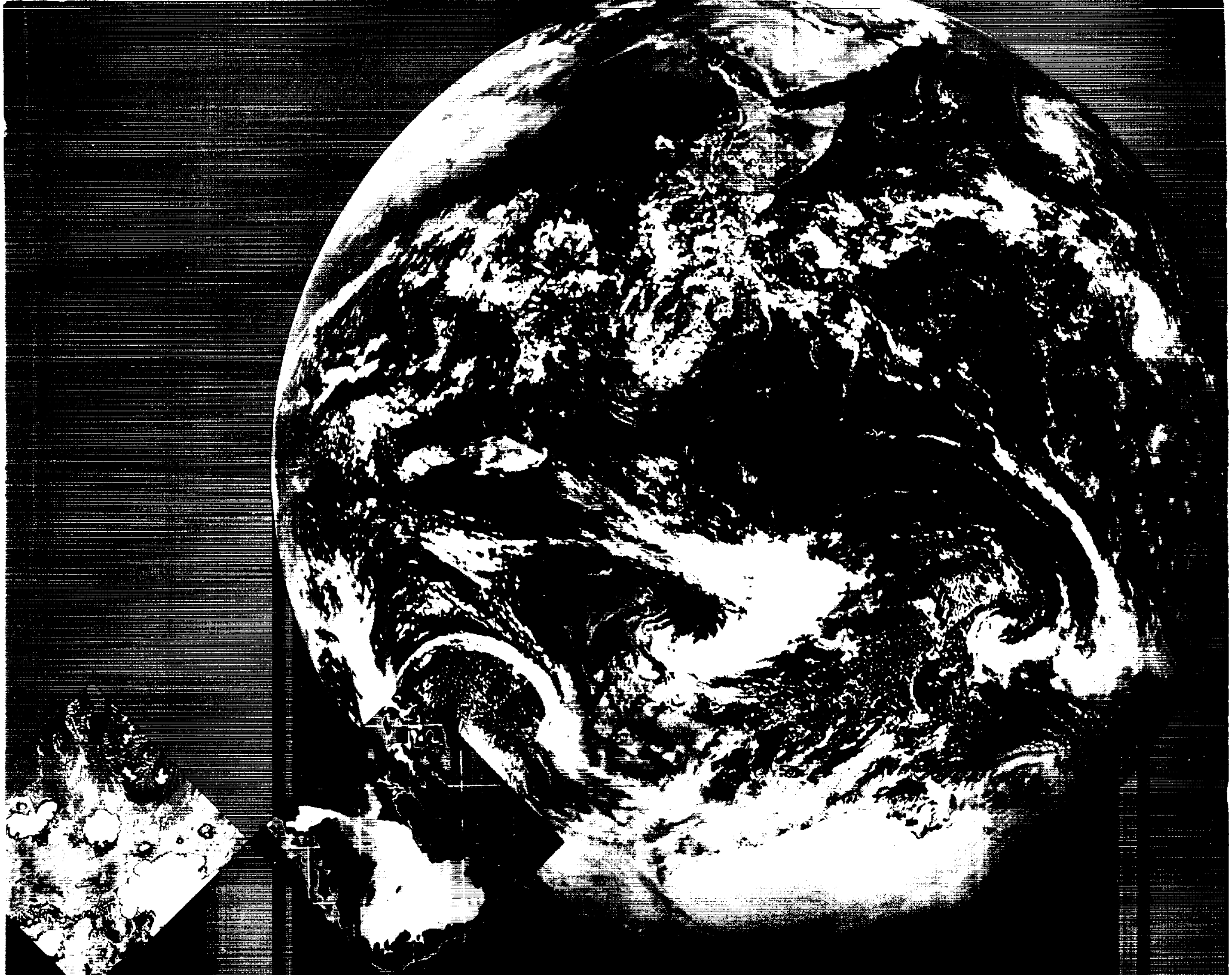

NASA

Earth Science and Applications Division

THE PROGRAM AND PLANS FOR FY 1988–1989–1990

NASA
EARTH SCIENCE AND APPLICATIONS DIVISION

THE PROGRAM AND PLANS FOR FY 1988-1989-1990

September 1988

National Aeronautics and Space Administration
Washington, D.C. 20546

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Foreword

Last year, in his Foreword to the first annual report on the activities of the National Aeronautics and Space Administration (NASA) Earth Science and Applications Division's (ESAD) Program, Ray Arnold, then Deputy Director, described the "high level of coordination and communication" underlying the Earth science community's developing ability to fully benefit from the vastly expanded observational and measuring capabilities and the enormous quantity of data which will become available on a global scale. ESAD has worked energetically during the year to maximize the science potential in the opportunities now available and this report has been compiled as the Division's contribution to the heightened requirements for the timely dissemination of scientific and programmatic information.

We are on the brink of an exciting era of multidisciplinary space-based satellite observation and simultaneous measurement of the inter-related physical, chemical, and biological processes which comprise the Earth system. Many countries are now part of the developing international effort to understand and to predict the interactions of these global forces and the effect of Man's activities on the Earth's environment. The challenge is to maximize these worldwide scientific contributions through the highest levels of cooperation, coordination and communication based on the development of a truly global information and communication system.

ESAD relies heavily on the participation in its work of the Earth science community, nationally and internationally. As such, this second report continues our effort to provide a relevant and timely account both of our current activities and of future directions in order to help the research and applications communities define how they might most effectively participate in the ESAD program.

The report describes the Division's research goals, priorities and emphases for the next several years as well as outlining its longer term plans. Following the general pattern of the first report, this year's report addresses:

- Highlights of recent accomplishments
- Current activities in FY 1988
- Research emphases in FY 1989
- Longer term future plans

We want this report to make as useful a contribution as possible to the work of the Earth science community. We therefore invite your comments and suggestions for increasing its value to our readers.

S. G. Tilford
Director
Earth Science and Applications Division
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Overview of Accomplishments and Activities

During the last year, the Earth Science and Applications Division (ESAD) has made significant contributions to national and international efforts to comprehend the many interrelated factors affecting the planet Earth. Recent work has served to underscore the need to understand the basic principles which govern those coupled physical, chemical, and biological interactions. ESAD is poised to embark on a comprehensive, long-term program of observation and measurement of the characteristics of the global environment to attain fuller knowledge of the processes of change at work and of the way in which human activities are affecting, or will affect, those processes.

One of the primary challenges in the study of Earth as a system is the understanding of the extent and causes of ozone depletion. The culmination this year of two major investigations—the 1987 airborne Antarctic ozone campaign and the Ozone Trends Panel Report published in March 1988—has led to a far greater appreciation of the nature and complexities of the problem and the possible need for further international action to address the situation. The Antarctic campaign showed that the chemical composition of the Antarctic stratosphere is highly perturbed compared with elsewhere on the planet; that the atmosphere has been denitrified and dehydrated; and that Antarctic ozone levels can change rapidly and dramatically, indicating that both chemical and meteorological processes affected Antarctic ozone abundance in 1987. Detailed understanding of the causal mechanisms at work requires further data analysis and laboratory investigations which the Division will undertake in the coming year. Among key findings of the Ozone Trends Panel Report is undisputed observational evidence that ozone-controlling source gases continue to increase on a global scale as a result of human activities, and that larger-than-predicted mean decreases in ozone levels have occurred at middle and high latitudes.

In accordance with the recommendation of the Earth System Sciences Committee (ESSC) of the NASA Advisory Council in its report, *Earth System Science: A Closer View*, released in January 1988, ESAD has made progress during the year on its program to establish an Earth Observing System (Eos), the focus of NASA's strategy for integrated study of the Earth and global change. Eos is a science mission whose goal is to advance knowledge of the entire Earth system on a global scale by developing a deeper understanding of the components of that system, the interactions among them, and how the Earth system is changing. Following completion of a series of instrument panel working group reports in 1987, a NASA Announcement of Opportunity (AO) was issued in January 1988 inviting the participation of the Earth science community in a wide range of interdisciplinary and multidisciplinary scientific investigations.

The Division's endeavors this year have been undertaken in the context of a new set of planning initiatives, which are providing valuable guidance to its overall implementation strategy, and a reorganization of the Division itself. In October 1987, Space Physics activities were established as a separate division within the Office of Space Science and Applications (OSSA) which incorporates programs in Solar Physics, Space Plasma Physics, and Cosmic Ray Physics. Simultaneously, the operational aircraft programs were transferred to ESAD.

The ESSC, established in 1983 to review the science of the Earth, to recommend an implementation strategy for global Earth studies, and to define NASA's role within such a program, has now completed its work. In the ESSC January report, the Committee defined the predominant goal of Earth science and applications as follows:

> "Obtain a scientific understanding of the entire Earth System on a global scale by describing how its component parts and their interactions have evolved, how they function, and how they may be expected to continue to evolve on all time scales."

The Committee defined four key factors to guide programmatic planning:

- The need to understand the Earth as a single, interrelated system
- The need to study global change through an integrated research program based on long-term continuous global observations of the Earth
- The need for an advanced information system to permit efficient data analysis, interpretation and modeling of Earth system processes by the international scientific community
- The need for stronger international coordination and collaborative international agreements to facilitate worldwide study of the Earth

In addition to the ESSC report, the first OSSA Strategic Plan was published in April 1988. This plan charts a course for the future based on a number of programmatic themes:

- Ongoing missions and research programs must be protected and assured
- Leadership will be pursued with fundamental and visible advances in key areas of space science through both major and moderate missions
- Short-duration, relatively inexpensive small missions of the size a university can develop are important, particularly in training the next generation of scientists and engineers
- It is time to begin capitalizing on the unique opportunities the Space Station offers, such as the multidisciplinary use of attached payloads and polar platforms for Earth science research
- The research and analysis program, which supports a vigorous and productive research community, needs enhancement in certain areas

In 1988 a major change in the structure of the NASA Advisory Committee (NAC) will be implemented. The three current advisory committees of NAC, the Space and Earth Science Advisory Committee (SESAC), the Space Applications Advisory Committee (SAAC) and the Life Sciences Advisory Committee (LSAC), are to be amalgamated. Two new committees will be formed: the Space Science and Applications Advisory Committee (SSAAC) and the Aerospace Medicine Advisory Committee (AMAC). SSAAC will cover 7 discipline divisions, including Earth Science and Applications, and be composed of some 21 members, including the chairmen of current division management councils. The goal is to provide both scientific objectivity and a breadth of view across disciplines without losing the accumulated experience and knowledge of many who now serve on NAC committees. Membership selection will be completed in time for a meeting of SSAAC in the fall of 1988.

Against this strategic planning backdrop, ESAD has made substantial progress this year towards meeting the program planning recommendations of ESSC and OSSA. The January 1988 AO for Eos represents a major programmatic advance in the potential U.S. contribution to the International Geosphere-Biosphere Program (IGBP)/Global Change Program and the centerpiece of ESSC's strategy for NASA. Prior to the release of the AO, a series of Eos reports had been published, outlining the science mission requirements and early definitions of proposed Eos facility instruments. Concurrent with the release of the Eos AO, the European Space Agency (ESA) and the Science and Technology Agency of Japan (NASDA) released coordinated announcements soliciting instruments for the payload of the European Polar Platform and proposals for use of the data from Japanese instruments on the NASA Space Station Platform.

Major observations such as those which comprise the Eos mission cannot do all that is needed to understand the Earth system. A program of Explorer-class missions, called Earth Probes, has been defined to meet those requirements, consistent with the recommendations of ESSC for the period beyond 1995. The Division has moved ahead during the year toward the initiation of a series of moderately sized Earth Probe missions. Following the recommendations of the ESSC, this series should include a Geopotential Research Explorer mission (GREM), the Tropical Rainfall Measuring Mission (TRMM), the Magnetic Field Explorer (MFE), the Mesosphere-Thermosphere Explorer (MTE), and a higher resolution gravity gradiometer mission.

The Phase A study and the Science Steering Group report on TRMM have been completed, showing that the mission is feasible within Explorer-level cost, and in March 1988 the cooperative U.S./Japan feasibility study was published. With approval in the FY 1990 budget of the Earth Probes line, this mission could be ready for launch by the mid-1990s. The TRMM payload is also a candidate for early deployment on the manned Space Station. Discussions with ESA on a joint geopotential mission for flight in the 1994 or 1995 time frame are continuing. The Mesosphere-Thermosphere Explorer concept was proposed to NASA's existing Explorer program (which excludes virtually all other types of Earth-related research) and has been accepted for study.

The Division's Applications Program to encourage the use of remote sensing for societal and economic benefit made substantial progress this year. A collaborative research and technology development program has been established between ESAD and the NASA Office of Commercial Programs (OCP) and a NASA Research Announcement soliciting remote-sensing applications/commercialization proposals was issued in August 1987. Twenty winning proposals were announced in March 1988, ranging from the study of remote sensing for microseepage and, by implication, for oil and gas exploration to enhanced potato production through high-resolution monitoring of experimental farms.

Significant achievements were also made in more traditional Earth science disciplines during the past year. NASA managed the year-long First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment (FIFE) with participation by some 150 scientists from over 30 institutions. Experiments such as FIFE are at the core of NASA's plan to develop a physically based approach to the use of satellite remote-sensing systems, and represent a key experimental element in ISLSCP. FIFE was designed to develop and validate algorithms to retrieve land surface properties and the fluxes of moisture and energy between the land surface and the atmosphere at the 15-km scale. Analysis of the data—the most comprehensive satellite data base on a single site—is in progress and initial results will be available in the latter half of 1988.

Another major milestone for NASA's imaging spectrometry program was the first research flight season in summer 1987 of the Airborne Visible Infrared Imaging Spectrometer (AVIRIS), which flies on the high-altitude NASA ER-2 aircraft. AVIRIS is a highly sophisticated research instrument, to be used in preparation for the proposed Eos High Resolution Imaging Spectrometer (HIRIS). AVIRIS is able to simulate HIRIS data, thus enabling scientists to gain experience with imaging spectrometer data sets well in advance of Eos.

In 1987 the International Satellite Cloud Climatology Project (ISCCP), designed to produce a 5-year global satellite radiance and cloud data set, completed its fifth year of data collection, and several significant conclusions are already apparent. Cloud cover over the oceans is about 10% higher than previously inferred, and while much of this is very low-altitude cloudiness, cirrus cloud cover also seems to be more common as well.

The Upper Atmosphere Research Satellite (UARS) and the Ocean Topography Experiment (TOPEX/POSEIDON) missions, both in development, continued to make progress toward launch in 1991. Fabrication of UARS is underway and critical design reviews of the Observatory and Central Data-Handling Facility (CDHF) have been completed. Three of the 10 instruments to be flown aboard UARS are scheduled to complete development by the end of the year, with the remainder scheduled for completion in FY 1989. Selection of the Science Definition Team for the TOPEX/POSEIDON project, an international effort in conjunction with the oceanographic mission of France's Centre National d'Etudes Spatiales (CNES), was completed in September 1987.

The Lidar Atmospheric Sensing Experiment (LASE), a modular design, automated lidar for atmospheric measurements, continues to make good progress towards its first flight in late 1989. The Critical Design Review has been completed and instrument buildup is underway.

The NASA Scatterometer (NSCAT) will provide frequent measurements of oceanic near-surface vector winds with high spatial resolution and global coverage. Because of the cancellation of the Navy's N-ROSS satellite, NSCAT is now proposed for flight aboard the Japanese Advanced Earth Observing Satellite (ADEOS) in the 1993-1994 time frame.

The international Earth science community faces a major challenge as it enters the era of interdisciplinary investigation of global change—the provision of adequate data-handling systems which will allow easy access for scientists around the world. In the U.S. a new Interagency Working Group on Data Management for Global Change (IWGDMGC) represents a high-level commitment by participants to facilitate data access. The goal is to provide by 1995 a national data and information system for global change that is consistent across agencies and involves the university and other user communities. In a joint effort with NASA's Office of Space Science and Applications' Communications and Information Systems Division (CISD), ESAD has established the Earth Science and Applications Data Systems (ESADS) initiative. ESADS will coordinate the various data system elements that support ESAD and in the coming years will be a major programmatic mechanism in NASA's upgrading of existing Earth science data systems in preparation for the Eos era.

ESAD Budget Priorities

A summary of the ESAD budget from 1984 to the present is shown in Appendix A of this report. It shows the FY 1989 Presidential Budget Request and reflects the changes in the Division's budget following its reorganization in October 1987, when the Space Plasma Physics Branch became a separate division and the Aircraft Program was transferred into ESAD.

The Division's budget planning anticipates the major changes that will occur in Earth system science in the mid-1990s with the availability of a new generation of advanced platforms in space. These platforms will greatly enhance our research capabilities, allowing more instruments to be in use and the opportunity for instrument servicing, modification and replacement by Space Shuttle crews.

The advent of the Eos era will enable a comprehensive suite of Earth system science investigations to be carried out in conjunction with NOAA's operational program, providing the community for the first time with the long-term, self-consistent data sets needed for understanding and predicting global processes. Efficient data management is a central concern and planning for the handling of both research and operational data has been initiated.

ESAD's budget priorities continue to reflect a firm commitment to Eos. Items planned for consideration in implementing the FY 1989 budget are:

- Eos Advanced Technology Development studies
- Earth Science Explorer definition studies (Tropical Rainfall Measuring Mission, Gravity Research Mission, Magnetic Field Satellite)
- Instrument development (ocean color, active and passive aircraft instruments)
- Advanced Data Systems definition
- Mission operations and data analysis (European Space Agency's Earth Remote Sensing Satellite, Alaskan SAR Facility operations, NIMBUS, and others)
- Applications initiative
- Aircraft replacement/modifications
- Active Cavity Radiometer Irradiance Monitor III development
- Land observations payload enhancement

TABLE 1-1. **ESAD PROGRAM CONTACTS**

Director	S. Tilford	453-1706
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Special Assistant to Director	W. Huntress	453-1707
Program Support Specialist	G. LeSane	453-1706
Data Systems Activities	E. Njoku	453-1748
Interdisciplinary/Global Change	R. Watson	453-1681
Geodynamics	E. Flinn	453-1675
Applications Sciences	L. Carpenter	453-1675
Staff Scientist	N. Douglas	453-1675
Ocean Processes	S. Wilson	453-1725
Air/Sea Interaction	J. Richman	453-1725
Polar Oceans	R. Thomas	453-1725
Ocean Circulation	J. Richman	453-1725
Ocean Productivity	J. Yoder	453-1725
Land Processes	R. Murphy	453-1720
Terrestrial Ecosystems	D. Wickland	453-1720
Geology	M. Baltuck	453-1720
Hydrology	G. Asrar	453-1720
Technical Support	M. Ruzek	453-1720
Atmospheric Dynamics and Radiation	J. Theon	453-1680
Climate	R. Schiffer	453-1680
Global Scale	R. Kakar	453-1680
Mesoscale	J. Dodge	453-1680
Atmospheric Chemistry	R. Watson	453-1681
Upper Atmosphere Research Program	R. Watson (actg)	453-1681
Atmospheric Theory	M. Prather	453-1681
Tropospheric Chemistry	R. McNeal	453-1681
Laboratory Measurements	M. Kurylo	453-1681
Eos	D. Butler	453-1681
Geoplatform	J. Dodge	453-1680
Remote Sensing Applications/ Commercialization Program	D. Thompson	453-1700
Aircraft Program	D. Thompson	453-1700
	J. Lehman	453-1700
Space Flight Programs	W. Townsend (actg)	453-1725
METSAT Development Operations/Landsat	J. Greaves	453-1723
Shuttle Payloads/Extended Operations	G. Esenwein	453-1723
SAR/LFC	R. Monson	453-1723
Satellite Development		
UARS	M. Luther	453-1723
TOPEX/NSCAT	W. Townsend	453-1725
Earth Probes Planning	D. Butler	453-1681
Space Station Planning		
Eos/Attached Payloads	A. Tuyahov	453-1723

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An International and Interdisciplinary Approach to Earth Science

With the launch of the first experimental satellites almost 30 years ago, the United States pioneered the study of Earth from space. This year's Presidential Directive on National Space Policy, approved January 5, 1988, underscores the importance of maintaining U.S. leadership in space—now under challenge from an increasing number of spacefaring nations. Such leadership demands a clear view of objectives, based on well-defined goals and plans and demonstrable accomplishment. "The drive for excellence, combined with the active achievement of program goals, firmly positions U.S. space science and applications for an exciting, productive future."[1]

The Earth science community, prompted perhaps in part by the celebration of the twenty-fifth anniversary of the International Geophysical Year in 1982-83, has come to the consensus that the naturally occurring events which take place on the planet are part of an integral process of interrelated and constant global change and that such a systemic and interdependent process can only be investigated and understood holistically. This view, together with a growing concern over the role of human activity in affecting the global environment, has focused scientific attention on the need for a new international, interdisciplinary, global-scale approach to the study of the Earth. We now believe that, in addition to discipline-specific inquiry, the Earth should also be studied as a synergistic system in which interdependent forces act upon each other to determine the planet's response to the changes being wrought on its environment.

Several initiatives within the national and international institutions of Earth science have endorsed this view. In 1986, the U.S. Committee for an International Geosphere-Biosphere Program (IGBP) stated that the challenge facing the international science community was to "describe and understand the interactive, physical, chemical and biological processes that regulate the Earth's unique environment for life, the changes that are occurring in this system, and the manner in which they are influenced by human actions." Such knowledge, the Committee said, "may well be essential for our survival."

More recently, the Earth System Sciences Committee (ESSC) of NASA's Advisory Council stated in its January 1988 report, *Earth System Science: A Closer View,* "Global observations, new space technology, and quantitative models have given us the capability to probe the complex, interactive processes of Earth evolution and global change." The overriding goal of Earth science and applications, it said, was to achieve a scientific understanding of the entire Earth system on a global scale by describing how its component parts and their interactions have evolved, how they function, and how they may be expected to continue to evolve on all time scales. With a more fundamental understanding of the global system, we might learn to predict both natural and man-made changes on time scales of decades to centuries and thus develop the capability of making appropriate decisions for the long term about the way in which we inhabit and use the planet.

Finally, the need for the development of an international, multidisciplinary approach to Earth science and the study of global change is further emphasized by NASA's Earth Observing System (Eos) and Mission to Planet Earth initiatives and the upcoming worldwide observance of International Space Year in 1992.

A Systematic Approach to Global Change

Interactive physical, chemical, and biological processes connect the oceans, continents, atmosphere,

[1]Office of Space Science and Applications Strategic Plan, 1988, p 3.

and biosphere of Earth in a complex way. Oceans, ice-covered regions, and the atmosphere are closely linked in shaping the Earth's climate; volcanism links inner Earth with the atmosphere; and biological activity significantly contributes to the cycling of chemicals (such as carbon, oxygen and carbon dioxide) essential to life. Human activity clearly has already had a major impact on the Earth system. There is thus an urgent need to understand the potentially major consequences, both beneficial and detrimental, of the enormous, global-scale changes which we have already observed the planet undergoing. The most recent work on the higher-than-expected rate of Antarctic ozone depletion is but one example of the measurable shifts already occurring within our system. We have also been able to observe and quantify increases in the atmospheric warming gases, carbon dioxide and methane, and we have noted important changes occurring in vegetation covers and in coastlines.

Global-scale models of the atmosphere have been developed; long-range weather prediction is now feasible. Extensions of this modeling approach to the stratosphere, the oceans, and the solid Earth are underway, and the development of a model for the coupled global system can now be envisaged. This systems approach is crucial to future efforts in Earth science and applications.

Current NASA programs are collecting global data on stratospheric ozone, on sea-surface and sea-ice variables, and on the Earth's radiation budget (the balance of radiation input and output between the Earth and space), a critical element in improving our understanding of climate. Approved future programs include the Upper Atmosphere Research Satellite (UARS), the NASA Scatterometer (NSCAT), and the joint Ocean Topography Experiment (TOPEX/POSEIDON) mission in conjunction with the French Centre National d'Etudes Spatiales (CNES).

Each of the approved future programs addresses a key aspect of the Earth system and a particular field of study for a few years. UARS will provide the first comprehensive measurements of the interplay among dynamic, radiative, and chemical processes in the stratosphere and mesosphere which determine the extent and durability of the ozone layer. NSCAT will provide global measurement of sea surface wind velocity and TOPEX/POSEIDON will provide the first detailed measurements of the global circulation patterns of the oceans. Each addresses a key aspect of the system and a particular field of study for a few years.

The United States and its international partners are now preparing to meet the demands of the interdisciplinary approach to Earth science presented in the IGBP study on global change. While missions such as the Earth Radiation Budget Experiment (ERBE), UARS, NSCAT and TOPEX/POSEIDON will provide essential building blocks of knowledge, the more comprehensive understanding of the Earth as a system requires enlarged concentrations of orbiting remote-sensing instrumentation, many simultaneous and calibrated measurements, and mission lifetimes of a decade or more.

Tremendous advances in space technology and scientific investigation and data collection techniques over the last few decades have taken us from our initial efforts to test and demonstrate remote-sensing capabilities, through the era of prototype operational spacecraft, and forward to the discipline-specific research missions currently flying or under development. This experience has in turn prepared us for the large, multidisciplinary, long-duration missions of increasing complexity upon which we are embarking today.

The Earth Observing System (Eos)

The Earth Observing System (Eos), to be carried out in conjunction with the National Oceanic and Atmospheric Administration (NOAA) polar operational program, will provide significant new opportunities to examine, analyze and finally achieve a greater understanding of the workings of the planet Earth. The Space Station Polar Platforms are crucial elements in the space infrastructure required for Eos, which has been recognized as the centerpiece of an overall strategy for Earth system science by the ESSC. At the same time, the IGBP report states that "the new technologies of spaceborne instrumentation and of high-speed computers allow, for the first time, the global synthesis of information needed for scientific understanding. These new technologies are central to advances in such fields as oceanography, geophysics, atmospheric dynamics, and solar-terrestrial physics." Both the ESSC and IGBP reports help establish the interdisciplinary and international context within which Eos can happen.

The Earth science community is truly international in extent. Its purposes are global; its findings are global in implication. The Eos concept will draw from the intellectual and financial resources of the international community and its unique benefits will be made available to all who are willing to participate. Eos is conceived not as a set of space hardware, but as an information system designed to integrate researchers and unite them with new sources and kinds of data to be provided by the space elements.

NASA is already working with the Earth observation offices of its Space Station partners—the European Space Agency (ESA), Japan and Canada—and with NOAA and the Earth science community on the definition and implementation of Eos to provide instruments and data systems to capitalize on the Polar Platform capability. A NASA Announcement of Opportunity (AO) soliciting payload development for Eos was released in January 1988 concurrent with an ESA announcement soliciting payload development for the European Polar Platform and a Japanese solicitation for uses of the data from their instruments on the NASA Space Station Platform. Instruments to fly as attached payloads on the manned Space Station are also being solicited by this AO.

Mission to Planet Earth

The Mission to Planet Earth describes a focused effort in satellite remote sensing and the associated multi-disciplinary research that will characterize our home planet and its global environment as an interacting system. The Mission to Planet Earth includes Eos, the Tropical Rainfall Measuring Mission (TRMM), and the geostationary platforms. The full scope of Mission to Planet Earth anticipates at least four platforms in sun-synchronous polar orbits (of which Eos is a part). NASA is currently considering providing two of these, with the others to be provided by ESA and Japan. Study of the required geostationary observing system is also underway. TRMM and perhaps other Earth Probe missions complete the envisioned observing capability. As with Eos, the highest priority element in Mission to Planet Earth will be the data and information system which integrates the activity.

Although these current plans for a Planet Earth initiative are fairly comprehensive and already embrace international cooperation among Europe, Japan and North America, there is certainly room to broaden this concept through contributions from the other spacefaring nations. At the International Space Year (ISY) Mission to Planet Earth Conference held at the University of New Hampshire, April 29-May 1, 1988, key officials of the world's space agencies agreed that Earth observations from space will be a major focus of ISY activity in 1992. They further recognized the tremendous potential of a Mission to Planet Earth approach to publicly demonstrate that space study not only generates spectacular science but can and has already produced solid, practical advances in the technical know-how essential to the increased welfare of mankind. The conference participants reached consensus on the need for a 15-year sustained effort of Earth observation from space and agreed that ISY in 1992 could serve to initiate such a long-term, broadly cooperative Mission to Planet Earth.

At the same time, the American Geophysical Union (AGU), taking its first-ever public policy position, has urged that the U.S. lead the international community in carrying out a Planet Earth initiative. In its statement, AGU points out the potential for improved bilateral relations with the Soviet Union through cooperation in such an effort.

Following the Washington Summit meeting between President Reagan and General Secretary Gorbachev in December 1987, it was announced in the Joint U.S.-Soviet Summit Statement that the two leaders had approved a bilateral initiative to pursue joint studies in global climate and environmental change, in such areas as the protection and conservation of stratospheric ozone and through increased data exchange. The statement noted that the two sides will continue to promote broad international and bilateral cooperation in the increasingly important area of global climate and environmental change.

Under the aegis of the U.S./USSR Bilateral Agreement on Space Cooperation, representatives from NASA's Earth science program visited Moscow in May 1988 to conduct the first in a series of meetings to discuss exchanges of data and other avenues of space cooperation relating to Earth science.

It is hoped that NASA's commitments to such programs as Eos, the full Mission to Planet Earth, and ISY will stimulate corresponding commitments from Canada, Europe, Japan and elsewhere to truly internationalize the use of space in the study of global change.

NASA is also continuing its support of non-space-based efforts by encouraging the U.S. Earth science community to pursue the study of global change and shape a national contribution to the International Council of Scientific Unions International Geosphere-Biosphere Program. The National Science Foundation (NSF) will play a major role in ground-based observations and fundamental research through its Global Geosciences initiative, and NOAA's enhancement of ground- and space-based operational measurement systems through their Global Change initiative will be an invaluable source of data. The United States Geological Survey (USGS) will contribute a major effort with in situ measurements and will provide for the archiving and distribution of space-obtained land-surface data for research and development purposes. In addition, the Department of Energy has a significant program on carbon dioxide. Other substantive contributions from the full range of U.S. agencies involved in Earth science will be coordinated to ensure full national participation in this critical international arena.

TABLE 2-1. **OBSERVATIONAL PROGRAMS FOR GLOBAL DATA ACQUISITION: REPRESENTATIVE**

Representative Space Programs

Program	**Agency/Status**	**Objectives**
POES: Polar-orbiting Operational Environmental Satellites (e.g., NOAA-7)	NOAA/Operating	Weather observations
GOES: Geostationary Environmental Satellite System	NOAA/Operating	Weather observations
DMSP: Defense Meteorological Satellite Program	U.S. Air Force/Operating	Weather observations for Department of Defense
METEOSAT: Meteorology Satellite	ESA/Operating	Weather observations
GMS: Geostationary Meteorology Satellite	NASDA (Japan)/Operating	Weather observations
METEOR-2: Meteorological Satellite-2	USSR/Operating	Weather observations
Landsat: Land Remote Sensing Satellite	EOSAT/Operating	Vegetation, crop, and land-use inventory
LAGEOS-1: Laser Geodynamics Satellite-1	NASA/Operating	Geodynamics, gravity field
Nimbus-7	NASA/Operating	Global ozone, aerosols, solar energy
SME	NASA/Operating	Solar energy
LAGEOS-2	NASA/PSN(Italy) Launch 1991	Geodynamics, gravity field
ERBE: Earth Radiation Budget Experiment	NASA-NOAA/Operating	Earth's radiation losses and gains
GEOSAT: Geodetic Satellite	U.S. Navy/Operating	Geodesy, shape of the geoid, ocean and atmospheric properties
GPS: Global Positioning System	U.S. Navy-NOAA-NASA-NSF-USGS/Completion 1990	Geodesy, crustal deformation
SPOT-1: Système Probatoire d'Observation de la Terre-1	France/Operating	Land use, Earth resources
SPOT-2	France/Launch 1988	Earth remote sensing
IRS: Indian Remote-sensing Satellite	India/Operating	Earth resources
MOS-1: Marine Observation Satellite-1	NASDA (Japan)/Launch 1988	State of sea surface and atmosphere
ERS-1: Earth Remote-sensing Satellite-1	ESA/Launch 1990	Imaging of oceans, ice fields, land areas
UARS: Upper Atmosphere Research Satellite	NASA/Launch 1991	Stratospheric chemistry, dynamics, and energy
NSCAT: NASA Scatterometer	Proposed Launch 1994	Ocean topography, surface winds
TOPEX/POSEIDON	NASA/CNES, 1991	Ocean topography

EXAMPLES OF APPROVED AND CONTINUING PROGRAMS

Representative Space Shuttle Instruments		
Program	**Agency/Status**	**Objectives**
ATMOS: Atmospheric Trace Molecules Observed by Spectroscopy	NASA/Current	Atmospheric chemical composition
ACR: Active Cavity Radiometer	NASA/Current	Solar energy output
SUSIM: Solar Ultraviolet Spectral Irradiance Monitor	NASA/Current	Ultraviolet solar observations
MAPS: Measurement of Air Pollution from Shuttle	NASA/Current/In development	Tropospheric carbon monoxide
SIR: Spaceborne Imaging Radar	NASA/Current/In development	Land-surface observations
SISEX: Shuttle Imaging Spectrometer Experiment	NASA/Planned	Spectral observations of land surfaces
Lidar: Light Detection and Ranging Instrument	NASA/Planned	Atmospheric properties, such as water vapor, aerosols, ozone

Representative International Programs for Measurements in Situ		
GEMS: Global Environment Monitoring System	UNEP/Begun 1974	Monitoring of global environment
World Ozone Program	WMO-UNEP-NASA-NOAA/ Operating	Atmospheric composition
Crustal Dynamics Project	NASA-23 nations/Begun 1979	Tectonic plate movement and deformation
Man and the Biosphere	UNESCO/Operating	Ecological studies
International Biosphere Reserves	UN/Operating	Long-term ecological studies
ISCCP: International Satellite Cloud Climatology Project (World Climate Research Program)	WMO-ICSU/Begun 1983	Measure interaction of clouds and radiation
ISLSCP: International Satellite Land Surface Climatology Project (World Climate Research Program)	WMO-ICSU/UNEP Begun 1985	Measure interactions of land-surface processes with climate
TOGA: Tropical Ocean Global Atmosphere Program (World Climate Research Program)	WMO-ICSU/NSF/NOAA Begun 1985	Variability of global interannual climate events
WOCE: World Ocean Circulation Experiment (World Climate Research Program)	WMO-ICSU-IOC-NSF-NASA-NOAA/1987	Detailed understanding of ocean circulation

TABLE 2-2. **OBSERVATIONAL PROGRAMS FOR GLOBAL DATA ACQUISITION: REPRESENTATIVE**

Program	Agency/Status	Objectives
Representative Space Programs		
POES: Polar-orbiting Operational Environmental Satellite System—follow-on missions (e.g., NOAA-K-L-M)	NOAA/Launch starting 1988	Advanced capabilities for weather observations
GOES:Geostationary Operational Environmental Satellite System—follow-on missions (e.g., GOES-Next)	NOAA/Launch starting 1990	Advances capabilities for weather observations
Radarsat Canadian Radar Satellite	NASA/Canada/Launch 1994	Studies of arctic ice, ocean studies, Earth resources, Antarctic ice sheet mapping
MOS-2: Marine Observation Satellite-2	NASDA (Japan)/Launch 1991	Passive and active microwave sensing
European Polar-Orbiting Platform (Columbus)	ESA/Launch 1996	Long-term comprehensive research, operational, and commercial Earth observations
TRMM: Tropical Rainfall Measuring Mission	NASA/Launch 1994	Tropical precipitation measurements
MFE: Magnetic Field Explorer	NASA/Start 1990, Launch 1994	Secular variability of Earth's magnetic field
MTE: Mesosphere-Thermosphere Explorer	NASA/Start 1995, Launch 1996	Chemistry and dynamics of upper atmosphere
SGGM: Supercooled Gravity Gradiometer Mission	NASA/Start 1997, Launch late 1990s	Gradient of Earth's gravitational field
Individual Instruments for Long-Term Global Observations		
Ocean Color Instrument	NASA-NOAA/Planned	Ocean biological productivity
ERB: Earth Radiation Budget instrument	NASA/Planned	Earth radiation budget on synoptic and planetary scales
Carbon Monoxide Monitor	NASA/Planned	Monitor tropospheric carbon monoxide
Total Ozone Monitor	NASA/Planned	Monitor global ozone
GLRS: Geodynamics Laser Ranging System	NASA/Eos/Planned	Crustal deformations over specific tectonic areas
Scanning radar altimeter	NASA/Planned	Continental topography
Eos: Earth Observing System/Polar-Orbiting Platforms, NASA-NOAA program	NASA-NOAA/NASA Start 1989, Launch 1996	Long-term global Earth observations
NASA research payloads	NASA/Planned	Surface imaging, sounding of lower atmosphere; measurements of surface character and structure; atmospheric measurements; Earth radiation budget; data collection/location of remote measurement devices
NOAA operational payloads	NOAA/Planned	Weather observations and atmospheric composition; observations of ocean and ice surfaces; land surface imaging; Earth radiation budget; data collection/location of remote measurement devices; detection and location of emergency beacons; monitoring of space environment

EXAMPLES OF PROPOSED FUTURE PROGRAMS

Individual International Programs for Measurements in Situ

Program	Agency/Status	Objectives
WOCE: World Ocean Circulation Experiment (World Climate Research Program)	WMO-ICSU-IOC-NSF-NASA-NOAA/1987 Enhancement	Detailed understanding of ocean circulation
IGBP: International Geosphere-Biosphere Program (Global Change)	ICSU/Proposed	Study of global change on time scales of decades to centuries
GOFS: Global Ocean Flux Study	NSF-NOAA-NASA/ Enhancement	Production and fate of biogenic materials in the global ocean
GTCP: Global Tropospheric Chemistry Program	NSF-NASA-NOAA/ Enhancement	Tropospheric chemistry and its links to biota
Ocean Ridge Crest Processes	NSF-USGS-NOAA/ Enhancement	Chemistry and biology of deep-sea thermal vents, plate motions, crustal generation
Sensing of the Solid Earth	NSF-USGS-DOD-NASA/ Enhancement	Large-scale mantle convection, studies of continental lithosphere
Ecosystem Dynamics	NSF/Enhancement	Studies of long-term ecosystems, biogeochemical cycles
Greenland Sea Project	ICSU/Planned	Atmosphere-sea ice-ocean dynamics

TABLE 2-3. **REPRESENTATIVE EXAMPLES OF PROPOSED SATELLITE MEASUREMENTS***

Measurement	Implementation: Current Era**	Implementation: Space Station Era
Solar energy output	ERBE, UARS, Shuttle instruments	Eos
Ice extent, dynamics	DMSP, ERS-1 (ESA), JERS-1 (Japan)	Eos, DMSP, Radarsat
Weather and climate: physical parameters	POES, GOES, DMSP, MOS-1, NSCAT, ERS-1 (ESA), JERS-1 (Japan), (World Weather Watch [WWW])	POES, GOES, DMSP, MOS-2, EOS, Radarsat, (WWW)
Stratospheric ozone chemistry & dynamics	UARS, POES, Shuttle instruments	Eos
Tropospheric chemistry	CO Monitor, Shuttle instruments	Eos
Ocean surface winds & ocean currents	NSCAT, TOPEX/ POSEIDON, ERS-1 (ESA), MOS-1, GEOSAT, (TOGA), (WOCE)	MOS-2, Eos, (TOGA), (WOCE)
Ocean spectral reflectivity, ocean productivity	Sea-WiFS (GOFS)	Eos
Precipitation, rainfall rates	TRMM	Rainfall mission over tropics, Eos, GOES
Surface spectral reflectivity, land-surface biology, continental geology	Landsat, Shuttle instruments, SPOT, (ISLSCP)	Eos, EOSAT, SPOT
Geopotential field & mantle circulation		SGGM
Continental topography	Scanning radar altimeter	Eos
Magnetic field		MFE
Vegetation cover	Landsat, SPOT, JERS-1 (Japan)	Eos
Crustal deformation and plate tectonics	LAGEOS-1, LAGEOS-2, GPS, SLR, LLR (VLBI)	GLRS, Eos, GPS, LAGEOS-1, LAGEOS-2, SLR (VLBI)
Land-surface energy and moisture budgets	Concept and technique development	Eos
Biome extent and productivity	Concept and technique development	Eos
Winds, especially in tropics	GOES, Concept and technique development	Eos

*Programs of complementary measurements in situ appear in parentheses; e.g., (WOCE).
**Current Era refers to period from 1986 until start of the Space Station era in the mid-1990s.

3

Data and Information Systems

Increasing our capability for using the large amounts of data being generated through remote sensing is of critical concern to the Earth Science and Applications Division (ESAD). Over the past 25 years, great strides have been made in developing satellite-based measurements to observe the Earth. New scientific insights and understanding depend on how successfully this flow of data can be transferred to those most capable of understanding and interpreting it. In Earth science missions at NASA, the emphasis is shifting from remote-sensing hardware alone to total information flow and data management.

Current Major Plans

Plans currently underway address two specific issues: (1) how best to create a data management system from existing discipline and flight project elements that will be capable of addressing interdisciplinary and multidisciplinary science questions of global scope, and (2) how best to provide, in advance, for handling the unprecedented flow of digital information that will be generated by the polar-orbiting space platforms planned for the Earth Observing System (Eos) of the mid-1990s. All of NASA's advisory committees recommend the immediate development of a system that will provide the widely distributed research community with easy access to interdisciplinary data.

