- Constrain the volume of intraplate volcanism by taking inventory of the number and size of undersea volcanoes;
- Improve models of relative plate motion by identifying and tracing oceanic fracture zones;
- Update resource assessments by mapping uncharted sedimentary basins on remote continental margins;
- Delineate regions of intraplate deformation and incipient subduction to understand plate/mantle dynamics;
- Improve our understanding of convergent plate boundaries by surveying subduction zones and back-arc basins.

Present Status. It is startling that the topography of Mars [*Carr et al.,* 1977] and Venus [*Masursky et al.,* 1980] has been mapped at a higher resolution than the topography of the Southern Ocean. There are still many 5 degree by 5 degree areas in the South Pacific, South Atlantic and Southern Indian Oceans that have not been explored by ships. Shipboard surveys to date have measured the large-scale (1000-10,000 km) variations in bathymetry, but fine scale bathymetry (10-100 km) is known only in isolated regions. Even with advanced swath mapping tools such as Seabeam, it would take many decades to survey significant portions of the sea floor in these remote areas.

Suggested Approach. Bathymetry cannot be directly measured from a satellite. However there are at least two ways that the space program can contribute to charting bathymetry. The first involves satellite-based navigation and communication. GPS navigation of research vessels is now required for taking full advantage of the high-accuracy swath mapping techniques such as Seabeam and SeaMarc. We perceive that during the next 20 years, unmanned ocean surface or subsurface vehicles may need to communicate with a central facility using a satellite link.

The second contribution from space techniques is to use satellite altimetry, which maps the topography of the equipotential sea surface (marine geoid), for locating features in uncharted areas [*Haxby,* 1985; *Sandwell,* 1984]. Details in the marine geoid reflect seafloor topography, especially at wavelengths shorter than 100 km. In addition to locating features, a complete two-dimensional mapping of the marine geoid could be used along with available shipboard bathymetric profiles to predict bathymetry in uncharted areas at 10 km resolution.

The basic approach is to take advantage of the correlation between the geoid or gravity field and bathymetry at short to medium wavelength [e.g. *Dixon et al.,* 1983; *Freedman and Parsons,* 1986]. High-accuracy and resolution geoid and gravity field data, derived from pulse-limited radar altimetry, may be used to interpolate between existing shipboard bathymetry profiles. This technique relies on the assumption that the relationship between gravity and bathymetry is uniform over small areas (~200 km by 200 km). Because of upward continuation of the gravity field from the sea floor to the sea surface, the best achievable horizontal resolution of predicted topography will be approximately twice the average water depth. Over the resolution band 10 km to 100 km, the estimated vertical accuracy of this technique is ~100 m (Figure 2).
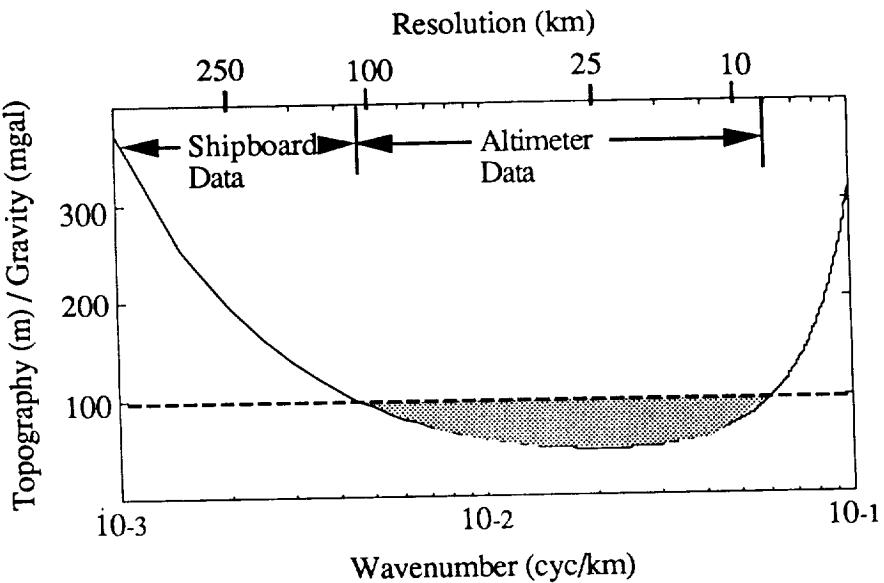
Figure 2. Ratio of sea floor topography to sea surface gravity for an Airy compensation model. Assuming a five-year altimeter mapping mission could recover the marine gravity field to an accuracy of 1 mgal at resolutions of 10 km, then this simple model predicts that marine gravity can be used to estimate sea floor topography on horizontal scales of ~10 km to ~100 km to an accuracy of 100 m. At longer wavelengths (resolution > 100 km) sea floor topography must be constrained by sparse shipboard profiles since the effect of isostatic compensation reduces the gravity effect.

GRAVITY FIELD

Gravity anomalies arise from lateral variations in density beneath the Earth's surface. These density variations may be caused by changes in either temperature or mineralogy, and thus an understanding of the Earth's gravity field at wavelengths less than the thickness of the lithosphere is *essential* to understanding the thermal and chemical differences between continental and oceanic lithosphere. We recommend that NASA work towards major improvements in the global gravity data base via

- **measuring the gravity field from space with an accuracy of a few mGals and a resolution of 100 km or less;**
- **encourage altimetric missions (e.g., ESA's ERS-1) to map the marine gravity field to an accuracy of 1 mGal with a resolution of 10 km.**

Note that for the purposes of measuring with radar altimeters the sea surface slopes arising from dynamic ocean effects such as currents, tides, and eddies, the oceanographic community requires a *gravimetric* marine geoid accurate to 20 cm at wavelengths of a few 100 km. Thus the gravity field requirements needed for solid Earth studies also satisfy the needs for oceanography.

Continental Gravity

Solving a number of problems central to the study of the structure and evolution of continental lithosphere requires accurate and detailed global gravity data. These problems include:

- the deep thermal and chemical structure of continental lithosphere. Continental lithosphere appears to be 2 to 4 times thicker than oceanic lithosphere. Is this deeper continental root solely a thermal effect, or does it require a chemically-

induced density reduction to stabilize it against convective overturn? This deep structure provides the context within which all the other problems must be examined.

- the process of rifting and extension. Uniform stretching models have proven extremely useful in describing rifting in the oceans, whereas recent studies of continental rifting have emphasized the role of subhorizontal detachment systems in accommodating extension. Are these differences real, and if so, what controls them? Progress in understanding the difference relies on deeper knowledge of the structure and dynamics of both kinds of rifts and the rheology of both types of lithosphere.

- the deep, and in many places the shallow, structure of mountain belts. Serious questions remain as to the mode and depth of isostatic compensation, the relative role of topographic and subsurface loads, the origin of the subsurface loads, and the long-term rheology of continental lithosphere involved in their evolution.

- subsidence and reactivation of sedimentary basins and passive margins. It is important to develop the ability to distinguish sedimentary, thermal, flexural, eustatic, and tectonic components of subsidence in order to address problems ranging from petroleum exploration to rheology of the lithosphere.

- the nature of major heterogeneities in thickness and density of the continental crust, which apparently persist for billions of years due to the strength of continental lithosphere, and may control tectonic evolution upon reactivation of the continental basement.

We list briefly below the present state of gravity information over the continents and the improvement needed to address these problems. For a more detailed discussion of the scientific problems, see reports by *Gravity Workshop* [1987], *Topographic Science Working Group* [1988], and *Mueller and Zerbini* [1989].

Present Status. Existing data in the public domain at 4-mGal accuracy and 100-km resolution cover only 22% of the area of the exposed continents. Political and geographical barriers prevent further acquisition by means of traditional ground surveys. Since many countries consider gravity data strategic information for missile guidance, there is little prospect of gaining access to classified data in the near future. As in the case of the topographic data base, individual surveys are referenced with respect to different base levels which complicates the compilation of data sets across national (and even state) boundaries.

Requirements. Figure 3 summarizes the gravity field requirements needed to address the above problems. For example, the density anomalies arising from differences in continental versus oceanic thermal and chemical structure between 100 and 400 km should give a surface gravity anomaly of 1 to 5 mGal. The deep continental gravity anomaly must be resolved across continental margins (i.e., by a satellite technique valid over both land and water), and requires no worse than 100 km horizontal resolution.

Gravity anomalies can distinguish among various models for lithospheric extension by constraining the thermal structure and flexural rigidity in rifts. Broad constraints would be obtained with gravity data accurate to 1 or 2 mGal at horizontal resolution of 100 km, attainable by spacecraft. Specific information on spatial variation of flexural rigidity, given low expected elastic thicknesses, requires 1 mGal accuracy at 20 km or better resolution, potentially attainable by aircraft survey. The requirements for gravity data over orogens needed to test models of continental rheology, mechanisms of plate loading, and the structure resulting from continental suturing are similar, although the accuracies need not be as great since the expected signal is higher over mountain belts than over rifts.

Global gravity data with 1 mGal precision and 50 km spatial resolution, combined with topography, bathymetry, and radar ice-thickness data, are required to determine the forces driving subsidence of sedimentary basins and the mechanics of the lithosphere. Data at

lower resolution would allow delineation or detection of sedimentary basins with petroleum potential hidden offshore, under ice-sheets, and under allochthonous crystalline thrust sheets.

High quality (5 mGal, 50 km resolution) gravity data, in conjunction with crustal seismic studies, can constrain the existence and mode of compensation of heterogeneities within continental lithosphere. This will allow assessment of their role in vertical motion of the continental lithosphere.

For all of these problems, sound interpretation of the gravity field in terms of the Earth's interior properties will require global topography known with great statistical accuracy at 25 km wavelengths. To achieve this, continental topography should be measured to better than 10-m accuracy at 1km horizontal resolution.
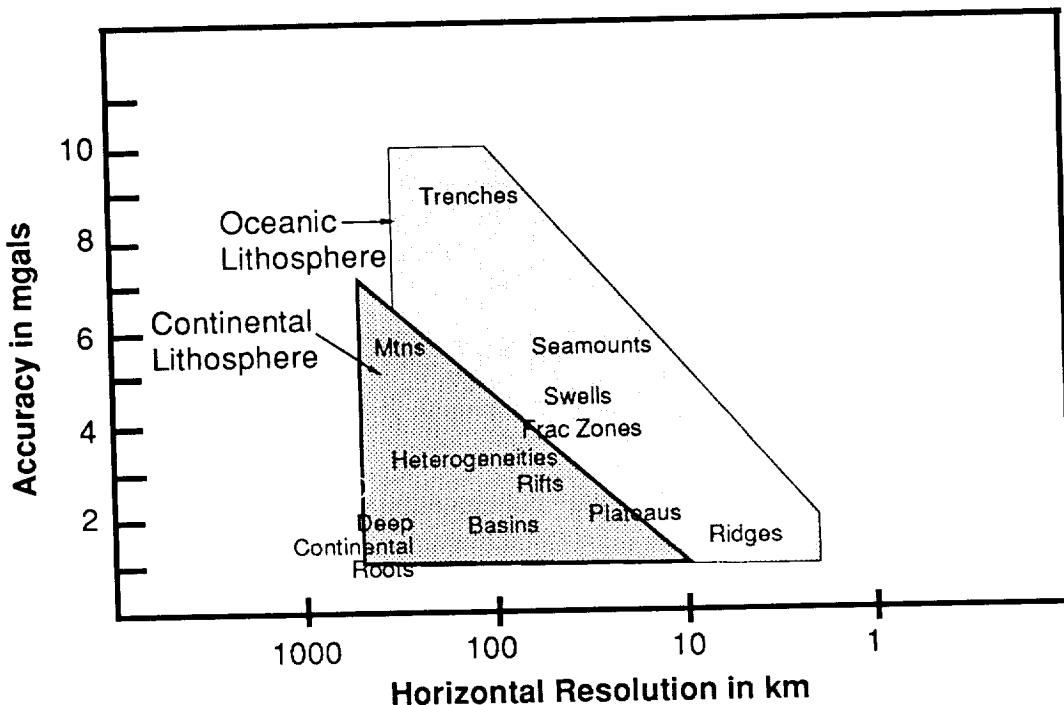
Figure 3. Summary of the requirements for gravity measurement accuracy as a function of spatial resolution needed to solve basic problems in lithospheric sturcture and evolution.

Marine Gravity

Altimeter data from Seasat and GEOS-3 amply demonstrated that satellite observations can yield major advances in our understanding of the thermo-mechanical structure and evolution of oceanic lithosphere. In the past decade, altimetry data over the oceans has been applied with much success to models of lithospheric structure in all major oceanic provinces, from the mid-ocean ridges where the lithosphere is formed to trenches where it is consumed. However, a number a outstanding problems concerning the oceanic lithosphere remain to be solved because available altimetric geoids lack sufficient resolution, accuracy, and/or continuity at shorelines. These problems include:

- lithospheric rheology and mantle dynamics at midocean ridges, and how they relate to topographic segmentation of ridges, axial horsts, and medial valleys. What is the relative importance of active versus passive rifting?
- the thermal structure of the upper mantle beneath fracture zones and how it evolves with time. Why does the simple thermal plate model, which so successfully

predicts the depth/age relationship for oceanic lithosphere, fail to describe the geoid anomaly measured across oceanic fracture zones? What are the relative roles of lithospheric flexure, thermal stress, variations in crustal structure, and small scale convection in explaining the discrepancy?

- lithosphere/asthenosphere interaction at subduction zones. What stresses act on the downgoing plate from its own negative buoyancy and resistance to penetration through a viscous mantle?

- the thermal structure of midplate swells, superswells, and their relationship to mantle plumes. Do these depth anomalies arise primarily from reheated lithosphere or thermal anomalies maintained in the convecting asthenosphere?

- the origin of oceanic plateaus and their mechanism of compensation. Which ones are simply thickened oceanic crust and which are continental fragments?

We list briefly below the present state of gravity information over the oceans and the improvement needed to address these problems. For a more detailed discussion of the scientific problems, see reports by *Gravity Workshop* [1987], *Topographic Science Working Group* [1988], and *Mueller and Zerbini* [1989].

Present Status. Because sea surface height is a fairly close approximation to the marine geoid (within a few 10's of cm), satellite altimeter missions such as Geos-3, Seasat, and Geosat, have provided a view of the marine gravity field far superior to what we have over the continents. In the Southern Oceans, the marine gravity field is better mapped than the bathymetry. Nevertheless, because the gaps in Geos-3 and Seasat coverage exceed 100 km at the Equator and because most of the Geosat data remains classified, we still do not know the marine gravity field to better than a few mGals at a resolution less than 100 km. Furthermore, better altimetry data alone will not satisfy many of the requirments for marine gravity, such as needing a *gravimetric* geoid for isolating dynamic sea surface slopes and a gravity field continuous at shorelines for modeling features at continental margins (e.g., subduction zones).

Requirements. Figure 3 summarizes the requirements in terms of accuracy and resolution of marine gravity data needed to address the problems listed above. The study of midocean ridges places the greatest demands in terms of accuracy and resolution, because the lithospheric plates are so weak on very young lithosphere that the gravity signal of interest is small and of short wavelength.

To address the question of the problem of the plate structure across fracture zones, we need a gravity field accurate to 1 mGal at a resolution of 50 km or less. To realize the full potential of such data, gravity field modeling must be also constrained by better topographic data from the oceans and seismic information on crustal structrure.

The largest gravity anomalies on Earth occur at trenches where the subduction of oceanic lithosphere into the mantle creates the greatest thermal, seismic, and geochemical anomalies. The large amplitude of the anomalies leads to accuracy requirements of only 5 to 10 mgals at 100- to 200-km resolution for studying plate interactions, but the gravity or geoid map must be continuous from the undeformed seafloor, across the outer rise, trench, forarc, and island arc to the overriding plate.

The large amplitude (10 m) and long wavelength (~500-1000 km) of the geoid signature from the thermal anomaly responsible for uplifting midplate swells is adequately mapped for the large northern hemisphere swells such as Hawaii, Bermuda, and Cape Verde, but those in the south-central Pacific, such as Society, Cook, and Austral, are barely resolved in both amplitude and planform [*McNutt and Judge,* 1990] against the background of the South Pacific superswell [*McNutt and Fischer,* 1987]. Thus more dense altimeter data with higher resolution would contribute to the study of swells in the South Pacific. In addition, such data would allow much better calibration of the flexural rigidity of oceanic lithosphere supporting the individual hot spot volcanoes capping these swells [*Watts,* 1978]. Because the base of the elastic plate corresponds to an isotherm near

500°C to 600°C [*McNutt and Menard*, 1982], by measuring the elastic plate thickness as a function of distance along the subsiding thermal swell as it moves past the hot spot, we can chart the depth to this isotherm as a function of time [*McNutt*, 1984]. This view of the evolution of one isotherm provides a strong constraint on the details of the thermal structure imposed by the hot spot that connot be resolved by the more general integral constraints on low density provided by the longer-wavelength geoid anomaly over the swell. A thorough understanding of the mechanism by which the hot spot reheats the lithosphere requires such knowledge of the vertical and lateral structure of reheating.

Satellite altimeter data have been used to estimate depths of compensation for a number of marine plateaus from the slope of geoid height versus topography [*MacKenzie and Sandwell*, 1986]. For smaller plateaus, the accuracy of this procedure is limited by the accuracy and coverage of existing satellite alimeter data. A complete gravity/topography study requires a field accurate to 1 mgal at a resolution of 50 km.

Suggested Approach. For many of these features the resolution requirements are so stringent (~10 km spatial resolution) that they can only be supplied from space via altimeters. In the case of subduction zones in particular, the necessity of having a field that spans the shoreline leads to the requirement that data be obtained using non-altimetric techniques, such as a gravity gradiometer in low orbit. Even if gravity data at the required resolution and accuracy is obtained, the ability to address many of these problems will be hindered by our extremely poor knowledge of seafloor bathymetry. Therefore, in support of potential field modeling, we also require a **non-altimetric** measure of the topography at comparable resolution to the gravity and geoid data. Although this can only be supplied by acoustic signals from surface ships, NASA can contribute to this effort by providing easy access to GPS technology for navigation.

MAGNETIC FIELD

The lithospheric magnetic field arises from minerals in the TiO_2-FeO-Fe_2O_3 ternary system behaving as permanent or induced magnets between the Earth's surface and the Curie isotherm, which is approximately 600°C for most geologically significant minerals. This signal is commonly termed the "crustal" magnetic field because the continental Moho appears to be a sharp magnetic boundary, but here we adopt the more general term "lithospheric" magnetic field to include the possibility of sources in the oceanic upper mantle beneath the crust but shallower than the Curie isotherm. Thus maps of the lithospheric magnetic field can be sensitive indicators of lithospheric mineralogy, temperature, and age (via the dependence of remanent magnetization on the strength and direction of the paleomagnetic field when the rocks last cooled through the Curie isotherm).

In a broad sense, the use of short and intermediate wavelength magnetic anomalies to trace surface structures into the subsurface and to infer the depth to an isotherm which controls the acquisition of magnetic properties is analogous and quite complementary to the interpretation of gravity anomalies. Both types of measurements suffer from the upward attenuation of field strength with altitude, which limits the resolution with which anomalies can be recovered from space. However, unlike the gravity field, the crustal magnetic field is contaminated by unmodeled secular variation of the core field whenever data from magnetic surveys acquired at different epochs are combined. Thus the case for acquiring a globally uniform field within a short period of time from space is even more compelling for magnetics than gravity.

The Magsat mission, which returned vector magnetic field data from elevations of 325 to 550 km between November, 1979 and June, 1980, is the best demonstration to date of the potential for satellite magnetic field measurements to contribute to studies of lithospheric composition, mineralogy, structure, and temperature. Many of the important scientific results for that mission are collected in the April, 1982 issue of *Geophysical Research*

Letters and the February, 1985 issue of the *Journal of Geophysical Research.* We recommend:

- a follow-on, lower altitude, vector magnetic field mission to measure the lithospheric field to an accuracy of 1 nT at a resolution of 100 km, combined with
- a higher altitude, longer duration mission to effectively model and remove secular variation from the lithospheric signal

for the purpose of addressing questions such as:

- the origin of intermediate-wavelength magnetic anomalies over oceanic lithosphere. Do these anomalies reflect lateral variations in thickness of the oceanic crust, depth to the Curie isotherm, or Fe-content in the shallow lithosphere?

- the magnetic effects associated with subduction zones and hot spot traces. How much is the Curie isotherm depressed or elevated? What are the Fe-Ti anomalies in the associated volcanics?

- lower crustal mineralogy and temperature beneath the continents. How does it contrast with that of oceanic lithosphere? Does it produce a large magnetic signal at continental margins? Can this contrast be used to distinguish oceanic from continental submarine plateaus?

- the depth to the Curie isotherm in continental areas. Can it be used to distinguish between thermal expansion versus crustal thickening as the explanation for plateau uplift?

- the relationship of large-amplitude magnetic lineations in the continental basement to ancient and modern tectonic motions, including continental rifting and suturing.

Present Status. As pointed out by *Langel* [1985], the Magsat data has not had the expected impact on quantitative studies of the Earth's crust because of its limited resolution for crustal studies (400-500 km wavelengths), problems with contamination from core and external fields, and north-south filtering of the data which leads to poor east-west resolution in the lithospheric anomalies.

Requirements. Based on the Magsat experience, we are now in a position to design a lower altitude magnetic mission, preferably flown during a solar minimum and in conjunction with a higher altitude, long-duration mission for core field studies. The availability of reliable data from such a mission is likely to lead to rapid advances in both theoretical as well as observational aspects of lithospheric field modeling. A higher resolution (~100 km), more accurate (~1 nT) global magnetic survey would allow us to address the questions listed above by better resolving the correlation of magnetic anomalies with tectonic features, lithospheric age, and mapped variations in crustal mineralogy (e.g., high Fe-Ti basalts from the Galapagos spreading center). For example, Figure 4 shows an intriguing correlation between Magsat anomalies in Asia with Cenozoic faults. However, the Magsat data does not have sufficient resolution for tectonic studies. A lower altitude mission would surely improve our understanding of the sources of the lithospheric magnetic field and how they relate to thermal and compositional heterogeneity of continental versus oceanic lithosphere.

Note that in addition to obtaining these high resolution lithospheric data, it is critical that we have better models of the core and external fields in order to convincingly separate the three magnetic signals. This can only be done by long-term monitoring of the secular variation as well as external field variations, since any contribution to the intermediate-wavelength signal arising from lithospheric sources should be "static".

Figure 4. The vertical component of the long-wavelength magnetic anomaly field derived from Magsat and downward continued to a uniform altitude near the Earth's surface, is compared to the distribution of major Cenozoic faults in southeast Asia. Strike-slip faults tend to be more localized above negative anomalies, whereas positive anomalies correspond to stable blocks and old cratons. From *Cohen and Achache* [1990].

MOYENNE MONTANTE ET DESCENDANTE DEAU SOL
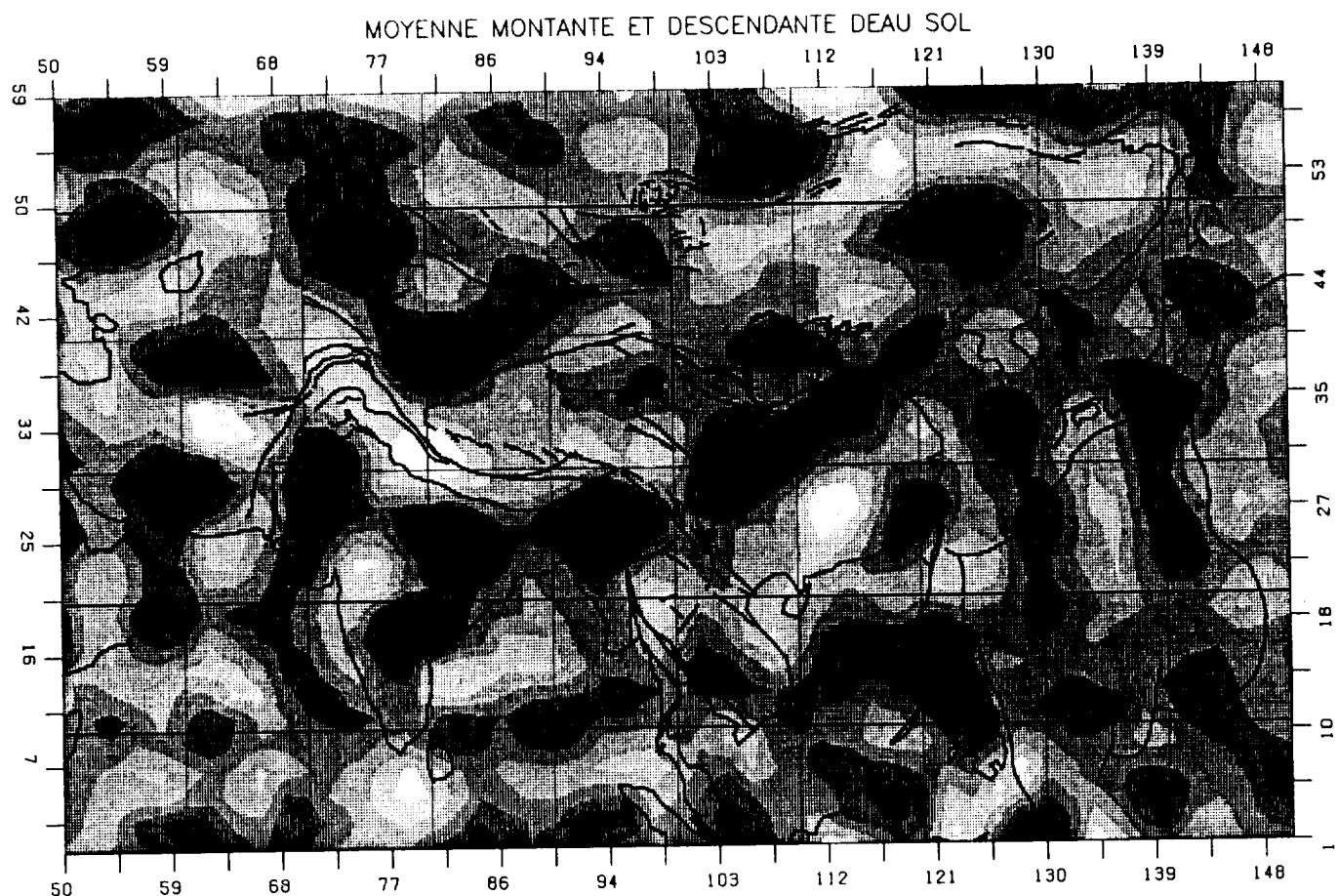
REMOTE SENSING OF CONTINENTAL GEOLOGY

Studying the continents is critical to understanding the lithosphere because the rocks they contain are the only record of Earth evolution before 200 Ma. Historically, the basic reference for such study has been geologic maps. The spatial distribution of rock units and structure, along with paleontological, chronological, compositional, and geometrical information summarized in geologic maps, are the basic data that allow detailed reconstruction of the evolution of continents. Specifically, geologic maps critically constrain global, regional and local determination of plate kinematics, intracontinental strain, and potential field-based models of the lithosphere and upper mantle. They summarize the sedimentological and paleontological record used to determine Phanerozoic climate change, sea level fluxuations, and biological events. They provide basic observations used for resource exploration, assessment, and development, including water, construction materials, minerals, and energy resources.

As a result primarily of NASA space technology, the concept of the geologic map has been expanded beyond that of a simple paper product. NASA-developed remote sensing methods have made it feasible to acquire gridded, digital, uniform-resolution geologic "maps" of continents. When these "maps" are combined with field and laboratory measurements, and other geologic, geophysical, and topographic data, they permit the 3-dimensional study of the geometry and kinematic development of continental crust. Such observations, coupled with theoretical models of mechanical properties of the lithosphere, will permit study of the dynamic processes responsible for the evolution of continental lithosphere. NASA's chief contribution to these efforts should be in

- **maintaining present remote sensing capabilities from satellites and aircraft, including instruments such as SAR, ITIR, and HIRIS planned for Eos;**
- **developing new hardware to provide higher spectral and spatial resolution in remote sensing data;**
- **making global data sets available to the research community at a *reasonable* cost; and**
- **supporting research that utilizes these data to address science objectives.**

Examples of potential research questions addressable by these methods include:

- Did plate tectonic processes operate in the early history of Earth? The composition and structure of rocks that were generated, preserved, and currently exposed at the surface, particularly in cratonic cores of continents, provide clues to the rate of crustal production and suspected higher heat flow during early Earth history that may have resulted in a tectonic style distinctly different from modern plate tectonics.

- What is the 3-dimensional kinematic history of continental crust? Three-dimensional, restorable kinematic models that portray the structural, sedimentological, and thermal history of continents are fundamental to interpreting deformational stresses and understanding the dynamic processes associated with continental evolution.

- What are the directly-observable, 3-dimensional characteristics of oceanic lithosphere? Numerous problems dealing with oceanic lithosphere formation, alteration by magmatic and hydrothermal fluids, transport, emplacement, etc., can be studied with remote sensing of ophiolites, fragments of oceanic lithosphere obducted onto the continents during plate collision or subduction events.

- What is the relationship between eustatic sea level change and continental tectonics during the Phanerozoic? Attempts to apply the concept that cyclical sedimentation in continental interiors is directly controlled by eustatic sea level changes to the detailed stratigraphic record in continental interiors have resulted in considerable controversy related to the relative contribution of tectonics and eustatics to these cycles [*Sloss*, 1984]. Resolution of this controversy requires an interdisciplinary approach which

includes image-based approaches to identifying the lithologic record of these events and determining the global geometry of the record in relation to the local, regional, and global tectonic and climatic record.

Results obtained from NASA SES scientific activities will also yield technology that can be transferred to the private sector for resource assessment, exploration and development.

Present Status

Remote measurements obtained from aircraft or satellite sensors provide gridded sampling and digital measurements of geophysical and geochemical properties of weathered rock surfaces exposed on the continents. Gridded data cannot be practically obtained using conventional geological methods. This characteristic of NASA-developed remote sensing technology provides a powerful tool for "mapping" the continents as well as identifying field sites for other studies.

Two approaches exist for extracting geologic information from remotely sensed data: 1) the photogeologic approach, and 2) the spectral approach. Both are aimed primarily at improved geological mapping that can be used to constrain stratigraphic, structural and geophysical models of crustal evolution in the same ways that conventional geologic maps are used.

The photogeologic approach uses knowledge about the weathering and erosional characteristics of strata and their tonal and topographic expression to map lithology and structure. This approach has evolved over a 50 year period using aerial photographs, and can be applied to pictures obtained from any image data acquired at wavelengths ranging from the visible through the microwave. With stereographic pictures, or combined topographic data and monoscopic pictures at the same scale, attitudes of geological surfaces can be measured directly.

The spectral approach uses knowledge about the physical interaction of electromagnetic radiation and rock/soil surfaces to extract compositional information from remotely sensed data. This approach is used principally in analysis of visible through thermal infrared (0.4-12.0 micrometers) multispectral remote sensing data, and is based upon theoretical, laboratory and field determinations of spectral properties of minerals, soils, rocks, and vegetation. This knowledge is the basis for aircraft and satellite sensor designs and image processing technique developments that make remote multispectral surveys of the continents a viable tool for lithologic mapping.

During the period 1982 through 1985, NASA developed new remote sensing systems including operational satellite systems such as TM, and experimental aircraft systems such as AIS/AVIRIS and TIMS. These systems, largely unknown to geologists, significantly enhance research capabilities and productivity.

Taken together, these NASA-developed technologies show that it is now feasible to measure remotely variations in attitude, thickness, and lithology of rocks exposed on the continents, thereby aiding development of quantitative models of the stratigraphic and structural evolution of continental crust. Below we describe specific remote sensing measurement capabilities that SES should maintain and new capabilities that SES should develop in order to implement these efforts.

Requirements

NASA remote sensing observations can contribute to resolving the scientific questions listed above by providing accurate compositional and structural information of continental lithosphere, in a synoptic format that facilitates intercontinental comparisons. Specifications for different instruments which sample the electromagnetic spectrum are given below.

Visible and Short Wavelength Infrared (0.4 to 2.5 micrometers). Global and relatively broad-band data acquired over these wavelengths is provided by the TM. Spectral and

photogeologic analyses of TM data have successfully been used to address a broad range of problems related to the composition, structure, and evolution of continental crust [e.g., *Abrams et al.*, 1983; *Abrams et al.*, 1985; *Lang et al.*, 1987; *Paylor et al.*, 1989]. TM multispectral data will serve as a basic data set for SES research. Cost of TM data will be the primary limitation for their use; SES should address this problem which will be exacerbated because global science objectives will result in larger geographic targets for continental research.

Recent trends in instrument development, spectral analysis, and photogeologic interpretation show a need for both higher spectral and spatial resolution than that provided by the TM. AVIRIS aircraft and HIRIS satellite high spectral resolution data will be required to obtain detailed compositional information over critical sites. SES should continue development of both systems and provide data over critical research targets.

SPOT, Large Format Camera and Soyozkarta data have shown the value of high spatial resolution data. A high priority goal for SES will be to provide one time, global, high spatial resolution (approximately 5 m) stereo panchromatic data to the research community.

Thermal Infrared (2.5 to 14 micrometers). Multispectral thermal infrared data have been used to address problems of compositonal mapping, especially those involving the silicate minerals, that cannot be addressed using data acquired at other wavelengths [*Kahle and Goetz*, 1983; *Kahle*, 1980; *Lang et al.*, 1987]. Diurnal thermal data additionally can be used to measure thermal inertia. The only operational multispectral thermal system available today is the TIMS aircraft system that samples the 8 to 12 micrometer interval in 6 channels. Continued operation and deployment of this system over critical research sites should be a high SES priority. A long term SES goal should be acquisition of one time, global, multispectral thermal data with at least the same spectral resolution as that provided by TIMS. The proposed ITIR system should logically have this primary objective. Additionally, SES should investigate the geological utility of multispectral data acquired over the 3 to 5 micrometer interval.

Synthetic Aperture Radar (active microwave). Synthetic aperture radar (SAR) is uniquely suited to photogeological studies in areas where rocks are hidden beneath clouds or vegetation, or in hyper-arid regions where thin sand layers obscure outcrops [e.g., *Blom et al.*, 1984; *Sabins*, 1983]. Presently, no global SAR coverage exists, although NASA has acquired Seasat, SIR-A and SIR-B orbital data over many regions. SES should provide SAR data over critical sites using the available aircraft system. A long term SES goal should be acquisition of a one time, global SAR data set. The proposed Eos SAR (or a free flyer equivalent) is a mission that would accomplish this goal.

Field Studies. A wide range of field studies is required in conjunction with remote sensing data acquisition and analysis. These include in situ validation studies (ground truth), especially for checking lithologies and structures. Field measurements, including VIS-IR and TIR reflectances and radar backscatter over known lithologies, quantitative determination of vegetation and soil cover, and soil moisture measurements are also necessary.

Ancillary field studies, not needed to interpret the remote sensing data but required to project remotely acquired surface information into the crust and lithosphere, are also required. These studies may include, but are not limited to, magnetic and gravity studies, borehole and core data, and seismic reflection data, as well as conventional geological field measurements and paleontological studies.

Laboratory Studies. Laboratory studies needed include spectral measurements of rocks, mineral, and soils as needed to interpret remote sensing measurements. X ray diffraction, chemical analyses, and radiometric age determinations are also required.

VERTICAL POSITIONING

There exist numerous measurements of *relative* vertical motions on the Earth's surface. The techniques for measuring relative motions are diverse and span all time scales. For example, we can infer the subsidence of carbonate reefs with respect to sea level over tens of millions of years from drilling atolls. The offset of Holocene sediments across fault scarps yields constraints on the relative vertical motion of adjacent crustal blocks over 10's of thousands of years. Coastal tide gauge measurements provide very precise contemporary estimates of the relative change in sea level, but such measurements only have relevance for geodynamics at coastal sites, and even then are limited by our understanding of the absolute rise in sea level as a function of position on the Earth's surface caused by global warming. Unfortunately, there are very few direct measurements of *absolute* vertical motions, which means that a number of key geophysical models remain untested and many fundamental geodynamic parameters remain uncalibrated. We recommend that NASA undertake an effort in the next decade to

- **improve the accuracies of absolute vertical positioning to the sub-millimeter level and gravimetry to the sub-microGal level to measure signals associated with the long-term mechanical deformation and thermal evolution of the lithosphere.**

Space technology has already advanced to the point where we can directly measure the horizontal motions of plates. If we also had sufficient accuracy and precision to resolve vertical motions, we could address problems such as:

- What is the present-day pattern and rate of post-glacial rebound? Better constraints on rebound from space observations (absolute vertical positioning, time-dependent gravity) will lead to improved models of the rheology of continental lithosphere and the viscosity of the sub-continental mantle.

- What is the present-day rate of eustatic sea level rise? Although most melting of the Pleistocene glaciers was accomplished 5000 years ago, eustatic sea level may still be rising at the rate of 0.5 mm/yr as the result of slow secular melting of glaciers caused by increases in atmospheric carbon dioxide [*NASA Advisory Council, Earth Systems Science Committee*, 1987]. Instruments such as coastal tide gauges only measure the sum of eustatic sea level rise plus post-glacial rebound plus any tectonic effects. By tying directly tide gauges to an absolute vertical reference frame, we can separate the sea-level changes from the post-glacial rebound and tectonic signals. **Priority in the next decade should be placed on understanding post-glacial rebound and its relationship to truly eustatic changes in sea level, otherwise we will be unable to resolve the signals from any of the other effects discussed below.**

- Why does the depth/age curve for oceanic lithosphere flatten with age? Has it reached thermal equilibrium so that it is no longer subsiding, or does an overprint from midplate volcanism make it shallower than expected, even though it still is subsiding?

- How rapidly do midplate swells rise and fall? Are the rates consistent with conductive transfer of heat in the oceanic lithosphere, or is dynamic flow required?

- Where are the areas of the continents current undergoing epeirogenic uplift and subsidence? Can we link these vertical movements to thermal and dynamic processes inferred from seismology and gravity to understand the formation of intracontinental basins and arches?

The demonstration that space geodetic techniques can be used to measure instantaneous plate velocities has without doubt been one of the stellar successes of the Crustal Dynamics Project. However, without good models for horizontal plate motions based on careful geologic and geophysical mapping of offsets that took many millions of years to form, we would have had no way to verify the geodetic results. Therefore it is critical that any

attempts to observe instantaneous vertical motions be integrated with a careful examination of the geologic record to estimate uplift and subsidence rates on million year time scales.

Requirements

Extremely stringent requirements in terms of accuracy in absolute positioning come from the rates of the vertical motions we seek to observe directly. Figure 5 illustrates the signal amplitudes relevant to the motions discussed above. Of the types of motions shown on this figure and discussed below, only the post glacial rebound is directly measurable with today's technology. We discuss the requirements for the others in the hope that this will drive technological improvements in vertical positioning systems during the next decade.

Although the following requirements are expressed in terms of the absolute change in elevation with time, the measurement of changes in gravity by an instrument fixed to the Earth's surface is an alternative to point positioning for detecting vertical motions. The signal expected depends upon how the vertical motion is compensated. For example, if the change in elevation dh is modeled as simply the free-air effect due to a change in the distance between the gravimeter and the center of the Earth with no net change in mass, then the gravity change dg is given by

$$dg/dh = -0.307 \; \mu gal/mm \text{ on land}$$

$$dg/dh = -0.265 \; \mu gal/mm \text{ under water}$$

with the effect being less under water due to the decrease in thickness of the water layer above the gravimeter. If an uplift is accompanied by an increase in mass of mantle density below the gravimeter, then the relevant gravity change is

$$dg/dh = -0.169 \; \mu gal/mm \text{ on land}$$

$$dg/dh = -0.127 \; \mu gal/mm \text{ under water}$$

Various models of isostatic compensation would predict gravity signals lying between these two extremes.

Since the current generation of absolute gravimeters is accurate to 3-10 μgal, it would take 10 to 20 years to resolve with a gravimeter vertical motions at the rate of 1 mm/yr. Sub-millimeter/yr rates of vertical motion are therefore not directly observable with the present gravimeter technology. For rates of motion at the mm/yr level, gravimeters can provide an independent check for precise vertical positioning if the change in mass accompanying the vertical motion is unknown (e.g., thermal contraction of the oceanic lithosphere), or an important complement to positioning if the mechanism is unknown. Note also that deployment of absolute gravimeters on the sea floor is an attractive alternative to determining submarine vertical motions through point positioning since the accuracy of the measurement is not limited by our knowledge of the speed of sound in sea water.

Post-glacial Rebound and Eustatic Sea-Level Rise. Although the maximum rates of post-glacial rebound (14 mm/yr) are centered on the formerly glacier-covered regions of Hudson Bay and Fennoscandia, simple models for the Earth's viscoelastic structure predict significant vertical (and horizontal!) motions at the mm/yr level over much of the globe. Certainly the first task in any program to understand vertical motions is to improve models of post-glacial rebound, since that signal is so much larger than any arising from thermal anomalies in the lithosphere or convection in the subcontinental asthenosphere.

We can exploit the large number of coastal tide gauge stations measuring vertical motion relative to sea level to improve the global coverage of instantaneous measurements of rebound in the following way. Suppose the eustatic rise in sea level (i.e., that change in sea level due to the addition of water to the ocean basins, assuming a stationary coast) could be modeled as the addition of a water layer of uniform thickness w everywhere in the oceans. Then by measuring the change in relative sea level and absolute vertical position at the same coastal site, one could uniquely determine the value for w and remove that from tide gauge measurements everywhere in order to obtain absolute vertical motions (i.e., the vertical motion of the coast with respect to the center-of-mass of the Earth) from the relative ones. Of course, the effect of a eustatic rise in sea level is not to add a water layer of uniform thickness everywhere. Rather, the new sea level surface must conform to an equipotential which is not merely parallel to the former equipotential because water, ice, and mantle rocks have been redistributed in the process of deglaciation. Thus we need to *simultaneously* solve the coupled problems of both rebound and sea level rise by comparing absolute and relative sea level changes at several locations. In addition, to solve the sea level problem we require a long-wavelength gravimetric (as opposed to altimetric) geoid accurate to 10 mm or less [R. Sabadini, personal communication, 1989].

The importance of solving the sea level problem goes far beyond the immediate goal for geodynamic purposes of separating tectonic from eustatic motions. Knowledge of eustatic sea level changes is critical for studies of global change, currently a high national priority. In addition, improved models of eustatic sea level changes at present will improve our understanding of how sea level rose throughout the Holocene, which can solve a number of difficulties in interpreting the Recent sea level record.

Thermal plate models. Suppose we wish to calibrate κ, the thermal diffusivity for oceanic lithosphere, by measuring directly the subsidence of young lithosphere. Predicted motions involving conductive cooling of the lithosphere can be calculated from the thermal plate model. The largest rates of subsidence occur on young oceanic lithosphere near the midocean ridges, but are still less than 2 mm every 10 years. The subsidence rate of old oceanic lithosphere, if indeed it continues to subside, is an order of magnitude smaller yet. Clearly we need even better accuracy than we have at present from space geodetic techniques, or we need long observing programs, if we want to directly observe the subsidence of the lithosphere. Even with measurements an order of magnitude better, we would have to devote much effort into understanding the noise spectrum for vertical motions at the level of 10's of micrometers. The prospect of measuring subsidence of the oceanic lithosphere using space-borne altimeters or gradiometers is even more gloomy. The predicted change in geoid as the plate contracts and subsides is only -0.15 μm/yr [*Parsons and Richter*, 1980] because the elevation change is locally compensated.

The rates of vertical motions associated with midplate swells can be very much larger. The only swell for which we have an estimate of the rise time is the Hawaiian swell, which is elevated 2.5 km in just 8 my assuming that the bathymetric profile southeast of Hawaii is steady state [*McNutt and Shure*, 1986], which yields an uplift rate of 0.31 mm/yr. Note that this rate of uplift is nearly twice the rate of subsidence for young oceanic lithosphere, and is therefore the principal observation evidence against any sort of conductive mechanism for transporting heat into midplate swells. If this relatively rapid uplift rate can be directly confirmed for Hawaii, and also measured for other hot spots on lithosphere of different ages in order to calibrate how the initial thermal structure of the lithosphere affects swell rise time, we would gain critical new constraints on the interaction of the lithosphere with hot spots. It would also be advantageous to monitor the subsequent subsidence of a midplate swell, but the characteristic rates are nearly an order of magnitude less.

It is more difficult to test thermal boundary layer models for the continents. For example, the predicted difference in subsidence rates for a 125-km thick plate and a 400-km thick plate, both of Early Paleozoic age, is only 0.007 mm/yr. If the thermal subsidence is offset by a chemical buoyancy effect [*Jordan*, 1975, 1978, 1988], the difference in

subsidence rates for the two plate models may be even less. The rate of epeirogenic movements in continental interiors caused by poorly known thermal and dynamic factors is larger, 0.03 mm/yr, based on the thickness of sedimentary units in intracratonic basins, but is still beyond reach with present technology.

**Vertical Signal and System Accuracy (mm)**
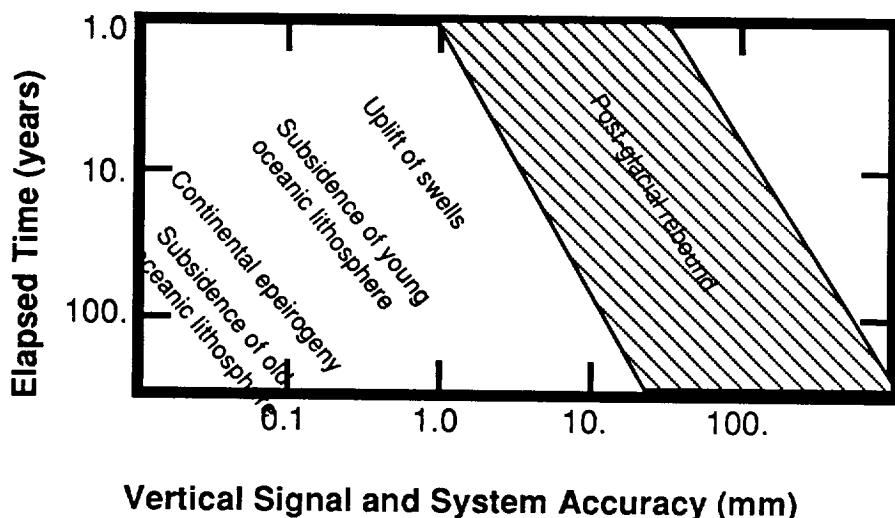
Figure 5. Trade-off between system accuracy and duration of observation campaign needed to resolve vertical geodetic signals. Even if a very long term program is initiated to measure directly these signals, the interpretation of the data will require first that the post-glacial rebound contribution be thoroughly understood and modeled before other, much smaller contributions can be interpreted reliably.

PRIORITIES AND RECOMMENDATIONS

Progress in understanding lithospheric structure and evolution is dependent upon availability of the global data sets described above which are more effectively acquired from space. Our prioritization assumes that the remote sensing instruments now in operation will continue to provide data throughout the program life. These include TM and SPOT satellite systems, the shuttle-borne SIR-C radar, and the ASAS, TIMS, AVIRIS, NS-001, SAR, and photographic aircraft systems. We also assume that planned EOS systems or equivalent including SAR, TIMS-class ITIR, and HIRIS be in operation as scheduled. We also assume that better altimetric coverage over the oceans is best achieved through the efforts of foreign space agencies due to classification issues. With these assumptions we prioritize our needs as follows:

1. Digital topography over the continents (30 m horizontal, 4 m vertical). These data are essential to all scientific objectives.
2. Gravity measurements (<100 km horizontal, 2 mGal). One approach is for NASA to contribute the GPS receiver and a drag-free system to ensure the success of the ESA Aristoteles mission, which would be an important first step in obtaining high resolution, global gravity data and for the purpose of demonstrating the feasibility of gravity gradiometry from space. However, it is unlikely that this mission will provide the accuracy and resolution we require. Therefore, NASA should pursue plans for a follow-on low-altitude gravity mission, such as the Superconducting Gravity Gradiometer Mission.

3. Magnetic measurements. Given the expense of flying missions in low-Earth orbit, we recommend that magnetic field measurements be included with both Aristoteles and SGGM gravity missions). A higher orbit, MFE-type mission is also important for isolating the core field from the lithospheric field.

4. High spatial (approximately 5 m) resolution stereo panchromatic data. One approach would be to use the Large Format Camera. This high spatial resolution stereo system fills an important void in planned remote sensing missions. The instrument should routinely be flown on the Shuttle and/or on some other platform until global stereo coverage is obtained.

5. Vertical Positioning. The exciting prospect of directly measuring the vertical motions associated with the evolution of the lithosphere is still a decade or more away, but it will continue to be an elusive goal unless we begin now to improve the accuracy of absolute vertical positioning and start acquiring baseline measurements of signals that can be resolved a decade or more later.

In addition to providing the basic global data sets described above, NASA is in a key position to

- **foster cooperation among the space agencies of the world to address major scientific and environmental problems, with a philosophy of maximizing data exchange and the development of complementary missions; and**

- **realize the scientific potential of this data by funding data analysis as well as acquisition.** Selection of specific investigations and geographic sites for study should be based on the results from peer review process.

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SECTION IV.

REPORT OF THE PANEL ON

VOLCANOLOGY

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SECTION IV.

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SUMMARY

Two primary goals are identified as focal to NASA's research efforts in volcanology during the 1990's. These goals are viewed as complimentary to those of other agencies, particularly in the fields of volcano monitoring, hazard assessment, and the investigation of the impact of eruptions on the atmosphere, climate and ecosphere. The two NASA objectives are: 1) 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 2) To understand the physical processes that lead to the initiation of volcanic activity, that influence the styles of volcanic eruptions, and that dictate the morphology and evolution of volcanic landforms.

These objectives should be addressed by: 1) Satellite-borne thermal and gas observations of new eruptions, and repetitive volcano monitoring using existing instruments (e.g., Landsat TM, SPOT, TOMS and AVHRR), and instruments to be incorporated on the EOS spacecraft (e.g., MODIS, SAR, ITIR, GLRS, MISR and HIRIS); 2) The compilation of a global baseline data set of satellite images of active and dormant volcanoes, from which temporal changes (over time periods of a few months to a decade or more) could be detected and monitored; 3) The development and use of ground-based remote sensing systems to provide high temporal resolution ground truth data (seismicity, tilt, temperature and gases emissions) via satellite read-out for the calibration of orbital systems; 4) The development of new sensor systems to provide more sensitive and precise sulfur dioxide and temperature determinations. Such a capability would be offered by the proposed Orbiting Volcanological Observatory (OVO), which would permit frequent observations (perhaps as often as once/day) at a high (10's of meter) spatial resolution over the UV to thermal infrared portion of the spectrum.

1. INTRODUCTION

The study of volcanoes and volcanic provinces crosses many interdisciplinary boundaries, from geology and geodynamics to atmospheric chemistry, climatology and ecology. Programs such as the International Geosphere Biosphere Program (IGBP), the International Decade of Natural Hazard Reduction (IDNHR), and the National Academy of Science's Global Change Program provide strong international and inter-agency motivation for the study of volcanoes and their products. That large-scale volcanic eruptions can have considerable effects on the Earth's climate is also becoming widely recognized in the Earth sciences community. Such observations date back over two centuries when Benjamin Franklin correlated the decrease in temperatures in western Europe with the 1783 eruption of the Laki volcano in Iceland. A new term, "Volcanic Winter", has been coined to describe the effects of large eruptions on hemispheric temperature and climate (Rampino *et al.*, 1988), and it is evident that both explosive and lava-producing eruptions can have major impacts on climate and the ecosystem (Handler, 1989). These relationships were recognized as significant by the Earth Systems Science Committee, but essential questions still remain, however, concerning the bounds of these effects in terms of degree, duration and spatial extent. The Volcanology Panel thus advocates that NASA undertakes investigations of the nature and dynamics of active volcanic processes, and the role of volcanism as an expression of global geodynamic processes, in order to further understand volcanic processes and the direct and indirect effects of volcanism on the global environment.

As surface expressions of the Earth's internal physical and chemical evolution, volcanic eruptions present uniquely challenging science problems because they operate over geologically short time scales, are inherently dangerous to observe at close hand, and are frequently located in remote areas where there are no suitably trained and equipped observers. Furthermore, while many minor eruptions in the more remote regions of the world may be completely unobserved, it has been estimated that between 20% and 30% of all subaerial eruptions unreported to the science community each year because of difficulties in communications (Mouginis-Mark *et al.*, 1989). Even under favorable conditions, the sheer scale of both lava-producing and explosive eruptions can be so great as to make useful ground observations hard to achieve. It is rare that sufficient manpower is available to make the necessary field measurements of the development of an entire lava flow field, or to sample the entire spatial and temporal dispersal of an ash plume. Similarly, geologic field mapping of volcanic landforms over hundreds to thousands of square kilometers is impractical at anything except a reconnaissance level.

Within the United States, Europe and Japan, most active volcanoes and volcanic provinces have been mapped in detail, studied petrologically, and investigated with a variety of geophysical techniques. In sharp contrast, many of the most devastating eruptions of recent times, such as that of El Chichon, Mexico in 1982, have taken place in developing countries on poorly documented volcanoes which were thought to be either inactive or not to present major hazards. Prior to its lethal eruption in 1951, Mt. Lamington, New Guinea was not even known to be a volcano. For the central Andes, Francis and de Silva (1989) reported that preliminary Landsat Thematic Mapper (TM) studies revealed that 50 - 60 volcanoes should be regarded as potentially active, whereas previously only 16 had been identified (Figure 1). Synoptic satellite-borne instruments provide such a means of obtaining this new overview of the distribution of active volcanoes, and of making quantitative estimates of global budgets of magmatic, thermal and volatile emissions from volcanoes. Correlations between the distribution of volcanoes and their tectonic setting, as well as the consideration of the frequency of eruption and magma chemistry of each volcano, can also provide information on regional crustal and mantle processes.

In recent years, much progress has been made in the use of both satellite and aircraft remote sensing techniques to collect data on volcanoes, and it is clear that many new aspects of volcanic eruptions, and the relationship between volcanoes and their tectonic setting, can now be studied by such methods. Indeed, the 1990's will see NASA play an increasing role in the monitoring and analysis of both lava-producing and explosive volcanic eruptions, and the deposits produced by these volcanoes. Although satellite and aircraft observations are limited at present by their infrequent

repeat coverage of volcanoes (one overpass every several hours to several weeks is typical), volcanological remote sensing offers a number of benefits. Satellite remote sensing observations allow: (1) all the world's volcanoes to be studied by the same techniques, thus providing a globally consistent data set which can be used to monitor temporal variations in volcanic activity, (2) collection of information on areas which are difficult to reach in other ways because of physical or political constraints, and (3) the utilization of a broad range of sensors working in wavelengths ranging from the ultraviolet to the microwave. These advantages apply to both airborne and orbital observations.

