Technology for the Mission to Planet Earth

Report of the Ad Hoc Review Team on Planet Earth Technologies

of the

Space Systems and Technology Advisory Committee

for the

National Aeronautics and Space Administration

Prepared on behalf of the Ad Hoc Review Team on Planet Earth Technologies by:
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One Space Park
Redondo Beach, CA 90278
1989

R11-1681

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Preface

This study originated at the July 1988 meeting of the Space Systems and Technology Advisory Committee (SSTAC) for the National Aeronautics and Space Administration (NASA), during a discussion of the Office of Aeronautics and Space Technology (OAST) Space Strategy. There was agreement among the SSTAC membership that earth sciences in general and global change in particular were likely to be emphasized by the incoming administration. The SSTAC members themselves expressed personal concern about the importance and urgency of conducting earth observations. As a result of this conversation, the Ad Hoc Review Team on Planet Earth Technologies was formed to produce a study assessing technology requirements for accomplishing space-based global observations.

The team members wish to acknowledge the contributions of Wayne Hudson, Assistant Director for Space, NASA Office of Aeronautics and Space Technology, who served as Executive Secretary of the Ad Hoc Review Team on Planet Earth Technologies, and Amy Graham, Technical Writing and Editing Supervisor, TRW Space & Technology Group Publications, who edited and coordinated the production of this report.

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1. Executive Summary

Mission to Planet Earth, from the 1987 Ride report to the National Aeronautics and Space Administration (NASA) Administrator, is a concept referring to the endeavor of making long-term, space-based global observations for the purpose of understanding earth system processes. Many scientists believe that it is urgent for us to pursue such a Mission to Planet Earth — that preserving our economy, quality of life, and perhaps even existence will depend on our ability to accurately predict global change.

The Ad Hoc Review Team on Space Technologies was formed to determine what technologies must be developed in the near term to support Mission to Planet Earth. Specifically, the group was asked by NASA to review plans for the Global Change Technology Initiative (GCTI) proposed by the Office of Aeronautics and Space Technology (OAST) for implementation in 1991. The principal charge to the team was to focus on technology.

The team included representatives from those groups most likely to be involved in spaced-based earth observations and global change investigations: the aerospace engineering, earth sciences, and operational user communities.

The study approach was to gather information from members of the earth science community concerning their observation goals and related technology needs, then evaluate NASA's proposed plans based on these inputs. This report presents the team's conclusions and recommendations.

The review team's central finding is that OAST has identified all the correct technologies to pursue, but that the mission and system architecture has not been developed sufficiently to permit determination of meaningful priorities. The key recommendation is to initiate architecture studies as soon as possible, preferably by 1990, in order to establish the foundation for Mission to Planet Earth planning and technology selection. These studies should include cost-benefit trade-off analyses as well as definition of a comprehensive operational concept. Also, the end user of these systems needs to be identified; the kind of data needed and use of the data obtained will significantly affect system design and architecture. The team considers the architecture issue to be a massive topic which encompasses far more than the concerns of OAST and GCTI: it is fundamental to the planning of any national, or even international, far-term earth observation mission.

Although the subject of costs could be addressed only in general terms given the current information, the team did agree that the proposed GCTI funding levels are seriously deficient, and need to be approximately an order of magnitude greater. With such significant budgetary limitations, the potential for major developments under GCTI is severely restricted; the fear is that a small amount of funding is spread too thinly among a number of important and deserving technology research areas. Current technology funding will not bring about the required advances to support the planned systems.

Another concern is the lack of focused leadership and overall direction for the Mission to Planet Earth. The team's conclusion is that the United States earth systems study effort — whether known as Mission to Planet Earth or something else — should be a focused program with strong and distinct leadership which moves forward quickly to define the program and address the issues raised in this report.

At the same time, global change studies in general should continue to be broadly based, combining both interagency and international programs. Whenever feasible, efforts should be made to coordinate research and exchange information in order to conserve our limited global resources and achieve the most comprehensive view of our earth system possible.

Specific recommendations of the review team are:

1. Long-term, space-based investigation of global change and the earth's systems, and the associated technology efforts, should be a focused program.
2. NASA's architecture studies should begin as soon as possible, and should include the performance of relative cost-benefit trade-off analyses and development of a comprehensive operations concept. The studies must also consider the end user's needs.
3. Funding should be provided for a focused program, supported by a significant increase in research and technology monies. The proposed GCTI budget should be increased by a factor of 10 to achieve the planned missions.
4. Pursuing new technology in the area of information processing is urgent, since it is fundamental to the practical success of any program of earth observation from space. Meeting the unprecedented challenges of collecting, processing, storing, and accessing the massive amounts of data obtained will require fresh approaches which produce technological breakthroughs.
5. The national program will need effective interagency integration and coordination, under strong, single-point leadership.
6. By 1991, after the recommended NASA architecture studies have been performed, another SSTAC ad hoc team should meet to reconsider questions of technology priorities, development schedules, and funding allocation.

2. Understanding Global Change

The earth has always been in a state of change. Severe weather patterns have tormented mankind throughout history. The average temperature of the planet has fluctuated, resulting at various times in the glaciation or desertification of large portions of the planet. The levels of the oceans have varied, geological forces have created and destroyed mountain ranges, and the continents have migrated across the earth's surface as a result of plate tectonic forces. Millions of plant and animal species have evolved and become extinct.

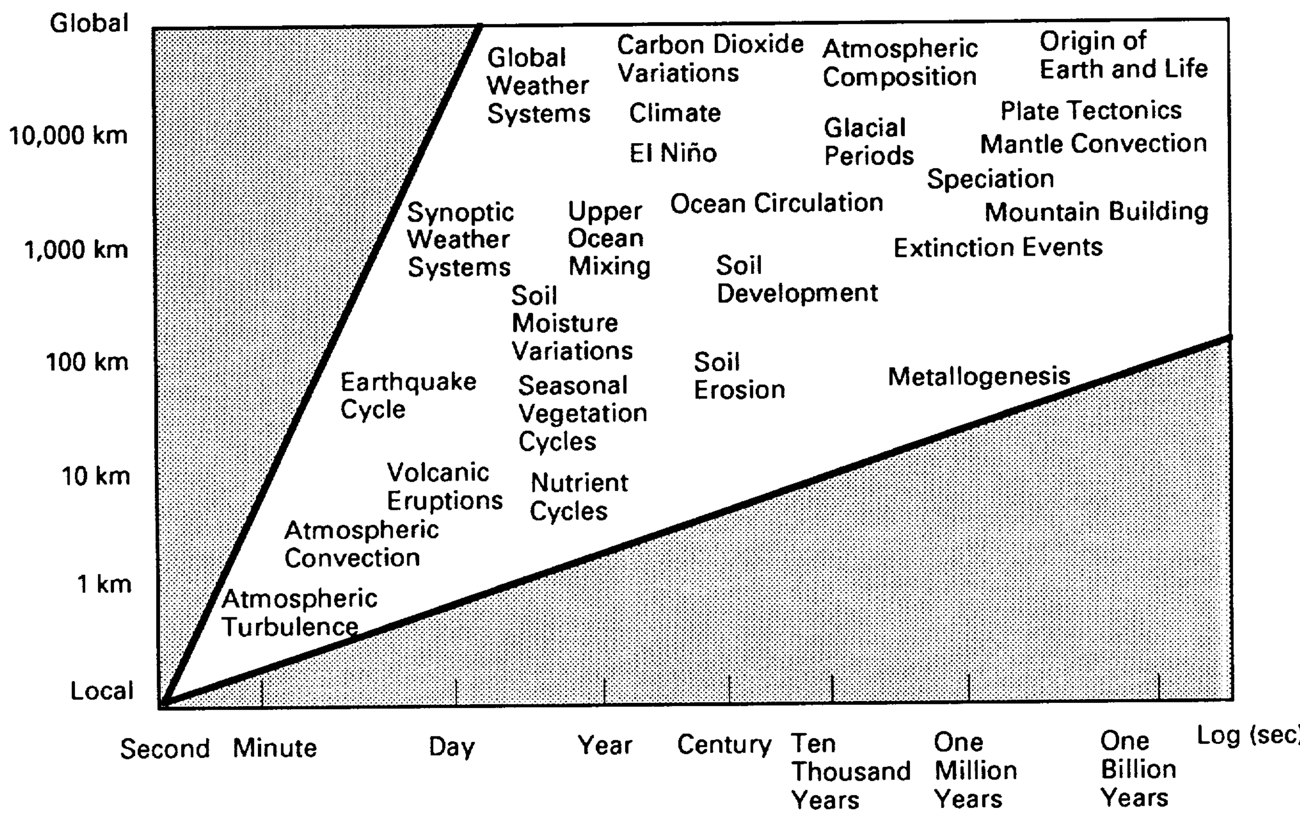
What is different now is both the increasing rate of change and mankind's role in it. Our participation in the earth's environment is significantly impacting many variables that have been reasonably constant and stable for thousands of years. Human activities such as energy usage, deforestation, industrial activity, and waste product handling are affecting the earth's atmospheric composition, its energy balance, and the viability of various plant and animal species. Scientists can say for certain that mankind is causing global change, and that the earth is changing at an increasing rate; what we do not know is the consequence of this change.