By the mid-1990s, we will need a multidisciplinary data management and access system that fully integrates most Earth science and applications components. This information system must provide a research-friendly environment and such features as quick location, cross-referencing, remote data browsing, and rapid electronic data delivery. We have a long way to go before achieving this fully integrated system because it represents a significant shift from some present practices and will require extensive coordination within NASA and with other agencies, private industry, and the international community.

Tables 2-1 and 2-2 show the continuing and proposed observational programs for the collection and analysis of Earth science data to the year 2000. Table 2-3 shows representative examples of current and proposed satellite measurements in the Earth sciences. These tables indicate the diversity of missions, experiments, and measurements which are the data sources for Earth science and applications research. This diversity, and the large volume of data to be managed, provide the ESAD Data Systems Program with a major challenge in satisfying the data requirements of its user community.

Coordination Within NASA

In planning for the transition to an integrated system that can address interdisciplinary science questions, we are building upon the extensive experience that exists within NASA's science and engineering programs. In particular, we are taking advantage of new data systems technology development performed by the Information Systems Office (ISO) (now in the Communications and Information Systems Division [CISD] of the Office of Space Science and Applications [OSSA]). The CISD has a range of experience in developing advanced data management systems, processing techniques, networks, science workstations, and standards. Interfaces with associated activities in the Office of Aeronautics and Space Technology, Office of Space Station, and Office of Space Operations are being established to ensure an integrated approach to the end-to-end information flow in both ground and space segments.

CISD's NASA Science Internet (NSI) program is providing the network services and infrastructure upon which much of the ESAD data system activities will build. NSI comprises two existing networks, the Space Physics Analysis Network (SPAN) and the NASA Science Network (NSN). SPAN originated from a "grass-roots" effort in the ESAD Space Plasma Physics Program (now in the Space Physics Division) as a prototype model for interchange of science data, with "hands-on" experience in computer networking, graphics standardization, and data-formatting techniques. As experience grew, Earth science disciplines joined the network, and SPAN presently provides hundreds of scientists with electronic mail, data center access, and data and graphics file transfer. To accommodate alternate data exchange protocols and non-vendor-specific hardware, the NSN was established recently and now serves a growing percentage of the Earth science community in a manner similar to SPAN. The NSI program provides management of and connectivity between the NASA networks, and is also developing connections to other agency networks such as NSFnet, ARPAnet, and others.

Central data cataloging and archiving have been established at the National Space Science Data Center (NSSDC) of the Goddard Space Flight Center (GSFC). An on-line master directory of space and Earth science data, which will be accessible through NSI and dial-up lines from around the world, is being developed at NSSDC. This NASA Master Directory (NMD) will provide scientists with summary information on NASA's data holdings, and will point users to catalogs and archives where more detailed data set information can be found and where data can be browsed or extracted. Some Earth science data sets reside in the NSSDC central archive; other data reside in distributed archives located at other NASA centers and universities. These distributed archives are mission- or discipline-oriented in nature, and include the Upper Atmospheric Research Pilot Data System, Crustal Dynamics Project Data System, Synthetic Aperture Radar (SAR) Data Catalog System, NASA Ocean Data System, Pilot Climate Data System, and Pilot Land Data System. Some of these are described in more detail in other sections of this report.

In some cases, the discipline data systems are under development as joint activities between ESAD and CISD. As a general philosophy, ESAD provides science requirements, science guidance, and data set functional support, while CISD provides technology development and demonstration for the data systems on a continuously evolving basis. In addition to these data center activities, we are supporting the development of a number of data acquisition and processing facilities and analysis tools for meteorological and atmospheric science applications. This includes ESAD participation in the UNIDATA, MIDDS, and McIDAS projects, involving use of workstation networks and large computers for real-time processing and analysis of satellite weather data.

Techniques for integrating the most successful aspects of the discipline data systems, the NSSDC, and the flight project data systems into the multidisciplinary Earth science data management system called for by researchers and NASA's advisory committees are the focus of the Earth Science and Applications Data Systems (ESADS) initiative. The ESADS initiative is a joint effort between ESAD and CISD to coordinate the various data system elements that support ESAD, and in the coming years will be a major programmatic mechanism for NASA to upgrade its existing Earth science data systems in preparation for the Eos era. In order to accomplish this, we must establish formal procedures and responsibilities for the flow of mission or experiment science data from flight projects and principal investigators to participating active archives, and from there to permanent archives. ESAD will achieve this by generating Project Data Management Plans (PDMPs) for each mission or experiment and Memoranda of Understanding (MOUs) or other agreements which will establish the relationships of the various NASA data systems to each other and to the data systems of other agencies.

Interagency and International Coordination

We are coordinating data systems planning with a number of other government agencies and international groups. Spurred on by recommendations from international scientific research programs such as the International Geosphere-Biosphere Program (IGBP), a new Interagency Working Group on Data Management for Global Change (IWGDMGC) has been formed, whose membership includes NASA, the National Oceanic and Atmospheric Administration (NOAA), the U.S. Geological Survey (USGS), the National Science Foundation (NSF), the U.S. Navy, the Department of Energy (DOE) and the Department of Agriculture (USDA). The IWGDMGC represents a high-level commitment by participating agencies to make it as easy as possible for scientists and others to get data appropriate to the study of global change.

The goal of the IWGDMGC is to implement by 1995 a virtual national data and information system for global change research that is consistent across agencies and involves and supports the university and other user communities. Current activities include developing and linking interoperable agency directories and catalogs, assessing the status of data collection, archiving, and distribution for certain high-priority measurements, formulating uniform data pricing and accounting policies, and coordinating international data exchange agreements.

Issues arising directly between NASA and NOAA relating to data management are addressed by the NOAA/NASA Data Management Working Group. Similarly, a

USGS/NASA Data Management Coordination committee has been established to implement provisions of the USGS/NASA MOU. In both cases, the groups provide a framework for implementation of network connections, common standards for exchange of data and metadata, sharing of information on new technology, and sharing of resources for data archiving and exchange.

We are also working with a number of international bodies for coordination of data management and systems, such as the Committee on Earth Observing Satellites (CEOS), which has two working groups, one on data management and one on sensor calibration and performance validation. Representatives of the seven Economic Summit nations have endorsed efforts to create a group called the International Forum for Earth Observation Using Space Station Elements (IFEOS) for users and providers of Earth observation and other payloads for polar platforms. IFEOS will seek opportunities to join its work with that of other international data management working groups. In addition, we are participating in an experimental data-sharing system sponsored by the United Nations, called the Global Resources Information Database (GRID), which links the United States, Europe, and Africa.

Eos Data and Information System Planning

Our studies and plans through FY 1989 represent stages toward meeting our major challenge—having a system in place to handle the deluge of data that will start flowing from the Eos instruments during the 1990s. Our planning is being done in close cooperation with NOAA, based on the premise that operational data are not only scientifically useful but will form a foundation for new and expanded measurement capabilities. We will also be working with NSF, whose recent initiative in supercomputing and networking complements our own requirements, and with the USGS, who have extensive experience in archiving and analysis of Earth science data.

The potential flow of raw data that will be obtained in the 1990s from low Earth orbit is estimated to be 1 terabyte (10^{12} bytes) per day. Eos instruments may potentially be sending back data from two NASA polar platforms, one European Space Agency (ESA) platform, one Japanese platform and from the manned Space Station. Although the communication of such volumes of data will not be easy, the real challenge lies in the data processing, archiving, and digesting into formats useful to researchers. To manage this unprecedented, high-speed, high-volume flow of digital information, the Eos Data and Information System (EosDIS) will need to provide the following:

- Near real-time processing of the data at least to units which can be used further without detailed knowledge of the sensor
- Distribution of data, on an international basis, to active archive sites for research data processing and evaluation
- Access to fully integrated interdisciplinary data, with intercomparison capability for such data
- A continuously updated, high-performance, and easily accessible data management system

We have started the preparations for Eos with specific efforts to make multidisciplinary use of existing data streams and of the several NASA pilot projects in the Earth science disciplines. The ESADS initiative and implementation activities arising from the interagency working groups are major steps in this direction. For Eos data, we envision a major augmentation of the ESAD data management infrastructure, comprising the following elements:

- **Active archives** will be facilities dedicated to a particular instrument or group of instruments, which will process, provide access to, and archive for limited time periods, Eos data. They will provide for scheduling, acquiring, and providing valid observations in the form of data in geophysical units to the overall system. These facilities will be provided by the Eos project and will be institutional responsibilities (as distinct from responsibilities of investigator teams).
- **Permanent archives** will be non-Eos facilities which take responsibility for the permanent archiving of Eos data, receive these data from Eos active archives, and provide long-term access to the data. The permanent archives may be NASA facilities or the responsibilities of other agencies, and agreements between Eos and such archives will be negotiated by NASA. (One Memorandum of Understanding [MOU] has already been signed with USGS.) Active archives may be collocated with the designated ("participating") permanent archives to facilitate the eventual transfer of responsibility for the data.
- **Computing facilities** will be made available to team members, principal investigators, and interdisciplinary investigators to develop and maintain science data processing algorithms, produce data sets, and assess data quality.
- **A communications network** will connect the various elements of the EosDIS with each other and with non-Eos data sources. This network will in-

clude links to other agencies and international organizations.

- **A management center** will coordinate, oversee, control, and account for usage of all aspects of the system, with direct accountability to the Eos Program Office and the research community.

When EosDIS becomes fully functional, it will interface with other integrated ESADS components. For this reason it is important that the development of EosDIS and ESADS elements proceed in concert, with evolution and implementation of common standards for: (1) directories and catalogs, (2) network protocols, (3) archive media and formats, (4) user interface and data access, and (5) accounting and billing.

Activities Through FY 1988

The initial focus of ESADS activities was a workshop held in Easton, Maryland, in late February 1987. A group of systems experts, user scientists, and NASA Headquarters data systems managers participated in developing a set of action items that would move existing data-handling facilities toward greater interoperability and sharing of resources. A "bottom-up" approach was adopted to ensure maximal use of existing expertise and interest. To identify current patterns and aid in assessing progress, benchmark questionnaires were distributed to ESADS personnel and to science users. The CISD is using the workshop report and action items to develop an ESADS Implementation Plan, which will form the basis for its ESADS Research and Technology Objectives and Plans (RTOP) funding for FY 1988-1990. Ongoing groups—the ESADS Committee of Science Users and the NASA Code EE Data Systems Committee of Headquarters managers—were formed to ensure continuity of the process and implementation of the action items.

Progress was made during FY 1987 in coordination of data management activities between agencies. The NOAA/NASA Data Management Working Group met frequently during the year and initiated new agreements concerning shared responsibility for the archiving of Earth science data sets. In addition, the NOAA/National Environmental Satellite, Data, and Information Service (NESDIS) became an active participant in the ESADS Lexicon and Catalog Interoperability activities. A MOU was signed between NASA and the USGS relating to management of Earth science data. The USGS/NASA Data Management Coordination Committee was formed to coordinate activities of the two agencies under this MOU. The IWGDMGC was formed, and achieved a commitment by member agencies to work jointly towards implementation of a virtual national data system for global change research by 1995.

ESADS planning activities for evolution towards an integrated Earth science data system are expected to continue through FY 1988 and FY 1989. These activities will also track relevant technology developments, such as the new, high-capacity optical disk and optical tape devices currently being developed within NASA and in industry. Plans for increased network connectivity are underway through the CISD NSI program, which will include sharing links and gateways with other agency networks, thereby facilitating improved interdisciplinary access to data and exchange of information between scientists. A NASA Master Directory (NMD) is being developed which will permit single-point, on-line searches for NASA Earth science data. To aid NMD development, we are sponsoring an effort to collect and document directory information on all NASA Earth science data for eventual entry into the NMD. Continuing activities will increase the amounts of new and useful Earth science data in the ESADS archives in FY 1988. Efforts will be made to speed the ingestion of high-quality, but currently unsupported, data sets into the ESADS archives during the coming year.

During FY 1988, we intend to work with the CISD and the NSSDC in revising NASA Management Instruction (NMI) 8030.1 governing archiving of NASA's Earth science and space data. We also intend to produce revised guidelines for the preparation of PDMPs by our flight missions. In addition, MOUs will be developed to govern the relationships of the ESADS discipline data systems and NSSDC. Together, these documents will provide the management framework necessary to delineate the roles and responsibilities of the flight projects, central and distributed data archives, and NASA Headquarters, in providing for effective management of NASA's Earth science data during the next decade.

The Request for Proposals (RFP) to industry for the EosDIS Phase B study was released in mid-FY 1988 and the selection process will be completed for two parallel studies to begin in the first quarter of FY 1989. As noted above, an MOU has been signed between NASA and the USGS in preparation for the permanent archiving of remotely sensed land data from the Eos instruments. A similar MOU covering cooperation between NASA and NOAA in the permanent archiving of selected ocean and atmospheric data is currently under development.

Interagency efforts (through the IWGDMGC) and international efforts (through the CEOS WGD) have accelerated during FY 1988. Interagency exchanges of data directories and network interconnections are taking place in order to improve capabilities for data set description and location by users. Technical subgroups in the areas of formats, catalogs, and data exchange have been formed to foster development of interagency standards.

Plans for FY 1989

Many complex issues are being studied as background for establishing a future data management system. These include the following:

- Determination of the management roles and responsibilities of the different organizations involved with science data access, especially flight projects and their discipline communities
- Development of technologies for handling high-capacity data during the Space Platform era of the 1990s
- Establishment of intra- and interagency relationships that would allow for efficient access to all research data generated by collaborating Federal agencies
- Planning of international agreements for future data exchange

These issues will form the framework for continuing activities through FY 1989. Cooperative efforts with other Federal agencies will be intensified during this period, in order to implement interoperable Earth science data management systems across the agencies. This will involve a number of test bed activities, using pre-Eos data sets and the evolving ESADS facilities, to gain experience in a simulated Eos environment.

The Phase B studies for EosDIS will be initiated, leading to detailed design concepts. These will be structured to provide conformity, as appropriate, with the evolving ESADS and interagency data management standards. During this period, a team will be formed of Eos investigators and other scientists to provide science guidance and involvement in EosDIS development.

4

Interdisciplinary Research Program

The goal of the Interdisciplinary Research Program—first funded in FY 1985—is to investigate and understand the long-term coupled physical, chemical, and biological changes in the Earth's environment on a global scale. The scientific community, now embarking on the study of the global-scale processes at work, has solid evidence that these processes are changing rapidly and that their rate of change has accelerated. Increasing atmospheric concentrations of carbon dioxide, methane, nitrous oxide, nitrates, and sulfates demonstrate change in the global cycles for the essential life-sustaining elements of carbon, nitrogen, and sulfur. The atmospheric burden of chlorine has increased substantially as a result of industrial production of chlorofluorocarbons (CFCs). Global energy and water cycles are changing. Because the land, atmospheric, oceanic, and biospheric processes are so strongly coupled, we need to study, understand, and learn to predict the response of the global environment to such changes from an integrated perspective—as a single coupled system—as well as from the viewpoint of specific disciplines.

Issues of current concern include the study of biogeochemical cycles and the various interactions occurring at the land-air, air-sea, and land-sea boundaries.

Questions of Global Concern

The Interdisciplinary Research Program continues to address some of the more interesting and challenging interdisciplinary questions about the global environment and the consequent habitability of the Earth. These include:

- How is the global climate system affected by increasing atmospheric concentrations of infrared active species such as carbon dioxide, methane, nitrous oxide, and CFCs; by changes in solar output and in the vertical distribution of atmospheric ozone; by El Niño events; by tropical deforestation; and by volcanic activity?
- How susceptible is the column content and vertical distribution of atmospheric ozone to changes in atmospheric concentrations of carbon monoxide, carbon dioxide, methane, nitrous oxide, and CFCs; how would changes in the total column content affect ecological productivity through changes in the flux of ultraviolet radiation reaching the Earth's surface?
- What is the initiation mechanism for El Niño events, and what are the consequences of these events for ocean circulation, ocean productivity, and the global atmosphere?
- What is the impact of tropical deforestation on global biogeochemical cycles and regional climate?
- What, if any, is the mechanism for "runaway" desertification?
- What are the processes involved in the formation of acid rain, and what are the consequences of acid rain for ecological productivity?

Current Program Activities

The Program encourages multidisciplinary research of broad scope and content, based on viewing the Earth as a single coupled system rather than as a set of individual components with most interest focused on long-term (10-100 years) coupled physical, chemical, and biological changes in the Earth's environment.

Much interdisciplinary research continues to occur within the other discipline-specific programs of the Earth Science and Applications Division (ESAD). Areas involved include land processes, ocean processes, the upper atmosphere, atmospheric dynamics/radiation, global biology, and supporting flight programs. A modestly funded effort, the Interdisciplinary Research Program serves as a catalyst for interdisciplinary activities by other branches, helping to integrate and place their activities within a broader context and supporting activities that do not fit readily within the purview of these separate disciplines. The Program is closely coordinated with all related Earth science research programs, with the National Science Foundation, and with international organizations.

The studies to be supported by the Program have been carefully focused after consultation with the scientific community. Starting in early 1986, research projects were funded in the three selected areas of atmospheric methane, land surface climatology and ocean productivity. These areas of research were selected for initial study because they were felt to be of scientific importance and diversity and to be at a stage where substantial progress in understanding the problems could be made. Moreover, the research would complement ongoing activities in related Earth science programs.

- **Atmospheric Methane:** Research is being conducted to understand the origins and consequences of the trend in increasing atmospheric concentrations of methane, which is currently rising at the rate of 1 to 1.5 percent per year. From ice-core data, it is evident that atmospheric methane has doubled since the time of the Industrial Revolution. The program funds researchers investigating the chemistry of methane in the Earth's atmosphere, the identification of its sources, and its microbiological mechanisms of formation and oxidation. Others are conducting measurements of the outward flux of methane from various sources. A number of papers given by NASA-funded researchers at a symposium hosted by the Division of Geochemistry of the American Chemical Society in Denver, Colorado in the spring of 1987, identified rice-growing regions, cattle-grazing areas, marine substrates, and termite colonies as particular sources of methane.

- **Land-Surface Climatology:** Studies are aimed at understanding the extent to which changes are taking place in climatologically important properties of the land surface, using the extensive space data now available for several key desert and plains areas.

- **Ocean Productivity:** Using ocean chlorophyll imagery based on measurements by the Coastal Zone Color Scanner on the Nimbus-7 satellite, and by incorporating image information into numerical models of ocean dynamics and biogeochemical fluxes, research is being conducted on an ocean-basin scale to develop a better understanding of the magnitude, variability, and fate of carbon fluxes in the oceans on an ocean-basin to global scale.

Plans for FY 1988 and FY 1989

The research activities funded in FY 1986 for a 3-year period are well underway. Annual workshops in each of our research areas are being held to bring together all investigative groups in each area supported by the Interdisciplinary Research Program, as well as teams doing research in the focus areas who are funded through other Earth science programs. These workshops create a forum for the discussion of individual results and serve to encourage the exchange of ideas and techniques among scientists involved in our interdisciplinary research.

While there is a desire to broaden interdisciplinary efforts to include one or two additional topics, perhaps in the direction suggested by the National Academy of Sciences, there is also strong concern to ensure that the program is focused towards making a real contribution to the work of ESAD. Any additional issues for study, for example, the question of atmospheric physics, should be firmly tied to and integrated with the work of the rest of ESAD.

Once the suite of investigations invited by the January 1988 Earth Observing System (Eos) Announcement of Opportunity (AO) has been selected, an evaluation of its interdisciplinary components can be made. In addition, a NASA Research Announcement to be issued in late August 1988 solicits proposals for up to 3-year research in:

- The role of the hydrological cycle in land-atmosphere interactions
- Trace gas fluxes from ecosystems and their fate in the troposphere
- Detection of changes and identification of forcings to the greenhouse effect in the climate system

These investigations will be funded through matching contributions from the science discipline branches and the Interdisciplinary Program itself to a total of $4.5 million a year. Proposals are due by mid-December 1988 with funding for successful proposals expected to begin in the summer of 1989.

Long-Term Projections

In order to accomplish the goal of understanding the global environment, the program will ultimately need to involve the full range of space-based, suborbital, land-based, and sea-based measurements, as well as laboratory, theoretical, instrument, and model development studies.

Despite modest initial funding, ESAD has begun a timely interdisciplinary research effort which will grow as funds become available. NASA's long-term approach to implementing an interdisciplinary approach includes a continuation of relevant ongoing research programs such as upper atmospheric research, atmospheric dynamics, and oceanic processes; expanding other areas such as global biology, tropospheric chemistry, and climate; and continuing to refocus the current Land Processes Program.

5

Geodynamics Program

Geodynamics is the study of the shape and form of the solid Earth and the manner by which its surface and interior are deforming. It is one of NASA's oldest programs, having its roots in the early discoveries of the "pear-shaped Earth" and the surprising lumpiness of the Earth's gravity field. The goal of the current NASA program is to understand the dynamics of the solid Earth and the structure and composition of its interior. Objectives include:

- To understand the movement of the tectonic plates making up the Earth's crust, especially the way the plates deform in response to the driving forces, the nature of these driving forces, and how the resultant deformation is related to the occurrence of earthquakes
- To accurately model the Earth's gravity field as a means of studying the Earth's interior
- To understand how the Earth's magnetic field is generated, how it changes with time, and how these changes are related to the Earth's rotation and to variations in climate.

Observational Techniques

To measure the motions of the major tectonic plates that form the Earth's crust requires exquisitely accurate measurements (to a few centimeters or better) of the movement of points separated by as much as 1,000 to 10,000 km. These measurements have not been possible with conventional, ground-level, line-of-sight techniques, because the cumulative error over long distances inherent in these techniques is many times larger than the total annual plate movement. Only space techniques provide the requisite accuracy. Here, the source of measurement (either a satellite, the Moon, or a radio star [quasar]) is observable from very distant points, and hence the measurement accuracy is essentially unrelated to the distance between points on the ground.

Also, space methods are the only way to measure the relative motion of plates, such as the North American and Eurasian Plates, where the land surfaces are separated by oceans. Today, using satellites and quasars as reference points, repeated measurements are being made of the motion of the major plates and the deformation at several plate boundaries.

Current activities in the Geodynamics Program are based on the following satellite methods:

1. To model the Earth's global gravity field, available surface measurements are combined with analysis of the perturbations of satellite orbits caused by the nonuniform distribution of mass within the Earth. Another measure of the Earth's gravity field is provided by spaceborne radar altimeters that map the ocean surface topography, which is approximately the oceanic geoid. The geoid is an equipotential surface intimately related to the gravity field.

2. Magnetometers on satellites provide detailed mapping of the Earth's global magnetic field; long-duration satellites also measure its temporal changes.

3. Laser ranging to satellites and the Moon are used to measure crustal motion and deformation, to monitor Earth rotation and polar motion, to track satellites for gravity studies, and to study Earth/lunar effects. The lasers, located worldwide in observatories and mobile stations or trucks, range to satellites equipped with corner-cube retroreflectors, such as NASA's Laser Geodynamics Satellite (LAGEOS-1), or to retroreflectors placed on the Moon by Apollo astronauts. By accurately timing the round-trip time of a very short pulse laser beam (a few picoseconds), the position of the laser station can be determined. The global Satellite Laser Ranging (SLR) network now includes 21 fixed sta-

tions, many supported and operated by other countries, and five highly mobile laser ranging systems. Lunar Laser Ranging (LLR) data are acquired by four stations in three countries.

4. Very Long Baseline Interferometry (VLBI), a technique first developed by radio astronomers to study distant astronomical radio sources, has been adapted by NASA to study Earth's crustal motion and deformation and rotational dynamics. This technique uses two or more large radio antennas to record the random noise microwave signals emitted by the radio sources. Very accurate hydrogen maser clocks and broad-band signal correlation techniques are used to determine the difference in time of arrival of the signal at the different stations. From these time differences, it is possible to determine accurately the distance between the stations. The global VLBI network now includes 14 radio antennas located in 6 countries, and 3 mobile VLBI stations.

5. Another technique under development by NASA and other organizations makes use of radio signals from the Department of Defense (DoD) Global Positioning System (GPS) satellites. Currently, an array of 6-8 test satellites is being used. When completed in 1990, the full constellation of 21 satellites (3 in each of 6 orbits and 3 spares) will be used by DoD for military navigation. Using special GPS ground receivers, measurements of crustal deformation with centimeter precision have been demonstrated for baselines of a few hundred kilometers. Extension of this precision to longer baselines is now under study.

Highlights of Recent Accomplishments

The new information provided by geodetic space techniques is beginning to dominate the analysis of crustal motion and deformation, and is providing new insights about the solid Earth and its interaction with the fluid atmosphere and oceans. As the applicability of the space techniques is proven, new operational monitoring systems have emerged. This success has, in turn, fostered improvements to measurement accuracy. The following are some of the significant accomplishments of the academic, interagency, and international team of investigators which contribute to the NASA Geodynamics Program:

- Measurements of the velocities of the major tectonic plates have shown general agreement with the rates and directions derived from geological models of tectonic plate motion. However, as the current-day measurements are refined due to better accuracy and the period of data acquisition increases, differences between the measurements and the models are becoming evident (see Figure 5-1). Some of these differences are significant and will require modification of the models; others may be indicative of periodic or sporadic motion.

- 13 years of SLR and 3 years of mobile VLBI measurements of deformation in the Western United States clearly indicate that crustal deformation in southern California is more complex than indicated by simple fault-oriented models and may involve broad-scale interactions between surface and sub-

FIGURE 5-1A. **SLR OBSERVED PLATE MOTION RATES FOR THE PACIFIC BASIN (MM/YR)**

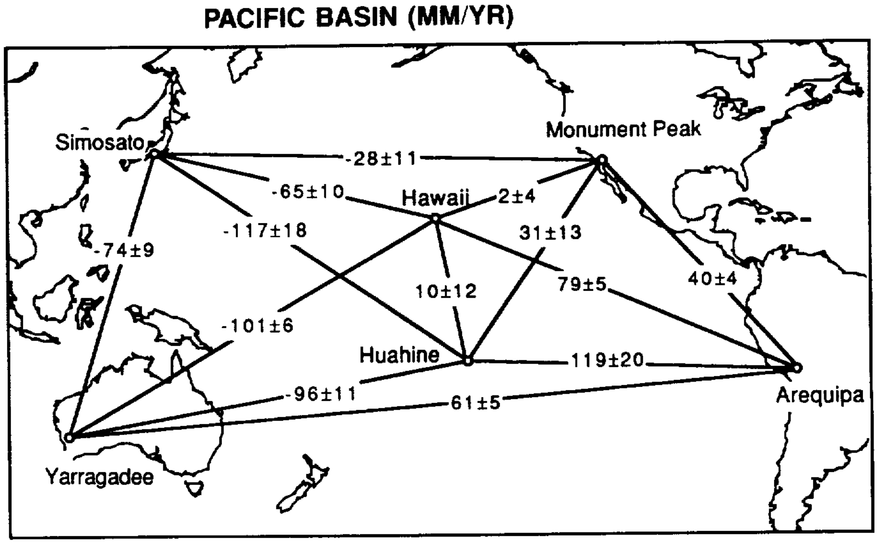
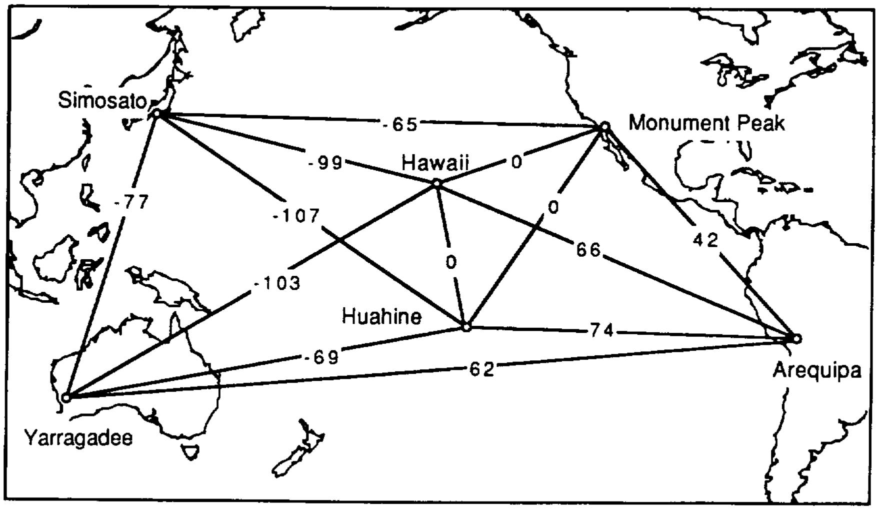


FIGURE 5-1B. **MINSTER/JORDAN PREDICTED PLATE MOTION RATES FOR THE PACIFIC BASIN (MM/YR)**



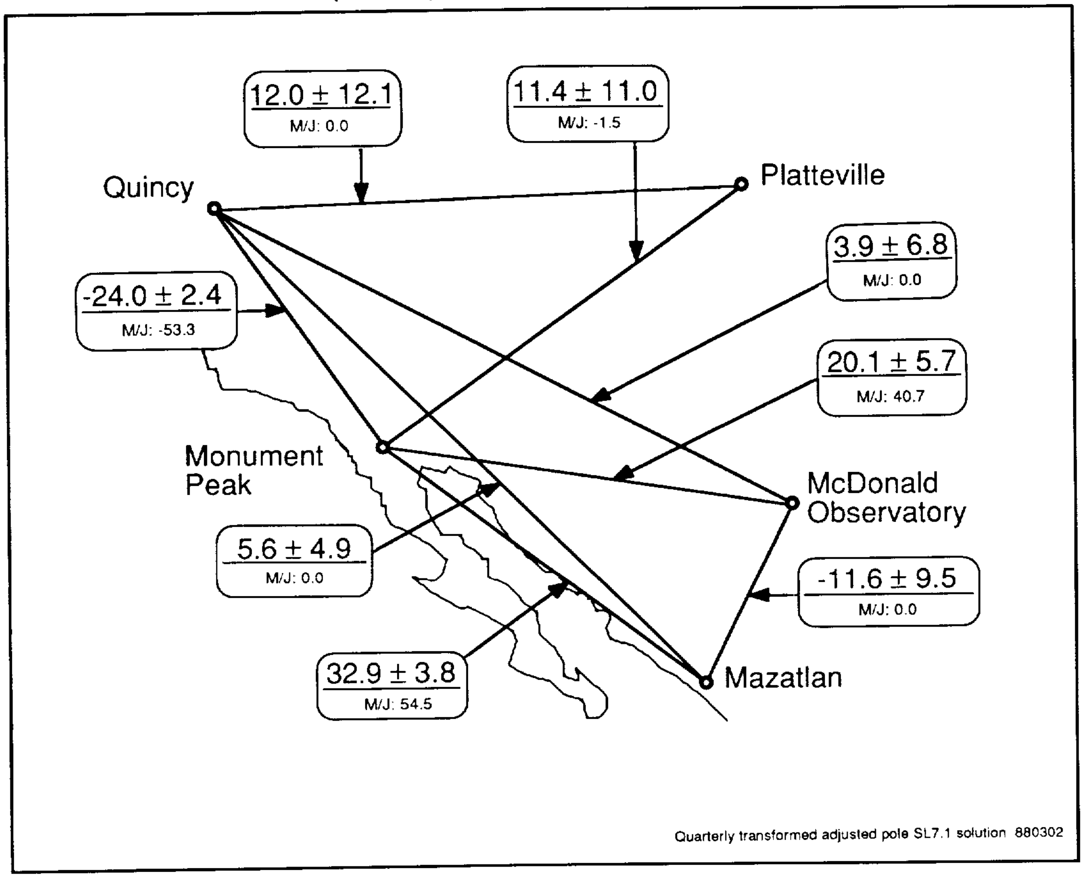
surface processes. The SLR measured rates are compared in Figure 5-2 with rates determined from the Minster-Jordan model. The smaller measured rates compared to the model for the Quincy to Monument Peak baseline, which crosses the San Andreas Fault, has led to a search of offshore faults for the missing deformation. The VLBI-determined rates are in general agreement with the SLR data, but show that most of the crustal motion across the San Andreas Fault is concentrated in southern California near the coast.

- Several years of mobile VLBI measurements in Alaska show no significant motion across the interior of Alaska. However, both Kodiak, Alaska, the site of a 1963 earthquake, and Cape Yakataga, Alaska, which is near the site of a major 1987 earthquake, showed considerable motion.
- A National Earth Orientation Service (NEOS) using VLBI has been established by the National Geodetic Survey of NOAA and the United States Naval Observatory. In 1987, the International Astronomical Union (IAU) and the International Union of Geodesy and Geophysics (IUGG) formally established a new International Earth Rotation Service (IERS) which will use data from VLBI, SLR, and LLR observatories.
- Satellite laser data have been used to derive new values for the solid Earth and ocean tides. The ocean tide values agree well with models developed using tide gauges. Similarly, agreement with models of solid Earth tides indicates the models are accurate to 1 percent or better. The tidal acceleration of the Moon inferred from the SLR data compares well with that determined from 16 years of LLR observations, and indicates that there is no significant non-tidal acceleration.
- In Figure 5-3, altimeter data from the Geodynamics Experimental Ocean Satellite (GEOS)-3 and Seasat missions have been used to make a map showing ocean surface features, a reflection of the topography of the ocean bottom.
- A special gravity field model has been developed using data from a selected set of 17 satellites. The new model, GEM-T1, has reduced the predicted orbit error for the French laser retroreflector satellite, Starlette, from 73 to 23 cm, and the Seasat orbit error from 50 to 25 cm.
- Improvements to SLR systems have resulted in single-shot precision at the sub-centimeter level. This has produced normal points (integrated averages over a 2-minute period) with accuracies of a few millimeters.

Current Emphases and Activities

Our research emphasis lies in four areas: tectonic plate motion and deformation; regional deformation at plate boundaries; Earth rotational dynamics; and geopotential fields. Major research activities include: (1) the Crustal Dynamics Project (CDP) carried out by Goddard Space Flight Center (GSFC); (2) research using the Global Positioning System (GPS) satellites in the Caribbean Basin and surrounding areas coordinated by the Jet Propulsion Laboratory (JPL); (3) the joint U.S./

FIGURE 5-2. **SLR OBSERVED PLATE MOTION RATES FOR WESTERN NORTH AMERICA (MM/YR)**



Italy development of LAGEOS-2; (4) studies of the Geodynamics Laser Ranging System (GLRS) instrument for the Earth Observing System (Eos), the Magnetic Field Explorer (MFE), the French/U.S. Magnolia/MFE Mission, and the Shuttle test of a cryogenic gravity gradiometer; (5) advanced development of laser and GPS technology; and (6) support for investigations and experiments by universities and other research organizations.

Crustal Dynamics Project

The principal objectives of the Crustal Dynamics Project are to measure and model the velocity of the major plates, to determine the stability of the major plates, and to study regional deformation in the Western United States and Alaska. The data acquired by the CDP are also used for studies of changes in the length-of-day and the Earth's polar motion. The project, scheduled to continue through 1991, is supported by international networks of SLR, LLR, and VLBI stations, and activities are conducted in cooperation with four other U.S. agencies and with scientists in more than 20 foreign countries. Of particular significance is the MedLas Program, a cooperative program between NASA and institutions from eight countries in Europe and the Middle East to study crustal deformation in the Mediterranean region using lasers. It is being carried out by the Working Group of European Geoscientists for the Establishment of Networks for Earthquake Research (WEGENER).

SLR data are acquired on a regular basis by fixed stations in 15 countries using LAGEOS-1, Starlette, and the Japanese EGP satellite. The VLBI data acquired by fixed radio antennas are scheduled in frequent observations distributed throughout the year. Mobile VLBI data are acquired in the Western U.S. in campaign bursts which typically include a dozen sites and are completed in a few weeks. Several months each summer, mobile VLBI systems are transported to Alaska to conduct measurements of the deformation associated with the subduction of the Pacific Plate under the North American Plate. All of these data are archived in a data information system and are available to investigators for analysis.

In 1987 the CDP and the WEGENER consortium completed the first set of MedLas measurements. Observations were made from sites in Greece, Turkey, and Italy using mobile laser systems operated by The Netherlands, the Federal Republic of Germany, and the U.S. In 1988 the German mobile system comes to the U.S. to join in observations with other NASA systems. The MedLas measurements will be conducted every 2 years.

Caribbean Basin Research

In 1983, at the direction of the U.S. Congress, preparations were made for the development of GPS systems for measurements of the motion and deformation of the Caribbean Plate. Tests of the GPS technique at sites in California were conducted in 1985 and 1986 in cooperation with the National Oceanic and Atmospheric Administration (NOAA), the U.S. Geological Survey (USGS), and several academic institutions. The first measurements in the Caribbean were carried out in 1986 and included five sites on Puerto Rico, Grand Turk, the Dominican Republic, and at Guantanamo Bay, Cuba. Future campaigns will include measurements related to the deformation of the Caribbean Plate at its boundaries with the South American Plate, the Cocos Plate (which includes Central America), and the Nazca Plate. JPL has undertaken the development of a new solid-state GPS receiver, which is smaller and cheaper than existing commercial receivers, to support this research.

Laser Geodynamics Satellite (LAGEOS)-2

In cooperation with Piano Spaziale Nazionale (PSN) of Italy, NASA is proceeding with plans for the launch of LAGEOS-2. This second LAGEOS will be identical to the LAGEOS-1 launched by NASA in 1976. Each satellite is a 60-cm sphere, covered with 426 corner-cube retroreflectors. LAGEOS-2 is scheduled for launch by the Space Shuttle in 1991, although the spacecraft will be ready for launch as early as mid-1990. An Italian Research Interim Stage (IRIS) will place the spacecraft in a 6000-km circular orbit with an inclination of 52 degrees. After launch, LAGEOS-2 will be used by the global laser network for crustal studies. A joint NASA/PSN Research Announcement was issued in early 1988, and selected investigations will be announced in March 1989.

Proposed Flight Projects

There is an urgent need to map the Earth's gravity field to higher spatial resolution and accuracy and to delineate temporal variations in the Earth's main magnetic field. These data are needed to advance understanding of the interior of the solid Earth, particularly the role of mantle convection in plate motion and the origin of the magnetic field. The gravity data are also needed to support the analysis of altimeter observations from the Ocean Topography Experiment (TOPEX). Of great interest is the inference from ground-based data of the association of a sudden acceleration of the westward drift of the magnetic field with variations in the length-of-day.

Experience has shown that fixed SLR and VLBI stations supplemented by mobile systems provide an adequate network for the long-term study of large-scale plate motions. However, measurements of the spatial and temporal variation of crustal strain in highly seismic areas requires frequent mapping of the positions of a large number of locations. Considering all of the major seismic areas in the world, the number of sites which should be monitored at least several times per year amount to several thousand. This is economically unfeasible with SLR, VLBI, or even GPS systems. The solution is a single laser in space which would range sequentially to a large number of corner-cube retroreflectors on the ground: this is the concept of the Geodynamics Laser Ranging System (GLRS). The GLRS would provide frequent global coverage of these areas and would respond quickly to assess the extent of crustal deformation following major earthquakes.

To support these requirements, we are pressing for approval of several flight activities: (1) development of the GLRS facility for flight on Eos, (2) a Space Shuttle test of a gravity gradiometer, (3) a Magnetic Field Explorer (MFE), and (4) a cooperative U.S./French program for magnetic field studies.

Conceptual (Phase A) studies of the GLRS are underway at GSFC, and will be followed by the initiation of Phase B studies in FY 1989. Fabrication of the GLRS is planned to begin in FY 1990, with an expected flight date of 1995. The GLRS is a rapid and inexpensive way of measuring deformations related to earthquake hazards, and as a way of involving many Third World countries that have real societal concerns about earthquakes.

The Geopotential Research Mission (GRM) was previously planned to provide the needed gravity field data and to acquire high-resolution magnetic field data for crustal studies. We are no longer considering this mission. Instead, we are anticipating that a proposed ESA flight of the French gravity gradiometer (GRADIO) will meet some of the needs of this research. Ultimately, a high-accuracy gradiometer will have to be flown, and we are planning that this will be the Supercooled Gravity Gradiometer Mission (SGGM) in the late 1990s. To further the development of the SGGM, which will be

FIGURE 5-3. **ALTIMETER DATA FROM GEOS-3 AND SEASAT MISSIONS FOR OCEAN BOTTOM MAPPING**

The map shows ocean surface features, a reflection of the topography of the ocean bottom.

capable of measuring the gradient of the field to an accuracy of 10^{-4} Eötvös (10^{-9} sec^{-1}), several orders of magnitude better than GRADIO, it is necessary to test the Supercooled Gravity Gradiometer (SGG) instrument in space. We are proposing, therefore, the initiation of a Space Shuttle test in the early 1990s. Because of its sensitivity and the need to measure the orientation of the SGG very accurately, the instrument and its Dewar will be suspended during flight in a sensing apparatus which will maintain the SGG in free-flight within the Shuttle bay. This is the same technique which is proposed for carrying the SGG in the SGGM spacecraft. Consequently, the Shuttle tests will provide valuable information on the performance of the SGG instrument and the design parameters for the free-flyer.

For the magnetic field studies, it is essential that the measurements be contiguous and span a decade or longer. The last survey of the field was completed by Magsat in 1980, and the field model derived from these data is now obsolete because of unmodeled changes in the field caused by secular variations. To separate the internal magnetic field from externally generated fields like the ring currents in the ionosphere and the electric polar fields, it is desirable to have measurements by satellites in different time zones. To meet these requirements, NASA and the French Centre National d'Etudes Spatiales (CNES) are developing a joint program of magnetic field studies. It is proposed that NASA launch an MFE as soon as possible. This would be followed by a French/U.S. mission (Magnolia/MFE).