In order to gain a global perspective of both contemporary volcanism and the link between the distribution of volcanoes and the structure of the Earth's crust and lithosphere, NASA must play a major role in volcano monitoring, hazard assessment, and the environmental impact of volcanic eruptions on world climate. Apart from direct effects in the vicinity of volcanoes, global climatic and atmospheric perturbations caused by major eruptions have historically been sufficient to significantly affect agricultural production, leading to widespread food shortages and famine (Sigurdsson, 1982). 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_2) and fluorine (F_2) (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, Krakatoa in 1883, and El Chichon in 1982), and the possible links between major eruptions, anomalous sea level pressure, and the strength of El Nino events (Handler, 1989) warrants particular attention, and is an interdisciplinary investigation that NASA can address.
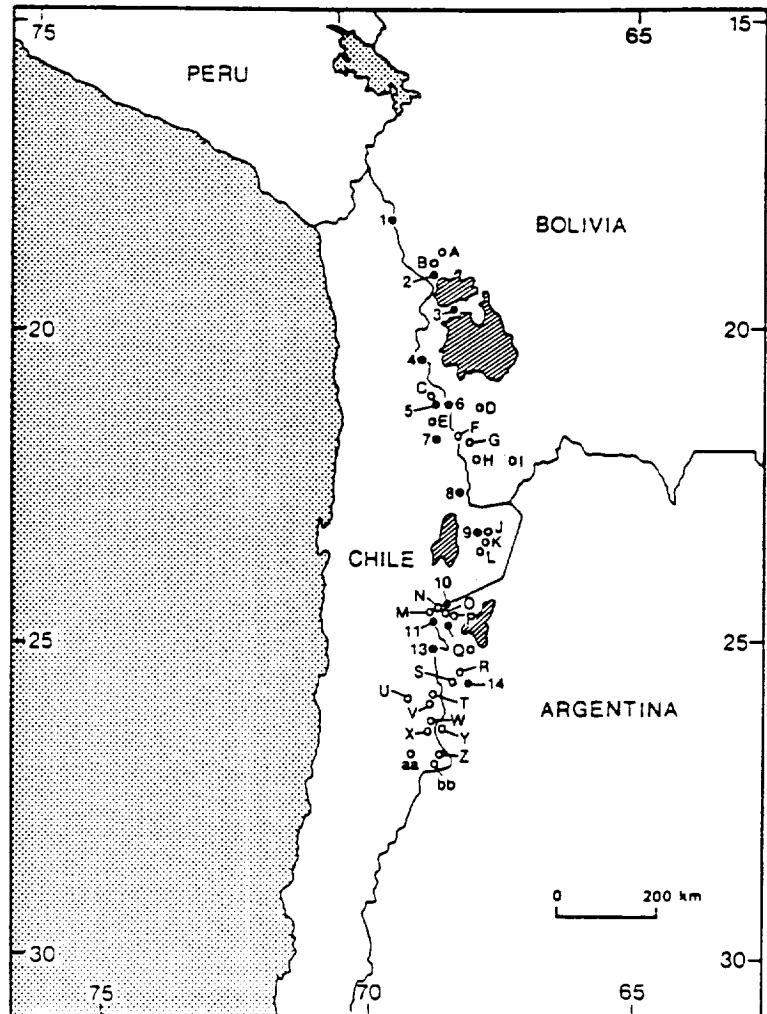
Figure 1 The locations of volcanoes in the Central Andes for which debris avalanches have been identified. Landsat TM data have revealed that 28 previously undescribed examples of breached volcanic cones, and 14 major volcanic debris avalanches, providing a new regional perspective of volcanism in this area. From Francis and Wells (1988).

There are two major goals that the Volcanology Panel has identified as key to NASA's research efforts in volcanology during the 1990's. These goals are viewed as complementary to other agency studies of volcanoes, wherein the U.S. Geological Survey may focus on volcano monitoring and hazard assessment, and the National Science Foundation may fund basic field and laboratory research. The two roles identified for NASA are: 1) 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 2) 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. These goals are described in detail in the next two sections.

2. CONTEMPORARY VOLCANOLOGY

The primary goal of NASA research in contemporary volcanology should be 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.

2.1: SPECIFIC QUESTIONS

The role of remote sensing in volcanology is a complementary one to measurements made in the field and laboratory. Remote sensing provides the regional overview of an eruption, permitting volcanic processes that extend over many tens to thousands of square kilometers to be studied at uniform spatial and spectral resolution, and to observe the temporal evolution of these phenomena (Figure 2). In certain instances, due to safety and/or geographic reasons, satellite or airborne data may be the only information available for certain volcanological parameters. The correlation of data for eruptions with measurements of temperature, rainfall, and biophysical processes can also best be achieved via satellite remote sensing techniques. Considerable emphasis will still be placed on field measurements of volcanic processes and landforms, because only in this way can high spatial and temporal resolution information (such as the thickness of a lava flow or ash deposit or the dynamics of an overturning lava lake) at a given locality be factored into the interpretation of the remotely sensed information. Meteorological and biophysical data will also be needed to assess the effects of eruptions on the entire Earth system. In this way, it is envisioned that the NASA Volcanology effort will interact closely with the research conducted by the U.S. Geological Survey, with NOAA for weather and climate data, with NSF-funded ecosystems research, and with efforts conducted by foreign scientists working on volcanoes in the field.

To reach our goal of understanding the dynamics of volcanic eruptions and their links with the lithosphere, atmosphere and climate, we have identified three specific questions that relate to the physical processes, eruption rates and dispersal of volcanic materials around the globe.

2.1.1. How does the distribution of volcanic gases and particles in the troposphere and stratosphere relate to the physics and dynamics of explosive eruptions?

A)   What are the thermal and velocity structures of eruption plumes as a function of altitude?

B)   How rapidly does an eruption plume lose its heat, and what is the temperature differential between the eruption cloud and the surrounding atmosphere?

C)   What is the mass and particle size distribution within an eruption plume as a function of distance from the vent?

D)   What is the rate of gas release from a volcano, and what is the relative proportion of one gas compared to another (e.g., mass of SO_2 vs. CO_2 or H_2O)?

E) How can the dispersal of particles within an eruption plume be related to the deposits of ash measured in the field?
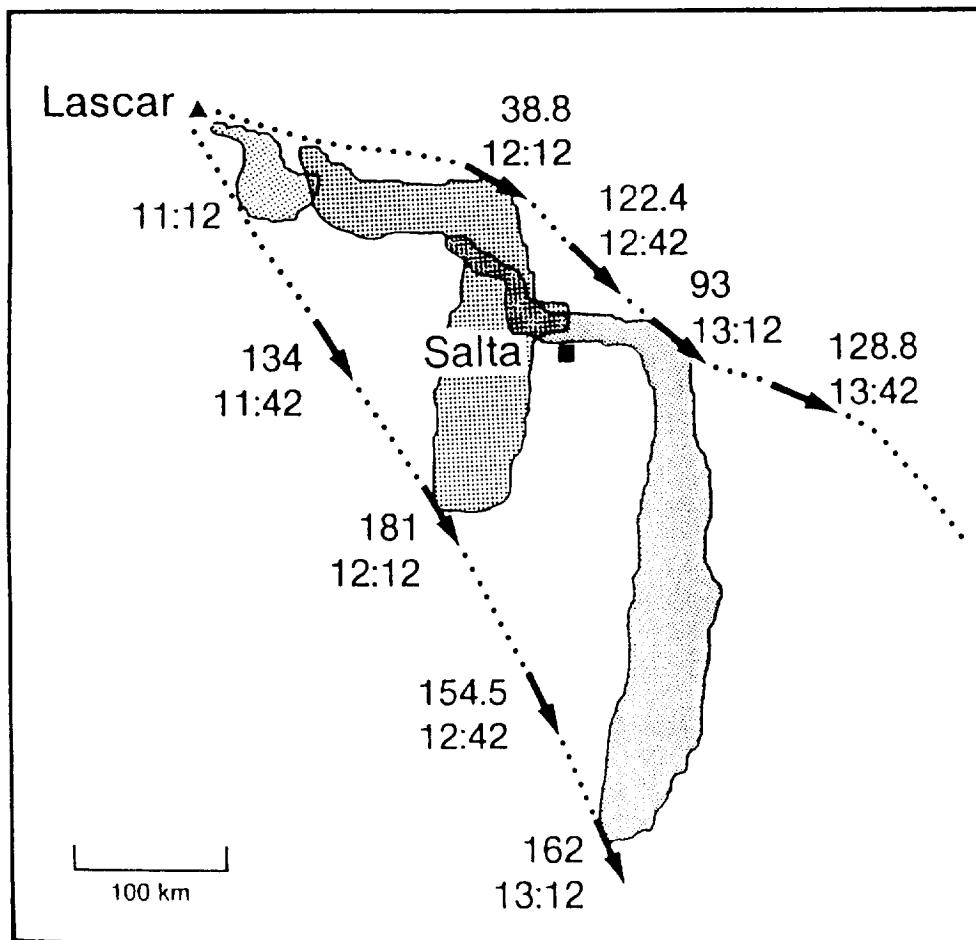
Figure 2. The changing structure of the eruption plume for the September 1986 eruption of Lascar Volcano was recorded by the GOES weather satellites. At each site the computed plume velocity (in km/hr) and time (UT) are given. From Glaze *et al.* (1989). The temporal evolution of future eruption plumes will be studied using the EOS platforms, and also represents one of the prime objectives of the Orbiting Volcano Observatory (OVO).

2.1.2. *What are the dynamics of effusive volcanic processes and how do they relate to the evolution of volcanoes (how do volcanoes work)?*

A) How does the eruption rate (volume per unit time) of lava erupted by a volcano vary over time scales of hours to weeks?

B) How is the rate of lava eruption related to the size, depth, replenishment rate and geometry of the magma chamber and conduit system of a volcano?

C) How does the surface deformation of a volcano during or prior to an eruption relate to the internal structure of the volcano?

D) What is the velocity flow field of a moving lava flow?

E) How fast does a moving lava lose its heat, and how does this cooling affect the rheological properties of the flow and the resultant surface features (pressure ridges, lava flow morphology, levee development)?

2.1.3. What are the effects of volcanic eruptions on the Earth system (climate, ecosphere, and hydrosphere)?

A) What is the residence time and distribution of volcanic gases and particles within the atmosphere following eruptions of different magnitudes?

B) What chemical reactions are associated with the eruption of volcanic gases on the local, regional and global scale, and how long do these effects persist?

C) What are the effects of volcanic eruptions on local and regional temperatures and rainfall, and how long do these effects persist?

D) What effects do major volcanic eruptions have on the ecosphere and hydrosphere, which areas of the globe are most sensitive to eruption-induced perturbations, and over what timeframe do these effects operate?

2.2: STRATEGY AND DATA REQUIREMENTS

In order to gain the required understanding of dynamic volcanic processes, their effects on the Earth system, and the hazards that they may represent, a concerted level of effort involving field and remote observations of volcanic processes is required. The most appropriate way to interpret remote observations is to develop "calibration sites" that are volcanoes for which considerable geophysical and field information already exists. Thus the remote sensing data can be placed in the context of both the historical eruptive history of the volcano and the geophysical and petrologic data, including seismics, gravity, magnetics, and trace-element geochemistry. Once the remote observations have been placed in the context of known characteristics of these volcanoes, it will be possible to more confidently extrapolate methods and interpretations to more geographically isolated volcanoes, or to volcanoes for which the supporting ground data sets are not available.

Three key requirements in understanding how volcanoes work, and their impact on the atmosphere, are: 1) the determination of the rate at which materials are erupted; 2) the assessment of the diversity (physical state, temperature, chemistry) of products erupted; and 3) where these materials are subsequently distributed. The ability to correlate these measurements with the short-term (hours to weeks) deformation history of the volcano also permits detailed numerical models to be developed regarding the internal structure of the volcano and the pre-eruptive history of the magma. Comparisons between the data for plume dispersal and information on air temperature, rainfall, and changes in plant productivity will also permit the effects of major eruptions on climate to be assessed.

Thus the NASA initiative to study dynamic volcanic phenomena should be orientated towards the development of a data base on volcanoes with good historic records and supporting geophysical and geochemical data, the interpretation of these data both in the context of the specific volcano under study and as a test for extrapolating these data types to other volcanoes, and the collection of remote data sets for other less well studied volcanoes around the world to permit inter-volcano comparisons. The specific research efforts needed to attain this objective are described in the next section.

2.3: RESEARCH EFFORTS

Six coordinated research efforts have been identified by the Volcanology Panel that enable NASA to make major contributions to our understanding of volcanic eruptions and the effects of this activity on the climate and environment.

2.3.1. Baseline Volcano Data Set:
Establishment of baseline satellite data sets (SAR and UV/vis/near IR) for ~120 of the world's most active volcanoes in order to determine initial conditions for rate of change studies.

Because many volcanoes erupt on a timescale of once every year to every decade, much can be learnt about the rate of change of the volcano (e.g., volume of lava erupted, rate of swelling of flanks due to inflation of magma chamber, removal of summit during an explosion) by comparing scenes of the volcano before and after an eruption. In order to conduct this temporal comparison, baseline data sets of the before eruption activity have to be collected. Approximately 50 Landsat TM scenes p.a. will be required for the first three years of the 1990's in order to assemble this baseline data set. SAR data from ERS-1, JERS-1 or SIR-C should be used to complement TM data in areas affected by frequent cloud cover.

The study of the rate of gas release from a volcano is also important for assessing the maturity of a magma body at depth. The frequent (daily to monthly) measurement of volcanic sulfur dioxide using an enhanced version of the TOMS instrument flown on NIMBUS 7 would provide an indication of new magma bodies being intruded at shallow depth or other changes in the shallow magma body. Thus initial gas flux value for each volcano must be established so that temporal changes over time periods of a few months to several years can be detected and monitored for their effects on the atmosphere.

Once the baseline data sets are collected, the plan would be to wait until an eruption has taken place and then collect a second set of satellite data, so that a "volcano difference map" at multiple wavelengths could be derived. These difference maps would then be interpreted in terms of volume of lava erupted, area and extent of vertical deformation, distribution of volcanic products (ash, pyroclastic flows etc.), and the rate of release of different gas species.

2.3.2 Field and Aircraft Studies:
Coordinated field and aircraft studies of well known type examples of volcanoes should be made in order to understand process-related phenomena: Hawaii (effusive) and Mt. St. Augustine (explosive). As stated earlier, these studies will be complementary to on-going programs currently funded by other agencies. NASA's role should be to develop new technologies and interpretation techniques that link field and airborne data to spaceborne measurements and interpretations. The availability of detailed field knowledge, as well as geophysical, petrologic and age data for volcanic phenomena studies, as well as the new remote sensing data collected by NASA, will be of mutual benefit to investigators from various agencies.

Kilauea Volcano, Hawaii has the best historic record for both geophysical (seismics, gravity, deformation) and geochemical (major and trace element) data. It is also easily accessible, erupts sufficiently frequently that the probability of monitoring an ongoing eruption is high, and is very safe to study at close hand. Detailed records of eruptions going back to the 19th century exist for Kilauea. It is also relevant that two other active volcanoes (Mauna Loa and Hualalai) could also be studied during a Hawaii deployment to provide inter-comparisons of basaltic shield development.

As presently envisaged, Mt. St. Augustine (Gulf of Alaska) appears to be a prime calibration site. It has erupted at least once each decade this century, producing large eruption plumes, pyroclastic flows and large variations in surface deformation. This is the most active "explosive" volcano in the United States, and while field logistics are more difficult than Hawaii (mainly weather and about 2 hour flight time from major airport) extensive ground work on deformation and

gas production have been done, along with several air/satellite comparisons during the 1986 eruption. Augustine is also located within the Alaska SAR Facility data mask, so that frequent coverage from ERS-1, JERS-1 and weather satellites is possible. Other calibration sites such as Mt. Etna or volcanoes in Central America are also possible, depending upon logistic, political and volcanic considerations.

Aircraft observations and ground studies (collection of calibration data for airborne sensors plus observations of field relationships and dynamic phenomena) of each of these sites to be made 3 - 5 times in ten years. The first deployment to each volcano should be in 1991 - 1992 timeframe, with site revisits occurring at intervals every 2 - 3 years. SAR data are required for regional lithologic mapping and structural studies, vis/near-IR plus thermal IR for analysis of thermal anomalies. Laser altimetry and radar interferometry data will be required for micro-topography and profiles of summit areas.

Satellite observations in UV to thermal IR, plus microwave measurements when available, to be made at least 4 times per year (more frequently on an as available basis during eruptions). Orbital SAR data will be required for interferometric studies of volcano growth.

2.3.3 Observations of New Eruptions and Volcano Monitoring:

The capability to deploy aircraft and obtain satellite images for any region of the world at short notice (a few days for satellite observations). Aircraft and satellite observations of active volcanoes, major new eruption sites, and the effects of eruptions on the atmosphere represent major research areas where NASA can contribute to our knowledge of volcanoes and their interaction with the atmosphere, climate and ecosystem. An additional 20 TM scenes p.a. for each of the 10 years of this program will also be needed for monitoring selected active volcanoes; it is expected that approximately 5 volcanoes will be imaged every three months to study the changes in thermal output of volcanic craters and fumaroles. It is fairly easy to select about 20 of the world's volcanoes that are quite likely to erupt between 1991 and 2000. Kilauea, Etna, Piton de la Fournaise, and several volcanoes in Indonesia and Central America have all erupted several times each decade throughout the 20th century.

It is highly likely that during the next decade, major eruptions (both lava-producing and explosive) will occur. The locations of this activity cannot be predicted, and so once an eruption is initiated the ability to obtain satellite data and, preferably, coordinated aircraft data, would permit dynamic processes (e.g., mass eruption rates, deformation rates, temperature and dispersal of a plume) to be investigated (Figure 3). With the advent of EOS platforms, this capability to identify new eruptions will be established, but the coordination of other satellite platforms and aircraft will still have to be implemented. It is implicit in the assumptions of the Volcanology Panel that EOS instruments, such as the SAR, ITIR, GLRS, and HIRIS will fly in the mid- to late- 1990's.

2.3.4: Effects of Volcanoes on Climate:

The study of the effects of volcanic eruptions on climate can be considered in three phases linked to the history of volcanic gases. The first phase concerns the origin of SO_2, Cl_2 and F_2, and their abundances as a function of magma type and the tectonic setting of the volcano. This knowledge will permit the extrapolation of data from one type of volcano/tectonic setting to the general population of volcanoes and geologic environments around the globe.

Secondly, gases and particles injected into the stratosphere can be transported around the globe, 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 the SO_2 to H_2SO_4 (which represent the aerosols that attenuate the solar radiation) is very important in order to study changes in atmospheric chemistry and climate.

Finally, modeling of the climate effects of these constituents is also important. It is necessary 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. Recent analyses have also suggested that cooling of the land surface by volcanic aerosols will transfer air mass from the ocean anticyclones to the continents, and may provide a link between low-latitude eruptions and the strength of El Nino events (Handler, 1989). In this manner, data on volcanic eruptions provide a direct input into other aspects of Earth System Science and promote true interdisciplinary studies.
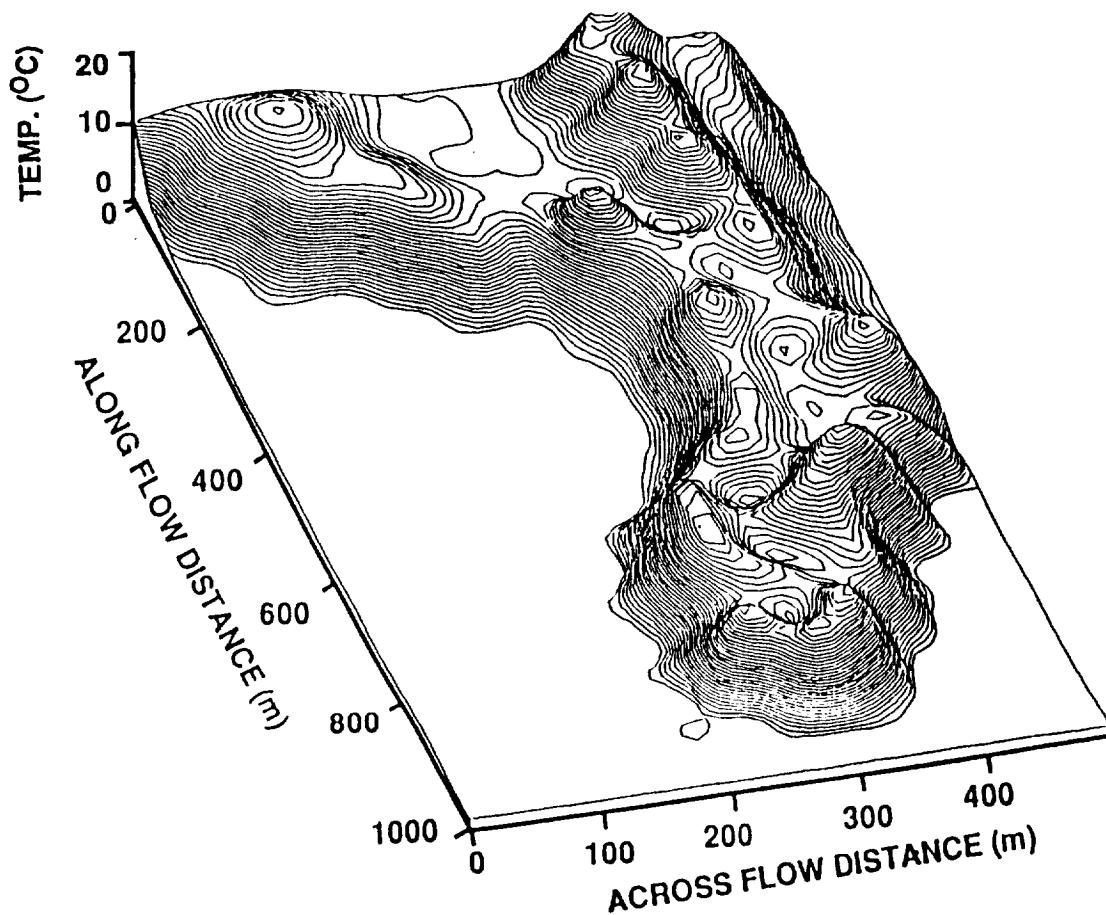
Figure 3. Thermal profile for the June 1984 lava flow erupted from Mt. Etna, Sicily, as derived from Landsat Thematic Mapper data. The flow direction of the lava flow is from top to bottom of the diagram. Vertical axis shows the decrease in temperature calculated for different parts of the flow; note the pronounced formation of "cool" edges to the flow. Data such as these permit the emplacement characteristics of the lava flow to be numerically modeled, thereby permitting the hazard potential of the eruption to be assessed. From Pieri (1989), unpublished data.

2.3.5. Automatic Field Monitoring of Volcanoes:

Field monitoring of remote active volcanoes using small automatic ground stations with direct satellite read-out capability should be carried out in concert with both space and airborne measurements. In this manner, field calibration and ground truth will be obtained for several volcanoes that may also be monitored by the U.S. Geological Survey or other agencies. Measurements made by these automatic field stations should include seismicity, tilt, temperature and released gas species. Approximately 1 - 3 stations required per volcano, for 5 - 10 volcanoes distributed globally.

Many changes on a volcano prior to an eruption are quite subtle, involving either cm-scale changes in relief (tilt), increasing seismicity (magnitude 2 - 4 earthquakes caused by subsurface movement of magma define conduit system), or temperature. These changes cannot be observed from space, nor is it feasible to have observers on the ground at many different sites. To overcome this limitation, remote measuring stations should be deployed on volcanoes known to be frequently active, thereby enabling their precursory activity to be more closely monitored.

In order to be used effectively, these field data should be transmitted back to a central data handling facility every day, using satellite relay capabilities. Similar technologies have already been used by NASA (and other agencies) in the study of ocean tides and currents, so that the methodology is already well proven.

2.3.6. Volcano Deformation Studies:

When magma is moving along a conduit system close to the surface of a volcano (top 1 km), the change in volume of the volcano is recognized as a swelling of the surface (vertical as well as horizontal displacements of a few centimeters to decameters). These changes in volcano shape provide key information on the rate of magma flow at depth, which can then be correlated with conduit geometry, the rheology of the magma, and the rate of flow of magma from the parent magma chamber to the surface.

We recommend the deployment of networks of GPS transponders or GLRS laser ranging retro-reflectors on limited number (~3) volcanoes to observe intrusive events and lava dome growth on active volcanoes and recently active volcanoes. Alternative technologies, such as the tracking of transponders placed on volcanoes via the TOPEX altimeter, may also be a method by which to study volcanoes close to the coast. Kilauea (Hawaii), Hualalai (Hawaii), Krafla (Iceland), and Piton de la Fournaise (Reunion Island), Mt. St. Helens dome and St. Augustine are options, although cloud cover over targets at certain times of year may become a problem. In many of these cases, international cooperation in the deployment and maintenance of the GPS networks will be essential for the efficient collection of the data and their correlation with other geophysical data sets.

In addition to monitoring the magnitude and style of deformation of a volcano during an intrusive event, much information about the dissipation of strain energy and the association between dike emplacement, earthquakes and subsidence of a volcano's flanks can be learnt by monitoring the deformation and relaxation rates of a volcano for several years after a major intrusive event. In both Hawaii and Iceland, several meters of vertical displacement may occur over a time period of a decade or more following the intrusion of a near surface dike that may have a horizontal extent of several tens of kilometers. Remeasuring the subsidence rates of the unsupported flank of Kilauea Volcano, and the central graben at Krafla in Iceland, would provide significant information on magma intrusion processes and the internal structure of each volcano. Due to the time scale involved, site revisit frequencies could be of the order of once per month to twice per year, with ranging conducted each time to about 15 - 20 targets.

In order to derive these deformation data, relative horizontal displacements on the order of 1 - 5 cm need to measurable from six - ten sites located along the rift zones of each volcano. Each network should extend for horizontal distance of 10 - 30 km. Vertical resolution of ~1 cm is needed to measure inflation/deflation rates of volcanoes due to changes in volume and pressurization of magma chamber. The ability to remeasure line-of-sight distances to each of the retro-reflectors once every day to once every week would be required.

Lava dome growth can also be studied in this manner, with the placing of 3 - 5 GPS receivers or GLRS reflectors on or around the dome. Growth rates of several hundred meters per year have been observed at Mt. St. Helens in the early 1980's, and such a process is related to the solidification of magma within the conduit, and its subsequent slow extrusion at the surface as the magma chamber pressure returns to its pre-eruption value.

2.4: INSTRUMENT DEVELOPMENT

While many of the volcanological investigations can be conducted via the use of current or approved new instruments, several of the proposed research efforts can only be realized with the development and deployment of new remote sensing instruments designed specifically for volcanologic (or geologic) investigations. Several such instruments have been identified by the Volcanology Panel. These instruments permit improvements in our ability to measure volcanic gases, thermal anomalies of surface features, sub-kilometer scale topography, and the ability to deploy mobile ground receiving stations for receipt of SAR data from remote locations.

2.4.1. Measurement of SO_2

The optimization of orbital UV spectrometers in order to improve the detection of sulfur dioxide in volcanic plumes is strongly encouraged, due to the established ties between volcanic eruptions and short-term climate change (Rampino *et al.*, 1988). Eruption rates of ~100 tonnes per day need to be detectable.

A key problem is the development of an instrument that would enable the measurement of gas released into the troposphere, since many effusive eruptions (e.g., Etna) do not inject sulfur dioxide into stratosphere. Higher spatial (~30 - 100 m/pixel) and, perhaps, spectral resolution (including IR) may be solutions. In the first instance, an augmentation to the TOMS instrument due to fly in the early 1990's would be the matching of band selection to more precisely discriminate the sulfur dioxide absorption bands. For the higher spatial resolution data sets, a new space platform, such as the Orbiting Volcano Observatory with new instrumentation (see section 2.5.1), will be required. These high spatial resolution data are required to enable smaller tropospheric plumes (low sulfur dioxide mass fluxes) to be investigated, and to study the sub-kilometer structure of large plumes. This new sensor must have off-nadir pointing capability in order to observe transient plumes (a few days to a month).

2.4.2. Automatic Ground Stations

The develop techniques for the detection and measurement of volcanic SO_2, CO_2, HCl and H_2O in the troposphere and stratosphere requires that techniques be developed for automatic field stations, then integrated into airborne and then spaceborne measurements. The goal will be to calibrate the spaceborne data. The key parameter to measure is either the ratio of SO_2/CO_2, or SO_2/H_2O, because these provide indications of depth of magma degassing and residence time of specific batches of magma at shallow depth beneath the surface. Kilauea, Stromboli and Mt. Etna are candidate targets. The mass flux of HCl is of great interest because it is known to vary considerably with tectonic setting, but few data currently exist to compare setting of volcano to production rate. Mt. St. Augustine and White Island (North Island New Zealand) are prime study areas.

Achieving this remote measurement of gas species and other volcanologically useful parameters requires the development of small automatic ground stations with direct satellite read-out capability. Daily read-out of seismicity, tilt, temperature and released gas species required from a network of approximately 1 - 5 stations per volcano, with up to 5 - 10 volcanoes so instrumented. These instrument packages should be sufficiently cheap that the loss of one (or several) during an eruption would not have a major impact. They should also be sufficiently small that they can be installed by volcanologists working on foot in rugged terrain, and consume sufficiently small amounts of power that they can run on batteries for about a year. In order to be used effectively, these field data should be transmitted back to a central data handling facility every day, using satellite relay capabilities.

2.4.3. SAR Algorithm Upgrades for Topography Determination

Small-scale topographic changes, due to the growth of volcanic domes or the intrusion of magma at shallow (< 1 km) depth can be sensitive indicators of intrusive activity. New lava flows or parasitic cones, or the removal of material during explosive eruptions, can also produce changes

of several to tens of meters in the topography of volcano flanks, which can then be related to the mass eruption rate of the volcano. While preliminary work has been done to demonstrate the feasibility of radar interferometry for topographic mapping (Gabriel *et al.*, 1989), additional algorithm development is required to derive these topographic measurements at the scale of ~3 - 5 m vertical and a spatial resolution of ~10 m (in order to study relief of individual lava flows). Routine application of these algorithms is required if the optimum use of radar interferometry and ERS-1 or JERS-1 data is to be achieved.

2.4.4. Mobile SAR Receiving Station

The deployment of a mobile orbital-SAR receiving station to Central America and Indonesia is advocated to collect ERS-1 and JERS-1 data of cloud-covered volcanoes and conduct regional tectonic mapping. These radar data are required to perform regional mapping of these very active volcanic regions at a spatial resolution of ~30 m over areas in excess of 10^6 km^2. It is expected that such deployments would be one-time events, and would be of sufficient duration to completely map each of these area.

There is a need to collect synoptic SAR date via this method prior to the deployment of the EOS SAR (currently scheduled for 1998 on N-POP-2), primarily because these data would be used to establish the long time-line data archive, and would be used to collect the radar-derived topography. The fixed geometry and single frequency/polarization capability of ERS-1 and JERS-1 make these spacecraft more appropriate than the EOS SAR for this task.

2.5: SPACECRAFT DEVELOPMENT

Several of the required measurements remain unobtainable even if the appropriate new instruments are developed; the orbital platforms and missions are currently not in the long-term planning of NASA. In order to change this situation, and to enable the data sets that are required to complete both the proposed volcanological science investigations and assess the effects of eruptions on the atmosphere and climate, we recommend four new spacecraft initiatives. These range in scale from a single instrument of use to a wide segment of the geophysical community to measure topography, to a low-cost volcanology free-flyer (an "Earth Probe" mission), to the installation of volcanology specific instruments on board a geostationary platform. These four spacecraft developments are as follows:

2.5.1. The Orbiting Volcano Observatory (OVO)

Develop the concept for a low-altitude (~330 - 500 km) volcanological "Earth Probe" mission. The Orbiting Volcano Observatory (OVO) would be used to study at high spatial resolution the distribution and rate of eruption of volcanic gases (SO_2, CO_2, HCl, H_2O) and the thermal characteristics (~20°C temperature resolution, 10 - 30 m spatial, ~10 - 30 km^2 areal coverage) of lava flows and volcanic craters at least once per week. Spatial resolution to be matched either with the capability of SPOT-1/2 panchromatic capability or HIRIS from EOS, depending upon the frequency of site revisits from EOS at this resolution. A key aspect of the OVO mission would be the ability to obtain high spatial resolution data with a frequent repeat cycle (perhaps once per day), thereby enabling short-term variations in temperature and gas flux to be studied.

2.5.2: Upgrades for TOMS Sensor

The opportunity exists to develop the TOMS instrument (due to fly on an early Earth Probe mission) for optimum measurement of volcanic sulfur dioxide, which will be particularly important for studies of the global effects of eruptions on atmospheric chemistry. Optimization of band selection in the 0.3 - 0.37 μm wavelength region will permit a better estimation of the mass flux of sulfur dioxide beyond what is currently possible with the existing TOMS instrument which has successfully been used to detect eruption plumes and to estimate the total mass of sulfur dioxide injected into the stratosphere (Table 1). It is also likely that the optimization of TOMS will enable tropospheric volcanic plumes to be studied, thereby opening up a new set of eruptions for investigation.

2.5.3: Medium Resolution Topographic Mapping

The lack of medium resolution topography for many of the areas of the world is a critical gap in our ability to interpret the geology and geomorphology of volcanoes (and other landforms). The Volcanology Panel supports the development of the capability to obtain digital topographic models of large (~100 - 5000 km^2) volcanic landforms at a spatial scale of ~30 m horizontal and ~10 m vertical. Resolution requirements are set at a scale attainable by orbital SAR interferometry or a scanning radar altimeter, which are likely to be the only global topographic data base that could be derived. In areas where cloud cover permits, either stereo SPOT scenes or laser altimetry should be used to provide 10 m horizontal and about 5 m vertical accuracy.

TABLE 1: VOLCANIC ERUPTIONS DETECTED BY TOMS
(Mouginis-Mark *et al.*, 1989)

VOLCANO	ERUPTION DATE	CLOUD TRACKED (DAYS)	TOTAL SO$_2$ (kTONNES)
SIERRA NEGRA	13th November, 1979	3	
ST. HELENS	19th May, 1980	4	340
ALAID	27th April, 1981	22	
AMBRYM	8th May, 1981	2	
PAGAN	15th May, 1981	2	
"MYSTERY"	26th December, 1981	+12	1000
EL CHICHON	29th March, 1981	+64	5000
GALUNGGUNG	5th April, 25th June, July 14th 1982	1, 1, 2	275
SOPUTAN	27th August, 1982	1	
COLO., UNA UNA	24th July, 1983	1	
MAUNA LOA	25th March, 1984	1	190
FERNANDINA	31st March, 1984	11	
SOPUTAN	25th May, 1984	2	
KRAFLA	5th, 10th, 18th September, 1984	3, 1, 1	35
RUIZ	12 September, 1984	1	
RUIZ	13th November, 1985	7	660

2.5.4: Volcano Deformation from Laser-Ranging

Develop the capability to detect topographic change on a volcano due to swelling (~1 cm vertical accuracy for installed monuments) and the eruption of lava flows (~1-5 m vertical for areas of 1 - 20 km^2 at a spatial resolution of ~30 m). This capability will most likely require the use of GLRS, but it may also be possible to collect the data with GPS or from measurements by TOPEX of transponders placed on the flanks of the volcano.

Space-borne laser ranging capability using to determine topography on a scale of 5 m (horizontal) and a few cm (vertical). Needed to study deformation of summit craters (e.g., Kilauea) and the slow growth of lava domes (e.g., Mt. St. Helens). The laser altimeter of GLRS is also required to profile newly erupted lava flows in order to estimate volume of lava erupted.

2.6 DATA ARCHIVES

As the volume and diversity of satellite and airborne data sets on volcanoes and volcanic eruptions increases during the 1990's it will become necessary to develop, either as a separate entity (the SES DIS) or as part of a larger EosDIS or inter-agency volcano investigation, a volcano data

archive. The links between SES DIS and the broader volcanology community will have to be established, and it is here that a strong inter-agency and international component has to the developed. The Smithsonian Environmental Alert Network (SEAN) should also be incorporated into this data system.

There are three aspects of data collection that the Volcanology Panel has identified that warrant implementation by NASA's Geology Program:

2.6.1. Synoptic Satellite Data

The development of a baseline data set of ~150 Landsat TM scenes is a key aspect of understanding the current structure of volcanoes. In addition, the acquisition of TM scenes for ~5 volcanoes known to be active every 3 months is proposed as a method for monitoring on-going activity. Together with other sets of data (TOMS, AVHRR, SPOT and GOES) for areas of explosive and effusive volcanism, these scenes will form a crucial component of the volcanological data set in preparation for EOS data. Synoptic data to include temporal coverage sufficient to track dispersal of eruption plumes around the globe. Provide mechanism wherein new orbital data (ERS-1, JERS-1, SIR-C, EOS etc.) can be added to this archive.

2.6.2. Supplemental Data

Supplementary aircraft, field and climatic data for the observed eruptions. These data to include geophysical measurements of volcanic constructs, digital terrain models of volcanoes and their surroundings, airborne thermal measurements of activity, and ground observations of eruption rates and dimensions. It will also be necessary for the volcanology community to gain easy access to data on vegetation productivity (such as the AVHRR measurements) and sea surface temperatures in order for the effects of eruptions on the global environment to be assessed.

2.6.3. Real-Time Data for New Eruptions

Ensure data availability for new eruptions in close-to-real time. These data to include TOMS, AVHRR, TM, SPOT, and GOES, but should also include future space missions such as ERS-1, JERS-1, SIR-C, and MOS-1/2. An interface between the volcanological community and the Earth Observing System Data and Information System (EosDIS) must also be developed.

3. VOLCANOES IN EARTH EVOLUTION

The primary goal of NASA research in the volcanic aspects of tectonics should be 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.

3.1: SPECIFIC QUESTIONS

In order to reach our goal of understanding the connections between the chronology, structure and geochemistry of volcanoes in different tectonic settings, we have identified three specific questions that relate to the distribution of volcanoes and their tectonic settings.

3.1.1.   *What material and energy transfer processes within the crust and upper mantle give rise to volcanoes?*

A)   What can the density, tomography and stress relationships under volcanic regions tell us about the temperature profiles and energy transfer processes of these regions? What is the distribution and diversity of volcanism as a function of regional tectonics?

B)   How does magma composition vary as a function of tectonic setting? Are there spatial variations in magma type within a single tectonic zone (e.g., intra-arc variations)? What is the gross morphology of volcanoes; what can it reveal with respect to types of volcanoes, their eruptive histories and subsequent changes due to subsidence or erosion?

C) What is the history of magma before it erupts as a volcano? Where are the sources of this magma? How does magma migrate to the surface?

3.1.2. *How can we improve our understanding of the structure, composition, physical properties and processes occurring within the lithosphere in order to determine how the spatial distribution of volcanic materials relates to their local and regional tectonic setting?*

A) How can the spatial and temporal distribution of volcanic cones and erupted materials be related to the spreading and subduction rates of tectonic plates?

B) What is the relationship between the volume and chemistry of released volcanic gases and the geochemistry of the underlying crust and lithosphere?

C) How do magma production rates for intraplate hotspot volcanoes relate to mantle processes, and what is the origin of mantle plumes?

D) What do the loading due to volcanic materials, strain release due to its erosion, and temperature alterations due to the presence of magma chambers reveal about the mechanical behavior and nature of the lithosphere?

E) How does the frequency of volcanic eruptions of the scale of $10^3 - 10^4$ years relate to that of tectonic movements? What is the influence of volcanic activity of the generation of seismicity and tectonic faults?

F) How is the dissipation of volcanic energy related to long-term crustal movements?

3.1.3. *Has the global character of volcanism changed through geologic time? If so, what geodynamic factors have been involved, and what have been the consequences?*

A) How has the character of volcanic activity evolved through time in contrasting tectonic environments, and how has this character been expressed in petrological and morphological parameters?

B) What are the current rates of volcanic activity in contrasted tectonic settings, and how do these relate to spreading and subduction rates? Can eruption rates be inferred from ancient volcanic environments and inverted to infer geodynamic parameters?

C) How do patterns of volcanic activity relate to variations in remotely-sensed gravity and magnetic fields?

D) What have been the effects of catastrophic volcanic eruptions on the global environment as preserved in the geologic record?

3.2: STRATEGY AND DATA REQUIREMENTS

The approach to the interpretation of volcanoes and their products in the context of regional tectonics and crustal structure involves both the regional lithologic and topography mapping of volcanic terrains, and the integration of this spatial information into crustal models using regional geophysical models. At the scale of an island arc or a hot spot trace, orbital data are required not only to provide the necessary area of coverage, but also the uniform quality of geophysical data (e.g., gravity, magnetics, topography).

The key aspect of this research involves regional mapping using satellite measuring systems

to produce baseline data sets on the distribution of volcanic phenomena, their topographic form, and their three-dimensional structure from potential field data. Such measurements will be correlated with crustal dynamics information, such as plate convergence rates, depth to Benioff Zone, gravity and magnetics anomalies. Geochemistry will also be included, because several topics of magma chemistry, such as the rate and species of volcanic gases exsolved along an arc have to date not been studied, and yet such information would provide crucial information on the geochemistry of the recycled subducted plate along a zone of convergence.

3.3: RESEARCH EFFORTS

The strategy for this task will be implemented via a series of coordinated remote sensing and field studies of selected key volcanic regions:

3.3.1 Regional Volcanic Landform Assessment:

It will be necessary to conduct a systematic regional assessment of volcanic landforms using satellite systems. Orbital SAR and/or SPOT/TM/HIRIS data sets should be used to identify and relate volcanic landforms to tectonic setting and the geochemistry of parent rocks. Early in the 1990's, a vigorous program of data acquisition using the Landsat TM (~50 scenes p.a. for three years) is proposed, which will be augmented by EOS, SIR-C and ERS-1 data in future years. The Circum-Pacific "Ring of Fire" is the most important area to study, but other volcanic areas, such as East Africa, are also important.

3.3.2. Derivation of Digital Terrain Models and Visualization of Volcanoes and Volcanic Provinces

Satellite altimeter observations can yield major advances in our knowledge of the structure and evolution of the lithosphere upon which volcanoes are constructed. Other Panel Reports (e.g. the Global Plate Motions and Landforms Panels) have also identified the need for continental- to global-scale topographic information that is referenced to a common datum (see also Topographic Science Working Group, 1988), and the Volcanology Panel strongly supports this topographic mission. Coupled with this need for altimetric profiles, the Volcanology Panel recognizes the need for the derivation of digital terrain models for volcanic constructs in order for volume and slope studies related to eruptive mechanisms to be conducted.

The Volcanology Panel recommends that aircraft and orbital sensors (SAR/GLRS/SPOT) should be used to derive digital terrain models for volcanoes and their surroundings. Some of the key problems in the interpretation of volcanic landforms is the determination of slopes and volumes for lava flows and pyroclastic materials. In many instances, such as in the Andes, even the absolute elevation of a volcano summit is not known to an accuracy of a few hundred meters.

3.3.3. Measurement of Regional Deformation Rates

With the use of GPS receivers dedicated to for use in active volcanic areas, establish line-of-sight baselines across regions of volcanic extension (fault zones and rift zones). These data will be required to compare the activity (frequency and style) of an individual volcano with the current deformation/tectonic history of the area. Plate boundaries (e.g., Caribbean, Aleutians, Indonesian arc and the Andes) are prime study areas for this type of investigation. It is believed that the existing effort by NASA's Geodynamics Program to develop and deploy GPS receivers will directly compliment this volcanology effort.

3.3.4. Identification of Thermally-Active Volcanoes

Currently, it is not known how many of the world's volcanoes are in the early stages of precursive thermal activity (e.g., warm summit lakes, fumaroles, warm lava domes), and yet such phenomena provide a significant insight into which volcanoes may become active in the next few years. An inventory of these volcanoes needs to be made, in part to provide input into the "Contemporary Volcanology" research effort (Section 2), but also to assess the distribution and rate of loss of heat from the Earth's crust with respect to tectonic setting, magnetics and geochemistry (gas flux). It is proposed that NASA determine the distribution of thermally active volcanoes

around the world, utilizing near-IR (e.g. Landsat TM) and thermal IR (e.g., TIMS and TIGER/ITR) instruments. Each volcano that is found to be thermally-active should then be monitored at least several times per year.

Development of spaceborne thermal infrared technology is also required to monitor thermally-active volcanoes. The ITIR instrument on EOS, and the potential OVO Earth Probe mission will both require developments in technology beyond the current airborne capabilities provided by the TIMS instrument.

3.4 FIELD GEOLOGY

Although much of this task can be completed via the use of orbital sensors, specific field work will be needed to support this effort. The installation and maintenance of field equipment related to the measurement of tectonic deformation rates, field observations of geological processes, and the collection of field samples will all be required. Specifics are as follows:

3.4.1: Installation of GPS Receiver Stations
Establish network of ~20 GPS stations in conjunction with Geodynamics investigators to assess rate of plate movement in areas such as the Andes, Aluetians, Indonesia.

3.4.2: Calibration of Satellite Observations
Collect field samples to calibrate remote spectral observations and to provide absolute dates for erupted materials. Observe field relationships to help interpret Quaternary eruptive processes. These observations should be conducted in conjunction with airborne campaigns that will bridge the gap between field observations and satellite measurements.

3.5 LABORATORY RESEARCH

Appropriate petrographic and trace element/isotopic studies to support the field and remote sensing effort. Dating of Quaternary surfaces to provide crucial temporal context of frequency of eruptions and rates at which tectonic deformation has taken place. Laboratory spectral measurements of volcanic materials and gases are also required for the UV to thermal infrared.

3.6 INSTRUMENT DEVELOPMENTS

None specifically for this effort but requires support from MODIS, HIRIS, TIGER (or equivalent ITIR), GLRS, GPS as well as satellite gravity and crustal magnetic measurements. Also relies on the continuation of data availability from improved Landsat and SPOT or equivalent aircraft data in order to develop regional data base of volcano/tectonic settings.

Requires deployment of mobile SAR receiving stations to Indonesia and Central America in order to capture orbital SAR data for these cloud covered regions. The stations are required because until the turn of the next century, it is unlikely that satellite radar data for geographically remote areas of the word could be obtained. The SAR data rates are so high that tape recorders cannot be used and, unless direct line-of-sight data transmission is possible, then no data can be collected.

3.7 SPACECRAFT DEVELOPMENT

In order to complete the planned regional investigation, support for obtaining data from the EOS platforms is required. These data will be required to map, at ~30 m resolution, large (10^5 - 10^7 km^2) areas of the world and will be used to assemble a basic inventory of volcanic landscapes.

3.8 DATA ARCHIVES

In order to investigate the relationship between the distribution of volcanoes and their tectonic settings, it will be necessary to establish three different pieces of the data archive, and to link these to other data systems such as EosDIS:

A) Establishment of a GIS archive for one-off data set at visible/IR/microwave frequencies for regions of Quaternary volcanism. Pacific Ring of Fire is top priority, but Italian volcanics and East African Rift Zone are also important.

B) Data reduction of laser altimetry/orbital SAR/visible stereo images to produce digital terrain maps of volcanic selected regions.

C) Access to geophysical data (magnetics, gravity, seismics and topography) necessary in digital form in order to correlate visible/IR/microwave data with regional features of tectonic setting.

4. INTERNATIONAL PROGRAMS

Volcanic studies require that many of the data to be collected as part of the NASA Volcanology Program are derived from volcanoes and eruptions outside the United States. Participation and collaboration of foreign geologists, meteorologists and ecologists will be critical for the overall success of this research effort during the 1990's. Several international programs are planned for the 1990's, and volcanology provides an important link between the solid Earth, the atmosphere and the biosphere. The International Geosphere Biosphere Program, the International Decade of Natural Hazard Reduction, and the Global Change Program are three such examples.

Currently there are a number of individual collaborations between NASA volcanologists and scientists in other countries that are likely to grow into important international efforts in volcanology. The following lists some of these ties identified by the Volcanology Panel, but it is likely that other individual or team efforts may also be currently underway:

4.1 U.S. - Italian Projects

NASA's C-130 aircraft has already flown over several of the Italian volcanoes, including Mt. Etna, Vulcano, Stromboli and the Rome Volcanic Field. These investigations include analysis of TIMS and TMS data for monitoring thermal characteristics of the volcanoes.

Strong interest has been expressed by the Italian volcanology community in the return of the NASA aircraft to Italy to measure temporal variations in these volcanoes. In addition, joint U.S. and Italian participation in the Orbiting Volcano Observatory Mission (see Section 2.5.1) has also been discussed.

4.2 U.S. - Soviet Projects

There are numerous explosive and effusive volcanoes in the Kamchatka Peninsula of the Soviet Union that are ideal candidates for comparison to Hawaii-style (e.g. Tolbachik) and explosive-style volcanism (e.g., Bezmianny and Kliuchevskoy volcanoes). While difficult to study in the field due to both their geographic isolation and political issues, two collaborative efforts between U.S. teams and the Soviet Eastern Academy are currently planned. At least one U.S. visit to Kamchatka is under discussion for 1990. Deployments of U.S. aircraft and the acquisition of U.S. and Soviet satellite data are currently being discussed.

4.3 U.S. - Chilean Projects

One of the key areas of the world where satellite volcanology has been developed has been in the Central Andes of Chile, Bolivia and Peru. Joint projects, based on the analysis of satellite

images (primarily Landsat), have been carried out by U.S., English, and Chilean geologists since the late 1970's. These joint projects will continue, particularly in the field of linking the distribution of volcanic landforms to the regional tectonics and crustal processes associated with the formation and evolution of the Andes.

4.4 U.S. - Ecuadorian Projects

The Galapagos Islands off the west coast of Ecuador are a prime area for the investigation of basaltic shield volcanoes that have formed in a tectonic setting different from the Hawaiian shields. Due to the greater spacing between the six active volcanoes, the shields in Galapagos have failed to produce the rift zones that are typical of Kilauea and Mauna Loa in Hawaii. Thus the Galapagos shield permit structural details of the way in which volcanoes grow (relative importance of intrusives vs. extrusives, size and location of the magma chamber) to be compared to the Hawaiian examples.

Two Space Shuttle Radar (SIR-C) experiments involve collaborations with volcanologists in Ecuador, and joint field visits to the Galapagos are planned starting in 1990.

4.5 U.S. - Icelandic Projects

NASA's P-3 aircraft has been flown over volcanoes in Iceland in 1988 and 1989, in order to test the utility of airborne laser altimeters in studying the deformation history of rift zones around Krafla Volcano, and to measure the erosional history of Surtsey Volcano. Collaboration between NASA, the U.S.G.S. and the Icelandic volcanology community is continuing.

5. STRAW-MAN TIME-LINE

In order to conduct the volcanological research necessary to support the investigation of contemporary volcanology and the role of volcanoes in Earth evolution, specific activities have to be phased for the ten year time period considered here. Manpower resources, both in the field and that available for data analysis also have to be budgeted for in addition to dollars spent. Thus the Volcanology Panel has attempted to define a ten year time line that includes instrument development, aircraft deployments, field instrument and satellite deployments that is both necessary to perform the science investigations and appropriate for the expected level of fiscal support and current NASA mission planning. The Volcanology Panel's recommendation for a ten year time line is as follows:

1991.	Initiate development of the Data Archive, and its links to EosDIS.
1991.	Initiate upgrades to TOMS sensor to enable better mapping of sulfur dioxide.
1991.	Plan for first aircraft deployments to Kilauea and St. Augustine.
1991.	Workshop to discuss New Start for Orbiting Volcano Observatory (OVO).
1991.	Initiate routine Landsat and SPOT data acquisitions of known very active volcanoes (Kilauea, Augustine, Etna, Sakarajima (Japan), Stromboli, Fournaise (Reunion Island, Indian Ocean).
1991 - 1993.	Build baseline data base of Landsat TM scenes of volcanoes that may be active within next decade.
1991 - 1992.	First aircraft deployments to Kilauea and Mt. St Augustine. Conduct concurrent field studies.
1992.	Deployment of SAR receiving station to Indonesia to capture ERS-1 and

JERS-1 data. Use these data to exercise data archive.

1992.   Phase A studies for OVO.

1992.   First flight of SIR-C radar. Conduct experiments of radar derived topography for Hawaii or other volcano (e.g., Galapagos, Reunion, Etna).

1992 - 1993.   Install first GPS receivers on Kilauea (top priority due to known geophysical and eruption characteristics). Timing depends on flight schedule of orbital laser ranging system.

1993.   Second flight of SIR-C radar. Perform radar interferometry experiment to test for temporal changes in volcano structure.

1993.   Phase B studies for OVO.

1993.   Data archive "user friendly" and operational, and contains growing volume of TOMS, SAR, TM, and SPOT data.

1993.   Deployment of SAR receiving station to Central America to capture ERS-1 and JERS-1 data. Note this is time-limited based on projected lifetimes of these free-flyers.

1993 - 1994.   Second set of aircraft deployments to Kilauea, Mt. St. Augustine or an as yet to be identified volcano. Target depends on level of activity since last flight. Conduct concurrent field studies.

1994 - 1995.   Install GPS receiver grid on Fournaise or Icelandic volcano (next priority, again based on known geophysical and eruption characteristics).

1995.   Potential New Start for OVO. Needed to complement EOS in 1997 - 2000 timeframe.

1995 - 1996.   Third set of aircraft deployments to Kilauea, Mt. St. Augustine or an as yet to be identified volcano. Target depends on level of activity since last flight. Conduct concurrent field studies.

1995 - 1996.   Install GLRS laser retro-reflector grid on Fournaise or Icelandic volcano (next priority, again based on known geophysical and eruption characteristics).

1996.   First EOS platform (N-POP-1) launch. Initiate collection of regional data sets to conduct volcano-tectonic studies. Use deployed laser ranging system to develop initial conditions for volcano stress analysis. Initiate volcano thermal survey.

1997 - 1998.   Fourth set of aircraft deployments to Kilauea, Mt. St. Augustine or an as yet to be identified volcano. Target depends on level of activity since last flight. Conduct concurrent field and EOS studies. Note this will be the first full-up comparison between EOS data sets and the higher spatial resolution data obtainable from aircraft and ground measurements.

1998.   Second EOS platform (N-POP-2) launch. Initiate global mapping of volcanoes with SAR for areas not previously visible to free-flyers and field receiving stations.

1999 - 2000.   Continue EOS-related investigations and plan for next ten years of NASA volcanology research.

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SECTION V.

REPORT OF THE PANEL ON

THE LAND SURFACE: PROCESSES OF CHANGE

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SECTION V.

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I. SUMMARY

The land surface has been modified throughout geologic history by climatic and tectonic processes. Today a third process, human activity, is changing the Earth's surface. If we are to assess the future impact of human activities on the Earth's ecosystem we need to know how these processes work and how they interact with one another. We not only need to know how climate, tectonism and human activities are affecting the Earth's surface today, but also how climatic and tectonic processes have modified the Earth in the geologic past. The geologic record shows us a "noisy" background of natural changes over millions of years to decades. The potential changes in the Earth's climate that are a subject of concern today must be detected against this background. The past also may be the most important key to understanding what happens to the Earth's surface as a result of changing climate. The record of past changes in climate is preserved in such places as sea and lake sediments, ancient ice, soils and chemical weathering deposits, eolian deposits and in landforms. To read this record we must integrate astute field and remote-sensing observations with knowledge of present physical and chemical processes, along with models that describe different rates and interactions over time.

The processes that we wish to understand not only extend back in time, they also impact large regions of the Earth. Field studies alone are not feasible for the whole Earth or even for large regions, especially under conditions of rapid change. To extend observations over large areas and to a global scale the inevitable choice is to use satellite remote-sensing measurements in conjunction with detailed knowledge from a few well characterized field sites.