These issues are not simply of academic importance. Our very survival may depend upon understanding global change. Phenomena such as the ozone hole and layer depletion, the buildup of greenhouse gases and the potential for global warming, the damage to our lakes and forests from acid rain, and the recent drought present threats not only to our economy, but also to our quality of life. Concern is growing among the world's citizens and leaders as well as its scientists.

Understanding global phenomena requires making observations of a high temporal and spatial resolution on a global scale, from a global perspective (Figure 2-1). This fact underscores the need to make observations from space; in no other way can we gather the data necessary to understand the earth's system. Although earth-based verification and calibration will be essential to producing accurate predictive models, collection of transitory data from a few spots here and there is inadequate for the task at hand. Earth system science seeks to understand system processes rather than isolated phenomena. In order to understand the whole picture, we must see the whole picture.

For example, consider the well-publicized greenhouse effect. Because of personal experience and media focus on recent climactic changes and droughts, most United States citizens probably assume that there is a global warming trend, and that the use of aerosols and the depletion of the ozone layer have something to do with it. However, data obtained from the Earth Radiation Budget Experiment (ERBE) spacecraft suggests that the overall trend actually may be toward earth cooling (Ramanathan 1989). In either case, the consequences are unclear. The point is that a substantial amount of data must be obtained over a long period of time (at least 10 to 15 years), and system models must be developed, before we can make any meaningful predictions or intelligently alter our behavior.

The task of understanding the earth is enormous and complex. To be ready for flights starting in the year 2000, new technology must be available for insertion into systems starting their development cycle in 1995 — less than 6 years from now. Although many needed technologies with broad applications are already under development, priorities must be established; in addition, solutions to some problems will require breakthroughs not yet imagined. Since it can take as long as 20 years for a technology to transition from conceptualization to mission application, the near-term urgency for addressing these issues is clear.



Source: NASA Office of Aeronautics and Space Technology

Figure 2-1. Earth System Processes Within Characteristic Spatial and Temporal Scales

3. Review Team and Study Plan

Genesis

The Ad Hoc Review Team on Planet Earth Technologies, a subcommittee of the Space Systems and Technology Advisory Committee (SSTAC) for the National Aeronautics and Space Administration (NASA), was formed to produce a study assessing technology requirements for accomplishing space-based earth observation. The concept for this review team, which originated at the July 1988 SSTAC meeting, grew out of a discussion on the Space Strategy for the Office of Aeronautics and Space Technology (OAST). Perceiving an immediate need to identify and prioritize the technologies crucial to accomplishing earth observation, the SSTAC recommended establishing this review team.

Membership

The team members included representatives from technology areas most likely to be involved in space-based earth observations and global change investigations — the aerospace engineering, earth sciences, and operational user communities:

- Chairman: Dr. Paul W. Mayhew, Vice President and General Manager, TRW Engineering & Test Division, Space & Technology Group

- Dr. Herbert Carlson, Chief Scientist, Air Force Geophysical Laboratory

- Dr. Alan W. Fleming, Manager, Controls & Mechanical Systems Operations, TRW Space & Technology Group

- Mr. Ellsworth E. Gerrels, Business Development, Astro-Space Division, General Electric Company

- Dr. William F. Hubbarth, Manager, Special Information Systems, IBM Federal Systems Division
- Dr. Wesley Huntress, Special Assistant to the Director, Earth Science Division, NASA Office of Space Science and Applications
- Mr. Leonard Schuchman, Senior Vice President, Stanford Telecommunications, Inc.
- Dr. James Sparkman, Physical Scientist, National Oceanic and Atmospheric Administration
- Dr. Gerald Yonas, Director, Technology Transfer, Sandia National Laboratories.

Charter

The charter of the review team was to:

> Provide an assessment of the technology requirements for the next generation (2000 and beyond) of earth science missions and systems from earth orbit. The scope of this study will include instrument technologies such as sensors, optics, and interferometers as well as pointing and control of large space structures, spacecraft bus technologies, information processing, and tether technologies applied to upper atmospheric science.

More specifically, the team's task was to review the proposed NASA OAST plans, especially those for the Global Change Technology Initiative (GCTI) starting in 1991, and recommend whatever modifications seemed appropriate. The members were encouraged to adopt a broad-based position, which might include the formulation and assessment of new missions. The principal charge to the team, however, was to focus on technology.

Key Questions

To facilitate the concentration of the team's attention on the most critical issues, NASA identified a set of key questions (Table 3-1).

Table 3-1. Key Questions Posed to Review Team

Does OAST have the correct goals and objectives?
Does OAST have all the correct thrusts? Elements?
What are your technology advocacy recommendations?
What is your prioritization of the elements?
Should this be a research and technology (R&T) base or a focused program? What should the deliverables be?
How does this program relate to similar programs in other agencies? Overlap?
How do in-space experiments fit into the technology development plans?
How does this program relate to the Civil Space Technology Initiative (CSTI)?
Are the budget projections realistic?
What are the other questions?

Source: NASA Office of Aeronautics and Space Technology

Objectives and Approach

As originally defined, the study's objectives were to: (a) identify needed technology developments for earth system science and operational systems for long-term global climate observation and prediction; (b) recommend technologies for the OAST GCTI, including those that should augment the OAST R&T Base program and those that should be pursued elsewhere within NASA; and (c) review NASA's preliminary technology roadmaps, budget estimates, and milestones.

The planned approach was to gather inputs from the earth science community concerning observation goals and related technology needs (see Appendix for a list of the presentations made to the team), then determine the technology drivers, and finally prioritize technology requirements.

As this report will show, the review team was unable to fulfill this plan completely. Although all elements of the objectives and approach were addressed, certain objectives were not fully achieved, primarily because the necessary groundwork has not been performed.

4. Earth Observation Programs, Missions, and Systems

United States Global Change Research

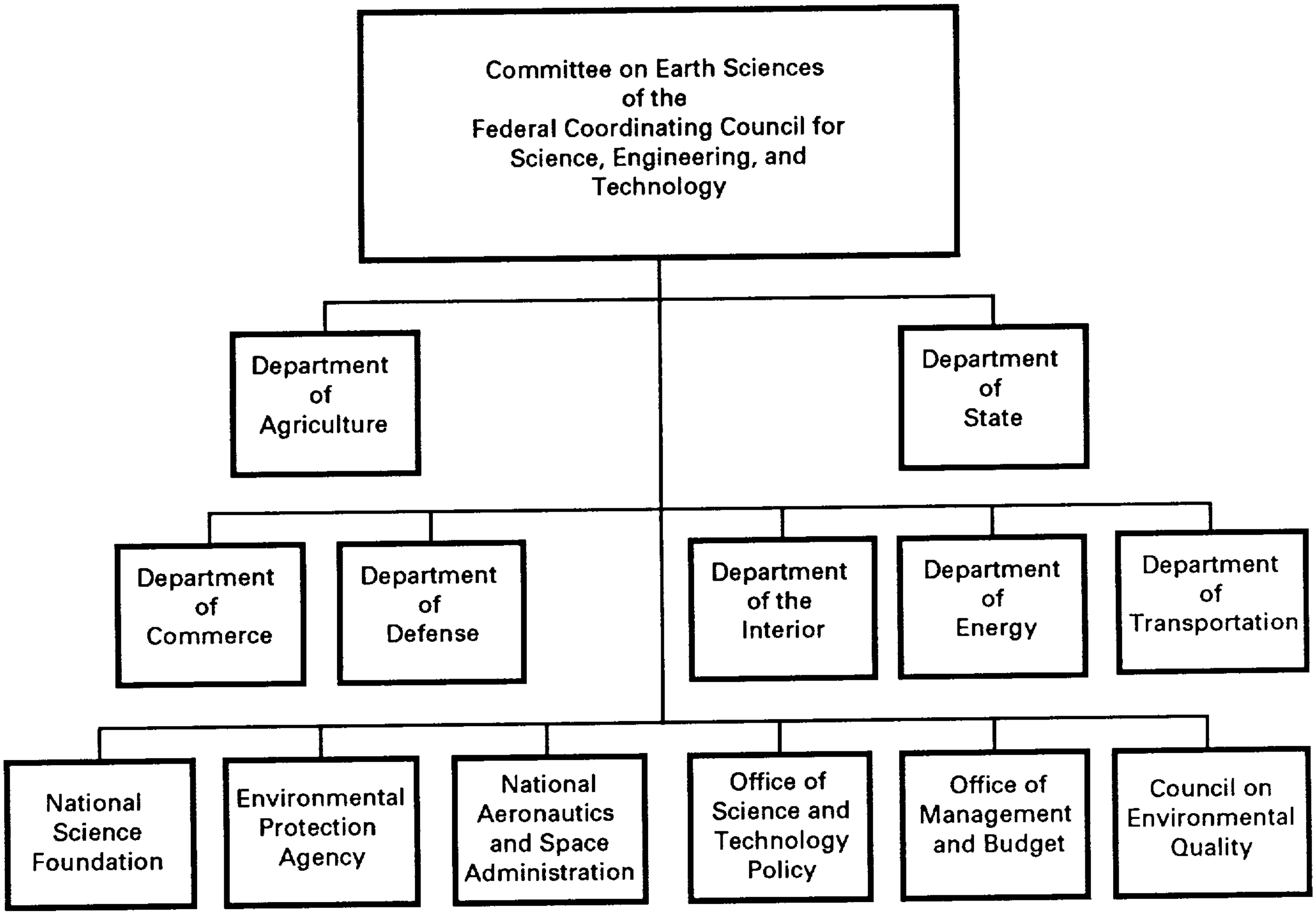
In *Our Changing Planet,* a report written to accompany the United States President's Fiscal Year 1990 budget, the Committee on Earth Sciences (CES) of the Federal Coordinating Council for Science, Engineering, and Technology (FCCSET) outlines "A Strategy for Global Change Research." A broad-based interagency organization, the CES includes representatives from 13 United States departments and agencies (Figure 4-1).