Conceptually, the MFE would be similar to Magsat. However, it would be placed into a higher altitude circular orbit to achieve the extended lifetime needed for studying the main magnetic field and its secular variations. The MFE should be started as part of the Explorer Program at the earliest opportunity.

Conceptual Studies

The Supercooled Gravity Gradiometer has been under study at the University of Maryland for the past 8 years. A three-axis instrument is being integrated for laboratory tests in late 1988. This same instrument will be used for tests of the validity of the inverse square law. A second instrument will be developed in 1989 and will be the prototype of the Shuttle test unit. Under the direction of the Marshall Space Flight Center (MSFC), an interagency study team has been considering concepts for the SGGM and the justification for the Shuttle test flight. The study team's report was completed in early 1988, and the team has now turned its attention to Phase B studies of the Shuttle tests.

We are continuing to support the development of advanced technologies for geodetic measurements. At GSFC, work is continuing on improvements to SLR and VLBI hardware and analysis techniques with the goal of achieving millimeter measurement accuracy. Part of this activity includes the application of two-color laser ranging and streak cameras to allow corrections for atmospheric dispersion, improved water vapor radiometers to correct for the wet parts of the atmosphere, and low noise radio wave receivers to increase VLBI sensitivity. At JPL, work is continuing on the development of a solid-state GPS receiver. This unit, named "Rogue," has undergone initial testing and will be ready soon for commercial fabrication. JPL is also supporting studies of methods for measuring the motion of the ocean crust. Since 70% of the Earth's surface is under water, many areas of tectonic interest such as spreading zones and large faults are submerged. Measuring crustal motions of a few centimeters at water depths of 1 to 2 kilometers from a platform bobbing at the surface is indeed a formidable task.

University Participation

A NASA Research Announcement (NRA) for the LAGEOS-2 mission was issued jointly by NASA and PSN (Italy) in early 1988. Successful proposals will be announced in March 1989.

The Geodynamics Program is closely coordinated with other Federal agencies, academic institutions, international groups, and foreign countries. It interacts with six advisory committees of the National Academy of Sciences and currently supports approximately 100 investigators at universities and other research laboratories.

Unsolicited proposals for support of research related to crustal motion and deformation, Earth rotational dynamics, structure and composition of the Earth's interior, core/mantle interaction, and geopotential fields are accepted at any time.

Plans for FY 1988 and FY 1989

The Crustal Dynamics Project will continue measurements of global plate motion and regional deformation associated with the North American, Pacific, and South American Plates.

A major Western Caribbean campaign will be carried out in early 1988 using GPS instruments. In 1989 the 1986 measurements at the northern boundary of the Caribbean Plate will be repeated. In 1989 the second WEGENER MedLas campaign will be supported.

Long-Term Projections

When the Geodynamics Program started in the early 1970s, NASA was the only organization in the world attempting to develop highly precise geodetic measuring systems. This situation has totally changed over the past 17 years, with many countries now building and operating the type of equipment pioneered by NASA and with other U.S. Government agencies and international groups using these systems for operational services. Each year additional countries consider joining these global studies, and for several countries geodynamics has become a very significant portion of their Earth science activities.

We project that the international portion of our activities will continue to expand. Of particular significance will be the continuation and expansion of joint activities, like WEGENER MedLas, where many countries participate in an area of strong scientific interest. After the formal end of CDP in 1990, NASA will continue its activities at about the same level of effort as an SR&T program.

The expected improvements in SLR, LLR, VLBI, and GPS measurements, including measurements on the ocean bottom, will allow studies, previously impossible, of the processes which are continually changing the face of the Earth.

A long-range international planning meeting was held in July 1988 in Erice, Sicily, under the sponsorship of the University of Bologna, NASA and several international organizations. It is expected that a plan for international space geodynamics for the period 1990-1999 will be produced. This plan will be considered again at a NASA-led planning conference during the summer of 1989.

The increased understanding resulting from the synergistic analysis of high-accuracy gravity data, long-term magnetic field data, highly accurate Earth rotational data, and precise crustal motion data, will revolutionize our concepts of the Earth, its interior, and its interaction with the fluid atmosphere and oceans.

Eventually, to further understand the processes which influence solid planets, the geodetic techniques developed to study the Earth will have to be applied to the detailed study of the other planets.

6

Land Processes Program

The Land Processes Program consists of four interrelated elements: the study of terrestrial ecosystems, the hydrologic cycle, geology, and remote-sensing science. The first three represent the space-based components of classical science disciplines, while the last element is the study of the physics and biology of the land surface as they relate to the interaction of electromagnetic radiation with the surface. The primary thrust is to conduct research in the Earth sciences (including the development of methodologies where appropriate) rather than to just develop instruments and techniques for scientific or applied use by others.

Current Emphases and Activities

The program focuses on determining the current state of the land surface, on understanding the processes which determine its state, and on measuring and modeling changes in the surface which may have important global consequences.

- **The Terrestrial Ecosystem Program element** is engaged in the study of the productivity of various biomes and the biogeochemical cycling of important elements.
- **The Hydrology Program element** is concentrating on land-atmosphere interactions, with special attention to the role of biology.
- **The Geology Program element** is focused on continental evolution and Quaternary geologic processes.
- **The Remote-Sensing Science Program element** supports the above endeavors through experiments and modeling of visible, infrared and microwave radiation with natural land surfaces.

Extensive use is made of data from currently operating satellite sensors such as the Landsat Multispectral Scanner System (MSS) and Thematic Mapper (TM) on Landsat-4 and -5, the Advanced Very High Resolution Radiometer (AVHRR) on the polar orbiters NOAA-9 and -10, and the multispectral and panchromatic sensors on the French SPOT (Système Probatoire d'Observation de la Terre) satellite. Data from completed missions such as Magsat and the Heat Capacity Mapping Mission (HCMM) are also in use, as are archival data from currently operating systems. Data from experimental Shuttle flights and airborne systems are equally important. Currently available data from the Shuttle were acquired by the Shuttle Imaging Radar (SIR) series, SIR-A and SIR-B, and the Large Format Camera (LFC).

Currently operating airborne instruments are:

- **Visible and near-infrared region:** Thematic Mapper Simulator (TMS), the Airborne Visible Infrared Imaging Spectrometer (AVIRIS), and the Advanced Solid State Array Spectrometer (ASAS)
- **Thermal infrared region:** Thermal Infrared Multispectral Scanner (TIMS)
- **Microwave region:** L-Band Pushbroom Microwave Radiometer (LBPBMR) and the P-, L- and C-band multipolarization synthetic aperture radar (SAR)

The L- and C-band SAR system was built to replace a similar system previously flown on the NASA CV-990 aircraft. The first flights of this new SAR took place in early 1988. (Aircraft sensor systems which are under development are described in the section entitled "Plans for FY 1989.")

The Land Processes Program also conducts field measurements within the context of the remote-sensing studies and provides limited support to several other types of activities, including instrument concepts and prototypes, instrument calibration, studies of radiative transfer theory, data system design, and image analysis methods.

Highlights of Recent Accomplishments

The First ISLSCP Field Experiment (FIFE)

This experiment is the centerpiece of NASA's plan to develop a physically based approach to utilization of satellite remote-sensing systems and the key experimental element in the International Satellite Land Surface Climatology Project (ISLSCP). FIFE was designed to develop and validate algorithms to retrieve land surface properties and the fluxes of moisture and energy between the land surface and the atmosphere at the 15-km scale (roughly a few pixels for the operational meteorological satellites).

Approximately 150 scientists from more than 30 institutions participated in this year-long experiment on the Konza Prairie in Kansas.[1] The experiment was managed by NASA with participation by the National Science Foundation (Division of Atmospheric Sciences and Division of Biotic Systems and Resources), the U.S. Department of Agriculture, the National Center for Atmospheric Research (NCAR), the U.S. Geological Survey, the U.S. Army's Cold Regions Research and Engineering Laboratory, the Canadian Centre for Remote Sensing, and the National Environmental Research Centre (NERC) in the United Kingdom. Satellites and a long-term network consisting of 19 automated weather stations were used to monitor the site throughout the year, weekly assays of the biological status of the site were made, and four intensive field campaigns totaling 57 days were conducted over the full range of the growing season. Figure 6-1 is a schematic representation of the experiment during one phase of the intensive field campaigns.

The highlight of the experimental program was the 10 days in which complete diurnal coverage was possible. Predawn and post-sunset flights were made to map surface temperatures and boundary layer fluxes. Morning and afternoon missions mapped surface temperatures and boundary layer fluxes as well as optical properties including bidirectional reflectances coinciding with the overpass of the satellites. The science teams operated their experiments primarily during the daylight hours, but some nighttime and predawn thermal infrared measurements were taken during each intensive field campaign. The resulting data sets provide a unique resource for the study of the functioning of a grassland ecosystem and its interaction with the atmosphere.

Surface measurements during the intensive field campaigns included enhanced radiation and soil moisture measurements from 32 meteorological stations, flux measurement from 24 stations using either eddy correlation or Bowen ratio techniques, radiosondes at 4-hour or shorter intervals, two atmospheric lidars and a sodar. Experimental sites were distributed over a variety of terrains including recently burned and unburned sites, grazed and ungrazed sites, and a range of slope and aspect conditions. Measurements of soil physical and chemical properties and surface and subsurface plant properties were made, and several investigators studied canopy optical and surface bidirectional reflectance properties. One major drainage basin was the focus of a detailed hydrological experiment. Atmospheric measurements were made to facilitate the calibration of all remote-sensing data.

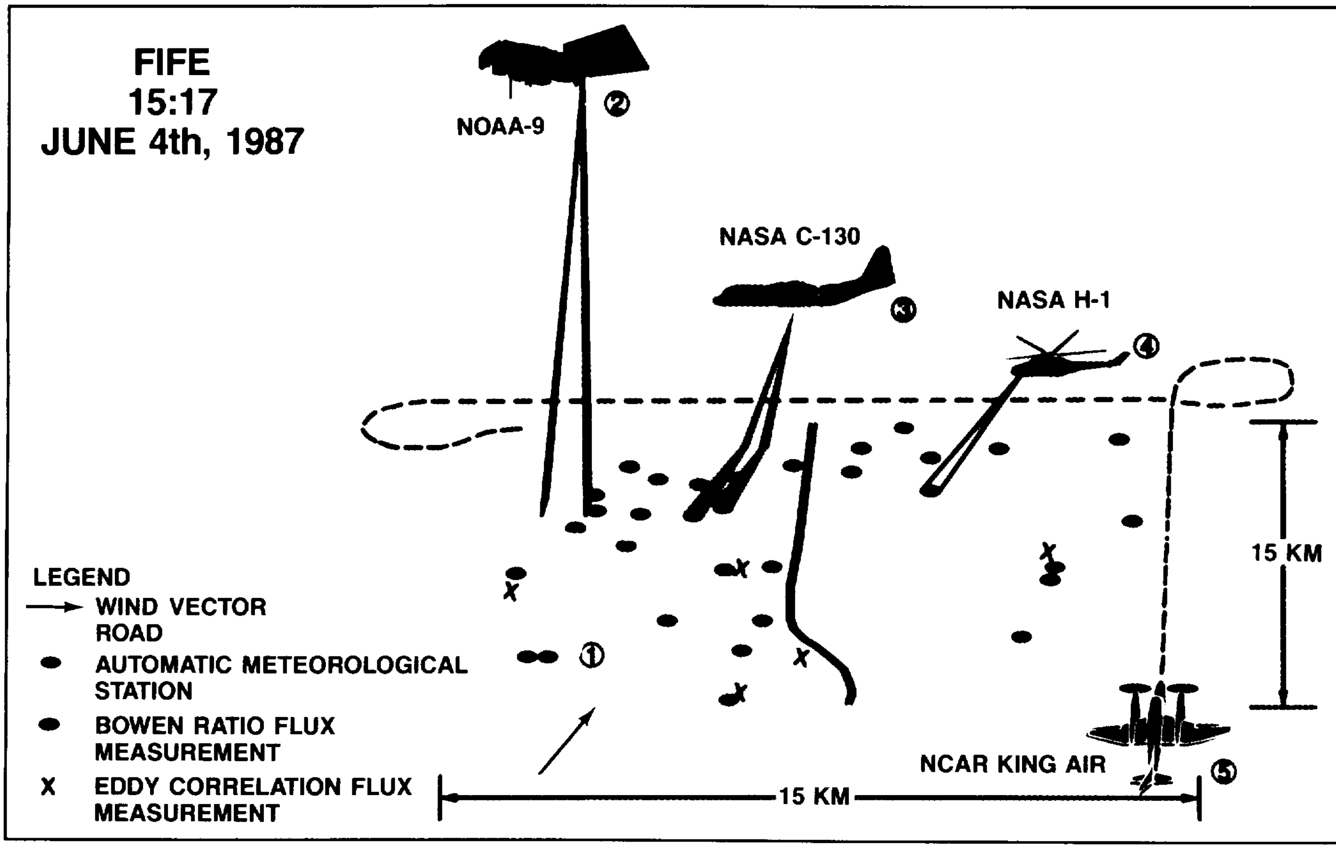
Eight different aircraft were used to obtain remote-sensing and in situ measurements of the land and atmospheric properties. The NASA C-130 conducted the primary remote-sensing missions, flying 156 hours over the FIFE site. The C-130 carried instruments operating in the visible, near-infrared, thermal infrared, and microwave wavelength regions. The NASA Bell helicopter flew a total of 109 hours over the automated meteorological stations, Bowen ratio and eddy correlation stations, and biological study sites. Three flux measurement aircraft, the NCAR and University of Wyoming King Airs and the Canadian Atmospheric and Environmental Research Ministry's Twin Otter, flew a total of 169 hours measuring latent and sensible heat flux and carbon dioxide flux at altitudes as low as 50 m above ground level. Additional measurements of surface properties were made by NASA's ER-2 and the NOAA Aero Commander aircraft.

The FIFE activities have resulted in the preparation of the most comprehensive satellite data base ever compiled for a single site. The AVHRR on NOAA-9 and NOAA-10 acquired over 1000 scenes of the eastern Kansas site, and eight Thematic Mapper images were acquired. Taking advantage of the pointable High Resolution Visible (HRV) sensor on the French SPOT satellite, 30 images were acquired. This resulted in better than weekly coverage during the main experimental phase. These data will provide detailed information on a range of phenological and annual climatic conditions over the tallgrass prairie area of the Midwestern United States.

Analysis of the experimental data is now underway. Initial results will be available during the latter part of 1988. All Level O and some higher level experimental

[1] A full description of the goals of the experiment can be found in the January 1988 *Bulletin of the American Meteorological Society* (Sellars, P.J., F.G. Hall, G. Asrar, D. Strebel, and R.E. Murphy).

FIGURE 6-1. **A SCHEMATIC REPRESENTATION OF THE FIFE SITE DURING A COORDINATED MISSION PLAN 2 ACTIVITY**



Flux aircraft overfly the 15-km square site, and the NASA C-130 and the NASA helicopter obtain high spatial resolution remote-sensing measurements while one of the current operational remote-sensing satellites images the area. Airborne sensors duplicate the off-nadir geometry of the satellite imaging system as appropriate. Ground-based sensors also duplicate the viewing geometry, and upwards of 25 flux measurement stations are operating at the same time.

data will be available to other researchers beginning in 1989.

AVIRIS

Construction of NASA's Airborne Visible Infrared Imaging Spectrometer (AVIRIS) was completed in late 1986 and it had its first research flight season in 1987. AVIRIS is a "whisk broom" scanning instrument which uses line arrays to acquire 11-km wide images in 220 bands, each 10 nm wide, within the 0.41-2.45 μm spectral region. It flies on a high-altitude NASA ER-2 aircraft. AVIRIS replaces the Airborne Imaging Spectrometer (AIS), an area array pushbroom instrument, which covered the spectral region from 0.9-2.45 nm and was flown on the NASA C-130 from 1982-1987.

AVIRIS represents an important milestone in NASA's imaging spectrometry program. It is a significant improvement over the AIS in its inclusion of the visible wavelength region and in its overall image quality. AVIRIS is not an experimental sensor test bed, as AIS was, but a fully operational research instrument designed for many years of use. It will be used in preparation for the proposed Earth Observing System (Eos) High Resolution Imaging Spectrometer (HIRIS). AVIRIS will be able to simulate HIRIS data, thus enabling scientists to gain experience handling and analyzing hyperdimensional optical data sets well in advance of the launch of Eos. AVIRIS will be flown in conjunction with other airborne prototypes of Eos instruments, such as the L- and C-band SAR, to acquire multisensor data sets for early studies of how to analyze and combine information from such disparate data sets. AVIRIS also will be used for HIRIS supporting studies, for example, to test editing modes, evaluate quantization methods, and to simulate signal-to-noise trade-offs with spatial and spectral resolution.

In May 1987 a group of 17 investigators was selected to conduct the first scientific evaluations of AVIRIS's performance, data character and quality, and scientific utility. These investigations were chosen to assess the radiometric, geometric, and spectral characteristics of AVIRIS over a range of challenging test sites including rock outcrops, snow, vegetation, and inland and oceanic waters. The ecology, botany, hydrology, oceanography, limnology, and remote-sensing science disciplines were all represented.

A total of 16 missions were flown between June 25, 1987 and October 21, 1987, acquiring data from over 32 different sites in support of investigations by 21 principal investigators. Most of the 1987 AVIRIS data is for sites in the Western United States, ranging in the Far West from Oregon to California to Arizona and east to Colorado and Wyoming. Schedule constraints for the NASA aircraft precluded extensive data acquisition in the Eastern United States, but sites in Florida and Minnesota were flown. Early engineering flights of AVIRIS produced images of high visual quality (see Figure 6-2). Preliminary results from the AVIRIS data evaluation program and other 1987 AVIRIS investigations were presented at a workshop held at the Jet Propulsion Laboratory in June 1988.

Current Activities

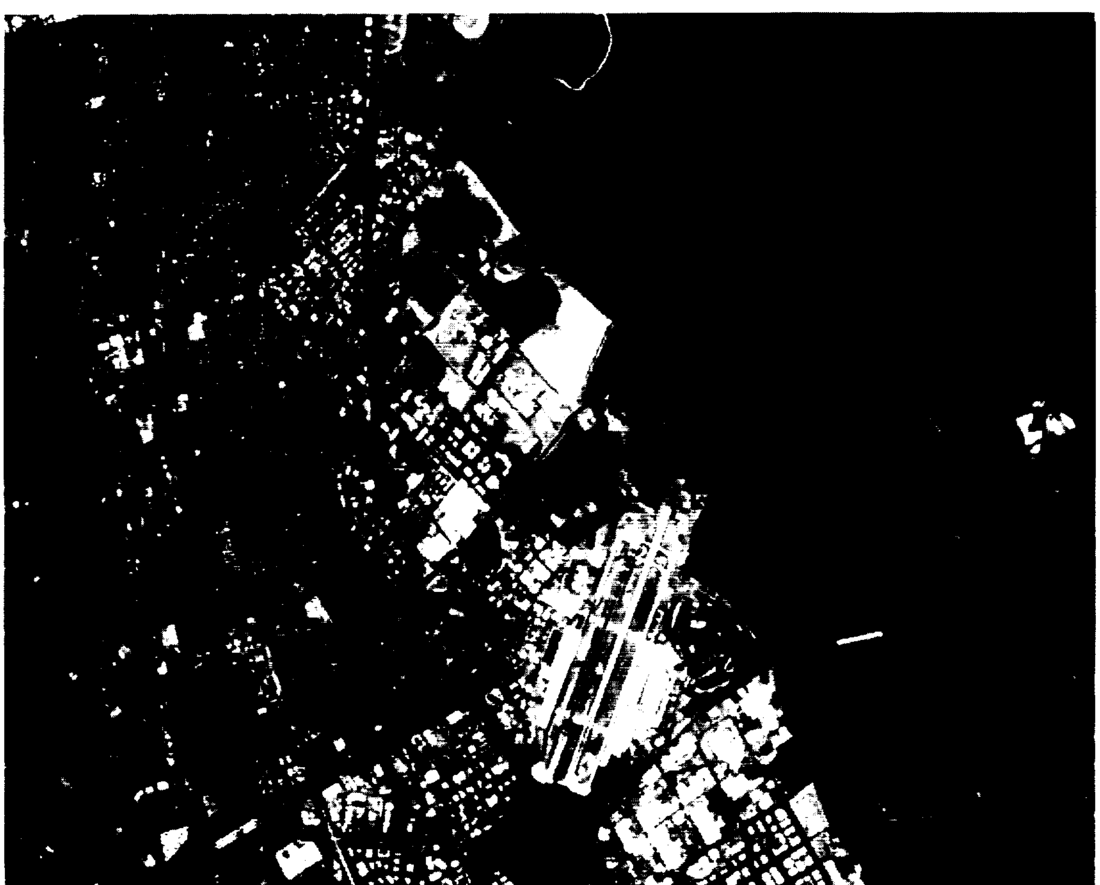
Terrestrial Ecosystems Program Element

The broad goal of the Terrestrial Ecosystems Program element is to achieve an improved understanding of the role of terrestrial biota in processes of global significance through the use of airborne and spaceborne sensors. Specific objectives are to understand:

- Biogeochemical processes and cycles
- Biotic contributions to the global energy balance
- Change in vegetation state and dynamics

Major research activities include analysis of multidate remotely sensed observations of vegetation patterns

FIGURE 6-2A. **IMAGE OF THE MOUNTAIN VIEW, CALIFORNIA, AREA ACQUIRED BY AVIRIS**



The image was made through band 30 of spectrometer A, centered on 0.683 μm.

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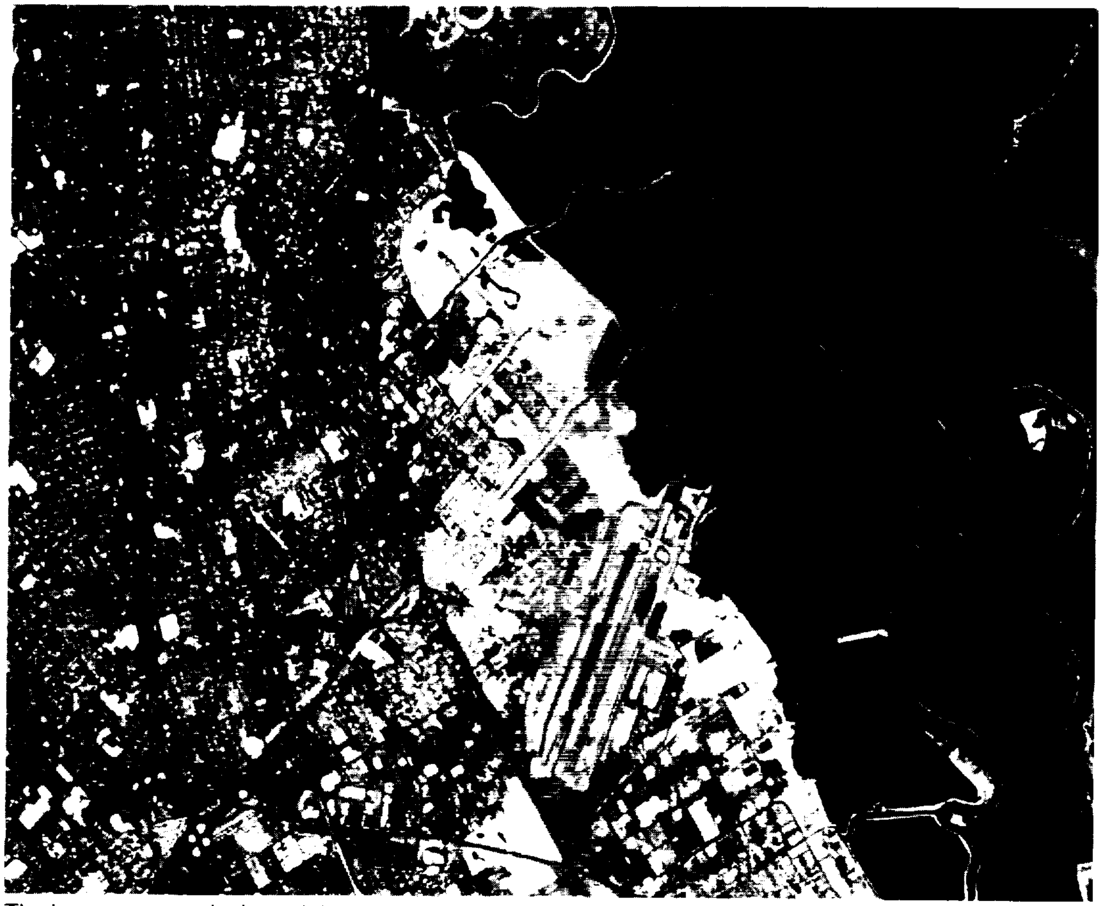
BLACK AND WHITE PHOTOGRAPH

FIGURE 6-2B. **IMAGE OF THE MOUNTAIN VIEW, CALIFORNIA, AREA ACQUIRED BY AVIRIS**



The image was made through band 68 of spectrometer B, centered on 1.014 μm. The spectral resolution for both images is approximately 10 nm. The images were made from raw data; no radiometric or geometric correction has been applied except for aircraft roll compensation which was performed during data acquisition. In addition to these two images, an additional 218 10-nm images across the spectral range from 0.40-2.45 μm were acquired simultaneously.

and processes, field- and aircraft-based measurement of ecosystem properties, and modeling of relevant ecological processes using remotely sensed inputs.

Research in 1987 focused on: (1) preparation and analysis of internally consistent, monthly, global vegetation index data sets for the study of terrestrial productivity during the period 1981-1986, (2) prediction of vegetation canopy chemistry using high spectral resolution, remotely sensed visible and infrared reflectance data, (3) estimation of evapotranspiration at the watershed-scale using airborne or spaceborne thermal infrared data, (4) analysis of patterns of change in vegetated landscapes over time through comparison of multidate satellite images, (5) examination of the spectral characteristics of stressed vegetation and investigation of their anatomical and physiological determinants, and (6) development of models of ecosystem productivity, biogeochemical cycling, and canopy structure which are driven primarily by remotely sensed data inputs. Major accomplishments for three Terrestrial Ecosystems Program projects are highlighted below.

Estimation of Canopy Biochemistry. If lignin and nitrogen can be estimated using only remotely sensed data, then it will be possible for the first time to monitor and predict a whole host of important ecosystem biogeochemical cycling processes on a large scale. Ecologists already have shown that the ratio of nitrogen to lignin in forest leaves can be used to predict the rates of decomposition and various nutrient cycling processes.

High spectral resolution reflectance data acquired by NASA's Airborne Imaging Spectrometer (AIS), the precursor to AVIRIS, have been used to estimate forest canopy lignin concentrations and forest ecosystem nitrogen mineralization. The AIS acquired a continuous reflectance spectrum from 0.9-2.45 μm with a 10-nm sampling interval. Results of previous laboratory studies indicated that stepwise multiple regression techniques could be used to predict lignin and nitrogen concentrations in dried leaves from laboratory spectrometer measurements of reflectance at high spectral resolution. In 1987 these results for lignin were extended successfully to the field for use with fresh leaves in forest canopies and an airborne spectrometer. Although the technique is correlative in nature, the regressions between measured and predicted lignin concentrations were very high, with a $r^2 = 0.85$, for a forested site with a large lignin concentration gradient in central Wisconsin. A strong inverse relationship ($r^2 = 0.96$) between canopy lignin concentration and nitrogen availability (through nitrogen mineralization) in undisturbed forest ecosystems suggests that canopy lignin may serve as an index of site nitrogen status. This enabled nitrogen status at the landscape level to be predicted from lignin estimates based on AIS data. Continued research in this project will test the robustness of the statistical technique and attempt to understand the biophysical basis for the relationship. Future research will use AVIRIS to extend the estimated technique to different ecosystems and to explore its applicability to additional canopy biochemical constituents, particularly nitrogen. Models of ecosystem processes which can accept remotely sensed estimates of canopy nitrogen and lignin concentrations are already being developed.

Analysis of Landscape Patterns. Secondary succession patterns and processes in the boreal forest of northern Minnesota have been studied through analysis of two Landsat MSS data sets collected in 1973 and 1983. A stochastic description of the key life-cycle states of community landscape elements was generated. A transition matrix describing the probability of change from one successional state to another was calculated based on classifications of the two Landsat scenes. The 10-year observations of this boreal forest region indicated that there are considerable successional changes at the landscape element level in an ecosystem which has been relatively stable over several centuries. Managed areas within the region were much more dynamic and heterogeneous than the wilderness areas. Stochastic descriptions such as this can provide input and verification for models of community development, landscape dynamics, and ecosystem stability. These results provide strong evidence that remote sensing can be used to provide the necessary inputs to ecosystem landscape models and to explore the dynamical behavior of ecosystems.

Estimation of Deforestation Rates. Normalized Difference Vegetation Index (NDVI) and thermal data of 1.1-km resolution from the AVHRR have been used to document large-scale deforestation in the southern part of the Amazon Basin. For the combined states of Acre, Rondonia, and Mato Grosso, total disturbance area and total deforested area were estimated at 165,742 km^2 and 89,573 km^2, respectively, confirming predictions of near exponential increases in the rate of deforestation for these areas. The image data also demonstrated the strong relationship between road building and the deforestation processes in the southern Amazon Basin. Data from 1982, 1984, and 1985 were used to delineate disturbance areas and then to generate estimates of the deforested area within them. NDVI data were used to identify zones of growing sensitivity which are more likely to be subject to human disturbances, and saturated pixels for channel 3 (3.55-3.93 μm) were used to estimate fire occurrence and frequency, both indicators of disturbance areas. AVHRR channel 3 also showed the best spectral contrast between the original forest cover and cleared areas, so brightness temperatures for channel 3 were used to generate supervised classifications of deforested areas within the identified disturbance areas.

Future Terrestrial Ecosystems Research. Future remote-sensing research in the Terrestrial Ecosystems Program will be directed toward understanding whole ecosystem response to changes in globally significant environmental factors. Studies which emphasize the transfer of ecological information from local to regional to global scales, and the converse, will be encouraged. Advance planning for the Terrestrial Ecosystems Program has produced interim recommendations for a research approach that includes: (1) the use of remote-sensing systems which span relevant spatial scales, (2) the use of spatial and temporal patterns to integrate among scales, (3) the development of mechanistic, nested or hierarchical models covering all relevant spatial scales, (4) the use of geographic information systems, (5) a strong regional focus, and (6) the use of gradients, drainage basins, and stressed systems as objects of study. A complete draft of the advance planning report for the Terrestrial Ecosystems Program is being published this year.

Hydrology Program Element

The goals of the Hydrology and Land Surface Climatology Program are to use remote sensing to achieve a better understanding of the regional and global storages and fluxes of the land component of the Earth's hydrologic cycle, to investigate the role of the hydrologic cycle in regional and global biogeochemistry and geomorphology, and to examine the interactions between land surface processes and regional and global climate. Specific objectives are:

- To measure land surface characteristics that control hydrologic responses and reflect hydrologic change
- To define the distribution (in time and space) of the physical parameters and atmospheric forcing that control soil moisture fluxes and associated runoff
- To improve understanding of snow and ice processes and their role in the hydrologic cycle
- To improve understanding of the role of the hydrologic cycle in the Earth's biogeochemistry

Major research activities include analysis of multidate remotely sensed observations of hydrologic processes, field- and aircraft-based measurements of land surface properties, and modeling of relevant hydrological processes using remotely sensed inputs. In contrast to the Terrestrial Ecosystems Program element, there is a much greater emphasis on the use of microwave observations.

Research in 1987 focused on: (1) development and interpretation of a global data set using the Scanning Multispectral Microwave Radiometer (SMMR) and the Special Sensor Microwave Imager (SSM/I), (2) investigations of the hydrologic properties of the Earth's land surface, including soil and snow properties, (3) energy and mass balance model development and experiments, including the French-managed Hydrological Atmospheric Pilot Experiment (HAPEX) and FIFE, (4) analysis of the existing 15-year record of Landsat and other satellite data for evidence of land-atmosphere interactions as a part of the ISLSCP Retrospective Analysis Program (IRAP), and (5) studies using general circulation models with interactive biospheres. Accomplishments in Hydrology Program projects are described below. The FIFE results are discussed above under "Highlights of Recent Accomplishments."

Global Microwave Data Sets. Global data sets have been developed for the years 1979-1985 of several indices using microwave data. An algorithm has been developed for estimating surface wetness from SMMR 6.6-GHz horizontally polarized brightness temperature (TB) over the U.S. southern Great Plains from 1979-1983. The ratio of the horizontally and vertically polarized brightness temperatures at 37 GHz is also a sensitive indicator of surface roughness, vegetation cover and surface wetness.

Empirical equations to relate surface wetness from TB and the polarization difference and the NDVI from AVHRR data have been developed. Analysis of global data from 1979-1985 demonstrates the feasibility of estimating evapotranspiration by correlating with vegetation spectral properties in the visible, near-infrared and microwave regions, rainfall, and the seasonal variation of atmospheric CO_2. Work planned for the future will address these issues over the Sahel, with the aim of mapping interannual variation of the Sahara-Sahel boundary.

Microwave Measurement of Northern Hemisphere Snow Cover. Data from the Nimbus-7 SMMR from 1979-1987 have been processed to produce assessments of the extent and magnitude of the seasonal snow cover in the Northern Hemisphere. Measurements at 18 and 37 GHz are used to estimate snow water equivalence. Because of the scattering of microwave radiation at these frequencies, the emissivity of dry snow is much lower than that of vegetation or soil and thus the brightness temperature decreases as the snow water equivalence increases. The use of the dual frequencies allows some of the effects of other physical characteristics of the snow to be eliminated.

The results compare favorably with the standard NOAA snow extent maps made from AVHRR data, but are not subject to obscuration by cloud cover and provide information on snow water equivalence as well as extent. Considerable interannual variability is observed in the data, owing to and contributing to the dynamics of the winter storm patterns in the Northern Hemisphere. An unexpected result of the measurements of snow cover has resulted from interaction with geodynamics researchers; the interannual variability in the seasonal snow cover apparently explains about 30 percent of the variation in the short-term wobble in the Earth's axis.

Several sources of error persist in our measurements of global snow cover. These must eventually be corrected to provide correct boundary conditions for long-range climate forecasting models. Work is planned to more carefully examine the snow retrieval algorithms used for the SMMR data and the SSM/I, launched on the DMSP satellite in 1987. We suspect that vegetation, particularly trees that extend above the snow pack, disrupts the relation between microwave brightness temperature and snow water equivalence. Wet snow produces a microwave signal that is similar to that of bare soil. Snow crystalline structure affects the microwave signal, and shallow snow packs with large, hollow crystals can produce a microwave signature very much like deeper snow packs with smaller or rounder crystals. Further work on these topics should allow for more accurate assessments of the Earth's climate and its interaction with the hydrosphere.

Future Hydrology Research. This work will continue with emphasis on land-atmosphere interactions and NASA's contribution to ISLSCP and the Global Change Program. A new NASA advanced planning study began in 1988 and the National Academy of Sciences is conducting a major new planning exercise on opportunities in scientific hydrology.

Geology Program Element

The goal of the Geology Program element is to derive a better understanding of the Earth's geologic history and processes that have shaped the surface of the Earth over time. Specific objectives are:

- To investigate the history and evolution of the continents from early formation through currently active accretionary, depositional, tectonic, deformational, and erosional processes
- To investigate Quaternary geologic history and processes in order to unravel the course of recent geomorphic, volcanic and climatic processes for a better understanding of the evolution of land surfaces and climate over the last million years

The broad scope of studies undertaken in the NASA Geology Program includes Earth investigations ranging from global studies (e.g., of the geomagnetic field and of volcanic emission into the Earth's atmosphere) to regional studies of individual mountain ranges and sedimentary basins, and development of techniques to improve: (1) interpretation of individual pixels in images of rock and vegetation terrains, (2) understanding of radar-detected texture in the identification of rock type, rock properties and emplacement, and weathering history, and (3) improved measurement of terrain topography.

Sedimentary Basins Study: The Wind River Basin. Studies in the Wind River Basin in Wyoming have developed techniques for detailed geologic mapping and structural interpretation from remotely sensed data. Satellite and airborne sensor data have been used to construct a stratigraphic section of the Wind River Basin which compares very closely to that constructed by geologists mapping in the field. The rocks of the area were deposited as sediments over 60 million years ago in a continental margin setting. Because the rocks in such a section are characteristic of certain depositional environments, it is possible to infer the depositional history of the basin from the sequence of rocks preserved therein. Its post-sedimentary deformational history can be reconstructed from the present geometry of rock sections, observable on a grand scale with satellite imagery, and can be checked with subsurface seismic and well-log data, using JPL-developed software. Working with this software and with satellite imagery displayed on a screen, a scientist can designate easily identifiable features on the Earth's surface, such as the surface trace of the boundaries between different kinds of rock strata, to allow computation of strata orientation.

The Wind River Basin was selected as the site of the Sedimentary Basins Study because, as an important petroleum exploration site, it has an extensive history of previous studies and results could be checked against a great library of existing information. In addition, the technology developed in this project is particularly applicable to geologic regions of economic as well as historical importance. Plans for future study include the use of remote sensing to reconstruct geologic history at sites which are less well known, possibly beginning with a tertiary basin in Southern Mexico.

The Sedimentary Basins Study has involved collaboration of nearly 30 scientists from 14 institutions, including seven universities. As this project reaches a milestone in fall 1988, a workshop summarizing regional geologic interpretation and technologic accomplishments to date is planned for that time. Because the technology developed for this project can be broadly applied to many geologic studies, particularly in sedimentary basins, the Secretary General of the International Union of Geological Sciences (IUGS) has arranged to feature these techniques in a special session of the next meeting of the IUGS in January 1989.

Tectonics of Northeast Africa. A fundamental question concerning the mechanism of crustal formation is being investigated in the region of the Red Sea. The geology of the area records the early formation of an ocean basin and its subsequent closure, culminating in island arc collision and suturing to form the continental crust of Saudi Arabia, Egypt and the Sudan (the Arabian-Nubian Plate) during the late Precambrian era (pre-600 million years ago). Prevailing opinion holds that most of the crust was formed during arc-associated volcanism at that time. However, if the crust was formed in this way, then 80 percent of the Earth's late Precambrian arcs would have had to be located in this small region, a statistical improbability.

An integrated study of satellite, Shuttle, field, and laboratory data suggests an alternative. Through identification of the rock types and ages located in the sutured crustal area and detailed mapping of the extent of their occurrence, it has been possible to identify exotic continental blocks or terrains which are much older than the surrounding late Precambrian material. Much of the volume of material in the sutured area may actually have been formed earlier than late Precambrian time, carried into its present location during late Precambrian closure of the basin, and sutured against the ancient crustal margin at that time. The faults and structural fabric resulting from this ancient activity dictated the geometry of rifting as the Red Sea began to open millions of years later (about 25 million years ago), as shown in Figure 6-3.

Improving Geologic Interpretation of Satellite-Detected Magnetic Anomalies. The resolution of satellite magnetic anomalies and the capacity to analyze them for lithospheric information has reached a stage where these data can provide a significant input to reconstructions of previous continental configurations. The utility of Magsat magnetometer observations for regional geologic analysis is significantly enhanced by normalizing magnetic anomalies for global attitude and intensity variations of the magnetic field of Earth's core. The resulting radially polarized anomalies of a reconstructed Gondwanaland (one of the two supercontinents which comprised most of the Earth's continental crust in pre-Mesozoic time) during the early Cambrian era 560 million years ago show remarkable correlation across present continental boundaries. This strongly suggests that a principal source of the anomalies are pre-rift terrains which acquired their magnetic characteristics during Precambrian tectonic and thermal events. Discrepancies in correlation across rifted margins reflect rift or post-rift modification of the magnetic characteristics of the crust or difficulties in reconstruction of the ancient configuration of the continents (see Figure 6-4).

Future Geology Program Research. Future remote-sensing research in the NASA Geology Program will encompass studies ranging in scale from regional to global. The NASA Geology Workshops in 1988 and 1989 will provide more specific directions for the accomplishment of these goals in the areas of volcanology, paleoclimatology, and sedimentary basins.

Remote-Sensing Science Program Element

The Remote-Sensing Science Program element is a cross-cutting activity which supports the three disciplinary program elements through theoretical modeling and field and laboratory measurements of land surface properties. At this time the focus is on obtaining a firm understanding of the physical, chemical, and biological factors which control the interaction of electromagnetic radiation with the surface. The aim is to develop the capability to determine surface properties with remote sensing with a minimum reliance on empirical or statistical techniques. Five classes of activity are underway: (1) visible and near-infrared models and measurements (largely of plant canopies), (2) Earth-space radiative transfer for atmospheric corrections, (3) electromagnetic properties of surface materials, (4) microwave models and measurements, and (5) radiometric calibration and verification.