NASA has a clear role in obtaining remote-sensing data of the Earth. Through its Solid Earth Science (SES) program, NASA has the potential to provide scientific leadership in studies of the land surface by conducting key research projects and by coordinating research activities with a broad spectrum of US and foreign agencies. The panel defined three main areas of study that are central to the SES effort: climate interactions with the Earth's surface, tectonism as it affects the Earth's surface and its climates; and human activities that modify the Earth's surface. We envision four foci of research: 1) process studies with an emphasis on modern processes in transitional areas; 2) integrated studies with an emphasis on long-term continental climate change; 3) climate-tectonic interactions; and 4) studies of human activities that modify the Earth's surface with an emphasis on soil degradation.

Research in these areas will involve field and laboratory measurements of morphometric, chronometric, textural and other physical, chemical and mineralogical properties of the land surface. Repeated observations will be needed to study processes that operate on time scales of decades or less. These field studies will need to be integrated with studies of remotely sensed images acquired from aircraft and satellites, and with studies that emphasize modeling. The scope of research is such that it can only be achieved if there is broad support from different federal agencies and international organizations.

The panel attached high priority to studies of changes to the land surface that affect life-systems. A special opportunity exists for NASA SES to take a leadership role in research on how climate change affects soil resources.

To achieve the ambitious goals of understanding the changing land surface, the panel emphasizes that it will be necessary to move quickly toward a research environment in which remote-sensing data are readily accessible in terms of cost and ease of handling. In anticipation of the EOS era it also is critical to expand the base of trained personnel who understand how to use remote-sensing technology, and at the same time can integrate remote observations with field data and theoretical models.

The panel concluded that there is a clear requirement for global coverage by high-resolution stereoscopic images and a pressing need for global topographic data in support of studies of the land surface. The requirement is common to all researchers, but does not by itself meet all their remote-sensing needs.

II. OUTLINE SUMMARY OF SCIENCE GOALS

Understand the processes that produce changes in the Earth's surface

      ---   key to the past climatic and tectonic record

      ---   key to present climatic and human impacts

    CLIMATE interactions with the Earth's surface

    TECTONISM as it affects the Earth's surface and its climates

    HUMAN ACTIVITIES that modify the Earth's surface

Understand the interactions of climate, tectonic and human processes

    SHORT AND LONG TERM

    LOCAL TO GLOBAL SCALES

III. SCIENCE PLAN

1) Modern Processes in Transitional Areas

Introduction. To observe, understand, and ultimately to predict global change - especially changes to the Earth's land surface - the best place to start is in the transitional areas of our planet. Transitional zones are especially responsive to changing climatic interactions with the Earth's surface, because their surface geologic materials or landforms (eolian sand deposits, glaciers, floodplains, etc.) are exceptionally sensitive to variations in climate-driven geologic processes and respond relatively rapidly to any such variations. Many such areas are particularly sensitive indicators of change because they are located within present climatic zones that are subject to shifting boundaries. The surfaces of transitional regions tend to be metastable; they are in 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 semiarid to subhumid margins of the extremely arid core deserts, margins of the polar regions (including permafrost), margins of glaciers, alpine glacial and periglacial terrains, the shorelines of lakes and coastal areas (including barrier islands, deltas, and wetlands), and many drainage basins.

Environmental changes in transitional regions have historically had severe impacts on flora and fauna (including humans), and environmental changes resulting from the predicted future global warming are expected to exert their greatest impact on humans and their facilities in these regions. In the context of NASA's Mission to Planet Earth and the U.S. Global Change Research Program, transitional areas are considered to be of the highest priority.

Process studies of the land surface are needed in order to study changes in the transitional environments. Studies must be tied closely to the technology for gathering real-time data on such climatic variables as precipitation, wind and temperature. A multidisciplinary effort is needed to gather and interpret data on such factors as vegetation cover, soil characteristics and hydrology, in addition to 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 badly needed to define sequences of events better, in order to help establish the rates of present processes and processes that operated under past climatic conditions.

Analysis of modern, on-going processes can greatly benefit from the satellite remote sensing record acquired over the 17-year period of the Landsat program. However, the geomorphic and stratigraphic indicators of climate change still need to be defined more reliably than is possible with the Landsat record alone.

Margins of Arid Regions. The transitional zones between the core deserts and adjacent semiarid to subhumid zones are particularly sensitive to changes in climate manifested by variations in precipitation, wind regimes, and vegetation cover. One of the first signals of disequilibrium between land surfaces and changing climatic conditions is a change in the relative effectiveness of running water *vs.* eolian (wind) activity. Typically, increased wind erosion occurs in areas formerly stabilized by vegetation which had been supported by runoff or directly from precipitation or from high groundwater levels. Reduction of soil moisture and loss of vegetation allow exposure of bare, dry and loose surface materials to wind, which winnows out the fine particles (e.g., soil nutrients) as dust, with consequent soil coarsening and loss of fertility. Continued wind erosion leads to segregation of sand-size particles into fields of mobile sand dunes, which can migrate into agricultural areas and settlements. Commonly, this degradation is exacerbated by increased runoff during the rainy season, leading to flash-floods, sedimentation in lakes and estuaries, and gullying. Frequently, such changes are attributed to "desertification" caused or influenced by human activity, but the evidence of repeated changes predating human occupation is also found in most areas. Wind erosion accounts for the generation of some 500 million tons of dust per year worldwide, but the prediction of damage to natural surfaces from wind erosion relies, at present, on models based on calculations for farm fields in agricultural regions. These models are not relevant to wind erosion on natural surfaces such as the desert scrubland used primarily for grazing purposes in much of the southwestern U.S, Central Asia, and arid regions of Africa, South America, and Australia.

Remote sensing by NOAA's weather satellites has made possible the global tracking of dust storms generated by wind erosion in the arid continental interiors -- from the U.S. High Plains to the Atlantic Ocean, from the arid steppes of China to Hawaii, and from the Sahara to the Caribbean and Florida. However, models that predict the generation of dust from natural surfaces are only beginning to be developed on the basis of systematic field observations and laboratory experiments. The convergence of improved satellite remote-sensing capabilities with new technologies for obtaining real-time ground measurements thus offers an opportunity to define eolian processes on the basis of data that was not previously obtainable. A spin-off of such studies would be the capability to include the

generation of dust (aerosols) from the world's arid regions in General Circulation Models of climate (GCM's), and to investigate possible feedback effects of dust on climate.

Other processes that are particularly diagnostic of climate changes in areas along the margins of arid regions include changes in vegetation type and abundance (e.g., as recorded in packrat middens), and changes in the discharge, sedimentation, and distribution patterns of stream systems, including changes in lake levels.

Permafrost and lakes. The polar regions of the Northern Hemisphere, especially in North America and Asia, have extensive concentric regions of discontinuous and continuous permafrost (frozen ground which seasonally thaws only in a thin active surface layer). Permafrost is one of the four major components of the cryosphere, all of which are extremely sensitive to climate warming. Thermal anomalies have been measured in abandoned wells in Alaska which represent a warming signal during the last century of at least 1°C as recorded in the permafrost. Permafrost also contains enormous quantities of methane, bound interstitially in ice as a clathrate which, if released in the atmosphere under global warming conditions, could add significantly to the atmospheric loading of greenhouse gases. Methane is 15 times more effective than carbon dioxide in its greenhouse effect. Periodic *in situ* and remote-sensing measurements of areal changes in permafrost, in association with estimates of the volume of methane contained, may allow predictions to be made of the amount of methane being released to the atmosphere from this source.

The times of freezeup and thaw of lakes are sensitive indicators of climate change in temperate and polar regions. There is an opportunity to combine the satellite image observation records with historical field data records to compile a long-term history of the times of freezeup and thaw of many lakes in North America, Europe, and Asia. These histories could be correlated with available climatological data. The wide geographic monitoring capability of satellite remote sensing would also permit the assessment of inter-annual variation of lake ice freezeup and thaw with latitude. These data sets would be another important addition to long-term assessment of the effect of global climate warming.

Glaciers. Glaciers originate on the solid Earth and, except for floating ice shelves along the coast of Antarctica and small ones off Ellesmere Island (NWT, Canada), glacier ice is generally restricted to the land. Changes in the areal extent and volume of glaciers affect sea level. For example, if the volume of glacier ice presently stored in Antarctica (91%), Greenland (8.3%), and all other ice caps and valley glaciers (0.7%) were to melt, sea level

would rise about 100 m. This would be equivalent to the rise in sea level 10,000 years ago following the end of the ice age.

Two key scientific questions are: (1) what is the rate of rise of sea level, and (2) how are the world's glaciers responding to global climate warming? The technology exists to answer these questions, using a combination of *in situ* measurements and remote sensing. For example, the U.S. Geological Survey has, for the past 10 years, been compiling a Satellite Image Atlas of Glaciers of the World based on Landsat multispectral scanner (MSS) images acquired in the mid-1970's. However, the high cost and lack of regional data coverage in the present Landsat program has precluded monitoring changes in most areas imaged in the 1970's, except for Antarctica. An interagency consortium of the USGS, NASA, and Scientific Committee on Antarctic Research (SCAR) Committee on Glaciology has funded the continuing acquisition of Landsat images of Antarctica to provide another data set in the late 1980's for comparison with the mid-1970's data set.

Coastal zones. The low-lying coastal zones of our planet are especially sensitive to climate-driven changes in the sea level. Sea level changes can result from fluctuations in glacier ice volume, changes in the shapes of ocean basins, and temperature changes in the oceanic water column. Sedimentation rates and transport patterns can be altered by climate-driven changes, changes in river position, and alterations in coastal geometry. Tectonic forces, isostatic rebound following deglaciation, and sediment compaction also can produce changes in the land surface with respect to sea level, and withdrawal of groundwater and of oil and gas in coastal areas can cause subsidence.

Satellite images provide a unique means of monitoring and measuring changes in coastal environments on a global basis. The Landsat MSS data provide a good record of changes over the past 17 years, but a continuing record is necessary as anthropogenic changes accelerate with increasing population and industrialization. If satellite data were available at a reasonable cost, changes in barrier islands, wetlands and other coastal features could be measured in a time-lapse sense to increase our understanding of the processes causing the observed changes. It may also become increasingly important to be able to predict coastline changes, in order to facilitate economic and social planning. A future rise in sea level may have the greatest global economic impact of all the forecast consequences of global change, as coastal areas worldwide have traditionally been the locus of human settlement and activity.

Fluvial Systems. Running water collected from precipitation or melted from the snowpack or from glaciers accounts for most erosion and sedimentation of the land surface, except in parts of the extremely arid core deserts. Even there, former river systems accomplished most of the lowering of the land surface and left their imprint on the topography and in widespread alluvial deposits. Rivers respond to changes in climate by altering their hydraulic gradient and consequently their geomorphic patterns and rates of sedimentation. In extreme cases, as when climate in the headwater region becomes extremely arid, or when capture or beheading occurs in response to tectonic or volcanic events, streams may dry up or even reverse their courses. A sequence of climatic or tectonic events that influenced the evolution of stream systems may be recorded by erosional features such as flights of terraces, or by stream network and channel characteristics (e.g., gullying and arroyo cutting) and by depositional features (e.g., floodplains, lake beds and terrace gravels). River systems integrate the response of the land surface throughout the entire drainage system to changes such as removal of vegetation (due to natural or human causes) or to uplift and subsidence.

2) The Continental Record of Climate Change

Introduction. Current predictive models of future global change are based primarily on modern climatological observations. Modern observations unfortunately lack any sense of climate change. The long-term record of climate change is preserved by the land surface and by terrestrial and marine sediment cores, ice cores, and other deposits. This record is the necessary link to understand how the land surface and associated distributions of life and life resources will respond to global change in the future.

Historical quantitative observations of weather and climate rarely extend back over a century. Older climate records covering hundreds of years to the entire Holocene come from cores in ice caps and tree rings. Recently, the COHMAP project integrated paleoecological, palynological, pluvial and other data to describe climatological reconstructions for the period since the latest glacial maximum: the last 18,000 years.

Other proxy records of climate extend much farther back in time. The Vostok ice core from Antarctica covers 120,000 years, and foraminiferal records from sea-floor cores span several glacial cycles. These data provide insight into global sea-level and temperature fluctuations, but they do not provide specific information on the land surface, where most

human activity occurs. There, our knowledge of the climate record before 18,000 B.P. is sketchy and incomplete. Yet if we are to understand and predict the natural and anthropogenic climate changes in the future, it is essential that we have a detailed knowledge of an entire glacial cycle, especially the interglacial/glacial transition. The previous 18,000 years spans the glacial/interglacial transition, which has already occurred.

Landforms. The terrestrial landscape is a dynamic surface that evolves through the interaction of internal processes (generally constructional, except for gravity) and external processes (generally erosional). Erosional processes are strongly controlled by climate, although the rate of landscape evolution is slow enough so that most landscapes record the impact of multiple processes related to global climatic changes over the past few million years. Landform interpretation forms the link between geodynamic solid-Earth processes and the external climate-induced oceanic and atmospheric processes. Landscapes are highly amenable to analysis on a regional scale by remote sensing from orbit, and thus are a central link in "Earth-systems science." In spite of this pivotal role, analysis of landscapes has received little attention compared to the explosion of activities in the atmospheric sciences, geophysics and geochemistry. The new technology of remote sensing has had little impact so far on the traditional field of geomorphology, although the potential exists to integrate the study of internal tectonic processes with an understanding of external climatic processes.

Soils The continental climate history has been impressed on the land surface of the Earth as landforms and as chemical weathering products, including soils and rock coatings. Whereas the regional distribution of landforms charts paleoclimatic zones, the degree and type of chemical weathering can be used to infer paleoenvironmental conditions, including precipitation and temperature regimes. Multispectral remote sensing has been shown to be useful in estimating soil type and development. Remote sensing is especially valuable because the extensive coverage and closely-spaced measurements distinguish different soil units and detect subtle or diffuse gradients. Coupled with age data for different surfaces weathering in the same fluvial or other geomorphic unit, remotely sensed information can be used to help reconstruct a continental climatic history. Because geologic surfaces dating from times throughout the previous glacial cycle (the last ~ 130,000 years) are locally well preserved, 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 the General Climate Models.

Even where remotely sensed spectra or other types of data are not directly applicable to soils mapping they may be used indirectly to map over large areas the units that have been defined at specific sites by conventional field methods. Soils develop in response to climatic factors, but also in response to a host of local tectonic, microclimatic and other influences that introduce considerable variability into soil profiles. One way to circumvent this problem is to study regional patterns of soil types that reveal large-scale patterns, devoid of local complications. Recent studies have confirmed that some soil units as defined in trenches or pits have distinct surface spectra that permit the discrimination and mapping of the defined unit over large areas.

Arid Lands. The spatial patterns and surface characteristics of arid regions change through time in response to variations in the amount and distribution of rainfall, which is controlled primarily by the interaction of topography with the movement of air masses by the global circulation system. Major changes in the land surface in response to climate change include shifts in the boundaries between core deserts and their less-arid margins, shifts in the amount and type of vegetation cover relative to bare rock and soil, variations in stream erosion, discharge (including lake levels) and sedimentation, variations in the relative effectiveness of wind erosion and resulting redistribution of surface materials, and variations in the chemical and mechanical characteristics of the materials, including soils.

Proxy evidence for these climatically induced changes is preserved in the distribution of erosional and depositional patterns on the land surface and in the chemical and mineralogical composition of the surface materials. Cores in desert basins (dry lakes) have long been a source of critical data on past climates. More recently a rich source of data on climate change in desert areas has come from paleovegetation records from ^{14}C-dated packrat middens. It is now important to be able to compare the paleovegetation record with the present regional distribution of desert vegetation, which can be mapped using new multispectral remote-sensing techniques. New stable-isotope analyses of desert varnish suggest that paleovegetation and paleoclimate information can be inferred from rock coatings in arid regions. Rock coatings to a large extent are controlled by the stability of the rock substrate to weathering and spallation, and also can be measured by remote sensing.

One of the most important links between arid landforms and climate is knowledge of surface "exposure ages." Until recently the main data available were radioisotope dates of volcanic flows and tephras. However, volcanic features are not present in all deserts, and

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they rarely are distributed conveniently in space and time for dating. New techniques are now under development that date carbonate deposits (travertine, tufa and shells), rock coatings (desert varnish), and rock surfaces containing chlorine or beryllium created by cosmic-ray bombardment. With continued dating of the exposure ages of sparsely vegetated desert surfaces and with better understanding of how surfaces evolve under different climatic conditions, it is likely that it will become possible to interpret more remotely sensed data in terms of geomorphic processes and time scales. Both spatial and multispectral remotely sensed data will needed to support regional analysis of arid regions. Combinations of data from different sensors will have to be used synergistically (for example Landsat TM merged with imaging radar) to investigate simultaneously the spatial and spectral characteristics of surfaces, and of the shallow substrate.

Glaciers. During the glacial maxima about as much ice accumulated on land as is present today in the Greenland and Antarctic ice sheets. A doubling of glacier ice volume occurred, sufficient to lower sea level about 100 m. Glacial geologists have been active for years, principally in North America and Eurasia in field mapping the maximum extent of the ice sheets, ice caps, ice fields, and valley glaciers. Various types of glacial deposits provide information about the former glacier, and terminal moraines provide accurate information about the position of the former margins of the above types of glaciers. Although the former areal extent of glaciers is well known in North America and Eurasia, such is not the case in the mountainous regions of Asia and South America. High-resolution (less than 5-m pixels) stereoimages (less than 10-m contours) would permit the delineation of moraines in such regions. With appropriate assumptions, models of ice volume could then be constructed for these mountainous regions.

Glaciers contain a continuous record of past atmospheric composition which can be accurately measured and dated through an entire interglacial-glacial cycle by analysis of ice cores. Ice cores also contain a datable record of pronounced volcanic and eolian activity, especially events which have had a global impact. Studies of the ice-core record of well-known, large historic volcanic events and dust storms from geographically diverse glaciers will provide a basis for interpreting older ice-core records of prehistoric volcanic eruptions and their probable effect on climate.

Accurate modelling of the areal and volumetric extent of past accumulations of glacier ice must be correlated with the sea-level record to determine the rate of sea-level fall and rise as it relates to the accumulation and ablation of ice sheets. The relationship of fluctuations of sea level to variations in global ice volume also can be linked to climate change (warming

and cooling) by inferred sea-surface temperatures recorded by organisms in marine sediments (foraminiferal studies), and by the atmospheric-composition record from ice cores. Ice cores from Antarctica (Vostok core) have provided a record back to the last interglacial. A deep continuous ice core from central Greenland is being recovered in 1989 under a program supported by NSF.

Large volumes of glacier ice on Earth (Greenland and Antarctica) probably have fluctuated widely over geologic time because of plate motion and mountain-building episodes. The onset of a major ice buildup in Antarctica probably began about 40 million years ago, as Antarctica was moving to its present location. Major ice buildups in North America and Eurasia had to await the opening of the North Atlantic, movement of the North American and European plates, sufficient continental elevations, and proper orientation of mountain ranges. Any modelling of past climates by models of global climate or by GCMs must take these geological, geophysical, and glaciological factors into account. The past geologic record provides the actual evidence of the effect of past climate change on the oceans and continents needed to confirm or reject the predictions of the GCMs. In particular, the geologic record of the most recent global warming interval (about 2.2 million years B.P., in the Pliocene Epoch) can provide us with an understanding of the probable response at different geographic locations of the predicted global warming by GCMs under an atmosphere enriched in CO_2 compared to today. Transitional areas are of greatest importance, because these regions are where GCMs predict the greatest change from present-day conditions (e.g., the temperature increase predicted for polar regions is 3-5 times that predicted for lower latitudes).

Lakes and oceanic shorelines. Shorelines of lakes and the continents can vary considerably over long periods of time in response to global climate change. Such changes, especially if recorded above present-day lake or sea levels, are present in the landscape. Lakes respond to changes in precipitation and evaporation on both the short and long term. For example, since the launch of Landsat in 1972, fluctuations in the volume of Lake Chad, north-central Africa, have been recorded on a sporadic basis. The Great Salt Lake of Utah in recent years has experienced a significant increase in volume in response to greater precipitation and less evaporation, resulting in the highest historic lake levels recorded. During the late Pleistocene and early Holocene, Great Salt Lake was the site of an enormous lake, "Lake Bonneville", the shorelines of which are preserved in the landscape. Numerous other intermountain lakes existed all over the western U.S., but of these pluvial lakes now small remnants or playas (dry lake beds) are found. Evidence of the former lake levels is

commonly preserved in the landscape, and in many cases is readily detected in Landsat images. Other parts of the world in which lakes form by internal drainage also respond to climatic change by infilling or evaporating. Examples are found in Africa, the Middle East, South America, Asia, and Australia.

Oceanic shorelines of continents shift in response to a rise and fall in sea level from melting of glacier ice or accumulation of ice sheets, respectively, one of the major impacts of global climate change. Because rivers meet the ocean "at grade," any shift in the sea level has a profound impact on fluvial erosion and deposition in the lower reaches of the river, the coastal plain, and associated delta system. Low-lying coastal areas are most affected by rising or falling sea level.

If greenhouse-gas loading (especially CH_4 and CO_2) of the atmosphere can be correlated with global temperature and the response of global ice volume to such conditions, then future sea levels can be predicted. Atmospheric CO_2 concentrations can be determined from glacier ice-core analysis and dated. If multiple stillstands of sea level can also be dated and correlated with CO_2 concentrations occurring at the same time, the rate of sea level rise can be calculated. The problem with predicting future sea levels from such an analysis is that the present-day rate of global warming and greenhouse-gas loading of the atmosphere is many times higher than the rate due to natural processes, so that the historic and geologic record yields only imperfect analogs for current conditions. Therefore, it is difficult to predict the response of the planet to this human-induced acceleration of natural processes. It is the interaction of the atmosphere (global warming) on glacier ice volume and the addition of glacier meltwater to the ocean that is the key process that must be understood before a predictive technique becomes possible.

3) Climate-Tectonic Interactions

Introduction. The surface of the Earth is the product of dynamic interactions between internal processes and external or solar-driven processes. An integrated approach to climate and tectonics can form a foundation for a comprehensive, physically based understanding of the interactions and feedbacks between the two major sources of energy which define the Earth system. This foundation, combined with improved models of the atmosphere and of the internal dynamics of the Earth, will facilitate predictive models of future changes in the land surface.

Traditionally, land topography has been used in geophysics mainly to analyze gravity. However, topography itself is a major tectonic signal that is little exploited. The causes for the regional elevation of western North America, for example, remain a major unsolved problem, and the morphologies of the Tibetan and Andean plateaus provide some the most important clues about the origins of these still enigmatic features. In contrast, regional and global scale morphology of the ocean floor and other planets has from the beginning been a primary and fruitful focus of tectonic study.

Tectonic Geomorphology. Climate-tectonic interactions are most evident where tectonic processes create landforms that interfere with the global atmospheric or oceanic circulation. This includes major uplifts, 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.

Neotectonic landforms such as fault scarps and coastal terraces are often relatively short-lived (on the order of 10^3 - 10^5 years.). At the other end of the feature-stability (residence) time scale are extremely ancient landforms (paleoforms), the recognition of which is rapidly increasing our understanding of continental paleogeomorphology. Ancient high-level erosion surfaces are present in many of the Earth's orogenic belts. These hold important clues about the development of orogenic topography. A significant percentage of the Earth's land area is represented by convergent margins, rift zones, and zones of transform motion. Within these areas, tectonism exerts a primary control on landform evolution, and studies of the landforms yield important information on the nature and processes of lithospheric deformation. On the other hand, landform evolution within the relatively quiescent shield areas of the continents is more closely related to changes in climatic geomorphology and the evolution of the continental drainage systems. Even in "stable" shield areas, the landforms are affected by subtle vertical movements that reflect poorly understood mantle processes such as the movement of lithospheric plates over "hot spots." Spaceborne platforms offer the most effective means of gathering data with sufficient regional coverage of all these landscapes.

Critical problems that can be addressed 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 planned new Visible and Near-Infrared (VNIR), Thermal Infrared (TIR) and Radar imagery, 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.

Volcanism. Volcanism and climate are linked in several ways. It is well known from historical and geological records that gases and dust produced during major eruptions change the global atmosphere and can influence climate. Less well understood are the effects of large ocean-floor eruptions on ocean currents and temperatures, which in turn can influence climate. On land, volcanoes and volcanic features are important parts of some mountain belts; and, as discussed above, mountains affect atmospheric circulation, and thereby climate. In addition, volcanic landforms, many of which can be radiometrically dated, show climate-dependent erosional dissection. Measurements of volcanic growth and dissection in accessible regions under known climatic conditions can be used to estimate the ages of less accessible volcanoes that are imaged from space.

The Volcanology Panel science report should be consulted for a more comprehensive treatment of the interaction of volcanic activity with the oceans and atmosphere and the use of orbital and airborne remote sensing techniques in the study of volcanic processes.

4) Human Activities that Modify the Earth's Surface

Introduction. The human aspects of climatic change include not only the effects of changes on prehistoric migrations but also on the later rise of great civilizations. For example, recent work indicates the presence, in the surficial geologic materials of the Sahara, of a record of climatic change spanning more than 200,000 years, which is closely related to human prehistory. Presently there are population pressures on many desert margins, with attendant problems of desertification (loss of vegetation, soil erosion, waterlogging and salinization). The impact of future changes, whether due to variations in climate or human activities (or both), cannot be assessed in the absence of regional analyses of the record of past changes recorded by the land surface.

During the past century both the rate of change on the Earth's surface and the area impacted by 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. Together, water and soil form the basis for life on the land surface. Since the beginning of permanent settlements, human activity has had an increasingly profound impact on soil degradation and associated changes in vegetation. Major human activities have been agriculture -- especially irrigation agriculture -- grazing of livestock, damming rivers, and deforestation. Today these activities have reduced the fertility of vast food-producing areas.

Soil degradation in some areas is now occurring so rapidly that its progress is difficult to measure using conventional ground-based mapping techniques. NASA's remote-sensing technology is uniquely capable of assisting ground-based programs to measure soil degradation globally and on a repetitive basis. Key capabilities of satellite remote-sensing technology include: synoptic coverage at useful map scales; estimation of chemical composition and abundance; and linkage to conceptual and quantitative soil-development models. Soil degradation includes aeolian and fluvial erosion and transport, waterlogging, and changes in chemical composition including salinization and acidification. Soil degradation is both a cause for and the result of changes in the type and amount of vegetation. Each process leaves tell-tale traces on the chemistry, soil texture, and morphology of the Earth's surface. The major changes on the Earth's surface resulting from agricultural activities and deforestation are sufficiently widespread that they may affect regional and even global climate.

Eroded soil is ultimately redistributed as wind-blown dust, as silt in reservoirs, as fields of sand dunes, and as alluvium in flood plains and deltas of river systems. Changes in the rate of fluvial erosion, transport, and deposition of sediment can have profound effects on human facilities and natural systems. The effect of increased sedimentation in estuaries, deltas, and other coastal environments is especially amenable to study with remotely sensed data.

Because of the special importance of the problem of soil degradation to life on Earth and because it is possible to measure key aspects of changes in soils by remote sensing, the panel recommends that the SES program explore the possibility of taking a leadership role in coordinating research on changing soil resources. Soil research is conducted by many US and international agencies, and any program would require close coordination; however, NASA uniquely is able to supply the broad perspective of remote sensing which will be necessary to treat soils on a global scale and in the context of global climate change.

IV. DATA REQUIREMENTS

1) Types of Measurements

Investigations of land surface processes that produce changes in response to climate, tectonism, and human activities require systematic, repetitive measurements (*in situ* at representative selected sites, and globally) of physical and chemical conditions of the Earth's surface at several spatial and temporal scales. This is best accomplished by a coordinated program of field and remote-sensing observations from aircraft and Earth orbit.

Physical characteristics important to land surface processes include geometry and distribution of landforms, surface roughness, thickness and distribution of eolian mantles, particle-size distribution, soil moisture and density, development of hardpan and caliche, and vegetation type and density. Chemical conditions of interest include rock type, weathering products, rock coatings and soil development. Most of these quantities may be derived from remote-sensing data: 1) visible and near-infrared data are sensitive to composition of surficial materials such as rock type and weathering products and to vegetation; 2) thermal infrared sensors are sensitive to rock type as well as bulk properties; 3) radar can be used to derive surface roughness, bulk properties, and potential subsurface horizons; 4) high-resolution (5-m) panchromatic images depict morphology in two dimensions (three dimensions if in stereo); and 5) topographic data quantitatively delineate landforms.

The areas covered by these investigations range from small and intensively studied "anchor sites" to large continental regions. Spatial and temporal resolution generally follow the

spatial scale, with higher-resolution rapid-repeat measurements required in the smaller areas, and lower-resolution coverage acquired 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 , and eolian flux (sand and dust in transit), and for solar radiation studies (thermal brightness and reflectance measurements). Some measurements are best collected by individual teams, and others by sensors on automated platforms.

Measurements from aircraft and satellite sensor systems will require high-resolution spatial and spectral data. Both panchromatic stereo imagery (10-m contour interval) and multispectral imagery with a pixel resolution of 5 and 10-m, respectively, are desirable. An L-band, HH Synthetic-Aperture Radar (SAR) system, with a minimum 30-m resolution is essential for imaging shallow subsurface topography and geologic structures in arid regions obscured by wind-blown sand sheets and low dunes.

Imaging spectrometer data coregistered in the visible, near IR, and thermal IR with a pixel resolution of about 30 m are required for investigations of the chemical and minerological composition of surficial geologic units, including soils, and for discriminating vegetation cover from bare soils, especially in arid regions. The interdisciplinary nature of many investigations will require that the bands chosen (for example, on the HIRIS) meet the needs of mineralogists and soil chemists as well as of botanists and field geologists.

Space-based measurements of precipitation (or soil moisture) and wind systems over the land surface, including aerosols of dust and volcanic origin, are greatly desired if the technology can be developed. Detection and tracking of airborne dust is best achieved from geostationary satellites with a continent-wide field of view and round-the-clock coverage, but detailed observation of dust-source areas requires archiving of daily local area coverage such as is provided by the polar orbiting NOAA AVHRR LAC system.

Although it is difficult to choose between spectral and spatial needs for studies of change on the Earth's surface, the one global data set which is lacking and is most needed by the Earth science community is global stereoimage and digital topographic data. The panel recommends, therefore, that a high priority is for NASA to launch a stereoimage mapping satellite at the earliest opportunity to acquire a global data set.

2) Remote-Sensing Data

The complexity of the Earth's surface is such that most investigative strategies closely couple intensive field work at critical sites and along transects ("anchor sites") with the more general regional perspective afforded by remote sensing. Thus, data must be acquired in the field and laboratory, as well as from spacecraft or aircraft.

NASA collects images from a variety of sensors aboard aircraft and spacecraft. Currently, NASA's airborne imaging program involves a C-130, ER-2, DC-8, and Lear Jet operating from Ames Research Center and Stennis Space Center. The terrestrial spacecraft program has centered on the Landsat series, Seasat, Shuttle, and Eos (yet to be launched). Additionally, NOAA routinely collects small-scale images for weather prediction. The images collected by sensors aboard these platforms forms an historical record extending back to 1972, and this record allows us to study phenomena and processes at the two-week to ten-year time scale.

Image requirements in terms of sensitivity and resolution are specified below (Tables I and II). These requirements are cast in terms of existing, planned, and future sensors. The requirements for studying land surfaces are unusual in that there is a heavy emphasis on compositional analysis requiring hyperspectral imaging spectral data.

TABLE I

Required Data

Elevation images (digital elevation models) for morphometric analysis.
$\Delta x = 30$ m $\quad\quad \Delta z = 20$ m (absolute), 2 m (relative)

- Topographic data for gradient images for analysis of radiance images.
$\Delta x = 50$ m $\quad\quad \Delta z = 1$ m (relative)

- High-resolution images for morphometric measurements.
Panchromatic, low sun
$\Delta x = 5$ m $\quad\quad$ SNR> 100 $\quad\quad$ swath width = 60 km
Stereo images

Base/height > 0.5 (10-m contours) SNR > 100   swath width: 60 km

fore/aft preferable (near-simultaneous)

- VNIR data for compositional analysis (hyperspectral or imaging-spectrometer data).

  Spectral region: 0.45 - 2.4 mm

  Number of channels: > 24 (if band centers selectable)

  Bandwidths: > 10 nm   Swath width: > 100 km   SNR: > 100

  Dynamic range: > 100 utilized gray levels

- Thermal infrared data

  Two times of acquisition: noon and predawn

  Spectral region: 3-14 mm

  Number of channels: 4 (3-5 mm),12 (8-14 mm)

  NEΔT< 0.1 K at 300 K Δx=60-90 m   swath width = 100 km

- SAR data

  LHH with Δx = 30 m   Sensitivity: 30-40 dB   Swath width:> 30 km

  Multifrequency (C- and P-band) data are highly desirable

  Multipolarization and multiangle images are useful

- Continental-scale images

  Continuous coverage, low spatial resolution

  Frequent coverage, moderate spatial resolution

TABLE II

Match of Data Requirements and Remote-Sensing Systems

- Topographic elevation and slope data

    Currently unavailable from NASA systems

- High-Resolution, low-sun panchromatic data

    Currently unavailable.

  Large Format Camera, SPOT, and Soyuzkarta are the closest approximations to required system.

Imaging Spectrometer Data

HIRIS (Eos) and AVIRIS (ER-2) are the closest approximations. The HIRIS spatial resolution (30m) is acceptable; the SNR may be too low; and the swath width (12 km) is too small. AVIRIS sensitivity is too low (SNR=25 at 2 mm). MODIS does not have all the required bands and the spatial resolution is too low.

Multispectral Data

TM spatial resolution and swath width are excellent. Sensitivity is too low (dynamic range is generally 5 bits) and the number of bands is too low.

Multispectral thermal IR data

TIMS (C-130) has too few channels but does have the required sensitivity. ITIR (Eos) has too low sensitivity (0.3 K) and too few channels, but the same instrument acquires VNIR data. The ITIR swath width (30km) is too small. A planned TM upgrade that would have included three thermal IR channels has been postponed indefinitely. No other instruments are currently planned. Satisfactory data collection thus requires an ITIR upgrade or a new sensor on an Earth Probe mission.

SAR Data

Eos SAR would give the required data, but its future is now uncertain. ERS-1, JERS-1, and Radarsat are acceptable, except for duty-cycle constraints, but the lack of SES input into priorities for coverage make acquisition of the needed data problematical.

Continental-scale images

GOES/METEOSAT (geosynchronous satellites) provide continuous images of most areas on the Earth with resolution of 4 km. The NOAA polar-orbit satellites provide frequent AVHRR coverage at 1-km nadir resolution. AVHRR images must now be requested in advance. For most applications, these data

are sufficient, but for covering short-term unpredictable events (e.g, dust storms) AVHRR data should be available retrospectively.

3) Data Volume

In studies of land-surface processes the data volume utilized will be controlled mainly by the manpower available for interpretation, and less by the scope of the projects or the number of images that can be acquired. Considering the availability of technically trained personnel in 1989, we anticipate that a realistic beginning program would require a data-equivalent on the order of ten new TM scenes. As an example, there might be four regions under study, each region initially requiring four TM-equivalents. The number of "TM-scene-equivalents" per region might be expected to increase by about two per year. In addition it is expected that it will be necessary to add one new region each year at the four TM-scene beginning data volume.

The actual data for each "TM-scene-equivalent" would not be restricted to TM, but would encompass any of the data types listed above. At least initially most of the data would be required for only one or two times per year (e.g., summer/winter). In order to integrate data from the variety of available sensors with each other and with topography, the data would need to be mosaicked and registered to a common base. Proper geocoding of all image data would automatically produce this result.

It is important to appreciate the magnitude of a truly global-scale remote-sensing research program designed to study global change. At the minimum, intensive study areas would need to be established in areas representing each of the types of sensitive geographic provinces -- for example, deserts in North Africa, central Asia, and the western United States, tropical and temperate rainforests, boreal forests, tundra, and so forth. These intensive local studies need to be coupled to regional-scale remote-sensing studies requiring both high-density data over many local sites similar in scale to those studied on the ground, as well as lower-resolution data of the region as a whole. The People's Republic of China is covered by 543 Landsat MSS images; this volume of data is of the same order of magnitude required for each regional study involving modern hyperspectral data (e.g., HIRIS) and data from the different spectral windows (e.g., VNIR and radar). Studies of this scope have not yet been attempted.

4) Accessibility and Cost of Data

There is a growing need, in support of two large national/international research programs (U.S. Global Change Research Program/International Geosphere-Biosphere Programme and NASA's "Mission to Planet Earth Program"), to: 1) provide easy access for all scientists, to past, present, and future satellite image/photographic data; 2) acquire a basic high-resolution (less than 5-m pixels) global dataset of the topography of the Earth (stereo images and digital terrain models); and 3) acquire on a continuing, long-term and systematic basis, repetitive coverage of the land and shallow-sea areas of our planet with a medium-resolution (30-m pixels) Landsat-type sensor. All satellite image/photographic data must be readily accessible to all scientists and affordable (cost of reproduction only), if adequate use of this data resource is to be made.

Landsat. The single most important quasi-repetitive global data set capable of monitoring changes on the Earth surface are Landsat 1-5 multispectral scanner (MSS) and Landsat 4 -5 Thematic Mapper (TM) images. Landsat MSS images comprise the longest set of medium-resolution coverage of our planet, beginning in July 1972. Since the recent commercialization of Landsat, image acquisition has been based on commercial rather than scientific reasons, hence the coverage has become sporadic. To measure processes of change on the land surface it is essential to have access to all of the existing Landsat data and to improve the continuity of coverage in the future. It is well known that Landsat data today are too costly to be fully utilized by most scientific investigators, including those supported under the Solid Earth Sciences program.

To achieve the objectives of the program where the Earth is truly to be viewed as a planet, we recommend that existing data (including all Landsat and NOAA AVHRR data) and future remotely sensed data be processed to a common reference base, and made available to all program-funded investigators. A precedent for this type of data support has been established by NASA's Planetary Program for the processing and provision of data (in hard-copy, map and image- mosaic form as well as in digital form, on disks) to its investigators of the other planets.

The civilian scientific community only has access to a small amount of high-resolution, stereoscopic image/photographic data. These data are from the Large Format Camera (U.S.) and the Metric Camera (ESA) -- both flown one time only on the Space Shuttle -- Soyuzkarta (U.S.S.R.), and the SPOT instrument (French-ESA). There is a significant

need for global high-resolution (5 m), stereoscopic (10-m contour) satellite image data. In addition to the use of such a dataset for stereoscopic imaging and topographic mapping of the land shallow-sea areas of our planet, the data could also be used to compile a global digital topographic data base. Alternatively, digital topographic data could be obtained by a laser altimeter.

It is notable that in NASA's exploration of other planets, investigators started out with a global approach, with global data sets to match, and only later concentrated on smaller areas and localities as more detailed, higher resolution data became available. In the case of Earth, because of political sensitivities between countries, comprehensive topographic and image data sets today are seldom available, even on a regional scale for areas outside the U.S., Europe, and Australia. For example, most of North Africa is very poorly mapped, with contour intervals of 100 m or more and inadequate representation of the surface topography. Many parts of Mars are mapped in more detail! Obviously, a serious study of global change will require adequate global data.

5) Ground-based Data Collection

Field and laboratory data need to be acquired with three main goals in mind:

- radiometric calibration of the remotely sensed images

- spectral and chemical characterization of the scene to calibrate and verify the image analysis

- input to predictive models

The first category consists of radiance and reflectance data, radar measurements of standard targets, and surface temperatures. The second category includes high-resolution field and laboratory spectra. Also included are radar scattermeter data, and such data as vegetation type and cover, lithologic and mineralogic information, and morphometric information. The third category includes isotopic dates and exposure ages, topography, soil type and development. Ground-based data collection should rely heavily on the expertise and facilities available through cooperative efforts with agencies such as USGS, NOAA, and USDA, which have operational responsibilities to obtain many types of field measurements.

The panel notes, however, that while there is increasing emphasis on studying the land surface at regional and global scales, at the same time budgetary restrictions threaten to limit the expanding participation of skilled field observers. The panel emphasizes that a strong program of on-going field studies in close cooperation with remote-sensing measurements is essential to be able to test models of global change.

6) Role of Other Agencies

The multidisciplinary aspects of the work envisaged in this program will require cooperative arrangements with other Federal agencies including NOAA and USGS, as well as participation by scientists from several agencies and academic institutions as co-investigators and collaborators on individual projects. Collaborative efforts that utilize data collected from established ground stations by other agencies would save unnecessary cost and efforts of duplication, and should be encouraged. Similar encouragement should be given to cooperation with foreign groups who can assist in the logistics required for field work overseas.

SECTION VI.

REPORT OF THE PANEL ON

EARTH STRUCTURE AND DYNAMICS

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SECTION VI.

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SUMMARY

The panel has identified problems related to the dynamics of the core and mantle that should be addressed by NASA programs. They include (1) investigating the geodynamo based on observations of the earth's magnetic field, (2) determining the rheology of the mantle from geodetic observations of post-glacial vertical motions and changes in the gravity field, and (3) determining the coupling between plate motions and mantle flow from geodetic observations of plate deformation; we also stress (4) the importance of support for interdisciplinary research to combine various data sets with models that couple rheology, structure and dynamics.

Core Fluid Dynamics and the Geodynamo

Fluid motions of the Earth's liquid outer core, an electrically conducting liquid, maintain Earth's main magnetic field against ohmic dissipation by a self-sustaining dynamo process. Those motions also cause a variety of time-dependent geomagnetic phenomena, such as an apparent slow westward drift of the non-dipole field, occasional short-term changes in the rate of geomagnetic secular variation (called magnetic impulses, or jerks), and sporadic, but geologically rapid excursions and reversals of magnetic polarity. This dynamo, one of but many in the universe, is special in that it can be probed up close and, in principle, for long duration.

To view a hydromagnetic dynamo is to see a fluid motion with the magneto-regenerative property, so an outstanding issue in core geophysics is the inversion of geomagnetic data for core fluid motion. As it stands, this inverse problem, even for surface fluid motion just beneath the core-mantle boundary, is highly non-unique (and non-linear), so dynamical assumptions are needed. The fluid motion has been presumed to be either purely horizontal, temporally steady, or in geostrophic balance. A variety of possible surface fluid motion patterns have thereby been derived which fit the geomagnetic data.

Such patterns can also be used for estimating a pressure torque on core-mantle boundary topography. This effect may explain decade fluctuations in the length-of-day, and these same motions certainly contribute to the delivery of convective heat flux from the upper core towards the core-mantle boundary. On the other hand, the electrical conductivity of the D" layer and lower mantle may be sufficient to electro-magnetically couple core fluid motions with the mantle, thus accounting for the decade-scale length-of-day changes. Clearly, the resolution of this issue has interdisciplinary aspects.

For such studies, the geomagnetic secular variation rate, at the core-mantle boundary, is as important as the main geomagnetic field itself. To time-differentiate the data, it becomes essential to obtain long-term, global, continuous geomagnetic field measurements. A decade of such observations from near-Earth satellites therefore remains of highest priority.

We recommend that NASA measure the three components of the vector geomagnetic field to one nanotesla accuracy in each component with global coverage from an altitude of 600 km or more and for a duration of at least one decade.

Because the Earth's outer fluid core is a contained rotating fluid, it possesses multiply infinite suites of free modes of oscillation. The simplest of these, which is a nearly rigid-body wobble of the fluid core relative to the mantle, may be responsible for an anomalous

retrograde annual term in the VLBI nutation observations. The period of the mode differs fractionally from the sidereal period by the order of the ellipticity of the core-mantle boundary. VLBI observations have been used to estimate a non-hydrostatic deviation of the shape of the core-mantle boundary of the order of 5%. Continued advances in improving VLBI measurement accuracies are needed to complement theoretical progress in core dynamics research. In addition, superconducting gravimeters which seem to hold the most promise for the detection of other members of the suites of core oscillations would provide very useful corroboration of VLBI results and better vertical control if installed at the same sites as the telescopes. We therefore recommend such deployment at a selection of globally-distributed VLBI sites. The direct detection of the principal core mode, called the free core nutation, and the discovery of other inertial modes which reflect details of density stratification in the core, would represent major advances in our understanding of core dynamics and structure.

Mantle Flow and Rheology

The solid earth is actively deforming at all spatial scales. At global scales, viscous rebound in response to the most recent episode of Pleistocene deglaciation may be the dominant contributor to this deformation. Current models of mantle rheology are based on geologic observations of this rebound, and are consistent with observations of slow changes in the lowest zonal coefficients of the earth's gravity field. By making global, geodetic observations of this ongoing deformation we can greatly increase our knowledge of the rheological structure of the mantle. We therefore recommend developing a capability to measure vertical surface motions associated with these deformations at millimeter precision over spatial scales of 1,000 to 10,000 km. More importantly, we recommend a long-term program to monitor concomitant temporal changes in the gravity field. This will confirm if the changes in the second zonal harmonic of the field that have been detected already in the LAGEOS satellite ranging data are indeed due to post-glacial rebound. Passive satellites similar to LAGEOS should, as a first priority, be employed to make these observations at long wavelengths (degree <8). High-precision, low-elevation, gravity field satellites such as SGGM could provide useful temporal observations at shorter wavelengths. These observations of vertical motion and gravity are also essential for interpreting motions resulting from the melting of the sheets and changes in sea level. The post-glacial rebound problem is intimately linked to that of global change.

Plate deformation

Motion of tectonic plates is a direct manifestation of mantle flow. At the same time the relative rigidity of the plates shield smaller scale motions from view. Deformation of plates, however, will reflect the stresses acting on the plates by underlying flow patterns. Measurement of relative plate motions will reveal any inconsistencies with plate rigidity. Direct measurement of deformation within plates can reveal patterns of deformation related to mantle flow, and will elucidate the mechanical properties and modes of deformation and fracture of the plates. The long term thermal evolution of the earth depends primarily on the heat transport throughout mid-ocean ridges. The geometry of plates, and hence the length and activity of spreading ridges, depends on how plates form, evolve and reform. Measurement of deformation in a large oceanic plate (the Pacific) and a plate with a possible incipient subduction zone (the Indian plate in the central Indian Basin) will reveal how oceanic plates fail and create new plate boundaries. Measurement of deformation in a continental region (North America) will indicate possible differences in the mechanisms of deformation of continents and oceans, and will bear on mechanisms of growth and

evolution of continents. Such studies are essential to understanding how the plates interact with convective heat transport and the evolution of the mantle.

Interdisciplinary Studies and Modelling

Understanding the dynamics of the mantle requires the integration of data from diverse sources with sophisticated modelling and computational capabilities. Gravity (or the geoid) directly reflects density heterogeneities that drive flow in the mantle. At the present the long wavelength field (degree <20) is sufficiently well determined for studies of large-scale flow. Short wavelength gravity (length scales < 500km) only reflects uppermost mantle and lithospheric densities, and together with topography and seismic data, bears on convective instabilities and structure beneath the lithosphere, and small scale lithospheric structure and deformation.

Other data sets bear on the convective evolution of the mantle. Isotopic data from basalts suggest heterogeneities that have existed for a major fraction of earth history, and also reveal the history of differentiation and crustal formation. Most recently, seismic data have revealed mantle heterogeneity that is partly consistent with the gravity field, and appears to reflect temperature or compostion fields related to flow. No single data set is complete or detailed enough to determine the flow and evolution of the mantle; rather models must be generated and tested against seismic, geochemical, plate motion, seismicity and deformation data. This requires treating a variety of data, and reducing basic data (e.g. seismic travel times) in terms of models constrained by other observations, such as plate motion and the history of subduction. Such an approach will require support for group of researchers with expertise and access to the relevant data. Sufficient computer resources, both in terms of speed and ability to treat large data sets, must also be available. At present, numerical models of convection directly relevant to the earth tax the largest computers. Substantial computer power is needed for basic modelling as well as treating large data sets. Development of sophisticated software requires support of trained specialists, working together with geodynamicists.

We also recognize the importance of laboratory and theoretical investigations of the physical properties of earth materials under conditions of high temperature and pressure found in the earth's interior. This data must be incorporated into models of flow and deformation that relate various observational data sets.

RECOMMENDATIONS

1. Monitoring of the earth's long wavelength magnetic field to produce models at 6 month intervals (or shorter). This to be done with satellite measurement of the vector field to an accuracy of 1 nT. in each component for at least a decade.

2. Measure secular changes of the earth's gravity to detect post-glacial rebound and changes in ice volume and sea level. This could be done with STARLETTE/LAGEOS style passive satellites or a long lived (>3 years) SGGM mission. The minimum required spatial resolution in the zonal harmonic coefficients is degree less than 8 and the required sensitivity is 10^{-12} per year.

3. Deploy superconducting gravimeters at globally distributed VLBI observatories in order to detect gravity changes caused by the internal dynamics of the core. This will also contribute to determination of vertical motions and polar motion.

4. Develop capability to measure secular motion (horizontal and vertical) as small as 1 mm per year in order to detect current post-glacial rebound and motions related to sea level variations.

5. Measure deformation within tectonic plates, with emphasis on intraplate deformation related to underlying mantle flow, and the ultimate appearance and disappearance of plates or plate boundaries.

6. Support interdisciplinary studies and analysis of related data sets (seismic, gravity, rotation, etc.) ; such data should be made accessible to the wider community. This should be done by support of research groups, including post-doctoral researchers.

7. Support modelling of dynamical processes in conjunction with analysis of relevant data sets through the provision of super-minicomputers (e.g. 10's of Mflops) for research groups, as well as access to supercomputers.

INTRODUCTION

The major questions considered by this panel dealt with strategies for improving knowledge of Earth's deep interior, from the highly conducting magneto-hydrodynamic fluid core, to the viscously convecting mantle. We were particularly interested in understanding how boundaries of the mantle interact with units below and above and transfer stress and heat. The major themes are therefore 1) study the hydrodynamo by observing Earth's evolving long wavelength magnetic field using a high altitude and long-lived, orbiting spacecraft; 2). Determine the rheology of Earth's mantle, especially its vertical structure from a campaign to measure both vertical crustal motions and secular changes in the long wavelength gravity field resulting from post-glacial rebound and; 3) determine the coupling between plates and mantle flow from geodetic observations of mantle deformations. We also stress the interdisciplinary nature of this research and request augmented support for both innovative research and improved analysis tools.

The pressing scientific issues discussed in this report are broken up according to both Earth structural units and measurement strategies. We begin by discussing core dynamics and end by looking at how the Earth relates to its sister planets and our moon.

LONG TERM FLUID CORE FLOW AND THE GEODYNAMO

The most obvious manifestation of the Earth's fluid core is the presence of a primarily dipolar magnetic field at Earth's surface . The apparent dipole axis is tilted by about 11° and presently moves at a rate of approximately 0.05°/yr. The non-dipole field shows drifts and motions on the order of 10's of kilometers per year or 1 millimeter per second. This dynamic behavior was probably the first indirect demonstration that Earth is not entirely solid. If the field observed at the Earth's surface is extrapolated to the core-mantle boundary, the magnetic field becomes much more complex and displays patterns which may be related to upwelling and downwelling fluid and the interaction with core-mantle topography.

The electrical conductivity of the fluid core is of the order of 3×10^5 s/m, while that of the mantle is at least 10^3 smaller. The drift of magnetic field lines with respect to the core fluid is much slower than the fluid velocities themselves (mm/sec). Magnetic field lines are effectively trapped on convective time scales and are stretched, sheared and compressed in a complicated fashion as part of the hydromagnetic process. This phenomenon, though not an entirely understood process, transfers energy back into the magnetic field so that, while it would otherwise decay by ohmic dissipation, it becomes regenerative. Since the convection itself is probably chaotic, this process is not steady. Occasional short term changes in the core field are characterized as "jerks" with time scales as short as a year. The paleomagnetic record reveals that the dipole character itself, and its average inclination to the rotation axis, appear to be maintained for time scales as long as 10^5 to 10^6 years, then suddenly change on time scales as short as 10^3 years and may reverse direction. The resulting record of seafloor magnetic lineations with reversed polarity was the first widely accepted evidence for plate tectonics.

As just described, to view the hydromagnetic dynamo is to see a fluid motion with the magneto-regenerative property. An outstanding issue in core geophysics is the inversion of geomagnetic data for the core fluid motion. As it stands, this inversion problem, even for surface fluid motion just beneath the core-mantle boundary, is highly non-unique (and nonlinear), so dynamical assumptions are needed. The fluid motion has been presumed to be either purely horizontal, temporally steady, or in geostrophic balance. A variety of possible surface fluid motion patterns have thereby been derived which fit the geomagnetic data.

Such patterns can also be used for estimating a pressure torque on core-mantle boundary topography. This effect may explain decade scale fluctuations in the length-of-day, and these same motions certainly contribute to the delivery of convective heat flux from the upper core towards the core-mantle boundary. On the other hand, the electrical conductivity of the D" layer and lower mantle may be sufficient to electromagnetically couple core fluid motions with the mantle, thus accounting for the decade-scale length-of-day changes. Clearly, the resolution of this issue has interdisciplinary aspects.

For such studies, the geomagnetic secular variation rate, at the core-mantle boundary, is as important as the main geomagnetic field itself. To time-differentiate the data, it becomes essential to obtain long-term, global, continuous, geomagnetic field measurements. A decade of such observations from near-Earth satellites therefore remains of highest priority.

SHORT TERM FLUID CORE DYNAMICS

Of the three fluid domains of the Earth, the outer core is by far the least accessible to observation. Like the oceans and atmosphere, its dynamics is dominated by the Coriolis effect arising from planetary rotation. At longer periods, months and greater, the fact that the outer fluid core is the seat of the geodynamo, responsible for the main magnetic field and the other phenomena just described, vastly complicates its dynamical behavior compared to its geophysical fluid sisters, the oceans and atmosphere. At shorter periods, less than months, the Lorentz interaction between the motion and the magnetic field and its supporting currents is fortunately negligible, and a purely mechanical description of core dynamics is possible, providing a window on core dynamics free of the complications of hydromagnetism.

We may therefore view the outer core at shorter periods as a rotating, self-gravitating fluid mass contained between the elastic boundaries provided by the mantle and inner core. Studies of the dynamics of such bodies have their roots in the classical literature of the nineteenth century. In this century, our knowledge of the general properties of rotating fluids has been greatly extended by laboratory experiments and theoretical and computational work .

It is known that the outer core possesses free modes of oscillation with periods which, in the simplest model, are bounded below by half the rotation period. At least one of these modes is capable of exchanging equatorial angular momentum with the mantle and is referred to as the 'free core nutation' because it is very nearly a rigid-body motion of the whole outer fluid core. Neglecting the finer details of realistic Earth structure, its period depends on the shape of the core-mantle boundary.

The anomalous resonant response arising from the free core nutation has been seen in both the records of observatory gravimeters and in VLBI nutation measurements which reflect, respectively, the response to diurnal tidal deformation and nutation. These observations have been interpreted to infer a flattening of the core-mantle boundary which differs from the hydrostatic value by 6%. Thus, we appear to be on the threshold of a new observational era in core dynamics which promises to improve observational accessibility to the core and its structure.

The question of whether or not there are other core modes in the real Earth that can exchange angular momentum with the mantle and crust, and are therefore susceptible to observation by the VLBI technique, is the subject of current research (Smylie, 1989). Should such modes exist and be observable, it is expected that they would be much more diagnostic of the details of core structure than the free core nutation, which to first approximation, is a bodily motion of the whole core. The direct detection of the free core nutation has yet to be confirmed, only an associated anomalous annual retrograde nutation has been unequivocally observed. Presently an upper bound of 0.3 milliarcseconds has been obtained. The continued evolution of the accuracy of the VLBI technique is thus of prime importance in core dynamics.