According to its charter, "The purpose of the Committee on Earth Sciences is to increase the overall effectiveness and productivity of Federal R&D efforts directed toward an understanding of the Earth as a global system." The committee's report attempts to define an overall United States Global Change Research Program, the goal of which is: "To establish the scientific basis of national and international policymaking related to natural and human-induced changes in the global earth system." The CES states that the scientific objectives of this program are to monitor, understand, and ultimately predict global change.

Mission to Planet Earth

The space segment of our nation's scientific efforts at earth observation falls within the scope of the National Aeronautics and Space Administration. NASA is responsible for advanced research and development activities to preserve United States preeminence in the exploration and exploitation of space. The Office of Space Science and Applications (OSSA) conducts NASA's scientific program activities, while the Office of Aeronautics and Space Technology (OAST) provides the advances in technology necessary to accomplish the programs. Both contribute to the technology base for operational space observations, which are the responsibility of the National Oceanic and Atmospheric Administration (NOAA).

The concept which encompasses NASA's long-term participation in earth observation is the Mission to Planet Earth, first suggested in the 1987 Ride report to the NASA Administrator entitled *Leadership and America's Future*



Source: *Our Changing Planet: A U.S. Strategy for Global Change Research*, A Report by the Committee on Earth Sciences To Accompany the U. S. President's Fiscal Year 1990 Budget

Figure 4-1. Membership of the Committee on Earth Sciences

in Space. Mission to Planet Earth is a proposed initiative which seeks to understand our home planet — how forces shape and affect its environment, how that environment is changing, and how those changes will affect us. Data gathered over a decade or more from a space-based global perspective can be compared with data from earth-based observations to produce models for global change which are more comprehensive — and presumably more accurate — than any present-day models. The goal is to obtain a comprehensive scientific understanding of the entire earth system by describing how its various components function, how they interact, and how they may be expected to evolve on all time scales. The ultimate challenge is to develop the capability to predict changes that might occur either naturally or as a result of human activity. Toward that end, the guiding principle behind the Mission to Planet Earth Initiative is the adoption of an integrated approach to observing earth. Implementation of this OSSA initiative has been proposed for Fiscal Year 1992.

Global Change Technology Initiative

While current OAST programs, particularly the Civil Space Technology Initiative (CSTI), support OSSA's near-term missions, new technology efforts will be necessary to progress into the next era of earth observation, beyond the 5-year scope of CSTI. To ensure availability of the technologies which will be required for the Mission to Planet Earth, OAST is developing a Global Change Technology Initiative (GCTI) for initiation in Fiscal Year 1991.

The goal of this initiative is to provide the technology needed to enable and enhance the long-term observation, documentation, and scientific understanding of the earth as a system. The GCTI's adequacy in providing for the technology needs of the Mission to Planet Earth is the primary focus of this study. Review and assessment of NASA's plans and strategies constitute the team's essential approach to the study.

Planned and Proposed Missions/Systems

The three proposed mission classes that form the space segments for the Mission to Planet Earth are the Earth Observing System (Eos), the Earth System Explorer missions, and the advanced Geostationary Earth Science platforms.

Eos, a series of low earth polar orbit platforms, each containing multiple scientific instruments, is being planned to begin deployment in the mid-1990s. Subsequent launches will provide growth in the number and quality of remote sensing capabilities through the year 2000, and continuous operation of the system at full capacity until at least 2010. The presently developing Eos strategy, which reflects extensive international cooperation in many program aspects, calls for two United States platforms, two European Space Agency platforms, and one Japanese platform. The Eos mission will create an integrated scientific observing system that will enable long-term multidisciplinary study of the earth.

Eos will establish the research capability of advanced instrumentation, including high-resolution spectrometers, multichannel radars, and space-based lidars, to yield measurements of earth system characteristics such as mineral composition, land-surface vegetation, cloud properties, deformation of continental plates, atmospheric winds, aerosols, boundary-layer properties, and certain trace constituents.

The second space segment is a proposed series of Explorer-class missions called Earth Probes, and the use of well-established instruments mounted on long-term platforms such as the space station. In addition to the powerful synergisms within Eos, there are some observing needs that require other low earth orbit (LEO) configurations or dedicated spacecraft. Notable examples include measurements of the earth's gravitational field from an orbit sufficiently low to yield adequate spatial resolution, measurements of the precipitation throughout the diurnal cycle with active microwave techniques, observations of the earth's magnetic field using sensors isolated from electrical interference, and in situ investigation of the properties of the thermosphere.

The third possible space segment of a total system for global earth observation consists of advanced platforms in geosynchronous earth orbit (GEO). These offer several advantages over other platforms. Foremost is the capacity for high temporal resolution, limited only by instrument design and cost, to be brought to bear on the study of rapidly changing, global atmospheric phenomena. This type of orbit also would provide a fixed reference geometry for a given earth location, facilitating data analysis and interpretation; this advantage has been demonstrated by operational geosynchronous satellites, in service since 1974, which carry imager/sounder instruments providing high-resolution visible and infrared images of the earth. The infrared channels of the sounding instruments yield frequent temperature and moisture profiles over large areas of the earth. Another major advance would be passive-microwave sensing of regions of precipitation. (The capability of microwave sounding is not now available because of the large antenna required for adequate spatial resolution at GEO altitudes.)

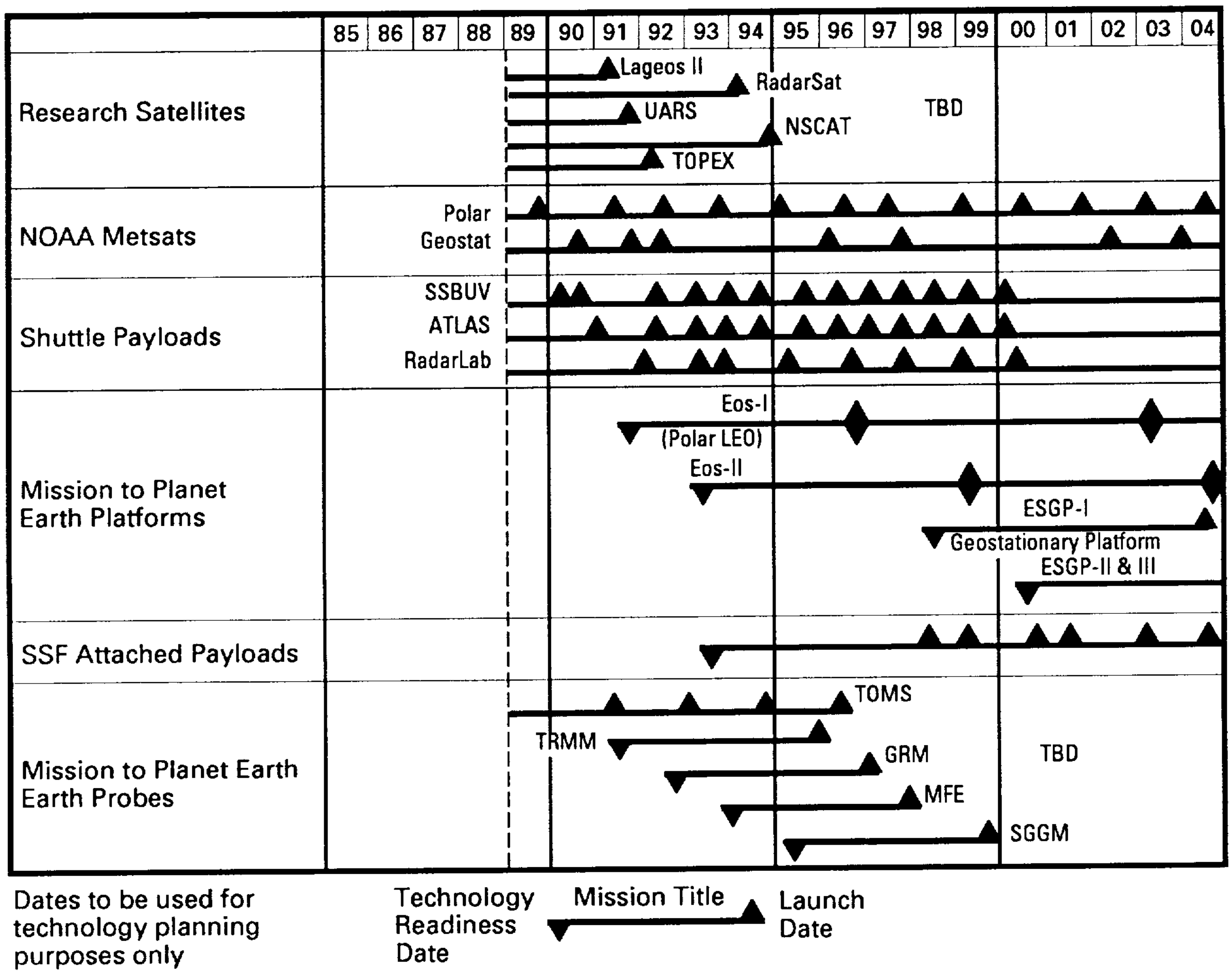
NASA's near-term and far-term plans for earth system science exploration are summarized in Table 4-1. Although some of the technology needs for near-term goals are partially supported through CSTI, efforts such as the later Eos investigations might benefit from technological advances resulting from GCTI. Early investment in an independent, focused technology program will help ensure that technology is ready and tested before developing programs commit to hardware development.