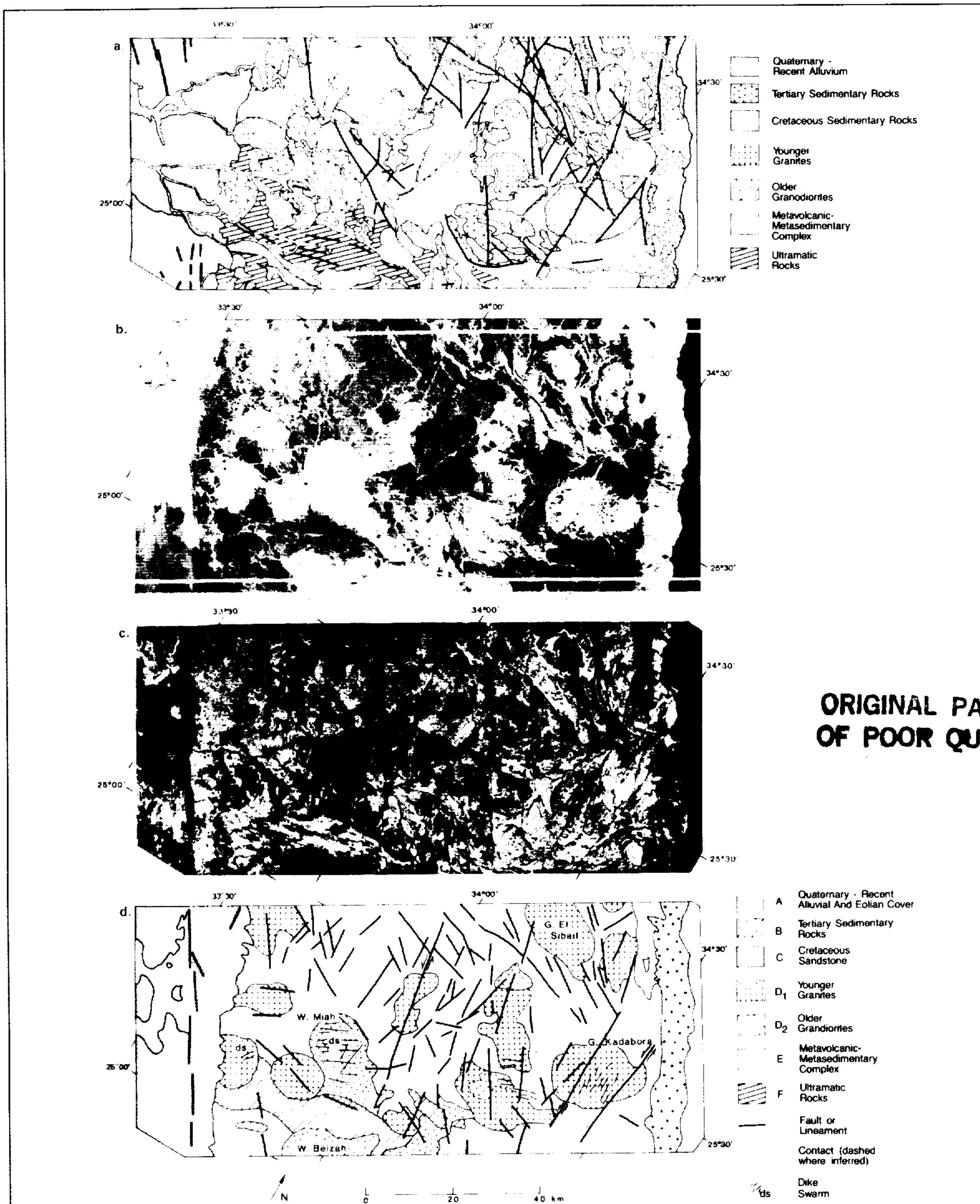
Atmospheric Effects on Anisotropy of Plant Canopy Reflectance. Measurements of the complete angular distribution of the sky irradiance field and the canopy bidirectional reflectance have been used to investigate the effects of variations in atmospheric optical depth on the canopy bidirectional reflectance. The study concentrated on measurements within the principal plane and on one band in the visible and another in the infrared, such as are used to calculate a vegetation index. The observed changes in reflectance for both wavelengths from irradiance distribution variations is interpreted to be largely due to changes in the shadow area viewed by the sensor for incomplete canopies such as pasture grass. For a complete canopy, soybeans in this case, increased specular reflection and increased penetration of diffuse irradiance into the canopy appear to be the primary physical mechanisms responsible for the observed reflectance changes (see Figure 6-5).

For larger solar zenith angles, observed reflectivities were found to be lower on a hazy day for the complete canopy cover of soybeans. Pasture grass reflectivity, however, increased with increased haze. For the full canopy, the increased diffuse irradiance was able to penetrate deeper into the canopy where it was absorbed. Decreased specular reflection also played a role. For the partial canopy, the diffuse irradiance was better able to reach the brighter soil background and reflectance was therefore increased. Since these effects are more pronounced in the visible than they are in the infrared, the vegetation index is significantly affected by changes in the atmospheric haze. In the visible region, changes of up to 80 percent were observed, while in the near-infrared region they were never more than 20 percent.

Work is underway to collect routine atmospheric aerosol data in the Sahel region of Africa, where much of the continental-scale research is being conducted by NASA and other agencies. At the same time, "bootstrap" techniques for estimating atmospheric properties from the existing satellite data are being developed, and an advanced sensor designed to more effectively estimate atmospheric properties is being studied.

Satellite Calibration and Radiometric Accuracy. Work continues on the radiometric characterization of

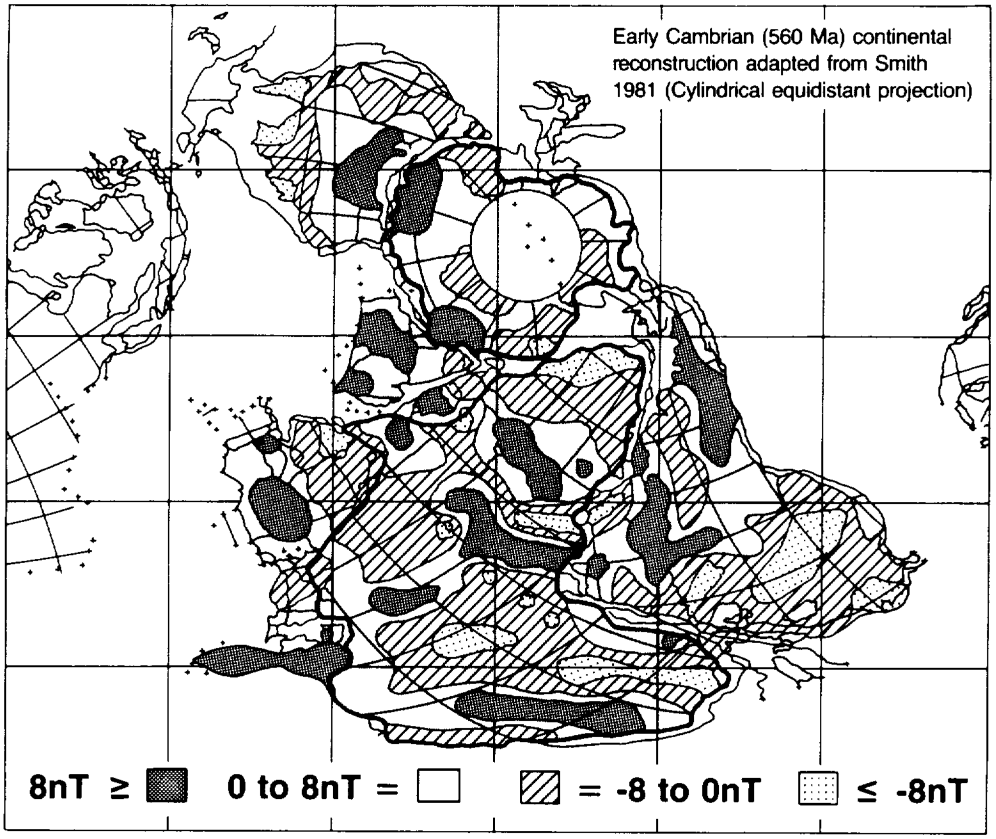
FIGURE 6-3. **CONTROL OF THE RED SEA RIFT STRUCTURE BY ANCIENT PRECAMBRIAN SUTURES**



(a) Geologic map of a portion of northern Sudan (from El Ramly and Hermana, 1978)
(b) Landsat band 7 image of the same area
(c) SIR-A image of the same area
(d) Lithologic and structural interpretation of the SIR-A and Landsat images (b and c)

Unit discrimination (units A-F) based on interpretations of both radar and Landsat images. Lithologic assignments to the units are based on comparison with (a). Faults and fractures (>5 km) are from the radar image only. Small areas of Quaternary-Recent alluvium (e.g., in the narrow wadis and on the coastal plain) are obvious on the radar image but are omitted from the interpretation for clarity.

FIGURE 6-4. **GONDWANALAND AND RADIALLY POLARIZED MAGSAT MAGNETIC ANOMALIES**



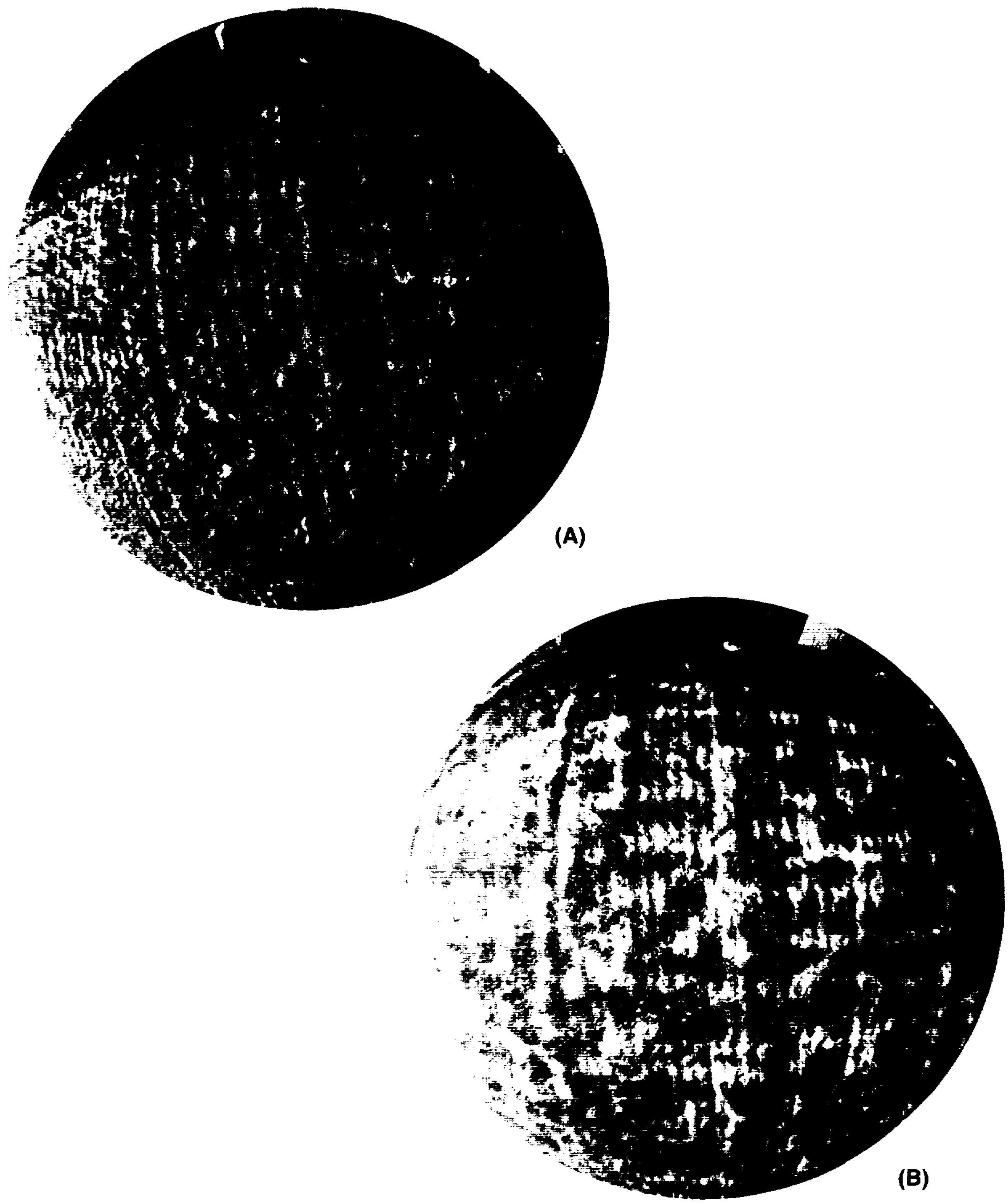
Radially polarized Magsat anomalies plotted on an early Cambrian reconstruction of Gondwanaland. The magnetic field anomalies are contoured at 8nT intervals.

the Landsat Thematic Mapper. We now know more about the radiometry of this instrument than any previous land sensor. The evaluation of how accurate radiometric measurements need to be, and how well we can achieve specified goals, remains an important issue for the Remote-Sensing Science Program. While some of the more traditional applications of remote sensing are not sensitive to radiometric uncertainty, some of the more quantitative applications require precise radiometric calibration. Data are periodically collected over the White Sands, New Mexico, site using aircraft and ground-based measurements and some atmospheric characteristics. These data show that, after initial drift between 2 and 8 percent, the Landsat Thematic Mapper visible and near-infrared detectors are stable to about 2 percent over the past 2 years. The short-wavelength infrared channels (1.75 and 2.2 microns) are not as stable and the source of variation is not yet understood, but it is thought to be correctable. The thermal channel is subject to systematic variations, but these are now well understood and accounted for in the calibration steps during production of the images. The thermal channel appears now to be performing within specifications, producing 0.5-degree accuracy in the at-satellite temperature. Of course, retrieval of surface temperatures requires additional knowledge about atmospheric properties at the time of data acquisition. Similar activities are underway for the AVHRRs on NOAA-9 and NOAA-10.

NASA is working cooperatively with the Centre Nationale d'Etudes Spatiales (CNES) in France on the ground calibration of SPOT-2, to be launched sometime after 1988. Calibration equipment which has been used to calibrate NASA sensors was shipped to Toulouse, France, and joint measurements were made using CNES and NASA equipment. This will allow future NASA sensors to be tied into the calibration of SPOT-2. Analysis of the data is underway.

Spectral Signatures of Geologic Rocks and Minerals. The spectral emissivity of geologic materials in the thermal infrared region of the electromagnetic spec-

FIGURE 6-5. **BIRD'S-EYE VIEW OF A TUFTED ORCHARD GRASS CANOPY ON A CLEAR DAY (A) AND A HAZY DAY (B)**



Considerably more sunlight reaches the bright soil background on the hazy day, increasing the visible reflectance considerably. A smaller effect is noted in the near-infrared. Denser canopies such as a mature soybean canopy show the opposite effect due to decreased specular reflection and increased canopy penetration.

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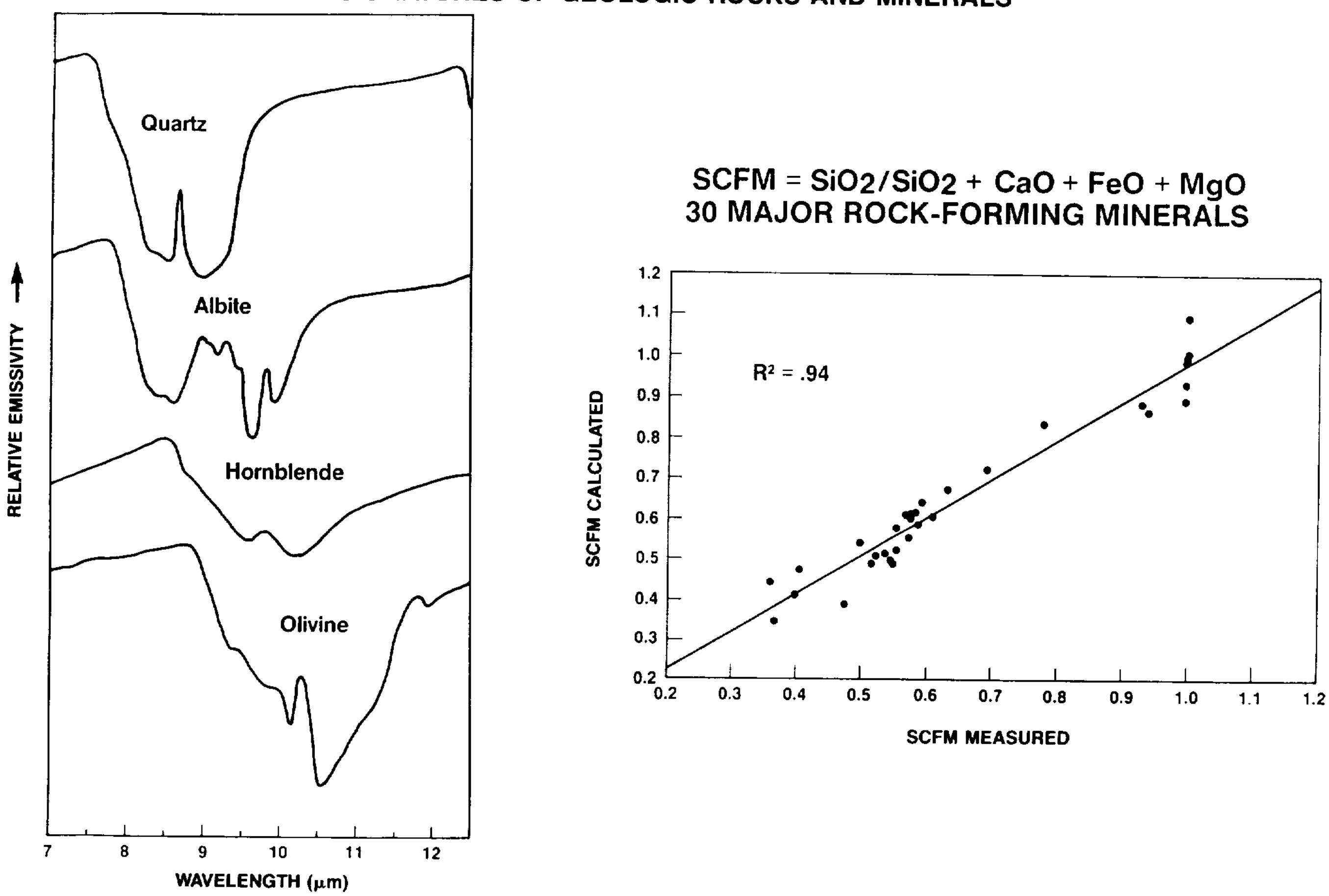
trum (8-14 microns) is being characterized by detailed laboratory studies and by aircraft and portable sensors in the field. Only the thermal infrared region contains diagnostic spectral information for the silicate minerals (which comprise the greater portion of the Earth's lithosphere). Current studies focus on understanding the emission spectra in terms of rock and mineral chemistry and structure and rock texture, with the goal of achieving greater precision in the remote mapping of geologic materials. Laboratory studies relating the measured ratio of silica to silica + calcium oxide + ferrous oxide + magnesium oxide to the ratio inferred from spectral emission measurements show a remarkable positive correlation. Because this ratio is directly related to mineral and rock composition and (in igneous rocks) to their petrogenesis, these studies could lead to the ability to make detailed rock identification remotely (see Figure 6-6). Associated studies focus on relating subtle thermal infrared remote-sensible differences in basalt chemistry and flow texture to tectonic setting. Related studies include mapping of the composition, thickness, and roughness of silica coatings on Hawaiian basalt flows and other volcanic rocks. Preliminary results indicate a good positive correlation between thickness and texture of silica coating and age of the lava flows.

Future Remote-Sensing Science Research. The range of new sensors to be deployed on Eos will become the basis for new multisensor studies and are

FIGURE 6-6. **SPECTRAL SIGNATURES OF GEOLOGIC ROCKS AND MINERALS**



(a) The relative emissivity of four key rock-forming silicate minerals is plotted against wavelength in the 8-14 μm region of the electromagnetic spectrum. This range is referred to as the Si-O stretching region and primarily involves displacements of the oxygen atoms. Note that the main feature in this range (the high shoulders surrounding a region of decreased emissivity punctuated by smaller increases) shows a systematic shift toward higher wavelengths as the ratio of silica to silica + calcium oxide + ferrous oxide + magnesium oxide (SCFM) decreases (highest for quartz, lowest for dunite).

(b) Based on this relationship, the SCFM of 30 rock-forming silicate minerals was calculated on the basis of the mineral emissivity. When plotted against SCFM values obtained by measurement of the chemical content of the minerals, a remarkably close correspondence is observed.

likely to dominate remote-sensing science activities in the future. Sophisticated atmospheric models have reached the point where they provide the required insights into atmospheric behavior and far exceed the measurement capabilities of potential satellite sensors. Consequently, the development of further atmospheric models will be deemphasized. Viable correction schemes using existing or planned sensors will be important. Canopy models for single-sensor simulations have reached a degree of maturity, and the emphasis will now be on canopy and scene models appropriate for multisensor studies. Modeling studies for geologic investigations are also required. Plans are being made for coordinated multisensor experiments to develop and validate models for use in the Eos era.

Other Branch Activities

Working Groups. The Land Processes Aircraft Science Management and Operations Working Group (ACMOWG) has been formed to advise on the coordination of aircraft planning activities, particularly in the case of major deployments, such as overseas or multitemporal experiments. In addition to long-term planning, the group is considering short-term issues, program balance, current program effectiveness and data handling. Emphasis is being placed on broadening access to the aircraft sensors for a wider range of users, including the university community. The group is interacting with discipline planning groups to recommend a multiyear plan for aircraft activity, taking into account, for example, the SIR-C program (see below) and the plans of other branches within the Earth Science and Applications Division (ESAD). Plans include increased efforts in 1989 to calibrate airborne instruments and develop methods for combining multisensor data at several sites of interest to the Land Processes disciplines, a possible deployment to Europe of the NASA DC-8 and ER-2 in 1990 or 1991, and airborne radar underflights associated with the first flight of the SIR-C mission in 1991.

In a report to be published in mid-1988, the Topography Science Working Group (TSWG), comprising university and NASA research scientists, has recommended that NASA begin a program to acquire a global topographic data set of vertical resolution of 1 m and horizontal resolution of 50 m, augmented in selected areas with higher resolution. The technology exists for the former in narrow beam radar altimetry, and for high resolution in Large Format Camera or SPOT stereogrammetry and in airborne laser altimetric systems. The group recommends that the global, regional and local topographic data sets be stored in a common, easily interpreted format on video disk or similar medium to facilitate widespread distribution and analysis.

SIR-C Science Activities. A Memorandum of Understanding signed in October 1987 by NASA Administrator Dr. James C. Fletcher and Dr. Heinz Riesenhuber, Minister of BMFT, West Germany, established cooperation in the Spaceborne Imaging Radar-C/X-Synthetic Aperture Radar (SIR-C/X-SAR) mission and further NASA/BMFT cooperation in Spaceborne Imaging Radar and X-band SAR activities during future Space Station activities. NASA, the Bundesministerium für Forschung und Technologie (BMFT, the West German Federal Ministry for Research and Technology), and the Consiglio Nationale delle Ricerche (CNR, the Italian National Research Council) are currently planning to fly an X-band system (X-SAR) in conjunction with the SIR-C mission. Comparison of SIR-C and X-SAR images could provide new insight into the backscatter response of the Earth's surface at different radar frequencies.

A NASA Research Announcement detailing opportunities for research associated with SIR-C was released in late June of 1987. SIR-C is one element of the NASA Spaceborne Imaging Radar Project which will culminate in the Earth Observing System SAR in the mid-1990s. SIR-C will be capable of acquiring C-band and L-band radar images of the Earth's surface at selectable incidence angles ranging from 15-60 degrees simultaneously at four polarizations (HH, HV, VV, VH). X-SAR can be operated in an imaging mode with VV polarization to obtain surface coverage with approximately 30-km ground swaths at incidence angles of 15-60 degrees. The Shuttle will fly at an altitude of approximately 225 km with an orbital inclination of 57 degrees during the 6-8 days of a flight mission. The first launch of SIR-C is expected in mid-1991, with a subsequent launch 6 or 18 months later to enable data acquisition during two different seasons.

SPOT Data Exchange. A 1986 agreement between NASA and the French space agency CNES allows NASA to purchase at a reduced cost 100 scenes of SPOT satellite imagery per year for the lifetime of the SPOT-1 and -2 spacecraft. In exchange, CNES-supported investigators are provided with access to data from NASA's airborne sensors. The Land Processes Branch coordinates data requests from funded NASA investigators as well as from scientists of the USGS, NOAA and USDA. A particular emphasis this year has been on assessing the radiometric characteristics of the sensor for application to detailed measurements of energy flux, as in the case of FIFE. Stereo SPOT imagery is being used to generate detailed topographic data for mapping purposes as well as determining local variations in net solar radiation in mountainous areas.

PIDAS. In 1987 several studies were conducted to assess the performance and data quality of the Portable Instant Display and Analysis Spectrometer (PIDAS), an instrument developed by the California Institute of Technology and the W. M. Keck Foundation. PIDAS is a field spectrometer which covers the range 0.4-2.5 μm. It acquires a complete spectrum in 2 seconds with spectral sampling intervals of 0.88 nm in the visible and 4.8 nm in the infrared range. NASA is considering supporting PIDAS as a facility available to members of the Earth science and applications programs for basic research and for evaluation of AVIRIS data. Results of the evaluation studies will be available in 1988.

Plans for FY 1988

Workshops. Fifteen workshops and study meetings are currently planned for calendar year 1988. These meetings are summarized in Table 6-1.

SIR-C. Approximately 180 SIR-C proposals have been reviewed by NASA HQ. Because the SIR-C/X-SAR Science Team is to include approximately 30 NASA-selected and -supported investigators and 10 DFVLR-PSN investigators, selection involved careful coordination to produce a complementary team of scientists. Announcement of selections was completed in July 1988.

First Aircraft SAR Scientific Flights. The airborne Synthetic Aperture Radar (SAR), operating at P-, L- and C-bands, collected its first data for scientific purposes on NASA's recently acquired DC-8 in January 1988. The P- and L-bands are now fully operational, with the C-band to be fully operational in 1989. With their quad-polarization capabilities, they will be utilized for geologic, biologic and hydrologic studies. This instrument closely matches the L- and C-band systems which will fly on the 1991 Shuttle mission, SIR-C, and serves as a pathfinder for the proposed Eos SAR.

Pilot Land Data System Build 1. The first implementation of the Pilot Land Data System (PLDS), called "Build 1," was declared operational in August 1987. PLDS is a prototype data and information system designed to satisfy requirements for a geology research project and the Land Processes Program's ISLSCP projects. Currently, PLDS consists of user support offices and on-line data catalog and inventory data bases at JPL and GSFC, a communication network linking all project members by means of high-speed lines or remote dial-up, and a limited number of inventoried data sets. Priority activities for 1988 include increasing the functionality of Build 1, ingesting additional data sets, and planning for "Build 2" of PLDS.

Advanced Sensors. Several additional advanced sensors have been considered for development during the 1987-88 period. In cooperation with the U.S. Department of Agriculture, a prototype "thinned aperture passive microwave" system for measurement of soil moisture is under construction. Design studies are underway for a very wide field area array sensor for determining atmospheric properties and surface bidirectional reflectances. A high-resolution thermal infrared profiling spectrometer is also under consideration.

TABLE 6-1. **LAND PROCESSES PROGRAM WORKSHOPS AND STUDY EFFORTS, 1988**

SAR Calibration Workshop	Pasadena, CA	March
ISLSCP African Workshop	Niamey, Niger	April
FIFE Investigator Workshop	Columbia, MD	April
Volcanology Workshop	Pasadena, CA	April
SIR-B Investigator Workshop	Pasadena, CA	April
AVIRIS Workshop	Pasadena, CA	June
PIDAS Workshop	Pasadena, CA	June
Paleoclimate Workshop	Seattle, WA	July
TM Science Program Workshop	College Park, MD	August
IRAP Workshop	Albuquerque, NM	October
HAPEX Workshop	Banyuls, France	October
FIFE Investigator Workshop	Columbia, MD	November
Remote-Sensing Science Annual Meeting	Cambridge, MA	November
Boreal Forest Experiment Workshop	Durham, NH	December

Advanced Planning. Advanced planning activities are continuing with publication of the Geology and Terrestrial Ecosystems Program Plans in 1988. Program planning exercises for Hydrology and Remote-Sensing Science were initiated in 1988 with preliminary publication in 1989. A report on the need for a global digital topography data set and establishing the sensor requirements and feasibility was published in early 1988.

Plans for FY 1989

Remote-Sensing Science Multisensor Airborne Campaigns. Beginning in 1990, NASA will conduct a series of modest-scale experiments to develop and validate models for the physically based analysis of multisensor data. The experiments will be designed to develop the understanding of the remote-sensing process in order to ultimately meet the needs of the program elements in Terrestrial Ecosystems, Hydrology and Geology. Thus, target study sites and model outputs will be based upon the scientific objectives of those elements, but the maturity and promise of the models will control experiment design and relative emphasis among the candidate experiments. These experiments will be precursors to others which will concentrate on the disciplinary science goals. In addition, these experiments will assess the feasibility of future discipline-driven science experiments and prepare for the science program of the Eos era. Cooperative interactions with members of the European scientific community are anticipated, with the second year of experiments probably taking place in Western Europe.

Ecosystems Multitemporal Experiments. In 1989 priority will be given to terrestrial ecosystems studies that require multitemporal airborne sensor coverage. Vegetation is dynamic over a growing season, and remote-sensing coverage at an instant in time captures only one stage of the annual cycle. It has been well-documented that multitemporal coverage of vegetation yields additional information about its characteristics. Further, to infer process information and to detect change, more than one data acquisition is a prerequisite. Thus, repetitive coverage of selected sites offers the opportunity to study dynamic, and not just static, properties of ecosystems. In the past the large number of prospective users and the limited number of aircraft hours have made it extremely difficult to acquire more than one, or rarely two, data sets over a given vegetated target for an individual principal investigator. To remedy this situation, the Terrestrial Ecosystems Program plans to select a small number of sites for multiple data acquisitions spanning the growing season and to encourage several investigators to conduct investigations at any one site. Priority will be given to the acquisition of multitemporal optical data (i.e., AVIRIS, TMS, ASAS, TIMS), but microwave data sets (L- and C-band SAR and LBPBMR) also will be required for at least one of the sites.

SIR-C Science and Calibration. We anticipate that we will fund approximately 30 science and a number of calibration experiments in the SIR-C mission over a 6-year period (FY 1989-1994). Most of the science cost will be incurred during the last 3 years when the mission will be flown and data analysis will be undertaken.

Alaskan SAR Facility. The Alaskan SAR Facility (ASF) will be ready by 1990 to acquire data from the polar-orbiting Earth Remote Sensing Satellite-1 (ERS-1) scheduled for launch that year by the European Space Agency (ESA). The polar-orbiting Japanese Earth Resources Satellite-1 (JERS-1), scheduled for launch in 1992, will also transmit data to the ASF. In addition to a radar sensor, JERS-1 will carry an optical sensor capable of acquiring stereo imagery, and will carry tape recorders such that data collected elsewhere can be transmitted to the ASF. The visible and short-wave infrared bands selected for this sensor were designed to be of particular use to solid Earth scientists.

Plans are already in place to receive, process and archive SAR data. An additional activity aimed at receiving and processing the optical data is under consideration. Innovative processing methods designed to optimize the radiometric and geometric properties of the data would be used. Methods to utilize the stereo optical data to develop terrain corrections for the SAR data would also be developed. The access to global observations by JERS-1 would significantly enhance many aspects of the land program.

Future Projections

The Land Processes Program is investigating a cooperative effort with the Earth Observation Satellite Co. (EOSAT) to develop a widefield sensor to be flown on Landsat-6 when it is launched in 1991. A 1987 study has shown that the currently planned Sea-Wide Field Sensor (Sea-WiFS), described in Chapter 7, could be augmented with two additional thermal infrared channels and an enhanced data system to provide near daily coverage of the Earth at a 1-km resolution.

The system would include four of the ocean color channels in the visible and near-infrared, each of which would produce two separate data streams, one with a gain and dynamic range designed to meet the ocean science requirement for analysis of very dark targets, and the other to meet the land science requirements for brighter targets and to cover a larger dynamic range.

Thermal infrared channels at 3.7, 9, 10 and 11 microns would be used to measure surface temperatures while correcting for atmospheric water and surface emissivity variations. In its research mode, the sensor could be operated at night so as to overcome the problems with reflected sunlight in the 3.7-micron region.

The visible and near-infrared bands would be used to estimate intercepted photosynthetically active radiation and the thermal bands to estimate stress. This combination would permit a better estimate of biological productivity over the entire globe.

Other studies beyond 1990 are the subject of current planning activities. It is expected that much of the work will be in the context of the international initiatives on global change which are being led by the International Council of Scientific Unions (ICSU) as well as activities under the auspices of the World Climate Research Program (WCRP). An ecologically oriented experiment compatible with the goals of ISLSCP is one possibility. Alternatively, a large-scale (400 km) land-atmosphere study under the auspices of ISLSCP and WCRP is possible within the context of the NSF-NOAA initiative, Storm Central. Cooperative programs with other space agencies will be featured during the next 10 years. Building upon the past cooperative scientific efforts with the European Space Agency and ministries in several European countries, plans are being developed to deploy the new NASA airborne sensors to Europe for joint calibration and scientific studies. Consideration is also being given to other sites based upon the scientific importance, local capabilities and supporting observations from future sensors such as the ESA's ERS-1.

7

Oceanic Processes Program

The goal of the Oceanic Processes Program is the development, evaluation, and application of spaceborne observing techniques to advance our understanding of the fundamental behavior of the oceans, as well as to assist users with the implementation of operational systems. We are working closely with the operational oceanographic community because many of the specific research questions being addressed by our program, once answered, will improve our capability to utilize spaceborne techniques for operational purposes.

Spaceborne Observational Techniques

The Oceanic Processes Program consists of three discipline areas and one ocean data systems area. The discipline areas—physical oceanography, biological productivity, and polar oceans—are supported by a number of spaceborne observational techniques. Building on the experience gained from Seasat and Nimbus-7, the Program is developing more advanced observational techniques in each discipline area, all involving collaborative arrangements with other agencies or governments. These include:

- **Physical Oceanography:** Satellite scatterometers and altimeters are used to observe surface roughness and topography, from which surface winds and ocean current response can be estimated. We are making plans to fly the NASA Scatterometer (NSCAT) aboard the Japanese Advanced Earth Observing Satellite (ADEOS) in the 1993-1994 time frame, as a result of the cancellation of the Navy Remote Ocean Sensing System (N-ROSS); and we are developing the Ocean Topography Experiment (TOPEX/POSEIDON), a dedicated altimeter mission to be conducted jointly with the Centre National d'Etudes Spatiales (CNES) and scheduled for launch in December 1991.
- **Biological Productivity:** Color scanners are used to observe chlorophyll concentrations, from which primary productivity can be estimated. An ocean color scanner, the Sea-Wide Field Sensor (SeaWiFS), is planned to fly aboard Landsat-6, a joint endeavor with EOSAT.
- **Polar Oceans:** Microwave Radiometers and Synthetic Aperture Radars (SARs) are used to estimate the characteristics of sea-ice cover and details of its motion, and altimeters to estimate ice-sheet topography. The Special Sensor Microwave Imager (SSM/I) will supply data from the Defense Meteorological Satellite Program (DMSP); SARs will fly aboard the European Space Agency's (ESA) Remote Sensing Satellite (ERS-1) and aboard the Japanese Earth Resources Satellite (JERS-1); and altimeters will fly on the Navy Geodetic Satellite (Geosat) and the ERS-1.
- **Ocean Data Systems:** The data systems area employs the latest computing and networking technology to facilitate access to these spaceborne data. The distributed NASA Ocean Data System (NODS) will have compatible nodes at the Jet Propulsion Laboratory (JPL), at the Goddard Space Flight Center (GSFC), at the NOAA/National Snow and Ice Data Center (NSIDC), and the NOAA/National Oceanographic Data Center (NODC). It will be linked to universities via the Space Physics Analysis Network (SPAN) and the National Science Foundation computer networks (NSFnet).

Highlights of Recent Accomplishments

Major recent advances have been made in both spaceborne sensing techniques and in our capability for providing data to the user community. These include:

- TOPEX/POSEIDON and NSCAT are both under development; TOPEX/POSEIDON is scheduled for launch in December 1991, and NSCAT is proposed for flight aboard the Japanese ADEOS mission in the 1993-1994 time frame.

- Science Definition Teams for both TOPEX/POSEIDON and NSCAT have been selected in response to Announcements of Opportunity; preparatory activities for each are underway.
- Formal agreement between EOSAT and the Department of Commerce has been reached for the development of Landsat-6; NASA and EOSAT have agreed in principle on support for Sea-WiFS (an improved version of the Coastal Zone Color Scanner [CZCS]), planned for launch in mid-1991.
- Development of the Alaskan SAR Facility (ASF) is progressing; formal agreements between NASA and both ESA and the Japanese National Space Agency (NASDA) have been reached for the reception of SAR data from the ESA's ERS-1 and SAR and optical data from NASDA's JERS-1.
- Preparations for the establishment at the National Snow and Ice Data Center of the first node beyond JPL of the NASA Ocean Data System are advancing; this new node will generate and archive sea-ice data products from the microwave radiometer aboard DMSP missions.

Present Activities and Future Thrusts

The four interrelated efforts of the Oceanic Processes Program—physical oceanography, ocean productivity, polar oceans, and ocean data systems—are described below.

Physical Oceanography Program

This Program emphasizes the development of improved spaceborne techniques to observe and study oceanic and meteorological parameters and is subdivided into two areas: ocean circulation and air-sea interactions.

Ocean Circulation Program. The goals of the Ocean Circulation Program are (1) to develop a satellite-borne capacity for measuring global ocean currents (and thereby general oceanic circulation and its variability), and (2) to determine the global transports of heat and momentum within the ocean, which to a large degree affect the Earth's climate. Specific objectives include the following:

- Extracting information from existing data sets (Seasat and Geosat) on tides, currents, topography, bathymetry, eddies, and fronts
- Assessing the impact of remotely sensed data in ocean forecasting models and developing techniques for assimilating altimeter and scatterometer data into numerical models aimed at the eventual routine use of these satellite products
- Improving understanding of the dynamical and thermodynamical processes responsible for the circulation of the ocean in order to provide a sound scientific framework for planned satellite missions

The basis for the Ocean Circulation Program is the TOPEX/POSEIDON altimeter mission, a new start in FY 1987. This 3-year mission will map the circulation of the world's oceans from detailed measurements of the sea surface topography. The high-precision radar altimeter can reveal details of currents, eddies, and other features of the ocean circulation and seafloor geologic structure. Combined with the ocean surface winds to be measured by NSCAT, TOPEX/POSEIDON will for the first time provide the synoptic, global description of ocean circulation needed for improved climate prediction.

We are working jointly with CNES to provide a sound scientific basis for interpreting the large amount of data expected from the TOPEX/POSEIDON mission. In laying this groundwork, we are placing emphasis on theoretical analysis, on modeling-based studies that are aimed at assimilating satellite and in situ data for research purposes, and on the analysis of historical data collected from space.

The major thrust is to ensure adequate preparation for full and effective use of TOPEX/POSEIDON data. Central concerns continue to be the analysis of historical altimeter data and the development of error analysis techniques and optimum data assimilation methods. Another primary thrust is the development of ocean models designed for handling huge amounts of satellite information, particularly altimeter data. The TOPEX/POSEIDON Science Definition Team will develop a science plan for the mission and make recommendations on design characteristics.

Because the TOPEX/POSEIDON design will address ocean variability, we plan to obtain early insight into these issues through the utilization of the Navy's Geosat data. These data will enable us to test and evaluate new techniques in orbit determination.

Other activities in the Ocean Circulation Program range from the development of algorithms to the full utilization of altimetric data for investigating ocean circulation and its variability. We are looking at pattern recognition techniques that can be used to identify and characterize eddy structure. Error analysis, the identification of errors in precise orbit determination, is an important program element. This analysis also includes identifying the errors propagated in ocean circulation models by mistakes made in data assimilation.

Seasat altimeter data continue to be analyzed. A new pattern recognition technique has been used to determine eddy distribution in the Southern Ocean and to make direct comparisons between in situ currents and altimeter-derived currents. We are currently attempting to determine whether the mesoscale fluctuations provide the principal mechanism by which heat, salt, and nutrients are transported meridionally across the Antarctic Circumpolar Current. We are also addressing how to achieve optimal filtering of altimetry data for use as inputs to ocean models of varying scales.

Air-Sea Interaction Program. The goal of the Air-Sea Interaction Program is to improve our spaceborne capability for observing useful oceanic and meteorological parameters, which will advance understanding of the physical processes occurring in those layers of the oceans and atmosphere close to the sea surface. Such parameters include surface wind stress, ocean surface waves, and surface wind-driven currents. Specific objectives include the following:

- Development of aircraft, orbiting, and in situ sensors for routinely and accurately observing ocean waves, surface currents, surface wind stress, and the vertical fluxes of heat, momentum, and moisture
- Data analysis of existing remotely sensed and in situ data sets, as well as of future data from focused field experiments conducted jointly with other agencies
- Conducting theoretical and laboratory studies to provide a better understanding of the interaction between electromagnetic radiation and oceanic dynamical processes
- Assessment of the impact of remotely sensed data on ocean forecasting models and development of techniques for assimilating altimeter and scatterometer data into numerical models aimed at the eventual routine use of these satellite products

The Air-Sea Interaction Program centers on the NASA Scatterometer (NSCAT), which will provide frequent measurements of oceanic near-surface vector winds with high spatial resolution and global coverage. In preparation for NSCAT, projects were undertaken to determine the intrinsic properties of gravity/capillary waves in the presence of longer gravity waves and wind fields. We are investigating the various dynamical processes that control the surface geometry in order to describe the statistical characteristics of the ocean surface.