Core modes that do not exchange angular momentum with the mantle and crust should still provide a gravity signal that is close to the observational levels being reached by gravimeters using the levitation of the proof mass in the field of a superconducting magnet. Indeed, there have been reports in the literature of such observations already having been made. Unfortunately, these results are based on only one superconducting gravimeter

record and a network of such instruments is required to eliminate the possibility of local oceanic basin modes or other spurious signal sources.

The detection of these modes would lead to much more precise determination of the density stratification of the fluid outer core than is possible by known seismic or other methods. This parameter is crucial to our understanding of the dynamo mechanism and heat and mass transfer in the core. Gravimeters also allow the measurement of local station tidal response and they sense polar motion, complementing VLBI records. Transient tectonic, atmospheric or climatic stochastic events which might displace the stations vertically, and therefore change gravity, will be observable by both the VLBI network and the collocated gravimeter. In fact, on terms less than a year in length, superconducting gravimeters are much more sensitive to vertical motion than the VLBI technique. This linked system will produce both complementary signals and corroborating evidence for real events which otherwise might be discounted. This type of relative gravimeter, although much more stable than other instruments of the relative type, is not appropriate for detecting very long term secular motions, such as those associated with glacial rebound. For this purpose, the strength of the VLBI technique is the fact that it is tied to a nearly absolute inertial reference frame (the quasar reference frame).

Convection within the fluid core is either driven by bouyancy resulting from the slow growth of the inner core as nearly pure iron freezes out of the alloyed iron mixture, heat sources within the inner core or fluid core, or lateral temperature variations across the core-mantle boundary. Of these options, the first appears most plausible, although it depends to some extent on the density contrast at the inner core boundary.

Earth nutations and wobble may be affected to a small extent by the density contrast, due to the resonant response of the inner core to forced wobble and nutation of mantle. The inner core itself has free rotational motions, similar to that of the mantle and the fluid core. Detection of these free modes or their influence on forced nutations may place constraints on the density contrast between the inner and outer core and the topography of the core mantle boundary.

THE CORE-MANTLE AND D" BOUNDARY

The 200 to 300 km thick transition zone, or D" layer, at the base of the mantle plays a profound role in mediating convective transfer of heat from the core to the mantle. The style of mantle convection, thermal and chemical plume formation and evolution, core fluid convective patterns, and hydromagnetic field generation, may very well depend on the chemical, thermal, rheological, and electrical properties of the D" layer as well as its lateral variation in vertical structure (Lay, 1989). High pressure laboratory studies have led to improved understanding of the physical properties of the outer core and lower mantle materials during the last decade. Perhaps the greatest advance has resulted from the examination of large suites of seismic travel times to search for systematic signatures caused by lateral mantle structure and core mantle topography using the tomographic technique.

The tomographic analysis of up to 10^6 P wave residuals and free oscillation frequency shifts have been extended to the core mantle boundary. These analyses reveal large (approximately 1 to 2%) velocity variations near the boundary and were initally interpreted in terms of excess topography of order 3 to 10 km peak to peak (Hager et al., 1985; Morelli and Dziewonski, 1987). As already discussed, comparison of hydrostatic models for forced nutation of Earth's spin axis with the observed periodic signature reveals a 2 milli-

arcsecond anomaly in the retrograde annual term (Herring et. al., 1986). The estimated accuracy of this measurement is now better than 5%. Neither errors in ocean tide models or atmospheric thermal tides could account for this effect. Although it might be due to the presence of other members of a suite of free core nutations which are yet undiscovered, the most compelling explanation is that the core-mantle boundary has an excess second harmonic ellipticity of 6%, equivalent to a 0.5-km increase in the equatorial relative to the polar radius. Analysis of gravimetric diurnal tidal signatures, although less accurate, appear to support this interpretation. The core-mantle boundry could have large, average topography in which the mean ellipticity is small (Morelli and Dziewonski, 1987). However, recent attempts to explain decade-scale changes in length of day (lod) in terms of momentum exchange at the core mantle boundary appear to require only 0.5-km scale core-mantle boundry undulations, in agreement with the nutation result but in conflict with simple seismic models of this boundary. This calculation uses temporal changes in the long wavelength magnetic field to infer the fluid velocity field at the core-mantle boundry. This calculation employs the frozen flux approximation and assumes a source-free, insulating mantle. Seismic tomography still provides the core-mantle boundary topographic structure, while the scale is determined by matching the observed 4-msec lod change with the predicted change from their model. The model employs a mountain torque approach to estimate the torque arising from a lateral pressure force caused by fluid motion across the topography. This calculation appears to rest on a series of complex models and neglects the possibility that electromagnetic interaction of the magnetic field with a highly conducting D" layer might account for part or all of the lod change. Nevertheless, these kinds of interactions have focused attention on D" vertical structure. Undulations at the top of D" may very well account for the seismic anomaly.

The existence of a distinct, and perhaps dynamically unstable, thermal boundary at the base of the mantle is predicted from theoretical models of mantle convection with a temperature sensitive viscosity. Early seismic evidence for the layer came from increased radial velocity gradients at the base of the mantle. Tomographic models exhibit large lateral variations in seismic P and S wave velocity, compared with the middle mantle. Precursors to the reflected S and P waves have been observed in some isolated patches of D" (Lay, 1989). Whether these represent a reflection at a density jump at the top of D" or lateral heterogenity in D" is uncertain. The patches with observed precursors correlate with long wavelength, high-velocity P wave tomographic anomalies, while the D" top is not seen in the Pacific, which corresponds to a low velocity P wave region.

The temperature contrast across the D" layer may be greater than 700° K based on the estimates of the minumum outer core temperature of 3800° to 4700° K. The core temperature range depends on whether sulphur (lower) or oxygen (higher) is the primary alloy component. The lower mantle adiabat is in the range 2600° to 3100° K. The melting point of perovskite at core-mantle boundry pressure is about 3800°K, so that "D" may be near the solidus and contain significant partial melt. Small-scale heterogeneity of order 5% has been inferred from analysis of scattered P wave phases (Bataille and Flatte, 1988). Small-scale convection within the layer itself may occur. High pressure experiments indicate that Fe is highly reactive with silicates at core-mantle boundry pressure, but it is unclear whether this reaction extends more than a few hundred meters above the core-mantle boundary. The importance of this process is that it could increase electrical conductivity within D" by 10^4.

DEEP MANTLE CONDUCTIVITY

The conductivity of perovskite and by extension the mid-mantle is not well determined, with laboratory values ranging from 10^{-2} s/m to 10^2 s/m. Its value also depends on the fraction of iron assumed for mantle composition. The 1969-1970 geomagnetic jerk may have occurred on a time scale as short as 1 year. However, the equivalent event at the core-mantle boundary may have occurred a decade earlier, if a similar event in Earth rotation is related to this magnetic jerk. Future space missions carrying magnetometer instruments to study the main field should strive to attain enough data to solve for magnetic field maps, perhaps every 6 months and on a regular basis. Capture of the onset of the next jerk could resolve many phenomena relating hydromagnetic "weather" and mantle electrical properties.

Several different approaches to this problem deserve support. High pressure laboratory experiments on appropriate mineral assemblages with both shock waves and heated diamond anvil presses hold promise for reaching the required range of pressures (about 80 to 130 GPa) and temperature (2000-5000° K). Long-term monitoring of the geomagnetic poloidal field may reveal magnetic impulses or jerks, whose diffusion through the mantle can constrain some weighted integrals of the conductivity, provided diffusion time-scales can be established by linking the onset of a jerk with a corresponding feature in the length-of-day data. Monitoring of the diffusion of the external field caused by the 22-year solar cycle provides additional constraints, especially on the upper mantle. Further theoretical studies are also needed because the electrical conductivity is closely associated with another important unknown quantity, the toroidal magnetic field in the mantle, which could be 10^2 larger than the poloidal field there. The toroidal magnetic field in the deep-mantle, as it diffuses into the mantle from below, generates currents and electromagnetic torque, changing Earth's rotation. Comparison of the estimated electromagnetic and pressure induced torques inferred from magnetic field variations and core mantle topography, can be compared with the long term length-of-day changes to infer diffusion time scales, bulk mantle conductivity and toroidal field strength.

In addition, mantle conductivity may serve as a proxy for temperature and thereby determine the geotherm. Knowledge of the geotherm could contribute to our understanding of the relative importance of chemistry and thermal expansion on variations in density with depth.

MANTLE STRUCTURE AND DYNAMICS

The Earth's mantle is a convecting system that transports heat from the interior to the surface. Some heat comes from within the mantle, from radioactive heat sources and from whatever secular cooling is occuring, and the rest comes from the core beneath the mantle. Heat from the core may come from radioactive decay, but more likely results from cooling. As the core cools, the solid inner core crystallizes from the liquid, releasing latent heat of crystallization. In addition, the precipitation of solid iron from the liquid outer core (which contains a lighter component) will result in an enrichment of the lighter component near the inner-core boundary. This light fluid wil be unstable and will flow upwards thereby displacing denser fluid. This process effectively converts gravitational potential energy into fluid motion and ultimately into heat.

The existence of the Earth's magnetic field requires a source of energy in the core where it is generated, which implies that some heat must be flowing into the base of the mantle. Estimates based on the ohmic dissipation of electric currents in the core suggest that the total heat flow from the core may be as large as 10 to 20 percent of the heat flow at the Earth's surface. If it is this large, the heat flux (per unit area) at the two boundaries would be of similar magnitude as would convective heat transport. Nevertheless, the bulk of the Earth's heat flow originates in the interior of the mantle.

The most obvious manifestation of mantle convection is the motion of tectonic plates on the surface. The plates comprise the thermal boundary layer of the convecting system, through which heat is transported by conduction. The temperature drop across this layer is around 1200 degrees C, based on the temperature of magmas that are erupted to the surface. Beneath this layer the temperature should be more or less adiabatic, with non-adiabatic variations that drive convective motions and heat transport. At the base of the mantle there should be another boundary layer, associated with heat flow out of the core. A nonadiabatic temperature difference will exist across this layer as well, but its exact magnitude is so far undetermined.

The boundary layer at the Earth's surface has particular characteristics, primarily owing to the extreme temperature dependence of the mechanical properties of earth materials. Because the layer is so much colder than the material beneath, it is much more resistant to deformation and forms a number (twelve or so) of essentially rigid plates that are in relative motion reflecting the convective motions beneath. The boundaries between the plates are not rigid at all but are zones of concentrated deformation which are relatively quite weak. These plates comprise a mechanical boundary layer, the lithosphere, as well as a thermal boundary layer. Where two plates diverge, hot material wells up from the interior, advecting heat to the surface. Where plates converge, material that has cooled off at the surface sinks back into the interior, where it cools off the surrounding mantle. The sinking boundary layer is apparent as the locus of deep earthquakes that occur as the strong, cold boundary layer is deformed. These provide the only direct evidence of the path of material within the mantle.

Where plates diverge, molten lava rises to the surface and forms a six kilometer thick layer of oceanic crust, which appears to form in the same fashion and with similar properties at all divergent boundaries. The magma, which probably forms by partial melting at around 50 km depth, transports heat to the surface very efficiently, and also heats the surrounding material to a uniform temperature from which it cools by conduction as the the plate moves away from the boundary. The plate subsides as it cools and contracts, and the resulting decrease in elevation (proportional to the square root of the age of the plate) is observed and confirms the hypothesized process of conductive cooling. By around 100 million years a

plate will have cooled to a depth of around 80 km. Eventually it sinks into the interior at a convergent boundary.

Spreading at divergent boundaries is always symmetric (or nearly so), so that new material is added to both plates at the same rate. In contrast, convergent boundaries are asymmetric, and only one plate sinks and is destroyed. As a consequence, the geometry and sizes of the plates are continuously changing as some plates grow while others shrink and ultimately disappear. A representative average lifetime for a plate is around 200 million years at present rates of plate motion. If no new plates were formed the number of plates would decrease until only one were left; thus new plate boundaries must form to create new plates in order to sustain the process. At present, we do not know how, where or why new plate boundaries form, only that they certainly have in the past and most certainly will in the future.

Although the oceanic parts of lithospheric plates appear to be rigid, the geologic history of continental parts presents a record of substantial deformation Furthermore, some regions (e.g. the Himalaya, the western U.S) are actively deforming now as evidenced by seismic activity and landforms such as recently uplifted mountains. An explanation for this is that the thicker continental crust (40 km or so) prevents the material in the upper mantle from becoming cold enough to be as strong as oceanic upper mantle, which is overlain by only 6 km of crust. The crustal material is relatively weak, and contributes little to the strength of the plate. Certainly some spreading ridges initiate in continents, as did the mid-Atlantic ridge that separates North America and Africa. Other ridges have intiated in oceanic lithosphere such as several in the western Pacific. But the creation of a new plate also requires the formation of a new subduction zone, and we have no evidence of how or where they form.

The variable geometry of plates affects the rate of heat flow of the Earth. Most of the heat flow is near spreading ridges, where hot material is close to the surface. Changes in plate geometry that substantially change the total length of ridges on the Earth will correspondingly change the heat flow. At present we do not know how much the Earth's total heat flow was varied, nor do we know how representative the current value (41 TW) is of the long term average. The history of the plate system needs to be well known in order to know the thermal history, and more importantly, the mechanism of plate initiation must be known in order to understand how the plate system and thermal state of the Earth evolve.

The fluid mechanics of the flow in the mantle is characterized by several dimensionless numbers: the Reynolds number is essentially infinitesimal, which means that inertia is unimportant and the forces driving flow are resisted by viscous stresses; the Prandtl number is essentially infinite, which means that viscous stresses are transmitted essentially instantaneously through the whole fluid, while thermal effects are only felt locally. The rate of convection is characterized by the Rayleigh number, which has been variously estimated from 10^6 to 10^9 depending on the depth of the layer that is convecting. These estimates depend on the surface heat flow, which is reasonably well known, the depth of the convecting region, which is taken to be either the entire mantle (3000 km) or the upper mantle (700 km), and various physical properties of the material, the most uncertain of which is the viscosity.

Estimates of the viscosity of the mantle come primarily from observations of the rebound of the Earth's surface following the melting of the Pleistocene ice sheets; these are primarily uplifted shorelines in North America and Europe, as well as some other regions that reflect motions in response to the increase in sea level. Models of this process have estimated the

radial variations of viscosity, and also indicate that vertical motions of the order of millimeters per year may still be occuring. There are still considerable uncertainties about the models, however. Most of the data comes from near the glaciated regions; since these happen to be continental shields (of great geologic age) the mantle beneath may not be representative of the entire mantle. In particular, the mantle beneath oceanic ridges where upwelling occurs should be hotter and perhaps considerably less viscous. Observations of secular changes in the Earth's rotation rate and changes in the shape of the Earth (expressed in the long wavelength gravity field) have also allowed estimates of the average viscosity. These are grossly consistent with the others, but the the absence of any spatial resolution makes comparisons relatively uncertain. Measurement of current uplift and determination of its spatial distribution would greatly increase our knowledge of the rheology of the mantle, which is essential for predicting vertical motions of the surface associated with long term loads such as changes in sea level, as well as for understanding convection and deformation in the Earth's interior.

Numerical models can at present treat some aspects of mantle convection, but there are severe limitations. The length scale of temperature variations in the mantle is dictated by the thickness of the thermal boundary layer on the surface. This is, on average, around 30 km, which is then the spatial resolution needed in a numerical model. For uniform coverage of the mantle, this would require a grid of 10^8 points, which is well beyond the capacity of the largest computers. The simulation of processes associated with partial melting and the formation of oceanic crust would require even more resolution. Thus, simulation of convection in the mantle is clearly impossible at present (and even for the forseeable future), and one must identify specific problems that are tractable and will shed light on particular aspects of the convective processes.

Observations of mantle convection, apart from plate motions, must be indirect: the near rigidity of the plates shields the upper mantle from view. Variations in density related to temperature variations (which drive the convective flow) cause variations in the Earth's gravity field; however these are detectable only within distances comparable to a few times the scale of the heterogeneities. Thus only the larger scale components of the density field in the deeper mantle are apparent beyond the surface. These large scale components may be averages over a smaller scale structure, and may represent only a part of the structure associated with convection in the mantle.

The most direct observations of the interior of the mantle have come from seismology: the inversion of travel times of seismic waves has yielded models of three dimensional seismic velocity variations in the mantle. The long wavelength components of this structure can be related to the lower degree components of the gravity field. Assuming that the seismic anomalies represent density anomalies as well, one can calculate the resulting effect on the gravity field. This yields a good comparison only if the mantle is assumed to be fluid (rather than strictly elastic), and in addition constrains the radial variations of viscosity. A further constraint comes from assuming that the seismic anomalies represent temperature variations. The resulting density variations drive flow in a viscous medium, thereby advecting heat. For this heat flux to be less than that at the Earth's surface places an lower limit on the ratio of the viscosity and the temperature variations [Hager and Clayton,1989].

More detailed tomographic studies hve been conducted for regions near subduction zones, and in the western U.S. These have revealed smaller scale features associated with the sinking of parts of the cold lithospere into the mantle. The detail achieved is only possible at present in regions with a dense array of seismometers, such as Japan and the western U.S. The development of portable seismic arrays will allow the extension of such studies to other areas of interest, such as regions of continental convergence or extension.

MANTLE RHEOLOGY

Background

In order to understand and model the exact manner in which the "solid" Earth, i.e., the mantle and crust, convect, it is essential that we know the consitutive or rheological laws which relate strain rate to stress. Regional geophysical and geological studies in conjunction with laboratory experiments have yielded rough estimates of viscosity for limited portions of the crust and upper mantle. Indeed, we know that outermost layer of the solid Earth - the lithosphere - is highly resistant to flow. Geological studies in conjunction with laboratory experiments have yielded rough estimates of the effective viscosity for limited portions of the crust and upper mantle . However, for the bulk of the mantle, particularly, the deep mantle, we have only a lumped estimate of viscosity (~4 x 10^{21} Pa s). This estimate was derived by detailed modelling of the ongoing viscous rebound of the solid Earth occurring in response to the last global deglaciation (of Wurm-Wisconsin ice) which began 18,000 years ago and largely ceased 6,000 years ago.(see Wu and Peltier, 1983; 1984) This modelling has been primarily constrained by geological observations of relative sea level (i.e., uplifted shorelines). Additional constraints include an apparently associated secular change in the second zonal harmonic of the gravity field (Yoder et al., 1983; Rubincam, 1984) of approximately -3 x 10^{-11} per year; this result is consistent with earlier inferences based on non-tidal secular changes in the length of day.

However, these existing constraints are not, by themselves, sufficient to do that which is needed, namely, a spatial mapping of the rheological structure of the mantle. Hager (1984) has inferred from models of gravity anomalies and subduction dynamics that large radial variations in viscosity may exist within the mantle. Seismic tomography implies that significant lateral variations of viscosity also exist. To begin mapping the rheological structure of the mantle, we need to begin a long-term program of precise, global geodetic observations of this ongoing postglacial rebound and associated processes.

DETECTION OF POST-GLACIAL CHANGES IN GRAVITY FIELD FROM PASSIVE SATELLITES

The zonal harmonics of the gravity field are symmetric about the polar axis and cause long periodic changes in the shape and spatial orientation of the orbit. The even zonal coefficients drive the precession of apse and node of a satellite. If the orbital inclination is high, the odd zonal coefficients induce an additional eccentricity-like orbital displacement.

The secular change in the second harmonic coefficient J_2 was initially observed through its effect on Lageos. This rate was confirmed more recently by analysis of three years of Starlette data. (Schutz et. al., 1989). In addition to a rate for J_2 of -2.5 $\pm$ 0.3x10^{-11} yr, they obtain rates for J_3: (-0.1 $\pm$ 0.3 x 10^{-11} yr) and for J_4: (0.3 $\pm$ 6) x 10^{-11} yr^{-1}. If the signal is due to rebound, then the J_3 rate should be relatively small because of nearly equal contributions to rebound from Northern Canada and Antarctica for this term. However, simple models predict that the J_4 rate should be near -1 x 10^{-11} and it is not yet clear if the observations are in conflict.

Present day melting of glaciers also contribute to secular change in gravity and cloud this simple interpretation. However, this component could conceivably be accounted for if runoff or ice-packs were closely monitored. As the harmonic number or degree is increased, the strains associated with that deformation is concentrated towards the surface. The relaxation of each harmonic order is therefore governed by the vertical distribution of

viscosity. Measurement of a low order suite of zonal harmonic coefficients could be inverted to obtain a radial viscosity profile. The zonal harmonics of degree ≤ 8 should suffice, given that Antarctica is enclosed within a nodal line of this spherical function. The ability to discriminate between various models requires an accuracy of about 10% or 20% or an uncertainty in J_n rate of roughly $\pm 10^{-12}$ /yr for low degree n. The proposed Stella and Lageos II missions should improve the secular gravity field determination. However,the orbital characteristics for these proposed satellites have not been chosen to improve the solution for the low order zonal harmonics . We therefore recommend that orbit design for future missions place high priority on zonal field resolution. This requirement may be satisfied by a combination of both ranging system upgrades and orbit adjustment. This strategy will also improve the solution for both tidal gravity contributions and the seasonal changes related to redistribution of air mass and groundwater.

The detection of tesseral gravity harmonics is much more difficult. Resonant satellite orbits must be chosen in which the orbit period is nearly a multiple of the day, such that longitudinal features on the Earth appear to move slowly with respect to the satellite. The most significant terms to sample correspond to the C_{22} and S_{22} coefficients, which are doubly periodic in longitude, and the singly periodic C_{31} and S_{31} terms. The former is important in that it will complete the second harmonic field (given that C_{21}/S_{21} can be sensed from the secular polar motion) and determine if its orientation is that predicted from ice sheet models. It could happen that lateral viscosity variations shift the pattern. The C_{31}/S_{31} term is especially important in that Antarctica; because of its polar symmetry it contributes very little to tesseral harmonic coefficients. The detection of this particular term could aid in better constraining the viscosity profile.

The maximum along-track acceleration in a nearly synchronous orbit is $\sim 2 \times 10^{-14}$ m/sec^2 if C_{22} is suddenly changed by 0.25×10^{-12}. Thus detection of this small, but secular signal requires accurate modelling of drag forces; drag can be partially inferred from the along track displacement. However a better method would be to launch two satellites in similar orbits with different area to mass ratios.

Suppose a satellite is initially stationed just below synchronous orbit so that it circulates with respect to points on Earth's surface every 600 days. Assume the orbit is circular and coplanar with Earth's equator to minimize perturbations from other effects. The C_{22}/S_{22} coefficiants would drive a 300 day, 2700 km oscillation along track. A C_{22}/S_{22} change of 0.25×10^{-12} would change the amplitude of this oscillation by about 40 cm. Lageos and Starlette orbit models have achieved fits which equal or surpass this value. Thus it appears feasible that the technique could be used to detect the C_{22}/S_{22} rates and the C_{31}/S_{31} rates as well. The detection of secular rates of other tesseral harmonic coefficients requires additional satellites in a variety of resonant orbits and orbit inclinations and eccentricities. The proposed first mission provides an excellent start.

The primary purpose for launching either a drag free, gradiometer instrument in low earth orbit (150 to 200 km. altitude) or a laser tracked, dual satellite system is to obtain a complete map of the Earth's gravity field with a spatial resolution of around 150 km. and sensitivity of a few mgals. The dual satellite system appears to have sufficient sensitivity at longer wavelengths such that it could detect rebound and other time-dependent changes in gravity with higher spatial resolution than could be achieved by tracking passive satellites. However, the proposed mission lifetimes of about 6 months severely limit their usefulness, given that seasonal mass displacements of air and water will dominate the signal over this period. We propose that a future gravity mission include a high altitude phase (600 km.) lasting from 1 to 3 years in order to avoid this limitation.

TERRESTRIAL OBSERVATORIES

In many earth science disciplines related to the Solid Earth Science Program, ground measurements are necessary, in addition to observations from space. It is proposed that modern, modular terrestrial observatories with a two-way satellite communication link would accommodate various needs of earth sciences as well as measurements in other fields, such as meteorology, atmospheric chemistry or soil properties. The concept of a terrestrial observatory should also be extended to permanent installations on the ocean bottom. Programs such as Global Change and International Decade of Hazards Reduction require a world-wide system of data acquisition, transmission, dissemination, and archiving. The following are examples of ground based measurements related to the Geodynamics Program:

1) Permanent GPS-receiver installations consisting of individual sensors or their arrays connected through a local telemetry system.
2) Volcanological observations.
3) Geomagnetic field measurements.
4) Seismic observations.
5) Gravity measurements with a super-conducting gravimeter.

It is expected that a terrestrial observatory would have a modular design allowing for future expansion or modification of measurements and be equipped with a computer system, or a local computer network, capable of a variety of "intelligent" decisions in addition to routine data reduction tasks, merging of different data streams, and scheduling of individual measurements. Local telemetry could be used in cases when arrays of instruments are used or a common site might be inappropriate for certain subsets of measurements. The stations would have a built-in common recording system using mass-storage media such as large capacity cassettes or optical disks, but the primary mode of data transmittal would be satellite telemetry. The capacity of this system would determine whether all the data or their selected subsets would be transmitted in real time or nearly real time.

Because of the two-way communications, the personnel at a terrestrial observatory could also request data from other stations or other information. In this mode, the role of a terrestrial observatory could be expanded from passive gathering of data to a research and training function. This is particularly important in the Third World countries, where there is the greatest shortage of personnel capable of operating and maintaining sophisticated equipment and where the benefits of co-locating different measuring systems would be most substantial. Integration of observations is, of course, also important in uninhabited locations such as ocean islands or interiors of deserts.

A global observing system requires international cooperation. The International Commission on the Lithosphere recently created a Coordinating Committee for Terrestrial Observatories whose task is to help to establish standards for data collection and exchange.

It is recommended that two or three prototype systems of multi-disciplinary terrestrial observatories with a different mix of measurements be developed and deployed in the United States and that an existing satellite telemetry system be used in the early stages of the experiment. The development of a long-term data transmission, dissemination and archival system should proceed in parallel. It is expected that some 100 globally distributed terrestrial observatories, each generating about 10 megabytes of data per day, will be needed to meet the program objectives. In addition, there is a need to transmit data from simpler, single-purpose measurement systems.

Real-time data transfer requires either dedicated terrestrial communications channels (telephone lines, point-to-point radio links etc.) or channels on geostationary communications satellites. An attractive alternative for low-rate data is the use of low-earth orbit (LEO) satellite store-and-forward communications.

Remote data collection through satellites has been demonstrated using ARGOS, ATS, MARISAT, and other systems. The 400 BPS one-way ARGOS links are the most commonly used.

It would be desirable to design new data collection systems that would enable those responsible for acquiring data during interesting periods to interrogate "smart" remote instruments to supply concentrated data for specific periods. This requires two-way communications.

Recent developments have made it feasible to launch low-cost (<$1 million, including all launch service costs) two-way store-and-forward satellites which work with small, low-cost (<$3000) ground terminals. With such inexpensive systems, it is feasible to dedicate one or more such satellites to special scientific measurement programs.

An example of these satellites are the small "microsat" satellites developed for radio amateurs by AMSAT (the Radio Amateurs Satellite Corp.); the Microsats are 24 cm cubes with 10 kg mass which cost $3-400,000 each. The satellite group at the University of Surrey (VoS) have developed and demonstrated similar techniques with the Digital Communication Experiments (DCEs) on several UoSats.

To launch such small satellites, Arianespace has made available the new ASAP (Ariane Structure for Auxiliary Payloads) which permits up to eight small satellites to "hitchhike" rides with a primary payload. Arianespace has suggested that the cost of including the ASAP and providing "piggyback" launches will be $1 million total -- i.e. < $125,000 per satellite. Four Microsats plus two UoSATS will fly from the ASAP that will be launched with SPOT 2 in November 1989. Other interesting launch opportunities involve the new private launch vehicles (PEGASUS and AMROC) being developed in the United States.

COMPARATIVE PLANETOLOGY

Earth's structure, long term evolution and biological uniqueness in our solar system cannot be completely understood except through studies of other terrestrial planets and their satellites. Presently our knowledge of these bodies is primarily based on surface imagery. For a few of these objects (Mars and Venus), preliminary maps of surface topography and low order gravity models are available. The just launched Magellan mission to Venus is to obtain a global topography map of 90% of its surface, with spatial resolution of 30 km and vertical resolution of 30 m. In fact, this map will be better than anything available for Earth. The mission objective is to obtain a map with sufficient accuracy to determine types of geologic units and, through comparison with similar features on Earth, to infer processes that operate in the interior which control geologic structure and evolution. Comparison of topography with gravity willbe used to infer crustal thickness, dynamic support mechanisms and, in general, answer the question: why does Venus, so similar in so many ways to Earth, appear to be a planet without plate tectonics like those on Earth?

Certainly one major difference is that Earth has a moon and Venus does not. In fact, our moon is even more remarkable in that its mass is comparable to the largest solid moons of the giant planets, whose masses are 15 to 300 times larger. Its relative size, iron compositional deficiency and anomalous tidal history have posed serious puzzles which influence our understanding of how the moon came to coexist with Earth. Although

several theories of lunar origin have been posed, the presently ascendant idea is that the moon formed from the debris left orbiting Earth after the impact of a Mars-size body, which occurred late in Earth's accretional history.

If lunar formation did strongly affect the Earth's internal state, then useful constraints on what happened probably can be obtained from information on the lunar interior. The offset of the lunar rotation axis with respect to the Cassini state for an elastic body indicates much higher dissipation of mechanical energy than can be explained from lunar seismic attenuation data and plausible Q values at tidal frequencies. The only likely explanation which has been suggested is the existence of a small fluid core, and dissipation by turbulent viscosity in the core.

Unlike Earth's core, the lunar core mantle boundary is more nearly spherical in shape. In any case, its ellipticity would have to be much larger than 0.004 in order to couple, through a Poincare pressure torque, the precession of the lunar core with the 18.6 year, 1.6^o amplitude, precession of the lunar obliquity. The shear at the boundary is almost certainly turbulent, and an estimate of the skin friction has been used to infer a core radius of about 330 km. This couple is probably unsteady and may provide a mechanism for exciting large lunar Chandler-like wobble and periodic length-of-day variations.

This explanation can be tested by looking for fluctuations in the free libration phase and amplitude. If a measurement accuracy of roughly a millisecond can be achieved over a decade period, the presence or absence of changes in the free librations would set fairly tight limits on the rotational torques on the mantle due to core motion. Thus accurate differential range measurements to the different lunar reflectors is recommended.

RECOMMENDATIONS

1.   Monitor the Earth's long wavelength magnetic field to produce models at 6 month intervals (or shorter). This could be done with satellite measurement of the vector field to an accuracy of 1 nT in each component for at least a decade.

2.   Measure secular changes of the Earth's gravity to detect post-glacial rebound and changes in ice volume and sea level. This could be done with STARLETTE/LAGEOS style passive satellites or a long lived (>3 years) SGGM mission. The minimum required spatial resolution in the zonal harmonic cooefficients is degree less than 8 and the required sensitivity is 10^{-12} per year.

3.   Deploy superconducting gravimeters at globally distributed VLBI observatories in order to detect gravity changes caused by the internal dynamics of the core. This will also contribute to determination of vertical motions and polar motion.

4.   Develop the capability to measure secular motion (horizontal and vertical) as small as 1 mm per year in order to detect current post-glacial rebound and motions related to sea level variations.

5.   Measure deformation within tectonic plates, with emphasis on intraplate deformation related to underlying mantle flow, and the ultimate appearance and disappearance of plates or plate boundaries.

6.   Support interdisciplinary studies and analysis of related data sets (seismic, gravity, rotation, etc.); such data should be made accessible to the wider community. This should be done by support of research groups, including post-doctoral researchers.

7.   Support modelling of dynamical processes in conjunction with analysis of relevant data sets through the provision of super-minicomputers (e.g. 10's of Mflops) for research groups, as well as access to supercomputers.

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FIGURE CAPTIONS

Figure 1
(a) Magnitude of the radial component of the Earth's magnetic field at the core-mantle boundary obtained by inversion of terrestrial observatory and Magsat data. Much of the time variability of the field is associated with the growth of a 'core spot' off the southeast tip of Africa.

(b) Horizontal velocity field at the top of the core inferred from variations of the magnetic field. This model assumes that the flow is completely toroidal, with no up- or downwelling.(Bloxham, 1989)

Figure 2
(a) Shear velocities in the mantle at depth 1200 km. (Woodhouse and Dziewonski, 1984), determined by waveform inversion of SH waves.
(b) P-velocity in the lower mantle (Dziewonski, 1984), determined from analysis of P-wave travel times.

Figure 1 (a)

Figure 1 (b)

20km/yr

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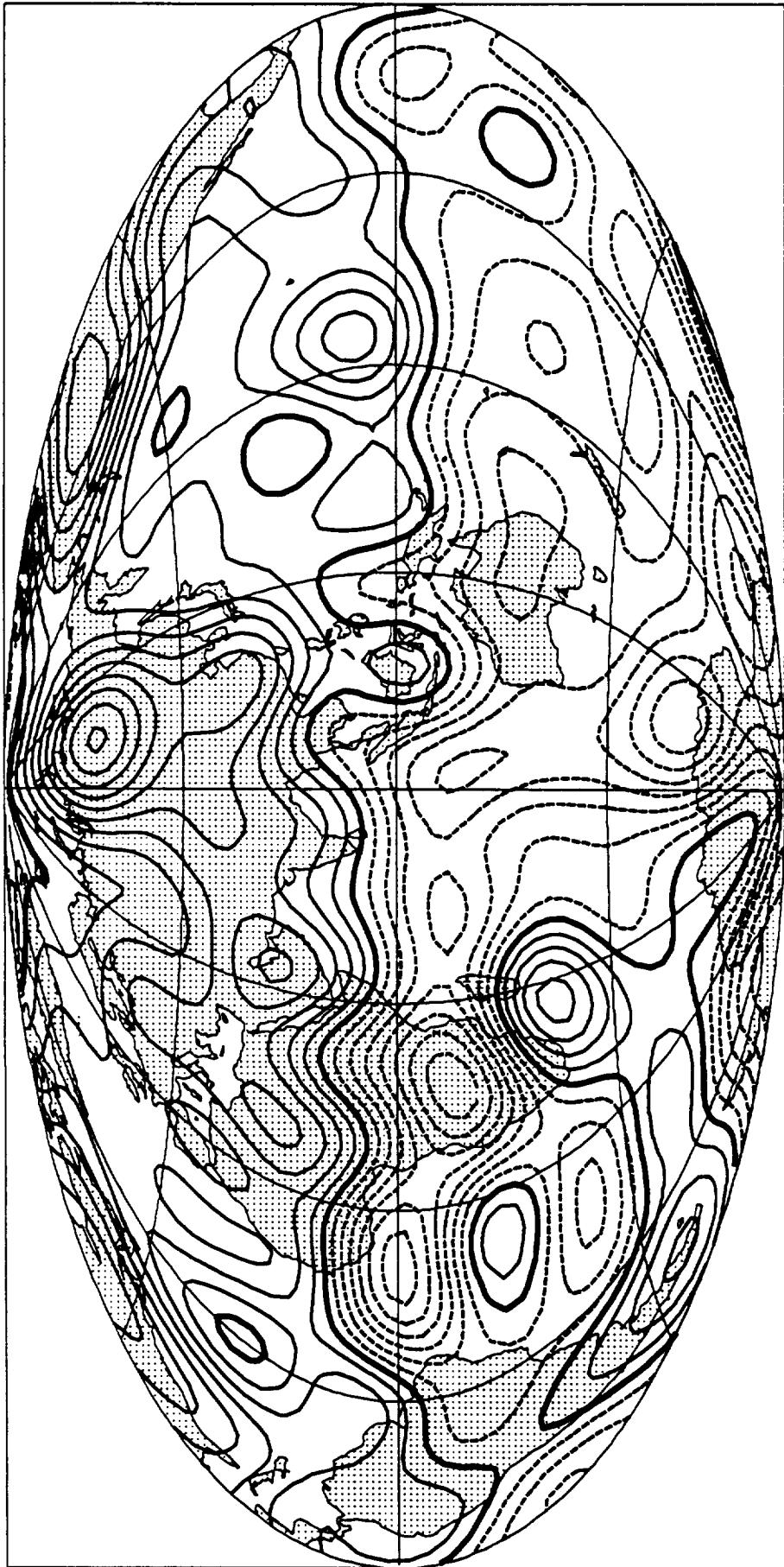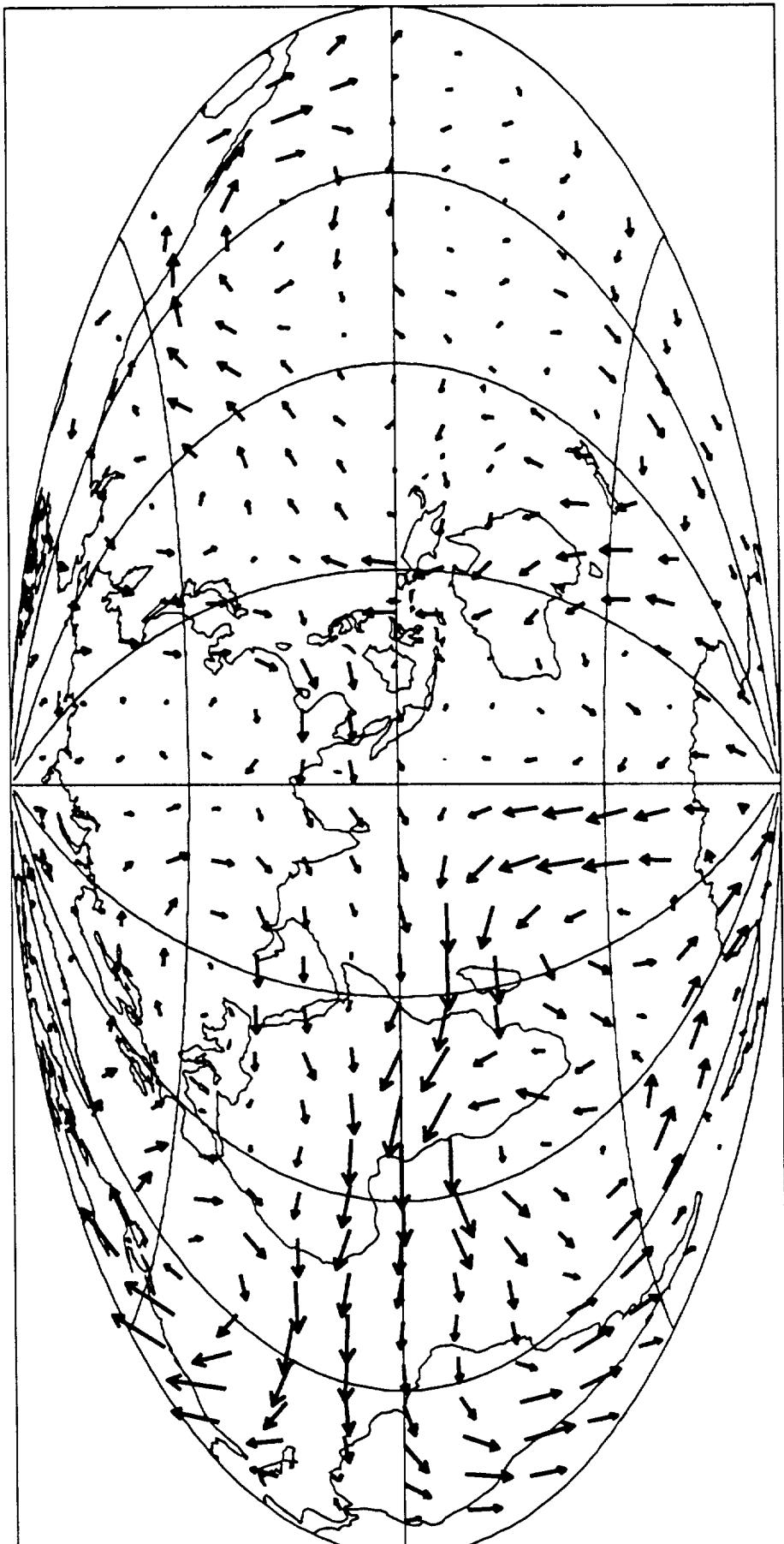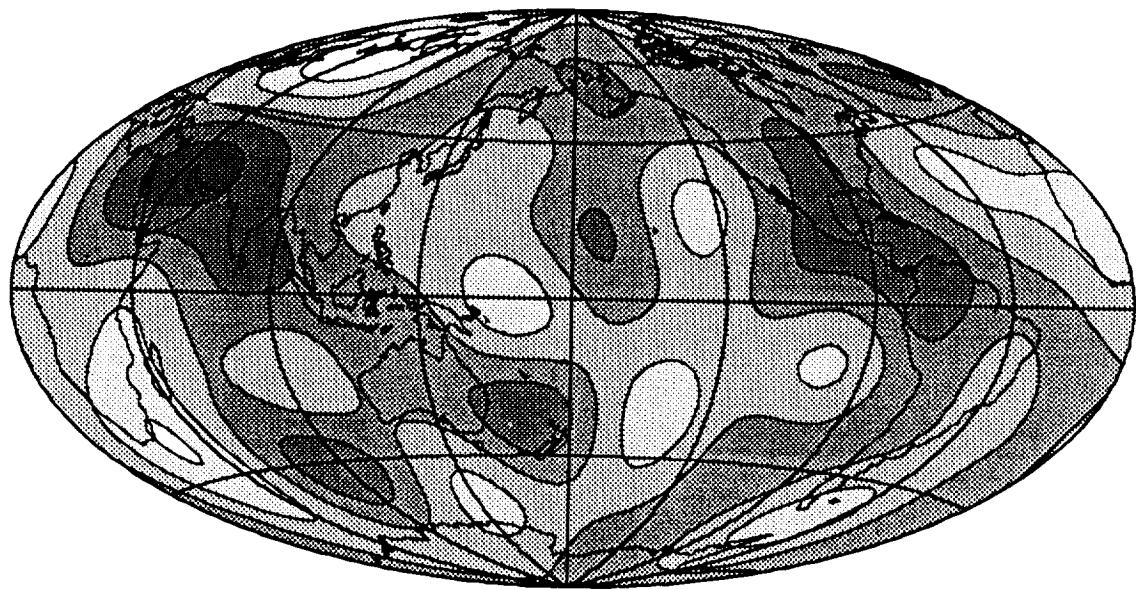
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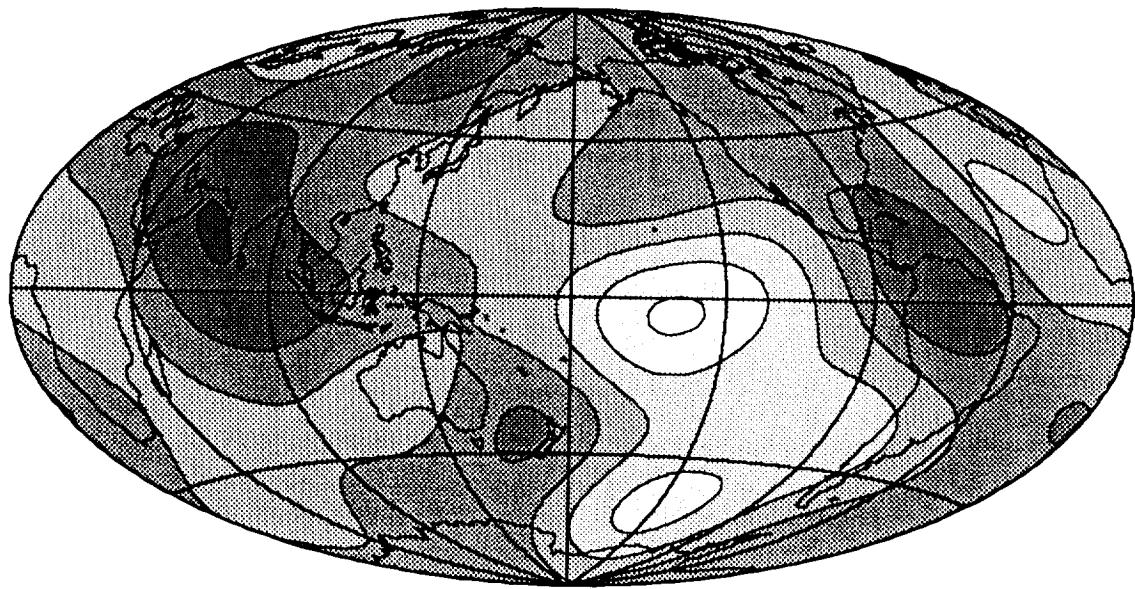
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Figure 2

SECTION VII.

REPORT OF THE PANEL ON

EARTH ROTATION AND REFERENCE FRAMES

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SECTION VII.

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1. SUMMARY

Introduction

Earth rotation studies (encompassing precession, nutation, polar motion, Universal Time, and the length of day) are significant because Earth rotation variations provide a unique and truly global measure of natural and man-made changes in the atmosphere, oceans, and interior of the Earth. These studies require the combined efforts of all the Earth science disciplines, and thus enforce a global perspective upon those disciplines and promote mutual interaction. Earth rotational dynamics depend upon the physical properties, structure, and processes within the Earth and contribute to all the disciplines concerned with these properties and processes. The Earth's rotation varies on time scales from minutes to millions of years, allowing Earth rotation studies to link related processes occurring over vastly different time scales, such as earthquakes with continental drift, weather with long term climate change, and water supply with glacial cycles. Finally, monitoring the rotational variations of the Earth is needed to properly determine the reference frames which are required for all studies concerned with motion of the crust and interior of the Earth. The enhancement and realizations of the reference frames and their connection are of key importance and are required for the proposed FLINN network

Current Status

Space geodetic techniques, including laser ranging to the moon and artificial satellites (LLR and SLR) and very long baseline interferometry (VLBI) using radio telescopes, have brought about a new age in Earth rotation and related studies. The length of day and polar motion are now routinely determined at the one to two milliarcsecond level, representing a ten-fold improvement in accuracy relative to traditional techniques based on optical astrometry. Periodic corrections to the standard nutation model have been determined to 0.1 milliarcsecond for many terms. These unprecedented accuracies, in combination with complementary geophysical observations of the atmosphere, oceans, seismic waves, and the magnetic field, have provided insights into the most fundamental properties of the Earth and their changes in time, such as: the measurement of changes in the Earth's equatorial bulge; bounds on the size of irregularities in the shape of the core-mantle boundary; landmark measurements of the rate at which lunar tides are slowing the Earth's rotation; detection of short-term variations in polar motion associated with atmospheric pressure variations; and understanding of the zonal angular momentum balance of the atmosphere as manifested in length-of-day changes over time scales from days to several years. In addition, the reference frames defined by SLR, LLR, and VLBI now agree to within a few centimeters as a result of common-site occupations by the various space-geodetic techniques.

Objectives for the Next Decade

The scientific objectives of Earth rotation studies for the next decade are as follows:

Observe and understand interactions of air and water (oceans, groundwater, and ice) with the rotational dynamics of the Earth, and their contributions to the excitation of Earth rotation variations, over time scales of hours to centuries;

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;

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;

Establish, refine, and maintain terrestrial and celestial reference frames.

Careful reference frame definition, refinement, and maintenance are of great importance in cartography and space navigation, and are essential to the six scientific objectives of the Solid Earth Sciences Program. For example, the terrestrial reference frame, which is determined in the course of Earth Rotation determinations and is linked to the extragalactic reference frame as well as to the center of the Earth, will be the best candidate to provide the primary reference frame to the FLINN network. In addition, observation and analysis of high precision Earth rotation variations will contribute to each of these six as follows:

Objective 1:

Earth rotation observations provide a unique way to study physical properties of and motions within the inaccessible core and to constrain magnitudes of viscous, magnetic and pressure forces acting at the core-mantle boundary.

Objective 2:

Earth rotation observations provide the basis for an absolute reference frame for the description of plate motion and associated mantle convection.

Objective 3:

Earth rotation variations arising from tectonic activity constrain the rheology of the lithosphere, and secular rotational variations may provide global constraints on other sources of mass redistribution such as sedimentation and erosion.

Objective 4:

High precision Earth rotation observations will provide integral measures of deformation, and its time history, associated with earthquakes and tectonic processes.

Objective 5:

Secular Earth rotation variations constrain the history of the glacial ice masses over the Pleistocene.

Objective 6:

Earth rotation observations provide integral measures of changes over the globe in the distribution and motion of air and water due to both natural and man-made causes. These observations also provide integral measures over the globe of the forces between the earth and its fluid envelope.

Requirements

To accomplish the Scientific Objectives, the following programs are required:

1. Improvements in observations and analysis

    Determine the rotation vector and its variations with the highest possible accuracy (at least 0.1 milliarcsecond) and with a sampling frequency of at least four cycles per day.

Improve analysis and modelling capabilities to a level commensurate with the improved spatial and temporal resolutions.

Collect improved ancillary data from geophysical, oceanographic, and atmospheric sources to enhance the interpretation and understanding of fundamental processes.

Pursue alternative synergistic and innovative approaches for Earth rotation measurements, such as the emerging global network of GPS stations and other new techniques.

2. Improvements in celestial and terrestrial reference frames and reference frame connections.

To monitor and refine the celestial and terrestrial reference frames needed for Earth rotation and crustal motion studies, as well as space exploration, the following actions are required:

Extend the quasar source catalogues to include additional suitable sources primarily in the Southern Hemisphere and along the galactic equator.

Expand the quantity, quality, and global distribution of LLR observations to allow the continuing and accurate determination of the dynamical reference frames, the Lunar/Planetary Ephemerides.

Enhance and monitor the origin, orientation, and scale of the terrestrial reference frames and their ties at the 1 millimeter level, using techniques such as SLR.

Tie the above reference frames together and to those defined by artificial satellites using techniques such as colocation or differential VLBI.

In coordination with other US agencies and other nations, establish a minimum of three space-geodetic observatories per major tectonic plate, at sites distant from the plate boundaries, with regular measurement programs to monitor intraplate stability.

Establish a program of regular auxiliary measurements, such as gravity, at key globally distributed sites.

3. Improved observations of crustal motion and mass redistribution on the Earth

To permit quantitative comparisons between Earth rotation variations and crustal deformation, millimeter-level geodetic positioning is required at selected locations, over distances of 100 km or larger, on time scales of days (for co-seismic deformation) to decades (for post-glacial rebound).

Quantitative comparisons between changes in Earth rotation and oceanic mass will require determinations of global sea level.

Such quantitative studies will also require suitable monitoring of temporal variations in the gravity field.

2. FOREWORD

The Earth is an interacting system with separate parts: the solid Earth, the atmosphere, the oceans, the liquid core and the solid inner core. These systems exchange energy and angular momentum among themselves, through a rich variety of geophysical processes, and studies of the motion of the Earth as a whole, as well as its parts, shed light on these processes, as well as on the properties of the Earth. Earth rotation variations provide a unique and truly global measure of natural and man-made changes in the atmosphere, oceans, crust, and interior of the Earth. Because Earth rotation studies require the combined efforts of all the Earth science disciplines, they enforce a global perspective upon those disciplines and promote mutual interaction. Earth rotational dynamics depend upon the physical properties and structure of the Earth and contribute to all the disciplines concerned with these properties. Because the Earth's rotation varies on time scales from minutes to millions of years, Earth rotation studies link related processes occurring over vastly different time scales, such as earthquakes with continental drift, weather with long-term climate change, and water supply with glacial cycles. Finally, monitoring the rotational variations of the Earth is fundamental to the definition of reference frames which are required for all studies concerned with motion of the crust and interior of the Earth.

The topics considered by the Earth Rotation and Reference Frame Panel fall into several categories: (1) the orientation of the solid Earth about its axis of spin (or its time derivative, the length of day or LOD); (2) polar motion, i.e., the motion of the rotational axis with respect to the solid Earth; (3) nutation and precession, the motion of the rotation axis of the solid Earth with respect to inertial space; (4) terrestrial and celestial reference frames, i.e. the coordinate systems to which the above determinations are referred. Temporal variations in the Earth's mass distribution and its geopotential as well as Earth tides will be addressed, as these phenomena affect the above enumerated topics, but they will not be covered in full depth. It is assumed that a complete treatment will be given by another panel. The topics described here are by their very nature interdisciplinary, drawing from and contributing to the fields of geodynamics, seismology, meteorology, oceanography, hydrology, astronomy and celestial mechanics. As such, we will be interacting with several panels including Earth Structure and Dynamics, Geopotential Fields, and Measurement Techniques. The panel has used the results of the Workshop, "Interdisciplinary Role of Space Geodesy" as a starting point; we refer the reader to Chapters 2 and 7 of the Workshop Proceedings (I.I. Mueller and S. Zerbini, editors; published in Lecture Notes in Earth Sciences Series; Springer-Verlag, New York, 1989) for a complete discussion of these topics and for references.

3. CURRENT STATUS

3.1 Introduction

Earth studies have embarked on a new era with the advent of highly accurate space geodetic techniques and the availability of complementary geophysical and meteorological data sets. Universal time and polar motion are routinely determined at the one to two milliarcsecond level of accuracy (one milliarcsecond corresponds to 3 cm on the surface of the Earth or to 0.07 milliseconds in time), with higher accuracy being achieved in some cases. Periodic corrections to the standard nutation model have been determined to 0.1 milliarcsecond for many terms. These technological advances have led to the detection and analysis of geophysically interesting variations in all areas of Earth dynamics. Several examples include: the detection and measurement of changes in the equatorial bulge (J_2) of the Earth, inferences concerning the core-mantle boundary topography, new landmark estimates of tidal energy dissipation in the Earth-Moon system, detection of short-term variations in polar motion and their association with atmospheric pressure variation, and analysis of intraseasonal oscillations in atmospheric momentum which cause observable changes in LOD.

The high accuracy of the space geodetic techniques and the analysis of the resulting data sets have stimulated new and important theoretical developments which will prove crucial to the interpretation of the data and to the understanding of the phenomena brought to light. Examples of such theoretical progress include the prediction of nutation and wobble based on fairly realistic Earth models, accurate description of global ocean tides (semi-diurnal, diurnal, and long-period), quantification of mantle anelastic effects on rotation, and modelling of the viscoelastic deformation of a stratified Earth.

3.2 Current Observations and Measurements

The modern measurement types include lunar laser ranging (LLR), satellite laser ranging (SLR) and very long baseline radio interferometry (VLBI). In each technique, changes in Earth orientation are monitored by observing extraterrestrial objects from the surface of the Earth. The observed objects are used to approximate a nonrotating reference frame, either directly in the case of slow moving objects, or from dynamical theories of their motion, in the case of planetary and satellite observations. In each case, Earth orientation is estimated from the apparent motion of the Earth with respect to this frame. The measurement types and programs are summarized briefly below.

Lunar Laser Ranging. Lunar laser ranging (LLR) data consist of estimates of the round-trip time of flight of laser pulses from terrestrial observatories to retroreflectors placed on the Moon's surface by the Apollo astronauts and by unmanned probes from the Soviet Union. Lunar laser ranging can provide the monitoring of Universal Time with a temporal resolution shorter than a day. The ability to model accurately the lunar orbit since the first observations in 1969 allows the determination of the Earth's nutations and long-term studies of variations in Universal Time, as well as the determination of many parameters of the Earth-Moon system. One asset of LLR is its ability to provide rapid determinations of the Earth's rotation; literally a determination can be made as the Moon sets. The current network consists of three observatories: McDonald Observatory (Texas), another atop Mt. Haleakala (Maui), and the third in southern France near Grasse.