The urgency of proceeding with the technology development necessary for accomplishing the Mission to Planet Earth is highlighted by Figure 4-2, a timeline indicating the multitude of possible spacecraft related to Mission to Planet Earth (triangles pointing up) and their associated technology readiness dates (triangles pointing down). Many of the technology readiness dates do not appear on this figure — they were judged to occur prior to 1989 — and almost none are indicated as being later than 1995. The figure demonstrates that we are rapidly approaching the point where significant resources must be applied to begin developing technologies necessary for the Mission to Planet Earth.

Table 4-1. NASA's Near-Term and Far-Term Plans for Earth System Science Investigations

Time Frame	Plans
Near Term: To 1995	Complete planned missions • Continue development and timely completion of ongoing missions • Extend and enhance continuing/operational earth observations by NOAA, NASA, and others Develop Eos instruments and platforms Initiate Earth Probe Explorer-class missions • Establish an Earth System Explorer series of missions • Fly other demonstrated instruments on available platforms Continue research • Expand and coordinate interdisciplinary earth system research and in situ measurements • Continue strong emphasis on earth science studies within major disciplines • Develop instruments and techniques for future use Develop ground data system • Pursue development of an information system for earth science
Far Term: 1995 and Beyond	Initiate new era of integrated global observations of the earth • Eos with NASA instruments, NOAA instruments, and foreign instruments • Complementary global research from ground, balloons, and airplanes • Continuation of Earth System Explorer missions • Advanced geostationary platforms to support new generation of research and operational measurements from GEO Expand and vigorously utilize the information system for earth system science Obtain sustained support by federal agencies for an expanded, coordinated, interdisciplinary program of basic research and process studies

Source: NASA Office of Aeronautics and Space Technology



Source: NASA Office of Aeronautics and Space Technology

Figure 4-2. Mission to Planet Earth Technology Mission Model

Review Team's Reactions to NASA's Mission Plans

One fundamental issue pervaded the review team's discussion of the Mission to Planet Earth and GCTI's support of it: lack of a coherent architecture. The committee felt hampered in their ability to assess OAST's GCTI plans because of insufficient mission and system planning and analysis. Adequate definition of architecture was viewed as prerequisite to addressing many technology issues. Considerations such as orbital configuration and constellation (including altitude and number of spacecraft), refurbishment capabilities, and platform and instrument lifetimes will significantly impact not only technology selection but also development and deployment costs.

Table 4-2 illustrates how the architecture impacts technology. As an example, the review team made a preliminary investigation of constellation designs and found questions of optimum design to be a function of altitude, orbit definition, sensor mask angle constraint, and number of satellites. Using a mid-orbit constellation (10,000 km), the projected results were very encouraging when compared to the selected geosynchronous constellation. If more detailed future analyses, including operational considerations, demonstrated that a lower orbiting constellation were indeed competitive, then such an option would significantly reduce the sensor apertures, which would in turn reduce technology risk and cost.

Table 4-2. Architecture-Related Technologies

Architecture Questions	Related Technologies
Cost-science benefit analysis: What do we lose if an experiment is dropped? How do we prioritize sensor instruments?	All sensor and information processing technologies
Operational concept: How is the information presented to the user and how does man operate the system?	Information processing, formatting, and data retrieval
Constellation design: How many satellites and at what altitude?	Instrument aperture and power, spacecraft structure, data storage, pointing and precision, and communications
Refurbishment: Do we design a modular replaceable spacecraft? Do we go for a long-life spacecraft or do we implement planned replacement?	Robotics and power

The review team's recommendation is that architecture studies be initiated as soon as possible — preferably by 1990 — in order to establish the foundation for Mission to Planet Earth planning and technology selection. These studies should include cost-benefit trade-off analyses as well as definition of a comprehensive operational concept. Moreover, the team considers this issue to be a massive topic which encompasses far more than the concerns of OAST and GCTI: it is fundamental to the planning of any national, and possibly international, far-term earth observation mission.

Other concerns of the team are closely related to the architecture question. For one, the end user of these systems has not been well defined; the kind of data needed and use of the data obtained will significantly affect system design and architecture. Also, little consideration has been given to ground-based systems to support space-based observations (e.g., sites for development, instrument calibration, and data storage, retrieval, sorting, and distribution).

Finally, there is a serious lack of focused leadership for the Mission to Planet Earth. While the Committee on Earth Sciences has presented a strategy for a United States Global Change Research Program, and has expressed an intention to produce a more detailed plan, it is more an advisory and review panel than a managing body. (In any case, its charter expires at the end of 1990.) There is an unmet need for focused program leadership and decision making for the Mission to Planet Earth. This is a national issue.

5. Technologies

Requirements Flow

Investigating what technologies will be required to perform future global observations, scientists at the Jet Propulsion Laboratory (JPL) (themselves very interested in potential long-term experiments) surveyed members of the scientific community to assess which types of observations will be most important for GCTI to support. Figure 5-1, devised by the JPL scientists, shows the requirements flow between scientific targets and enabling technologies, starting with the observable global phenomena and progressing through measurement parameters and observing systems to key technology needs.

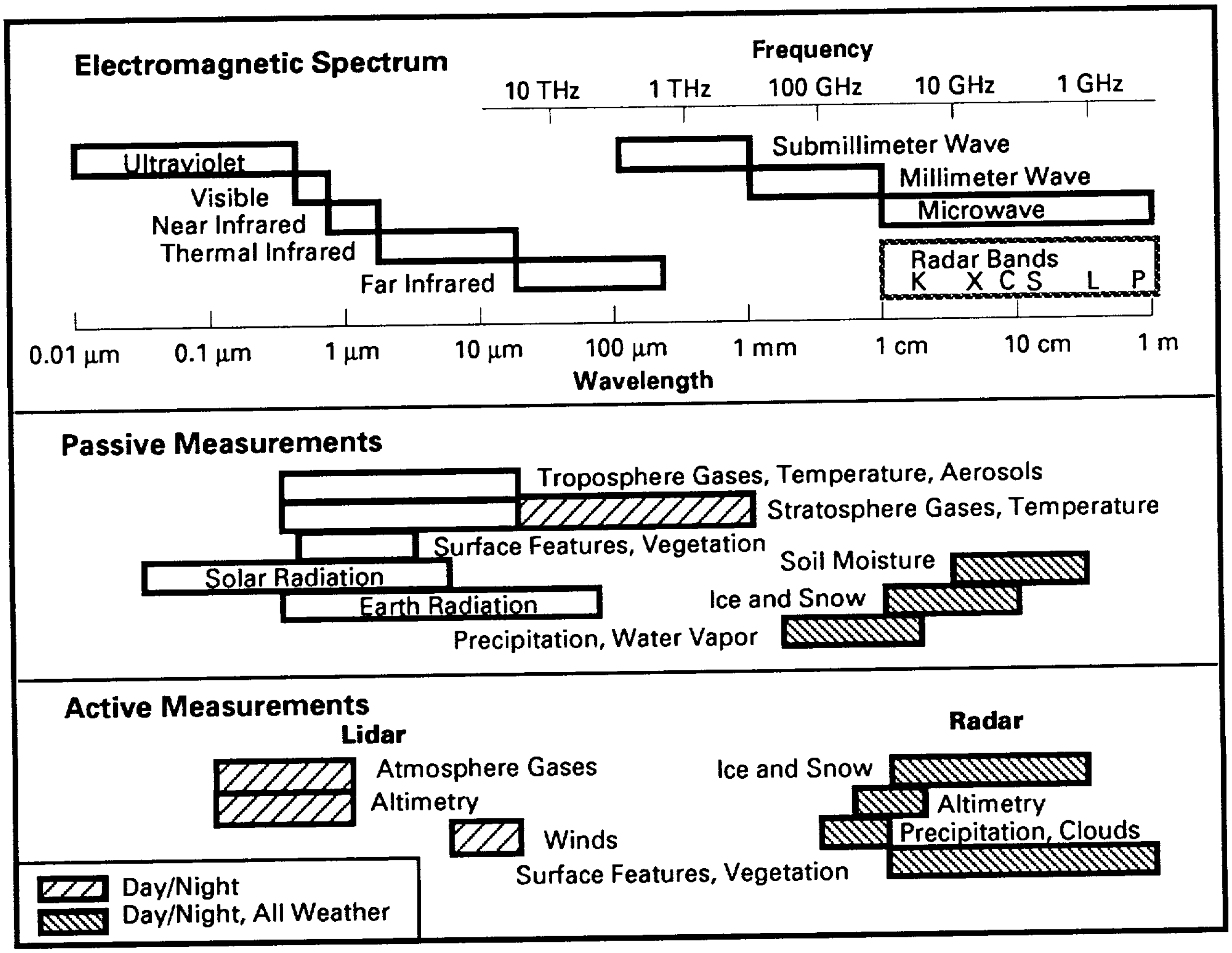
As the authors of this chart point out, it presents only a preliminary list. The next step will be to somehow weight the measurables in terms of importance, which will aid NASA in prioritizing required technologies. This is a difficult task, however, because the scientists involved in global change research consider all measurements important. "How can we know," they ask, "exactly which data ultimately will prove to be significant?" Figure 5-2, which summarizes global change measurement regimes, suggests the breadth of coverage involved in obtaining these data.