Due to the cancellation of N-ROSS, it is now proposed to fly NSCAT on the Japanese ADEOS mission in the 1993-1994 time frame. Other options previously considered, such as the Air Force's Defense Meteorological Satellite Program (DMSP) and Space Test Program (STP), and the TOPEX/POSEIDON mission, will be kept under review.

A Science Definition Team has been selected for NSCAT. During the prelaunch phase, this team will make recommendations on design characteristics for best meeting the mission objectives. The team will also develop a science plan for the mission.

A major concern for the Air-Sea Interaction Program is ensuring complete and effective use of scatterometer data. Individual projects deal with all aspects of this issue, from error analysis to atmospheric model development. Our atmospheric model will have the potential for time-continuous assimilation of scatterometry winds. We will continue to work toward improving our understanding of the relationship between scatterometry and the sea surface wind field. We expect soon to establish a sound physical basis for relating radar backscatter to sea surface stress.

Several NASA investigators participated in the Frontal Air-Sea Interaction Experiment (FASINEX), in which two aircraft measured directional wave spectra and radar backscatter from Bragg scatterers. On a particular day, an abrupt change in the radar backscatter was observed when crossing the surface temperature front in the ocean. While the wind blowing over the ocean was near constant across the front, the measured wind stress, atmospheric stability and surface gravity wave spectra changed markedly. The data from this flight should provide an excellent case study for the role of surface gravity waves, wind stress and atmospheric stability in modulating the capillary waves responsible for Bragg scattering and electromagnetic radiation.

The Air-Sea Interaction and Ocean Circulation Programs participate in projects of the World Climate Research Program (WCRP), the Tropical Ocean Global Atmosphere (TOGA) experiment, and the World Ocean Circulation Experiment (WOCE). In support of the TOGA program, we are studying the circulation of the tropical oceans with the broad goal of understanding and learning how to model the sea surface temperature and sea level elevation with a focus on simulating the coupled ocean-atmosphere interaction. Two new models have been developed to study and attempt to forecast El Niño, a major perturbation in the atmospheric and ocean circulation in the tropics and mid-latitudes. In addition, a pilot study, the TOGA Heat Exchange Program (THEP), is underway to evaluate the potential for determining air-sea heat fluxes from remotely sensed data. Due to problems of data availability, the pilot study is focusing on the eastern tropical Pacific. The monthly mean fluxes for the 1982-83 El Niño have been computed, and work has already started on the non-El Niño period of 1979-81. The data set from this pilot study will be available through NODS.

In support of WOCE, we are studying the direct measurement of the forcing mechanism (wind stress) and the ocean response (sea level) by spaceborne sensors and the assimilation of these data into numerical ocean models. Combined with in situ observations obtained by WOCE, this research should tremendously increase our understanding of the physics that govern circulation of the ocean.

Ocean Productivity Program

The goals of the Ocean Productivity Program are to improve our capability to quantify oceanic phytoplankton biomass and primary productivity on regional and global scales; to better understand physical processes that control phytoplankton productivity, such as upwelling and stratification; and to determine the role of phytoplankton in major biogeochemical cycles that impact global climate. Specific objectives of the program include the following:

- To utilize CZCS-based estimates of phytoplankton biomass and productivity for improving present estimates of ocean productivity, with an emphasis on ocean basin and global scales
- To evaluate the accuracy of phytoplankton biomass and productivity estimates based on CZCS measurements and, where necessary, improve the algorithms defining these relations
- To utilize CZCS and AVHRR measurements for improved description and understanding of the physical processes that control spatial and temporal variability in phytoplankton productivity
- To encourage biological oceanographers to integrate large satellite and in situ data sets so that the role of phytoplankton in the global carbon, nitrogen, phosphorus, and sulfur cycles may be better quantified
- To develop advanced ocean color sensors and other instrumentation that will improve both aircraft and satellite measurements of ocean color and the algorithms that convert ocean color measurements to phytoplankton productivity

Major efforts continue to improve techniques for determining chlorophyll pigment concentrations and estimating ocean primary productivity from CZCS ocean color measurements. We need firm estimates of primary productivity based on both regional- and ocean basin-scale, time-series studies. Chlorophyll pigment observations derived from the CZCS provide the prime source of data for making meaningful estimates of the rates of organic particulate carbon production and deposition, carbon dioxide assimilation, and the significance of interactions with agricultural and natural nutrient inputs. Such estimates will greatly assist in overcoming present uncertainties about the total carbon fixation rate in the oceans—a key factor in the global carbon cycle because fluxes in the oceans are biologically controlled.

Processing of CZCS Data. In the last 3 years, important advances have been made both in the techniques used to determine chlorophyll pigment concentrations from the CZCS and in the capability for processing CZCS data within the oceanographic community. At present, CZCS data are routinely analyzed at GSFC and JPL and at eight university sites. Improvements include refinement of sensor degradation and calibration corrections, understanding the effects of enhanced scattering by particulates, understanding the effects of absorbance by dissolved organic material on in-water algorithms, and development of techniques required for ocean basin-scale and global-scale compositing of CZCS and AVHRR imagery.

We are presently developing a new CZCS archive at GSFC that will include both Level 2 products, such as maps of phytoplankton pigment concentration and irradiance attenuation coefficient (K), and Level 3-4 products, such as biweekly and monthly ocean basin and global-scale composites of phytoplankton pigment concentration. A prototype composite color image showing phytoplankton chlorophyll concentration in the entire North Atlantic Ocean was widely distributed throughout the oceanographic community. A second prototype global image was incorporated into a poster that was also widely distributed.

Several of our principal investigators are using CZCS-derived maps of chlorophyll concentration to develop and verify numerical models of ocean productivity and its relation to the ocean's physical and chemical characteristics. We are continuing our modeling efforts regarding such regional-scale processes as the effects on phytoplankton productivity of winds (Northeastern U.S. continental shelf) and of the Gulf Stream (Southeastern U.S. continental shelf).

Basin-scale Models. A new focus concerns developing models that will describe the dynamics of phytoplankton productivity for the entire North Atlantic Ocean. The goal of these basin-scale models is to understand the role of ocean biology, including phytoplankton, in the global carbon cycle. Models on such large scales are new to biological oceanography, and our program is making a major contribution in this area. We hope to continue in this direction and encourage our investigators to link their biological models with basin- and global-scale circulation models that can be developed using NSCAT and TOPEX measurements.

Using an inexpensive, unique Airborne Oceanographic Lidar (AOL) system, the Wallops Flight Facility continues to develop airborne techniques aimed at oceanographic processes studies, satellite ocean color algorithms, and satellite data validation. The Multichannel Ocean Color Scanner (MOCS) has been refurbished and is now available. In conjunction with NOAA, we are also developing an inexpensive, reliable Oceanographic Data Acquisition System (ODAS) that will make aircraft color and temperature data widely available to the oceanographic community.

An improved ocean color instrument that would meet the ocean science community's recommendation for a biology mission to determine chlorophyll content of ocean surface layers and provide visualization of ocean currents is proposed. The Earth Observation Satellite Company (EOSAT) is planning for a Sea-Wide Field Scanner (Sea-WiFS) to fly on Landsat-6, scheduled for launch in late 1990. Under the EOSAT plan, NASA would share the cost of the sensor and develop a global data processing system and archive in support of GOFS and other science programs. Assuming that EOSAT remains viable, NASA's opportunity to support research use of Sea-WiFS data will require budget augmentations beginning in FY 1989; the necessary funding is under review.

Polar Oceans Program

The goal of the Polar Oceans Program is to use spaceborne sensors to determine the characteristics of the polar ice cover and to understand how these are influenced by and in turn influence the atmosphere and ocean. Such issues are of central importance to global habitability in that processes occurring in the polar regions have significant effects on the Earth's hydrological and energy cycles. Our immediate concern is to improve our capability of measuring from space the extent, type, movement, and surface characteristics of the polar ice cover. This involves detailed analysis of data from radiometers aboard Geosat and the Nimbus series of spacecraft and from the SSM/I aboard the DMSP spacecraft, in conjunction with collection and analysis of ground-truth data from the ice surface. We also support modeling programs both to improve our understanding of remotely sensed data and to incorporate satellite data into large-scale models of ocean-ice interaction. Specific objectives include:

- **Sensor Development:** Improve the performance of radar altimeters over ice, and investigate the potential of laser altimeters for detecting changes in ice-sheet volume
- **Data Processing and Archiving:** Develop techniques for rapid processing of sensor data in a form suitable for research purposes and archive appropriate data sets in an easily accessible format. Data sets include Electrically Scanning Microwave Radiometer (ESMR), Scanning Multifrequency Microwave Radiometer (SMMR), and SSM/I brightness temperatures and sea-ice parameters; SAR imagery and derived products (floe sizes, ice velocity, and ice type); altimetry data and ice-sheet topography; and iceberg statistics
- **Research:** Incorporate space-derived data within numerical models of sea ice, ocean, ice sheets and climate; investigate global and mesoscale sea-ice problems, the heat budget of the polar oceans, sea-ice time series for climate trends, and mass balance of the polar ice sheets

Sea-ice Studies. Currently, a prime focus is research on algorithms for calculating sea-ice concentration, type, and velocity from active and passive microwave data. The most promising data sources, having broad applications in both the scientific and commercial communities, consist of the multifrequency SSM/I aboard the present series of DMSP spacecraft, the Synthetic Aperture Radar (SAR) aboard the ESA's ERS-1, to be launched in 1990, and NASDA's JERS-1 mission. We are closely coordinating our data studies with associated research of NOAA, the Office of Naval Research (ONR) and Canadian and European investigators.

Recent progress in these sea-ice studies has increased our confidence in applying microwave techniques to such oceanic problems as how polynyas are formed and contribute to deep-water formation, the role of the marginal ice zone in vertical transport processes, and the identification of leads and floe structure (needed for supporting operational programs through the ice pack). We have made advances in the following areas:

- Calculation of ice type concentrations by means of the differences in microwave brightness temperature between first-year and multiyear ice

- Better identification of the ice margin by means of algorithms that correct for weather effects on the microwave signature
- Understanding of basic scattering processes from sea ice by analyzing data collected from in situ and airborne measurements during the Marginal Ice Zone Experiment (MIZEX)
- Examining the radiometric properties of new thin ice, desalinated ice, and snow-covered ice through the extensive use of a controlled environment facility at the Cold Regions Research and Engineering Laboratory in New Hampshire
- Developing rapid techniques for deriving sea-ice motion from sequential SAR images
- Comparison of ice-sheet topography in Greenland derived from Seasat and Geosat altimetry data to detect whether ice volume has changed

Data Acquisition and Archiving. The Special Sensor Microwave Imager (SSM/I) was successfully launched in June 1987 as part of the DMSP. To make gridded brightness temperature data and derived products from SSM/I available to the polar community, NASA's JPL and NOAA's National Snow and Ice Data Center (NSIDC) in Boulder are implementing at NSIDC a node of the NODS dedicated to SSM/I data. Data processing has begun at JPL and software for loading SSM/I data and producing maps of sea-ice concentration and extent have been put in place at NSIDC. In addition, a validation and calibration team has collected an extensive data set for validating derived sea-ice parameters, including measurements from a series of underflights.

We are also working with aircraft, Seasat, and Shuttle Imaging Radar data to prepare for the opportunities to acquire similar data from three SAR-equipped satellites planned for launch in the early 1990s: ESA's ERS-1, Japan's JERS-1, and Canada's Radarsat. Since ESA's ERS-1 has no provision for recording data onboard, the data received by the satellite must be transmitted in real time to ground receiving stations within view of the satellite. An ad hoc group of researchers has been organized to develop algorithms that extract sea-ice concentration and ice type from SAR data.

Alaskan SAR Facility (ASF). We have begun to develop a new research facility, the Alaskan SAR Facility (ASF), to receive, process, analyze, and archive SAR data from these spaceborne instruments. The University of Alaska-Fairbanks (UAF) site was selected for its maximum reach over the Arctic Ocean—the area of greatest potential benefit from SAR technology.

Funds for the facility design and construction were authorized in the FY 1986 budget and will continue through FY 1989. Development of the facility's key element, a new SAR processor, has started at JPL. This processor will be capable of handling data from all three satellites, processing raw data into images in about 1/10th real time. The ASF will be operational by the time ERS-1 is launched. The January 1986 agreement between NASA and ESA for the acquisition of ERS-1 data provides a basis for direct readout of SAR data within coverage of the ASF, as well as the exchange of data sets such as those from NSCAT, the ESA scatterometer aboard ERS-1, and NASA's Spaceborne Imaging Radar. A similar agreement was signed in January 1988 between NASA and NASDA.

The report of the Satellite Remote Sensing for Ice Sheet Research Working Group recognizes satellite altimetry as the major technique for ice-sheet investigations and discusses several new applications of satellite technology for studying the extent, topography, and variability of polar ice sheets. The Navy has now released Geosat data collected over ice sheets, so this important data set will serve as a benchmark for such future altimetry missions as ERS-1.

Ocean Data Systems Program

In recent years a pressing need has developed for efficient data archiving and management systems capable of assimilating data from past, present, and proposed satellite sensors. Future archival systems must be able to handle the large amounts of oceanographic satellite data anticipated in the 1990s.

The goal of the Ocean Data Systems Program is to provide the ocean research community with easy access to spacecraft data through development of a distributed data management system, the NASA Ocean Data System (NODS). This data system will use the latest computing, storage media and networking technologies to archive, catalog, and disseminate oceanographic satellite data and other allied data sets. Specific objectives include:

- Implementation of the first fully functional node of NODS at JPL as the central hub of a distributed system, using data from Seasat and GEOS-3 sensors, West Coast time-series (CZCS/AVHRR), and DMSP SSM/I data
- Upgrading the NODS/JPL archive and catalog capability to accommodate data from future NASA satellite missions and allied satellite and in situ data sets of interest to the ocean research community

- Development of additional nodes of NODS, as appropriate, to include other major archives of oceanographic data and to provide access to supercomputer facilities for ocean modeling and data assimilation
- Provision of network access to NODS for research users via high-speed communications links to all major oceanographic institutions and research centers
- Assistance in coordination within NASA and between agencies (NASA, NSF, NOAA, Department of Defense) in development of the ocean component of future interdisciplinary Earth science data management activities

The Pilot Ocean Data System (PODS) at JPL became the first operational node of the NASA Ocean Data System (NODS), the new ocean science support facility, in FY 1986. This was accompanied by a shift in funding responsibility from NASA's Information Systems Office to the Oceanic Processes Branch. At the same time, a science advisory group, the Satellite Ocean Data Systems Science Working Group (SODSSWG), with NSF, NOAA and Navy representatives, was formed to guide the Branch in its development of NODS and to ensure the responsiveness of NODS to the needs of the ocean research community.

Computer network access to NODS is currently provided via 9.6 kb/s SPAN links to approximately 15 oceanographic institutions. Other institutions can access NODS via Telenet. An augmented version of the NODS archive software has been developed and a copy transported to the NSIDC to support future processing and archiving of DMSP SSM/I data for polar ice research. NSIDC will thus become a second NODS archive node. Prototype versions of the NODS Global On-Line Data (GOLD) catalog software were provided to five institutions for testing and to determine the enhancements required for a future distributed NODS catalog.

SODSSWG now has five subpanels dealing with archiving, cataloging, networking, non-NASA missions, and with a NODS advisory function. Through SODSSWG membership and subpanels, we have received feedback on the initial NODS activities and we are working to upgrade its capabilities. Discussions have also been opened with other agencies (NOAA, NSF, and Navy) to improve coordination of their respective ocean data system activities with NODS. In particular, the WOCE/TOGA Data Management Working Group now meets jointly with SODSSWG to ensure coordination of satellite and in situ data management for the major ocean research programs.

Conceptual Studies

Various Science Working Groups (SWG) have been convened during the past few years to advise the Program on particular issues (see Table 7-1, Recent NASA Science Working Groups). The focus of these groups has been to define the science questions addressable by particular ocean satellite sensors and to develop corresponding performance specifications for these sensors and/or their associated data systems. An example is the SWG that convened to assess and report on the potential of several planned spaceborne instruments for acquiring observations of ice sheets (glaciers). The group recommended use of radar altimeters already proven for conducting glaciological research from space, and supported development of a satellite laser altimeter with a smaller footprint to provide more accurate measurements of ice surface elevations.

The Moderate Resolution Imaging Spectrometer (MODIS) Instrument Panel Report, published in 1986, formulated requirements for the visible and infrared sensor that is projected as part of Eos, the Earth Observing System. This key Eos instrument will provide global observations for terrestrial, oceanic, and atmospheric Earth systems research. Topics discussed by the MODIS panel include onboard and orbit calibration requirements; onboard commandable data processing and compaction; sensor dynamic ranges required for ocean, land, and cloud climatology studies; data system and data product requirements; archiving and distribution; validation procedures; and unique scientific opportunities resulting from simultaneous observations by MODIS and the High Resolution Imaging Spectrometer (HIRIS). We are currently forming an SWG to assess the practicality of placing radio transponders on polar-orbiting satellites as high-data-rate, high-quality complements to existing communications channels. This potential plan could meet the need for improved communications between surface field parties and ships at high latitudes with the rest of the world, now limited by propagation disruptions and inaccessibility to most geosynchronous satellites.

University Participation

From the 60 or so proposals received in response to NASA's July 1986 Announcement of Opportunity (AO), soliciting science investigations that utilize TOPEX/POSEIDON data, an international team of 38 principal investigators has been selected by NASA and CNES to participate in the TOPEX/POSEIDON Science Program. NASA has selected 20 projects (shown in Table

TABLE 7-1. **RECENT NASA SCIENCE WORKING GROUPS**

Science Working Group	Chairman	Established	Report
Alaska SAR Facility Pre-Launch Science Working Team	Frank Carsey, JPL Willy Weeks, UAF	6/1987	—
Sea Surface Temperature Archiving Science Working Group	Peter Cornillon, URI	3/1987	—
Sea-WIFS Working Group	D. James Baker, JOI	2/1987	8/1987
Polar Communications Working Group	Ted Rosenberg, U. of Md.	8/1986	10/1987
Satellite Ocean Data System Science Working Group:	D. James Baker, JOI	11/1985	see below
NODS Advisory Panel	Otis Brown, U. of Miami		3/1987
Networking Panel	Chet Koblinsky, GSFC		5/1987
Archiving Panel	Mark Abbott, OSU		9/1987
Non-NASA Missions Panel	Frank Eden, JOI		6/1987
Cataloging Panel	Peter Cornillon, URI		—
Ice Sheet Science Working Group	Robert Thomas, JOI	4/1984	11/1985
Programme for International Polar Oceans Research (PIPOR) (publication co-sponsored with ESA)	Preben Gudmandsen, Technical U. of Denmark	1/1985	9/1985
Ocean Surface Energy Fluxes Science Working Group	Peter Niiler, SIO	3/1984	8/1985
West Coast Chlorophyll Temperature Time Series Science Working Group	Mark Abbott, OSU	6/1984	6/1985
SSM/I Sea Ice Research Science Working Group	Norbert Untersteiner, U. of Washington	12/1982	6/1984
In Situ Science Working Group	Russ Davis, SIO	9/1981	3/1984
ERS-1/SAR Sea Ice Study Team	Gunter Weller, U. of Alaska	4/1982	12/1983
Satellite Ocean Color Science Working Group	John Walsh, BNL/Stonybrook	10/1981	12/1982
Satellite Surface Stress Team (S-Cubed)	James F. O'Brien, FSU	7/1981	7/1982
TOPEX Science Working Group	Carl Wunsch, MIT	2/1980	3/1981

7-2, Overview of TOPEX/POSEIDON Science Program) that will contribute directly to the goals of the World Ocean Circulation Experiment (WOCE) and the Tropical Oceans Global Atmosphere (TOGA) program.

ESA has also released an AO for acquiring ERS-1 data. The Programme for International Polar Oceans Research (PIPOR) published a description of its interest in SAR data over the Arctic Ocean and surrounding seas. PIPOR, as well as groups interested in polar glaciology and geology, has submitted proposals to ESA asking to use SAR, radar altimeter, and passive microwave radiometer data.

An AO for the entire Eos system, including requests for proposals utilizing MODIS observations, was released by NASA Headquarters Office of Space Science and Applications (OSSA) in spring 1988. Proposals in response to this AO will be used to select members of the MODIS Science Team, which will serve as the scientific advisory group during instrument development and operation.

Plans for FY 1988 and FY 1989

The results of the analysis of the first year of Geosat data should start appearing over the next 2 years. We expect the results to help us define the questions and the requirements for NASA's altimeter mission, and to begin the transition from looking at ocean variability to examining the absolute circulation of the ocean—the main goal of TOPEX/POSEIDON.

The program will begin to look at the physical basis for major corrections to altimeter data, i.e., sea-state bias or electromagnetic bias, as well as water vapor path length and inverse barometer response corrections. These will be examined through a coordinated program of field studies, theoretical studies and analysis of historical data. In particular, the question of frequency dependence for sea-state bias will be addressed by aircraft flights using multifrequency altimeters.

TABLE 7-2. **OVERVIEW OF THE TOPEX/POSEIDON PROGRAM**

Principal Investigator	Title	Institution
Large Scale Ocean Circulation:		
Dr. Lee-Lueng Fu	Circulation of the Gyres of the World Ocean: Observation and Modeling Using TOPEX/POSEIDON Altimeter Data	Jet Propulsion Laboratory, CalTech
Dr. W. Timothy Liu	Low Frequency Variability of Sea-Level as Related to the Heat Balance of Global Oceans	Jet Propulsion Laboratory, CalTech
Dr. Chang-Kou Tai	An Integrated Research Program for TOPEX/POSEIDON with Emphasis on the Pacific Ocean	University of California, San Diego
Dr. Carl Wunsch	Altimetry Research in Ocean Circulation	Massachusetts Institute of Technology
Mesoscale & Regional Ocean Circulation:		
Dr. George Born	The Use of Satellite Altimetry in the Study of Weakly Defined and Variable Oceanic Gyres	University of Colorado
Dr. Keisuke Taira	Oceanic Transports of Mass, Heat and Salt in the Western North Pacific	University of Tokyo
Dr. James L. Mitchell	The Dynamics and Energetics of Mid-Latitude Western Boundary Currents: A Comparison of the Kuroshio Extension and the Gulf Stream	Naval Ocean Research and Development Activity
Dr. Bruce C. Douglas	Analysis of TOPEX/POSEIDON Altimeter Data for Global Studies of Sea Level Variability, Absolute Dynamic Topography, Geophysics, and Tide Model Improvement	National Geodetic Survey
Dr. P. Ted Strub	Equatorial and Eastern Boundary Current Variability in the North and South Pacific Ocean	Oregon State University
Dr. Derek M. Burrage	North Australian Tropical Seas Circulation Study —Stage II	Australian Institute of Marine Sciences
Dr. Dudley B. Chelton	Mesoscale and Large-Scale Variability of the Antarctic Circumpolar Current	Oregon State University
Dr. John A. Church	Dynamics and Topography of the South Pacific, Southern and Indian Oceans: Ocean Transport and Variability Studies	Commonwealth Scientific & Industrial Research Organization, Australia
Tropical Ocean Circulation:		
Dr. Roger Lukas	Studies of Tropical Ocean Dynamics Using the TOPEX/POSEIDON Altimeter-Derived Sea Surface Topography	University of Hawaii
Dr. Eli Joel Katz	Sea-Level Response to Wind-Forcing in the Tropical Atlantic	Lamont-Doherty Geological Observatory of Columbia University
Geophysics & Geodesy:		
Dr. Richard H. Rapp	Altimetry Research in Ocean Circulation	Ohio State University
Dr. John M. Wahr	A TOPEX/POSEIDON Study of the Ocean Effects on Observations of the Earth's Interior	University of Colorado
Dr. Byron D. Tapley	The Determination and Interpretation of Ocean Surface Topography Using TOPEX/POSEIDON Altimeter Data	University of Texas
Dr. James G. Marsh	Ocean Topography Mapping, Improvement of the Marine Geoid and Global Permanent Ocean Circulation Studies from TOPEX Altimeter Data	Goddard Space Flight Center, NASA
Dr. Jiro Segawa	Application of Precise Altimetry of the Study of the Precise Leveling, the Earth's Gravity Field and the Rotation of the Earth	University of Tokyo
Tides:		
Dr. Braulio Sanchez	Global Ocean Tide Mapping Using TOPEX Altimetry	Goddard Space Flight Center, NASA

Studies are underway in the Air-Sea Interaction Program to evaluate the impact of vector winds obtained from scatterometry and scalar winds obtained from altimeters and passive microwave radiometers. Numerical weather forecast models and tropical ocean circulation models are being pursued. In addition, the air-sea heat flux data set produced by the pilot THEP study will be available in late 1988 or early 1989 for model impact studies and evaluation.

Two new aircraft scatterometers at the KU- and C-bands are being built to support field studies aimed at improving understanding of radar backscatter. Simultaneous flight of these instruments will enable comparisons of the relative accuracies to be obtained from the ESA ERS-1 C-band scatterometer and NASA's NSCAT KU-band scatterometer. The C-band will be installed in summer of 1988; the Ku-band will be installed in mid-1989.

In late 1990 NASA will participate in the Surface Wave Dynamics Experiment (SWADE), flying both scatterometers and radar wave spectrometers in support of our model function development effort and as a possible verification experiment for the ERS-1 active microwave instrument.

The Polar Oceans Program will focus on the completion of the validation of derived sea-ice products from the passive microwave SSM/I on the DMSP spacecraft. The task of processing and archiving SSM/I data from the polar regions will be transferred from JPL to NSIDC. Compatible sets of data from ESMR and SMMR will also be archived at NSIDC.

The Receiving Ground Station (RGS) will be installed at the Alaskan SAR facility at UAF and the development of the SAR processing system at JPL will be completed in preparation for its transfer to UAF in early 1990. Development of the Archive and Operations System (AOS) will continue so that delivery of the completed system can be made prior to launch of ERS-1. In addition, a Geophysical Processing System (GPS) to extract high-level derived products such as ice motion, concentration and type from the SAR imagery will be completed. These products will be archived and distributed by AOS. To this end, an intense effort is being made to analyze the aircraft SAR data collected in March 1988 over the Bering, Beaufort and Chukchi Seas.

In altimetry efforts over ice, our prime goal is to complete retracking of the first 18 months of Geosat data over Greenland and the Antarctic ice sheets. We shall then assess, based on perceived application of these data to research problems, whether to continue to retrack data from the ERM mission of Geosat.

We continue to encourage the application of all these data sets to research problems in close collaboration with NSF and ONR. In particular, we shall be working with the science community to refine preparations for applications of ERS-1 data to research over the polar oceans and ice sheets.

In the area of Data Systems, FY 1988 and FY 1989 will see the operational implementation and testing of the NODS SSM/I processing and archival system. At present, the archiving is being undertaken at both NODS and NSIDC, with the full transition to NSIDC planned for FY 1990. Newly acquired optical disk storage techniques will be demonstrated for the first time by NODS for the SSM/I archival system. Archiving of a new, global, CZCS-derived chlorophyll data set will be accomplished at GSFC (in the NSIDC) in a manner compatible with NODS. Discussions have begun with NOAA/NODC to study the feasibility of archiving AVHRR sea surface temperature (SST) data for the research community at NODC as a node of the NASA Ocean Data System. A Science Working Group for SST archiving has been set up which is looking specifically at the feasibility of determining global SSTs for use in climatological research.

In preparation for data from TOPEX, NSCAT, and the Alaskan SAR Facility, NODS is actively working with the flight projects to provide a common access point, user catalog, and archive system for accessing these varied data sets via NODS. NODS is also upgrading its computer networking capabilities by increasing the number of SPAN links to institutions and participating in development of the NASA Science Internet (NSI), sponsored by NASA's Information Systems Office and Office of Space Tracking and Data Systems.

We will continue to support international efforts to determine the role of the oceans in climate as part of the World Climate Research Program (WCRP). We cooperate closely with groups sponsored by the World Meteorological Organization (WMO), International Council of Scientific Unions (ICSU), and Intergovernmental Oceanic Commission (IOC). We are also exploring the potential contributions of satellite techniques to the Global Ocean Flux Study (GOFS) and the Programme for International Polar Oceans Research (PIPOR).

For the WOCE and TOGA programs, our potential contribution involves using such satellite techniques as altimetry and scatterometry to assist in determining the general circulation of the oceans, its effect on redistribution of global heat, and the resulting influence on atmospheric climate. GOFS, a major component of NSF's Geosciences Initiative, requires satellite ocean color measurements for global estimates of primary productivity. NASA is working with EOSAT to explore the option of putting an ocean color instrument on Landsat-6. NASA's role would be to purchase data for the research community and to develop a global data processing and archive system in support of GOFS and other science programs. For PIPOR, use of microwave radiometry and SAR could help improve our understanding of polar ice cover, including its growth and movement.

Future Projections

Both global weather and long-term climate change are strongly linked to ocean behavior. In the past two decades, observations from meteorological satellites have significantly improved our ability to forecast weather. However, improving our ability to predict climate requires a better understanding of the role of oceans in the global climate system than we possess at present. New global information available from satellites, coupled with data from the ocean interior and our greatly enhanced computer capability, can meet this need.

The heads of the Federal ocean-related agencies, via the Ocean Principals Group, have developed a national long-range plan for ocean research, and we supported NSF as the lead agency in this endeavor. This plan will be updated annually. Similarly, we supported the efforts of the Interagency Arctic Policy Research Committee to prepare a 5-year plan for Arctic research. Several elements of the plan, drafted in response to the Arctic Research Policy Act, rely heavily on remotely sensed data and research.

We anticipate that aspects of the NASA Oceanic Processes Program will continue to be addressed by numerous groups within the National Academy of Sciences. For example, we at NASA participated in the interagency oceanography reviews recently conducted by the Ocean Studies Board. We will be working closely with the SODSSWG to advise NASA on how best to meet the satellite and associated in situ data needs of the oceanographic community.

Tables 7-3 and 7-4 provide a list and description of approved and proposed ocean-related spacecraft to be built over the next decade by the United States and other countries. We are exploring potential areas of mutual interest with sponsors of these spacecraft, particularly the extent to which we might pursue cooperative work and provide mutual access to spaceborne data.

TABLE 7-3: **OCEAN-RELATED SPACECRAFT: NEXT DECADE**

Satellite	Sponsor	Ocean-Related Sensors Comments	Launch	Status
NOAA Series	NOAA	IR (AVHRR)	Ongoing	Operational
Geosat	USN	ALT	3/1985	Operational
MOS-1	JAPAN	CS, IR, MR	2/1987	Operational
DMSP Series	USAF	MR (SSM/I)	6/1987	Operational
	NASA	Data Facility with NSIDC		Approved
SPOT-2	CNES	Tracking System	1988	Approved
MOS-1B	JAPAN	CS, IR, MR	1990	Approved
ERS-1	ESA	ALT, SAR, SCAT, IR	4/1990	Approved
	NASA	Alaskan SAR Facility		Approved
Landsat-6	EOSAT	CS (Sea-WiFS)	6/1991	Proposed
	NASA	Data Purchase & Facility		Proposed
TOPEX/ POSEIDON	NASA	ALT, Tracking	12/1991	Approved
	CNES	ALT, Tracking		Approved
N-ROSS	USN	ALT, MR		Cancelled
JERS-1	JAPAN	SAR, VR	1992	Approved
	NASA	Alaskan SAR Facility		Proposed
ADEOS	JAPAN	VS, CS (OCTS)	1993	Proposed
	NASA	Contribute SCAT		Proposed
ERS-2	ESA	ALT, SAR, SCAT, IR	1993	Proposed
SOLID EARTH	ESA	GRADIO	1993	Proposed
RADARSAT	CANADA	SAR	1994	Contingently Approved
	NASA	Contribute Launch		Proposed
	NOAA	Distribute Data		Proposed
Gravity Mission	ESA/NASA			Possibility

TABLE 7-4. **DESCRIPTION OF OCEAN-RELATED SPACECRAFT APPROVED/PROPOSED FOR THE NEXT DECADE**

Geosat	This is a U.S. Navy-sponsored mission to provide the Defense Mapping Agency with a larger quantity of altimeter data of Seasat quality. The primary 18-month mission to map the marine geoid was completed in the fall of 1986. Following this is a continuing oceanographic mission (known as the Exact Repeat Mission) having a 17-day repeat cycle and a 150-km equatorial track spacing. In general, the mean sea surface data from the initial 18-month geodetic mission will be classified, with the residuals from this surface being unclassified. Data from the second 18-month mission are unclassified.
MOS-1	The purpose of this mission is to establish Japanese technology for Earth observations and to carry out practical observations of the Earth, primarily focused on the oceans. MOS-1 is all passive, has a 2-year design life, and will be in a sun-synchronous orbit.
DMSP Series	This is a series of U.S. Air Force operational meteorological satellites in sun-synchronous orbits. For those satellites launched between 1986 and 1991, there will be a microwave radiometer (the Special Sensor Microwave Imager, or SSM/I) aboard having four frequencies over the range from 19 to 85 GHz. As SSM/I data are useful in characterizing sea ice, snow cover, surface winds, and atmospheric water, NASA plans to acquire these data for research purposes.
SPOT-2	This French satellite will carry the prototype of the DORIS tracking system, which will be subsequently flown as a French contribution on the TOPEX/POSEIDON mission.
MOS-1B	This is a duplicate of MOS-1.
ESA's ERS-1	The European Space Agency's First Remote Sensing Satellite is a marine science and applications mission whose purpose is to establish, develop and exploit ocean and ice applications of remote-sensing data. On board the spacecraft, planned for sun-synchronous orbit, will be a C-band SAR (for obtaining high-resolution maps and, in a low power mode, for use as a wave scatterometer), a radar altimeter and an along-track scanning radiometer. The satellite is planned for launch in April 1990. Acquisition and exchange of ERS-1 data between ESA and NASA is the subject of a Memorandum of Understanding (MOU) signed in January 1986.
Sea-WiFS	Sea-WiFS is an improved version of the Coastal Zone Color Scanner which operated on Nimbus-7 from 1978-1986. EOSAT is planning to put Sea-WiFS on Landsat-6. NASA's role would be to share the cost of the sensor and develop a global data processing and archive system to support research users of Sea-WiFS data.
TOPEX/ POSEIDON	This is a dedicated altimeter mission whose data—when combined with data from NASA's Scatterometer proposed for flight on the Japanese ADEOS mission—will be utilized to advance our understanding of the general circulation of the oceans. TOPEX/POSEIDON is a joint mission between NASA and CNES. Agreement has been reached whereby NASA will provide the satellite and TOPEX sensors and CNES will provide an Ariane launch and the POSEIDON sensors. The orbital characteristics are: inclination of 63 degrees, altitude of 1300 km, equatorial track spacing of 300 km, and track repeat of 10 days. Primary tracking will be provided by DMA's Tranet system. Satellite design studies have been completed, and according to present schedules, TOPEX/POSEIDON will be launched in December 1991, thus providing overlap with ADEOS.
N-ROSS	This U.S. Navy mission has been cancelled.
Japan's ERS-1 (JERS-1)	The objective of this Japanese mission is to establish SAR technology for Earth observations and to carry out observations of the Earth, primarily focused on terrestrial applications. JERS-1 will be in a sun-synchronous orbit and will have an L-band SAR with a 2-year design life. Development is underway. An agreement between NASA and the Japanese government regarding access to SAR and optical data from this satellite at NASA's Alaskan SAR Facility has been consummated.
ADEOS	This is the proposed Japanese Advanced Earth Observation Satellite. It is viewed as an intermediate step between the JERS-1 and the technically more sophisticated Japanese Polar Platform. NASA is proposing to fly NSCAT on this mission.
ERS-2	This is a duplicate of ESA's ERS-1.
SOLID EARTH	This is a proposed ESA mission to fly the GRADIO system for the purpose of improving our understanding of the Earth's gravity field.
RADARSAT	This is a mission employing a C-band SAR to monitor sea-ice characteristics in the Arctic Ocean and marginal seas. Measurements would be used to support shipping and petroleum exploration operations principally in the Beaufort and Labrador Seas by providing forecasts of sea-ice conditions. The Canadian government has recently approved Radarsat contingent upon working out acceptable arrangements with NASA and NOAA.
Gravity Mission	There is proposed either an ESA mission (a piggyback launch with ERS-2) or a possible ESA/NASA mission, whose objective would be to improve our understanding of the Earth's gravity field.

8

Atmospheric Dynamics and Radiation Program

NASA's Atmospheric Dynamics and Radiation Branch research and development is aimed at improving the basic understanding of how the Earth's atmosphere behaves—particularly the dynamics and radiation of the troposphere, which contains 85 percent of the atmosphere's mass. Both climate and weather result from air motions (dynamics) and radiative interactions produced by uneven heating by the Sun and the subsequent response by the atmosphere to that heating. The goal is to understand and ultimately predict the future state of the atmosphere, with improvements in weather forecasting as a desirable by-product of increased scientific understanding.

Current Research Emphases

The core research/analysis effort focuses on problems in the atmosphere addressable by space technology. Virtually all of the nearly 450 studies supported by the program have some connection with space-based research. The program's three main thrusts consist of research in global-scale processes, mesoscale processes, and climate.

- **The Global Scale Processes Research Program** deals with large-scale atmospheric behavior on time scales of 1 to 14 days and distances of 50 km to a planetary scale of 10,000 km. The Program stresses the development of advanced remote-sensing instruments, advanced analysis techniques to improve the utility of existing meteorological satellite data, and numerical models capable of both atmospheric diagnosis and prediction.
- **The Mesoscale Processes Research Program** looks at processes occurring over the shortest timeframes—a few hours to several days—and distances on the order of 10 to 200 km; the Program aims at understanding the behavior of the atmosphere on short time scales and over local to regional areas, focusing on localized severe weather such as severe convective storms; tornadoes; small, strong downdrafts called microbursts; and larger-scale phenomena such as tropical storms (hurricanes).
- **The Climate Research Program** deals with extended time intervals, ranging from several weeks to decades, and spatial scales from regional to global. In support of the National Climate Program, NASA research focuses on exploiting space observations for improving our understanding of global processes that influence climate and its predictability. NASA serves as the lead agency responsible for solar and Earth radiation research. One of the primary goals of the National Climate Program is improved prediction of climate variability for months, seasons, and beyond. Close cooperation with NOAA, including the National Weather Service and the National Environmental Satellite, Data, and Information Service (NESDIS), is crucial and includes shared information/programs and joint publication of results in scientific journals, books, and papers for the research and operational communities. As research needs and operational needs are similar but not necessarily the same, we consider our ongoing dialogue with NOAA to be of paramount significance.

Our intent is to conduct atmospheric programs that emphasize modeling, observations, and analysis in a balanced manner. To ensure such balance, external peer review panels are convened every 2 to 3 years to review the programs and make recommendations; each task we support also receives an individual peer review. The programs are being constantly improved, reviewed for balance, and assessed for ways of introducing new ideas and technologies. As with any scientific problem, our approach consists of the following major components:

1. **Make observations.** We use data now available from satellites and develop new remote-sensing techniques that will improve our ability to measure the atmosphere, the Earth's surface, and even the behavior of the Sun.

2. **Translate the data generated by remote sensing into meteorological and climate parameters** useful for meteorologists in weather and climate analyses and prediction. Many of our activities use physical and empirical methods to translate the rather abstract remote-sensing products—such as radiance or irradiance measurements—into useful meteorological parameters.

3. **Integrate the data with ground-based and other observations.** Once the remotely sensed and space-observed data have been analyzed, we combine and test the findings against complementary ground-truth measurements and other data, trying to recognize patterns of behavior.

4. **Develop models.** We have a host of different models describing various processes, sub-elements of processes, or the behavior of the atmosphere as a whole. General circulation models include all processes, from dynamics on a small (usually parameterized) scale through the large scale, in which the dynamics are described in terms of an initial state, motion, and radiative input. These models need to reflect the complex nature of the atmosphere and of the surfaces that are absorbing or emitting radiation, including the interaction of clouds through the atmosphere and the radiative energy balance. A complex model is required to provide a time-dependent description of atmospheric behavior. Ultimately, we hope to develop a general circulation model capable of predicting a future state of the atmosphere with considerably better accuracy than is currently possible.

We also use models to simulate the types of observations needed to adequately describe whatever phenomenon is to be measured. These models help to define the accuracy, coverage, and frequency needed for the measurement. Thunderstorms, for example, require frequent observations on a very small scale (minutes apart with resolution of 1 km or less) compared with 3- to 6-hour observation times and up to 100-km resolution for continental snowstorms.

Highlights of Recent Accomplishments

The Tropical Rainfall Measuring Mission (TRMM)

Evaporation of water vapor onto the atmosphere and its condensation to produce rainfall is at the heart of the Earth's habitability for man and other species. The TRMM is being proposed as a space system for measuring tropical rainfall and its variations. The Phase A study has been completed, after more than a year of effort on the part of the Advanced Missions Analysis Office at the Goddard Space Flight Center (GSFC). It shows that the mission is feasible within the modest cost typical of Explorer-class missions, and that with approval in the FY 1990 budget, could be ready for launch by September 1994.