Satellite Laser Ranging (SLR). In this technique, very short laser-generated pulses of light are transmitted to retroreflectors mounted on the surface of artificial satellites; the round-trip travel times of these pulses (and hence the path lengths) are measured. A series of SLR measurements from a global network of about twenty stations permits the determination of orbital parameters, a

satellite ephemeris and relative station locations. High-quality Earth rotation data, as well as other quantities of geophysical interest (e.g., plate motion and gravity field studies), are generated by SLR. The best geodetic data come from laser ranging to the LAGEOS (Laser Geodynamics Satellite) target, a dense sphere placed in a high (6000 km) orbit. The orbit of this satellite can be used as a nonrotating reference system only for periods short compared to a year. Because polar motion induces a diurnal residual motion of an observatory (as seen from a nearly inertial reference frame), the stability of the LAGEOS orbit is sufficient to provide highly accurate and stable polar motion estimates, while LAGEOS UT1 estimates diverge from the true UT1 after a few months. The LAGEOS data are used, however, in studies of high-frequency changes in the UT1 or LOD. LAGEOS determination of polar motion and Earth rotation rate variations are made every three days.

Very Long Baseline Interferometry (VLBI). Radio interferometry is currently used to make highly accurate measurements of UT1 (the orientation of the Earth's rotation axis in space (nutation and precession), and polar motion with observing times of from a few hours to a day. The VLBI measures the interferometric group delay, the difference in the time of arrival of a radio signal at two or more radio telescopes. The delay rate (the time derivative of the interferometric phase delay) is generally measured as well. The interferometric delay between two telescopes is a direct estimate of the projection of the baseline vector (the vector between the telescopes) in the direction of the radio source. Observations from one baseline are thus not sensitive to rotation about that baseline. For single-baseline results (two stations), two components of Earth orientation are determined: local universal time, UT0 and the variation of latitude. Multibaseline VLBI can measure all three components of the Earth orientation if some of the baselines are nonparallel. Regular independent VLBI estimates of the Earth orientation are now produced routinely every five days with UT0 determined daily

International Cooperation. The above-described programs are coordinated under the auspices of the IAU/IUGG International Earth Rotation Service (IERS), for a unified determination of the Earth's orientation and the maintenance of celestial and terrestrial reference frames. The most recent (1989) realization of the IERS Celestial Reference Frame includes 268 radio sources, which would include only 41 without the NASA contribution. The IERS Terrestrial Reference Frame is based on 20 colocation sites, which would be 13 without the NASA only sites; similarly, the total number of sites in the reference frame would drop by about 25% without NASA.

3.3 Reference Frames

Solid Earth science has become the subject of intensive research during the last decades, involving plate tectonics, on both the intraplate and interplate scale, i.e., the study of crustal movements and of mantle connection, and the study of Earth rotation and of other dynamic phenomena such as the tides. Related efforts are directed towards improving our knowledge of the gravity and magnetic fields of the Earth and of the Earth's internal structure. A common requirement for all these investigations is the necessity of a well-defined coordinate system (or systems) to which all relevant observations can be referred and in which theories or models for the dynamic behavior of the Earth can be formulated. In addition, reference frames are of great importance in navigation and cartography. In view of the unprecedented progress in the ability of geodetic observational systems, as well as in the theory and model development, there is a great need for the definition, practical realization, and international acceptance of suitable coordinate system(s) to facilitate such work. The reference frames of VLBI, LLR and SLR are an inherent part of the above applications. Naturally, the goal is to have the frames themselves determined well above the measurement accuracy in order to optimize and combine the information content from the various complementary techniques. In general, each space geodetic system defines a reference frame based on technique-dependent considerations. Furthermore, each technique makes some unique contribution to reference frame considerations. For example, the VLBI technique

provides a direct link to the already adopted celestial reference frame, but it has no sensitivity to the Earth's center of mass and measures baselines. Conversely, SLR is sensitive to the center of mass but is nearly independent of the adopted celestial reference frame. LLR is sensitive to the center of mass, defines its own celestial reference frame, the lunar ephemeris, which is a component of the planetary ephemerides, is of great importance in space navigation and in the unification of reference systems.

Contemporary geodesy has led to the development of two principal celestial coordinate systems: the planetary/lunar ephemeris frame based on the major celestial bodies of the solar system; and the extragalactic frame constructed from observations of quasars. It should be noted that both the extragalactic and ephemeris frames generate complementary terrestrial frames as well. Other celestial and terrestrial frames are developed through the analysis of the data from Earth-orbiting satellites [e.g. GPS (Global Positioning System), Doppler, laser reflecting satellites such as LAGEOS or ETALON]. The celestial and terrestrial coordinate systems from a single technique and class of target are related through adopted parameters, which are determined and published by the IERS. Each frame is rotated and translated with respect to the others; these offsets may be time variable.

Measurements are inherently more accurate in their "natural" frame and hence should always be reported as such. However, to benefit from the complementarity of the various techniques, knowledge of the frame interconnections (the rotation translation and the time-variable offset) is essential. The lunar/planetary system, integrated in a joint ephemeris, is by its nature unified by the dynamics. The radio frame is tied to the ephemeris frame in several ways; one is via differential VLBI measurements of planet-orbiting spacecraft and angularly nearby quasars. Another is the determination of a pulsar's position in the ephemeris frame (via timing measurements) and the radio frame (via radio interferometry). Very Large Array (VLA) observations of the outer planets (Jupiter, Saturn, Uranus and Neptune) or their satellites provide an additional tie between these two frames. At the present time, the links between VLBI, LLR and SLR have been obtained through the use of colocated systems using both fixed and mobile instruments. Although a few sites exist where more than one space geodetic technique is used in a permanent mode of operation, most ties between systems have been determined with mobile occupations of the same or a nearby geodetic mark. In such applications, the accuracy of local survey ties is of critical importance. In 1989, comparisons between VLBI and SLR using more than ten sites at which the local survey ties were known resulted in RMS differences of 2-3 cm after application of determined translation, rotation and scale parameters. This agreement is near the internal system accuracy of the respective techniques.

3.4 Variations in the Length-of-Day

The exchange of angular momentum between the atmosphere and solid Earth is evident in fluctuations in the length-of-day (LOD) at periods of a year and less. Recent improvements in Earth rotation measurements have been accompanied by improvements in numerical models and measurements of Earth's global atmosphere which can be used to calculate the atmospheric angular momentum (AAM). Both U.S. and foreign meteorological services maintain global atmospheric models for weather forecasting; surface and upper-air wind data and other meteorological measurements are assimilated into these models on a regular basis. Certain atmospheric variables, including pressure and horizontal wind velocity, are estimated at each model grid point at twelve-hour intervals by combining measurements of these variables with their forecasted values in a statistically optimal fashion. Calculation of an effective atmospheric excitation function, c, a three-dimensional pseudo-vector including Love number corrections for rotational and surface loading deformation of the Earth, can be made directly from the meteorological data. From intercomparisons between fluctuations in c_3 (the axial component of c) and in LOD, it has been established that non-tidal rotation rate variations over time scales less than about two years are

largely due to atmospheric effects. There is a dominant seasonal cycle and additional variability on the intraseasonal (30 to 60 day) and interannual time scales. The correlation between LOD and AAM is so well established that numerical forecasts of atmospheric angular momentum are now being considered for the purpose of predicting Earth rotation variations. There are also short-period fluctuations in the LOD due to solid Earth and ocean tides which arise because of tidal perturbations in the Earth's inertia tensor. The largest tidally induced LOD fluctuations occur for the fortnightly, monthly, semi-annual, and annual tides. The amplitudes of these oscillations are sensitive to mantle anelasticity, which is not well constrained in this frequency range.

On interannual time scales, LOD changes appear to be related to atmospheric and climatic phenomena such as the quasi-biennial oscillation and the El Niño / Southern Oscillation. However, at periods of more than several years, the "decade" fluctuations remaining in the LOD series are so large (maximum amplitude ≈ 5 msec) in amplitude that they cannot be atmospheric in origin. Their most likely cause is torques exerted by the core on the overlying mantle. In addition, the effects of long-period variability in the global ice and water budget may affect the rotation rate over several decades.

Because we have no direct access to the core, Earth rotation observations are of prime importance in the study of the structure and dynamics of the Earth's deep interior. In general, torques can be produced at the core-mantle boundary by viscous, electromagnetic, topographic and gravitational coupling. Two candidate mechanisms under investigation for these decade variations are: (1) topographic torques due to dynamic pressure forces associated with core motions acting on undulations of the core-mantle boundary, and (2) torques of electromagnetic origin arising through Lorentz forces in the weakly-conducting lower mantle which could be significant if the unknown electrical conductivity of the lower mantle were sufficiently high. Estimates of topographic torques can be made from core motion deduced from geomagnetic secular variation in combination with core-mantle boundary topography deduced either directly from seismic tomography, or from dynamic models of the lower mantle based on tomographic and long-wavelength gravity anomaly data. Geodetic torque estimates inferred from the LOD provide a means of checking results from seismology and geomagnetism and imposing constraints on the models used.

3.5 Precession and Nutation

The external torques applied to the Earth by other bodies in the solar system (mainly the Sun and the Moon) cause a change in the direction of the Earth's rotation axis, its figure (or "body") axis, and its angular momentum axis. These motions are loosely referred to as precession and nutation, with precession being the secular-like part of the motion (period = 23,500 years) and nutation the more rapidly varying part. The response of the Earth to these externally applied torques is approximately that of a rigid body. However, there are observable effects that arise because the Earth is deformable, with a solid-inner core, fluid-outer core, anelastic mantle, fluid oceans, and an atmosphere. It is these effects of the Earth's deformability that make nutations geophysically interesting.

Currently, nutation series are computed assuming that the individual periodic components of the nutations can be linearly superimposed, and thus that the complete motion of the body axis with respect to inertial space can be obtained from the sum of all of the periodic nutations, precession, and the long-period motions due to polar motion. The sum of individual nutations of different periods form a nutation series. The IAU 1980 nutation series forms the basic series with which observations of the nutations are compared. Modern space geodetic techniques have already disclosed errors in this series which are related to the incompleteness of the geophysical models on which the theories are based. The most notable of these is an error in the retrograde annual nutation of about 2 mas amplitude. This correction has been interpreted as being due to the

flattening of the core-mantle boundary (CMB) deviating from its hydrostatic equilibrium value by about 5%. A similar discrepancy between theory and observations has been recently observed in tidal gravity data, with results which are consistent with this increased flattening of 5%. This flattening result is of similar magnitude with the results inferred from studies of decade fluctuations in the LOD, described above, and is proving to be a valuable constraint on core/mantle boundary maps, based on tomographic and other data.

3.6 Polar Motion

Polar motion consists mainly of nearly circular oscillations at periods of one year (the annual wobble) and about 433 days (the Chandler wobble), with amplitudes of about 100 and 200 milliarcseconds (mas), respectively, together with a long-term drift of a few milliarcseconds per year. In addition, astrometric data sets exhibit decade time-scale polar motion, of amplitude less than 50 mas, while analysis of geodetic data reveals rapid polar motion, with peak-to-peak variations of approximately 2 to 20 mas, fluctuating on times scales between two weeks and several months. Comparisons with meteorological data suggest that these latter motions are at least partially driven by surface air pressure changes, as modified by the response of sea level to atmospheric loading. The annual wobble is due to the integrated effects of seasonal variations in mass distribution and the motion of air and water and thus provides an important global measure of seasonal variability on the Earth. The source of the Chandler wobble is uncertain and is under active research; candidates with various degrees of plausibility are the atmosphere and ocean, movements of ground water, seismic deformation and hypothetical torques from the core. Continual and improved monitoring of polar motion combined with improved models of air pressure and ground water may resolve the degree to which the atmosphere drives polar motion. The changing distribution of water in the ground and oceans and on the surface is likely to be important at periods of a year and longer. On time scales of hundreds to thousands of years, water storage variations in the polar ice caps and the associated loading deformation of the solid Earth is a dominant influence on polar motion. Although one must account for other secular variations in these calculations, much of the observed secular drift of the pole in this century can be explained by redistributions of water and ice together with the post-glacial rebound following the last Pleistocene deglaciation around 20,000 years ago. Contributions from plate motions, seismic deformation and present day melting of glaciers are also present; the study of these long-period polar motions is hampered by systematic errors in the optical astrometric data which must be relied on prior to 1976.

3.7 Tides, Temporal Variations of the Geopotential and Related Problems

Because the degree two spherical harmonics mass redistribution causes Earth rotation variations, it is sensible to examine time variations in other spherical harmonic constituents of the gravity fields in order to understand the physical processes which produce the redistribution. Comparison of LAGEOS-I orbit node residuals with accurate Earth rotation measurements from other techniques can be used to isolate changes in rotation caused by mass redistributions which affect the Earth's oblateness or the J_2 gravitational coefficient. The analysis reveals three significant nodal residual signatures in LAGEOS' orbit: an acceleration, together with annual, and semiannual periods. These signatures reflect temporal variations in the gravitational harmonic J_2 which measures the oblateness of the Earth and, hence, the polar moment of inertia. The seasonal terms are thought to be caused by a combination of ground water and air pressure changes and are equivalent to a 2 ms amplitude Earth rotation rate signature. The secular acceleration of the node

implies a rate of change of J_2 ($\dot{J_2}$) which is consistent with historical observations of the nontidal acceleration of the Earth's rotation and models of the viscous rebound of the solid Earth determined

from the decrease in load due to the last deglaciation. The determination of $\dot{J}_2$ is a significant milestone in that it is the first clear-cut demonstration of a secular change in the Earth's gravitational field. The long-term change is equivalent to a rate of change of J_2 of between -2 and -3 x 10^{-11} per year, and implies that the average mantle viscosity is about 3 x 10^{22} poise.

Perturbations in satellite orbits can also be used to infer tide heights (combined ocean and solid-Earth and Meteorological tides). Such perturbations depend on the tides' world-wide characteristics, and thus provide a global view of tides never before possible. Recently a landmark in tidal studies was achieved by the simultaneous determination (using a number of satellites) of 616 spherical harmonic components of 32 major and minor ocean tides. Finally, the use of satellite altimetry to map ocean tides has already begun, and shows much promise for eventually yielding high-resolution global tide heights, at least for the major tides.

4. OBJECTIVES FOR THE NEXT DECADE

4.1 Introduction

Earth rotation studies encompass precession, nutation, polar motion, Universal Time, and length-of-day. The scientific objectives of these studies are as follows:

Observe and understand interactions of air and water (oceans, groundwater, and ice) with the rotational dynamics of the Earth, and their contributions to the excitation of Earth rotation variations, over time scales of hours to centuries;

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;

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; Establish, refine, and maintain terrestrial and celestial reference frames.

Careful reference frame definition, refinement, and maintenance are of great importance in cartography and space navigation, and are essential to the six scientific objectives of the Solid Earth Sciences Program. For example, the enhancement and realization of reference frame are of key importance in the proposed FLINN Network. In addition, observation and analysis of high-precision Earth rotation variations will contribute to each of these six as follows:

1. Earth rotation observations provide a unique way to study physical properties of and motions within the inaccessible core and to constrain magnitudes of viscous, magnetic and pressure forces acting at the core-mantle boundary.

2. Earth rotation observations provide the basis for an absolute reference frame for the description of plate motion and associated mantle convection.

3. Earth rotation variations arising from tectonic activity constrain the rheology of the lithosphere, and secular rotational variations may provide global constraints on other sources of mass redistribution such as sedimentation and erosion.

4. High-precision Earth rotation observations will provide integral measures of deformation, and its time history, associated with earthquakes and tectonic processes.

5. Secular Earth rotation variations constrain the history of the glacial ice masses over the Pleistocene.

6. Earth rotation observations provide integral measures of changes over the globe in the distribution and motion of air and water due to both natural and man-made causes. These observations also provide integral measures over the globe of the forces between the Earth and its fluid envelope.

4.2 Reference Frames Requirements

Improvements in system performance and the coupled measurements will drive reference frame requirements. The improvements in system performance required to meet our goals must be regularly monitored to avoid systematic errors that could be misinterpreted as Earth rotation signal. Such an assessment should be accomplished by direct comparison and colocation of techniques, which has the additional benefit of contributing to monitoring the reference frame, including the stability of the center of mass. Local ground surveys are needed at colocation sites. Earth rotation results can be directly compared between techniques to determine systematic differences in those systems. It is expected that GPS will have an increasingly important role in the reference frame aspects, especially in determining ties between the systems. As the GPS system matures, it will be necessary for GPS to define its own reference frame, including the determination of the center of mass. The center of mass origin defined by the space geodetic techniques has applications to areas which need an absolute determination of position, such as monitoring global sea level changes with the use of tide gauges.

In addition, improved ephemeris-radio frame ties can be accomplished by VLBI observations of pulsars, additional VLA observations of the outer planets and satellites, future differential VLBI experiments (such as that with orbiting spacecraft around Jupiter and Saturn), or space VLBI. Observations of LAGEOS and LAGEOS type spacecraft, illuminated by radar, would also greatly help to tie the SLR and VLBI reference frame. The millisecond pulsar PSR1937+214, having a period of 1.6 msec, has exceptionally low timing noise. Its position in the ephemeris frame can be measured to ~ 1 mas. This will allow a radio-planetary frame tie limited only by the accuracy of an interferometric position measurement. Roughly, a factor of five improvement (down to the 5-10 mas level) is expected here with the full implementation of VLBI observations.

Transforming between terrestrial and celestial coordinates requires knowledge of precession, nutation, as well as polar motion and UT1. LLR and VLBI detect significant corrections to the precession constant and nutation. The direction of the precession, or equivalently the location of the pole about which the precession takes place, is specified by the obliquity and the dynamical equinox. Both are determined by LLR.

4.3 Variation in Length-of-Day

The NASA EOS concept of an interdisciplinary mission is ideal for the type of investigations discussed here. The resultant data would allow for a better understanding of the total Earth system. The scientific problems highlighted here are not only of intrinsic interest for understanding variations in Earth rotation, but they also address important areas of research in each of the disciplines involved. For example, more extensive atmospheric and oceanic data will lead to a better knowledge of the dynamics and physics of the atmosphere and of the coupled atmosphere-oceanic system. Measurements of interest include improved determination of atmospheric pressure, stratospheric and tropospheric winds and oceanic circulation. Further, these data,

coupled to highly accurate geodetic measurements of the Earth rotation vector, would permit new insights into the coupling mechanisms between the solid Earth, oceans and the atmosphere.

Thus far, most investigations relating LOD variations to changes in AAM have addressed the degree to which a balance is satisfied between these two quantities without regard to the torques responsible (computing torques is a difficult task with the data currently available). Studies aimed at achieving an improved understanding of the coupling mechanisms that link the solid Earth, atmosphere and oceans will be intimately tied to improving climate models. Better rotation data might lead to further identification of features in the atmospheric circulation that are poorly understood. To take full advantage of an improvement in the rotation accuracy, though, the accuracy of the meteorological data needs to be improved independently. The present uncertainties in the meteorological data are probably the same order or larger than the oceanic contributions to subseasonal LOD variations. Better knowledge of the atmospheric contribution would enable the use of rotation results to help assess global oceanographic models and altimeter-derived currents. In addition, improved determinations of the water cycle (that within the atmosphere, ground-water and oceans) are required to assess its effect on Earth rotation rate and polar motion, an area to which EOS and GEWEX (Global Energy and Water Cycle Experiment) can make a useful contribution. Coordinated, intensive, interdisciplinary measurement campaigns involving geodetic, meteorological and oceanographic data should be organized in conjunction with WOCE, TOPEX, and other relevant international programs; the resultant data sets would provide new insights into the coupled solid-Earth /atmosphere /ocean/hydrosphere system. For example, subtraction of atmospheric effects with more accurate data sets may allow oceanic and seismic contributions to be isolated. In addition, the benefits of high-frequency Earth-rotation measurements will extend to seismology (source phenomena and possible earthquake prediction) and studies of mantle anelasticity (by solving for the tidal LOD fluctuations). The largest LOD tidal fluctuations are produced by the fortnightly, monthly, semi-annual, and annual tides. The amplitudes are sensitive to mantle anelasticity, which is not currently well constrained in this frequency range. The fortnightly and monthly terms are potentially the most useful, because the LOD signal from the atmosphere and oceans is much smaller than at the seasonal periods.

On interannual time scales, continued studies of global or regional phenomena and indices, such as the El Niño/Southern Oscillation and the quasi-biennial oscillation, will lead to further advances. Here, the possibility exists that the ocean may contribute significantly to the momentum budget. In some respects, it is remarkable that a discernable role for the oceans in contributing to non-tidal LOD changes on any time scale has yet to be found, given that large amounts of momentum are likely being exchanged through frictional stresses between the atmosphere and ocean. It is conceivable that the ocean is simply transferring momentum between the atmosphere and solid Earth without acquiring any net momentum itself, but present measurements are inadequate to demonstrate the expected connection and elucidate the details. The oceans also affect the tidal response of the Earth through the rich spectrum of oceanic tides. From measurements of tidal changes in LOD we can hope to assess ocean tide models, constrain mantle anelasticity as a function of frequency, and possibly learn about the frequency dependence of core-mantle coupling. Quantifying the sources of energy dissipation due to tidal friction that cause a secular increase in LOD is critical for understanding the anelasticity of the Earth as well as the evolution of the Earth-Moon system. The loading of the solid Earth by the oceanic tides causes displacements that affect all geodetic measurements; their exact nature depends on the heterogeneous elastic properties and structure of the solid Earth over the range of tidal frequencies, as well as on global ocean tide characteristics. All these require better global models of oceanic tides than are presently available.

Secular variations in the rotation rate can be caused by tidal friction, post-glacial rebound, the melting of ice in the polar caps and continental glaciers, other secular changes in the surficial water budget (such as an increase in atmospheric moisture accompanying global warming), tectonic activity, mantle convection and core evolution. The effect of melting ice could conceivably

be as large as 4×10^{-3} msec/year, depending on the rate of melting or accumulation from the different ice sheets. This number assumes that one-half of the observed global rise in sea level comes from the melting ice caps. However, it may be that the polar caps have ice budgets that are close to being in balance and that the observed non-steric sea level rise is due to mountain glaciers. In this case, the effect on the rotation rate would be about an order of magnitude smaller.

How could improved LOD observations help on these longer time scales? The most likely way of discovering what is occurring is to search for time-dependent correlations between the rotation observations and independent data sets such as temporal gravity results, magnetic observations, and meteorological and oceanographic variables. The answer lies in improving both these complementary data sets as well as those for Earth rotation. The goal should be to have decade-scale variability accurate to a few parts in 10^{11} for m_3. One advantage would be that the probability would increase of finding correlations with the important secondary effects, such as with those variables that reflect global warming.

4.4 Precession and Nutations

Since the adoption of the IAU 1980 nutation series, two sets of corrections based on theoretical considerations have been suggested. First, corrections due to the effects of ocean tides that are as large as 1.1 mas for the 18.6 year principal nutation, and 0.6 mas for the semi-annual nutation. Second, corrections for the effects of anelasticity of the mantle have been proposed. In addition, VLBI observations of the nutations have disclosed corrections to the retrograde annual nutation, prograde semi-annual, prograde 13.7 day, and the long-period nutations (the combination of the 18.6 year, 9.3 year, and the precession constant). These latter long period corrections cannot yet be separated accurately because of the short (7.5 year) span of Mark III, dual-frequency band VLBI data. Lunar Laser Ranging data, now spanning a twenty-year period with range accuracies varying from 25-30 cm in the early seventies to 2-3 cm currently, are useful for determining of these long period terms. A combination of LLR and VLBI is beneficial.

Overall, we see that the agreement between the IAU 1980 nutation series and the VLBI results is very good considering that the individual terms of the IAU series are rounded to 0.1 mas. Of the 32 corrections to the IAU series that were estimated, 11 corrections exceed 0.1 mas, and only seven corrections exceed 0.15 mas. For all but one of these seven corrections, corrections to the IAU series expected are based on the extension of the geophysical models used to derive this series. However, those theoretical corrections do not agree with the observed corrections. The one observed correction to the IAU series for which no geophysical model has been proposed that would predict a large correction is the 13.66 day prograde term. For this term the VLBI derived correction is -0.34 mas. Such a correction could arise if the changes in the principal moments of inertia of the mantle due either to tilting the mantle's rotation axis or to an external potential, are not corrected in the current nutation models. However, it is not clear that this relationship could be incorrect given the direct effect of such a parameter on the k_2 Love number. Instead, the effect may enter through an effect of the ocean's response.

One other correction that is anomalous by its absence is the freely excited core nutation. This free mode, which is analogous to the Chandler wobble, has a free period of about one day as seen from an Earth-fixed frame. The current bound of its amplitude placed by VLBI data is <0.4 mas. The question naturally arises as to why this mode is not excited to the expected level. From the solution to the forced nutation problem, estimates of the eigenfrequency of this mode and a lower bound on its damping time have been tightly constrained, and thus we must conclude that either the theory of the excitation of this mode is currently not correct, or that there is little power in the diurnal band which could excite this mode. Observations of the freely excited mode might also give insight regarding the damping and excitation processes. The excitation may be particularly

interesting as it may give us information concerning stochastic processes in the core at diurnal periods.

Even now there are questions about the structure of the Earth which need to be answered to obtain agreement between the observed and theoretical nutations. The constraints which will be placed on the Earth models should become even stronger as more VLBI and LLR data are obtained. In the next decade, accurate estimates of the precession constant, with uncertainties <0.001"/century, about two orders of magnitude smaller than current uncertainties, and the 18.6 year nutations (uncertainty <0.1 mas) should be obtained when there is a sufficient duration of VLBI and LLR data to allow these long-period terms to be estimated separately. Based on observational evidence and the expected effects of changes in the flattening of the core-mantle boundary, ocean tides, and the anelasticity of the mantle, we know that corrections of the order of 1-2 mas for the 18.6 year nutation and 0.1-0.3"/century for the precession constant are needed for these terms.

In addition to space geodetic data, other ancillary data will be needed in the future to fully exploit the advantages of using nutation to study the dynamic response of the Earth to externally applied torques. Already it is clear that the effects of ocean tides are not negligible, and in the future we will need to know their contribution to better than 0.01 mas (about 2% of the effect on the semiannual nutation). Also, models for the dynamic effects of currents in the ocean will be needed. The long-term stability of the VLBI and LLR reference frames also needs to be established.

The analysis of nutation will yield information about the anelasticity of the mantle, dissipative coupling of the fluid core to the mantle, coupling of the solid-inner core to the fluid-outer core and the mantle, the principal moments of inertia of the Earth, and the excitation of the Earth with periods near one day (particularly those from the atmospheric and oceanic loading). Improved nutation results could also provide useful constraints on mantle anelasticity at diurnal periods (where information is sorely lacking). A factor of 5 or so improvement in the nutation results would yield accuracies that are better than the differences between anelastic models. The major limitation, even now, however, is probably due to uncertainties from other effects -- principally from the ocean corrections. Hence coupled improvements as discussed above are required. In general, the presence of the fluid-outer core, and possibly the solid-inner core, have major effects on the nutation, and thus nutation studies, may provide sensitive probes of the internal dynamics and structure of these parts of the Earth. Improvement in the nutation theory could yield some valuable information about the shape of the inner core/outer core boundary for the seismic evidence is currently meager. Although researchers have investigated individual spherical harmonics, no attempt has been made to map the boundary, and it is very difficult to separate undulations of the boundary from horizontal variations in composition in the seismic inversion models. An order of magnitude improvement in the nutations could give some interesting results through observations of either the forced nutations or, less likely, of the freely-excited inner core nutation. It does seem reasonable at this time to expect that nutation series coefficients with uncertainties of about 10 marcsec will be determined within the next decade by VLBI. The complexity of the Earth models that will result will increase our knowledge of the Earth's interior and its dynamics.

4.5 Polar Motion and Temporal Variations of the Geopotential

Polar motion studies suggest a number of unsolved problems that will require new measurements and study in the next decade. These problems include:

Contribution of air and water to polar motion excitation

Advances in geodetic measurement techniques during the past decade have led to the first unambiguous detection of polar motions on time scales between about two weeks and several months, which are driven at least partially by surface air pressure changes. A considerable fraction of intraseasonal atmospheric changes, however, reside at periods shorter than two weeks, about the current resolution limit of the polar motion excitation as deduced from polar motion data. Hence, it seems likely that very rapid polar motions on time scales of less than two weeks exist, so that high-accuracy and high-frequency measurements need to be obtained to detect them and to identify their excitation sources.

Annual polar motion is due to the integrated effects of seasonal variations in mass distribution and motion of air and water and thus provides a valuable global measure of seasonal variability on the Earth. Although major contributors to annual polar motion have been identified, there remains a significant discrepancy between the observed annual wobble and that which is predicted from meteorological observations. This discrepancy implies a lack of understanding of seasonal variability in the mass distribution on the Earth. Among the interesting problems that need to be addressed in understanding the annual wobble are the dynamic behavior of the oceans in response to surface forcing by barometric pressure and winds at seasonal time scales, and the seasonal variation in water storage on the continents. On time scales longer than a year, polar motion may also provide a uniquely global measure of climate variability as the Earth responds to long-term changes in ice volumes and inland water storage. The role of the atmosphere and oceans in the excitation of the 14-month Chandler wobble, and longer period polar motion needs to be quantitatively assessed so that the residual polar motion can be firmly attributed to non-meteorological/oceanographic sources.

Non-atmospheric sources of polar motion.

Research performed thus far seems to indicate that the atmosphere typically accounts for less than half of the variance in polar motions, whether they be at the Chandler, annual or rapid time scales. Thus there may be a source of excitation besides air and water. Mass displacements associated with earthquakes and slower tectonic events (co-seismic, aseismic, or post-seismic) may directly excite the Chandler wobble at the currently observable level; the current accuracy of measurements of pole position coupled with corrections for atmospheric effects should allow a major earthquake (moment $\sim 10^{29}$ dyne-cm) to be seen. The co-seismic displacements from an extremely large earthquake (such as the 1960 Chilean earthquake) could excite the Chandler wobble to 20 masec. The excitation from a moderately large earthquake is typically orders of magnitude smaller. In addition to the displacement in the pole position, a secular change in the LAGEOS node rate would be seen.

More exciting, perhaps, is the possibility of observing the effects of slower, aseismic displacements; those associated with earthquakes may even be precursors, and, in any event, may produce displacements and strains unpredicted at present. It is unclear what the excitation from an aseismic slip might look like. However, less than millimeter-level accuracy and high temporal resolution are needed to resolve the effects of all but the largest individual events and to see if the observed effect of an earthquake is adequately described by the elastic theory. The problem is that it is difficult to distinguish the solid Earth signal from meteorological effects and to be confident of time-dependent correlations between the polar motion and earthquake in the presence of meteorological effects. A better understanding of the meteorological forces that drive polar motion variations are required to separate the meteorological signal from that of the solid Earth response to earthquakes and other tectonic phenomena. Post-seismic anelastic relaxation would also contribute to polar motion; if observed, this would illuminate crust and lithosphere rheology and the nature of strain propagation following earthquakes.

Longer term mass redistributions due to post-glacial rebound, current ice melting and other phenomena also contribute to present long period secular polar motion and to temporal changes in the components of the gravity field. These are effectively monitored by the analysis of the LAGEOS (and LAGEOS-like satellite) nodal residuals. Mass redistribution might one day be "imaged" by combining SLR and Earth rotation change since each type of measurement is sensitive to different spherical harmonics. Improvements in modeling and measuring post-glacial rebound will lead to a better determination of secular polar motion and to the separation of this effect from current air and water mass redistributions, including melting of ice sheets and glaciers. The effects of melting ice (polar ice caps and continental glaciers) could possibly be as great as 1-2 mas/yr in polar motion, if one-half the observed global rise in sea level comes from the ice caps. As noted earlier, it may be that the polar ice caps have ice budgets that are nearly in balance, and that a large portion of the sea level rise is caused by mountain glaciers. In this case, the effects on the polar motion would be ~0.5 masec/yr. Removal of post-glacial rebound from the secular trend will also allow the cumulative effect of earthquakes and related phenomena on polar motion to be constrained.

The explanation for the decade-scale variability in polar motion requires further study. One major source could be the exchange of angular momentum between the core and mantle; in fact, present data would limit the amount of topographic core-mantle coupling. Mantle deformation caused by core pressure change and the effects of long-period variability of the global ice and water budget, including long-period behavior in the ocean, could be a factor as well. As with decade variations in LOD, we recommend improved polar motion series (accurate to a few tenths of a milliarcsecond) and improved coupled complementary data sets such as gravity, geomagnetic and oceanographic data. Long-term continuation of homogeneous series of polar motion measurements is essential for accurate determination of decade and secular polar motions, given the systematic error in the data available from before 1976.

From known amplitudes of semi-diurnal and diurnal ocean tides, we can expect the short-period tides to perturb polar motion periodically with typical amplitudes of 0.1 mas or larger. Thus, measurements of high-frequency polar motion may allow discrimination between different theoretical tide models, shedding light on ocean dynamics at daily time scales. The tidal signals are dominated by the signals from semi-diurnal and diurnal solid-earth tides; careful analysis of the polar motion data may yield information on high-frequency mantle anelasticity. It should also be possible to pick out the amplifications caused by the fluid core free resonance, which is narrow-band and nearly diurnal; such detection would provide a supplemental view of core properties to that recently obtained from nutation studies.

The "inverted barometer" and role of the oceans.

Complicating the analyses of polar motion excitation are uncertainties about the manner in which the ocean responds to forcing by the atmosphere above it and the degree to which this response is then communicated to the solid Earth. Data are currently inadequate to determine the detailed dependence of the transfer function between sea level, atmospheric pressure, and wind stress forcing. Theoretical delineation of this transfer function, based on realistic ocean modeling, is also required.

4.6 Tides and Tidal Dissipation - An Example of a Multitechnique Approach

Dissipation of rotational kinetic energy in the tides have had the largest single effect on the LOD over the history of the Earth. Thus improved determinations are important and provides an excellent example of the complementarity of various techniques and how different systems and techniques can be used together in attacking a problem. LLR determines the recession of the Moon

which is primarily due to tidal dissipation in shallow seas. The present estimate of the rate of change of lunar mean orbital angular velocity is -24.9 ± 1.0 arcseconds/century^2, equivalent to 3.7 ± 0.2 cm/year in mean distance. The uncertainty of this measurement will be reduced to less than 0.5 arcseconds/century^2 by 1990.

LAGEOS' orbit is also perturbed by the Earth's dynamic tidal gravity field, sensing the amplitudes of individual tidal constituents. Measurements of a variety of tidal components using LAGEOS and other satellite data can be used to predict independently the lunar recession rate. A satellite prediction for lunar acceleration from measured tides is -25.3 ± 0.6 arcseconds/century^2. Comparing the LAGEOS data with the lunar measurement will indicate if there is a significant non-ocean-tide component of lunar acceleration. These data can then be compared with estimates of lunar dissipation caused by solid friction and core-mantle friction, consistent with the observed lunar libration (the Moon's rotation) signature. The solid friction mechanism predicts a small but measurable 0.4 arcsecond/century^2 contribution to lunar acceleration, while that from core friction is several times smaller.

Other combinations of data could reveal the fraction of tidal dissipation due to solid friction in the Earth. The vertical motion represented by the principal tidal constituents can now be estimated with about 1% uncertainty by the IRIS network. A modest improvement in this system together with more data may reveal the phase lag caused by solid friction, if the contribution from ocean tides can be accurately removed using tidal models. The planned TOPEX mission, among other things, will obtain topographic maps of the major tidal constituents. The solid Earth elastic model constructed from seismic data indicates a 1% decrease in mantle rigidity in the 1 to 3000 second period band. This effect is attributed to anelastic dispersion. Some models for this dispersion predict that there may be an additional 1% increase at diurnal frequencies and it could be as large as 10% for the 18.6 year zonal tide. Thus, the complementary tidal data from each of these systems will eventually determine the anelastic dispersion parameters of the solid Earth.

5. REQUIREMENTS

Requirement 1. Determine the rotation vector and its variations with the highest possible accuracy (at least 0.1 milliarcsecond) and with a sampling frequency of at least four cycles per day.

Improve analysis and modelling capabilities to a level commensurate with the improved spatial and temporal resolutions.

Collect improved ancillary data from geophysical, oceanographic, and atmospheric sources to enhance the interpretation and understanding of fundamental processes.

Pursue alternative synergistic and innovative approaches for Earth rotation measurements, such as the emerging global network of GPS stations and other new techniques.

Rationale. Changes in the Earth rotation vector are a consequence of changes of the inertia tensor of the solid Earth and Earth's response to both periodic and irregular applied torques. The recommended measurements will observe the periodic torques applied to the Earth by external planetary bodies, the resonances in Earth rotation due to the fluid-outer and solid-inner cores, and additional aperiodic variations to study the dynamic response of the solid Earth to external forces and forces applied by its fluid parts (atmosphere, oceans, and fluid-outer core). None of the currently available AAM series has the temporal resolution needed to provide the estimates at periods less than diurnal. Recent improvements in global atmosphere modeling suggest that the

global weather forecast models should be able to provide the information in the near future. Efforts should be taken to obtain AAM information with smaller sampling times as it becomes available.

The high-frequency data and complementary analyses can be expected to lead to delineation of short-period tidal, atmosphere, and "coseismic" effects on wobble and LOD. These in turn will improve our understanding of broad-band wobble excitation processes and seismic source behavior, fluid-core resonance characteristics, and mechanisms of ocean/atmosphere coupling to the solid Earth. Both the accuracy and frequency of geodetic measurements of variation and polar motion need to be improved. Discrepancies between LOD variations and AAM at very high frequencies are currently smaller than the errors associated with each of these quantities individually, which are typically somewhat less than 0.1 ms (1.5 mas). From the examination of AAM data (available on a sub-daily basis), we can deduce that the sub-daily variations in LOD could be 0.05 milliseconds (or 0.75 milliarcseconds) in magnitude or less. To study these signals, the measurement needs to have smaller uncertainties; the accuracy should be on the order of 0.007 milliseconds or 0.1 milliarcseconds. Semi-diurnal variations exist; hence a measurement program of several cycles per day (at least four per day) is needed. At this level, the effect of earthquake excitation and water motion could be investigated more fully.

The coupling, transfer, and storage of angular momentum involving the fluid and solid parts of the Earth would be determined with the aid of complementary geophysical, atmospheric and oceanographic data. Also, it is clear that as the accuracy of observations of the rotation of Earth improves, the distinction between nutations and short-period polar motion will become less clear. In the future, we will need to treat Earth rotation as a process having a continuous spectrum with power at all frequencies. Superimposed on this continuous spectrum will be the spectral lines at frequencies near ≈ 1 cpd associated with forced nutation. In particular, the contribution of the continuous spectrum will need to be removed from nutation results before these latter can be fully exploited for studying the response of the Earth.

The high accuracy of the data (boosted even more for the daily to weekly data by averaging over the sub-daily values) will lead to improvements in our understanding of aseismic and other tectonic processes, and oceanic and atmospheric variability -- through their effects on wobble and LOD -- on time scales ranging from sub-daily through interannual to decadal. The roles of ocean dynamics versus mantle anelasticity in modifying the long-period tidal variations in LOD and -- for the first time -- wobble should become clear, while the assumed minor role of the ocean in exciting non-tidal LOD should at last be detectable. Eventually, on even longer time scales, phenomena thought to excite secular polar motion and secular changes in rotational speed, e.g., viscous mantle rebound, redistribution of surficial mass (water, ice, and lithospheric), core couples, and tidal friction, will become better understood as the rotational features are measured with greater detail. The response of the solid Earth depends on its internal rheological properties which are not amenable to direct study. These measurements would also support the maintenance of a terrestrial coordinate system in which millimeter point positions could be expressed.

Requirement 2. To monitor and refine the celestial and terrestrial reference frames needed for Earth rotation and crustal motion studies, as well as space exploration, the following actions are required:

Extend the quasar source catalogues to include additional suitable sources primarily in the Southern Hemisphere and along the galactic equator.

Expand the quantity, quality, and global distribution of LLR observations to allow the continuing and accurate determination of the dynamical reference frames, the Lunar/Planetary Ephemerides.

Enhance and monitor the origin, orientation, and scale of the terrestrial reference frames and their ties at the 1 millimeter level, using techniques such as SLR.

Tie the above reference frames together and to those defined by artificial satellites using techniques such as colocation or differential VLBI.

In coordination with other US agencies and other nations, establish a minimum of three space-geodetic observatories per major tectonic plate, at sites distant from the plate boundaries, with regular measurement programs to monitor intraplate stability.

Establish a program of regular auxiliary measurements, such as gravity, at key globally distributed sites.

Rationale. A common requirement for all geodetic and geodynamic investigations is the necessity of well defined conventional inertial and terrestrial reference frames to which all relevant observations can be referenced and in which theories or models for the dynamic behavior of the Earth can be formulated. This requirement is particularly important to enable separation of station motions caused by global tectonics and local crustal deformations from the rotational characteristics of the Earth. The requirement is vital in the intercomparison and combination of results from the various space techniques.

Requirement 3. Improved observations of crustal motion and mass redistribution on the Earth. To permit quantitative comparisons between Earth rotation variations and crustal deformation, millimeter-level geodetic positioning is required at selected locations, over distances of 100 km or larger, on time scales of days (for co-seismic deformation) to decades (for post-glacial rebound).

Quantitative comparisons between changes in Earth rotation and oceanic mass will require determinations of global sea level.

Such quantitative studies will also require suitable monitoring of temporal variations in the gravity field.

Rationale. Taking measurements at a variety of temporal resolutions allows a number of topics to be addressed:

High-frequency measurements (such as diurnal, semidiurnal) would allow deformation and rotation fields due to the solid Earth, atmosphere and ocean tides to be studied. Nearly step-wise changes caused by crustal displacements associated with major earthquakes would be observed.

Seasonal temporal resolution would permit the mass displacement from the hydrosphere and the atmosphere to be measured and analyzed.

Long-time observations would determine quasi-secular changes driven by post-glacial rebound and present-day glacial melting.

Deformation of the Earth's surface and temporal changes in Earth's gravity field should be simultaneously monitored using space geodetic techniques with very high spatial and moderate time resolution. It is expected that these will elucidate both the radial and lateral elastic as well as anelastic structure of the Earth's interior. To distinguish among the various proposed sources of secular polar motion, thus allowing more reliable determination of mantle viscosity structure and inferences of alternative mantle rheology and facilitating the detection of global warming

indicators, the gravity field and surface deformation should each be determined, at least four times per year. This should be complemented by regional deformation measurements. With this sampling rate, many of the sources of seasonal variation in the hydrosphere and atmosphere can be isolated, helping in the interpretation of semi-annual as well as annual signals in geodetic (satellite, rotational, and tidal) time series; this sampling rate also allows the seasonal periods to be better eliminated in the analysis for secular polar motion and secular changes in rotation rate.

SECTION VIII.

REPORT OF THE PANEL ON

GEOPOTENTIAL   FIELDS:

GRAVITY FIELD

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SECTION VIII.

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1.0 SUMMARY

1.1 Introduction

For nearly three decades models of the Earth's gravity field based on satellite tracking data have been under continual development. These models, of ever increasing size and accuracy, have been used to help understand the structure of the solid Earth and the shape of the ocean surface.

Several geodetic spacecraft have been launched during the last two decades during which most of the progress has been accomplished. The GEOS-1, -2, & -3 spacecraft of the mid-sixties to mid-seventies introduced flashing lights and altimetry, and brought laser ranging methods to the forefront. The Transit series of spacecraft exploited Doppler tracking and the Lageos spacecraft brought definitive recovery to the low degree and order field, including the first measurements of both the secular change and the seasonal variations in the Earth's flattening term, J_2. Secular variations of J_2 and J_3 have been observed using Starlette.

On global scales, present satellite models have accuracies of order +/-7 mGal at their highest resolution of 400 km. Over ocean areas, where altimeter data are available, our knowledge at 100 km is about +/-4 mGal, along-track accuracies can be much better. The fundamental limitation is track spacing. Over the continents surface gravity data are available in a number of areas, particularly North America, Europe and Australia. However, there are many continental areas for which there is very limited good quality data. It is estimated that only 20% of the continental areas are known to +/-5 mGal at a horizontal resolution of 100 km (Mueller and Zerbini, 1989).

1.2 Science Requirements

The requirements for gravity modeling have been described in the reports of several recent workshops. For the purposes of preparing a program plan, we assume that the overall requirements for gravity, taking into account the technology that can be expected to be available during the next decade, stipulate an accuracy of 1 mGal at 100 km resolution on a global scale and 2 mGal at 10 km resolution in local regions.

Specific gravity field requirements for oceanography, the continental lithosphere, the ocean lithosphere, mantle convection, and temporal variations in gravity are discussed in this report.

1.3 Data Acquisition

The only method available for improving the long wavelength gravity field to date has been through the tracking of spacecraft from stations on the Earth's surface and by the tracking of one spacecraft by another. Ground-based tracking of the next decade will include laser ranging, and several microwave techniques, including GPS, the French DORIS system, and the German PRARE. At the present time, these methods represent the most precise techniques for ground-based spacecraft positioning.

For the determination of the short wavelength terms in the gravity field the satellite-to-satellite tracking technique appears to have the potential of providing 100 km scale information. To obtain shorter wavelengths a low altitude spacecraft is necessary but the limited visibility from ground stations fails to produce adequate data to properly resolve the large number of high frequency terms. Two basic methods for satellite-to-satellite tracking exist; the high-low method and the low-low method. The high-low tracking of a satellite with present-day GPS could yield the gravity field down to wavelengths of 250 to 500 km with high precision. Candidates for this type of approach are TOPEX/Poseidon, Gravity Probe-B, and ARISTOTELES.

An important method for obtaining the global short wavelength gravity field is with an orbiting gravity gradiometer. Currently two approaches are being developed: one in Europe and the other at the University of Maryland. The former is aiming at a precision of 10^{-2} EU and is the prime instrument on ARISTOTELES. The latter, a super-conducting gravity gradiometer, is the instrument that is planned to be flown on the SGGM which would have a precision of 10^{-4} EU as it's goal.

An even greater resolution of the gravity field by space methods (1 mGal at 10 km) can be obtained indirectly by satellite altimetry with very close cross track spacing. In addition, airborne gravity or gradiometry combined with GPS tracking can be applied to specific areas of interest.

Absolute gravity measurements are important for determining time varying components of the Earth's gravity field. These measurements are of particular interest at VLBI, SLR and GPS and tide guage sites for relating gravity changes to crustal motion. Surface gravimeter measurements can be acquired in small regions of specific interest to support these efforts.

Higher resolution recovery of periodic and secular changes could be obtained by one of the following concepts: a) a series of separate missions that can solve for the long wavelength field with high precision such as with GP-B and SGGM; b) tracking of geodetic satellites with different inclinations such as Lageos and Etalon; c) using a constellation of low cost satellites with laser, microwave, or GPS tracking by selecting appropriate altitude, eccentricity and inclination; and d) by extending the lifetime of the drag-free GP-B equipped with GPS significantly beyond the nominal lifetime.

1.4 Recommended Program

The program in priority order recommended by the Panel on the Earth's Gravity Field is as follows:

1. *Fundamental, and of high priority, is the funding for the analysis of the proposed missions, of existing data, and the data to be acquired from the missions.*

2. *ARISTOTELES augmented with a GPS receiver (1997).*

3. *Advanced Gravity Field Mission with the technology to be defined (1999).*

4. *GPS guided airborne gravity (or gradiometry) acquisition in selected land areas (1993).*

5. *GP-B with GPS (1996).*

6. *Gravity Field Time Variation Missions (1998).*

7. *Ocean altimeter with a 10 km resolution (1997).*

2.0 INTRODUCTION

For nearly three decades, models of the Earth's gravity field based on satellite tracking data have been under continual development. These models, of ever increasing size and accuracy, have been used to help understand the structure of the solid Earth and the shape of the ocean surface. In the United States, these techniques have been developed at the Smithsonian Astrophysical Observatory, the Goddard Space Flight Center, the Ohio State University, at the University of Texas at Austin, and at the Air Force Geophysics Laboratory. In Europe, where similar research was underway the main centers of activity were at Groupe de Recherche de Geodesie Spatiale (GRGS) in France and Deutsches Geodatisches Forschungsinstitut (DGFI) in Germany.

The method from which the gravity field is derived from spacecraft tracking data is by the standard process of inversion to estimate the mathematical parameters used in describing the gravity field. The tracking data provides information about the motion of a satellite. The deviations of the motion predicted by a prescribed theory using numerical values for the model parameters are used to determine the additional forces, including corrections to the gravity model parameters, that need to be applied to explain the spacecraft motion. The advantage of the space data is that a global representation of the Earth's gravity field can be obtained in this manner. Solutions for the Earth's gravity field derived from a global network of satellite tracking stations provide an almost homogeneous representation of the field that is capable of representing nearly all the longer wavelength features and providing the framework for higher resolution modeling. The addition of surface gravity data and altimeter data into these "satellite solutions" to form "combination solutions" has permitted the resolution to be improved over both continental and oceanic areas.

Several geodetic spacecraft have been launched during the last two decades during which most of the progress has been accomplished. The GEOS-1, -2, & -3 spacecraft of the mid-sixties to mid-seventies introduced flashing lights and altimetry, and brought laser ranging methods to the forefront. The Transit series of spacecraft exploited Doppler tracking and the Lageos spacecraft brought definitive recovery to the low degree and order field, including the first measurements of both the secular change and the seasonal variations in the Earth's flattening term, J_2. Together these spacecraft, and many others of "opportunity", have been used to develop the present models of the Earth's gravity field and components of the ocean tides.

Temporal variations of the gravity field include contributions from the solid Earth and ocean tides caused by the gravitational attraction of the sun and the moon; from tides due to meteorological effects such as atmosphere, ground water and snow; from changes in the Earth's structure due to earthquakes and volcano eruptions; and the post-glacial rebound caused by the Pleistocene deglaciation which began about 18,000 years ago. The state-of-the-art solid Earth Tide model is developed by Wahr [1981]. Ocean tide solution developed using hydrographic techniques include Schwiderski and Parke solutions, etc. A partial list of recent satellite derived tide solutions include the GEM-T1 tide solutions and the TEG-1 tide solutions. Secular variations of J_2 have been observed using Lageos, and secular variations of J_2 and J_3 have been observed using Starlette.

With the availability of new *in-situ* and satellite data and the computational resources to assimilate the observations into numerical models, all fields of oceanography are moving to establish global observing programs. Such measurements will greatly constrain estimates of oceanic transport of heat, salt and other tracers, as well as the exchanges between the oceans and atmosphere. Studies of sea level time series have revealed a variety of oceanic phenomena, including waves, tides, mesoscale eddies, the large scale circulation, the heating and cooling of the oceans, and the El Nino-Southern Oscillation (e.g., Wunsch, 1972; Wyrtki, 1981; Cheney, et al., 1983). Secular trends in sea level (e.g., Barnett, 1983) and some tidal effects can reflect either oceanographic or geophysical phenomena and distinguishing their effects is essential for understanding long term ocean processes.

The objective of the Geopotential Panel is to:

> *Develop a program of data acquisition and model development for the Earth's gravity and magnetic fields that meet the basic science requirements of the solid-Earth and ocean sciences.*

In the following sections, the requirements for gravity information and models through the end of the century is briefly reviewed, the present status of our knowledge and data acquisition techniques is described, and an outline of a program to meet the requirements is presented.

3.0 SCIENCE REQUIREMENTS

The requirements for gravity modeling have been described in the reports of several recent workshops, including the Interdisciplinary Nature of Space Geodesy held in Erice, Sicily, Italy, (Mueller and Zerbini, 1989) and the Gravity Field Workshop held in Colorado Springs, Co, (NASA, 1987). Much of the following summary has been excerpted from the Erice Report. These reports and the more detailed requirements described in the other sections of this document state the scientific problems that can be addressed with better gravity information and it is evident from these reports that the better the data the greater range of scientific problems that can be studied. For the purposes of preparing a program plan, we assume that the requirements for gravity, taking into account the technology that can be expected to be available during the next decade, can be described by the spectrum shown in Figure 1. This states that the smallest resolution required globally is 100 km with local regions represented at scales of 2-20
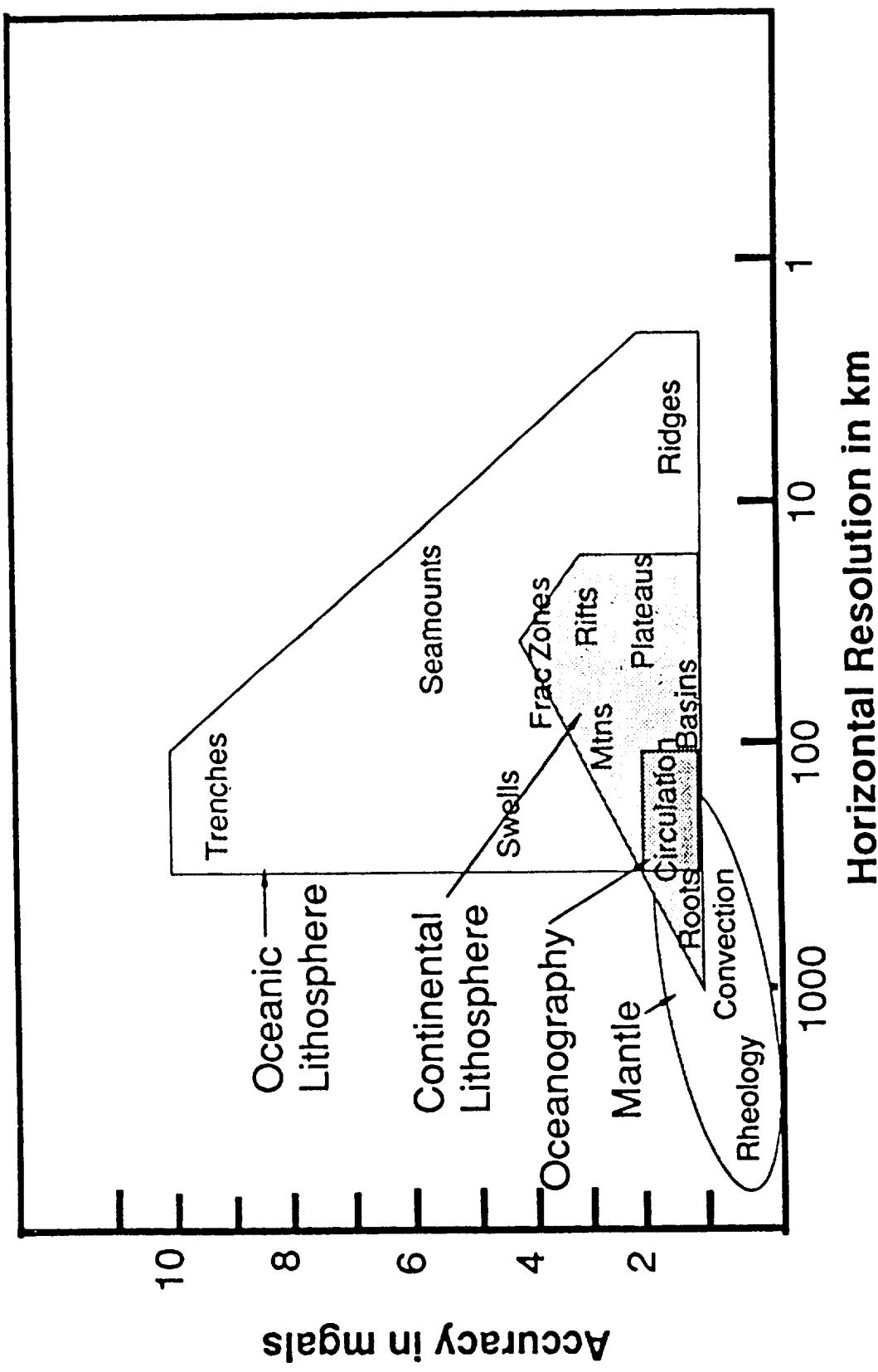
Figure 1   Summary of requirements for gravity measurement accuracy as a function of spatial resolution for the problems discussed in this report.

km. An accuracy of 1 mGal at 100 km resolution is required on a global scale and 2 mGal at 10 km resolution in local regions.