There have been efforts made to rank desired measurements according to their criticality. A 1988 report of the Earth System Sciences Committee of the NASA Advisory Council listed 56 global variables that require sustained, long-term observation and measurement (Table 5-1). Of these, 15 items were rated essential for understanding global change, 10 of which are inadequately studied at present:

- Atmospheric pressure
- Rainfall/precipitation
- Vegetation cover/color index

- Soil moisture
- Biome parameters (extent, productivity, and nutrient cycling)
- Sea surface temperature
- Ocean wind stress
- Ocean circulation
- Ocean chlorophyll
- Small-scale plate deformations.

In another report, written in 1987, an ad hoc group of the Committee on Space Research (COSPAR) discussed what new technologies should be developed to measure those parameters which have so far remained unobservable from space, but are crucial for the study of global change. Included among these parameters are the rate, intensity, and distribution of global rainfall; the changing chemistry of the troposphere; and the fluxes of energy and gases between the biosphere and the atmosphere. The COSPAR group recommended that high priority be given to studying techniques for the measurements of precipitation, soil moisture, and tropospheric chemistry and aerosols.



Source: NASA Office of Aeronautics and Space Technology

Figure 5-2. Global Change Measurement Regimes

Table 5-1. Sustained Long-Term Measurements of Global Variables

Variable	Importance*	Technique
External forcing		
Solar irradiance	Essential	Active cavity radiometer
Ultraviolet flux	High	Ultraviolet spectroscopy
Index of volcanic emissions (into atmosphere)	Substantial	In situ case studies Stratospheric aerosols Visible Infrared images Ice-core acidity
Concentrations of radiatively and chemically important trace species		
CO_2	Essential	In situ
N_2O	High	In situ Infrared emission Infrared occultation Infrared interferometry
CH_4	High	In situ Infrared emission Infrared occultation Infrared interferometry
Chlorofluoromethanes (CFM)	High	In situ Infrared interferometry
Tropospheric O_3	High	In situ Aircraft Lidar (surface)
CO	High	Surface Infrared spectrometry Infrared emission
Stratospheric O_3	Essential	Ultraviolet reflectance Dobson Sondes Microwave Infrared emission Infrared occultation Infrared interferometry Lidar (surface)

* For documenting and understanding global change

Source: *Earth System Science, A Closer View (A Program for Global Change),* Report of the Earth System Sciences Committee, National Aeronautics Advisory Council, 1988.

Table 5-1. Sustained Long-Term Measurements of Global Variables (Continued)

Variable	Importance*	Technique
Concentrations of radiatively and chemically important trace species (continued)		
Stratospheric H_2O	High	Frostpoint Infrared emission Infrared occultation Infrared interferometry
Stratospheric NO_2	Substantial	Occultation Visible spectrometry Infrared emission Infrared interferometry
Stratospheric HNO_3	Substantial	Various Infrared limb scan
Stratospheric HCl[3]	Substantial	Various Infrared interferometry Occultation Infrared emission
Stratospheric aerosols	High	Occultation Lidar (surface)
Atmospheric response variables		
Surface air temperature	Essential	In situ
Tropospheric temperature	Essential	Radiosonde Infrared Microwave
Stratospheric temperature	High	Radiosonde Microwave Infrared interferometry Infrared limb scan
Pressure (surface)	Essential	In situ Microwave
Tropical winds	High	Radiosonde Cloud motion Doppler lidar
Extratropical winds	Substantial	Radiosonde Doppler lidar
Tropospheric water vapor	High	Radiosonde Microwave Infrared Lidar

*For documenting and understanding global change

Table 5-1. Sustained Long-Term Measurements of Global Variables (Continued)

Variable	Importance*	Technique
Atmospheric response variables (continued)		
Precipitation	Essential	Raingage Infrared Microwave Radar
Components of earth radiation budget	High	Wide field of view Scanner
Cloud amount, type, height	High	Surface observations Satellite imaging In situ
Tropospheric aerosols	Substantial	In situ Visible reflectance Lidar
Land-surface properties		
Surface radiating temperature	Substantial	Infrared Microwave
Incident solar flux (surface)	Substantial	In situ Visible
Snow cover	Substantial	Visible Infrared In situ Microwave
Snow water equivalent	Substantial	In situ Microwave
Ice-sheet volume (changes)	Substantial	Lidar
River runoff (volume)	Substantial	In situ
River runoff (sediment loading)	Substantial	In situ
River runoff (chemical constituents)	Substantial	In situ
Surface characteristics (for albedo, roughness infrared, and microwave emittance)	Substantial	In situ Visible Microwave Infrared Radar
Index of land-use changes (broad classification of surface and vegetation type)	High	In situ Visible High resolution Infrared

*For documenting and understanding global change

Table 5-1. Sustained Long-Term Measurements of Global Variables (Continued)

Variable	Importance*	Technique
Land-surface properties (continued)		
Index of vegetation cover	Essential	Color Microwave Test sites
Index of surface wetness	Substantial	In situ Microwave
Soil moisture	Essential	Surface energy and moisture balance
Biome extent, productivity, and nutrient cycling	Essential	In situ Visible Infrared spectrometry
Ocean variables		
Sea surface temperature	Essential	In situ Infrared Buoys Microwave Visible
Sea-ice extent	High	Microwave
Sea-ice type	Substantial	Radar Microwave In situ
Sea-ice motion	Substantial	Surface drifters Radar
Ocean wind stress	Essential	In situ wind Microwave Scatterometer
Sea level	High	Tide gage Altimeter
Incident solar flux	Substantial	Visible
Subsurface circulation	Essential	In situ
Ocean chlorophyll	Essential	Color In situ
Biogeochemical fluxes	High	In situ
Ocean CO_2	High	In situ

* For documenting and understanding global change

Table 5-1. Sustained Long-Term Measurements of Global Variables (Continued)

Variable	Importance*	Technique
Geophysical variables		
Plate motions	High	Very large baseline interferometry Laser Altimetry
Plate deformations (small-scale)	Essential	Laser Positioning by satellite Seismic In situ Satellite imagery
Polar motion and earth rotation	Substantial	Very large baseline interferometry Lunar ranging
Time-dependent magnetic field	Substantial	Satellite In situ
Changes in gravity	Substantial	Satellite tracking

* For documenting and understanding global change

Technology Thrusts

While considerable work remains to be done in prioritizing observation goals and thus technology requirements, NASA has defined major areas of focus and key technologies to emphasize in the GCTI.