The TRMM Science Steering Group (SSG) Report has also been published; the culmination of 2 years of study by a panel of experts in the remote sensing of rain, algorithm development, modeling of radiative transfer, and atmospheric circulation modeling and analysis. The report notes the inherent difficulties of systematically measuring tropical rainfall and states that space measurement is the only way to achieve more accurate global documentation. The current plans for TRMM include three principal instruments, the most innovative of which is the first quantitative precipitation radar to be flown in space. Its radar will give good rain measurements over both land and ocean, and can obtain the height profile of the precipitation content from which the profile of latent heat release can be estimated.

The second instrument is a cross-track scanning multichannel dual-polarized passive microwave instrument to give good measurement of rainfall rates over oceans. The third instrument is a high-resolution visible and infrared sensor, the Advanced Very High Resolution Radiometer (AVHRR), so that rainfall measurements from the other two instruments can be used to better interpret visible/infrared data from past and future operational satellites. For this reason, TRMM is often referred to as a "flying rain gauge" with a high potential contribution to the World Climate Research Program's rain climatology initiative.

In March 1988 the cooperative United States/Japan feasibility study on TRMM was issued. The next task is to obtain approval for progress on the Phase B Definition Phase, which could begin as early as July 1988.

The International Satellite Cloud Climatology Project (ISCCP)

The ISCCP, designed to produce a 5-year global satellite radiance and cloud data set, completed its fifth year of data collection in 1987 (see Figure 8-1). Significant achievements in analysis of these data were the resolution of radiometer calibration problems, final testing and refinement of the analysis methods, initiation of operational production of cloud analyses, and the beginning of research using cloud analyses. Several significant conclusions are already apparent from this early work:

- Cloud cover over the oceans is about 10 percent higher than inferred from earlier observations
- Much of the "extra" oceanic cloud is very low altitude cloudiness, but cirrus cloud also seems to be higher, over both ocean and land
- Although clouds are highly variable on small scales, the larger variations of cloudiness seen in the figure are associated with variations on spatial scales greater than 100 km and time scales of 1-3 days.

With all the elements of the ISCCP processing system now operational (except the INSAT component), it represents the first comprehensive, global, multisatellite data collection, processing and quantitative analysis system ever established. It is the closest realization of a truly global Earth-observing system that we currently have.

The Laser Atmospheric Sounding Experiment (LASE)

LASE is a remote-sensing development which will use lasers to measure profiles of atmospheric water vapor and, eventually, temperature with unprecedented accuracy and vertical resolution from high-flying aircraft. The system, expected to fly in late 1989, is very rugged, completely automated and self-adjusting so that development of a satellite version will be a relatively simple step. The project is being developed at the Langley Research Center, with support from GSFC and the French CNES. Phases A and B have been completed and the instrument is almost ready. It is scheduled for delivery in 1989.

High Resolution Infrared Sounder/Microwave Sounding Unit (HIRS/MSU) Data Processing

Processing of HIRS/MSU data has been used to produce the first set of a 10-year self-consistent atmospheric/land/ocean data set. This first year coincides with the Global Weather Experiment and extends from December 1978 through November 1979. The data set includes many fields not available on a physically self-consistent, global basis. Included are estimates of cloud height and fractional cloud cover, atmospheric heating rates, radiative fluxes of heat, moisture and momentum, soil temperature, precipitation and many other atmospheric parameters.

The SPACE-MIST Experiment

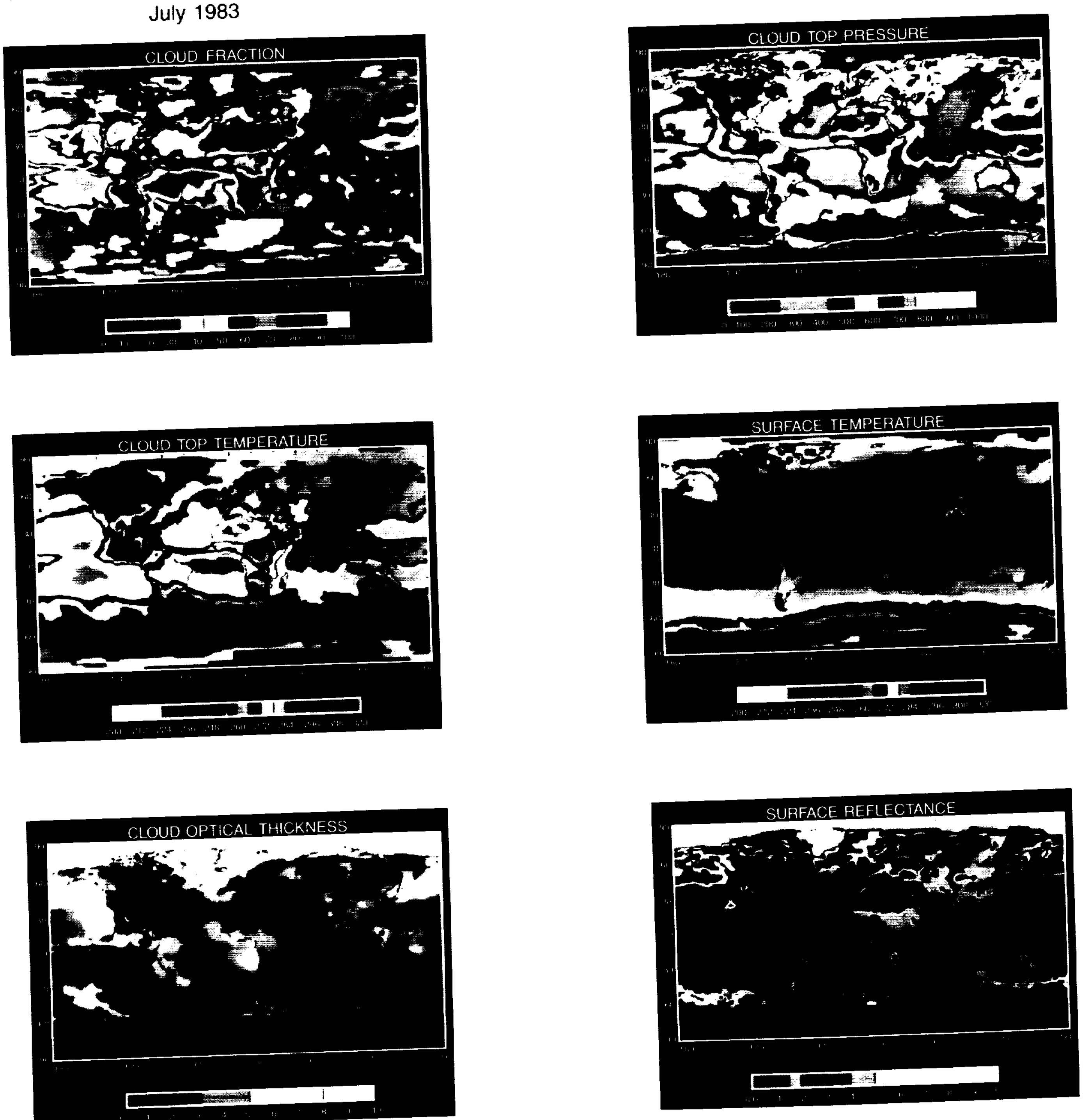
The combined Satellite Precipitation and Cloud Experiment (SPACE) and Microbursts in Severe Thunderstorms (MIST) Experiment was a regional field activity concerned with precipitation processes on the mesoscale. Many forms of data concerning the atmosphere were used including high-altitude sensing at visible infrared and microwave frequencies, radar, balloons, several satellites and direct in situ aircraft observations. The experiments were located in northern Alabama and in Tennessee. Many publications have been produced as a consequence of this experiment, yielding a new understanding of precipitating cloud systems that are not related to frontal passages or hurricanes. The SPACE part of the experiment is improving our understanding of cloud kinematics, cloud dynamics and thermodynamics, mesoscale kinematics, and water budgets. The MIST project addresses the extent and intensity of microbursts, their relation to other factors such as precipitation, and why thunderstorms may or may not contain microbursts.

Interdisciplinary Activities

In recent years, we have come to perceive the atmosphere as a cohesive body and to realize that many factors which we thought were inconsequential do, in fact, influence both climate and weather. We now know that climate pertains not only to the atmosphere itself—the traditional way of thinking about climate—but also depends strongly on the behavior of the oceans and the land. Climate therefore is by its nature an interdisciplinary subject, and the Atmospheric Dynamics and Radiation Program combines with other NASA branches in sponsoring appropriate interdisciplinary studies.

Our global-scale models now include air-sea and air-land interaction factors, which until recently had been recognized but neglected. Our current activities emphasize measurement of precipitation, a major component of the hydrological cycle. The study of precipitation is important because moist ground has a very significant impact on instabilities in the atmosphere, both on local thunderstorms as well as large synoptic-scale storms. We can no longer ignore the atmospheric boundary layer and the amount of moisture flowing through that layer from the Earth's surface. Both land and water

FIGURE 8-1. **INTERNATIONAL SATELLITE CLOUD CLIMATOLOGY PROJECT (ISCCP).** Mean parameters for July 1983



These maps display the global distribution of the primary cloud and surface parameters obtained from the analysis of satellite imaging data from the world's operational weather satellites, averaged over the first month of the ISCCP data collections, July 1983. The visible and infrared images obtained by these satellites are sampled every 3 hours and at a spacing of 30 km. In the complete cloud data set, the analysis results are reported for the whole globe every 3 hours at a reduced spatial resolution of about 280 km.

Continue next page

CLOUD FRACTION (upper left). This parameter represents the fraction of satellite image pixels that were determined to contain cloud; this combines fractional areal coverage with frequency of occurrence.

CLOUD TOP PRESSURE (upper right). This parameter represents the average vertical position of the cloud tops determined from their temperature.

CLOUD TOP TEMPERATURE (middle left). This parameter is determined from the infrared radiances measured by the satellites and represents the amount of thermal radiation emitted by the clouds. Together with cloud fraction and surface temperature, this parameter determines how much thermal radiation is emitted to space by each location on Earth.

SURFACE TEMPERATURE (middle right). This parameter is determined from the satellite infrared radiances when no clouds are present, and represents the amount of thermal radiation emitted by the Earth's surface.

CLOUD OPTICAL THICKNESS (lower left). This parameter is determined from the visible radiances measured by the satellites (no results are reported near the South Pole since there is no sunlight during July). It represents the amount of solar radiation reflected by clouds. Together with cloud fraction and the surface reflectance, this parameter determines how much solar radiation is reflected to space by each location on Earth.

SURFACE REFLECTANCE (lower right). This parameter is determined from the satellite visible radiances when no clouds are present and represents the amount of solar radiation reflected at the surface at visible wavelengths.

surfaces provide heat and moisture to the atmosphere, which also needs to be reflected in our atmospheric models.

Rainfall in the tropics exemplifies the type of issue that has global-scale climatic implications. In the tropics, latent heat release, a by-product of the precipitation process, serves to fuel the heat engine that drives the Earth's general circulation. Changes in tropical rainfall patterns can stimulate planetary wave development and movement, which affects not only the tropics but also the middle latitudes. Our planned precipitation studies, therefore, may have predictive value in seasonal terms by providing information on the release of latent heat input into the general circulation. Of course, such studies will also help us to understand drought and flooding and perhaps even to predict them.

On a global scale, we also need to understand the climatic effects of man's activities. Deforestation, paving, use of fertilizers and fluorocarbons, and burning of fossil fuels are influencing the radiative energy balance and changing the atmosphere's ability to absorb, reflect, or transmit incident solar radiation and emitted radiation from the Earth, and thus the local heating, cloudiness, and precipitation patterns, as well.

Conceptual Studies

Currently, we are studying several promising technological advances in active remote-sensing systems. Until a few years ago, virtually all our remote sensing was done passively by measuring received (passive) energy—energy emitted or reflected by either the atmosphere or the surface. Performance has been stretched close to the theoretical limit through such means as minimizing noise, improving the detectors, and narrowing the spectral bandwidths of the receivers.

We are now working to develop active systems, making use of the very rapid advances occurring in laser and radar technology. Laser instruments send energy out at a specified wavelength (e.g., at the resonance of some atmospheric constituent such as oxygen); the measurement obtained by the laser through a stimulated emission or a reflection by the target provides information not available through passive means.

Active sensing lasers can help us resolve the vertical structure of the atmosphere, because this technology provides vertical resolution that is unachievable in passive sensing. With lasers, it is possible to range-gate the pulse source of energy and identify the location in the atmosphere from which the pulse is being reflected or emitted. Lasers will be extremely valuable instruments when they can be flown above 70 to 80 percent of the atmosphere, looking down to make measurements. To be deployed in the difficult space environment, laser instruments must be rugged enough to withstand vibrations and cold, while being able to operate automatically without retuning or realigning the instrument during operation.

Lidar Instruments

We are developing lidar (Light Detection and Ranging) instruments to perform the following space-based functions:

1. In its simplest application, lidar is being used for looking at aerosols suspended in the atmosphere. These measurements can help us understand what the atmospheric aerosol loading is in terms of the radiative energy balance. Lidar can also be helpful for looking at cloud tops and studying cloud heights, which have an important bearing on the radiative balance.
2. Differential absorption lidars transmit at more than one frequency. The ratio of reflected energies provides a measurement of gas temperature, making it possible to derive a temperature profile. Both water vapor and pressure profiles can also be measured with this technique.
3. Another promising technique is the use of coherent lidar to measure the Doppler shift of backscattered laser wavelength due to dust, pollen, or other airborne particles which move with the wind. Wind profiles can be determined because the lidar pulses are controlled in frequency. Doppler lidar is an active remote sensor with a demonstrated capability to map the vertical profiles of wind over large volumes of clear air with <1-km height resolution in the troposphere. Such an instrument has the potential for providing data which would be of great benefit for initializing, validating, and improving mesoscale and general circulation models.

Use of the carbon dioxide (CO_2) laser offers the most promising technology for developing a Doppler lidar Wind Sounder. To develop a space-based CO_2 lidar system, design parameters depend heavily on the magnitude of atmospheric backscatter (β) at the wavelengths operated by that laser. A planned field experiment in 1989 will estimate geographic and temporal variations in the magnitude of β, using observations from both ground-based and airborne laser systems. The shorter wavelength provides an added advantage in the availability of isotopic CO_2 laser lines, which suffer less attenuation as a result of CO_2 naturally present in the atmosphere.

Lightning Measurements

We also believe that a sensor could be developed for observing all the lightning on the entire viewed surface of the Earth from a geostationary satellite during both day and night. Such an instrument would measure not only the amount of lightning, but its duration, location, movement, and intensity. This lightning sensor would be derived from an aircraft-based sensor already developed that is able to distinguish lightning strokes even in broad daylight.

An experimental sensor is currently being studied for possible placement on NASA's Geostationary Operational Environmental Satellite (GOES-Next) spacecraft. This will enable us to conduct the planned scientific studies of storm development processes, including storm severity measurement. A lightning mapper would have many practical applications in such areas as the location of forest fires started by lightning and the rerouting of power distribution lines to prevent electrical blackouts caused by lightning. Figure 8-2 shows the high correlation of lightning frequency and precipitation intensity.

Precipitation Measurements

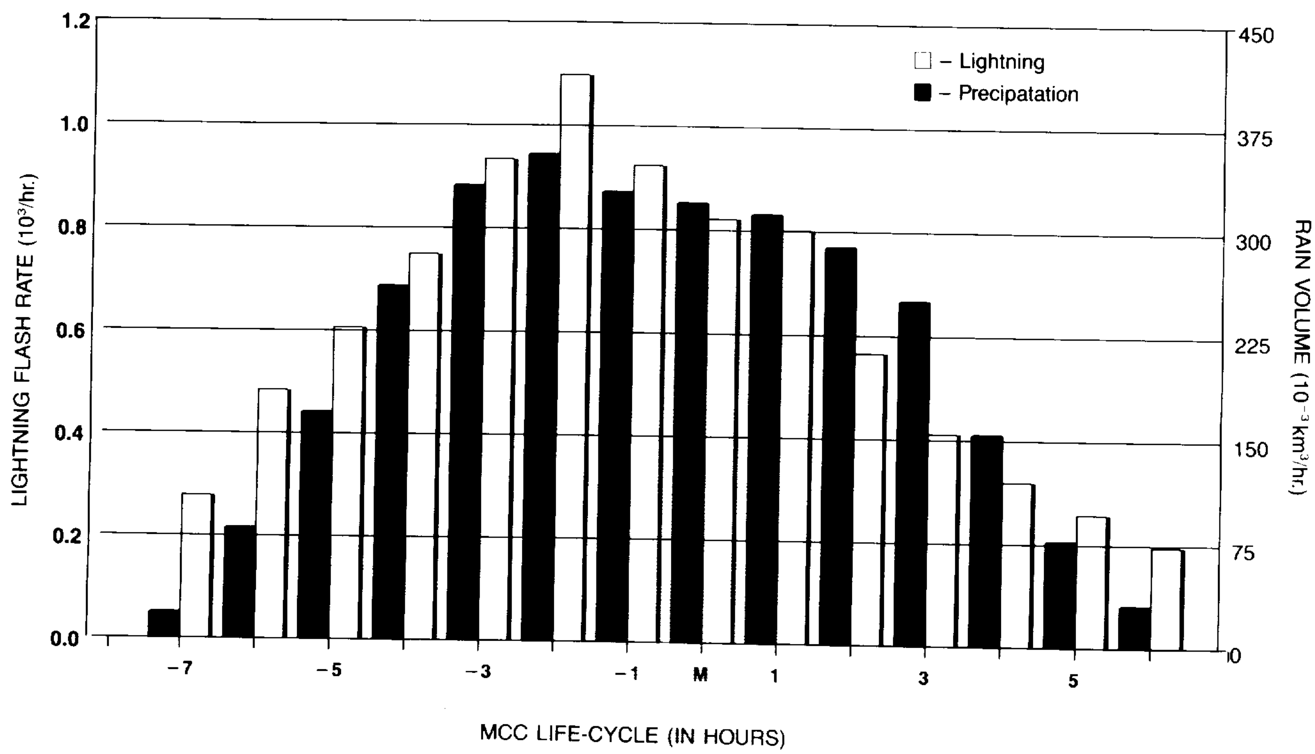
We are presently using airborne instruments for direct precipitation measurements. The measurement of precipitation involves using active radar sensing at multiple frequencies to provide a large dynamic sensitivity range, as well as information on raindrop size and distribution and the depth of the raining layer; both parameters are needed to determine total rainfall. Active radar sensing can be used in combination with passive microwave techniques to do areal mapping of rainfall. With satellite-borne measurement opportunities, we may soon be able to monitor the global extent of precipitation or at least rainfall in the tropics, which is very important to studies of global general circulation.

Tropical Rainfall Measuring Mission (TRMM). More than two-thirds of global precipitation falls in the tropics and subtropics (between 30 degrees north and south), and the latent heat released by this rainfall plays a vital role in driving low-latitude circulation and in the overall global heat budget.

TRMM is a conceptual proposal to measure tropical precipitation from a low-inclination orbit using a combination of active and passive microwave sensors, together with a visible/infrared sensor to overcome many of the previous limitations of remote sensing of precipitation from space. In addition to investigating the role of tropical latent heating in the global atmosphere, the data are important to test the realism of climate models and their ability to simulate and predict accurately on a seasonal time scale. Other scientific issues, such as the effects of El Niño on climate, could be addressed with a reliable, extended time series of tropical rainfall observations.

The passive microwave sensor will provide information on the integrated column precipitation content, its areal distribution, and its intensity. The horizontal resolution will allow the definition and investigation of most rainfall types, including convective cells. The planned

FIGURE 8-2. **HOURLY PRECIPITATION AND LIGHTNING IN MESOSCALE CONVECTIVE COMPLEXES**



Note: The lightning rate is based on 10 MCC cases; rainfall rate is based on 3 MCC cases, which are centered on the maximum cloud extent.

active microwave sensor (radar) will define the layer depth of the precipitation and provide information on the intensity of rain reaching the surface, a key factor in determining the latent heat input to the atmosphere. The very high resolving power will also better define the coverage and intensity of rain, and permit the measurement of rain over land, where the passive microwave channels have less sensitivity.

The visible/infrared sensors will provide very-high-resolution information on cloud coverage, type, and top temperatures, and also serve as the link between these data and the long-term and virtually continuous coverage by the geosynchronous meteorological satellites.

The unique combination of sensor wavelengths, coverages, and resolving powers, combined with the low-altitude, non-Sun-synchronous orbit, provides a sampling capability that should yield monthly precipitation amounts to a reasonable accuracy over a 500 x 500 km grid. Use of these data is also being considered for experiments involving soil moisture and vegetation.

The cooperative efforts now underway with Japan to study precipitation will continue. The Japanese Science and Technology Agency is studying the possibility of participating with NASA in a precipitation-measuring mission by providing a special radar designed to make precipitation measurements from space.

Global Scale Processes Research Program

As described under "Highlights of Recent Accomplishments," processing of the HIRS/MSU data has been used to produce the first year of a 10-year self-consistent atmospheric/land/ocean data set, including many fields not available on a physically self-consistent, global basis, such as estimates of cloud height and fractional cloud cover, atmospheric heating rates, radiative fluxes of heat, moisture and momentum, soil temperature, precipitation, and other parameters. The data set is produced using an interactive forecast retrieval-analysis system which makes combined use of three major related systems: the temperature retrieval system, the fourth-order general circulation model, and the objective analysis scheme. All of these systems have been developed and are in use at GSFC. Using data collected by the Television Infrared Observing Satellite (TIROS-N)/NOAA low-earth-orbiting operational satellites, the physical retrieval system provides improved atmospheric temperature-humidity profiles compared to those produced operationally, and, in addition, also produces estimates of total atmospheric ozone (O_3) burden, sea- and land-surface skin temperature, and cloud-top height and effective cloud fraction from analysis of the radiances.

The annual mean sea-level surface temperature (3 a.m., 3 p.m. local time average) and total clear air precipitable water are shown in Figures 8-3 and 8-4. Comparison of these data with cloud fraction and altitude derived by the same processing system shows that areas of high clouds in the tropics over land correspond to areas of low surface temperatures. This result is a consequence of the low diurnal variation of ground temperature in areas having large amounts of precipitation. These same regions also show up as having maxima in total precipitable water. Both findings are consistent with those of the regional study over Africa.

Figures 8-5 and 8-6 show zonal mean values of land surface temperature and clear air precipitable water for the same period. Both fields have patterns which are very similar to each other, with surface skin temperature and humidity closely following the seasonal cycle. The amplitude of the oscillation is very small in the Southern Hemisphere, which is mostly ocean, and increases toward the north, with the largest amplitudes northward of 40°N latitude. This seasonal dependence at high latitudes was found to be almost totally absent in the cloud parameters.

It is expected that these data will be a valuable resource in future investigations to better understand how the components of the earth/atmosphere/ocean system influence global-scale atmospheric dynamical processes.

Mesoscale Processes Research Program

A regional field activity, started in spring 1986, is concerned with precipitation processes on the mesoscale. Data from the project are currently being analyzed. The experiment, called SPACE-MIST, combines the Satellite Precipitation and Cloud Experiment (SPACE) with the Microbursts In Severe Thunderstorms (MIST) Experiment.

Under the management of the Marshall Space Flight Center, the SPACE project has collected measurements from a network of radars, balloons, and surface precipitation instruments located in southern Tennessee

FIGURE 8-3. **HIRS/MSU RETRIEVED SURFACE TEMPERATURE.** Annual mean 1979

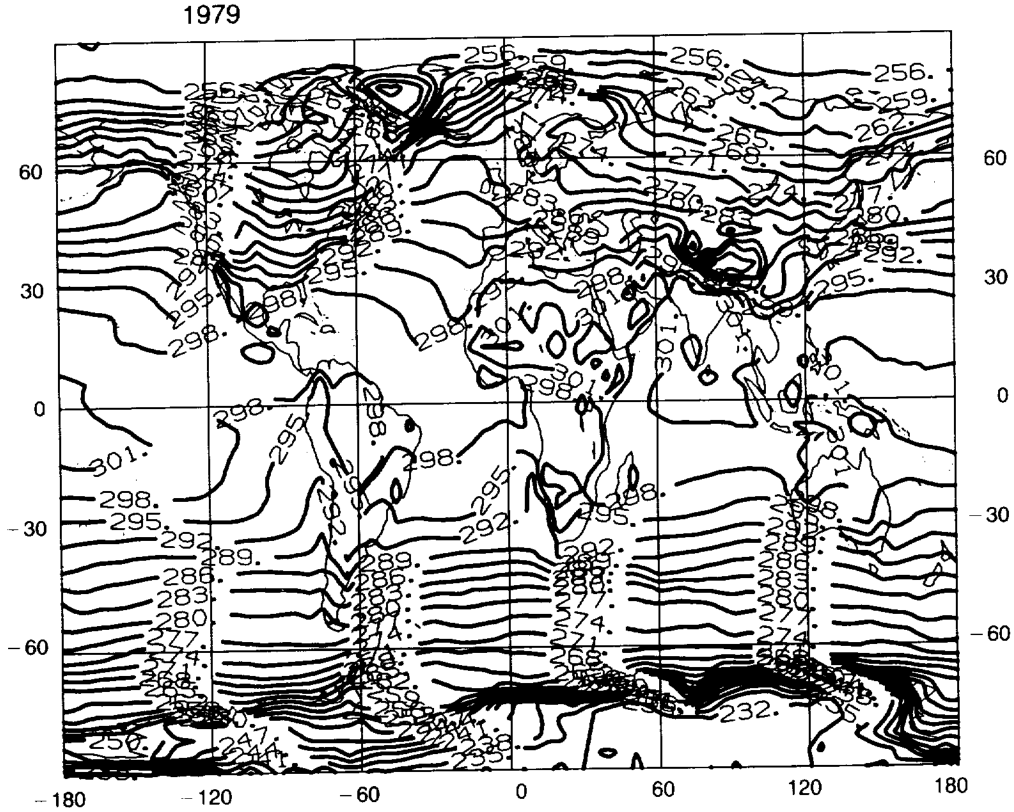
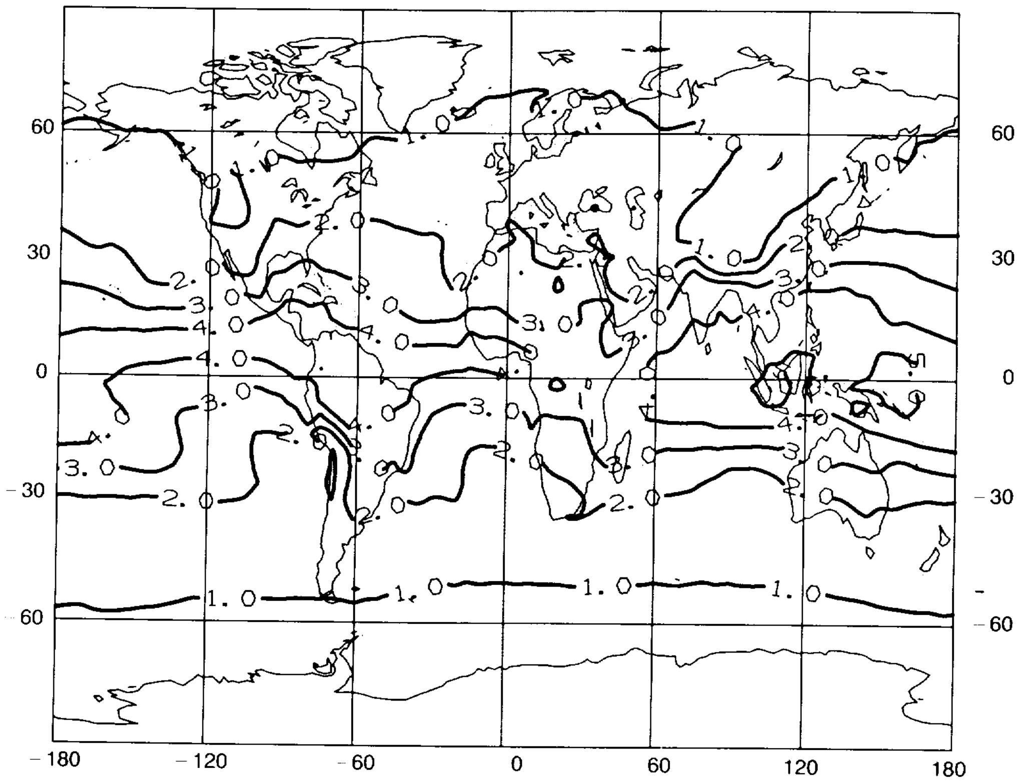


FIGURE 8-4. **HIRS/MSU RETRIEVED CLEAR AIR PRECIPITABLE WATER.** Annual mean 1979



and northern Alabama, combined with satellite data over this area. Microbursts were measured using Doppler radar. The SPACE project will enable us to develop a better understanding of cloud kinematics, cloud dynamics and thermodynamics, mesoscale kinematics, and water budgets.

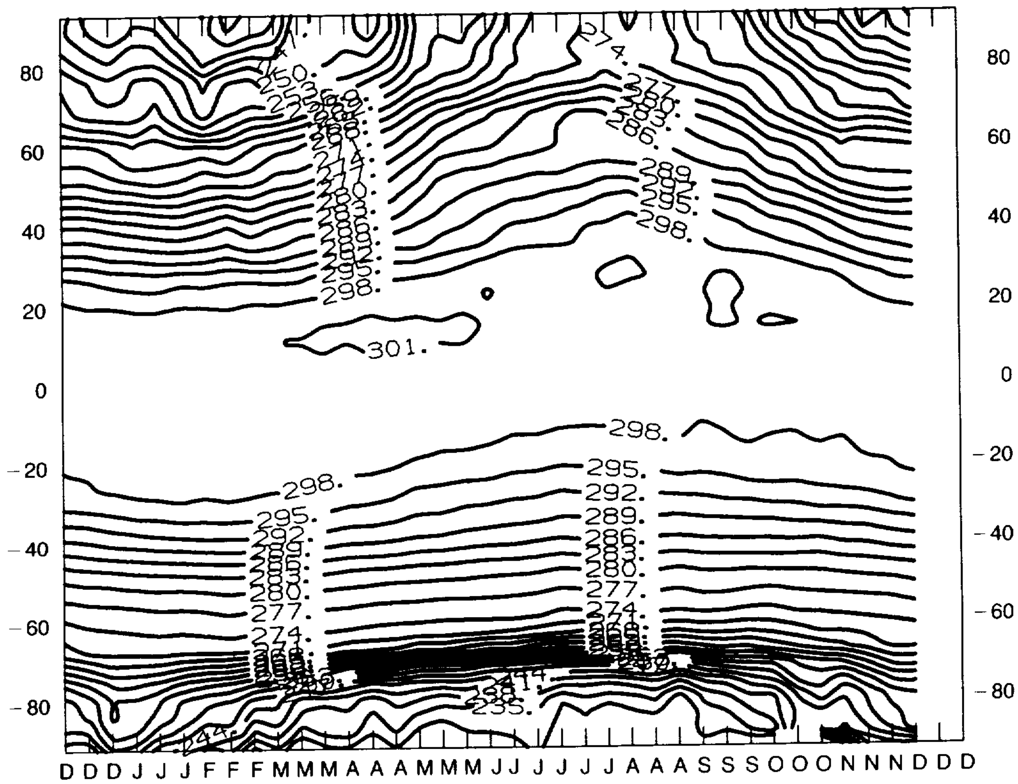
The MIST project, carried out by the University of Chicago, used a broad data base to study the conditions causing microbursts—downdrafts on a small scale that can adversely affect airplanes when landing or taking off. The types of questions being addressed include how extensive and intense microbursts are; whether they are related to other factors such as precipitation; and why some thunderstorms contain microbursts whereas others do not.

The long-awaited Request for Proposal for the Lightning Mapper Phase B Design Study is planned for release in 1988. This marks the end of the feasibility assessment phase of the sensor development process and the beginning of the paced effort to provide one research sensor for GOES-M, which is currently planned for launch in mid-1994.

In support of TRMM, as well as the Earth system science thrust in general, the Mesoscale Program is trying a prototype of the Eos style of real-time, interactive, networked data system. We have chosen the passive microwave sensor (SSM/I) on board each of the successive DMSP satellites as the source of the data, because of the broad spectrum of science and applications which can be derived from the five SMMR-like channels. Since we are emphasizing atmospheric moisture and precipitation estimation, we are calling the SSM/I data acquisition, interpretation and product distribution system, WETNET. (See Figure 8-7 for an illustration of SSM/I data flow.) Data available over this system will begin to make possible estimates of the component fluxes of the global hydrologic cycle.

Still another category of meteorologically useful data is that of total ozone observations. While formerly thought to be useful primarily for studies of the integrated effects of chemical processes and dynamics in the stratosphere, we now recognize that total ozone maps on a frequent schedule can be very useful in delineating jet stream locations and indicating locations of deepening low pressure systems. (Figure 8-8 illustrates total ozone distributions before, during and after the heavy Veterans Day snowstorm which paralyzed the Washington, D.C. area on November 11, 1987.) These maps were made by using the TOMS sensor on the deteriorating Nimbus-7 polar-orbiting satellite.

FIGURE 8-5. **HIRS/MSU RETRIEVED SURFACE TEMPERATURE.** December 1978-December 1979 Zonal Mean



Climate Research Program

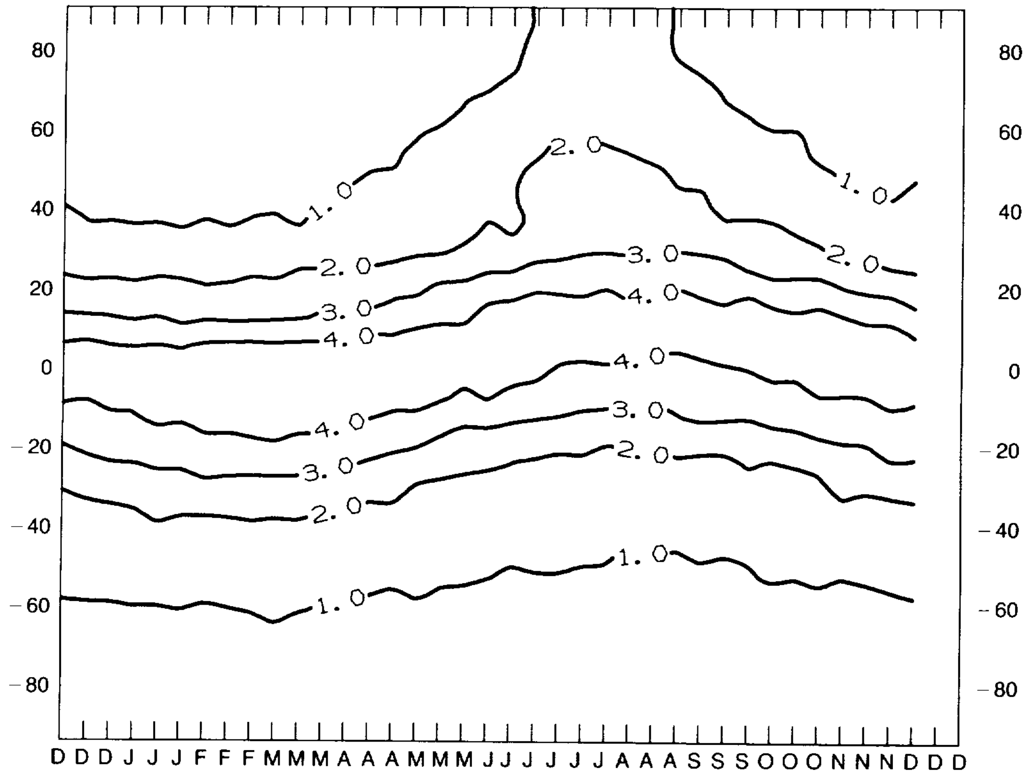
A major activity in 1987 involved validation of the data acquired by the Earth Radiation Budget Experiment (ERBE) satellite program. ERBE, which began observing the Earth's radiation balance in December 1984, is providing important data that will help improve climate models and, in particular, help assess the role of global cloudiness in influencing climate variability.

Because changes of only 1 to 2 percent in cloudiness could significantly affect the impact of the global carbon dioxide warming effect, the ERBE program represents a major breakthrough in understanding the warming and cooling of the Earth. The full effect of CO_2 forcing will depend on as yet inadequately understood feedbacks between atmospheric changes and the radiative forcing terms. The monitoring of the radiation budget at the top of the atmosphere has therefore emerged as a key component of a climate monitoring system— the Earth radiation budget serving as both a tracer of climate change and a forcing function, which effects further change.

In addition, continued support will be provided to the International Satellite Cloud Climatology Project (ISCCP). This first project of the World Climate Research Program (WCRP) involves collecting and analyzing satellite radiance data in order to infer the global distribution of cloud radiation properties and to improve the modeling of cloud effects on climate. Although we have been looking at clouds from space for 25 years, until now no definitive global data set for clouds has existed. The ISCCP project to produce a 5-year global satellite radiance and cloud data set, with globally uniform coverage of various cloud cover indices, completed its fifth year of data collection in 1987. The ISCCP research component coordinates studies to validate the climatology, improve cloud analysis algorithms, improve modeling of cloud effects in climate models, and investigate the role of clouds in the atmosphere's radiation budget and hydrological cycle. The ISCCP has begun routine processing of a global cloud climatology. The maps shown in Figure 8-1 display the global distribution of the primary cloud and surface parameters obtained from the analysis of satellite imaging data from the world's operational weather satellites, averaged over the first month of ISCCP data collection, July 1983. The visible and infrared images obtained by these satellites are sampled every 3 hours and at a spacing of about 30 km.

The First ISCCP Regional Experiment (FIRE) is a U.S.-sponsored field program designed to collect and analyze regional data to aid in validating the ISCCP

FIGURE 8-6. **HIRS/MSU RETRIEVED CLEAR AIR PRECIPITABLE WATER.**
December 1978-December 1979 Zonal Mean



global data set. NASA is playing a lead role in gathering cloud data at a number of test sites from GOES, NOAA, and Landsat satellites, along with comparative aircraft and ground-based measurements. The first FIRE field experiment was conducted in central Wisconsin in October 1986 to study the cirrus cloud systems associated with pre-warm frontal systems and jet streams. The second field experiment was performed over the eastern Pacific in July 1987 to study the marine stratus cloud system off the coast of California. Both experiments involved coordinated surface, aircraft, and satellite observations of cloud properties which will be used in multiscale comparisons with results of a variety of theoretical and empirical model predictions, leading to improvements in our understanding of cloud-radiation-dynamics interactions and their influence on climate. It is expected that the availability of these data will permit major advances in our ability to parameterize clouds in climate models.

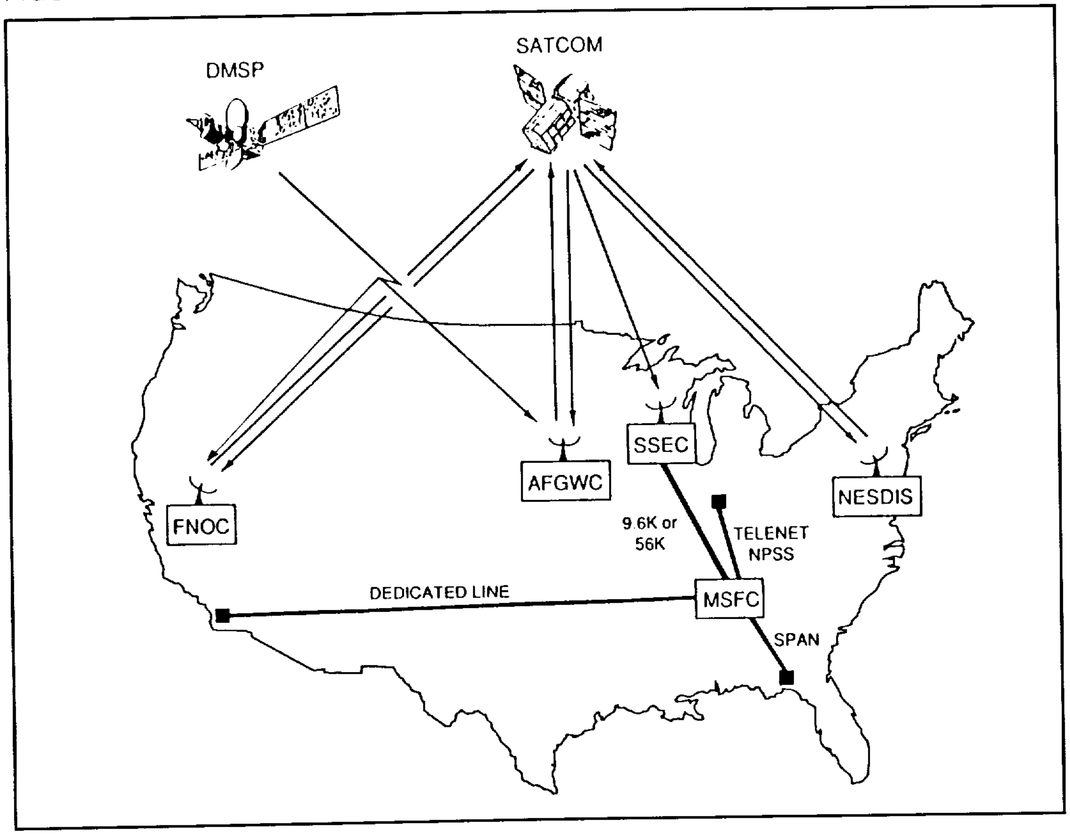
Plans for FY 1988 and FY 1989

The Tropical Rainfall Measuring Mission is a major thrust of the Atmospheric Dynamics and Radiation Branch. As described under "Highlights of Recent Accomplishments," we shall be using a combination of active and passive microwave sensors and a visible/infrared sensor to overcome many of the previous limitations in the remote sensing of precipitation from space. With the Phase A conceptual study and the Steering Group report both complete, we are now undertaking instrument design studies, sampling studies, and analysis of precipitation data, as well as the development of advanced precipitation estimation algorithms based on microwave and infrared interactions.