The importance of gravity information to the understanding of processes that affect the Earth on a timescale of decades is predominantly through the oceans and their interaction with the atmosphere. The undisturbed mean ocean surface conforms to the ocean geoid and departures of sea level from this surface imply circulation and the transport of heat and nutrients. Knowledge of the geoid is essential for understanding the input of the circulation to the atmosphere and changes in these quantities have major implications for Earth's climate.

The locations at which gravity is desirable varies appreciably not only with their intrinsic nature, between regions of intense volcanism and tectonism, such as ocean ridges or underthrust belts, but also with the other data available. Since gravitational attraction is indeterminant as to source depth, it must be constrained. The interpretation of gravity also is generally dependent on some model of activity in the region interpreted, such as the direction of motion and thickness of lithosphere involved in an underthrusting. The existence of correlative data and models varies appreciably from place to place. Obviously, those where they already exist, without adequate gravimetry, should have priority. But also it can be said that gravimetry itself will stimulate ideas and generate campaigns to collect the complementary data (e.g., the seamounts turned up by satellite altimetry). Hence the primary guide, if uniform coverage on a continental scale is not affordable, should be the existence of intense activity, as indicated by the topography. Among the land areas not yet surveyed, most obvious are large segments of the Andean and Alpine orogenic belts.

3.1 Oceans

Knowledge of the gravity field is useful in three ways for ocean studies: a) to compute the mean ocean currents (proportional to the gradient of the difference between mean sea level and the geoid) and constrain transports of heat, tracers and nutrients; b) to distinguish time changes in sea level caused by time changes in the geoid from those associated with ice melting or ocean heating; and c) to compute precise orbits for altimetric satellites, which requires an extremely precise estimate of the gravity field at $l, m < 40$.

For oceanographic purposes the accuracy of the geoid in ocean areas is required to be less than 5 cm for half wavelengths greater than 500 km. To achieve their maximum utility, altimetric satellites need to be tracked with the greatest possible accuracy: presently laser ranging and GPS. Geodetic reference systems consistent across satellites and tide gauges need models of the gravity field that both introduce minimum error in the orbit computation for altimetric satellites and that can be subtracted from altimetric sea level to yield the time-averaged dynamic topography of the oceans. Finally, to properly interpret observations of slow apparent changes in sea level tied to "global change", whether observed by satellites or tide gauges, the reference systems must be consistent over time scales where plate motion and crustal deformation affect the positions of satellite tracking and tide gauge sites, and the time changes in the gravity field with equivalent geoid changes must be distinguishable from oceanographic trends in sea level. For the geoid, such changes need to be known to a centimeter over a decade.

Specific gravity field requirements for oceanography are: a) a field of sufficient accuracy and resolution for the *a-posteriori* computation of the TOPEX/Poseidon orbit to 1 cm radially (gravity field error); b) a marine geoid of 25 km resolution and 1 cm accuracy (rss); c) the time history of satellite tracking station positions in a common reference system; and d) changes in the low degree and order gravity field for understanding the changes in mean sea level (geoid accuracy) of 1 cm/decade.

3.2 Continental Lithosphere

Although tremendous advances have been made in understanding the oceanic lithosphere from satellite-derived data, understanding the continental lithosphere has progressed much less. Global geoid models derived from perturbations in satellite orbits (to degree and order 50), and surface measurements have contributed some to our understanding of the continents. Currently, gravity data with a resolution of 4 mGals at 100 km is only available for 22% of the Earth's continental areas. But these areas are more heterogeneous and variable than the oceanic areas.

Continental rifting and extension is directly related to the process of mountain building and earthquake generation, as well as mineral and petroleum distribution. A few rifting areas continue into opening new oceanic areas, most fail. Mapping of continental extensions, both vertically and horizontally, is far from complete, but addressable with gravity data. Gravity is available in detail for North America and study thereof shows large scale structure in North America, with some offsets from the topography, indicating buried loads. Thermal structure of these areas can be addressed with gravity data with a resolution of 1-2 mGals over 100 km. But tectonic structure requires going down to 10 km.

Sedimentary basins and passive continental margins have been a prime focus of exploration geophysics for some time due to the deposits of petroleum reserves. The cause and changes in subsidence rates reflect in the mechanical behavior of the continental lithosphere. Gravity data of 1-2 mGal over 20 km would provide new and invaluable information in this area.

Models of compensation of mountain belts have been completely turned around with proper gravity maps. These belts are not simply isostatically compensated, but are partially supported by lithospheric flexure and entail significant subsurface loads. Continental areas, world-wide, are in a wide variety of relative ages; gravity data of 2-5 mGals over 50-100 km over all continental areas would better quantify the lithospheric structure. The deep structure of the continental lithosphere is often tied to the chemical or thermal boundary of the base of the lithosphere. Mapping this base requires 1-5 mGal data with 100-400 km wavelengths.

3.3 Oceanic Lithosphere

Altimeter data from GEOS, Seasat and Geosat have led to a significant increase in our understanding of the thermal and mechanical structure, and evolution of oceanic lithosphere, an advance not shared by the understanding of the continental lithosphere. Although the sub-satellite tracks have inter-track gaps of up to 150 km, along-track data provides information of mass distribution within about 10 km of the track. Decreasing inter-track spacing to 10 km will lead to resolution of most of the gravity signatures of

the detailed volcanic and tectonic processes generating the lithospheric structure, whose scale is comparable to the thickness of the oceanic crust, 6 km.

Gravity signatures indicate that mid-ocean ridges are largely compensated at shallow depths: i.e. the ups and downs of topography are matched by internal variations of opposite sign. At wavelengths >400 km, the topography seems supported by thermal isostasy and/or dynamic mechanisms in the mantle. However, at shorter wavelengths, other processes (thermal, mechanical, chemical and hydrothermal) are important, and are not well understood. Data relevant to these processes have been measured by spatially limited ship tracks, which have poorer resolution than the satellite-derived oceanic geoid. The morphology of the oceanic lithosphere is strongly dependent on the spreading rate, which in turn affects the levels of isostasy, which in turn affects the gravity signal and topography. Understanding lithospheric structure leads directly to understanding the geophysical processes in spreading zones. Gravity data, especially on a world-wide scale, is very important in these studies.

Fracture zones are not as well understood as are spreading zones. There are significant variations in the correlation of geoid height indicative of differing generation at oceanic rises and differing post-rise volcanic history. Supporting datasets must have a 1 mGal resolution at 50 km wavelength.

Oceanic plateaus extend over 30% of the oceans, lack focused seismicity, and have complex magnetic patterns. Seismic data are ambiguous as to whether these areas are continental or oceanic in character. Gravimetry will help infer the processes and histories of these plateaus.

Mapping the seafloor has been remarkably advanced by satellite-derived geoids. Not only large-scale features, such as subduction zones, are clearly evident, but even small, previously uncharted seamounts are evident. With the oceanic lithosphere covering the majority of the Earth's surface, solid statistical analysis can be had in comparing the geoid and bathymetry. The transfer function relating the two breaks down at wavelengths <200 km, largely due to the inadequacy of the track spacing in existing altimetry data. Seafloor topography, in regions lacking adequate bathymetry, could be determined from a geoid with 20 km resolution of 20 km and 0.3 mm sea-surface height.

Subduction zones have the largest anomalies in the oceanic portion of the Earth. Gravity data for these areas are required at 5-10 mGal at 20 km wavelengths. Much progress has been made in understanding these areas, but dissipating processes, effective rheology, and eventual deposition of oceanic slabs are still poorly known. The key in these studies is a consistent dataset transitioning from the ocean, over the subduction zones and continental margins, well into the continental lithosphere. These data cannot be obtained from satellite altimetry, and hence aircraft must be used.

3.4 Mantle Convection

Mantle convection processes are fundamental to the evolution of the entire Earth. The existence of oceans, atmosphere, volcanism and plate tectonics (hence the existence of life itself) is intricately linked with mantle convection. Continental crust has lifetimes approaching the lifetime of the Earth, while oceanic crust is frequently, on a geologic scale, recycled. Gravity measurements provide some of the few available direct views of

mantle processes, and are particularly sensitive to density irregularities that generate flow.

Seismic tomography has had an outstanding history over the past decade, but cannot unambiguously define the geochemistry of the mantle. However, maps of seismic velocity provide a severe constraint on rock density, which in turn constrains gravity models. This is an important constraint on the degree to which mantle flow is compartmented, both laterally and vertically. The depth of oceanic slab penetration beyond the subduction zones, small-scale convection directly beneath the lithosphere, and even the number of vertical convection cells are not yet known. Proper mapping of the mantle obviously required global datasets. Gravity information with an accuracy from 0.1 mGal at 500 km wavelength is desirable to address these problems.

The age of the lithosphere can often be measured by the age of rocks as the lithosphere passes over hot spots. Hot spots are long-lived thermal anomalies, thought to be tied to the core-mantle boundary, or the boundary between the upper and lower mantle. Thermal expansion over hot spots, thinning of the lithosphere and the structure of plume-lithosphere interaction can be addressed with gravity data of a few mGals over 30-50 km. Identification of plume signatures could lead to the discovery of new or forming hot spots (most obviously as seamounts in areas of poor bathymetry).

3.5 Temporal Variations in Gravity

Temporal changes in gravity that may be measurable arise from post-glacial rebound, ocean and solid Earth tides, large earthquakes, seasonal variations in groundwater and melting of icecaps. Many details are not known and timescales can range from minutes to hundreds of years.

Post-glacial rebound is a current vigorous subject of research, because it is the principal measure of mantle viscosity important to convection. Vertical rebound rates are as high as 1 cm/yr, changing local gravity by 0.001 mGal/yr. Gravity data to this accuracy over 3000 km wavelengths are required. Current glacial melting will raise sea level by 0.05 cm/yr, changing gravity by only 0.00002 mGal.

The driving mechanism for the Chandler Wobble is most likely seasonal weather variations, but seasonal variations of ground water may have some effect. Gravity variations associated with this mass transfer will be about 0.004 mGal/yr.

Volumetric changes due to magma flow in volcanic areas or due to thrust faults result in 0.2-1.0 mGal/m vertical movement, measurable by nearby surface gravimeters, but have too short wavelengths to measure from space. The 1964 Alaskan earthquake should have had a change of 0.1 to 1.0 mGal. Consistent and long-term monitoring of global gravity might lead to remote gravity observations of volcanic and earthquake activity.

4.0 CURRENT STATUS

Since 1985, there has been an intensive effort to re-analyze the existing satellite tracking and altimeter data and to include improved surface gravity data in the gravity model effort. The investigations have been stimulated by requirements for improved gravity models to support the objectives of altimeter satellite missions such as TOPEX and ERS-1 and the positioning and baseline measurement requirements of the Crustal Dynamics Project.

The largest global satellite gravity models are currently of degree and order 50 and have been derived from tracking data on as many as 30 different spacecraft. These models incorporate a variety of data types, some including altimetry. There is a critical need for a gravity mapping mission to extend the results of this current effort. Table 1 lists potential new spacecraft missions that can be expected to contribute to our knowledge of the gravity field during the next decade. All the missions listed in Table I will contribute to improve the gravity field but only the last three missions are dedicated to studying the static, short-wavelength component of the Earth's gravity field. None of these three missions is currently approved. The others all contribute to the low degree and order (only) or through altimetry to the oceanic geoid but none will be able to significantly improve upon our knowledge at the 100 km resolution.

On global scales, present satellite models have accuracies of order +/-7 mGal at their highest resolution of 400 km. Over ocean areas, where altimeter data are available, our knowledge at 100 km is about +/-4 mGal, along-track accuracies can be much better. The fundamental limitation is track spacing. Over the continents surface gravity data are available in a number of areas, particularly North America, Europe and Australia. However, there are many continental areas for which there is very limited good quality data. It is estimated that only 20% of the continental areas are known to +/-5 mGal at a horizontal resolution of 100 km (Mueller and Zerbini, 1989).

Large global gravity models that incorporate virtually all available data, including tracking, altimetry, and surface gravity data, have been developed over a number of years. These models, complete to degree and order 180, and 360, use the satellite models as the basis for the low degree field and subsequently add on the altimetry and surface gravity to provide the higher resolution over the oceans and the continents. These models thus try to retain the long wavelength information best derived from the satellite tracking data while introducing additional data that extends the model into the short wavelength regime.

5.0 MEASUREMENT TECHNIQUES

The only method available for improving the long wavelength gravity field to date has been through the "classical" method of tracking spacecraft from stations on the Earth's surface and by the tracking of one spacecraft by another. Ground-based tracking of the next decade will include laser ranging, and several microwave techniques, including the GPS, the French DORIS system and the German PRARE. At the present time, these methods represent the most precise techniques for ground-based spacecraft positioning.

TABLE 1: POTENTIAL NEW SATELLITE MISSIONS USEFUL FOR GRAVITY MODELING

LAUNCH	MISSION	TRACKING SYSTEM	APPROVED
1989	Etalon-2	laser	yes*
1989	SPOT-2	DORIS	yes*
1992	ERS-1	laser, altimetry, PRARE	yes
1992	Lageos-II	laser	yes
1992	TOPEX	laser, altimetry, DORIS, GPS	yes
1993?	Stella	laser	no
1994 ?	Lageos-III	laser	no
1996 ?	GP-B	laser, GPS	no
1997 ?	ARISTOTELES	gradiometry, GPS	no
1999?	SGGM	superconducting gravity gradiometer	no

* in orbit

So far there has been only a minimal amount of the satellite-to-satellite tracking data type suitable for gravity modeling but its potential through the application of GPS probably makes it the most important method for the next decade. Indeed, continuous tracking of a spacecraft has already been found from the experiments conducted between the ATS spacecraft and GEOS-3, for example, as a powerful data source for gravity modeling.

For the determination of the short wavelength terms in the gravity field the satellite-to-satellite tracking technique appears to be a tracking method that has the potential of providing 100 km scale information. To obtain the shorter wavelengths a low altitude spacecraft is necessary. However, the limited visibility of such a spacecraft from a reasonable number of fixed ground stations fails to produce adequate data to properly resolve the large number of high frequency terms. Two basic methods for satellite-to-satellite tracking exist; the high-low method, such as GPS tracking a lower altitude spacecraft, and the low-low method that was proposed for the Geopotential Research Mission (GRM) in which two spacecrafts in almost identical orbits track each other at a separation of about 100 km. For GRM the tracking was microwave Doppler with a planned capability of around 1 micrometer/second. Recently, a new low-low satellite-to-satellite concept involving laser Doppler has been proposed as an alternative to microwave with the claim that considerable greater accuracy (two orders of magnitude) may be obtainable. However, the high-low tracking of a satellite with present day GPS could yield the gravity field down to wavelengths of 250 to 500 km with high precision. Candidates for this type of approach are TOPEX/Poseidon, Gravity Probe-B, and ARISTOTELES.

An important method for obtaining the global short wavelength gravity field is with an orbiting gravity gradiometer. Several instrumental techniques have been proposed over the last two decades and currently two approaches are being developed, one in Europe and the other at the University of Maryland. The former is aiming at a precision of 10^{-2} EU and is the prime instrument on ARISTOTELES. The latter, a superconducting gravity gradiometer, is the instrument that is planned to be flown on the SGGM which would have a precision of 10^{-4} EU as it's goal.

An even greater resolution of the gravity field by space methods (1 mGal at 10 km) can be obtained indirectly by satellite altimetry with very close cross track spacing. However, this method is limited to ocean areas and contamination due to ocean circulation is unavoidable, reduced only by averaging over repeating ground tracks. In addition, airborne gravity or gradiometry combined with GPS tracking can be applied to specific areas of interest. This method is not yet fully operational, but field tests so far look promising.

Absolute gravity measurements are important for determining time varying components of the Earth's gravity field. These measurements are of particular interest at VLBI, SLR and GPS and tide guage sites for relating gravity changes to crustal motion. Surface gravimeter measurements are the standard "classical" measurement of gravity and can be acquired in small regions of specific interest to support these efforts.

Time variations of the long-wavelength components of the gravity field can be divided into periodic variations, such as tides, and secular variations, such as due to post-glacial rebound. Earth and ocean tides can be recovered by classical satellite tracking methods but with limited resolution. The low degree and order tide solution can be determined

using tracking data collected from geodetic satellites such as Lageos and Starlette. There are good indications that higher degree and order tide solutions can be recovered using ocean altimeter data.

Secular variations of gravity have been recovered in J_2 and J_3. Higher resolution recovery of periodic and secular changes could be obtained by one of the following concepts: a) a series of separate missions that can solve for the long wavelength field with high precision such as with GP-B and SGGM; b) tracking of geodetic satellites with different inclinations such as Lageos and Etalon; c) using a constellation of low cost satellites with laser, microwave, or GPS tracking by selecting appropriate altitude, eccentricity and inclination; and d) by extending the lifetime of GP-B equipped with GPS significantly beyond the nominal lifetime.

6.0 PROGRAM ELEMENTS

In order to define the elements of the gravity program we considered the requirements to be divided into four classes:

o   *Gravity Data Analysis*

An on-going gravity data analysis and technique development program, which will improve the gravity field using data from historical and approved missions. This program will be critical in maintaining the program resource base to support future gravity missions.

o   *High Resolution Gravity Field*

This requirement is for the determination of the gravity field to a resolution of 50 km with an accuracy of 1 mGal and a 2 cm ocean geoid. A complementary need is the determination of the global geoid through degree 40 (450 km resolution) with an accuracy of 5 cm. A determination of the gravity field with a 10 km resolution, 2 mGal accuracy in the oceans, and selected land areas is an additional requirement.

o   *Long Wavelength/Moderate Resolution Gravity Field and Ocean Geoid*

The longer wavelength parts of the Earth's gravitational field are considered here to include gravity models up to degree 50. This is a substantial change from the usual definition which has been up to degree 10. However, we use this distinction to make a substantial contrast with new requirements and possibilities.

o   *Time Variations*

The time variations to be considered are periodic (tidal) and secular in nature. The ocean tide variations are to be determined for a satellite at 1000 km altitude, to degree 15, 60 constituents, to 0.01 cm. At the ocean surface the expansion should be complete to degree 60, 60 tidal constituents, to 1

cm. The secular variations of the geopotential should be determined to degree and order 8 with a geoid change accuracy of 1 cm/decade.

To meet the above requirements we consider the techniques needed in several categories.

6.1 High Resolution Gravity Field Information

The high resolution gravity field is considered (very loosely) to be defined by spherical harmonic expansion greater than degree 100. Several types of missions are feasible and should be supported.

A mission that will satisfy some of the high resolution requirements is the ARISTOTELES mission and the recovered anomaly field will be a significant improvement over existing information. In order to obtain useable long wavelength information a GPS tracker should be added through a NASA/ESA cooperative effort. It is expected that 100 km resolution to an accuracy of 4 mGals, with a substantial improvement in long wavelength information will be obtained. This mission is planned for 1997.

In order to obtain an improved resolution and accuracy it is necessary to have an advanced technology gravity field mission. This advanced mission would achieve a resolution of 50 km with an accuracy of 2 mGal. This mission would be launched by the end of the decade. The prime candidate for this mission is the SGGM. Other alternatives, such as the laser Doppler system, should be studied.

High resolution information in the ocean areas could be derived from a satellite altimeter mission. This mission should have a repeat cycle of 180 days to achieve a 10 km resolution. The length of the mission should be at least two years so that noise-like effects can be averaged out. The ESA ERS-1 mission could come close to meeting these requirements.

The acquisition of gravity data over land, at a resolution of several km is essentially impossible with a space mission. To acquire such data a ground-based mission is required. This is best done by airborne gradiometer with GPS navigation. Such technology now exists and is being developed by the U.S. Navy and the U.S. Air Force (through the Defense Mapping Agency). Interagency agreements could be pursued to obtain this data in areas of high geophysical interest.

6.2 Long Wavelength/Moderate Resolution Gravity Field Determination

The determination of the very long wavelengths can be improved through the analysis of data to be obtained from satellites recently placed in orbit, or being proposed for launch in the near future.

Significant information to degree 50 can be obtained with satellites having a precise GPS tracking instrument. A prime candidate for such a mission is GP-B which is planned for an altitude of 650 km. Error analysis indicates that such a mission could define the potential field to degree 40 (450 km) with an implied cumulative geoid accuracy of 5 cm. This high accuracy geoid determination will be of specific value in ocean circulation studies.

It should also be noted that the ARISTOTELES with GPS mission has the potential for significant gravity field improvement at the longer wave length. Advantages over GP-B would be lower (200 km) altitude. A disadvantage would be the effect of drag at the lower altitude.

6.3 Determination of the Time Variations of the Geopotential and Tidal Phenomena

As noted earlier, the time variations of interest, which may be related to global climate change lie in two areas: periodic (tidal) and secular changes in the geopotential caused by mass displacements in the Earth. The secular changes are related to rheological changes in the Earth's mass distribution associated with post-glacial rebound of continental land mass and with possible melting of polar ice caps. The seasonal changes, which are stochastic in nature, are related to the mass exchange by the solid Earth and atmosphere with weather and/or climatic phenomena.

Tidal phenomena give critical information related to the structure of the Earth as well as providing information needed in orbit determination. There are a number of scenarios to meet the requirements outlined in Section 6.0. These include:

A.   Utilize data from three missions separated in time by several (3-5) years. Candidate missions could be TOPEX/Poseidon (1992), GP-B (1996) and the Advanced Gravity Field Mission (1999). Each of these missions would be equipped with a GPS tracker.

B.   An alternate technique is to launch a specific satellite whose orbit would be optimized to determine time variations.

C.   Another alternative would be to launch several inexpensive satellites to be placed in orbits of different inclinations and eccentricities. Analysis of long time variations from such satellites as Lageos-I, Lageos-II, Ajisai, Etalon, Starlette, Stella, etc., provide estimates of changes in the low-degree and order terms.

6.4 Computational Techniques

The standard approach to the solution of the gravity field is the use of the least squares inversion method. The general solution for a high resolution gravity field involves a comprehensive geophysical inverse problem which places unique requirements on both advanced numerical algorithms, efficient data processing techniques and on improvement in supercomputer technology. Significant efforts will be required for the development of a vectorized, efficient, out-of-memory, numerical algorithm to perform the solution of a linear system on the order of 140,000 parameters, which is beyond the memory capability of current supercomputers. Other computational techniques associated with the numerical property of geopotential field solution include the use of the orthogonal properties of the geopotential and the use of stable algorithms for the evaluation of a large series. These methods place special requirements on the measurement sampling rate and the orbit properties, but, if these requirements are satisfied, they can lead to a substantial reduction in the computational requirements.

7.0 PROGRAM PRIORITIES

The various missions and activities discussed in this report have been examined in terms of the scientific requirements for gravity field data and the availability of funding. In Table 2 these missions and activities are prioritized assuming no increase in funding (0% growth rate), a 10% growth rate, and a 20% growth rate.

The Panel's recommended program assumes a 10% growth rate, and is described below in priority order:

1. *Fundamental, and of high priority, is the funding for the analysis of the proposed missions, of existing data, and the data to be acquired from the missions.*

2. *ARISTOTELES augmented with a GPS receiver (1997).*

   A low cost mission augmenting the ESA mission

3. *Advanced Gravity Field Mission with the technology to be defined (1999).*

   A major mission with much background work completed.

4. *GPS guided airborne gravity (or gradiometry) acquisition in selected land areas (1993).*

   A low cost mission to be based on existing technology.

5. *GP-B with GPS (1996).*

   A low cost augmentation of a planned mission. This priority may be higher depending on aspects of the ARISTOTELES mission. Ideally, both ARISTOTELES and GP-B, both of which are low cost missions to the SES program, should be flown.

6. *Gravity Field Time Variation Missions (1998).*

7. *Ocean altimeter with a 10 km resolution (1997).*

   This mission may be satisfied in a number of ways including new satellite launches, utilization of data from missions at various times, or the extension of the length of one (e.g., GP-B) or more missions.

TABLE 2: PROGRAM PRIORITIES AT DIFFERENT FUNDING GROWTH LEVELS

	Growth Rate		
Priority	0%	10%	20%
1	Data Analysis	Data Analysis	Data Analysis
2	ARISTOTELES	ARISTOTELES	Adv. Gravity Mission
3	GP-B	Adv. Gravity Mission	ARISTOTELES
4	Adv. Gravity	Airborne GPS Mission	Airborne GPS
5	Airborne GPS	GP-B	GP-B
6	(High-res. altimeter)	Time Variations	Time Variations
7		(High-res. altimeter)	High-res. altimeter

Note: Projects in ( ) cannot be accomplished at this growth rate

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SECTION IX.

REPORT OF THE PANEL ON

GEOPOTENTIAL   FIELDS:

MAGNETIC FIELD

CONTRIBUTORS

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SECTION IX.

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SUMMARY

The objective of the NASA Geodynamics program for magnetic field measurements is to study the physical state, processes and evolution of the Earth and its environment via interpretation of measurements of the near Earth magnetic field in conjunction with other geophysical data. The fields measured derive from sources in the core, the lithosphere, the ionosphere and magnetosphere of the Earth.

Density differences in the Earth's outer core drive a motion there which sustains the main geomagnetic field by dynamo action. This dynamo, together with the core-mantle boundary (CMB) and the electrically conducting lower mantle constitute a physical system of great intrinsic interest and considerable utility in monitoring and understanding other Earth subsystems. For example, it has been suggested that the reversal frequency of the main geomagnetic field may vary with and indicate the thickness of the thermal boundary layer at the base of the lower mantle, thus giving a historical record of the convective phenomena in the lower mantle which produce hot spots and are responsible for plate tectonics.

Improving our understanding of how the geodynamo works is a major issue in modern geophysics. This system is clearly non-linear, and its dimensionless parameters cannot yet be reproduced on a laboratory scale. It is accessible only to theory and to measurements made at and above the Earth's surface. These measurements include essentially all geophysical types. For example, seismology and gravity give evidence for undulations in the CMB and for temperature variations in the lower mantle which can affect (or be affected by) core convection and hence the dynamo. Measurements of the magnetic field and its temporal variation give the most direct access to the core dynamo and the electrical conductivity of the lower mantle. Only space measurements can provide the global and quasi-instantaneous description of the Earth's field required to fully describe its time and length scales. These measurements should be supplemented by ground based observatory data as well as analysis of the paleomagnetic record.

Permanent and induced magnetization in the Earth's lithosphere reflect the effects of present and past magnetic fields, and chemical composition as well as the thermal and chemical history of rocks in the crust and upper mantle. These have been influenced by tectonic history and retain part of the record of that history. Data are required from surface, as well as by satellite surveys, but only low altitude satellite surveys can be made in a reasonable time and in a sufficiently self-consistent manner to measure the extremely long wavelength magnetization undulations which apparently originate deep in the crust and, possibly, in the upper mantle. Ambiguities in interpretation require that interpretation include geophysical data of all types, with particular emphasis on seismic, tectonics, gravity and heat flow data.

The ionosphere supports a current system almost steady relative to the sun. This current system includes longitudinal jets at the equator and in the auroral zones and a tidal current with a strong longitudinal variation. The Earth rotates past these quasisteady systems, and sees them as external signals. Satellites are above the ionosphere, so in the gaussian representation of the field they see the ionospheric magnetic

field as internally generated. Observatories see it as externally generated. If both types of data are available, the ionospheric signal can be isolated unambiguously.

Time and Length Scales

Time variations of the Earth's magnetic field on time scales of seconds to decades allow us to determine mantle conductivity from the surface down the the CMB and to study the kinematics and dynamics of the geodynamo. Thus it is essential to have quasi-continuous measurements of the geomagnetic field **over several decades,** and aliasing prevents us from obtaining such data by taking a snapshot of the field with a short satellite mission every ten years or so.

The spatial scales of the internal magnetic field vary from the very long wavelength features caused by electric currents in the core, to wavelengths of only a few m produced by highly magnetized rocks at the surface. In general terms, wavelengths between 40000 km down to 4000 km represent core sources, while signals shorter than 3000 km represent lithospheric sources. The signals in the middle are from both sources, which cannot be untangled in this domain. In addition, external currents can produce signals at all wavelengths. In order to extrapolate these signals down to the CMB, good spatial coverage is essential, and aliasing from the lithospheric signal must be removed. Similarly, in order to study the lithospheric field, global spatial coverage must be obtained. Magnetic observatories provide neither good spatial coverage nor protection from spatial aliasing. Aeromagnetic and shipborne surveys cannot provide sufficient data in a reasonable time frame. It is difficult to obtain both lithospheric and core fields in one satellite mission. **High resolution in the lithospheric field requires a low satellite altitude and hence a short life time, whereas useful measurements of the core field must extend over decades.**

Progress and Requirements

Satellite vector data are a requirement if the present geomagnetic field is to be studied properly. Additional information could be provided at earlier geologic times if a concerted effort is made to collect magnetic direction information recorded in lakes and in archaeological samples such as kilns and baked hearths. But the main thrust is to improve our collection of data in the future by a long term series of observations of the field from satellite. The Earth Observing System (Eos) is due to launch a mission to measure the magnetic field no earlier than 1998. Effort should be made to fill the gap between this and Magsat data (collected in 1979/1980) by collaboration with CNES in the MFE/Magnolia project, which would monitor the field for a minimum of five years, and with ESA in the Aristoteles project, which would measure the field at a considerably shorter wavelength than Magsat, provided that a vector magnetometer is deployed. Limited coverage of some low latitude areas could be obtained from a tether instrument deployed from the Space Shuttle. A magnetic field gradiometer could be developed for future deployment.

In order to make the most effective use of the satellite information, additional magnetic observatories, especially some in ocean basins, are needed. Accompanying this effort there must be more work done on modeling

the external field both to study its sources and to help in isolating lithospheric and core field information. In addition, more rock magnetic measurements need to be done on appropriate samples to help constrain the crustal models produced from the magnetic field and other information.

Panel recommendations

The recommendations of this panel are as follows:

(1) Initiate multi-decade long continuous scalar and vector measurements of the Earth's magnetic field by launching a 5 year satellite mission to measure the field to about 1 nT accuracy. This mission could be MFE/Magnolia.

(2) Improve our resolution of the lithospheric component of the field by developing a low altitude satellite mission. This could be accomplished by including a magnetometer with about 1 nT accuracy on the ESA Aristoteles mission. A vector instrument would give considerably better information than a scalar instrument. If Aristoteles cannot measure the low altitude magnetic field at sufficient accuracy, we recommend that a magnetometer and boom be placed on SGGM to give the lithospheric vector field at about 1 nT accuracy.

(3) If in fact Aristoteles has a 1 nT vector magnetometer and an extended [3 yr] high altitude phase, then it would also contribute to our understanding of the secular changes of the Earth's magnetic field. This is a third priority recommendation, contingent on the above conditions.

(4) Support theoretical studies and continuing analysis of currently available data to better understand the source physics and to improve the modeling capabilities for the different source regions.

(5) Develop a gradiometer device for magnetic field measurements in order to improve the short wavelength information and isolate the fields from in situ currents.

(6) Improve the recording of the time varying field by installing new observatories in critical areas (especially the ocean floor) and by upgrading some observatories.

(7) Continue rock magnetic and electrical conductivity studies of deep crustal rocks and analogs of mantle rocks to help constrain magnetic and electrical models for the lithospheric field.

8) Improve our understanding of the long term variations of the field by continuing paleomagnetic studies of archaeological samples and rapidly deposited sediments from lakes and the ocean floor.

9) Look ahead vigorously with plans for future missions, including the GOS experiment on Eos and subsequent missions timed so as to obtain near continuous coverage for several decades. Such plans should also include a multi-satellite mission configuration for thorough study of the local time morphology of the external fields.

Introduction: The evolution and dynamics of our planet affect all of us. Yet the processes and forces involved are in-the-main hidden from view in the deep interior of the Earth. Few tools are available to probe that interior: seismology, gravity, magnetism, Earth rotation, heat flow and geodesy. Three sources contribute to the magnetic field near the Earth: currents in the core, magnetization in the upper lithosphere, and currents outside the Earth and their induced components inside the Earth. The core, or main, field is by far the largest; because it must travel through the mantle, this field yields information both on the region of its generation and on the electrical conductivity of the mantle. In extracting this information the temporal variation of the field is at least as important as its description at a particular epoch. The time variations of the main field occur over periods from months to decades and beyond and, as a result, require continuous and long-term measurements for an adequate characterization.

Electrical currents outside the Earth form a part of the natural plasma laboratory called the magnetosphere and ionosphere. Of particular interest to solid Earth studies are those currents flowing in the ionosphere and along the magnetic field lines connecting the ionosphere and the magnetosphere. The magnetosphere transfers large amounts of energy to the ionosphere and, via ion-neutral coupling, the upper atmosphere through mega-Ampere field aligned electrical currents at auroral latitudes. Meridional currents within the ionosphere have been discovered and associated with the Equatorial Electrojet. These time-changing external fields cause induced fields in the Earth's crust and mantle the study of which yields information regarding the conductivity of these regions.

Lithospheric magnetic fields are called anomaly fields because in practice what is studied is the residual field when estimates of the core and external fields have been subtracted from the measured field. Maps of anomaly fields have been derived from aeromagnetic and shipborne data for many years and used in the formulation of geological/geophysical models of the crust. Investigations with aeromagnetic and shipborne magnetic data have mainly concentrated on the relatively localized anomalies associated with small scale geologic features and localized mineralization. However, in the past few years there has been an increased interest in studies of the broad scale anomalies that appear in regional compilations of aeromagnetic and shipborne data. Satellite anomaly maps are of recent origin and describe only the very broadest scale anomalies. Originally it was thought impossible to detect fields of lithospheric origin in satellite data. However data from the POGO and Magsat satellites showed that low altitude data contain separable fields due to lateral variations of magnetization in the upper lithosphere, thus opening the door to a new class of investigations.

Ground based magnetic field measurements are seriously deficient for main field studies, both in their spatial and temporal distribution. It is fair to say that main field geomagnetism has reached the point where accurate global vector data extending over a significant time span, ideally

decades or more, are required for significant advances. It is evident that such data can only be acquired from space. Previous measurements of the geomagnetic field from space onboard Kosmos-49, the POGO satellites, and Magsat, have made significant contributions. However the Kosmos and POGO measurements were of the field magnitude only and the Kosmos and Magsat lifetimes were very short. Accurate global vector measurements over an extended time span are lacking.

Similar deficiencies plague the study of lithospheric fields. Usually, localized surveys conducted by ship and aircraft cover too limited an area to map anomalies of the tens and hundreds of kilometer size and do not provide the three components of the field. Piecing together smaller surveys results in distortion and aliasing, particularly if the surveys were acquired at different epochs and the main field has changed significantly. Satellite data are global in nature, eliminating problems of political boundaries and logistics. Data from the POGO and Magsat satellites have demonstrated that lithospheric fields can be studied from satellite altitudes. However, these analyses have also shown that lower altitude data are needed to bridge the gap between the shorter wavelength features measured by aircraft and ships and the very long wavelengths measured in currently available satellite data.

Gauss's Representation of the Field: In regions where no current flows the magnetic field, **B**, can be represented as the gradient of a scalar potential, Ψ.

$$B = - \nabla \Psi \tag{1}$$

The usual representation for Ψ is:

$$\Psi = a \sum_{n=1}^{\infty} \sum_{m=-n}^{n} [g_n{}^m(t) \, (a/r)^{n+1} + q_n{}^m(t) \, (r/a)^n] \, Y_n{}^m(\theta,\phi) \tag{2}$$

Here a is the radius of the Earth, r is radial distance from the center of the Earth, θ is colatitude, ϕ is east longitude, $Y_n{}^m(\theta,\phi)$ is the surface spherical harmonic of degree n and longitudinal order m, and $g_n{}^m$ and $q_n{}^m$ are functions of time alone. As far as Maxwell's equations are concerned, $g_n{}^m$ and $q_n{}^m$ can be chosen arbitrarily. They are called the Gauss coefficients of **B** relative to $Y_n{}^m$.

If Ψ_g and Ψ_q are the sums obtained in (2) from the $g_n{}^m$ alone and the $q_n{}^m$ alone, then $-\nabla\Psi_g$ is the magnetic field produced in the atmosphere by sources inside the Earth (r<a), and $-\nabla\Psi_q$ is the magnetic field in the atmosphere produced by sources outside the Earth (r>a). If **B** is known everywhere on the spherical surface r = a at time t, then $g_n{}^m(t)$ and $q_n{}^m(t)$ can be determined exactly. Without magnetic satellites, **B** is measured at about 200 magnetic observatories, giving 600 scalar data at time t. Then the series (2) is fitted to the data by one of three methods. The oldest is to truncate the series at a value of n small enough that considerably fewer than 600 Gauss coefficients must be determined. More recently, the whole series has been retained, and uniqueness of the coefficients assured by seeking that field which fits the data to within its estimated error and is smoothest (in one of several precisely defined senses) at the core-mantle boundary. The third method is like the second except that it imposes on the Gauss coefficients not a smoothness criterion but a Bayesian a priori subjective probability distribution. The first two

methods produce at least one model which fits the data, but do not address the question of how many models will work. This uniqueness problem can be solved by the third method, but the availability of the prior information required for that method is debated. Recently, a fourth method, based on Neyman's confidence sets, has been worked out in principle. It is objective, solves the uniqueness problem, and provides rigorous error bounds for the results of the first two methods. Its software implementation has only just begun. The magnetic observatories are mostly in the northern hemisphere, mainly in Europe, so the advent of satellite data has improved the spatial distribution of the data as well as greatly increasing their number; but satellite coverage in the time domain remains inadequate - Magsat having been launched a full decade ago and POGO data ceasing eight years prior to Magsat.

In the relatively thin spherical shell where near Earth satellite measurements are made, electric currents are not negligible, so use of the Gaussian model (1) and (2) for B is not entirely accurate. To include average effects from these currents, an alternative is to write $B = \nabla \times (rq) + \nabla \times [\nabla \times rp]$, q and p being scalar fields. In the atmosphere, q = 0 and $\nabla^2 p = 0$, and this model reduces to that of Gauss. It can be used to find the Gauss coefficients in the atmosphere by combining satellite and observatory data. This, and more detailed, modeling of field-aligned current systems is still at a relatively early stage. Determinations of local current density have been limited by both the quality and quantity of the available field observations, a situation which can be remedied by additional satellite data. Development, testing, and application of quantitative modeling methods for high latitude current systems will further both space plasma physics investigations and our ability to separate magnetic fields from sources internal and external to the Earth.

Sources of the Field: Except during magnetic storms, more than 99% of the magnetic field B at the Earth's surface is produced by electric currents in the conducting liquid core, driven by a self-sustaining dynamo process: fluid flowing across magnetic lines of force of B generates e.m.f's which drive the electric currents which maintain B. The remainder of B is produced by electric currents induced in the mantle and the oceans by time variations in B; by permanent and induced magnetization in the crust and, possibly, in the upper part of the mantle where the temperature is below the Curie temperature of magnetic minerals; by tidal currents excited in the ionospheric dynamo (driven mostly by the thermal solar tide); and by the effects of the solar wind plasma in distorting the magnetopause and in producing the field-aligned currents in the magnetosphere which generate magnetic storms and aurorae.

Length Scales: At the Earth's surface, all but about 10% of the magnetic field produced by the core is the field of a dipole at the Earth's center inclined at 11 degrees to the axis of the Earth's rotation. The strength of the dipole field is about 60,000 nanoTesla (nT) at the poles and 30,000 nT at the equator. The remainder of the field has a complicated spatial pattern; Figure 1 shows contours of the radial component of B after the dipole field has been subtracted.

A quantitative summary of the importance of the various horizontal wavelengths at the Earth's surface can be obtained by considering
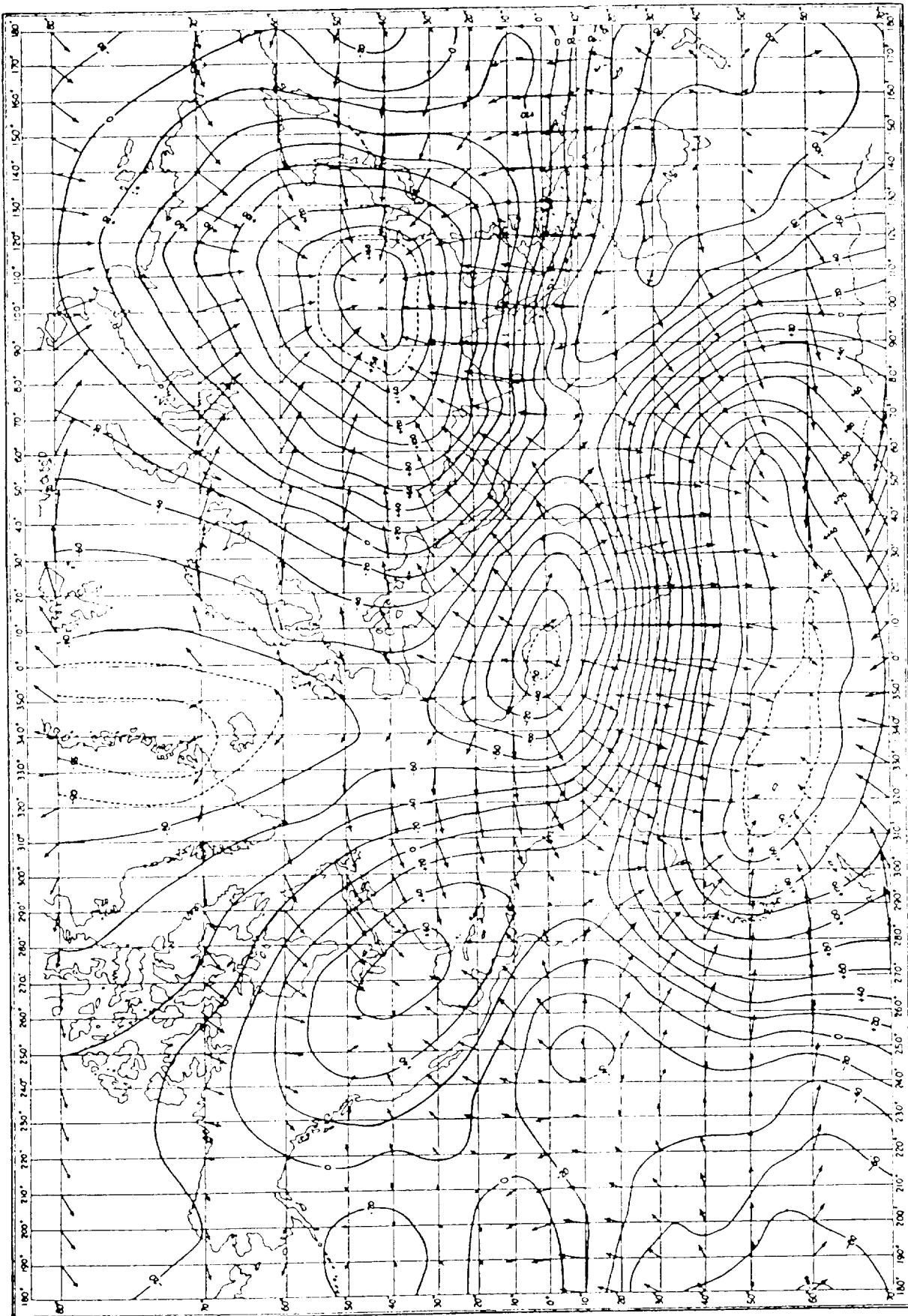
FIGURE 1. Non-dipole field for 1945. The contours give the vertical field at intervals of 0·02 gauss. The arrows give the horizontal component, an arrow 0·3 mm. long represents 0·1 gauss.

separately the fields B_n for various spherical harmonic degrees n. By definition, $B_n = -\nabla\Psi_n$ where:

$$\Psi_n = a \sum_{m=-n}^{n} g_n^m(a/r)^{n+1} Y_n^m(\theta,\phi) \qquad (3)$$

(Fields of external origin are neglected in this treatment). The function Ψ_n has a horizontal wavelength on r=a about equal to $4\pi a/(2n+1)$, so the strength of the "signal" in B at this wavelength can be measured by $<|B_n|^2>$, the average over the Earth's surface of $|B_n|^2$. Figure 2 gives a graph of the observed $<|B_n|^2>$ as a function of n for low n. For a random (spatial white noise) source in the core, $\ln<|B_n|^2>$ would be expected to decline nearly linearly and at least as rapidly as it does from n = 1 to n = 12 in Figure 2; for a random source in the crust $\ln<|B_n|^2>$ would be approximately independent of n (actually $\simeq \ln(2n+1)$) as it is for n>16 in Figure 2. The usual interpretation of Figure 2 is that at the surface of the Earth B_n comes mainly from the core for $1 \leq n \leq 12$, mainly from the crust for 16<n, and that both sources contribute in $13 \leq n \leq 15$.

With existing satellite data, the crustal portion of the spectrum can be extended to an n of about 50 which corresponds to a wavelength of about 800 km. It is more convenient for anomaly fields to talk about characteristic size in km, where by characteristic size we mean the distance between the half-amplitude contours of an anomaly. Aeromagnetic and shipborne surveys map anomalies of characteristic size 10's to 100's of km. The upper limit depends upon the area and spacing of the survey, on the altitude of the survey above the sources and on the relative accuracy to which the spacing between data points is known. In principle, all of the crustal field could be mapped by aircraft; in practice the survey size is limited by political boundaries and by logistic considerations. Satellite data can, in principle, be recovered from altitudes as low as 150 km. Characteristic sizes of 150 km and greater should be recoverable from data at that altitude. Figure 3 shows how the relative amplitude and the resolution of magnetic anomalies vary with altitude.

Spatial variations in the anomaly field reflect variations in the near-surface magnetization. Magnetization variations are not only due to variations in the amount of titanomagnetite and titanomaghemite, and the relative amount of titanium in these minerals. Other contributors are variations in topography and in the depth to the Curie isotherm. Magnetization content variations reflect the past history of the rock: the chemistry of the rock source and the processes by which it was formed, the thermal and mechanical history of the rock formation, and alteration due to diagenesis and metamorphism.

Important spatial variations of the magnetic field are produced by external currents. Among these are the field of order 200 nT near the equator, produced by an equatorial electric current in the ionosphere (the equatorial electrojet), the Sq fields of order 10 - 40 nT from the ionospheric dynamo, and the fields of up to 2000 nT which appear in and poleward of the auroral zones. The magnitudes given are at the surface of the Earth. The equivalent spatial resolution of previous magnetic field investigations has been limited to approximately 0.5 km. These experiments have shown that high local field aligned current densities can occur over spatial scales of 1-10 km. Optical observations of auroral forms have shown that fine structure exists down to length scales as small as tens of meters.

Figure 2. The observed $\langle |B_n|^2 \rangle$ as a function of n for low n

$$R_n = (n + 1) \sum_{m=0}^{n} [(g_n^m)^2 + (h_n^m)^2]$$

SURFACE OF EARTH

CORE-MANTLE BOUNDARY

CORE: $R_n = 1.349 \times 10^9 \, (0.270)^n \, (nT)^2$

SUM

CRUST: $R_n = 37.1 \, (0.974)^n \, (nT)^2$

IX-12
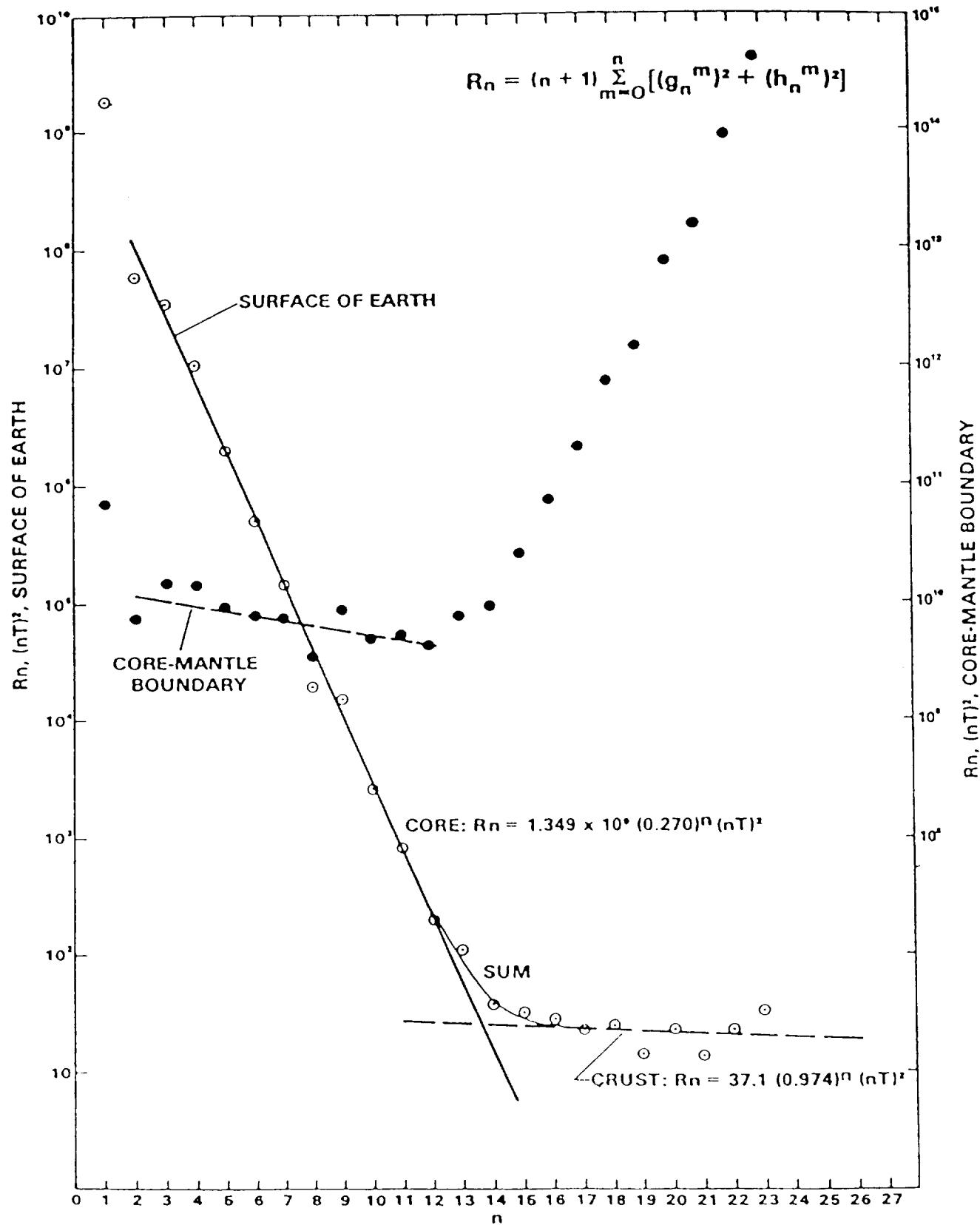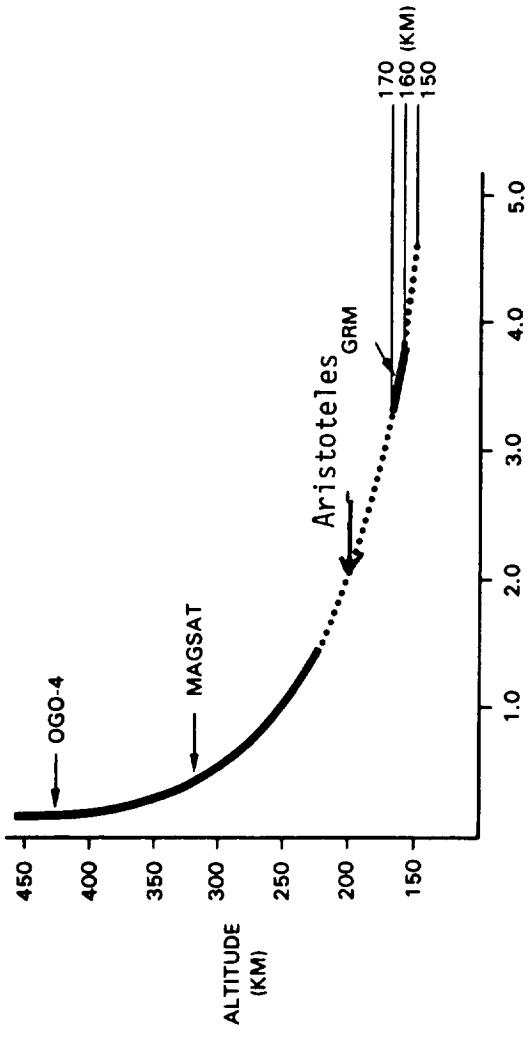
Relative Magnetic Anomaly Amplitude as Observed at Spacecraft

$$\text{RESOLUTION} = \frac{\text{AVG. VALUE OF MAXIMA OVER BODIES}}{\text{VALUE OF SADDLE BETWEEN MAXIMA}}$$
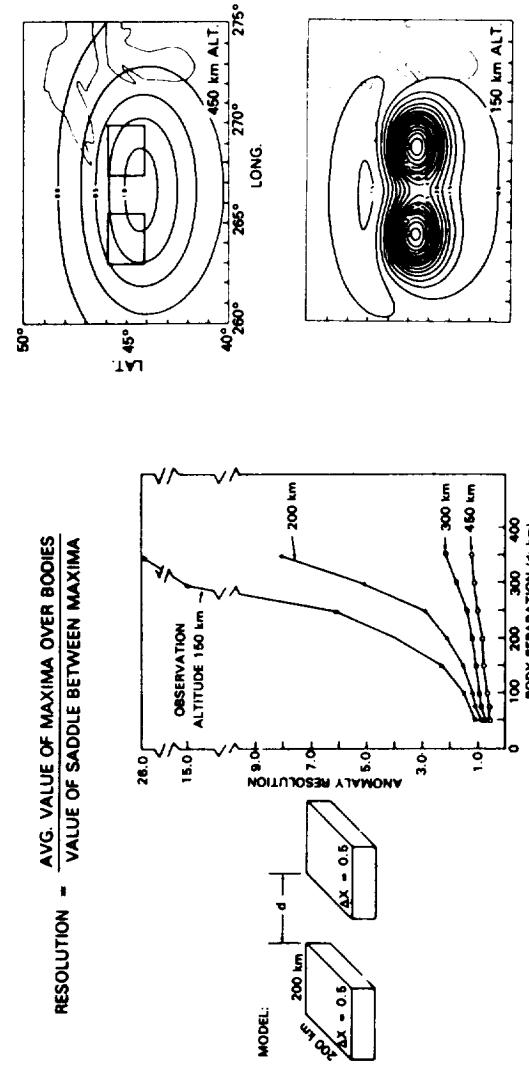
Resolution of Magnetic Anomaly as a Function of Altitude

Figure 3

Time Scales: Remanent magnetization of ancient rocks suggests that the geomagnetic field strength has not changed by more than a factor of three or four over the last 3 billion years, except that it drops by a factor of 5 or more during reversals. These reversals have occurred with increasing frequency during the Cenozoic, and the current average rate is about six per million years, but the pattern is random rather than periodic. For example, the typical period between the last few reversals has been of order 170,000 years, but it has been over 700,000 years since the last complete reversal. There was a 30 million year period in the Cretaceous and another long period in the Permian which were free of reversals. During an individual reversal, the intensity of **B** may be anomalously low for about 10,000 years or less, and the reversal of its direction is typically completed in about 4000 years. Archaeological evidence (magnetization of baked hearths and pots) indicates that the field intensity 2000 years ago at some sites was 50 percent higher than at present. In the last century the dipole has been decreasing at an average rate of about 0.05 percent per year. Between 1600 and 1800 the direction of the field at Paris and London changed by 34 degrees.