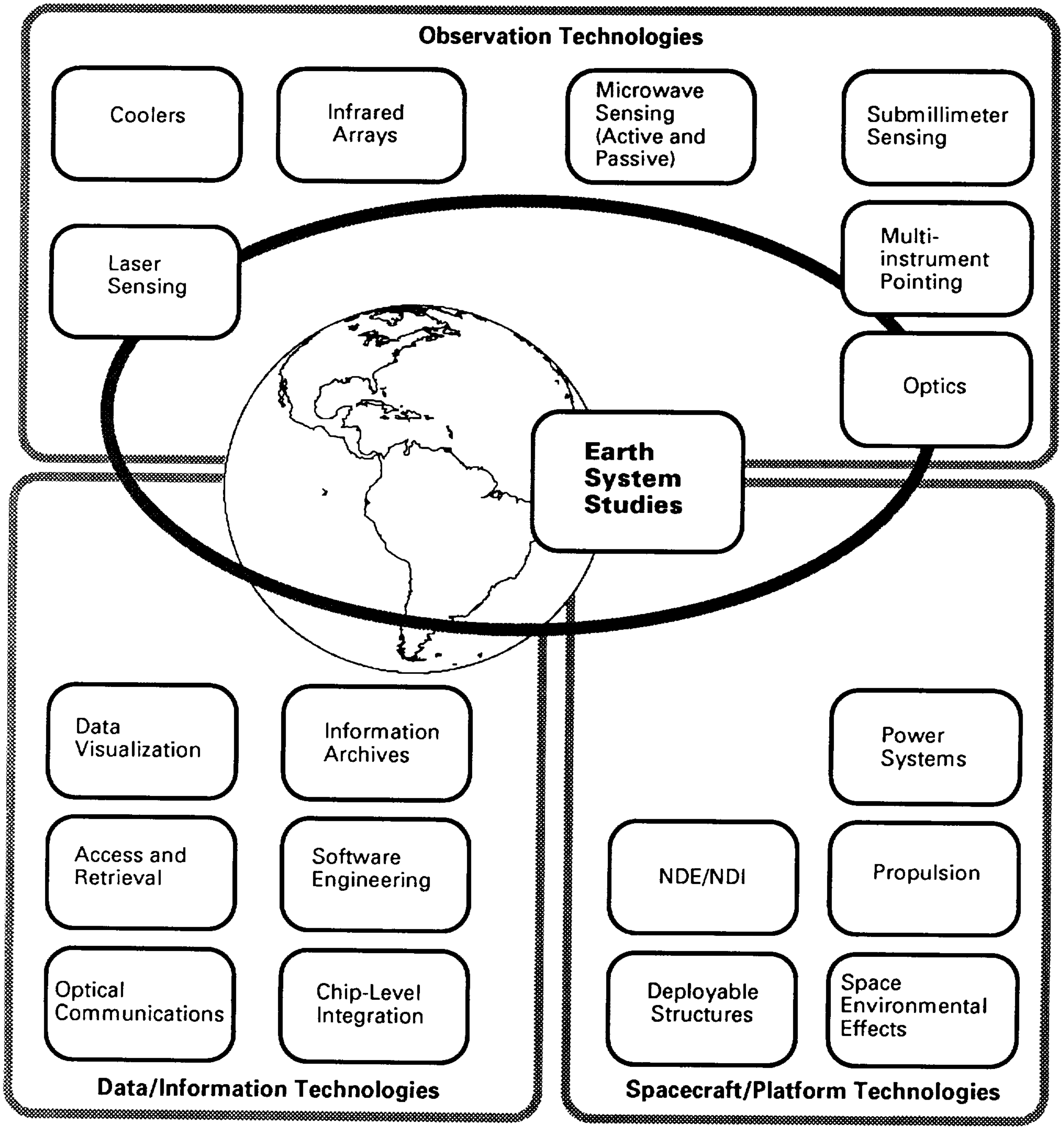
As stated by Dr. Sally Ride in her report to the NASA Administrator, Mission to Planet Earth requires advances in technology to enhance observations, to handle and deliver the enormous quantities of data, and to ensure a long operating life. The three themes identified by Dr. Ride form the basis for the structure of the GCTI. The Observation Technologies thrust will advance the technology to enhance observations, the Information Technologies thrust will advance the technology to handle and deliver the enormous quantities of data, and the Operations Technologies and Spacecraft Technologies thrusts will advance the technology to ensure a long operating life. Figure 5-3 is an overview of OAST's assessment of the key technologies targeted within each of these GCTI thrusts.

Observation Technologies

The GCTI Observation Technologies thrust will focus on the scientific requirements for sustained, long-term measurements of global variables through the development of spacecraft and space-based instrument technologies. This thrust will include precision pointing and vibration control, optical systems, cryogenic systems, laser and radar sources for active sensing, sensors and detector arrays, and the study of approaches to enhance instrument stability and calibration with decreased degradation from contamination and space environmental effects.

Table 5-2 presents OAST's assessment of key technologies necessary for long-term global observations, and the related GCTI development goals that have been proposed; each technology's primary mission association — whether with Eos or LEO/GEO platforms — is indicated also. NASA's rationale for highlighting these particular technology and development needs is summarized below.

One of NASA's basic assumptions is that full implementation of Mission to Planet Earth will include placing observation platforms in GEO. This assumption has influenced NASA's selection of key technologies to be emphasized in the GCTI. Many chosen technologies are not altitude dependent; a number are.



Source: NASA Office of Aeronautics and Space Technology

Figure 5-3. Key Global Change Technologies

Table 5-2. Observation Technologies Emphasized by OAST

Eos Technologies	Development Goals
• Cryogenic coolers	• Develop a backup to the Oxford cooler
• Infrared arrays	• Develop detector arrays in the 12- to 20-micron regime
• Active microwave	• Develop lightweight antennas and power-efficient electronics
• Laser sensing	• Establish fundamental R&T optics program
• Pointing and control	• Develop multi-instrument pointing modeling tools
LEO/GEO Technologies	• Enable solid-state lasers for space science
• Microwave sensing	
• Optics	

Source: NASA Office of Aeronautics and Space Technology

NASA's scientists and technologists feel that a major advantage of GEOs for earth observing platforms is the ability to acquire continuous observations with high temporal resolution. Earth system processes which require high temporal resolution observations also require high spatial resolution. Despite the substantially greater altitude of GEOs over the orbits of the Eos and the Explorer-class missions, the phenomena observed require the highest possible spatial resolution. This in turn means greater requirements for precision pointing and platform control.

Technology developments in precision pointing and vibration control for remote sensing instruments are important for the accurate pointing of multiple instruments and for large (up to 80 meters in diameter) radiometric antennas. The goal is to allow simultaneous and continuous observation of the earth by multiple instruments with minimal interference. In NASA's proposal, this effort would work synergistically with the efforts proposed under the Spacecraft Technologies thrust, and would develop technologies for precision alignment and/or compensation for deformations, momentum compensation for scanning instruments, and inter-instrument isolation. The pointing requirements of the precision instruments on the platform mandate that the large radiometric antennas not disturb the dynamics of the entire platform.

To allow high-quality, long-term, and continuous observation of earth processes on local to synoptic scale from GEO, optical systems technology research needs to be conducted. This should include diffraction gratings, ultraviolet thin films, electro-optic crystals, acousto-optic filters, hologram optical elements, and optical system performance modeling. Such research would develop an optics technology base supporting ultraviolet, visible, and infrared high-resolution (spatial, spectral, and temporal) observation of the earth.

Technology research and development in cryogenic systems would provide long-term instrument cooling while handling the thermal input of continuous observation of the warm earth. These coolers and systems would require integration with platform thermal systems.

Advanced sensors and detector arrays would permit remote sensing across the electromagnetic spectrum from the microwave to the ultraviolet (see Figure 5-2). Three regions of the spectrum, the submillimeter range (300 to 3000 GHz), the millimeter range (30 to 300 GHz), and the thermal infrared range (5 to 20 microns), are especially critical for understanding global climate change. (The region from 10 to 200 GHz is particularly useful for metrology.)

The submillimeter range is used for measuring trace species in the upper atmosphere related to ozone chemistry. The millimeter range is used for precipitation monitoring. Both require developments in sensors as well as supporting systems such as mixers and oscillators. The thermal infrared range corresponds to the peak of the thermal emission from the surface of the earth, and is the region of the spectrum in which the greenhouse gases play a crucial role. The materials for these sensors must be highly reliable and stable, with minimum impact from contamination, radiation, and the space environment. This will allow the long-term, sensitive measurements necessary to detect long-term changes in global climatic parameters that are buried beneath the day-to-day variations in weather. Two-dimensional detector arrays for the 12- to 20-micron range are beyond the capabilities of current technology.

Large precision antennas would enable microwave sounding with adequate spatial resolution from geosynchronous orbit. Since it is estimated that about half of the earth's rainfall occurs in short-lived, small-scale storms, resolution corresponding to the size of these storms (10 km) is needed to provide complete rainfall monitoring data. Observations at 36 GHz with an earth footprint of 10 km require an antenna diameter of 40 meters. These large antennas would require precision shape correction and steering to allow coverage of the globe, either mechanically or through receiver array adjustments. Measurements above about 36 GHz require solid surface reflectors while lower frequency measurements can use large mesh reflectors. Unfilled aperture or interferometric techniques could provide an alternative approach for the large antennas needed for frequencies less than 36 GHz. Special microwave-transparent structural materials may be necessary to achieve the instrument performance requirements. Array feeds will be required for effective off-boresight pointing and scanning.

Information Technologies

In the Information Technologies thrust, human factors research in scientific visualization, and research in both on-board and ground data/information technologies such as software engineering, advanced computing, data storage, and data/information networks will support the technology needs for the Mission to Planet Earth. This will include development of integrated computer models for earth system science and an information system capable of enabling the analysis and understanding of integrated data sets from both space-based and in situ instruments.

Table 5-3 presents OAST's assessment of key technologies necessary to handle the unprecedented data loads associated with the Mission to Planet Earth; the related GCTI development goals are given also. NASA's rationale for highlighting these particular technology and development needs is summarized below.