In the Mesoscale Processes Program the SPACE and MIST experiments made FY 1987 a year of intense, integrated observations of the atmosphere. During FY 1988, we concentrated on analyzing and interpreting the data, focusing on the planned experiment objectives and on the basic atmospheric interactions being studied. A number of other projects will receive new or additional emphasis in FY 1989, including the following:

- The assimilation of land surface and atmospheric boundary layer inputs into mesoscale models
- A study on the integration of available lasers and Doppler lidar signal processing equipment on the NASA DC-8 to enable an affordable replacement of the three-dimensional mesoscale wind mapping

FIGURE 8-7. **SSM/I DATA FLOW**



capability lost with the destruction of the CV-990 aircraft

- Continued work with NOAA, the National Science Foundation, and the Department of Defense to reach agreement on the scope of each agency's participation in the Storm Scale Operational and Research Meteorology (STORM) Program
- Establishment of a NASA/NOAA Cooperative Project between the Goddard Space Flight Center (GSFC) and the National Meteorological Center (NMC) to improve data sharing and forecast model improvements
- Development of four-dimensional computer displays of numerical model outputs
- Development of a two-beam, nadir-viewing Doppler radar for the high-altitude ER-2 to study precipitation motions within storms
- Studies of efficient ways of using the new, advanced multichannel scanner on the GOES-I through -M operational spacecraft

In addition, during FY 1988 the Mesoscale Processes Program is implementing a model data-sharing system, using the Defense Meteorological Satellite Program's Special Sensor Microwave Imager (SSM/I) for developing precipitation and water vapor algorithms (see Figure 8-7). Plans will be developed for high-altitude precipitation estimation flights over tropical cumulus clusters, and planning will be started for a mesoscale air-sea interaction study based upon satellite and ocean surface observations.

The Climate Research Program will continue routine processing of ISCCP radiance and cloud data at Goddard Institute for Space Studies (GISS) as planned. In accordance with a recommendation made by the Joint Scientific Committee (JSC) for the World Climate Research Program (WCRP) last year, the 5-year period of ISCCP data collection (1983-1988) will be extended by 2 years to compensate for the extended period during which the global satellite coverage was incomplete (e.g., no GOES-East in operation). This extension will also allow more time for the climate modeling community to begin experimenting with ISCCP data prior to conclusion of the project.

Involvement with Project FIRE will continue although no new additional FIRE field experiments are planned for the immediate future. This project aims to validate and improve ISCCP algorithms and cloud/radiation models. The emphasis is now on analyzing the vast quantities of data collected during the cirrus and marine stratocumulus missions. A major scientific workshop in July 1988 will evaluate and compare preliminary FIRE scientific results. Its conclusions will aid in assessing the need for further field measurements and a decision will be made in the fall of 1988. Other priorities of the Climate Research Program include:

- Cross-calibration of the Earth Radiation Budget Experiment (ERBE) measurements with Nimbus-6 and -7 Earth Radiation Budget Satellite (ERBS) measurements to extend the record back to about 1975

- Initiation of preliminary definition/design studies for broadband ERBS follow-on instruments to be deployed on the Space Station/Polar Platform in the mid-1990s

- Continuation of research on algorithms to derive surface radiation budget (SRB) parameters from merged operational satellite data

Studies sponsored by the Global Scale Processes Research Program have shown that a satellite-borne wind profiling system will make a significant increase in our understanding of atmospheric dynamical processes and our ability to predict weather. Concept feasibility studies of a Laser Atmospheric Wind Sounder (LAWS), as a facility instrument in the Earth Observing System and as a candidate attached payload to the Space Station, have been initiated in FY 1988. To supplement these studies a global survey of atmospheric backscatter amount and variability, at laser wavelengths, will be made in FY 1989. To better understand the distribution of atmospheric aerosol backscatter, a Global Backscatter Experiment (GLOBE) has been initiated. The goal is to observe the geographic and seasonal variability of aerosol backscatter through a combination of ground-based, airborne, and satellite measurements. In FY 1989 a series of aircraft flights, utilizing laser backscatter instrumentation on the NASA DC-8, will provide the profile information necessary to integrate the satellite and ground-based data into a seasonal and geographic model. GLOBE will result in a physical model of the backscatter variations based on these observations and on our accumulated knowledge of aerosol physics. The results will also benefit space lidar system design by helping to determine the laser power and telescope aperture required for adequate signal-to-noise considerations.

Long-Term Projections

Plans for future activities reflect three interlocking themes: our increasingly sophisticated atmospheric models, which indicate where gaps exist in our knowledge of meteorological and climate parameters; the need to develop new remote-sensing techniques and instruments to fill these knowledge gaps; and the current recognition that atmospheric processes are interdisciplinary in nature.

The Global Scale Research Program is seeing an increased emphasis on the development of new remote-sensing techniques. It is important not only that we develop new measuring capabilities, but that we better understand the impact of satellite measurements on weather forecasting. Because of the winding-down of the Global Atmospheric Research Program (GARP), the need to emphasize pure analysis and modeling has crested.

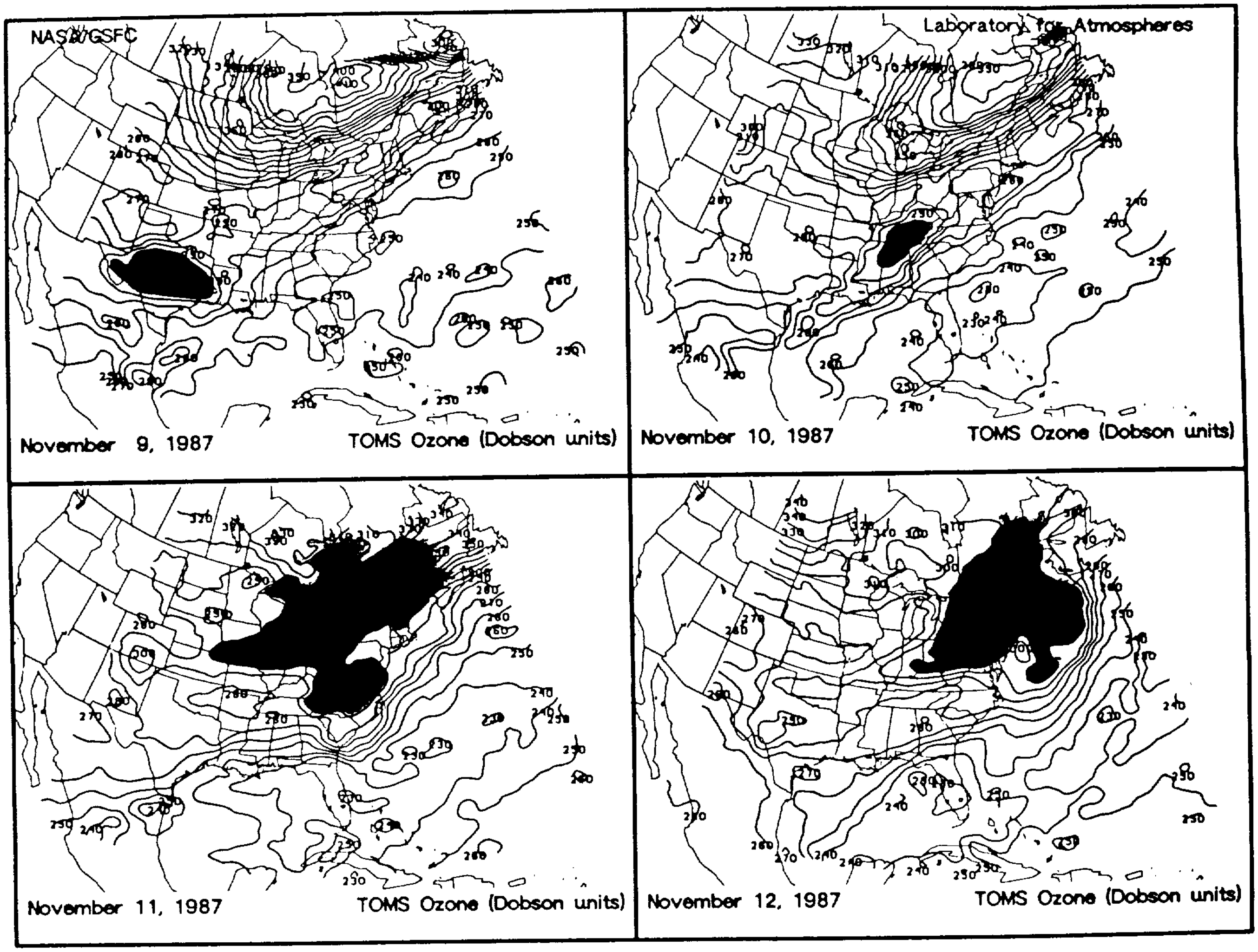
In the Mesoscale Research Program, advances in modeling, computing capabilities, and observational techniques (including space observations and a network of ground-based Doppler radars) will enable us to undertake the kind of modeling in the mesoscale that has been done on a global scale for several decades. These components are embodied in the proposal for a new, large-scale, national program called Storm Scale Operational and Research Meteorology (STORM). This major field program is designed to make measurements that will help detect, understand, and predict the development of severe weather. A unique combination of all currently available techniques will be used, including satellites, radars, ground-based stations, and advanced scientific models and computers.

We expect STORM to be a major thrust in the next few years, with NASA playing a significant role in this program along with NOAA and the National Science Foundation. NASA has in place the sensing and retrieval techniques to make good use of data already available from operational satellites, as well as models capable of ingesting the satellite data.

The major long-term plans for the NASA Climate Research Program focus on exploiting the global data sets acquired by ERBE and ISCCP to improve our understanding of radiation and clouds in climate. Scientific investigations by the ERBE Science Team and through unsolicited proposals will apply these data to climate model validation studies, diagnostic studies of climate variability (e.g.,El Niño), and assessment of the prospects of detecting long-term climate change (e.g., because of carbon dioxide buildup in the atmosphere).

Further cloud studies will be pursued under the FIRE program. Particular emphasis will be given to the per-

FIGURE 8-8. **TOTAL OZONE DISTRIBUTION - VETERANS DAY SNOWSTORM, 1987**



sistent marine boundary layer stratus clouds off the California coast to evaluate their influence on the Earth's radiation budget. Extensive field studies of these and the previously mentioned cirrus clouds will continue through 1989 with an alternating focus on each cloud type. Together with the ISCCP global cloud climatology, FIRE results should allow substantial progress in understanding the role of clouds in climate.

9
Atmospheric Chemistry Program

The Atmospheric Chemistry Program is a comprehensive research and technology effort designed to investigate and monitor the chemistry and physics of the atmosphere from the ground to 80 km, including the troposphere, stratosphere, and mesosphere, on a global scale, and to assess as accurately as possible the perturbations to the atmosphere caused by man's activities. It consists of two components: the Upper Atmosphere Research Program and the Tropospheric Chemistry Program. These programs aim to improve our basic scientific understanding of the global atmosphere and to develop accurate methods for assessing its susceptibility to significant chemical and physical change. Major thrusts lie in the areas of upper atmospheric research, stratospheric air quality research, and tropospheric air quality research. To accomplish these goals, efforts are underway to:

- Improve upper atmosphere and global troposphere models, validate them, and assess their uncertainties
- Measure important trace chemical constituents, temperature, and radiation fields throughout the atmosphere
- Develop sensors capable of making chemical and physical measurements of the upper atmosphere and the global troposphere both directly and remotely from space
- Assemble and maintain the existing long-term data base of stratospheric and tropospheric ozone measurements to aid in the detection of long time-scale natural variations and man-made ozone changes
- Determine the effects of global tropospheric chemistry on the atmosphere
- Conduct theoretical and field studies of tropospheric/stratospheric exchange
- Carry out laboratory kinetics and spectroscopy investigations to support these activities

A variety of in situ and remote-sensing techniques are needed if we are to determine and understand the distribution of ozone and other trace species in the atmosphere. Data sets from satellites, including Nimbus-4, -6, and -7, the Solar Mesospheric Explorer (SME), the Stratospheric Aerosol and Gas Experiment (SAGE), and National Oceanic and Atmospheric Administration (NOAA) and Department of Defense (DoD) satellites, are now generally available to the scientific community. The global distribution of ozone record covers the last decade, and simultaneous observations from the Nimbus-7 satellite of temperature, solar flux (wavelength resolved), and a number of trace constituents are available for a 7-month period in 1978-79. These data are being exploited to determine whether trends in the amount of atmospheric ozone are detectable and to understand processes directly involved with such trends.

Upper Atmosphere Research Program

The Upper Atmosphere Research Program (UARP) is a large, comprehensive research program, with NASA playing a leadership role as mandated by Congress under the Clean Air Act of 1976 and the FY 1976 NASA Authorization Act. The program aims to expand our knowledge about the important upper atmosphere environment. An improved scientific understanding of the physical, chemical, and meteorological processes that control the concentration and distribution of atmospheric ozone will provide us a basis for predicting the impact of natural and man-made phenomena on the ozone layer.

The habitability of Earth depends on maintaining the protection of the ozone layer, which keeps out biologically harmful ultraviolet light. Ozone (O_3) also controls the temperature structure of the stratosphere, which has consequences for both weather and climate. It is now recognized that ozone depletion occurs from complex, coupled causes. Changes in the atmospheric concentrations of several trace substances are strongly coupled and should not be considered in isolation. The specific substances involved include chlorofluorocarbons, carbon monoxide, carbon dioxide, methane, nitrous oxide, and the nitrogen oxides. In addition to their effect on stratospheric ozone, these same trace gases exert a pronounced influence on the Earth's climate. The direct radiative effects of these trace gases on atmospheric temperature are approximately additive.

As our understanding of the ozone problem has increased, its complexities have become more apparent. Although most of the key stratospheric constituents have been observed and generally agree with the predictions of our photochemical models, our observations show detailed disagreement with our predictions, which suggests that the predictive capacity of the models needs to be improved. The significant changes observed in ozone include depletion in the upper atmosphere, consistent with expected changes from increasing chlorines in the atmosphere, and large depletions (about 50 percent) in total ozone over the Antarctic in spring, which were unexpected.

As our major current program objective, we aim to predict the future state of the atmosphere through computer models. Using the best understanding available from fundamental physics and chemistry, we construct numerical simulations (models) of atmospheric behavior and use the models to test our understanding of atmospheric chemistry and dynamics. A substantial theoretical effort is underway to develop a hierarchy of models for how the stratosphere and mesosphere behave chemically, radioactively, and dynamically. Although there is still considerable uncertainty in the predictions, we expect our models ultimately to predict how the ozone layer will respond to natural or man-made changes.

Specific areas of investigation include the following:

- Determination of the way trace gases are distributed in the upper atmosphere, particularly those that influence the ozone balance
- Observation of ozone in terms of its global distribution, vertical profile, and temporal variations
- Improvements in the theory of upper atmospheric photochemical processes, validating the theory through comparison with actual measurements
- Improvements through both theory and measurements in the understanding of atmospheric dynamics and transport processes
- Determination of the characteristics of motions responsible for exchange of air between the troposphere and stratosphere
- Determination of the geographic distribution and strengths of sources and sinks for stratospheric compounds
- Measurements of ultraviolet solar irradiance and its temporal variations
- Laboratory studies in spectroscopy, photochemistry, and chemical kinetics pertaining to interpretation of atmospheric measurements and theoretical simulation of the atmosphere

Tropospheric Chemistry Program

The aim of the Tropospheric Chemistry Program is to understand the chemical cycles that control the composition of the troposphere and to assess global atmospheric susceptibility to chemical change. We know too little about the important role played by tropospheric chemistry in biogeochemical cycles. The troposphere acts as the source and sink for chemicals in the stratosphere. Tropospheric chemistry and transport govern the distribution of trace species within the atmosphere and alter the chemical state in which trace elements move through the atmosphere. Tropospheric chemical changes can affect global hydrological processes, the cycling of nutrient compounds, the accumulation of infrared active gases in the atmosphere, rain and snow acidity, and the rate of ozone depletion in the stratosphere and mesosphere by man-made chemicals introduced through the troposphere.

Understanding the chemical processes in the troposphere on a global scale is critical if we are to predict, and potentially ameliorate, harmful man-made changes to the global environment.Human activity can alter the source and sink strengths of tropospheric chemical species and change atmospheric chemical cycles in directions that inhibit the atmosphere's ability to cleanse itself. The resultant changes in global atmospheric chemical composition can affect our climate. We have known for several years that increased carbon dioxide in the atmosphere from burning fossil fuels can produce a global warming through the "greenhouse effect," but other gases and trace species that now appear to be accumulating in the troposphere, including methane, nitrous oxide, carbon monoxide, and chlorofluorocarbons, can cause a similar effect.

Objectives of the Tropospheric Chemistry Program are to:

- Develop techniques for remote and in situ measurement of the concentrations and fluxes of key tropospheric species

- Determine meteorological and chemical influences of the troposphere on the atmosphere as a whole, particularly the stratosphere
- Understand the chemistry of global tropospheric species and causes of changes in chemical composition
- Develop a realistic general circulation model of the global troposphere, including its chemistry, for use in field experiment design and data analysis
- Develop and implement a strategy for chemical measurements from space platforms

Within the Program, a series of field experiments, called the Global Tropospheric Experiment (GTE), emphasizes the development, testing, and evaluation of techniques capable of measuring, under field conditions, the minute concentrations of key chemical species in the atmosphere. Establishing such accurate measurement constitutes a necessary first phase in implementing a global tropospheric chemistry program. The second phase, now beginning to be addressed by GTE, focuses on widespread, systematic measurements of trace species via an aircraft sampling program, supported by modeling and laboratory studies. We expect the third phase—space-based measurements as a primary tool for global-scale investigations of tropospheric chemical and transport processes—to begin in the 1990s. The space techniques and measurement strategy will be based on the aircraft studies and extensive modeling now underway.

Highlights of Recent Accomplishments

During the last 2 years, the Atmospheric Chemistry Program has made a number of major advances, most notably the completion of the Antarctic ozone hole campaign and the publication of the Ozone Trends Panel Report, both of which are described in further detail below.

The Stratosphere-Troposphere Exchange Project (STEP)

A major field measurement activity in 1987 was the Stratosphere-Troposphere Exchange Project (STEP) campaign conducted using the ER-2 flown out of Darwin, Australia to investigate the processes responsible for the transport of gases across the tropopause, and the mechanism responsible for the dehydration of the stratosphere. Analysis of data from this mission has been delayed by the Antarctic aircraft campaign, but is expected to occur within the next year.

Network for the Detection of Stratospheric Change

NASA has begun the implementation of a ground-based Network for the Detection of Stratospheric Change. Ozone lidar and microwave measurements are currently being assembled and tested. When complete, the network of 5-6 stations will provide the capability for early detection of changes in the composition of the stratosphere and the means to understand the causes of those changes. The completed network, including ultraviolet and infrared spectrometers, will also provide a capability for correlative measurements for the Upper Atmosphere Research Satellite (UARS).

Two- and Three-Dimensional Stratospheric Models

The UARP has been instrumental in the development over the last 2 years of two-dimensional stratospheric models as the current mainstay of assessment. Such models simulate the chemistry and dynamics of the stratosphere, and have been used to analyze and interpret satellite data and to make predictions of the impacts of increasing atmospheric levels of trace gases on atmospheric ozone. The models calculate the stratospheric distribution of ozone and other gases as a function of latitude, season and altitude, thus providing a more realistic comparison with observations. The application of two-dimensional models as the basic assessment tool for future changes has led to more specific predictions which may more easily be tested using future measurements.

More recently, support has been initiated for several three-dimensional models of stratospheric chemistry and dynamics which rely heavily on the three-dimensional general circulation models of the stratosphere and troposphere also supported through this program. While still in the developmental stages and not yet ready for current assessments, these models are expected to provide a major predictive capability for global change, since they will be able to include the impacts of climate change and the effects of tropospheric chemistry. Future research in the UARP will increasingly rely on these complex and expensive models for both assessment studies and the assimilation of satellite data (such as preparation for the UARS).

Global Troposphere Experiment/Atmospheric Boundary Layer Experiments (GTE/ABLE-2)

The two missions that comprise the Global Troposphere Experiment/Atmospheric Boundary Layer Experiments (GTE/ABLE-2A and -2B) have been successfully completed. The first ABLE mission (GTE/ABLE-1) was conducted in 1984 over the tropical Atlantic Ocean in the vicinity of Barbados. The second experiment, conducted in 1985 and 1987, took place in the wet and dry seasons over the Amazon tropical rain forest in Brazil with aircraft and ground-based experiments. GTE/ABLE-2 was the largest atmospheric chemistry field experiment ever done in the Amazon. The project included more than 60 people from the United States, as well as 100 Brazilian researchers.

The Brazilian site is highly significant for understanding global tropospheric chemistry. The tropical rain forest plays a key role in controlling the chemical content of the global troposphere and affects the climate of the Western Hemisphere. This important ecosystem is rapidly changing because of massive deforestation and development. In its present state, it is a key region of the globe for tropospheric studies, and the changes in it are likely to have profound effects. The prediction of these effects requires a much higher level of understanding than we presently have of the tropical forest ecosystem and its interactions with the global ecosystem.

The GTE/Chemical Instrumentation Test and Evaluation (CITE)-2 Mission

Analysis of data and preparation of publications are underway following the GTE/Chemical Instrumentation Test and Evaluation (CITE)-2 mission, conducted in FY 1986. The experiment involved several studies of the nitrogen family, including a nitrogen budget/instrument intercomparison experiment. This experiment tested and intercompared instruments measuring concentrations of nitrogen dioxide, PAN, and nitric acid. Coordinated measurements were also made of other odd nitrogen species to determine the abundances and partitioning of the major reactive nitrogen species in the continental and oceanic troposphere.

The Airborne Antarctic Ozone Experiment

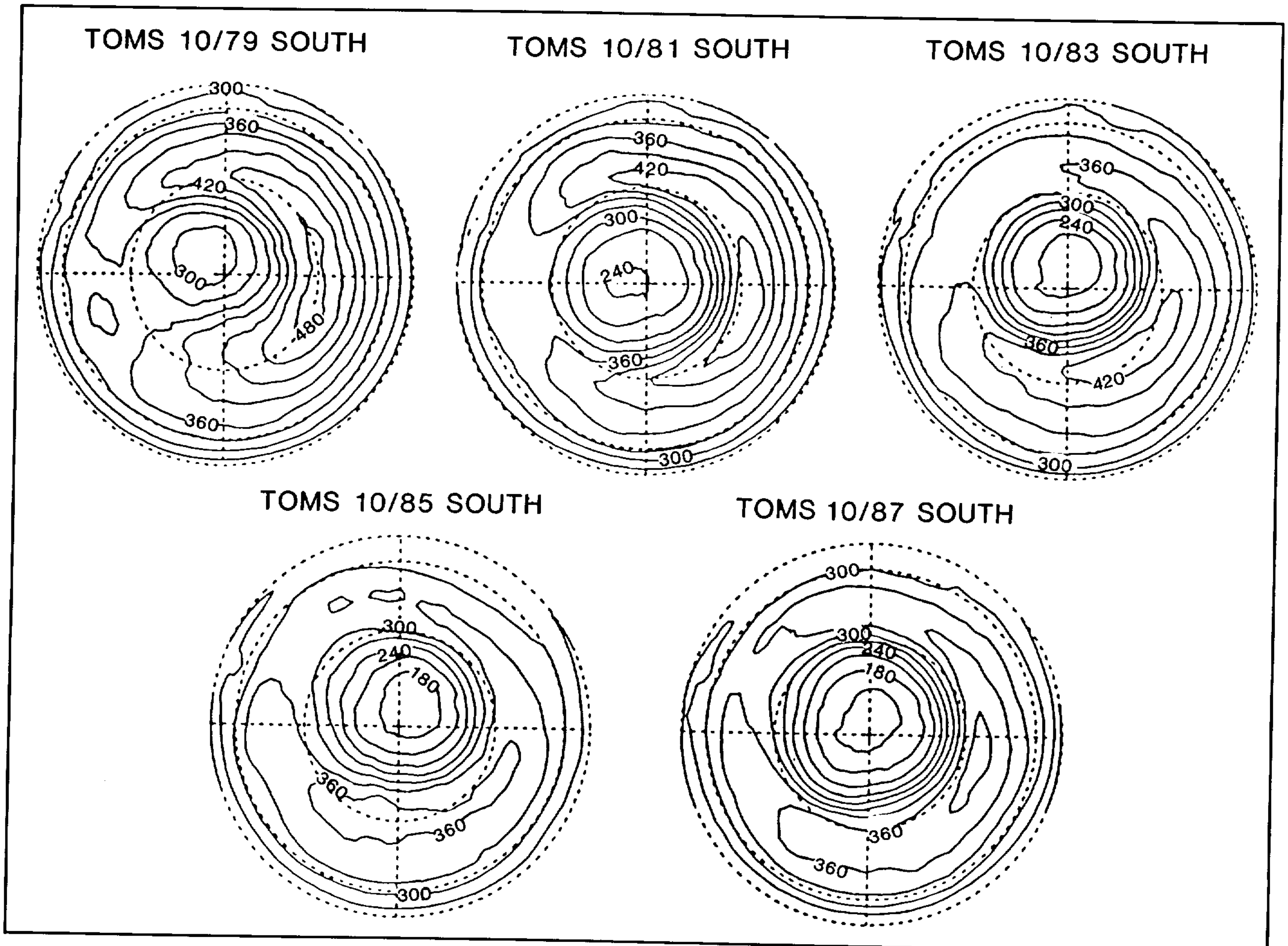
Another major event during FY 1987 was the planning and successful implementation of the Airborne Antarctic Ozone Experiment. The austral springtime decrease in total ozone over Antarctica has been of considerable interest to the UARP since the first reports by the British Antarctic Survey in 1985. The October average of column ozone had been roughly constant from 1958 to the late 1970s, but declined from the late 1970s until 1984 by approximately 30 percent. Examination of data from the Total Ozone Mapping Spectrometer (TOMS) on Nimbus-7: (1) confirmed the British data; (2) showed that the ozone decrease occurred throughout the polar vortex (the ozone "hole"), an area the size of the continental U.S.; and (3) documented the "hole's" temporal evolution, i.e., it develops after sunlight reaches the vortex in late August. The TOMS data also indicated that the region of "high" ozone outside the vortex has also declined by roughly the same amount from 1979-1985 (see Figure 9-1).

Three basic theories were proposed to explain the phenomenon. The first argues that the hole is caused by human activities through the increased atmospheric loading of chlorinated (CFCs) and brominated (halons) chemicals. These compounds efficiently destroy stratospheric ozone in the Antarctic environment because of special geophysical conditions that exist in this atmospheric region. The second theory attributes the ozone hole to recent atmospheric circulation changes resulting in the transport of ozone-poor air into Antarctica. The final theory posits the cyclical destruction of ozone by periodically enhanced abundances of oxides of nitrogen produced by solar activity.

In order to improve our understanding, the NASA UARP, together with NOAA, NSF, and the Chemical Manufacturers Association, mounted several expeditions: ground-based observations at McMurdo Station in 1986 and 1987 (NOZE-1 and NOZE-2) and a major aircraft campaign in August-September 1987 using the NASA ER-2 and DC-8 aircraft flying out of Punta Arenas, Chile. Much of the NOZE-1 data have been published. The observations of nitrogen dioxide (NO_2), chlorine monoxide (ClO), chlorine dioxide (OClO), $ClONO_2$, HNO_3, and hydrochloric acid (HCl) demonstrated that the region was chemically perturbed compared to the normal stratosphere (consistent with a chemical cause of the ozone hole), and refuted the solar activity theory. Balloon ozone-sonde data showed the vertical extent and structure of the ozone hole. Results from the recently concluded NOZE-2 campaign should be forthcoming within the next year.

Preliminary results from the aircraft campaign were announced in September 1987, with detailed publication in the spring of 1988. ER-2 instruments measured the distributions of ozone (O_3), ClO, bromine monoxide (BrO), odd nitrogen (NO_y), NO, and water in the vicinity of the aircraft at altitudes ranging from 12 to 18 km above the Earth's surface, within the altitude region where ozone is undergoing depletion. Instruments aboard the DC-8 measured the abundances of H_2O and O_3 in the vicinity of the aircraft, the vertical distribution of

FIGURE 9-1. **ANTARCTIC OZONE CONCENTRATION**



Progressive thinning of Antarctic ozone minimum documented by the TOMS instrument on the NIMBUS-7 satellite. (October monthly averages, 1979-1987)

O_3 for approximately 10 km above the aircraft, and the total column amounts of O_3, HCl, $ClONO_2$, OClO, BrO, HF, NO, NO_2, and HNO_3, as well as a number of other constituents above the aircraft altitude.

The temporal and spatial distributions of long-lived chemical tracers and dynamical variables were measured in order to understand atmospheric motions. These included measurements of N_2O, CH_4, $CFCl_3$ and CF_2Cl_2, CCl_4, and CH_3CCl_3. In situ measurements of all of these species were made from both the ER-2 and DC-8, and column measurements of most from the DC-8. In an effort to explore the role of heterogeneous processes, the size distribution, abundance, and composition of particles were determined by instrumentation aboard the ER-2, and the vertical distribution of aerosols from 12 to 28 km by the DC-8 lidar. Atmospheric pressure, temperature, lapse rate, and winds were also measured aboard the ER-2 to determine the state variables and dynamical structure of the atmosphere. The aircraft mission made intensive use of real-time satellite data, ozone-sonde data, and forecasting and analyses by the British Meteorological Office. Scientists and scientific organizations in the United Kingdom, France, Argentina, Chile, and New Zealand participated in the aircraft campaign.

Based on the data released to date, the following picture of the Antarctic ozone hole has emerged:

- Column ozone between August and November of 1987 was lower at all latitudes south of 60 degrees than measured in any previous year. Balloon-sonde and DC-8 aircraft data demonstrated that ozone was depleted in the altitude region between approximately 14-24 km. Satellite data showed that ozone did not simply change smoothly with time, but in some instances changed dramatically over large spatial scales in the matter of only a day or so. These rapid changes in ozone indicate that meteorology plays a critical role in contributing to ozone changes in Antarctica.

- The chemical composition of the Antarctic stratosphere is highly perturbed compared to elsewhere on the planet. The distribution of chlorine species is significantly different from that observed at mid-latitudes, as are the abundance and distribution of nitrogen species. The amount of total water within some regions of the vortex is significantly lower than anticipated.
- The abundance of the chlorine monoxide (ClO) radical within the chemically perturbed region (values near 1 ppbv) was elevated by a factor of more than 100 relative to that measured at mid-latitudes at the highest altitude at which the ER-2 was flown, about 18.5 km, steadily decreasing towards lower altitudes, and dramatically decreasing outside of the chemically perturbed region.
- Chlorine dioxide (OClO) was observed both day and night at highly elevated concentrations compared to those at mid-latitudes. The column content of hydrochloric acid (HCl) which is one of the major chlorine reservoirs at mid-latitudes, is very low within the chemically perturbed region. The bromine monoxide (BrO) radical was observed at concentrations of a few pptv within the chemically perturbed region of the vortex at the flight levels of the ER-2.
- The ER-2 observations of the abundance of odd nitrogen (NO_y) show, like total water, very low values within the chemically perturbed region of the vortex, indicating that the atmosphere has been denitrified, as well as dehydrated. Abundances of NO_y of 8-12 ppbv were observed outside the chemically perturbed region, while abundances of 0.5-4 ppbv were observed inside the chemically perturbed region. A similar large change was observed for one of the nitrogen components, i.e., nitric oxide. In addition, some of the NO_y observations suggest that NO_y component species are incorporated into polar stratospheric cloud (PSC) particles. Nitrate was observed in the particle phase on some of the filter samples and on some of the wire impactor samples taken in the chemically perturbed region of the vortex. The column measurements of nitric oxide, nitrogen dioxide, and nitric acid made from the DC-8 exhibit a strong decrease in the abundance of these species towards the center of the vortex. These low values of nitrogen species are contrary to all theories requiring elevated levels of nitrogen oxides, such as the proposed solar cycle theory.
- The data offer no support for sustained large-scale upwelling. In the restricted region covered by the ER-2, 54 to 72 degrees south latitude and from altitudes of 12.5 to 18.5 km, measurements of CFC-11 and N_2O, which act as tracers of air motions, show no evidence of a general increase in abundances above about 14 km during the aircraft mission, although there were instances of structure and elevated values. Dramatic, large-scale changes in the ozone column occurring on time scales of 1 to 2 days indicated a meteorological role in at least some portions of the ozone hole.

Detailed understanding of the exact causal mechanism responsible for the Antarctic ozone hole will require further analysis of the experimental data, as well as additional laboratory investigations of the possible chemical cycles that may be involved. The preliminary conclusion that can be reached at the present time is that the weight of the observational evidence indicates that both chemical and meteorological processes perturbed the ozone abundance in 1987.

The Ozone Trends Panel Report

The publication of the Ozone Trends Panel Report in March 1988 was another major event for UARP and created a great deal of interest within the scientific and lay communities. In October 1986 NASA, in collaboration with NOAA, the Federal Aviation Administration (FAA), the World Meteorological Organization (WMO), and the United Nations Environmental Program (UNEP), convened the Ozone Trends Panel, which involved over 100 scientists in a reevaluation of two 1985 reports on the decrease in ozone levels, one on springtime Antarctic levels and the second on a global scale. The Ozone Trends Panel performed a critical reanalysis and interpretation of nearly all ground-based and satellite data for total column and vertical profiles of ozone. In addition, a series of theoretical calculations for comparison with the reanalyzed ozone data was made and a uniform error analysis applied to all the data sets reviewed that contained information on the vertical ozone distribution. The key findings of the Panel are:

1. There is undisputed observational evidence that the atmospheric concentrations of source gases important in controlling stratospheric ozone levels (CFCs, halons, methane, nitrous oxide, and carbon dioxide) continue to increase on a global scale as a result of human activities.

2. Calculations using two-dimensional photochemical models predict that between 1969 and 1986 increasing atmospheric concentrations of trace gases would have caused decreases in ozone levels ranging from 0.5% to 1.0% in summer and 0.8% to 2.0% in winter, in the Northern Hemisphere between 30 and 60 degrees latitude.
3. Analysis of data from ground-based Dobson instruments, allowing for the effects of natural geophysical variability, shows measurable decreases from 1969 to 1986 in the annual average of total column ozone ranging from 1.7% to 3.0%, between Northern Hemisphere latitudes of 30 and 63 degrees. The decreases are most pronounced in winter, ranging from 2.3% to 6.2% averaged for December through March. Dobson data are not adequate to determine total column ozone changes in the tropics, subtropics, or Southern Hemisphere outside Antarctica.
4. The model calculations are broadly consistent with the observed changes in column ozone, except that the mean decreases at middle and high latitudes in winter are larger than predicted. The observed changes may be due wholly, or in part, to the increased atmospheric abundance of trace gases, primarily CFCs.
5. The Solar Backscatter Ultraviolet (SBUV) and Total Ozone Mapping Spectrometer (TOMS) instruments aboard Nimbus-7 have provided continuous global records of total column ozone since October 1978. Due to instrument degradation, however, the data archived as of 1987 cannot be used alone to derive reliable trends in global ozone.
6. The SBUV and TOMS data have been normalized by comparison with nearly coincident ground-based Dobson measurements in the Northern Hemisphere. The resulting column ozone data, averaged between latitudes 53 degrees south and 53 degrees north, shows a decrease of about 2.5% from October 1978 to October 1985, approximately coincident with the decrease in solar activity from the maximum to the minimum in the sunspot cycle.
7. Theoretical calculations predict that the total column ozone would decrease from solar maximum to solar minimum by an amount varying from 0.7% to 2%, depending on the model assumed for solar ultraviolet variability. Thus, the observed decrease in ozone from the satellite data between late 1978 and late 1985 is predicted to have a significant contribution from the decrease in solar activity during this period.
8. Theoretical calculations predict that local ozone concentrations near 40 km altitude should have decreased between 1979 and 1985 by 5 to 12% in response to the decrease in solar ultraviolet output and the increased atmospheric abundance of trace gases. This range represents the decreases predicted from the different models for the latitudes 30 to 60 degrees north for all seasons.
9. Analyses of satellite (SAGE) and ground-based (Umkehr) data taken since 1979 show small decreases in ozone concentrations; these decreases peak near 40 km altitude with mean values of 3% and 9%, respectively. These observational values agree within the range of their errors.
10. Stratospheric temperatures between 45 and 55 km altitude have decreased globally by about 1.7°K since 1979, consistent with decreases in upper stratospheric ozone of less than 10%.
11. Thus, this assessment does not support the previous reports based on SBUV and TOMS data of large global increases since 1979 in the total column of ozone (about 1% per year) or in the ozone concentration near 50 km altitude (about 3% a year). These reports used data archived as of 1987, and the trends obtained were erroneously large because of unjustified and incorrect assumptions about the degradation of the diffuser plate common to both the SBUV and TOMS satellite instruments.
12. There has been a large, sudden, unexpected decrease in the abundance of springtime Antarctic ozone over the last decade. Ozone decreases of more than 50% in the total column and 95% locally between 15 and 20 km have been observed.
13. Total column ozone in the austral spring of 1987 at all latitudes south of 60 degrees south was the lowest since measurements began 30 years ago.
14. In 1987 a region of low column ozone over Antarctica lasted until late November or early December, which is the longest since the region of low ozone was first detected.
15. While the column ozone depletion is the largest in the Antarctic springtime, ozone appears to have decreased since 1979 by 5% or more at all

latitudes south of 60 degrees south throughout the year.

16. The unique meteorology during winter and spring over Antarctica sets up the special conditions of an isolated air mass (polar vortex) with cold temperatures required for the observed perturbed chemical composition.

17. The weight of evidence strongly indicates that man-made chlorine species are primarily responsible for the observed decrease in ozone within the polar vortex.

Current Activities

Atmospheric Chemistry Program activities fall into four broad categories: field measurements, laboratory studies, theoretical studies, and data analysis. In addition, every 2 years legislation requires an assessment of the state of the stratosphere and our knowledge and predictions about its future condition.

Field Measurements

The major thrust of both branches of the Atmospheric Chemistry Program—the Upper Atmosphere Research Program and the Tropospheric Chemistry Program—lies with field experiments. The Tropospheric Chemistry Program is currently focusing on the GTE series of experiments, consisting of the Atmospheric Boundary Layer Experiments (GTE/ABLE) and Chemical Instrumentation Test and Evaluation (GTE/CITE) projects. The projects aimed at developing and validating required new instruments are done concurrently with field measurement projects that utilize existing, proven instruments. Both types of projects are used to study atmospheric chemistry in environments of prime scientific interest, such as the tropics, agricultural wetlands, and the interface between the stratosphere and troposphere.

The Upper Atmosphere Research Program uses both in situ and remote-sensing techniques with ground-based instruments, aircraft, balloons, rocket platforms, and satellites. For example, the Atmospheric Trace Molecules Observed by Spectroscopy (ATMOS) investigation, based aboard a 1985 Space Shuttle, has provided a wealth of spectroscopic data that will be used to calculate the concentrations and distributions of more than 40 constituents of the upper atmosphere. The complex analysis and interpretation of these measurements is nearing completion and the entire data base will be archived in the National Space Science Data Center (NSSDC) at NASA's Goddard Space Flight Center.

A recent workshop dealt with how to make long-term measurements of ozone and other species from the ground as a validation of our models and as an early detection of stratospheric changes. Experts in modeling, data analysis, and atmospheric measurements evaluated which would be the most critical tests and which the most satisfactory techniques, as well as how to coordinate a measurement strategy. Also examined were the number of stations needed for a system to detect changes in the stratosphere, using many of the new techniques that have been developed over the last 10 years.

Atmospheric dynamics studies are continuing. These include: (1) studying the exchange of air between the troposphere and stratosphere using aircraft, and (2) studying turbulence and gravity wave phenomena using ground-based radar. In this regard, the Stratosphere-Troposphere Exchange Project (STEP) has utilized NASA aircraft measurement platforms to investigate this irreversible transfer of gases and aerosols from the troposphere to the stratosphere and to explain the extreme dryness of the stratosphere. The final mission under this project was completed in early 1987; data analysis from the many instruments is underway.

In August-November 1986 and 1987, the Upper Atmosphere Research Program co-sponsored ground-based atmospheric monitoring expeditions to Antarctica. The second of these expeditions coincided with NASA's Airborne Antarctic Ozone Experiment (co-sponsored with the NSF, NOAA, and the Chemical Manufacturers Association) described above, which used the NASA DC-8 and ER-2 aircraft as measurement platforms. Key measurements of a number of atmospheric constituents and parameters were made in an effort to explain the occurrence and deepening of the Antarctic ozone hole that has appeared during the polar spring for the past decade. When the data analysis from the composite set of experiments is completed, we hope to be in a better position to advance the chemical or dynamical theories that will explain this phenomenon.

Laboratory Studies

Under controlled conditions of temperature and pressure, studies are carried out on such topics as chemical kinetics and spectroscopy. These laboratory studies provide the basic input data for our computer models. The studies in spectroscopy and chemical kinetics are relevant to the interpretation of atmospheric measurements and to theoretical simulations of the atmosphere.

Other study areas include photochemistry and the development of calibration standards.