The secular variation $\partial_t B$ is quite easily observable in magnetic observatory records, and is of the order of 60 nT/yr. It varies greatly with position and time. About 25% of the energy in $\partial_t B$ at the Earth's surface can be removed by subtracting from $\partial_t B$ the field obtained by rotating the **B** pattern rigidly and steadily westward at about 0.2 degree/year. It is now believed that the secular variation is produced by fluid motion in the upper core, and that this motion may include a general westward rotation but also a large spatially variable component.

Magnetic storms produce large changes in **B**. A very large storm on April 16, 1938 changed $|B|$ at Potsdam by 2000 nT in 15 minutes. Most storms produce changes of a few hundred nT, and die out over several days. The changes are so rapid that a satellite cannot distinguish them from spatial variations, and it would appear to be essential to use observatory records to supplement the satellite data during magnetic storms.

It remains a hotly debated question what are the minimum time periods detectable in the magnetic signal from the core. The conductivity of the lower mantle is poorly known, but if it is at least as high as the conductivity at a depth of 1000 km, then core field fluctuations with periods shorter than one year will be screened out and will not be seen at the surface. The data at present do not exclude the interpretation that periods shorter than 10 years are strongly attenuated. What is needed to resolve these questions is an accurate measurement of the frequency content of the Gauss coefficients. Continuous satellite measurements might resolve the issue.

A distinct global change of the rate of secular variation was detected at about 1969-1970. This change was called the geomagnetic impulse or jerk. The change seems to have taken place in less than 1 year. Unfortunately only scalar satellite data are available at this time (and these ceased in 1970!) and these, even together with observatory data, are not able to resolve either the spatial or temporal characteristics of the jerk with sufficient accuracy for definitive studies of either its nature or the conductivity of the mantle through which it passed.

High latitude ionospheric and field aligned current systems exhibit variability on time scales ranging from 11 years, the solar cycle, to periods of <1 sec for electromagnetic plasma waves and instabilities.

To the extent that lithospheric sources are remanent rather than induced, they should not change measurably with time. Induced anomalies have magnetization strength proportional to the main field and so will change with the main field. However those changes are less than 1% of the anomaly magnitude per year which is not detectable with present measurement accuracies. This provides a test of the anomaly source. If it is found that what is thought to be the anomaly field changes significantly with time then that field is most likely not from a lithospheric source but from a contaminating core or external source.

Separation of core, crustal and external fields is one of the major problems in geomagnetism. The spatial spectra of the three sources overlap; e.g. in Figure 2 the lithospheric field is present for degree lower than 13, but it is masked by the core field. Similarly, the core field is present for degree greater than 13, but it is masked by the lithospheric field. It would seem that the fields in these "masked" regions will never be observable. This implies limitations on analyses of both the core and lithospheric fields which must be recognized. The external field covers the entire spectrum, but its temporal variations seem to be distinctly different from those of the core and lithospheric fields for the portion of the spectrum where the core field is observable. Analyses of satellite data have been successful in isolating and modeling the long wavelength external field. There remain some effects of low amplitude which still require modeling, e.g. from persistent field aligned currents and from seasonal variations in the magnetospheric configuration. To date these are apparently only observable in the Magsat data and they have yet to be adequately modeled.

Separation of the lithospheric and external fields has been only partially successful. This is true for both surface (including airborne and shipborne) and satellite data. Periods when data clearly show magnetic disturbance can be used profitably to study the sources of disturbance and the regions of the Earth in which induced fields occur. However, there are apparently no times when the external fields are totally absent from the Earth. Even at the most quiet magnetic times there are some localities where external fields are present. This is particularly true for the auroral and polar regions and also for daylight hours at all locations. In principle, simultaneous global measurements both at the Earth's surface and above the ionosphere would allow a good separation. Such measurements are not available. In practice, separation has been accomplished by decomposition of satellite data into parts which vary with geographic position and/or universal time from those which vary with dip or dipole latitude and/or local time. In some cases surface data beneath the satellite track have also been used. Some of these methods have generated considerable debate regarding the meaning of the results. Further theoretical and analytical analyses are needed.

Correlations of B with Other Geophysical Phenomena: There appears to be a weak correlation between the westward drift rate of B and the variations in the length of the day, which is proportional to the reciprocal of the angular momentum of the mantle. A stronger correlation , 0.71, exists between the rate of change of the dipole and the variations in the length of the day (see Figure 4). Such correlations would be expected from the electromagnetic coupling between the core and a conducting lower mantle, or from the effects of non-hydrostatic core pressure on the topography of the CMB.
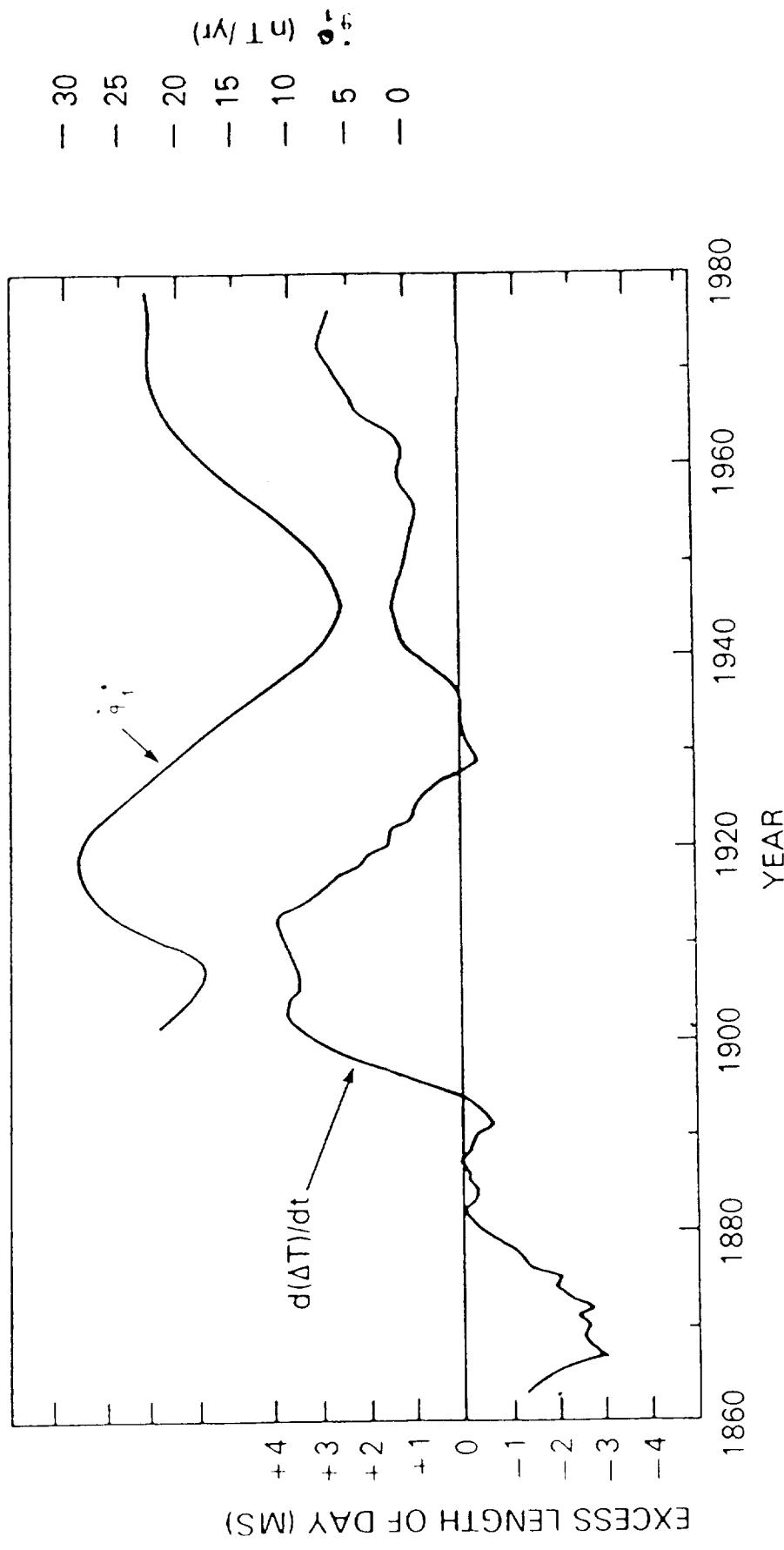
Figure 4.

A correlation of about 0.8 has been observed between the non axisymmetric parts of ₩ and the geoid if both are truncated at n = 4. Whether this correlation is important and what it means is an open question. It has been suggested recently that the Chandler wobble may be excited by fluctuations in the fluid motion in the core. If so, the Chandler wobble and magnetic time series should be correlated in some way, since presumably both have the same cause.

Of all physical quantities that can be measured in the plasma environment of the Earth, the magnetic field plays the defining and unifying role, physically tying points of different regions of geospace together, guiding charged particles, plasma waves and electric currents, trapping thermal plasma and energetic particles, and transmitting stresses from one region to another. The magnetic field provides the fundamental link between the solar wind and the magnetosphere (regulating the efficiency of the energy transfer and the solar wind dynamo), and between the magnetosphere and the ionosphere (with the field-aligned currents playing the role of communicator between the corresponding MHD and resistive plasma regions). Also, it is the magnetic field which "projects" the effects of magnetospheric processes onto the high latitude ionosphere, converting the latter into a giant viewing screen of geospace behavior. Measurement of the magnetic field thus provides basic information on the magnetosphere without which any attempt at quantitatively piecing together and understanding the entire solar-terrestrial system would be severely impaired.

As will be discussed later, the geologic interpretation of magnetic anomaly data is non-unique. Observed anomaly values can be reproduced by an infinite number of distributions of magnetization within the upper lithosphere. A similar situation is true for interpretation of gravity anomalies. Reduction of this ambiguity is achieved by constraining models through the use of other geologic and geophysical data. One method of reducing this ambiguity is by the joint analysis of gravity and magnetic anomalies. This is complicated by the fact that the gravity data do not have two distinct source regions like the magnetic data (core and crust, not mantle); gravity sources are contained continuously throughout the interior of the Earth. Models can also be constrained by noting the boundaries of known geologic and tectonic regions, by noting seismic boundaries, and by taking into account measurements of topography, heat flow and other quantities.

Representation of anomaly fields. In practice, equation (2), truncated at suitable n, is used to represent the field from the core. Other methods are generally used to represent the lithospheric field. In particular, a formalism has been developed for synthesizing Bouguer gravity measurements or magnetic anomaly data on an irregular three dimensional grid. The synthesis consists of a mathematical representation of the data in terms of discrete point masses for gravity or of dipoles for magnetics at the Earth's surface or at some appropriate fixed depth below that surface. In this method the satellite magnetic anomaly data are represented by an array of dipoles at the Earth's surface. The dipoles are assumed to be aligned along the direction of the Earth's main field, as determined by a spherical harmonic model, and their magnitudes are determined so as to best reproduce the anomaly data in a least-squares sense. The resulting synthesized fields are correct whether the underlying

magnetization distribution is induced, remanent or some combination. But the resulting magnetization distribution has meaning only if the magnetization is induced, an assumption that is often made but is still subject to debate. This kind of model is called an equivalent source model. Figure 5 shows a satellite anomaly map of the U.S. reduced to 400 km altitude by this method. The resulting dipole moments can be converted to depth-integrated magnetization, provided the appropriate depth is known. Such magnetization values (defined as the magnetic moment per unit volume) are determined under the assumption that the magnetic crust is of constant thickness with constant magnetic moment throughout the layer. Because the satellite altitude is large compared to typical layer thicknesses, the anomalies computed from the equivalent source solution depend directly upon the product of magnetization and layer thickness, i.e. if the magnetization is doubled and the thickness halved the computed anomaly will be unchanged.

Nonuniqueness of anomaly data interpretation. There are at least two fundamental sources of non-uniqueness to be considered in analysis of magnetic anomaly data. The first is that the presence of the large field from the core effectively masks all surface anomalies below spherical harmonic degree 14 and adds unknown amounts to the degree 14 and 15 coefficients. Some of the consequences for interpretation of not knowing the low degree field have been investigated, but more effort is needed. A related problem is that in some instances it was found that an along track trend removal applied to the data for the average map has distorted the zero level and seriously affected interpretation of the anomaly pattern.

The second source of non-uniqueness is inherent in the nature of the inverse problem. When any equivalent source solution is produced, it is possible to add or subtract certain magnetization distributions which have no effect on the external field. These magnetization distributions are known as annihilators, and they vary according to the geometry of the source region. This means that the original solution is not unique.

For the case of a spherical shell, the annihilator is any magnetization whose direction and intensity are directly related to any field whose source is within the shell. Various schemes have been suggested to deal with this problem of non-uniqueness. One approach has been to compute magnetizations and then add the magnetization due to some annihilator so as to obtain solutions which are considered more realistic than the equivalent source solution alone. The justification for this procedure is that magnetizations computed from the equivalent source technique are both positive and negative but that only positive magnetizations should result from induction. The suggested procedure is to add the magnetization due to some annihilator until all resulting magnetizations are greater than or equal to zero. This is a reasonable procedure provided it is realized that this solution is still not unique.

The existence of one or more annihilators means that a basic ambiguity exists in magnetization solutions which can only be removed by using other geophysical experience or data to restrict the solution.

Figure 5

Physical processes which operate on the Earth may be duplicated or may have related counterparts on other planetary bodies. For example, it appears that not only the gas giant planets but also Mercury, and possibly some of the Jovian satellites, have functioning dynamos. While the exploration of our solar system functionally lies in a separate division within NASA, it is not only proper but essential that this separation not hinder the integrated studies that are so necessary for understanding the underlying physical phenomena.

The study of planetary geopotential fields has already begun with flyby missions of several planets and satellites and orbiting missions at Venus and Mars. Magnetic field measurements conducted by Pioneer Venus Orbiter found no measurable planetary magnetic field; it is concluded that Venus has no internal dynamo. The interpretation of measurements at Mars from the Soviet Mars 2 and 3 missions have been disputed. Some researchers claim evidence for a weak planetary field, with magnetic moment $\lesssim 10^{12}$ Tm^3; others think that the measured fields were magnetosheath field lines compressed by the solar wind and draped across the planet. Hopefully, measurements on the upcoming Mars Orbiter will prove definitive. Two useful passes of magnetic field data from Mariner 10 showed that Mercury had a magnetic field that could only be explained as due to an internal dynamo field. Its moment is about 10^{13} Tm^3. It is debated whether the dynamo is self-sustaining or driven by thermoelectric currents. Dynamo fields have been found at Jupiter (moment = $1.5 * 10^{20}$ Tm^3), Saturn (moment = $4.6 * 10^{18}$ Tm^3), Uranus (moment = $3.9 * 10^{17}$ Tm^3), and Neptune, but all of these measurements are limited to flyby passes and do not provide enough information to characterize more than the dipole, quadrupole, and some of the octupole fields. Though limited, these data have provided grist for the mill of theoreticians since each measurement has had an element of surprise. Jupiter's magnetosphere is extremely large and corotating at a very fast angular velocity; Saturn's field is considerably weaker than was expected on theoretical grounds and it's tilt is smaller than can be measured ($< 1^o$); the field at Uranus shows strong quadrupole and octupole terms and is tilted at a 60° angle from the rotation axis; the field of Neptune is apparently similar to that of Uranus.

There is no evidence of dynamo fields from any of the Jovian satellites or from Titan, although the possibility of a dynamo field at Io has not been ruled out.

In each case, the magnetic field measurement has provided key data used in formulating theories regarding deep internal planetary structure. However, except for Venus, the available measurements are inadequate for thorough studies. In principle, measurement of the temporal change of a planetary dynamo is sufficient to determine the radius of its conducting core. This, however, requires higher accuracy data over a longer time period than now available.

There is a good possibility that Mars once had a dynamo field. If so, there may be measurable crustal anomaly fields that, properly mapped, would give clues about the structure and evolution of the Martian crust.

In depth investigations will require planetary orbiters rather than flyby missions. Present plans call for such measurements to be acquired by the Mars Observer, by the Cassini spacecraft at Saturn and by Gallileo at

Jupiter. Unfortunately, Galileo will be in an equatorial orbit and so will not survey the global field distribution of Jupiter. Further, a Phase A study for a Mercury orbiter is scheduled to begin in FY 91. Such missions are to be encouraged. Further, investigations comparing physical processes on the different planets, including the Earth, should be called for by NASA and "Earth scientists" encouraged to participate in both missions and studies.

The data relevant to lunar magnetism are controversial. Some people believe that the paleomagnetic data from lunar rocks, and the presence of magnetic anomalies from impact structures, argue for an ancient lunar dynamo and therefore a liquid nickel-iron core. Others suggest that plasmas induced by the impacts could have produced sufficiently strong fields to have caused the observed magnetizations without the need to call for a lunar dynamo.

The following objectives have been formulated on the basis of the background presented in the previous sections. Although broad in nature, the objectives will be met through very specific analyses, the outline of which is set forth in the section on Investigation Procedures.

Objective 1: Main Field Modeling: Accurate determination of the Gauss coefficients is a prerequisite for all scientific studies involving the main field. Secondarily it is important for such applications as derivation of magnetic charts, computing charged particle trajectories in the magnetosphere, small craft navigation and background removal for measurements of lithospheric fields. The first objective of the Geomagnetic Studies is to derive an accurate description of the main magnetic field and its secular variation for all epochs possible.

Objective 2: Secular Variation and LOD Variations: Accurate determinations of length of day (LOD) variations are obtained today with very long baseline interferometry (VLBI) and Satellite and Lunar laser ranging (SLR, LLR). It has been shown that on time scales of weeks to a few years, LOD variations are remarkably well correlated with the variations of the angular momentum of the atmosphere. This is interpreted as an exchange of angular momentum between the atmosphere and the Earth's mantle. On a larger time scale, from years to decades, there appears to be a correlation between the secular variation of the magnetic field, in particular the westward drift and the change of the dipole, and the variations of the length of the day. Such a correlation could be accounted for by electromagnetic coupling between the core and the conducting lower mantle. For example, it has been proposed that LOD variations follow secular variation changes with a time delay of the order of 10-15 years. If this correlation, which is debated, could be substantiated and the time delay more precisely determined, or if a different (reversed) correlation, proposed by some, could be established, it would give information both on the lower mantle conductivity and on the strength of the toroidal field at the core-mantle boundary. This latter field has no surface magnetic expression, and hence is not accessible to direct magnetic measurement. Further, if there is such coupling, then there is also a possibility of a connection between the secular variation of the geomagnetic field and excitations of the Chandler wobble. The second objective of the Geomagnetic studies is to investigate the correlation between the geomagnetic field, variations in the LOD, and the Chandler wobble.

Objective 3: Outer Core Fluid Motions and Earth Rotation: As previously mentioned, the secular variation is believed to be produced by the motion of the fluid in the outer core. Therefore, secular variation data provide information about the kinematics of this motion and a starting point for understanding its dynamics. Eventually, we may learn its energy source and whether the fluid in the upper core is stably stratified. This influences the net rate at which heat is transferred out of the core into the deep mantle. Knowledge about the core motion will also make a valuable experimental contribution to dynamo theory. Therefore, the third objective of the Geomagnetic Studies is to study properties of the fluid core.

Objective 4: The Electrical Conductivity of the Mantle: The electrical conductivity of the mantle is an important physical parameter for geodynamic studies. Indeed, it may provide information regarding the thermal state of the mantle and thus the convection pattern therein. Also, in order to estimate the motion $\underline{u}$ at the top of the core the fields $\underline{B}$ and $\partial_t\underline{B}$ have to be continued downward to the Core-Mantle boundary (CMB). Uncertainty in this computation arises from the extremely poor knowledge of the conductivity of the mantle; presently available models for the conductivity of the lowest mantle differ by several orders of magnitude.

Conceptual advances in this subject are needed; however it is already clear that the problem cannot be solved without good values of $g_n^m(t)$ over a period of decades. The fourth objective of the Geomagnetic Studies is to study the conductivity of the mantle.

Objective 5: Geologic and Geophysical Models of the Crust and Upper Lithosphere: Magnetic anomalies reflect important geologic features such as composition, temperature of rock formation, depth to Curie isotherm, remanent magnetism, and geologic structure (faulting, subsidence, etc.) on scales from local to global. Satellite measurements are limited to regional and global scales. Magnetic field data can help delineate the fundamental structure of the very old crystalline basement underlying most continental areas. Magnetic fields can also elucidate facts about ocean lithospheric structure. Long wavelength anomalies due to time periods of constant geomagnetic polarity have been detected in satellite data. Shorter wavelength observations will allow finer scale features to be seen. Also, some areas of the oceanic crust seem to have become demagnetized due to large thicknesses of sediment, driving the crustal temperature above the Curie point. Thus magnetic anomalies, when correlated with other geophysical and geologic information, furnish information important to understanding the evolution and state of the lithosphere. The fifth objective of the Geomagnetic Studies is to model the state and evolution of the crust and upper lithosphere.

Objective 6: Ionospheric, Field-aligned, and Magnetospheric Current Systems: Field-aligned currents (FAC's) play an important role in the coupling of energy between the distant magnetosphere and the lower ionosphere and atmosphere and form the basis of the three-dimensional magnetospheric current system for a wide range of conditions. These currents are also the critical ingredient in a wide variety of auroral processes including particle acceleration and wave generation. The basic characteristics of FAC's have been determined with previous near-Earth satellites, but the relationship of these currents to interplanetary phenomena and the primary generation mechanisms for these currents are not well known.

The characteristics of large-scale currents that flow in the ionosphere have been studied for nearly a century using ground-based magnetic field observations, but few satellites have obtained magnetic field observations with the accuracy and knowledge of attitude and baselines needed to measure these currents. Observations from Magsat have demonstrated that these ionospheric currents can produce significant magnetic perturbations at low satellite altitudes and that, at high latitudes, these ionospheric currents are intimately related to the FAC system. It was also shown from Magsat data that a current of a few million amperes flows in an antisunward direction below the satellite altitude

during storms but is absent during magnetically quiet times. This is consistent with a partial ring current model with closure through the ionosphere. An understanding of these currents is critical not only to an accurate representation of the core and lithospheric magnetic field, but also to our understanding of the coupling of energy from interplanetary space into the magnetosphere and into the Earth's atmosphere.

Low-latitude ionospheric currents, the Sq and equatorial electrojet systems, are prominent at sunlit local times. Low-latitude meridional currents have been postulated to be a result of the upwelling of plasma at the magnetic equator. These meridional currents were first measured by Magsat at dawn and dusk local times. The sixth objective of the Geomagnetic Studies is to measure and characterize field aligned and ionospheric currents and to understand their generation mechanisms and their role in energy coupling in the interplanetary-magnetospheric-ionospheric system.

Objective 7: Measurements of Planetary Fields: Physical processes vary from planet to planet and both the differences and similarities are important to our understanding of those processes. Just the existence or nonexistence of a planetary dynamo field places requirements on any theory regarding the internal structure of the planet. Measurement of the fields from different dynamos reveals something of the range of characteristics which the theory must take into account. Lithospheric field characteristics give information regarding lithospheric structure and evolution and about the past history of the planet's interior. The seventh objective of the Geomagnetic Studies is to cooperate with and support programs to measure and model the magnetic fields of planetary bodies.

Based on the preceding paragraphs, this section outlines the elements needed in a balanced Geomagnetic Program. It is to be emphasized that such a program must be part of a broader program in modeling the Earth and its environment as a whole. The proper interpretation of geomagnetic data requires simultaneous understanding of related geophysical data, including Earth rotation, polar motion, seismic data (including tomography), heat flow, gravity, and topography, and other relevant data types including laboratory measurements.

Measurements: Measurements of the geomagnetic field are routinely made at the standard observatories. Most data are sent to and archived at the National and World data centers.

Periodic field surveys are conducted by various organizations around the world, on the ground, by aircraft and by ship. Again most of the data are archived at the data centers mentioned above.

NASA can play a positive role with respect to the data collecting and archiving organizations. Both the observatories and the data centers are undersupported. As a user, NASA should assume some of the responsibility for encouragement and support of these facilities. Organizations, both domestic and foreign, who acquire data should be urged, by NASA, to provide data rapidly to the appropriate data center. The development of methodologies for data reduction and quality control by data users should be coordinated with and made available to those engaged in data reduction and archiving.

However, ground based magnetic field measurements cannot do the whole job. The distribution of magnetic observatories is limited to land areas. Within the land areas they are concentrated in the more developed nations, e.g. Europe, North America, Japan and Australia. This situation is partly addressed by aeromagnetic and shipborne surveys. However, such surveys provide only scalar measurements, with limited additional geographic coverage and then only at particular epochs and are therefore of limited use in detailed investigation of temporal change.

In order to determine the spatial and temporal spectra of the magnetic field of the core, accurate global vector data are required, extending over a significant time span, ideally decades or more. Logistic, economic and political considerations dictate that such data can only be acquired from space. Previous satellite measurements of the geomagnetic field have made significant contributions. However, many of these measurements were of the field magnitude only, often from satellites whose lifetimes were very short. Accurate global vector measurements over an extended time span are lacking and NASA is in the best position to acquire and make such data available.

This deficiency will be partly addressed by the Geomagnetic Observing System (GOS) investigation on the Earth Observing System (EOS) second NASA platform. That mission is not scheduled for launch until 1998 and is scheduled for termination in 2013. If it comes about, GOS will make a significant contribution to main field geomagnetism. However, the last previous satellite survey was conducted by Magsat in 1980, 18 years prior to the scheduled launch of GOS. The time gap is large and is a limiting factor on the usefulness of the combined data. It is highly recommended that the gap be filled as much as possible by a free-flying mission

launched before Eos. One candidate is the MFE/Magnolia mission under study jointly by NASA and CNES, the French space agency. With possible launch in 1994, MFE/Magnolia would significantly lessen the gap between Magsat and GOS and, with GOS, would provide 19 years of continuous monitoring of the geomagnetic field. That is more than 1.5 solar cycles, which is desirable. The other candidate is the Aristoteles gravity gradient mission under planning by the European Space Agency (ESA). This is planned for launch in 1994 or 1995 into a near polar orbit. The mission profile includes several months at a high altitude followed by at least six months at 200 km after which the altitude would be raised to 600-700 km and data acquired for about another three years. Studies are underway to evaluate the feasibility of including a magnetometer experiment as part of the mission.

Aristoteles would acquire data useful not only for studies of the main field, but would also provide the best available data for lithospheric studies. At 200 km the anomaly data would have amplitudes of several times and a resolution at least twice as fine as that of Magsat. This mission, or one like it, is clearly the next step in mapping and understanding large scale magnetic anomalies on a global scale.

Another possibility for obtaining short wavelength data to study lithospheric magnetization is to put a magnetometer on the Superconducting Gravity Gradiometer Mission (SGGM). This is due to fly in 1999, in a near 200 km, high inclination orbit with a lifetime of six months.

As pointed out in the Background, the geomagnetic field has time scales from years to centuries. If we are ever to really understand the geodynamo measurements will have to be made over the longest as well as the shortest time scales. Such measurements need not be continuous. For time scales of centuries, samples at 10-15 year intervals would be adequate. However, thorough study of periods up to 100 years dictates that at some time a nearly continuous span of data spanning a century is needed. It is highly recommended that NASA immediately follow up the GOS experiment with follow on missions to extend the time interval of continuous coverage to at least two solar cycles, preferably more. Plans should then include periodic missions at 10-15 year intervals until beyond the end of the 21st century.

There has been some success in determining the Earth's field during the past few centuries by reanalyzing old data, which in the early days was almost entirely shipborne inclination and declination data. The farther back in time this is attempted, the longer the minimum wavelength recorded in the data and the greater the time smoothing.

It is possible to get a very rough idea of the temporal change of the magnetic field by analyzing paleomagnetic samples, in particular those from lake sediments and from archeological remains such as baked hearths and kilns. Although these data are of much lower quality than directly measured components of the field, it is possible that with enough results the time varying dipole and quadrupole components of the field could be established.

At some time during the period of continuous data acquisition, an attempt should be made to separate the external and internal fields for an extended period of time. This will require multiple satellites in orbits of differing local time together with a massive campaign for simultaneous acquisition of global surface measurements.

Acquisition of satellite data in no way negates the value of surface data. The observatory data, in particular, are as important to satellite observations as vice versa. The variations of several hundred nT in less than an hour which occur during magnetic storms would be very difficult to interpret from satellite data alone. Such time scales can result in serious aliasing of the satellite data. Further, definitive separation of fields from ionospheric sources both from fields of magnetospheric origin and from fields of origin internal to the Earth requires measurements both below and above the ionosphere. A goal of the Geomagnetic Studies program should be to enlarge and enhance the array of sites at which absolute magnetic measurements are acquired on a continuous basis. There are two concerns to be addressed to accomplish this. First, technology for making such measurements on the ocean bottom needs to be developed and implemented. The most difficult part of this task is the problem of measuring the attitude of the instrument relative to three known axes so that the field components can be measured. The second concern is the reliable acquisition of data in third-world countries, especially those prone to governmental unrest. This problem is at least partially addressed by the recent and continuing development of relatively low cost, automated, vector instruments. Such are in use and/or under test at several of the national observatory networks. However their development does not guarantee their deployment and operation. That involves political as well as scientific issues which we would encourage NASA to address.

Data deficiencies plague the study of lithospheric fields. Aeromagnetic surveys usually (though not always) are of too limited an area to study anomalies over regions tens of kilometers in size and almost never cover enough area to study regions hundreds of kilometers in size. Piecing together smaller surveys results in distortion and aliasing, particularly if the surveys were acquired at different epochs and altitudes, and the main field has changed significantly. Satellite data are global in nature, eliminating problems of political boundaries and logistics. Data from the POGO and Magsat satellites have demonstrated that lithospheric fields can be studied from satellite. However, these analyses have also shown that lower altitude data are needed to bridge the gap between the shorter wavelength features measured by aircraft and ships and the very long wavelengths measured in currently available data. At present, no missions at lower altitude than Magsat are approved. Studies are underway to investigate the feasibility of including a magnetometer on the Aristoteles mission of ESA, to fly at about 200 km altitude in about 1996. Such a mission is highly desirable for lithospheric anomaly mapping.

For core studies, satellites must collect vector measurements of the geomagnetic field. Even perfectly accurate scalar data can fail to determine an external harmonic potential field. Numerical experiments suggest that scalar data can determine such a field if it is nearly dipolar and some vector data are available on the surface at the magnetic equator. The USGS is installing twelve such surface stations. Unfortunately, the results from these numerical experiments must be used with caution since most surface stations lie on local magnetic anomalies which can be several percent of the main dipole field. These anomalies can be measured by means of a campaign of vector satellite measurements, and once measured they can contribute to a subsequent scalar campaign. MAGSAT estimated the anomalies under the observatories extant in 1980, but such information will not be

available for the new USGS observatories. A further difficulty is that the numerical experiments assume no external sources. At the magnetic equator, the external sources associated with Sq and the equatorial electrojet are particularly strong. Moreover, at satellite altitudes, electric currents can produce one percent deviations of the geomagnetic field. At the accuracy required for core studies, vector measurements of the field are essential. The coverage must be global and of high accuracy. Each component of the field should be measured to at least 3 nT, including instrument, position, and attitude errors. The scalar field should be measured to 1 nT to serve as a check on drift in the vector instruments.

Another possibility for studying shorter wavelength features is to use a magnetic gradiometer. The gradient of a periodic magnetic field of a certain wavelength is obtained by dividing by the appropriate wavelength. The result of this is that if a structure gives a peak in its field power spectrum at a certain wavelength, the peak in the power spectrum of the gradient will be shifted to a shorter wavelength. Of more importance is that the core field is of very long wavelength, some external fields have very long wavelength signals, and local fields from field aligned currents contribute a curl in the gradient measurement. Thus, measurement of the total gradient tensor should, in principle, permit more accurate separation of fields from these sources from fields due to lithospheric sources. All nine components of the tensor must be measured because currents do flow at the satellite position, so that the field is not curl free. Gradient measurements should be taken in addition to, not in place of, the usual three component field measurements.

The sensitivity requirements for measuring gradients due to lithospheric fields can be roughly estimated by consideration of a spherical harmonic representation of the field potential, e.g. equation 2. In this case, for each degree and order, the elements of the gradient tensor have the form,

$$T_{ij} = f_{nm}c(m\phi)L_n^m(\theta)[a/r]^{n+3}/a, \qquad (4)$$

where a is the mean Earth radius, $c(m\phi)$ is the sine or cosine function, n and m are the degree and order, and L is an associated Legendre function or its first or second derivative. The quantity f_{nm} is a multiplying factor which depends upon the degree and order; for large n it goes as n^2, n, m, nm or 1. For estimation purposes, neglect c and L_n^m and assume that the gradient goes as

$$G = f_n[a/r]^{n+3}[R_n]^{1/2}/a \qquad (5)$$

where f_n is taken to be 1, n or n^2 and where R_n is the lithospheric component of the spectrum shown in Figure 2. Using a conservative estimate of R_n, the gradients computed from equation (5) are shown in Figure 6. The lower curve is for $f_n = 1$ and gives an estimate of the sensitivity of gradient measurement necessary if the smallest meaningful gradients are to be detected. The top curve is for $f_n = n^2$, which also gives information about terms in n*m, and applies particularly to radial gradients of the radial and eastward field and to longitudinal gradients of the radial and eastward field. The most difficult gradient to detect will be the latitudinal gradient of the north component. From this figure it is apparent that useful gradient information should be obtainable with sensitivities of 10^{-4} nT/m and better but that sensitivities of the order of 10^{-7} will be necessary to detect the smaller gradients.

Figure 6

Spherical Harmonic Degree, n

Gradient in nT/m

$f_n = n^2$

$f_n = n$

$f_n = 1$
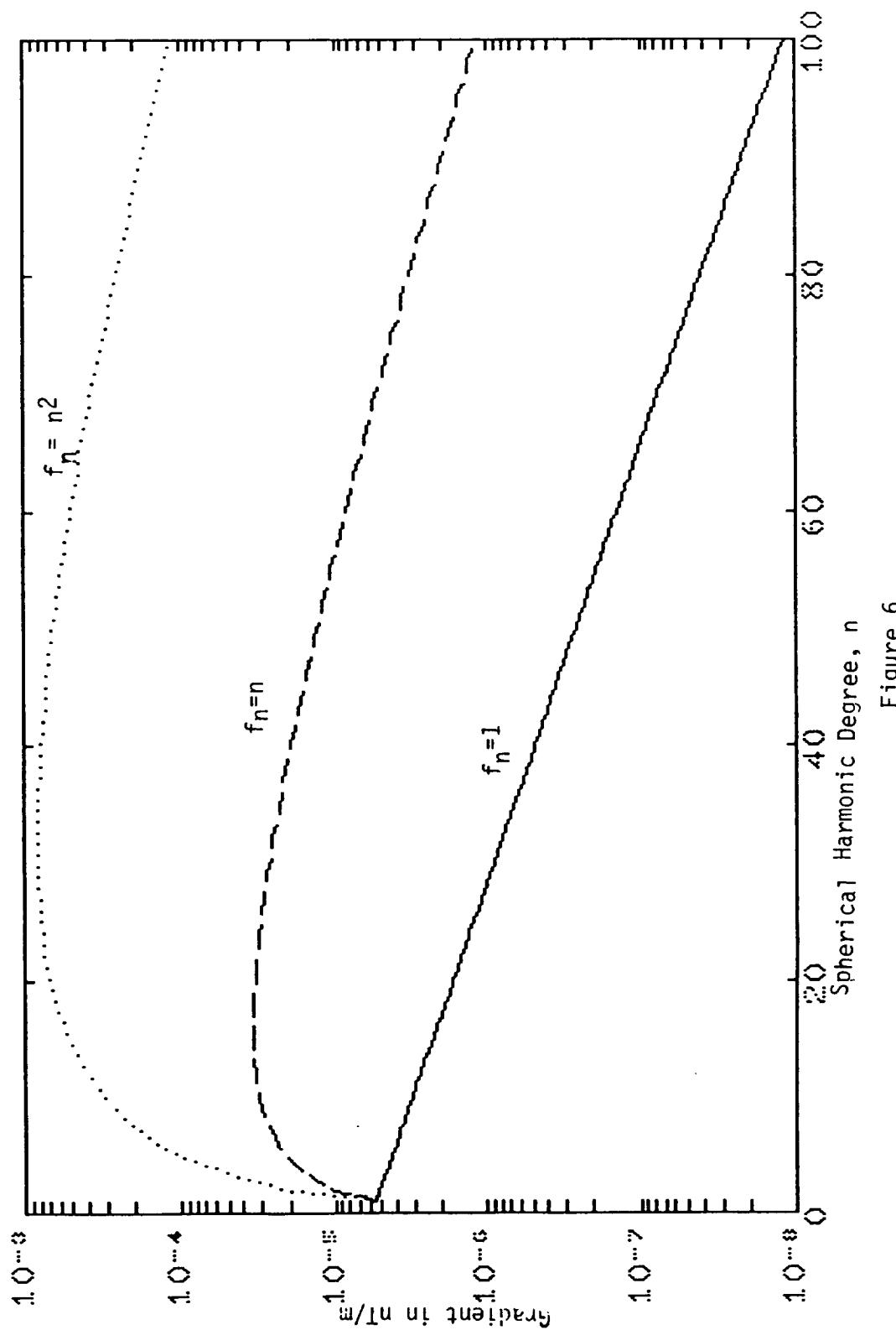
The gradients from field aligned currents will be larger, often reaching 10^{-2} nT/m or higher. Detection of the main features of in situ currents in the auroral belt should be possible with gradiometers of minimal sensitivity. The gradients expected of meridional currents at lower latitudes are unknown.

Magnetic gradiometers have been developed using superconducting quantum interference device (SQUID) magnetometers. A squid magnetometer designed as a gradient device measures the difference in flux linkage through two parallel coils separated by a known distance. Sensitivities as low as $5*10^{-7}$ nT/m have been claimed in the laboratory. In order to improve sensitivity it is necessary to increase the area of the coils and/or increase their separation. The sensitivity is directly related to the product of these quantities, i.e. to the volume of the instrument.

Further studies of the usefulness, accuracy and sensitivity requirements of gradient measurements are called for. These should include meaningful simulations of realistic lithospheric features. It should also be kept in mind that the presence of field aligned currents at satellite altitude is both an opportunity and a complicating factor. In situ measurements of the curl of the field will give the first direct measurement of the total current density, a key quantity in determining the energy input into the auroral belt and in studying ionosphere-magnetosphere coupling. However in the regions of such currents, their gradients will likely dominate the measurements and mask gradients from lithospheric sources. Also, such currents are likely to be highly filamentary, at least in some locations. In that case, the distance between the parallel coils will, in part, determine if one is measuring a very local phenomenon, i.e. filamentary current, or a broad average current. Finally, gradient measurements in a plasma are particularly sensitive to local effects of the probe and vehicle, which may deflect the current carriers. This question needs careful study.

A third way of collecting better information on the lithospheric field is by using a tether from another spacecraft, such as the Space Shuttle. Tethers can be 100 km long; if then the shuttle is orbiting at an altitude of 200 km, the magnetometer would be only 100 km above the Earth's surface. This altitude would give tremendously higher resolution than Magsat. However, the global coverage would be lost, for two reasons. Firstly, in order to make use of the lower elevation, a mission would have to continue for twice as long as Magsat to obtain adequate spacing of flight lines to make full use of the lower elevation. Secondly, the present inclination capability of the shuttle is limited to below about 57°, excluding data acquisition at the higher latitudes regardless of the flight length. Nevertheless, certain low latitude targets could be very well surveyed in a few days if the mission coverage profile were well planned.

An additional complicating factor is that the measurements would be acquired near to or in the actual location of E region ionospheric currents. This, of course, presents an unprecedented opportunity to study those currents. Study of the data separation and analysis problems should be carried out as part of the feasibility studies for such an experiment. Preliminary flights of tethered magnetometers are expected in 1991 or 1992, but these are engineering flights and of little scientific value.

While it is clear that the scientific objectives set forth issue a clarion call for additional data, particularly from satellites, this is not

to negate the usefulness of existing data. It may be true that the most obvious studies and applications of the existing data have been carried out, but there are still many questions that can be addressed with existing data. If anything, such analyses require increased support just because the easy work has been done. Examples of such ongoing studies are refinements of the decomposition of satellite data into core, lithospheric and external parts; improvements in analysis and interpretation of the lithospheric signal; optimization of field models by refinement of the external field representation; and application of new error analysis methods so that the true extent of our knowledge of inner Earth parameters becomes clear.

Main field and large scale external field modeling is the backbone of much of the data analysis. This will be accomplished as an extension of currently ongoing research. Models will include internal, induced, and external fields and will describe those fields as a function of time. Where possible, earlier data from satellites and/or surface measurements will be combined with future data to form the longest possible time series. The ability of any inverse problem to describe the real world depends both upon an accurate parameterization of the problem and on the observability of the phenomena in the data. Satellite data result in good geographic data coverage in a period of time short compared to significant variations in the core and lithospheric fields. This results in good observability. But the external fields are relatively fixed in local time with substantial variability in universal time. A single satellite cannot isolate these fields. Even with proper parameterization, no model is able to represent the combined internal and external fields to the accuracy of the data; from a single satellite the parameters are simply not observable. Multiple satellites are required, e.g. three in orbit simultaneously at evenly spaced local times.

Studies of the core, mantle, and Earth rotation include theory and numerical experiments. The following paragraphs describe how surface magnetic data are used to study the fluid motion just below the core-mantle boundary (CMB). Estimates of the electrical conductivity in the lower mantle range from 10^{-2} to 10^5 Ω^{-1} m^{-1}; clearly it is not well known. Electrical conductivity in the core is about 10^6 Ω^{-1} m^{-1}. In discussing magnetic fields whose length scales are of the order of the Earth's radius and whose time scales exceed a few years, the mantle can be treated as an insulator and the core as a perfect conductor. If B_n and $\partial_t B_n$ from the core can be measured for $1 \leq n \leq N$ on the Earth's surface, B and $\partial_t B$ can be extrapolated down through the mantle and computed at the CMB with a circle of confusion whose radius is about $180/N$ degrees. Since B_r and $\partial_t B_r$ are continuous across the CMB, their large scale structure is known in the fluid just below that boundary. Treating the core as a perfect conductor with velocity u implies that B is advected with the fluid. In consequence, just below the CMB, where $u_r = 0$,

$$\partial_t B_r + \nabla_H \cdot (B_r u) = 0 \tag{7}$$

here ∇_H is the horizontal gradient. Equation (7) is one scalar equation connecting the two horizontal components of u, u_θ and u_ϕ. Clearly (7) cannot determine u uniquely unless other assumptions are made about u or other information is available. One assumption now being tested, which would determine u from (7), is the possibility that u is steady during

intervals of a few decades or less, (to be precise, $b|\partial_t \underline{u}| \ll |\underline{u}|^2$, where b = core radius). One source of additional information about $\underline{u}$ is the momentum equation. It has been argued, for example, that $\underline{u}$ is geostrophic except near the equator. Although this does not suffice to determine $\underline{u}$ from (7) everywhere at the CMB, it does greatly reduce the non-uniqueness. Another assumption commonly adopted to minimize the non-uniqueness is to make the spatial variation in $u_\phi/\sin(theta)$ as small as possible and to minimize u_θ. This is the westward drift hypothesis.

Obviously, good values of $\underline{B}_n$ and $\partial_t \underline{B}_n$ near the Earth's surface for $1 \leq n \leq 12$ (the degrees for which lithospheric fields can be neglected) are essential to these investigations. Furthermore, near-surface magnetic data can be used to test the assumptions underlying the foregoing discussion: is the conductivity of the lower mantle negligible in such calculations (present data suggest it could be)? Is flux conserved (mean field dynamo theory suggests not, but present data suggest it might be)? Is the motion approximately steady (present data suggest it could be) or geostrophic (present data suggest that it could be except in a band several degrees wide at the magnetic equator)? Such questions probably cannot be settled without several decades of satellite observations.

Experimental studies will utilize the results of the main field and secular change modeling. Models of the fluid flow near the CMB can be derived directly from the data or from the analyzed data by numerical application of geophysical inverse theory. For example, the non-linear inverse problem posed by equation (7) and the hypothesis of piecewise steady flow is solved iteratively for $\underline{u}$ using a weighted least squares algorithm with options for requiring a geostrophic radial vorticity balance and spatially smooth flow. Hypotheses such as steady flow are tested by determining if the resulting flow predicts an adequate fit to the evolving Gauss coefficients. Corrections for mantle conductivity or core ellipticity, or some allowance for core resistivity, can in principle be made to make such tests more definitive. Success or failure of a hypothesis demands improvement of the means to test it or the geophysics supporting it. This systematic approach provides a basis for improved scientific understanding of the core geodynamo; it neither requires nor excludes major breakthroughs in theory, but does require global, long term, quality data.

Geomagnetic field behavior (e.g., westward drift) apparently correlated with changes in the LOD are calculated from the evolving Gauss coefficients. These coefficients and improved mantle conductivity estimates lead to improved estimates of electromagnetic core-mantle coupling. Topographic core-mantle coupling can be calculated from seismo-tomographic estimates of the CMB topography and any geostrophic core surface flow. The latter implies a specific non-hydrostatic pressure field at the top of the core which exerts a mechanical torque on the CMB topography. This torque predicts changes in the angular velocity of the Earth which can be compared with Earth rotation data to test the agreement of fluid flow and topography models.

All of the analyses described above contribute to our knowledge of the state of the core and the functioning of the geomagnetic dynamo. Similar analyses should be applied to data from other planetary bodies, as the data quality and amount permit. Comparative studies will then provide additional constraints for the theory of planetary interiors in general and for the possible modes of operation of planetary dynamos in particular.

__Conductivity models__ will be derived for the mantle and crust. There are two ways of determining the conductivity of the mantle. It can be probed "from below" using signals originating in the upper core and observed at the surface. This method requires a precise determination of the Gauss coefficients during rapid and isolable events such as the 1969 jerk. It can also be probed "from the top" by the analysis of the external and internal (induced) parts of $\underline{B}$ at various frequencies. This last method also requires a good knowledge of the time dependence of the Gauss coefficients. The penetration depth, p, of a signal at a given period T in a layer of conductivity σ is given by $p = (T/\pi\mu_0\sigma)^{1/2}$. If data were available for one or more 11 year sunspot cycles, it might be possible to obtain the conductivity of the lower mantle without making prior assumptions about the kinematics of fluid motion at the top of the core, as is required in the method "from below".

If an abrupt impulse, or jerk, is measured in an otherwise slow change, then mantle filter theory can be applied to constrain mantle conductivity. If not, then the frequency dependent amplitude ratios and phase shifts of separated, long period external and externally induced internal fields will still constrain laterally homogeneous estimates of the mid and deep mantle conductivity. Furthermore, the cross correlation between external and internal Gauss coefficients with different degrees and different longitudinal orders can test the importance of lateral variations in mantle conductivity. More detailed interpretation of the analyzed data in terms of laterally heterogeneous mantle conductivity and other mantle properties requires more detailed theoretical studies. Acceptable separation of externally induced internal fields from core induced fields at periods exceeding 1 year may require iteration between core flow and mantle conductivity models. If the mantle conductivity is low enough, and if the core current boundary layer is weak enough, then it may be possible to probe motions below the CMB using horizontal field components. If not, then there may be a strong toroidal magnetic field in the deep mantle.

For determining conductivity models of the crust and upper mantle, data from individual satellite passes will be closely coordinated with simultaneous ground-based observations at standard magnetic observatories and temporary variometer sites. Surface maps of magnetic transients will be constructed in space and time at ground level which can be compared against profiles of data sampled by overhead satellites. Algorithms exist for interpolating ground-based data along the flight path of the satellite at its so-called "foot-print". A number of efficient local interpolation forms have been developed. Some of these methods have been recently extended to allow for a variety of __a priori__ constraints on the attributes of 2-D smoothing polynomials (e.g. smoothness, flatness, etc.).

Typical satellite data samples signal periods extending from a few minutes to many months. This encompasses Sq and broad-band Dst at latitudes of $\pm45°$, auroral substorms at higher latitudes, and pulsations at all latitudes. Because ionospheric current systems will generally be found between the satellite and the ground sites, one has to account for these intervening sources in the analysis. This problem will be explicitly addressed as a joint generalized inversion, where both satellite and ground based data are used to solve simultaneously for the distribution of primary current sources in space and for the induced secondary sources in the solid

Earth. The latter, of course, leads to the conductivity as a function of depth and, with refined modeling, to lateral variations in that conductivity.

The mathematical formulation involves the inversion of the observed vector field components in space and time directly, rather than, as is conventionally done, going through formal spherical harmonic and Fourier decompositions of the observed data. The direct approach is appropriate since it is well known that one can effectively estimate vertical conductivity profiles without full knowledge of the source field geometry; one can do so knowing only the actual field components and their horizontal first and second derivatives over a restricted region of the Earth's surface. These data parameters will be used in a maximum-likelihood inversion scheme that minimizes a weighted L_2 norm of the prediction error and one of several minimization conditions on the solution simplicity (e.g. L_2 norm of the solution length, model flatness, or model roughness).

Continued laboratory measurements of the electrical conductivity of analogs of lower mantle materials are required to support both theoretical studies and geomagnetic deep sounding results.

Models of the lithosphere are the objective of the study of lithospheric anomaly fields. There are many kinds of models; their common purpose is to generalize observations and make predictions. In order to arrive at a most comprehensive model, and to minimize model non-uniqueness, other data must be used. Figure 7 shows the sorts of data which can be used to constrain lithospheric models, and their relationship to satellite magnetic field or gradient measurements. A first attempt to use magnetic data might be to construct an equivalent source model. Then application of various amounts of annihilator might be done to arrive at a magnetization model which makes most sense in light of the other data available for the area under consideration.

Equivalent source models require **a priori** selection of the direction of magnetization. It is possible that information might be gained about magnetization direction by producing equivalent source models for a variety of directional constraints on the magnetization and comparing these to what is known about the structure from gravity or seismic information. Alternatively, if the shape of a magnetized body can be determined **a priori** from other information, then an inversion may be done on lithospheric magnetic anomaly data to obtain magnetization vector information. This method has been successfully applied to seamount magnetization, but it could, in principle, be applied to satellite information over well defined magnetized bodies.

Application of model constraints from seismic, gravity and heat flow measurements to magnetic models is perhaps most easily applied in forward rather than inverse modeling. Prior inverse modeling can furnish guidance to the magnetization distribution to be chosen in a forward model. Forward models have the advantage of greater ease of representing sharp boundaries delineated by seismic and aeromagnetic data and by known tectonic features discovered in surface exploration.

Models must be constrained by knowledge of the magnetic properties of the rocks responsible for the magnetic anomalies. This class of investigations is of scientific importance and wide applicability in its own right, but its specific importance to NASA programmatic goals is clear: without such "ground truth", modeling of magnetic anomaly data is lacking an important physical constraint.

Data (examples)

Satellite
Magnetics
Gravity
Imagery (regional)

Correlative
Seismic
Heat flow
Field geology
Comparative planetology

Satellite
Imagery (visual/IR/thermal)
Altimetry
Radar
Passive microwave

Correlative
Aeromagnetic
Surface gravity
Detailed seismology
Magnetotelluric
Petrologic/radiometric
Tilt, vertical movement
Mineralization distribution

Increasing size of region

Lithospheric Models

Overall regional model

Relative magnetization/curie isotherm depth
Density
Structure/topography/megalineaments

Regional velocity structure
Regional heat flux
Geologic/tectonic maps
Evolutionary models

Refined composite
model for selected
subregions

Tectonic history
Resource assessment.
Hazard assessment

Fig. 5—Synthesis of geologic/geophysical models (idealized outline).

Figure 7

Stimulated by the Magsat mission, laboratory studies of deep crustal rocks began at Goddard Space Flight Center. A new picture of deep crustal magnetization has emerged from these studies, and has significantly aided geologic interpretation of Magsat data. But at the same time a number of important scientific controversies have developed. Resolution of these controversies will have significance not only to satellite data interpretation specifically, but to several fundamental questions of the petrology of the lithosphere and its evolution. Examples of these questions are: Given the evidence for enhanced magnetization (several A/m) at deep continental crustal levels, is this due to viscous enhancement of magnetization, and if so what petrologic evolution is implied by the required distributions of mineralogies and magnetic domains? Can lower crust formed by prograde metamorphism of rocks of sedimentary parentage be distinguished from lower crust formed by magmatic underplating through contrasting magnetic petrologies and associated long wavelength magnetic anomaly fields? Can regions of the upper mantle have anomalous magnetic properties because of large-scale variations in chemistry or oxidation state? If so, under what conditions should the continental magnetic layer be associated with the entire lithosphere instead of just the crust? Is it generally true, as has been suggested, that processes in the deep crust related to chemistry and oxidation state tend to produce magnetite Curie points near 550° C, or are there significant regions characterized by low Curie points? The question is relevant not only to problems of petrology and chemical flux in the deep crust, but to models of crustal temperature. These questions can be answered only through considerable further sample collection and laboratory measurement. For the continental areas, results are still relatively few, and ongoing support is essential.

There are considerably more data on the rock magnetic properties of the oceanic lithosphere both from direct measurements on samples collected from the ocean basins by drilling and dredging, and by sampling ophiolite suites on land. Further work is necessary to determine how the magnetic properties of ophiolites are changed during the process of emplacement of these oceanic lithospheric sources into continental blocks. Controversy exists concerning the location of the magnetization resulting in the long wavelength field measured in satellite data. Some would maintain that crustal magnetization may be sufficient, while others insist that a large part of that magnetic field must originate in the lithosphere below the crust. Also, controversy still exists as to the source of the short wavelength sea floor spreading anomalies, some calling for magnetization through the total oceanic crust, while others require only a 0.5 km thick layer composed of the pillow lava sequence of seismic layer 2A. Long wavelength magnetic anomaly studies, more rock magnetic measurements, and emplacement models are necessary to unscramble this important problem. The problem of oceanic lithospheric magnetization is also made more complex in that both remanent and induced magnetization may be important, especially for the deeper seismic layer 3. Serpentinisation of ultramafic rocks or of olivine crystals with the gabbroic rocks of layer 3 can also cause complexities because this process creates secondary magnetite which can produce very high secondary magnetization in the serpentinites, whose time of acquisition may be uncertain.