It has been suggested that the entire data base for the United States Internal Revenue Service amounts to some 30 trillion bits of information. In contrast, by the mid-1990s, space-based remote sensing observations of the earth may be acquired at the rate of about 10 trillion bits per day. This trend would continue with the addition of the earth science geostationary platforms. Converting this data stream into useful information that can be understood and applied by the user community will be a high-payoff area for technology development. Human factors research to enhance scientific visualization will seek ways to improve the man/machine interface for the interchange of scientific information, and to use the unique pattern recognition and cognitive capabilities of human beings to review and assimilate the massive amounts of data that will be received.

Table 5-3. Information Technologies Emphasized by OAST

Eos Technologies	Development Goals
• Optical communications • Data information visualization • Information access and retrieval	• Enable rapid human recognition of features and trends in multispectral and multidimensional data • Develop integrated sensor/preprocessors • Create environment for reliable, complex software • Develop high-rate communications capability to transfer massive amounts of data • Allow for scientific utilization of massive data archives
LEO/GEO Technologies • Sensor/processor chip-level integration • Software engineering	

Source: NASA Office of Aeronautics and Space Technology

Mission to Planet Earth platforms call for on-board processors capable of handling the high data rates and large data volumes generated by the multiple scientific and operational instruments, necessitating the development of space-qualifiable component technologies such as on-board, high-performance integrated circuit fiber optic transceivers and low-power, high-speed, radiation-hard GaAs processors.

Software engineering research must develop the tools and techniques to enhance software reliability, and facilitate the use of new parallel architectures for high-performance parallel processor computers, the processing architecture needed for global ocean-atmosphere-biosphere systems simulations.

NASA points out that the nature of geostationary orbits greatly simplifies high-bandwidth, direct data communications by remaining fixed relative to the earth, allowing dedicated ground stations that can provide the needed telemetry capability without interruption. These geostationary science platforms could also be used as relay stations for the collection of data from other geostationary platforms not in view from the United States; from low earth orbiting platforms including the Eos; and from aircraft, ocean floats, and other in situ sensors. In addition, these platforms might be used for the dissemination of scientific information to the national and international scientific communities. For these applications, technology development leading to possible flight demonstrations of laser communications may be needed.

Operations and Spacecraft Technologies

In the Operations Technologies thrust, automation technologies for on-board and ground-based systems will enable more flexible spacecraft operations and interspacecraft coordination. Operations automation technologies for on-board and ground-based systems will seek to automate the routine and/or repetitive housekeeping functions associated with the day-to-day operation of spacecraft, either on board the spacecraft, utilizing advanced data system capabilities, or in the ground mission operations computer system. System approaches that minimize the interaction of spacecraft subsystems will simplify the command generation process, and could allow telescience, the direct control of scientific observations by the scientists from their home institutions. This will also increase the capabilities/cost ratio by enabling more efficient ground operations for these long-duration missions. It is unclear whether, and at what point, on-orbit servicing will become a viable option. The energy required to access polar and geostationary orbits limits the ability to perform servicing missions and will increase the importance of long life, increased reliability, and increased efficiency in the use of expendables.

Under the Spacecraft Technologies thrust, the long-term, sustained nature of the Mission to Planet Earth will be enhanced through basic technology research and development to increase spacecraft reliability and lifetime. This thrust will include technologies in areas such as reliability and quality assurance, nondestructive inspection and evaluation, long-life materials and structures, platform structural concepts, power and propulsion systems, thermal control systems, platform charging, and space environmental effects.

Table 5-4 presents OAST's key technologies necessary to assure a long operating life for the Mission to Planet Earth observation platforms, and the related GCTI development goals. NASA's rationale for highlighting these particular technology and development needs is summarized below.

Technology research in long-life materials and structures will be aimed at developing and characterizing new structural materials for long-term operation in both low and geostationary earth orbit environments. This research would include scaling up and characterizing promising new material systems into structural subelements for large precision platforms and reflector support structures; currently available materials may not provide the required specific stiffness and thermal stability for very large structures.

Propulsion research and technology should concentrate on the development of long-life, high-specific-impulse, low-contamination propulsion systems for orbit transfer, orbit maneuvering, and stationkeeping. Power research and technology aims are to develop high-performance, autonomous, lightweight,

Table 5-4. Spacecraft Technologies Emphasized by OAST

Technologies	Development Goals
Eos Technologies	
• Nondestructive evaluation and inspection	• Allow real-time condition monitoring of spacecraft structure
LEO/GEO Technologies	
• Power systems	• Develop components, materials, and concepts to enable deployment/ operations of large earth science platforms
• Propulsion (reliable, low contamination)	• Select and develop environmentally stable systems and coatings
• Space environmental effects	• Develop high-energy density power systems
• Deployable structures	• Develop long-life, high-performance, low-contamination propulsion

Source: NASA Office of Aeronautics and Space Technology

and reliable power generation, storage, and distribution components for high-density power systems to support platform operation, active sensing, and propulsion with minimum maintenance and ground interaction. These systems will allow advanced science, advanced propulsion, and improved communications, as well as the possible use of electric propulsion to minimize propellant requirements for platform orbit transfer and on-orbit stationkeeping.

Research and technology development in space environmental effects should include integrated thermal control systems and designs for advanced earth science platforms.

Spacecraft charging is a concern of all geosynchronous spacecraft, and the phenomenon is increased by size and voltage levels. Improvements in platform charging models would allow better understanding of vulnerability to spacecraft charging of the Mission to Planet Earth platforms, and technical approaches for mitigation would allow long-term operation without interruptions or damage from geomagnetic substorms. Similar research should be conducted in contamination, radiation damage, and debris damage.

Review Team's Reactions to NASA's Technology Assessment

After reviewing NASA's proposal, considering scientists' "wish lists," and discussing possible technologies for the Mission to Planet Earth, the review team concluded that NASA has identified all the technologies necessary to support the OAST GCTI.

The review team identified the Information Technologies thrust as the most important to pursue vigorously. The data loads which will be generated by the sensing systems of the Mission to Planet Earth platforms are massive and unprecedented, almost beyond realistic comprehension. The current Eos project estimate is that its platforms will transmit in a few days as much data as the entire space program has sent to earth since 1958. Current resources and technologies are incapable of handling this magnitude of data flow. If any technology area needs a revolutionary breakthrough to enable long-term global observation, it is information processing.

Otherwise, the team felt that it was not possible for them to prioritize the recommended technologies using the information made available to them. Inputs received from the scientific community tended to be all-encompassing; scientists expressed interest in nearly every measurement and every instrument imaginable for global change studies. While the review team recognized that all the proposed measurements are important, they agreed that some differentiation must be made, at least for the purposes of establishing development schedules and budgets. Spreading the funds too thinly means inadequate coverage in every area. Until the measurement goals are ranked, the technologies cannot be prioritized.

Before any group can determine which technologies should be emphasized, in what order, and when, the groundwork must be done: cost-benefit trade-offs must be performed, the user and his needs must be defined, and the architectural and operational concepts must be refined.

The committee's recommendation is that after architecture studies have been performed, and scientists have progressed in prioritizing their investigations and instrument needs, a similar ad hoc group should meet again (no later than 1991) to reassess technology needs and priorities. This group did not, in fact, view their effort as a one-time event. The identification and prioritization of needed technologies are ongoing, dynamic processes; similarly, this study should be done iteratively, again and again, as the focus of Mission to Planet Earth becomes sharper.

In considering related technology programs, the review team expressed concerns about duplicate efforts occurring inadvertently or in isolation. To some extent, the FCCSET Committee on Earth Sciences can act as a coordinating agency to avoid redundancy of development and unnecessary expenditure of funds; however, the team recommended the formation of a special advisory group to compare, share, and use (to the extent possible) research and development which is under way.

6. Funding and Management

Technology Initiative Categories

OAST has divided the technologies targeted under GCTI into three initiative categories:

- **Eos Technology.** Technologies for low earth orbit application, directly related to Eos needs, either as backups for planned high-risk capabilities, or as future upgrades or parts of replacement platforms.
- **Low Earth Orbit/Geosynchronous Earth Orbit (LEO/GEO) Technology.** Long-lead, high-priority technologies that need to be started now in anticipation of a major agency thrust in space-based observation of the earth.
- **Mission to Planet Earth Technology.** Key technologies that must be pursued as part of a major agency thrust in space-based observation of the earth.

Table 6-1 presents the target technologies associated with each of these initiative categories.

Funding

Table 6-2 presents OAST's global change technology budget for Fiscal Years 1991 through 1995. In reviewing this budget, the team again stressed the point that it is impossible to evaluate priorities without better definition of science goals and overall program focus. Other conclusions regarding the proposed funding were:

- The budget is inadequate in all areas except optical communications. Support for development of all other technologies should be increased by at least a factor of 10.
- Funding is especially weak in the Information Technologies. Data collection, transmission, application, storage, and retrieval are fundamental to the realization of all mission goals, and should be emphasized.
- System studies should be front-end loaded, rather than rear-end loaded. Architecture studies, including cost-benefit trade-off analyses and operations plan definition, should begin at once.

Table 6-1. Technologies Associated with GCTI Initiative Categories

Eos Technology

- Cryogenic cooling systems
- Long-wave infrared arrays
- Microwave radar
- Laser sensing
- Precision pointing and vibration control
- Optical communications
- Data/information visualization
- Information access and retrieval
- Nondestructive evaluation and inspection
- Eos system studies

LEO/GEO Technology

- Microwave sensing
- Optical systems
- Sensor/processor chip-level integration
- Software engineering
- Power systems
- Propulsion
- Space environmental effects
- Deployable structures
- LEO/GEO system studies

Mission to Planet Earth Technology

- Biological sensors
- Thermal control
- Neural networks
- Advanced storage concepts
- Computing
- In situ sensors
- Instrument calibration
- Space mechanisms/tribology
- Tethers
- Information fusion
- Operations automation
- Ultraviolet sensors
- High-altitude aircraft

Source: NASA Office of Aeronautics and Space Technology

Table 6-2. Global Change Technology Funding (FY91$, M)

Technology Area	1991	1992	1993	1994	1995
Eos Technology					
Coolers	3.0	5.0	5.0	4.0	4.0
Infrared arrays	3.0	4.0	6.0	6.0	6.0
Microwave radar	1.0	1.0	1.0	1.0	1.0
Laser lidar	2.0	3.0	4.0	5.0	5.0
Pointing	4.0	8.0	12.0	12.0	12.0
Optical communication	7.0	14.0	14.0	6.0	4.0
Data visualization	1.0	2.0	4.0	4.0	4.0
Access/retrieval	1.0	2.0	3.0	4.0	4.0
NDE/NDI	1.0	2.0	4.0	4.0	4.0
LEO systems analysis	1.0	1.0	1.0	1.0	1.0
Subtotal	24.0	42.0	54.0	47.0	45.0
LEO/GEO Technology					
Microwave sensing	1.0	4.0	6.0	6.0	6.0
Power and propulsion	3.0	6.0	10.0	12.0	12.0
Chip-level integration	2.0	2.5	3.0	3.5	5.5
Optics technology	2.0	4.0	7.0	7.0	7.0
Software engineering	2.0	3.0	5.0	5.0	5.0
Space environmental effects	1.5	3.0	5.0	5.0	5.0
Deployable structures	3.0	6.0	10.0	10.0	10.0
Advanced systems studies	3.0	5.0	6.0	6.0	6.0
Subtotal	17.5	33.5	52.0	54.5	56.5
Total	41.5	75.5	106.0	101.5	101.5

Source: NASA Office of Aeronautics and Space Technology

Management

Management issues pervaded the review team's discussions. The questions of who will manage a long-term Mission to Planet Earth program, for whom, and for what purpose are closely related to considerations of end use, system architecture, and operations concept. The team's concensus and conviction was that the United States efforts at earth systems studies — whether known as Mission to Planet Earth or something else — should be a focused program. Moreover, the program should have strong and distinct leadership which moves forward as quickly as possible on definition of the program and clarification of the issues raised in this report.

At the same time, it was agreed that the program should continue to be broadly based, combining both interagency and international efforts. (NASA should guard against allowing a largely in-house, NASA-dominated technology effort to evolve.) In the words of Presidential advisor William R. Graham, director of the Office of Science and Technology Policy, "An effective and well-coordinated federal research program is crucial to this effort. The program must be both national and international, since global change crosses political as well as physical boundaries." We must make more effective use of all resources that have the potential of contributing. Special efforts will be required to achieve coordination among the many agencies performing research and development in technologies that have application to the Mission to Planet Earth.

7. Conclusions and Recommendations

Responses to Key Questions

In response to NASA's original list of questions, the review team offered the following conclusions:

- *Does OAST have the correct goals and objectives?*

  The GCTI goal statement should read as follows: "Develop the technologies that enable and enhance the long-term observation, documentation, and scientific understanding of the earth as a system." The final GCTI objectives should read: "Develop spacecraft, platform, and operations technologies to enable consistent long-term collection of these data." The OAST goals and objectives are appropriate and broad enough to encompass the required work.

- *Does OAST have all the correct thrusts/elements?*

  The basic thrusts of the GCTI are correct.

- *What are your technology advocacy recommendations?*

  NASA has selected the right technologies to address, and the selected technologies are indeed required, but virtually all are underfunded. The review team was not able to indicate which ones should be emphasized (or emphasized first), because there has been insufficient work done to support the architecture definition; the technologies and their implementation must be viewed as part of the bigger picture.

- *What is the prioritization of the elements?*

  If there is a priority identifiable now, it is the Information Technologies, because data processing capabilities are fundamental to the success of all elements of the program. However, once again, architecture studies and cost-benefit trade-off analyses must be performed before meaningful priorities of the other technologies can be established. Similarly, scientists must determine their priorities among the targeted measurements. All the elements are considered important; all should be pursued — the questions are, which should be pursued first, and how should funding be allocated?

- *Should this be an R&T base or a focused program? What should the deliverables be?*

  The GCTI should be predominantly a focused program with continued R&T base support — but the program should not be driven or constrained by the R&T base program. More specifically, the OSSA should have a focused program, with OAST supporting the development of a related set of technologies. In keeping with this approach, the GCTI must be viewed as urgent and funded sufficiently to make a program like Mission to Planet Earth possible.

- *How does this program relate to similar programs in other agencies? Overlap?*

  This is a good question which poses a major concern. The field of earth system science is complex and massive, with ample opportunity for duplication of effort, lack of visibility, cost inefficiencies, schedule mismatch, and confusion in performance capabilities with the many agencies participating. This challenge will require a well-organized coordination activity, both nationally and internationally. Within the United States, it may be appropriate to form an interagency council which has as its charter the exchange of information, insofar as possible, to avoid duplicate expenditures of time, effort, and money.

- *How do in-space experiments fit into the technology development plans?*

  It is likely that most of the technology areas in the GCTI either will be performed and demonstrated in space by other organizations or can be validated by ground-based testing; only a minimum amount of space-based testing may be required for GCTI (unless it becomes the dominant United States' space technology thrust). It would be helpful, certainly, to fly high-risk experiments before including them on any operational Mission to Planet Earth platforms. However, due to the high cost of space assets, initial "experiments" should have some operational capability.

- *How does this program relate to CSTI?*

  The CSTI, the High-Performance Computing Initiative (HPCI), and similar programs (e.g., Department of Defense programs) form a solid baseline for some of the GCTI technologies.

- *Are the budget projections realistic?*

  The proposed GCTI funding levels are seriously deficient, and need to be approximately an order of magnitude greater. With such significant budgetary limitations, the potential for major developments under GCTI is also restricted. The fear is that a small amount of funding is spread too thinly among a number of important and deserving technology research areas. Current technology funding will not bring about the required advances to support the planned systems.

- *What are the other questions?*

  Who is the end user of these systems and what does he really need? Based on the observation and measurement needs, which are the most important technologies to pursue first?

  Are only GEO-based platforms along with LEO platforms necessary to accomplishing Mission to Planet Earth? Much of the data obtained from GEO may be obtainable from mid earth orbit and LEO also. Do the added benefits justify the added costs?

  Where is the leadership for the Mission to Planet Earth?

Recommendations

The recommendations of the Ad Hoc Review Team on Space Technologies are:

1. Long-term, space-based investigation of global change and the earth's systems, and the associated technology efforts, should be a focused program.
2. NASA's architecture studies should begin as soon as possible, and should include the performance of relative cost-benefit trade-off analyses and development of a comprehensive operations concept. The studies must also consider the end user's needs.
3. Funding should be provided for a focused program, supported by a significant increase in research and technology monies. The proposed GCTI budget should be increased by a factor of 10 to achieve the planned missions.
4. Pursuing new technology in the area of information processing is the most urgent, since it is fundamental to the practical success of any program of earth observation from space. Meeting the unprecedented challenges of collecting, processing, storing, and accessing the massive amounts of data obtained will require fresh approaches which produce technological breakthroughs.
5. The national program will need effective interagency integration and coordination, under strong, single-point leadership.
6. By 1991, after the recommended NASA architecture studies have been performed, another SSTAC ad hoc team should meet to reconsider questions of technology priorities, development schedules, and funding allocation.

Appendix

Technical Presentations Made to Ad Hoc Review Team on Planet Earth Technologies (October 1988 to May 1989)

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Acronyms

CES	Committee on Earth Sciences
COSPAR	Committee on Space Research
CSTI	Civil Space Technology Initiative
Eos	Earth Observing System
ERBE	Earth Radiation Budget Experiment
FCCSET	Federal Coordinating Council for Science, Engineering, and Technology
GCTI	Global Change Technology Initiative
GEO	geosynchronous earth orbit
HPCI	High-Performance Computing Initiative
JPL	Jet Propulsion Laboratory
LEO	low earth orbit
NASA	National Aeronautics and Space Administration
NDE/NDI	nondestructive evaluation and inspection
NOAA	National Oceanic and Atmospheric Administration
OAST	Office of Aeronautics and Space Technology
OSSA	Office of Space Science and Applications
R&T	research and technology
SSTAC	Space Systems and Technology Advisory Committee

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