SECTION X.

REPORT OF THE PANEL ON

INTERNATIONAL PROGRAMS

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SECTION X.

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SUMMARY

Since the beginning of the space age there has been a need for international cooperation. The organizational scheme of these cooperative activities has varied from case to case. Some activities have been placed under the aegis of international scientific bodies, others have been based on ad hoc arrangements. For most of the important scientific results obtained in the field of Earth Sciences based on space techniques, the contribution of international cooperation has been quite substantial. International cooperation in Earth Sciences not only helps in solving problems which are of a global and multi-disciplinary character, but also a better understanding of both our physical and social world. The NASA SES Program must be seen as part of a worldwide endeavor, recognizing that a comprehensive study of the Solid Earth can only be meaningful if all the national and international entities are prepared to contribute to the achievement of agreed goals.

The success of any cooperative effort depends on the observance (or neglect) of a number of ground rules or critical factors. International cooperation is no exception and is subject to the same general conditions, complicated by such things as the prevalence of other languages, the observance of different cultural and educational backgrounds, and operation under varying political structures. As a result, particular elements or ground rules may take on more significance in one relationship than another. Even so, certain basic critical element can be identified which will smooth the road to success in any cooperative venture.

The strengths of international cooperation lie in the avoidance of duplication, the extended base of scientific competence, and the larger reservoir of technical competence. These provide an attractive basis for political agreement and program approval. The weakness on the other hand are the disadvantages brought about by the need to hold more extensive and extended negotiations which can result in the introduction of added restrictions and, in any case, bring about a certain dependence on foreign partners.

Scientific research in the area of Solid Earth will be dictated primarily by the large international programs until far into the 21st century:

* the International Decade for Natural Disaster Reduction (IDNDR)

* the International Geosphere-Biosphere Program (IGBP)

* the International Geological Correlation Program (IGCP)

* the International Lithosphere Program (ICL) which includes projects aimed at making significant contributions to the IDNDR and IGBP, namely:

  - Instability of Megacities
  - Risk Assessment of Volcanic Hazards
  - Global Geoscience Transect Through Hazardous Regions
  - Real Time Tectonics
  - Terrestrial Observatories

Additional impetus is expected to come from environmental-related programs such as the:

- World Climate Research Program (WCRP)
- Global Change Program
- Tropical Oceans and Global Atmosphere Program (TOGA)
- Tropical oceans Circulation Experiment WOCE)

Suggested areas of cooperation include:

1. Cooperation in the installation and operation of ground tracking facilities for the different observing techniques. (SLR, VLBI, GPS, DORIS, PRARE);

2. Collaboration in spaceborne instrumentation and missions. (ARISTOTELES, SGGM, TOPO, OVO);

3. Access to observational data and data handling.

The International Panel (consisting of 13 representatives of international countries and agencies):

* Expresses satifaction that the NASA Solid Earth Science Planning Conference recongnizes the importance of international cooperation and international programs.

* Believes that Solid Earth research needs will greatly benefit by the organization of appropriate international programs, with NASA participation, and well-defined objectives, procedures, and responsibility between partners.

* Suggests that all efforts should be made to relate and coordinate the activities of the different SES projects (includings NASA's) with the relevant major international programs through the established international bodies such as IDNDR, IGBP, ICL, and others.

The Panel recommends that NASA participates and takes an active role in:

1. the continuous monitoring of existing regional networks such as the WEGENER/Medlas networks;

2. the realization of high resolution geopotential and topographic missions;

3. the establishment of interconnection of the reference frames as defined by different space techniques;

4. the development and implementation of automation for all ground-to-space observing systems;

5. calibration and validation experiments for measuring techniques and data, including remote sensing;

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6. the establishment of international spaced-based net-works for real-time transmission of high density science data in standardize formats;

7. tracking and support for non-NASA missions; and

8. the extension of state-of-the-art observing and analysis techniques to the developing countries.

The Panel urges NASA to participate in the organization and implementation of courses, seminars, and training programs especially for the developing countries. Finally, the Panel stresses the importance of the use of proper monumentation and accompanying documentation for the studies of the Earth's geometry, kinematics, and dynamics.

1. Introduction

Since the beginning of the space age there has been a need for international cooperation. The fact that satellites were covering most of the Earth's surface required that satellite tracking stations be distributed around the world in order to calculate precise orbits.

The first satellite geodesy results were obtained in the late 1950's for the determination of the flattening of the Earth and the discovery of the third order harmonic term in the Earth's gravity field. These results were derived from observations provided by tracking stations established in different countries. The same was also true for the determination of station coordinates that became feasible in the early 1960's, and enabled geodesists for the first time to tie together the different geodetic datums.

When it was realized that the study of the Earth using space techniques in terms of its size, shape and gravity field, required global tracking coverage, different international observation campaigns were organized under bi- or -multinational arrangements. The Geodetic Satellite Program initiated by NASA and the InterCosmos Project established by the USSR Academy of Sciences were typical multilateral activities in the 1960's. The first real internationally organized observation and analysis program in this field was ISAGEX (1971), which was initiated by CNES and operated under the auspices of IUGG-IAG and COSPAR. It should be pointed out that NASA has been quite active in participating and initiating these and other such international programs.

The organizational scheme of these cooperative activities has varied from case to case. Some activities have been placed under the aegis of international scientific bodies, others have been based on ad hoc arrangements.

International cooperation in Earth Sciences using space techniques has not only been limited to the organization of observation campaigns, and the exchange of data. It has extended also to theoretical work and development of software, as well as to the analysis, the modelling, and the interpretation of the results. Joint development programs such as LAGEOS 2 and TOPEX/Poseidon are also examples of such international cooperation.

It should be recognized that for most of the important scientific results obtained in the field of Earth Sciences based on space techniques, the contribution of international cooperation has been quite substantial. International cooperation in Earth Sciences not only helps in solving problems which are of a global and multidisciplinary character, but also a better understanding between nations, peoples and disciplines, contributing to a better understanding of both our physical and social world.

2. The Rationale for International Cooperation

It is important to realize that the NASA Solid Earth Science Program must be seen as part of a worldwide endeavor, recognizing that a comprehensive study of the Solid Earth can only be meaningful if all the national and international entities are prepared to contribute to the achievement of agreed goals.

2.1 Scientific Cooperation

In the fields of Solid Earth Sciences, investigations cover new topics of such complexity that in most instances it can no longer be considered the prerogative of an individual agency, nation or group of nations to assume sole responsibility for their organisation, operation and analysis. The major issues in Solid Earth research are global in nature and have to be addressed appropriately. Thus, encouraging international cooperation among scientists and extending the base of scientific competence should be one of the axioms of NASA's policy for international cooperation.

2.1.1 Assessment of the Strengths and Weaknesses of International Cooperation

The success of any cooperative effort depends on the observance (or neglect) of a number of ground rules or critical factors. International cooperation is no exception and is subject to the same general conditions, complicated by such things as the prevalence of other languages, the observance of different cultural and educational backgrounds and operation under varying political structures. As a result, particular elements or ground rules may take on more significance in one relationship than another. Even so, certain basic critical elements can be identified which will smooth the road to success in any cooperative venture.

From the outset, it can be assumed that each of the participating groups or agencies is seeking, through the cooperation, to upgrade its own competence, by accessing those areas of superior ability or accessibility that are available to the other partners. This is not only a legitimate stance, but it can be used to the general benefit of the community of participants, if negotiations are carried out in the appropriate manner. One-way exploitation of potential partners leads ultimately to unnecessary antagonisms and tensions between the participants.

2.1.2   Critical Elements

Past experience has highlighted a number of critical elements which have influenced the success of different activities. These elements are usually identified by association with the appearance of some problem or other which should preferably not be repeated. A key element lies in the selection of the right partners. Where these are in any case dictated by circumstances, this becomes a search for the appropriate contacts.

It can always be assumed that a participant's involvement occurs against a justified background of national, agency or institutional interest. The motivation for participation may, for example, be dictated by the economic interests or by the technological advancement of the society in which the participating group exists, by scientific interest, by the efforts to improve access to advanced technologies, education and management, by the need to expand or upgrade industrial effort, by exposure to potential natural hazard, or by a combination of these factors. Furthermore, there are differences in budgetary systems which need to be identified and compensated for, where necessary.
Accepting this, it is desirable to have a clearly identified concept of the motivation of the various participating groups, and it is essential that the scientific objectives be clarified early in the cooperation. Procedures and areas of responsibility also need to be defined, documented and agreed by all partners in the early phases of the activity. Position papers which are prepared and published by one agency or institution without consultation with the other partners are susceptible to misinterpretation and create unnecessary sensitivities.

Another area deserving particular attention addresses data access and sharing conditions, which should be agreed from the beginning and the conclusions made known to the community of active participants.

2.1.3. The Strengths and Weaknesses

The foregoing comments make it apparent that international cooperation can be characterized by a number of strengths and weaknesses. The strengths lie in the avoidance of duplication, the extended base of scientific competence, and the larger reservoir of technical competence. These provide an attractive basis for political agreement and program approval.

The weaknesses on the other hand are the disadvantages brought about by the need to hold more extensive/extended negotiations which can result in the introduction of added restrictions and, in any case, bring about a certain dependence on foreign partners.

It seems apparent, however, that the advantages outweigh the disadvantages.

2.2. Programmatic Cooperation

The study of the Solid Earth system, in particular its structure and its potential fields, is dynamic and requires on the one hand a complete coverage of the planet on a continuous basis and on the other hand an appropriate time repetitivity of observations at different spatial scales (local, regional, global), depending upon the various scientific disciplines or application domains considered. The corresponding time scales vary from years to hours. Gravity field mapping, for example, requires repeated determination once or twice per decade, whereas the investigations of short-term variations in the Earth's rotation rate approach time scales as short as hours. These examples may help to explain the difficulties encountered in defining programs that satisfy a maximum variety of Solid Earth Sciences. These challenging requirements can only be met through the coordinated definition of the different observation programs. Given the oft conflicting requirements of the various disciplines, there is the risk that attempts to combine several disciplines within the programs of any one agency or nation or even on a single spacecraft will compromise on the characteristics and requirements of each and, in addition, will exceed the financial possibilities of the planning agency. Furthermore, in order to exploit the full scientific and technical competence of the international community and, at the same time, reduce the costs of a program through sharing of development work, facilities and operations, NASA is invited to examine for each element of the proposed Solid Earth program the possibilities of joint international efforts in the forms of contribution of hardware, operational support or data analysis and interpretation. Joint campaigns for sensor calibration and data validation are just two examples for such international cooperation.

3. Past Experience and Current Status of International Cooperation

Except for remote sensing, where international coordination is somewhat limited, apart from some areas such as data formats, data dissemination and calibration experiments, the space geodesy community has been forced to set up multi- and international tracking programs from the very beginning of the space age.
In the mid-seventies cooperation returned to a multilateral situation. Examples of the valuable multilateral activities of this period are the tracking of the U.S. altimeter satellites GEOS-3 and SEASAT. The usefulness of radar altimetry data from both of these spacecraft was greatly improved by the deployment of additional, temporary Doppler tracking receivers at various sites around the world and laser tracking by non-U.S. systems.

International cooperation improved quantitatively and qualitatively with the implementation of the Crustal Dynamics Project (CDP) at Goddard Space Flight Center (GSFC) in 1979 and the reorganization of a Commission on the International Coordination of Space Techniques for Geodesy and Geodynamics (CSTG) in 1980 as a joint commission of the International Association of Geodesy (IAG) and the Committee on Space Research (COSPAR) of the International Council of Scientific Unions (ICSU). The Crustal Dynamics Program established cooperative arrangements with over twenty countries. The CSTG has initiated and coordinated various international observation campaigns through its subcommissions

for VLBI, SLR and GPS tracking techniques and CSTG projects and is still doing so. One of the best examples of a cooperative international program was the MERIT (Monitoring of Earth Rotation and Intercomparison of Techniques) program with its two international observation campaigns in 1982 and 1984. Through MERIT, and based on its results, the International Earth Rotation Service (IERS) was formally established in January 1988. Composed of global network tracking stations, coordination centers and international analysis and archiving centers the service has been functioning well since its establishment and can be taken as a good example of the sharing of international operations and organization. A similar approach is under consideration by the CSTG GPS Subcommission for the maintenance of a terrestrial reference frame and the generation of Earth orientation parameters for the handling of geodetic GPS requirements within the IERS. The objective is to establish centers for the acquisition and dissemination of data, as well as for standardized GPS orbit calculations and product generation as an extension to the existing CIGNET.

Regional international cooperation in the measurement of crustal deformations was first done under the WEGENER-MEDLAS Project in the Mediterranean region. Beginning as a loosely organized group of NASA scientific investigators in Europe, WEGENER has grown into a well coordinated international project with 30 European, African, Asian and North American institutions from 14 countries being directly involved. In the meantime this project has received the endorsement of the ICSU Inter-Union (IUGG & IUGS) Commission on the Lithosphere (ICL), the Council of Europe and of CSTG. The WEGENER Project has started to expand in several ways in the last two years. GPS densification measurements are being carried out in various areas of the Mediterranean by varying combinations of US and European groups and these measurements are being repeated at regular intervals. A link connecting the WEGENER Project with the IDEAL Crustal Dynamics Project of the InterCosmos group is under discussion.

Cooperative GPS measurements were carried out in the Caribbean, Andean South America and the South West Pacific by JPL in cooperation with partners from Europe, South America and Canada. Similar bilateral and multilateral arrangements to conduct deformation studies using GPS techniques are being prepared between Australian, European, Japanese, U.S. and U.S.S.R. groups and potential partners in China, India, Indonesia and Papua-New Guinea. Cooperation is also developing between some of these countries in the field of VLBI.

4. Cooperation in the 1990's

Scientific research in the area of Solid Earth will be dictated primarily by the large international programs until far into the 21st century:

- the International Decade for Natural Disaster Reduction (IDNDR)
- the International Geosphere-Biosphere Program (IGBP)
- the International Geological Correlation Program (IGCP)
- the International Lithosphere Program (ICL) which includes projects aimed at making significant contributions to the IDNDR and IGBP, namely:

- the Instability of Megacities
- Risk Assessment of Volcanic Hazards
- Global Geoscience Transect Through Hazardous Regions
- Real Time Tectonics
- Terrestrial Observatories

Additional impetus is expected to come from environment-related programs such as:

- the World Climate Research Program (WCRP)
- the Global Change Program
- the Tropical Oceans and Global Atmosphere Program (TOGA)
- the Tropical Oceans Circulation Experiment (WOCE)

as well as through special programs such as the International Space Year (ISY) and others. These large programs have become known to the public, to political planners, and to decision-making committees and should thus become the driving forces for Solid Earth Science Programs insofar as both multi-disciplinary engagement and budgetary aspects are concerned.

Two further aspects influence the financing and realization of Solid Earth Programs and therefore also international cooperation, be these defined by NASA or other (also non U.S.) agencies. These are the Polar Platforms currently being prepared by the Space Station partners (NASA, ESA, Canada and Japan) and the definition of new climatological and environmental programs and their accompanying budgetary requirements. These systems offer opportunities for Solid Earth Science, but they also bring with them certain risks. The opportunities offered by these systems comprise primarily the limited possibility to fly internationally coordinated SES instruments. These include for example the Geodynamics Laser Ranging System (GLRS), the Geoscience GPS Instrument (GGI), PRARE-extended (PRAREE) and remote sensing systems. The joint internationally sponsored and coordinated use of such systems can contribute significantly to the achievement of the objectives defined by the JDNHR, JCL and other major international programs.

On the other hand, the dangers implied by these systems lie in the risk of one-sided orientation towards climatological and environmental (C and E) research, or alternatively, the reduction of space for SES instrumentation to an unacceptable minimum. To these comes the risk that C and E research is considered to be of such overwhelming importance that budgetary limitations are set on SES research.

The first of these risks can only be averted by well coordinated and well founded pressure to fly SES instrumentation on EOS A/B and EPOP 1/2. The second problem touches on the more general aspect expressed in the necessity for an increased coordination of international cooperation in the Solid Earth Sciences. In many countries there is a probability that funding for SES research will be reduced (or maintained at its current level) in favor of WCRP, IGBP and other climatological/atmospheric programs. This probable tendency can only be overcome by spreading the load through international cooperation if SES research is to be significantly advanced.

Areas of cooperation which would enable the cost of SES to be shared more equitably can be defined, with the objective of reducing cost to the individual state or agency without sacrificing the integrity of global and regional solutions to the urgent problems to be solved. These include:

(i)   Cooperation in the installation and operation of ground tracking facilities for the different observing techniques. There are enough countries in the world which, with good will, can participate in the realization of those networks (SLR, VLBI, GPS, DORIS, PRARE) which are necessary for the achievement of the objectives of SES.

(ii)   Collaboration in spaceborne instrumentation and missions. High resolution geopotential and topography mapping missions are a typical example of highly complex and expensive missions.
        Their output is fundamental to Solid Earth Sciences and their products serve the local international geoscience community. There is no reason why one agency or country should carry the financial burden of such missions. Bilateral or multilateral cost-sharing is more satisfactory, even if the share of each partner is not equal. There exist already examples of such bilateral arrangements in Solid Earth Sciences such as the joint USA/Italy Lageos 2 Satellite. The ARISTOTELES mission, under definition by ESA represents a good opportunity to exploit a broad international effort for the realization of a zero order gravity gradiometer mission. A similar approach could be followed later on in this decade for a first order gravity gradiometer mission, such as SGGM.

        Similar approaches in sharing payload and/or mission costs are applicable to a topography mapping mission (TOPO) and a volcanology mission such as OVO.

(iii)   Access to observational data and data handling.
        It is important to realize that very large amounts of data will be produced by future space missions and microwave systems in densification areas in order to meet requirements for higher spatial and spectral resolution and repetitive measurements. This will require a major international effort in data handling. In the framework of each program data collection, distribution and archiving procedures will have to be agreed upon, whereby the emphasis is to be placed on easing accessibility on the part of the international community. International arrangements for the establishment of large, regional multidisciplinary data bases are a requirement of the near future.

        It is clear that political and economical developments can have negative impact on the quality and continuity of cooperative bilateral or multilateral activities. It would, however, be wrong policy to use this argument as a leading criteria when establishing long term programs which could most cost effectively be implemented by incorporating elements of international cooperation.

In this spirit NASA should perhaps also consider an intensified collaboration with the international partners along the items (i) and (iii).

5. Recommendations

The International Programs Panel

- **Expresses** satisfaction that the NASA Solid Earth Science Planning Conference **recognizes** the importance of international cooperation and international programs.

- **Believes** that Solid Earth research needs and will greatly benefit by the organization of appropriate international programs, with NASA participation, and well defined objectives, procedures, and responsibility between partners.

- **Suggests** that all efforts should be made to relate and coordinate the activities of the different Solid Earth Science projects (including NASA's) with the relevant major international programs through the established international bodies such as the INTERNATIONAL DECADE OF NATURAL DISASTER REDUCTION (IDNDR), INTERNATIONAL GEOSPHERE-BIOSPHERE PROGRAM (IGBP), INTERNATIONAL LITHOSPHERE PROGRAM (ICL) and others.

- More specifically, based on discussions and exchange of experience between the members, the panel **recommends:** that NASA **participates** and takes an active role in:

    (1) the continuous monitoring of existing regional networks such as the WEGENER-MEDLAS networks to investigate real time tectonics and the extension of such networks to other critical areas of important tectonic activity, such as the Sinde-Burmese-Himalayan area, the South East Asian islands and the Andes; furthermore such networks should be extended to cover active volcanic zones;

    (2) the realization of high resolution geopotential and topographic missions;

    (3) the establishment of interconnection of the reference frames as defined by different space techniques (SLR, LLR, VLBI, GPS, PRARE, DORIS). Emphasis should be placed on providing sufficient stations on the Southern hemisphere for all systems;

(4) the development and implementation of automation for all ground-to-space observing systems;

(5) calibration and validation experiments for measuring techniques, including remote sensing, in support of Solid Earth Science. Similar efforts should be developed for the validation and calibration of data;

(6) the establishment of international space-based networks for real-time transmission of high density science data in standardized formats;

(7) tracking and support for non-NASA missions;

(8) the extension of state of the art observing and analysis techniques to the developing countries.

The International Panel recognizes the importance of the proper education and training for the success of Solid Earth Science Programs and urges NASA to participate in the organization and implementation of courses, seminars, and training programs especially for the developing countries.

Finally, the International Panel stresses the extreme importance of the use of the proper monumentation and accompanying documentation for the studies of the Earth's geometry, kinematics and dynamics.

APPENDICES

APPENDIX 1

Country: Australia

Objectives: Australia has a wide range of activities in the disciplines covered by NASA's Solid Earth Science Program. These match all of the major scientific objectives developed by the various scientific panels in this meeting and involve space-based measurement as an integral component. Only these space-based issues are discussed below.

Program Elements:

Observing Programs:

- VLBI - facilities exist at Parkes and the Australian Telescope as well as at NASA's Tidbinbilla site. A cooperative program exists between the University of Tasmania and the U.S. National Geodetic Survey.

- GPS - support for international programs and comparison with VLBI sites

- Laser Ranging - based at Ororral Valley, support for international geodynamic and oceanographic objectives. Support is also given to NASA's laser tracking facility at Yaragadee (Western Australia).

- Satellite Remote Sensing - Landsat, MOS-1, meteorological satellites, based at Alice Springs

- Aircraft Remote Sensing - multispectral scanner systems, mid-infrared laser reflectance spectrometer

- Monitoring crustal motions in Papua/New Guinea to determine the deformation between the South Bismarck Sea, the Solomon Sea, the Woodlawk Basin, and the Papuan Peninsula

Current International Activities:

- Comparison of long GPS baselines with laser and VLBI baselines

- VLBI source catalogue improvements

- Precision vertical datum for altimetry studies

- Analysis of remote sensing imaging acquired as part of the C130 mission to Australia

- Comparison of the TIMS and Mid-infrared Laser Reflectance Spectrometer data

APPENDIX 2

Country: Canada

Area: Space Geodesy and Geophysics

Objectives:

- Application of GPS and VLBI to determination of crustal motion and to monitor earth's rotation

- Investigation of global dynamics by superconducting gravimetry

- Establishment and maintenance of VLBI reference system

- Investigation of the geoid, sea level and ice dynamics

- Delineation of contemporary postglacial rebound and sea level change

- Assessment of west coast seismic hazard

Program Elements:

- GPS/VLBI measurements of crustal deformation

- GPS orbit determination

- Participation in SEDI

- Planned participation in IERS monitoring

- VLBI terminal and correlator development

- Tracking of GEOSAT and analysis of altimetry data

- Planned tracking and applications of ERS-1, SPOT-2, TOPEX, EOS polar platforms

- Postglacial rebound monitoring (GPS, VLBI, absolute gravimetry)

- GPS and absolute gravimetry monitoring of Cascadia subduction zone for earthquake hazard assessment

- Geophysical applications of visible, infrared and radar imagery

Current International Activities:

- CIGNET GPS network

- NGS/NASA cooperative VLBI at Algonguin Radio Observatory and "mobile" sites

- UNAVCO GPS network

- GOTEX 1 campaign

- Casa Uno and Iceland campaign

- Proposed IERS participation by ARO

- Superconducting gravimeter network participation

- Development of instrumentation for Soviet Radio Astron. Project

- Participation in international absolute gravity base-station network

- Participation in TRANET, DORIS and PRARE tracking networks

Current and Future Cooperative Programs:

- Proposed NASA GLRS observations along Cascadia subduction zone

- Cooperative crustal deformation monitoring with NASA in Alaska/Yukon area and proposed extension to Cascadia subduction zone

- International GPS campaigns and global tracking network

- U.S./Canada cooperation in postglacial rebound and NA plate stability

- Geophysical satellite tracking

- RADARSAT

APPENDIX 3

Country: Federal Republic of Germany

Objectives:

- Understand the evolution, structure and dynamics of the European Lithosphere-Asthenosphere system

- Monitoring of Earth orientation and maintenance of reference frames

- Assistance in monitoring global sea level

- Modelling of global and regional geopotential fields

- Investigation of ice dynamics

- Investigations of global and regional plate motions and deformations

- Earthquake hazard assessment

- Remote sensing of the national territory and other regions (e.g. Antarctica)

Program Elements:

Current:

- Fundamental Station Wettzell SLR, VLBI, GPS, TRANET, superconducting gravity meter, broadband seismometer

- Mobile laser MTLRS - 1

- WEGENER/MEDLAS Project: regional and continental

- GPS surveys

- Analysis of SLR, VLBI, GPS, Doppler, gravity and magnetic data

- Absolute & superconducting gravity meters

- DEKORP deep seismic sounding

- Magneto-telluric sounding and deep continental drilling

- Stress measurements in deep boreholes, from fault plane solution and overcoring

- L/C/X band receiving antennas

- MOMS, metric camera

- Antarctic SAR/VLBI antenna

- Precise Range and Range Rate Equipment (PRARE(E))

- MOMS-02, XSAR

Current International Activities:

Bilateral:
- Measurement of VLBI baselines

- Wettzell-Madrid-Hartebeesthoek-Shanghai

- Anatolian Fault motion studies (TCGG)

- Superconducting gravity measurements at Richmond, Florida (USNO/IfAG)

- Mobile VLBI campaign in Europe (NGS/IfAG)

- Development of a new absolute gravimeter (NGS/IFAG)

- IRIS and intensive VLBI measurement (NGS/IfAG)

- TRANET Doppler measurements and Wettzell (DMA/IfAG)

- Gravity field modelling (GRGS/DGFI)

- Calabrian Arc Project (Univ. Bologna/DGFI)

- Bocono Fault Project (Univ. Maracaibo/DGFI)

- CASA Project (JPL/DGFI)

- Space data analysis (SRC Warsaw/DGFI)

- SLR data analysis (AC Moscow/DGFI)

- ERS-1 Processing and Archiving Facility (ESA/DLR/DGFI)

Multilateral:

- CDP laser and VLBI measurements in Wettzell

- WEGENER/MEDLAS laser measurements in the eastern Mediterranean

- MEDLAS densification in the Aegean and Tyrrhenian

- CIGNET-GPS tracking

- EUREF-GPS measurements in western Europe

- European Laser Data Collection Center

- PRARE network deployment

- European Geotraverse

Future Plans for Cooperation:

- Installation and operation of SAR/VLBI receiving station at the Antarctic Peninsula (Esperanza) from summer 1990/91 onwards for the ERS-1 mission

- Operation of PRARE system for ERS-1 (1991 onwards)

- Development of PRAREE system for Polar Platform System (1989 onwards)

- Development and operation of a transportable integrated measuring system at sites in the southern hemisphere

- Calibration of USSR SLR system(s)

- Development and operation of gravity mission with InterCosmos (SAGSAT/1993-95)

- MOMS-02 Shuttle flight (1993)

- XSAR Shuttle flight (199?)

APPENDIX 4

Country: France

Area: Solid Earth related space activities managed by CENTRE NATIONAL D'ETUDES SPATIALES (CNES)

Objectives: Understand the dynamics of the Earth and determine its internal and surface structure and evolution. This includes:

- Land topography, tectonics, geology, geomorphology

- Crustal motions in seismic and volcanic area

- Gravity field modelling, temporal variations, Earth and ocean tides, crustal structure

- Oceanic lithosphere dynamics, plate motion

- Magnetic field modelling: core, lithospheric, ionospheric and magnetospheric

- Core dynamics, mantle conductivity

- Mantle convection

Program Elements:

- Scientific investigations: geodesy, remote-sensing, geopotential, altimetry, planetology

- Space geodetic measurement and analysis: SLR, LLR, RF tracking (TRANET, DORIS, GPS), altimetry

- Remote sensing: SPOT, TM

- Stratospheric balloon surveys

- Development of gravity gradiometry technology

Current International Activities:

- Approved programs and missions:

  - SPOT 1, 2, 3, 4

  - DORIS (on SPOT 2,3,4, TOPEX, POSEIDON)

  - GPS

  - STELLA + ultra-mobile laser station

  - LLR

  - TOPEX/POSEIDON (altimetry + DORIS)

  - GEOSAT 1,2 (Doppler, laser tracking, altimetry)

  - MARS OBSERVER

  - MARS 94

  - MAGELLAN

- Related ground activities:

  - Seismic tomography

  - Surface observatory (INTERMAGNET, GEOSCOPE, LITHOSCOPE)

  - ODP

  - Numerical modelling

  - Laboratory experiments and measurements (deformation, high P/T materials, geochemistry, magnetic properties,...)

  - Magsat data analysis

Future Cooperative Programs:

- MFE/MAGNOLIA

- GRADIO/ARISTOTELES

- Geophysical data collection and distribution

APPENDIX 5

Country: Greece

Objectives:

> Greece is a country of high tectonic activity, and as a result a great effort is being made to understand the mechanisms of tectonic motions and earthquakes.
>
> The fact that Greece is a sort of natural laboratory for tectonic and earthquake research creates a lot of international interest, and as a result several bi/multi/international programs have been developed. All these programs are coordinated by the Hellenic National Committee for Geodesy and Geophysics.

Program Elements:

> Space techniques for geodesy and geodynamics have been used for a long time in Greece. The Dionysos Station has been operating since 1967 and has participated in most of the relevant international programs. As a matter of fact, most of the space activity in Greece has been in connection with international programs.
>
> Today, the measurement and interpretation of crustal motions with the use of SLR and GPS techniques are being emphasized.

Current International Activities:

> Greece participates in the WEGENER/MEDLAS program with 6 SLR sites. Measurements were made in 1986, 1987, and 1989.
>
> Since 1987, 6 GPS networks for monitoring crustal movements have been established through international programs with the participation of groups from the USA, UK, Germany, Switzerland, and the Netherlands. One hundred and forty-four (144) monitoring sites have been carefully selected and monumented. These cover most of the country, with a larger number of sites in Central Greece. One hundred and thirteen (113) points have already been measured once, while the remaining 31 will be measured this September. The networks are interconnected and tied to the SLR network.

Future Plans for Cooperation:

> It is anticipated that the already established network of sites will be remeasured at about 2-year intervals. New networks, or extensions of existing ones, are being considered, but the current workload is already quite high while funding is quite low.

APPENDIX 6

Country: India

Objectives: To model the evolution, structure and dynamics of the Indian lithosphere and the subjacent mantle in a planetary perspective.

Program Elements:

•   current
o   in preparation

- Geopotential fields
- Deep seismic soundings
- Wide-band magneto-tellurics
- Isotope and trace element chemistry of mantle-derived rocks
- Seismic tomography
- Earthquake hazard assessment
- In-situ stress measurements
- Theoretical frameworks for modelling
- o SLR, VLBI, and GPS studies:

Current International Activities:

Bilateral: International cooperation exists in varying measure in all the ongoing programs, but these are limited to opportunities for joint work provided by exchange visits of scientists under bi-lateral programs:

- Isotope chemistry - UCSD
- Seismic tomography - USGS
- Modelling frameworks - CNRS
- In-situ stresses - FRG
- Earthquake hazard - IPE, USSR-AS

- Intense deformation zone of central Indian Ocean - Institute of Oceanology, USSR-AS

Current and Future Cooperative Programs:

An international cooperative program to initiate SLR, VLBI and GPS studies towards constraining inter-plate velocities and intraplate deformation is still under discussion, especially concerning the fabrication and installation of the antenna and Mark III recorder. Meanwhile, steps have been taken to develop the front-end and down-converter systems, as well as a hydrogen maser. Joint synchronous experiments with FRG, Japan and USSR have also been agreed to in principle.

APPENDIX 7

Country: Indonesia

Objectives:

Indonesia is a country of active deformation:

- Meeting of 3 global tectonic plates: Indo-Australian plate, Eurasian plate and Pacific plate with all the 3 characters: convergence, subduction and spreading

- Forming of island arcs

- High volcanic activities (108 active volcanoes)

- High seismicity - frequent large earthquakes along plate margins

The active deformation of the Earth's crust in this part of the world exposes Indonesia to frequent natural hazards which cause the destruction of human life and infrastructures. A national program has been set up for mitigation of natural hazards: earthquakes, volcanic eruptions, tsunamis, etc.

Within the scope of this national program an international cooperation is sought to support the national objectives with due consideration of the transfer of technology, especially the application of space technology to monitor the dynamics of the Earth's crust and its impact on the environment.

Program Elements:

- Study of regional deformation and strain accumulation in relation to earthquakes along the tectonic plate margins

- Study of tides and tidal phenomena as well as the ocean dynamics (INSTEP = Indonesian Sea Through Experiments) due to flow of waterbodies from the Pacific to the Indian Ocean

- Application of remote sensing to monitoring volcanic activities

Current International Activities:

1. Indonesia - USA (U.S. National Science Foundation) - Japan (Earthquake Research Institute of the Univ. of Tokyo) - Australia (Univ. of New South Wales)

   - GPS observations along the Sumatra Fault System (the oblique plate convergence between the Indo-Australian plate into the Eurasian plate) and the subduction of the above mentioned plates in the southern part (Java trench)

   - 14 receivers deployed to observe 60 stations from 22 August to end September 1989

   - Code name: GPS-GPS (Global Positioning System for Geodynamic Project of Sumatra)

   - A project of 5 years repeated at 2 years' interval; for the subduction part - annual repetition

   - Includes transfer of technology to Indonesian scientists in GPS network observations and data analysis

   - Australia will observe at Christmas Island and Yarragaddee (VLBI station)

2. Bilateral cooperation between Indonesia and the Netherlands within GPS-GPS campaign, gravity observations will be carried out

   - First order gravity network in Sumatra

   - Establishing a calibration line in Java

   - Observations of gravity profiles along levelling lines in Sumatra, Java (completed), Kalimaian, Sulawesi

3. Bilateral cooperation between Indonesia and Australia on tides and tidal phenomena

   - Establishing a network of tidal stations to support the ASEAN Project on Tides and Tidal Phenomena

4. Bilateral cooperation between Indonesia and the USA (US-DMA)

   - Airborne geomagnetic survey in the straits of Macassar and Sunda

Future Plans for Cooperation:

- Cooperation with neighboring countries for establishing a network of fiducial stations for GPS observations

- Require assistance for establishing a network of absolute gravity stations (hardware requirement)

- Upgrading of tidal stations for satellite data transmission/ telemetering to national database center and to World Oceanic Data Center. If these stations are upgraded, they can be used for tsunami early warning system

- Telemetering of volcanic activities and its integration with seismic network stations

- Involvement in Spaceborne Radar (SAR) mission for topographic mapping, due to cloud and haze problems in tropical area, when using optical system

- Involvement in ERS-1 tracking (PRARE)

APPENDIX 8

Country: Italy

Objectives:

The National Research Council (CNR) has established a national program in Solid Earth Geophysics. The activities connected to space are mainly addressed by ASI (Italian Space Agency). For geodesy and geodynamics in the 90's ASI is planning to establish a multidisciplinary program oriented to Earth observation. This program will be similar to other Agency programs (e.g. the NASA Mission to Planet Earth) and will be connected to major global efforts such as the Long Term Change Monitoring Program. In this framework projects related to the use of space-based techniques for regional and global geodynamics studies, geopotential and magnetic field, lithosphere structure and evolution, land cover monitoring, long term change monitoring are envisioned. This program will comprehend experiments, theoretical studies, but also development of new sensors, spacecraft and ground stations. These techniques will possibly be applied to planetary exploration.

Program Elements:

- Space geodesy and geodynamics

- Remote sensing

Current International Activities:

- LAGEOS II Project (ASI/NASA)

- Tethered Satellite System (ASI/NASA)

- STS based SAR-X system (ASI/DLR/NASA)

- Maintain at Matera a fundamental station with permanent colocation of major precise positioning techniques (SLR, VLBI). Cooperation exists with NASA with regard to participation in major observing programs and technological upgrade.

- Two VLBI stations (Medicina, Noto) are partially devoted to space geodesy measurements in IRIS, both equipped with prime focus S/X receiver are operated by the Institute for Radioastronomy of the CNR.

- Cooperation with NASA for the development of new laser ranging systems and for the operation of the fixed system at Matera.

- Participation in the WEGENER consortium activities. Six standard pads have been constructed (Lampedusa, Milo, Basovizza, Cagliari, Medicina, Matera) for mobile Laser systems operation and colocation with other instruments.

- Densification of the MEDLAS network by means of GPS in the central-southern Mediterranean (Univ. of Bologna/DGFI).

Future Cooperative Programs:

- LAGEOS III mission under consideration (ASI/NASA)

- Establish an international effort for processing, archiving and distribution of LAGEOS II and III data

- Establish a permanent GPS network in Italy (SLR and VLBI sites) to support the global tracking network

- Extend the existing cooperation on SAR development (SAR-X) to aspects related to data archiving and processing

- Under evaluation: the opportunity of bilateral remote sensing missions for monitoring volcanoes

- Under evaluation: an Italian participation in the Aristoteles mission.

APPENDIX 9

Country: Japan

Objectives:

Solid Earth related activities in Japan correspond to its specific geographic location as follows:

1. Establishment of the marine geodetic control networks based on satellite geodesy, comprising three stages:

   • Connection of the Tokyo Datum to the world geodetic system based on SLR observations of Lageos and other geodetic satellites

   • Connection of principal islands to the Japanese mainland based on SLR observations of Ajisai and LAGEOS by using fixed and transportable systems

   • Connection of islands to the principal islands by using geodetic observations of the navigation satellite systems, NNSS and GPS.

2. Observation of the global plate motion by using SLR and VLBI techniques including the Antarctic Continent.

3. Observation of the polar motion and the Earth's rotation parameters by using SLR and VLBI techniques.

4. Detection of regional crustal deformations by using GPS technique for the purpose of predicting earthquakes and volcanic eruptions.

5. Application of satellite altimeter data for detecting the precise geoid, gravity anomaly field, crustal structure, sea bottom topography, ocean dynamics, ocean tide, etc. To obtain precise altimeter data SLR is used to track altimeter satellites and to calibrate altimeters.

6. Precise marine positioning on the sea surface and on the sea floor based on GPS technique.

7. Improvement of the geopotential field in the Northwestern Pacific region based on the terrestrial and aerial observations introducing existing and future satellite-based data.

8. Volcano observations using LANDSAT and MOS-1 data.

9. Detailed land topography and geological observations by using SAR data (RADARSAT, JERS-1).

10. Researches on formation of back-arc basins, deep structure of the ocean lithosphere, collision of tectonics in South Fossa Magna, structural evolution of the Japanese islands and formation and evolution of the lithosphere, which were conducted under the International Lithosphere Project (ICL).

Improvements in data analysis techniques and hardware development (SLR, VLBI, GPS, etc.) are also required to achieve the above objectives.

Current International Activities:

Various Solid Earth related activities are being conducted through bilateral, multilateral, and international cooperation:

- **CDP:** SLR and VLBI observations are being conducted in cooperation with NASA within the framework of the Crustal Dynamics Project. Data and information exchange has been successful, and cooperation is quite successful.

- **IERS:** Simosato SLR station and Kashima VLBI station are acting as the observation stations of IERS. The National Astronomical Observatory (NAO) is acting as a full-rate VLBI data analysis center for IERS. NAO is also acting as the IRIS-P network center.

- **Ajisai Observation:** The Japanese geodetic satellite "Ajisai" was launched into a rather low orbit and it flashes brightly. It is easy to observe Ajisai by using a small SLR system. Ajisai observations are being achieved through bilateral cooperation.

- **ERS-1 and TOPEX/Poseidon:** Satellite altimetry is a very effective technique for geodetic, geophysical, and oceanic investigations. Japan has proposed studies using ERS-1 and TOPEX/Poseidon data. SLR observations of the altimeter satellites will be made in order to obtain precise orbits and calibration of altimeters.

- **Plate Motions by VLBI:** Joint bilateral experiments are being performed by Japan and China, Canada and Australia.

- **DELP:** The Japanese national program for the International Lithosphere Project has operated from 1985-89.

Future Plan for Cooperation:

It is desirable to maintain and improve international cooperation on current activities to achieve the initial objectives. Cooperation on hardware improvement and on the establishment of newly developed hardware is also required. Cooperation on satellite tracking and data collection for ERS-1 and TOPEX/Poseidon satellites will be established. The cooperation of related countries may be desirable for some regionally intensified projects in the region of Eurasia and the Western Pacific where tectonic activities are quite strong.

The Japanese remote sensing satellites JERS-1 and ADEOS are scheduled to be launched during the 1990's. International AO sensors will be installed on board the ADEOS.

Data exchange in Earth science will become very important in the future, and some international data base systems based on advanced computer and communication technology will need to be organized. The data base needs to be open in principle to all potential users.

APPENDIX 10

Country: Peoples' Republic of China

Objectives:

1. Tectonic motion

   • Global plate motion and regional crustal deformations especially in seismically active regions

   • Research: mechanism of the driving forces of plates

   • Application: earthquake prediction

   • Measurements: via VLBI, SLR, GPS and seismological, geologic means

2. Space geodesy

   • Precise 3-D national geodetic network and participation of global terrestrial reference system

   • Measurements: via VLBI, SLR, GPS

3. Geopotential field

   • Upgrade the local geopotential field and fill the gap of the global data

   • Measurements: via SLR and gravimeters (superconducting and classical)

4. Earth rotation and related topics

   • Monitor and conduct research on the variations of Earth rotation, explore the correlations of these variations with some geophysical phenomena, and the reactions of the solid, oceanic, atmospheric Earth

   • Measurements: via SLR, VLBI

5. Mean sea-level monitoring

   • by using VLBI and GPS, connect the tide gauges to the global terrestrial reference system

6. Remote sensing of the Solid Earth through satellites and apply findings to many fields.

To meet the above mentioned objectives, a VLBI network including Shanghai (operational), Urumqi, and Kunming is being developed, along with an SLR network including Shanghai, Wuhan, Chang-chun (operational at present), Beijing, Kunming (in 1990) and Urumqi (planning stage). The GPS and gravimetry campaigns are being organized. The participating institutions are:

- Chinese Academy of Sciences

  Shanghai Obs, Yunnan Obs, Urumqi Station, Chang-Chun Station, Institute of Geology and Geophysics (Wuhan), etc.

- State Seismological Bureau

  Institute of Geology (Beijing), Institute of Seismology (Wuhan)

- State Survey and Mapping Bureau

  Institute of Survey and Mapping (Beijing), University of Survey and Mapping (Wuhan)

- State Administration of Oceans

  Involved in mean sea-level monitoring and remote sensing.

Current International Cooperation:

1. Plate Motion

   Shanghai VLBI and SLR stations are participating in the CDP and cooperating with Kashima, Simosato, Wettzell, etc. for baseline measurements.

2. Earth Rotation

   Shanghai Observatory is one of the data analysis centers in IERS for the global VLBI, SLR, LLR data.

   Shanghai and Wettzell are conducting an intensive ERP program one month/year in 1989-1991 via VLBI

Future Plans for International Cooperation:

1. Earth Rotation

   More involved in IERS for terrestrial reference system. Earth rotation monitoring data analysis and research.

2. Plate Motion

   Continue the CDP, join the Eurasian-Pacific region project conducted by USSR, India, Japan, and related countries.

3. Join the mean sea-level monitoring program.

4. Join the global tracking of TOPEX, ERS-1, etc.

APPENDIX 11

Country: Sweden

Area: Space Geodesy

Objectives: Participate in NASA Solid Earth Program with VLBI and
                ESA/NASA satellite programs. A national GPS group with 4
                receivers has been formed for regional geodetic studies.
                Development of a water vapor radiometer (WVR) for extensive
                mapping of tropospheric variations for calibrating precise baselines.

Program Elements:

- Monthly scheduled geodetic VLBI measurements (20/yr) at ONSALA.

- Altimetry experiments "Arctic Geodynamics" on ERS-1, TOPEX/Poseidon

- GPS regional geodetic studies and tectonics

- Consideration of joint geodetic VLBI station in Chile, together with W. Germany and U.S.

- Post glacial rebound related to sea level, ice and geodynamics studies.

Current International Activities:

- Participation in IRIS/VLBI Network

- Participation in GPS experiments in Scandinavia and Arctic

- Altimetry for gravity and tide studies in the Baltic and Norwegian Sea and Arctic Ocean

Current and Future Cooperative Programs:

- Potential of operation of Chilean VLBI site

- GPS cooperative projects

- Future gravity field mission participation

- ERS-1 "Arctic Geodynamics Project" with U.S. and Canadian participants.

APPENDIX 12

International Agency: InterCosmos

Objectives:

The main objectives of the InterCosmos program in the field of space geodesy and geophysics are:

1. Space Geodesy: stations positioning, geodetic reference frames.

2. Geodynamics:

   - Global and regional tectonics, plate and intraplate deformations

   - Global gravity field improvement: separate resonant harmonics, low-degree terms.

   - Earth rotation parameters.

3. Thermosphere Model Improvement

Program Elements:

1. Taking into account that accurate knowledge of satellite orbits is a key question for solving all above-mentioned problems, a network of satellite tracking stations is permanently extending. At the present time, 9 laser stations are in operation. The II generation laser systems SBG (20 cm), Crimea (6-20 cm), ULIS-630 (20 cm) and others are being used.

   The mobile laser system ULIS-M is in preparation.

2. The project IDEAL - Investigation of Deformations of Eurasian Lithosphere: A combination of terrestrial and space methods for plate deformation studies along the plate boundaries and Alpine-Asiatic mountain belt.

3. The joint programs of laser ranging of different geodetic satellites (Lageos, Starlette, Ajisai,...) and Doppler campaigns for station positioning.

4. Two Soviet passive geodynamic satellites, Etalon 1 and 2 with laser retroreflectors, were launched in 1989 into the near circular orbit with an inclination of 64·8° and semiaxis of 25,500 km.

5. The geodetic satellite GEO-IK was put into orbit on May 30, 1988 with the orbital parameters: h ~ 1,500 km, i = 74°. The satellite is equipped with a Doppler transmitter, a flashlight system, and laser corner reflectors and is supposed to be used for gravity field improvement and regional geodetic networks.

6. Dedicated VLBI - network "Quasar" aiming at:

   - Constructing and coordinating a reference system based on extragalactic radio sources

   - Determining and monitoring Earth rotation parameters

   - time synchronization.

   The network will consist of 8 antenna systems with a diameter of 32 m (for radio sources), 8 antennae of 1.3 m for navigation satellites. The scheme of proposed sites for antennae is attached.

   The time schedule of network construction is 1992 - first two antennae, and 1995 - experimental tests of full network.

7. Developing the navigational GLONASS system (now 10 satellites in orbit) and improvement of the positioning accuracy.

8. Project "System of Aeronomical Satellites" (1993)

   Collection of new experimental data about the state of the upper atmosphere in a wide range of helio-geophysical conditions and improvement of the existing models, mainly at altitudes of 200-500 km (sensitive microaccelerometer, mass spectrometer, and complex of instruments for measurements in the ionosphere).

Current International Activities:

   - IERS (SLR and data analyses)

   - WEGENER (SLR and data analyses)

   - CDP-NASA - (input of SLR data)

   - DORIS - CNES (beacon-antenna at Yuzhno-Sachalinsk)

   - LASSO (ESA)

   - Satellite laser tracking in India (ISRO)

Future Plan for Cooperation:

1. WEGENER - IDEAL

   SLR and calibration of Soviet laser systems (DGFI and IfAG, West Germany).

2. IERS (SLR, LLR, and VLBI), data analyses

3. ERS-1 - laser tracking, data analyses

4. Plate deformation investigation program in Asia (IDEAL Project with Indian and Chinese participation).

Proposal to NASA:

Cooperation of the CDP and IDEAL projects in Asia: SLR of the Lageos and Etalon satellites and GPS network.

INTERCOSMOS SIR NETWORK: as of July 1, 1989

1181 - Potsdam, GDR

1953 - Santo de Cuba, Cuba

1884 - Riga, USSR

1873 - Simeiz, USSR

1893 - FIAN, USSR

7811 - Borowiec, Poland

1148 - Ondrejov, Czechoslovakia

1101 - PLANA, Bulgaria

1901 - Helwan, Egypt - CSSR

APPENDIX 13

International Agency: European Space Agency

Objectives:

- Development of the space segment for scientific and applications missions.

- Build the corresponding space transportation system, together with the necessary ground infrastructure.

- No mandate in data analysis and interpretation.

Program Elements (in earth observation only):

- European Remote Sensing Satellite Program ERS-1, to be launched September 1990 for ocean, ice, coastal zone investigations by microwave remote sensing techniques.

  - SAR (swathwidth 100 km, resolution 30 m).

  - Radar altimeter.

  - Precise Range and Range-rate Equipment PRARE.

  - Laser Retroreflector.

- Earthnet: ESA's remote sensing satellite ground segment, at present comprising 5 ground stations located in Europe, Canada, Canary Islands. Acquisition, processing and archiving of data from remote-sensing satellites and (later) ERS and Polar Platforms.

- Meteosat Operational Program, a series of three geo-stationary meteorological satellites to be procured and operated for EUMETSAT.

  Implementation Period 1989 to 1993

- Earth Observation Preparatory Program EOPP

  - multi-disciplinary study program to advanced program conception and definition to system feasibility (Phase A) level.

  - limited technology research for advanced instrumentation.

- Solid Earth Program in preparation is ARISTOTELES to be launched in 1995 with primary (gravity field) and optional (magnetic field, geodetic point positioning) mission objectives. Orbits: 200 km (6 months) and 700 km (few years)
  Payloads under consideration: gradiometer, magnetometer, GPS receiver, precise tracking system
  Data analysis studies: simulate gradient sensor derivation; simulation of regional gravity potential recovery.

Current International Activities:

ESA plays an active role in many international groups and committees concerned with the coordination of existing and future Earth observation missions:

IPOMS	IFEOS
CGMS	ICWG
CEOS	

Typical examples of current cooperation:

- Use of data - ERS-1 Announcement of Opportunity (1986)

- Tracking support - ERS-1 worldwide laser tracking

- Acquisition support - ERS-1 SAR data reception by NASA station in Fairbanks

- Joint development - Space Telescope

Elements of ESA/NASA Cooperation:

ESA-NASA Solid Earth Plans:

1985:	AGU Spring Meeting GRM Steering Committee discussed opportunities of combining GRM (USA) and POPSAT (ESA)
1986:	SESAME WORKSHOP recommends the pursuit of European Solid Earth program with USA
1986/87:	Joint ESA/NASA study team examines options
1987:	MATERA WORKSHOP - consensus about single-spacecraft geopotential mission

1987/89: ESA continues with feasibility study (Phase A) for ARISTOTELES

July 89: Coolfont report of NASA Program Panel indicates that NASA now sees concrete ways for cooperation between the two Agencies.

GLOSSARY OF ACRONYMS AND ABBREVIATIONS

AIS	Airborne Imaging Scanner
ARISTOTELES	Application and Research Involving Space Techniques Observing The Earth's field from Low Earth orbiting Satellite
ARGOS	Data storage and forward channel on European satellites
ASAP	Ariane Structure for Auxiliary Packages
ASI	Agenzia Spaziale Italiana
ATS	Advanced Technology Satellite (NASA)
AVHRR	Advanced Very High Resolution Radiometer
AVIRIS	Airborne Visible and Infrared Imaging Spectrometer
BMTF	Bundesministerium fur Forschung uad Technologic (Germany)
CDP	Crustal Dynamics Project
CDDIS	Crustal Dynamics Data Information System
CIGNET	Cooperative International GPS Network
cm	Centimeter
CMB	Core-Mantle Boundary
CNES	Centre Nationale d'Etudes Spatiales (France)
CNR	Consiglo Nationale della Ricerche (Italy)
Cospar	Committee on Space Research (UN)
CSTG	Commission for coordination of Space Techniques for geodesy and Geodynamics
DGIF	Deutsches Geodaetisches Forschungsinstitut (Germany)
DoD	Department of Defense
DORIS	Dopplar Orbitography and Radio positioning Integrated by Satellite
DSGS	Densely Spaced Geodetic Systems
E	Eotvos Unit (10^{-9} sec-^{2})
ESSC	Earth Science System Committee
EOS	Earth Observing System
EOSDIS	Earth Observing System Data Information System
E-POP	Earth-Polar Orbiting Platform (NASA/NOAA)
ESA	European Space Agency
ERS-1	ESA Remote Sensing satellite
Etalon	Passive laser satellite (USSR)
FLINN	Fiducial Laboratory for an International Natural science Network
FRG	Federal Republic of Germany
GCM	General Circulation Model
GEOS	Geodynamic Experimental Ocean Satellite
GGN	Global Geophysical Networks
GOES	Geostationary Operational Environmental Satellite
GOS	Geomagnetic Observing System
GP-B	Gravity Probe-B
GPS	Global Positioning System
GRGS	Groupe de Recherches de Geodesie Speciale (France)
GRM	Geopotential Research Mission
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
IDNDR	International Decade for Natural Disaster Reduction
IfAG	Institut fuer Angewandte Geodaesie (Germany)
IGCP	International Geological Correlation Program
IGBP	International Geosphere-Biosphere Program
IR	Infrared
IRIS	International Radio Interferometric Surveying
ITIR	Intermediate Thermal Infrared Radiometer
IUGG	International Union for Geodesy and Geodynamics
IUGS	International Union of Geological Sciences
IWG	Investigator's Working Group
JERS-1	Japanese Earth Remote Sensing satellite
JPL	Jet Propulsion Laboratory
Km	Kilometer
Lageos-I	Laser Geodynamics Satellite (U.S.)
Lageos-II	Laser Geodynamics Satellite (Italy)
Landsat	Land monitoring satellite
LEO	Low Earth Orbit
LFC	Large Format Camera
LLR	Lunar Laser Ranging
LOD	Length Of Day
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)
MISR	Multi-angle Imaging Spectro-Radiometer
MLRS	McDonald Laser Ranging Station
mm	Millimeter
MODIS	Moderate resolution Imaging Spectrometer
mr	Milliradian
ms	Millisecond
MSS	Multi-Spectral Scanner
MSFC	Marshall Space Flight Center
MTLRS	Modular Transportable Laser Ranging System
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
Pegasus	Air-launched rocket

POGO	Polar Orbiting Geophysical Observatory
Poseidon	Spaceborne altimeter on TOPEX (France)
pps	Pulses per second
PRARE	Precise Range And range Rate Equipment (Germany)
RadarSat	Radar Satellite (Canada)
rms	Root mean square
SAR	Synthetic Aperture Radar
Seasat	Ocean dynamics monitoring satellite (NASA)
SES	Solid Earth Science
SESDIS	Solid Earth Science Data Information System
SGG	Superconducting Gravity Gradiometer
SGGM	Superconducting Gravity Gradiometer Mission
SLR	Satellite Laser Ranging
SNR	Signal to Noise Ratio
SPOT	Systeme Probatoire d'Observation de la Terra
Starlette	Passive laser satellite (France)
Stella	Passive laser satellite (France)
TIMS	Thermal Infrared Multispectral Scanner
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
UT	Universal Time
UV	Ultraviolet
VLA	Very Long baseline Array
VNIR	Very Near Infrared
VLBI	Very Long Baseline Interferometry
WEGENER	Working group of European Geo-scientists for the Establishment of Networks for Earthquake Research

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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. 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, and geopotential fields.

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