A comprehensive program of spectroscopic studies in the ultraviolet, infrared, and microwave regions supports the field measurements program. These studies should also improve accuracy in calculating the penetration of solar radiation through the atmosphere.

A number of laboratory kinetics and photochemical studies are currently underway. Important new data have been obtained on NO_3, HO_2, and $ClONO_2$ reactions. We have also confirmed the recent significant revisions in rate coefficients for the key reactions O + ClO and OH + HCl. We now know more under stratospheric conditions about reaction rates that strongly affect the hydroxyl radical concentration, such as OH + HNO_3 and OH + HO_2. Important investigations of the coupling between the ClO_x and BrO_x reaction cycles (particularly the reaction between ClO and BrO) are also being conducted. Most recently, the role of heterogeneous chemistry in the stratosphere has been given serious attention because polar stratospheric clouds may possibly be involved in development of the Antarctic ozone hole. Studies are also underway to examine the rate of formation, absorption spectrum, and photolytic decomposition of the ClO dimer, which may be an important role player in the chemically perturbed Antarctic stratosphere.

Instrument Development

The space-based instruments now available have very promising potential for upper atmospheric research, including the ability to determine the profiles of atmospheric species by observation of the absorption of infrared solar radiation as it passes through the atmosphere. However, we still need to examine the available instrumentation and identify, with the assistance of modeling experts, where gaps exist in our measuring capability.

Measuring gases and trace species in the troposphere presents severe difficulties because of the instrument sensitivity required. The most important chemical species involved in global biogeochemical cycles need instruments capable of operating in the parts per trillion range (for NO_x) and parts per quadrillion range (for HO_x) against the natural atmospheric background. In addition, the in situ instruments must function reliably on aircraft and/or at complex ground sites as diverse as the Amazon tropical rain forest and the Arctic tundra. For boundary layer experiments, a time response of 10-20 Hz is required to make flux measurements. For experiments on troposphere/stratosphere exchange, a time response of 1-2 Hz is required.

We have determined from workshop studies that the most important achievable space-based measurement for the near term is a gas cell radiometer that can provide a global map of CO concentration at three different altitude levels instead of at the single level already achieved by the MAPS instrument aboard the Shuttle. For ground-based and aircraft measurements of H_xO_y species—tropospheric species that are the toughest to measure but are the key reactive intermediaries in most chemical cycles controlling atmospheric composition—the most promising tools for measuring OH and HO_2 are laser-induced fluorescence systems and long-path absorption, possibly combined with global-scale chemical techniques that would use small quantities of reactive tracers released into the atmosphere. In early FY 1987 a workshop was held at the Goddard Institute for Space Studies (GISS) on the subject of flux measurement technology, and results are expected to be available in early FY 1989.

As a major emphasis, we are currently developing second-generation OH and HO_2 detection instruments that should have sufficient sensitivity to make global measurements from aircraft. Other projects being supported address the following development needs:

- Other H_xO_y species measurements
- Improved NO_x measurement capabilities
- Ammonia and nitric acid measurement techniques
- Fast flux detectors for CO, NO, and O_3
- Use of differential absorption lidar in the ultraviolet to measure ozone and aerosol profiles

Theoretical Studies

We have a comprehensive program of theoretical studies, using one-, two-, and three-dimensional models in support of our other activities that study dynamical processes. Our models form the backbone of any assessment and help guide the experimental portions of the program, such as instrument design. Models provide a framework for analyzing measurements of the atmosphere and also allow us to calculate processes and chemicals that often cannot be measured because of their short life or small concentration.

In the past, our prediction of stratospheric ozone depletion depended on one-dimensional models of the atmosphere. These contain considerable chemical and radiative detail but do not include dynamical effects. Also, these models highly parameterize the vertical dimensions but cannot give horizontal definitions, averaging the atmospheric levels like the layers of an onion.

One-dimensional models are still useful to us but no new investments are being made in this type of model.

Our workhorse tool for stratospheric predictions is now the two-dimensional theoretical model, which we are working to improve as a core prediction tool.

Based on the simple, original model in the 1950s of a four-reaction cycle, which did not work, we have added a succession of chemical species to our models—oxygen, hydrogen, nitrogen, and chlorine and sulfur species. We are now fairly confident that all major chemical species are included in our models.

Our two-dimensional models add the equator-to-pole latitude dimension, averaging around longitudes, which allows for seasonal effects and a realistic treatment of the dynamics in the atmosphere. This is extremely important for climate prediction, because it can reflect the tropical air masses moving into the stratosphere and coming down at the poles, meaning that ozone-depleted air in the higher altitudes is being directly carried into the pole regions.

A very substantial investment is currently being made in the development of three-dimensional models. This effort involves relatively large groups of researchers who are attempting to develop three-dimensional models into the most fully predictive tools possible. The new three-dimensional models will be general circulation models for both the troposphere and stratosphere, providing detailed treatment of the dynamics and radiation in the atmosphere. The treatment of chemistry will be highly parameterized. It should be noted that observed depletion of Antarctic ozone during the polar spring is an occurrence which was not predicted nor can be adequately explained by current atmospheric models based on homogeneous chemistry. Significant progress in this area is expected over the next few years.

Modeling and Data Analysis

We want to identify key areas of uncertainty in the understanding of tropospheric chemistry and transport, to develop measurement requirements for field investigations, and to help develop optimal global sampling strategies for our field measurement projects. Our current models are becoming more sophisticated in their treatment of meteorological and source/sink processes.

We are developing and refining one- and two-dimensional photochemical models with parameterized transport as an aid in field experiment design and data analysis. Also underway is the inclusion of atmospheric chemistry into a general circulation model. The resultant model will allow calculations of the large-scale dynamical processes that transport reacting and nonreacting atmospheric chemical species through the atmosphere. The model will eventually include treatments of such processes as chemistry inside clouds and the role of cloud chemistry in transporting chemicals through the atmosphere.

Data analysis, especially of large satellite data sets, is and will continue to be a major activity. Our efforts include: (1) satellite data analysis, involving comparison of satellite measurements with all models in order to explain the data, and (2) cohesive data analysis, such as the Global Gases Experiment, where all the available data need to be assessed, involving comparison of large ground-based measurements with satellite data. Large-scale data systems are required for these types of analyses, especially those involving satellite data.

Our knowledge of stratospheric O_x, HO_x, and NO_x is being greatly expanded by the recent availability of several large validated data sets. These include the Limb Infrared Monitor of the Stratosphere (LIMS), Stratospheric and Mesospheric Sounder (SAMS), and the SBUV/TOMS instruments on the Nimbus-7 satellite, and the SAGE instrument on the AEM-2 satellite. For example, from the second SAGE, launched in 1984, the trace species and temperature data are proving extremely useful for global models and for testing certain facets of our theories about coupling between chemistry, dynamics, and energetics.

The data from a series of international intercomparison campaigns are currently in the final analytical stages. The results are proving the accuracy of our current measurements for ozone, nitrogen dioxide, and other gases. The campaigns being analyzed include the following:

- A series of three campaigns to measure ozone, employing both in situ and remote-sensing balloon and rocket-borne instruments
- Two campaigns to measure several key atmospheric constituents including HNO_3, NO_2, NO, HCl, HF, O_3, H_2O, CH_4, and OH. The campaigns utilized eight different techniques on 31 remote-sensing balloon-borne instruments, such as grating spectrometers, radiometers, and Fourier transform interferometers. The sensors used the visible, infrared, far-infrared, and microwave regions of the electromagnetic spectrum in both the absorption and emission modes.
- Three campaigns to measure water vapor, which employed in situ and remote-sensing balloon-borne instruments.

Plans for FY 1988 and FY 1989

To track atmospheric changes in the period before the Upper Atmosphere Research Satellite (UARS) is launched, the UARP expects to carry out a series of measurements of limited duration from airborne and balloon instruments. Activities that will set the stage for the use of UARS data are also planned for the near term.

With the UARS Observatory, due for launch aboard the Shuttle in 1991, we hope to have an extended mission providing, for the first time, a long-term set of measurements on how the stratosphere is changing. UARS will give us a 6-month detailed "movie" of how the three-dimensional stratosphere works chemically. Its key focus will be to elucidate the coupling of chemical, radiative, and dynamical processes, as well as to examine diurnal variations to a degree never before achieved. The extensive data base, now in the planning stage, will allow study of the mechanisms of atmospheric variability and the response of the upper atmosphere to such external factors as solar activity. We also plan to develop passive and active remote sensors for the UARS.These sensors will also have Space Shuttle applications.

The extensive analysis of the data taken during the recently completed STEP missions will continue throughout the next year. These results will underlie the further testing and development of theories regarding troposphere-stratosphere transport and hypotheses for stratospheric dehydration.

A highly accelerated program of data reduction and analysis has been undertaken by the participants in the 1987 Airborne Antarctic Ozone Experiment. The interpretation of the extensive body of meteorological and chemical data was completed in late spring of 1988. In May, a Polar Ozone Symposium was held in Snowmass, Colorado, where members of the international scientific community had access to the most recent field and laboratory results. It was decided to undertake a major Arctic effort, similar to the 1987 Airborne Antarctic Ozone Experiment, based in Stavanger, Norway, in January or February 1989.

During this time period we also plan to begin implementation of a ground-based Network for the Detection of Stratospheric Change. This long-term measuring network will be designed to provide the earliest possible detection of changes in the composition and structure of the stratosphere, the means to understand the causes of those changes, and the ability to predict the future results of these changes. We are now able to identify places in the atmosphere where ozone changes can be expected to occur first. For example, depletion of ozone by stratospheric chlorine is predicted to first be evident as a loss of ozone near 40 km long before any detectable change in the column abundance of ozone itself.

A high level of instrument precision is needed when looking for early warning signs of ozone depletion in the upper atmosphere, because the expected depletion is only a few percent. We need both to determine the long-term changes and to separate these true changes from the daily or weekly variations and from variations within the measuring instruments. Although this proposed network is intended for long-term trend detection, it will provide extremely valuable scientific returns in the near future. It will enable us to study the temporal (diurnal, monthly, seasonal, and annual) and spatial (latitudinal) variability of atmospheric composition and structure. It will also provide the basis for ground-truth and complementary measurements for satellite systems. The instrumentation and technology to accomplish the systematic measurements for such early detection are for the most part available. Decisions will be made on instrument selection, site selection and management, and calibration and data quality control, to name just a few. The success of this network will require a high level of interaction and cooperation among several agencies within the U.S. Government as well as participation of the global scientific community.

Based on the in-depth analysis of the results from both the aircraft and ground-based 1987 Antarctic ozone expeditions, a decision will be made regarding the need for and scheduling of future Antarctic measurement campaigns. As a result of the findings of the Ozone Trends Panel, an aircraft and ground-based Arctic ozone campaign, similar in scope to the Antarctic campaign, will be conducted from Norway in January and February, 1989.

The Tropospheric Chemistry Program's GTE/ABLE-2 field experiment completed in 1987 was the second in a series of missions to study key atmospheric gas source regions and their coupling into the boundary layer of the troposphere. A third experiment in this series, GTE/ABLE-3, with the Electra aircraft and a ground-based experiment component, has been designed to understand how chemicals emitted from high latitudes and wetlands find their way into the upper troposphere, and thence to the global atmosphere. A mission to Alaska (GTE/ABLE-3A) was conducted during the summer of 1988. A second mission (GTE/ABLE-3B) is planned in northern Canada during the summer of 1990.

The GTE/ABLE-3 experiments are aimed at source and sink questions and will include fast flux measurements within the boundary layer. The experiments include coordinated ground-based and aircraft measurements. We will obtain quantitative information about the sources and sinks for important trace gases and aerosols located at high northern latitudes.

For FY 1989 and beyond, we are currently planning several field experiments in different global regions. A third GTE/CITE experiment will be conducted to assess the effectiveness of various techniques for measuring the sulfur species that are important in the global sulfur budget. In addition, a DC-8 based experiment, now in the planning stages, will explore the effects of the Walker circulation on the distribution of trace gases over the Atlantic and Pacific Oceans.

Future Projections

These research activities are multiyear efforts aimed at reducing some of the current uncertainties in our scientific understanding of upper atmospheric composition and change. Thus, the balanced research program of field measurements, laboratory studies, theoretical studies, and data interpretation will continue at the same level in the near future. For the long term, we are particularly concerned about providing continuous data sets of the upper atmosphere and about being able to detect and provide early warning of ozone change.

In terms of data sets, we are now looking toward the post-UARS time period. Our emphasis is on establishing long-term, satellite-based data comparable to the currently available ground-based data. It is extremely important that the data sets begun by UARS be extended continuously after the UARS mission ends; such continuity can be provided by means of instruments that will be flown on Eos.

Our present ongoing measurements come from an instrument that measures upper stratospheric ozone on a NOAA weather satellite—the Solar Backscatter Ultraviolet (SBUV) ozone monitor. We plan to develop a similar unit for flight on the Shuttle to perform a consistency check of this instrument at 1-year intervals. This check will permit a periodic, sensitive calibration of NOAA's SBUV instrument.

Other specific thrusts now planned for the future include the following:

- Continuation of a balanced program of in situ and remote-sensing measurements of atmospheric constituents from balloon-borne platforms; increased emphasis on multisensor platforms to perform intercomparisons and to obtain comprehensive data sets
- Development of a satellite ground-truth program, based on a ground-based program of regular Dobson and automated Umkehr Dobson measurements, together with a three-station, balloon-based sampling program
- Studies of the chemical composition of the lower stratosphere, with increased effort to measure the reservoir species recently detected by the Shuttle-borne ATMOS instruments, such as $ClONO_2$, HO_2NO_2, and N_2O_5
- An accurate assessment of the budget and partitioning of the odd hydrogen, nitrogen, and chlorine families
- Flux studies of source gases from key ecosystems
- Application of ground-based lidar and microwave techniques to determine stratospheric structure and composition
- Use of MST radar systems to study the dynamical processes in the stratosphere

Future plans for the Tropospheric Chemistry Program respond to the research directions indicated by the National Research Council (NRC) report, *Global Tropospheric Chemistry: A Plan for Action*. This report proposes a major new national and international program in global tropospheric chemistry and is the culmination of a comprehensive study by the NRC Board on Atmospheric Science and Climate. NASA's recommended role in this proposed program is significant: (1) development of a space component and remote-sensing instruments, and (2) utilization of NASA facilities and management capabilities for large-scale field experiments, of which GTE/CITE and GTE/ABLE are ongoing examples.

To carry out the proposed global tropospheric plan, certain preliminary steps must be taken. We are making progress on these steps, which include:

- Continued instrument development, particularly focused on the design, testing, and intercomparison of high-sensitivity instruments for studying chemical composition
- Field experiments focusing on source/sink studies, boundary layer/ free troposphere interchange, and troposphere/stratosphere exchange
- Modeling studies with emphasis initially on diagnostic tools and measurement strategy development and later on data analysis and trend forecasting

10
Applications Activities

Significant progress has been made in space technology in the 29 years since the first civil satellite was launched. Today's enhanced remote-sensing capabilities have led to the development of new perspectives on the very complex interactions of air, oceans and land. While satellite observations play a routine role in weather forecasting today, their potential application to a host of practical concerns has as yet barely been tapped. The realization of the value of remote sensing to such issues as land management, climate forecasting, ocean resource development and management, marine operations, urban planning, crop and forest yield predictions, oil and mineral development and the monitoring of the desertification process has only just begun.

Over the past 3 years we have been reassessing NASA's involvement in the application of remote sensing for such social and economic benefit as it relates to our basic Earth system science research. The development of a long-term applications strategy and plan for the Earth Science and Applications Division (ESAD), the release in August 1987 of a NASA Research Announcement soliciting remote-sensing applications/ commercialization proposals, and the formation of a collaborative research and technology development program between ESAD and the Office of Commercial Programs (OCP) represent significant steps in our program of applications planning activities.

A major milestone was reached in March 1988 when 20 winning proposals were announced, in response to the previous year's solicitation, on projects ranging from the application of remote sensing to wildlife habitat characterization and management in forest regions to the commercial development of an Ice Data and Forecasting System (IDFS) for oil, gas and related arctic-based shipping activities. Other projects being funded include the application of geographic information systems by scientists from the U.S. Geological Survey (USGS) and the U.S. Forest Service (USFS) to the assessment of landslide hazards over large areas; the investigation of the role of remote sensing for micro-seepage detection and, by implication, for oil and gas exploration; enhanced potato production techniques through regular high-resolution monitoring of experimental farms; and the use of integrated satellite sea surface temperature (SST) and ocean color scanner (OCS) data to locate fish populations and develop an Optimum Track Ship Routing (OTSR) system, based on a knowledge of major ocean currents. A complete list of funded projects is provided in Table 10-1.

Proposals have been supported from industry, government, universities, and NASA centers, concentrating on applications of data available from existing sensors (spaceborne and airborne prototypes). We particularly encouraged teaming arrangements among industry, universities, and government with an intent of evolving the research towards operational or commercially viable products within 3 years.

NASA's applications projects are funded jointly by ESAD and OCP. In addition, each proposing team has brought a large portion of its own resources to bear on the planning and implementation of their project. A collaborative approach between ESAD and OCP has been established to implement remote-sensing applications/ commercialization endeavors, and the scope of activities, associated resources, implementation plan, and management interfaces has been solidified to:

- Provide operational users with access to advances in remote-sensing techniques and technologies that can improve their services
- Stimulate broader use of remote-sensing technology by communicating information about NASA's Earth science program to the user community
- Gain feedback from the operational community regarding its needs and use this information to focus future program planning
- Emphasize joint public/private sector projects to which teams have been willing to commit their own technical/scientific and financial resources
- Stress a remote-sensing applications program for the near-term

TABLE 10-1. **REMOTE SENSING APPLICATIONS/COMMERCIALIZATION PROGRAM**

Project Title	Principal Investigator	Affiliation
Detection of Seasonal and Annual Changes in Migratory Waterfowl Habitats in the Central Valley of California	Dr. David S. Gilmer	USDA-Fish & Wildlife Service, CA
Applications of Remote Sensing for Landslide Hazard Assessment	Dr. Leonard Gaydos	NASA Ames Research Center and USGS, CA
Development of Practical, Cost Effective Methods Utilizing Satellite Data for Forest Resources Management	Dr. Mark Jadkowski	James W. Sewall Company, ME
Use of Spectral Resolution Imaging Techniques for the Detection of Surface Alternation Effects Associated with Hydrocarbon Reservoirs	Dr. Mark Settle	ARCO Oil & Gas, TX
Commercial Development of an Ice Data and Forecasting System (IDFS)	Mr. A. George Mourad	Batelle Columbus Division, OH
Development of Application of Remote Sensing of Longwave Heating from TIROS Operational Sounder (TOVS)	Dr. Robert G. Ellingson	University of Maryland, MD
An Evaluation of Current, and Recommendations for Future, Uses of Remotely Sensed Data for Commercial Forest Inventory	Dr. Gregory S. Biging	University of California, Berkeley, CA
Application of the Airborne Color Imager for Commercial Fishing	Mr. Robert C. Wrigley	ARC, CA
Compiling and Editing Area Sampling Frames Using Digital Data for Land Use Analysis and Boundary Definition	Mr. George Hanuschak	USDA, D.C.
Application of Remote-Sensing and Image-Processing Technologies: Sediment Transport and Land-Loss Processes, Coastal Louisiana	Dr. Harry H. Roberts	Louisiana State University, LA
An Environmental and Archeological Assessment of the Piedras Negras Region of Guatemala and Mexico	Dr. Tom Sever	Middle Tennessee State University, TN
Automated Satellite-Based Alarms: A Proposal to Develop & Operate a Satellite Based Fire Detection & Monitoring Program for Western U.S.	Dr. David A. Hastings	NOAA/NGDC, CO
Commercial Environmental Sensitivity Index (ESI) Mapping Using Remote-Sensing and GIS Technology	Mr. Basil Savitsky	RPI International, Inc., S.C.
Locating Subsurface Gravel Deposits with Thermal Imagery	Mr. Douglas E. Scholen	USDA Forest SErvice, GA
Efficient Updates of Vector-Coded Geographic Information Systems Using Remotely-Sensed Data	Dr. Douglas A. Stow	San Diego State University, CA
Applying Remote-Sensing and GIS Techniques in Solving Rural County Information Needs	Dr. Chris J. Johannsen	Purdue Research Foundation, TN
Satellite Inventory of Minnesota Forest Resources	Dr. Marvin E. Bauer	University of Minnesota, MN
Using Landsat to Provide Potato Production Estimates to Columbia Basin Farmers and Processors	Mr. Frank G. Lamb	Cropix, Inc., OR
Geographic Information Analysis: An Ecological Approach for the Management of Wildlife on the Forested Landscape	Dr. William J. Ripple	Oregon State University, OR
Algorithm Development for an Integrated Satellite APT* and Ocean Color Scanner Receive/Process/Display System for Ocean-Going Vessels	Dr. Kenneth W. Ruggles	Systems West, Inc., CA

*APT—Automatic Picture Transmission

OCP will use its established mechanisms to select and assist Centers for Commercial Development of Space (CCDS), as well as to facilitate and implement commercial entrepreneurial projects. The ESAD element of the program will concentrate on providing basic research and development with a focus on helping the community evolve towards operational or commercial viability.

In addition to the applications/commercialization program activities currently underway, we are also continuing to work with OCP to ensure compatible and consistent approaches to the private sector. OCP is now funding the Space Remote-Sensing Center at the Institute for Technology Development in Bay St. Louis, Mississippi, and the Center for Real-time Satellite Mapping at Ohio State University, Columbus, Ohio. ESAD is implementing a staff reorganization with the appointment of an Applications Program Manager which will provide the visibility and cross-fertilization which this activity certainly deserves.

Background

The first step in defining our role in relation to the applications community was taken in June 1986, when the Remote Sensing Subcommittee of NASA's Space Applications Advisory Committee (SAAC) drafted a set of goals, assumptions, and objectives to be used in developing a long-range remote-sensing applications plan. The framework formulated by SAAC served as the basis for a strategic approach developed by the Applications Working Group—a group of experts from the user, academic and science communities—who were invited by NASA to participate in a week-long applications workshop in August 1986.

The outcome of the workshop was a two-part report entitled *Linking Remote-Sensing Technology and Global Needs: A Strategic Vision*. The methodology used by the Working Group was to develop a long-range strategic goal for guiding NASA's applications program and then to define the technical steps necessary for achieving this goal. The near-term research objectives selected by the Working Group and presented in the report are examples of needed, high-priority applications research. Part I of the report, the Executive Summary, was delivered to NASA and SAAC by the Applications Working Group chairman in February 1987 and published in April. The Full Report, Part II, was published in June 1987.

The Applications Working Group report represents a strategic approach rather than a complete plan. The SAAC Remote Sensing Subcommittee is expected to review the Working Group strategy, using it as a resource for developing a long-term strategic plan for NASA's applications program. SAAC's strategic plan will be forwarded to Congress in response to their directive in the FY 1984 Authorization Act. That legislation requested NASA to develop an applications program strategy and plan "to ensure that the Nation is investing sufficiently and wisely" in this important area.

11
Airborne Science and Applications Programs

Research aircraft have a long history of contributing to advances in atmospheric, oceanic and terrestrial geosciences. Much of the recent rapid increase in mankind's understanding of the environment would not have been possible without these aircraft and their inherent three-dimensional maneuverability and ability to complement other types of environmental observations.

Observational Methods

In Situ Observations

This most traditional use of research aircraft has set the pace for progress in several areas of the atmospheric sciences: air flow dynamics, air chemistry, radiation and cloud/aerosol physics, and air pollution. The capability of conveying a variety of sensors to critical parts of the atmosphere has allowed fundamental discoveries concerning how physical quantities are correlated in stormy and quiescent conditions. Such observations can be compared with data from surface-based or satellite-borne remote sensors. The aircraft may measure the same quantity as the remote device, thus providing a calibration of remote-sensing technology, or it may measure quantities which cannot be determined remotely, thus allowing a correlation between in situ and remotely sensed variables.

Deployable Sensors

In the atmosphere, the dropwindsonde has provided information on the structure of storms at sea. In oceanography, surface buoys and expendable bathythermographs dropped from aircraft provide both surface and subsurface data. Land-based instruments may also be deployed from aircraft into remote continental regions.

Remote Observations

The aircraft's ability to carry sophisticated remote-sensing instruments to the region of interest, for a carefully planned study or for a quick observation of newly developed phenomena such as a storm, a volcano, or drought-stricken crops, together with its ability to remain on station for several hours, makes it an ideal platform for gathering scientific data. The range of application includes all domains: the atmosphere, land surface, ocean, and ice. Imaging radar, imaging visible infrared and thermal spectroscopy provide information about the land-surface composition and structure in terms of rock, soil and vegetation. Both ocean and land biological productivity can be determined from airborne sensors, and ocean-surface temperature, wave roughness, and ice thickness can be mapped quickly over large areas of remote seas. In the atmosphere, airborne lidar and radar are beginning to provide a more detailed picture of storm cloud and boundary layer structure. In addition, airborne spectroscopy is providing information on trace gas and particle concentrations at altitudes above the aircraft.

An extension of this activity is the use of aircraft for the development of remote sensors which will later be placed on orbiting satellites. Like the satellite, airborne instruments can look down on the atmosphere, ocean, and land from a great height; but, unlike its satellite-borne successor, the airborne instrument is readily available for modification. Virtually all the satellite-borne sensors used in achieving the recent rapid progress in the geosciences were developed first as airborne instruments.

When viewed together, the portion of our environment which can be investigated with research aircraft is very large. The observable phenomena, in descending order of altitude, include:

- Low stratosphere chemistry and dynamics
- Tropopause and jet stream mixing processes

- Free-troposphere storms and clear air dynamics and chemistry
- Boundary layer turbulence and chemistry
- Land surface structure and composition, temperature, roughness, thermal inertia and moisture
- Ocean and lake surface chemistry, biology, temperature, color, and wave activity
- Ocean subsurface hydrographic thermal structure and currents

These applications are constrained only by the limits on aircraft altitude and range capability, and the in situ or remote-sensing technology.

The geographical domain is similarly great. A variety of processes from pole to equator have been studied:

- High-latitude studies (arctic haze layer, sea and land ice, polar cyclones, Antarctic ozone hole, boreal forest, permafrost, and other ecosystems, regional tectonics, volcanism, and geomorphology)
- Mid-latitude studies (soil moisture, polluted boundary layers, severe convective storms, ocean currents and eddies, ocean productivity, forest ecosystems, land-atmosphere interaction)
- Subtropical studies (ocean wind stress, hurricane structure, forest ecosystems)
- Equatorial studies (equatorial ocean currents, rain forest ecosystems, moisture fluxes)
- Transaltitudinal studies of tectonic and geomorphic processes, volcanology, and geologic history

At present, several aircraft are provided by three NASA centers to support Earth science. The objectives of this activity are to:

- Conduct in situ and remote measurements for research in Earth observations
- Develop and simulate instruments for Shuttle and free-flying spacecraft
- Underfly Shuttle and free-flying spacecraft sensors to acquire "verification" and calibration data

Current Aircraft Status and Activities

ESAD research programs are supported by three types of aircraft flown from Ames Research Center and by five types of aircraft operated by Goddard Space Flight Center's facility at Wallops Island, Virginia. Table 11-1 provides a list of these aircraft and their operational characteristics. In addition to these, the National Space Technology Laboratories (NSTL) operates a Lear Jet in support of ESAD programs. Activities planned for each of the research aircraft are described in the following paragraphs. Table 11-2 lists major airborne Earth science investigations planned for FY 1988 through FY 1991. Instruments presently flown and those planned requiring support from the NASA Airborne Science and Applications Program from FY 1988 to FY 1992 are listed in Table 11-3.

Lockheed ER-2

The ESAD supports two ER-2 aircraft. These high-altitude instrument platforms accommodate an exten-

TABLE 11-1. **RESEARCH AIRCRAFT TYPICAL PERFORMANCE CHARACTERISTICS**

Aircraft	Manufacturer	Model	Altitude (Feet)	Range (Miles)	Endurance (Hours)	Payload Weight	Payload Power	Agency
ER-2 (2)	Lockheed		70,000	3,200	7.0	2,700		NASA/ARC
C-130	Lockheed	NC-130B	24,000	2,000	7.0	20,000	26.0 kW+	NASA/ARC
DC-8	MACDAC	72	40,000	6,000	12.0	30,000	80.0 kW	NASA/ARC
Electra	Lockheed	L-188	25,000	2,000	7.5	19,000	40.0 kW	NASA/WFF
P-3 Orion	Lockheed	P-3A	25,000	2,000	7.5	13,600	33.0 kW	NASA/WFF
Skyvan	Short Bros	SC-7	15,000	650	4.0	5,000	2.8 kW	NASA/WFF
Sabreliner	Rockwell	T-39	41,000	1,400	3.25	1,500	3.0 kW	NASA/WFF
Helicopter	Bell	UH-1B	10,000			2,000	3.5 kW	NASA/WFF
Lear Jet	Gates Lear Jet	23-049	41,000	1,000	3.0	750	4.0 kW	NASA/NSTL

NOTE: Please note that aircraft performance values vary with payload, altitude, air temperature, type of mission, weather conditions, etc. For more details on specific capabilities, please contact the aircraft facility manager for the pertinent agency as listed below:

NASA/ARC: Earl Peterson (415) 694-6092; NASA/WFF: David Roberts (804) 824-1541: NASA/NSTL: Kenneth D. Cashion (601) 688-1930

TABLE 11-2. **INSTRUMENTATION THRUSTS IN NASA AIRBORNE SCIENCE**

Aircraft	Instrument	Discipline	Future Flight Availability
ER-2	Advanced Microwave Precipitation Radiometer (AMPR)	Atmosphere	FY 89
	Advanced Visible-IR Imaging Spectrometer (AVIRIS)	Land	FY 88
	High Resolution Interferometer Spectrometer (HRIS)	Atmosphere	FY 89
	Lightning Research Pallet	Atmosphere	FY 90
	Microwave Precipitation Radiometer (MPR)	Atmosphere	FY 89
	Thermal Infrared Multispectral Scanner (TIMS)	Land	FY 88
DC-8	Aerosol Sampling Probes	Atmosphere	FY 89
	Airborne Doppler Lidar System (ADLS)	Atmosphere	FY 90
	Airborne Rain Mapping Radar (ARMAR)	Atmosphere	FY 91
	CO_2 Backscatter Lidar	Atmosphere	FY 89
	CO_2 Isotope Focused CW Laser	Atmosphere	FY 89
	CO_2 Pulsed Laser	Atmosphere	FY 88
	Synthetic Aperture Radar (C,L,P Bands) (SAR)	Land, Oceans	FY 88
	Visible/Near IR Backscatter Lidar	Atmosphere	FY 89
C-130	C-Band Scatterometer (C-SCAT)	Oceans	FY 89
	KU-Band Scatterometer (KUSCAT)	Oceans	FY 89
	Thermal Infrared Imaging Spectrometer (TISS)	Land	FY 91
ELECTRA	Raman Lidar Moisture Sounder	Atmosphere	FY 91
P-3	Multibeam Radar Altimeter (MR)	Oceans	FY 89
SKYVAN	Geoscience Airborne Laser Altimeter (GALA)	Land	FY 88

Instruments Related to Space Station/EOS

Airborne SAR for Synthetic Aperture Radar
ASAS for Moderate Resolution Imaging Spectrometer
AVIRIS for High Resolution Imaging Spectrometer
TAL-BR for High Resolution Multifrequency Microwave Radiometer
TIMS for Future Thermal Infrared Sensor

sive group of investigator-furnished sensors used for upper atmospheric measurements. Among these are the Cloud Lidar System (CLS), Advanced Microwave Moisture Sensor (AMMS), Microwave Temperature Sounder (MTS), Microwave Cloud Radiometer (MCR), Multispectral Atmospheric Mapping Sensor (MAMS), High Resolution Interferometer Sounder (HIS), Cloud Top Scanner (CTS), and a pallet of 12 lightning sensors. Meteorological sensors planned for the ER-2 include the High Resolution Interferometer Spectrometer (HRIS), the Microwave Precipitation Radiometer (MPR), the Advanced Microwave Precipitation Radiometer (AMPR), and the Lightning Research Package.

The ER-2 is also equipped with a family of remote and in situ sensors used for upper atmospheric research. The platforms also accommodate a complement of sensors maintained by Ames Research Center for observations of the Earth's surface. The latter group includes the 11-channel Daedalus-Thematic Mapping Simulator, a linear array scanner, and photographic systems.

The Airborne Visible Infrared Imaging Spectrometer (AVIRIS) represents a significant milestone in NASA's Imaging Spectrometry Program. It completed its first research flight aboard the ER-2 during FY 1987. (Details of the flight can be found in Chapter 6.) AVIRIS is a fully operational research instrument designed for many years of use, and by simulating HIRIS data, will provide useful handling experience of complex data sets in advance of the Eos era. In FY 1988 AVIRIS replaces the Airborne Imaging Spectrometer (AIS) as the principal operational instrument. AIS is configured to accept a 64 $\times$ 64 array hybrid focal plane and is being used to provide spectrographic data for continued science studies. The ER-2 also flies the Thermal Infrared Multispectral Scanner (TIMS), providing simultaneous collection of AVIRIS and TIMS data.

A new laser instrument, the Lidar (Light Detection and Ranging) ER-2, is being built that will provide very precise control of the signal from the laser and equal precision of the reflected signal. Lidar ER-2 is designed to be a solid-state, fully automatic laser which is fully tunable on the ground between flights. It will be flown on an ER-2 aircraft to demonstrate its ability to measure water vapor in the atmosphere beginning in 1989. Starting in 1991, a modular lidar instrument will begin taking measurements of pressure and temperature with a French wavemometer and a new laser from Goddard Space Flight Center (GSFC).

The major research uses for these aircraft lie in the areas of atmospheric and climate research, mesoscale

TABLE 11-3. **FUTURE THRUSTS IN NASA AIRBORNE EARTH SCIENCE INVESTIGATIONS**

	FY 1988	FY 1989	FY 1990	FY 1991	FY 1992
ATMOSPHERE					
ER-2	FIRE Latitude Surveys	FIRE Latitude Surveys Ozone Hole (Arctic)	FIRE Latitude Surveys	FIRE (TBD) Latitude Surveys Ozone Hole (Antarctic)	(TBD)
DC-8	SAR Surveys (Arctic, Kansas)	Ozone Hole (Arctic) JOPE GLOBE	(TBD)	Ozone Hole (Antarctic)	(TBD)
ELECTRA	ABLE-3A	TRACE-A CITE-3	ABLE-3B CITE-4	(TBD)	(TBD)
OCEANS					
DC-8		Polar Ice Surveys/ SAR (Arctic/Antarctic)	Polar Ice Surveys/ SAR (Antarctic)	Polar Ice Surveys/ SAR Laser Alt. (Antarctic)	Polar Ice Surveys/ SAR Laser Alt. (Antarctic)
P-3	ESMR-SSM/I (Beaufort Sea, Bering Sea) Arctic Ozone Ocean Surveys LIDAR Surveys	ESMR-SSM/I (Svalbard) GOFS MR/Laser Alt. (Greenland)	Laser Alt. (Greenland)	GLRS SWADE (N. Atlantic)	GLRS
C-130		FIFE	FIFE Eos Surveys	FIFE Eos Surveys	Eos Surveys
LAND					
ER-2	AVIRIS Surveys	AVIRIS Surveys MAC-US Comm. Flights	AVIRIS Surveys (Greenland) MAC-Europe Comm. Flights	AVIRIS Surveys Comm. Flights	AVIRIS Surveys
DC-8	SAR Surveys	SAR Surveys MAC-US Comm. Flight	SAR Surveys/ Pre-SIR-C (Greenland) MAC-Europe	SIR-C Underflight	SAR Surveys
C-130	TIMS Surveys	TIMS Surveys Eos Simulation FIFE MAC-US Comm. Flights	TIMS Surveys Eos Simulation MAC-Europe Comm. Flights	TIMS Surveys Eos Simulation Comm. Flights	Eos Simulation
T-39		Laser Alt. Surveys MAC-US	Laser Alt. Surveys	(TBD)	(TBD)
Skyvan	GALA	(TBD)	(TBD)	(TBD)	(TBD)

ABLE — Atmospheric Boundary Layer Experiment
AVIRIS — Airborne Visible/Infrared Imaging Spectrometer
CITE — Chemical Instrumentation Test and Evaluation
Eos — Earth Observing System (Space Station)
ESMR — Electrically Scanning Microwave Radiometer
FIFE — First ISLSCP Field Experiment
FIRE — First ISCCP Regional Experiment
MR — Microwave Radiometer
MAC — Multisensor Aircraft Campaign
SIR-C — Shuttle Imaging Radar-C
Laser Alt — Laser Altimeter
GLOBE — Global Backscatter Experiment
PIS — Polar Ice Surveys
SAR — Synthetic Aperture Radar
SSM/I — Special Sensor Microwave Imager
STEP — Stratospheric—Tropospheric Exchange Project
TRACE — Transport and Chemistry Near the Equator
JOPE — Joint Participation Experiment
SWADE — Surface Wave Dynamics Experiment
GLRS — Geodynamics Laser Ranging & Altimetry System
GOFS — Global Ocean Flux Study
GALA — Geoscience Airborne Laser Altimeter
COMM — Commercialization Flights

processes, land processes, oceanography, life sciences, and sensor development. The ER-2 made significant contributions to the 1987 Antarctic Ozone Experiment. Further ozone experiments, including an Arctic campaign and latitudinal surveys of the chemical composition of the lower stratosphere and an array of land processes investigations, are among the major tasks planned for the next 4 years. These will also include a multitemporal ecosystems analysis, a multisensor aircraft campaign in the U.S. and Europe, and a survey over Greenland.

Lockheed C-130B

A suite of sensors is provided for use on this multipurpose remote-sensing platform; these include an 8-channel Thematic Mapper Simulator, TIMS, 15-cm and 30-cm metric cameras, and an L-band and C-band radar scatterometer. Up to 10 investigators may be present to participate, during a flight, in the data collection. A weather radar, radar altimeter, closed-circuit television, and data acquisition system are provided as general support equipment. Used for hydrological, ecological and geological research, climate research, oceanography, land processes, and sensor development, the C-130 was deployed over Kansas from April to October, 1987, in support of the First ISLSCP (International Satellite Land Surface Climatology Project) Field Experiment (FIFE). FIFE data were collected during four intensive field campaigns which involved both NASA (mainly the C-130, the Gates Lear Jet and the Bell Helicopter) and other aircraft systems, as well as satellite systems, to evaluate the effects of climatic fluctuations on soil and vegetation properties and processes which ultimately influence global energy, water and human resources. The C-130 is supporting geologic, ecologic and hydrologic research, ocean/scatterometer research, wetlands studies and biomass combustion work, as well as other requirements in FY 1988. Other major work planned for the C-130 will be in support of the Earth Observing System and the land processes multisensor aircraft campaigns, both beginning in 1989, and the Surface Wave Dynamics Experiment (SWADE) in 1990. KU-band and C-band scatterometers will be added to the C-130 sensor complement in 1989 in support of ocean research.

McDonnell Douglas DC-8

The DC-8 is being modified to meet NASA's need for a multipurpose flying laboratory. This aircraft has significantly more range and payload than its predecessor, a Convair CV-990. A synthetic aperture radar (SAR) system operating at L-, C-, and P-band wavelengths, multiple look angles, and in all polarization modes has been installed. The P- and L-bands are now fully operational, with the C-band to be available in 1989. Data-gathering flights began in 1988. This aircraft SAR enables the design that will be implemented in the spaceborne SIR-C to be tested and also provides an interim sensor capability for gathering scientific data.

Investigators are also able to use an assortment of general support equipment, including metric and panoramic cameras, a data-recording system, Doppler and weather radars, and a radar altimeter. The first expedition flown by the DC-8 was in support of the Antarctic Ozone Experiment in September-October 1987. New instruments planned for the DC-8 include the CO_2 Isotope Focused CW Laser for the Global Backscatter Experiment (GLOBE), an Airborne Rain Mapping Radar (ARMAR), a Visible/Near Infrared Backscatter Lidar for GLOBE, and Aerosol Sampling Probes for GLOBE. Major expeditions ahead include the Arctic Ozone Experiment (1989) and GLOBE (1989). Major research thrusts with the DC-8 during FY 1989 and early FY 1990 will involve SAR surveys, ERS-1 planning and calibration flights and GLOBE.

Lockheed L-188 Electra

The Electra is currently used to support a major atmospheric science program for NASA called the Global Tropospheric Experiment (GTE). Scientists from several NASA field centers and universities have equipped the aircraft with a suite of 12 instruments designed to investigate in detail the dynamics of tropospheric chemistry over the Amazon jungle. The suite consists of differential absorption lidars, in situ chromatographs, and grab samples that are each keyed to a specific chemical species. GTE Amazon expeditions were completed in 1987 and plans call for several more expeditions to other parts of the globe over the next few years. Other programs include the Chemical Instrumentation Test and Evaluation (CITE), Transport and Chemistry Near the Equator (TRACE), and Atmospheric Boundary Layer Experiment (ABLE).

During the summer of 1987, data obtained from Electra flights were used to support the Stratospheric Aerosol and Gas Experiment (SAGE II) ground-truth program. This research utilizes an upward-looking lidar to measure and map aerosols in the stratosphere while underflying the SAGE II satellite. In July-August 1988, the Electra will fly the ABLE3A mission to the Arctic from Alaska. The Electra has long been configured for development work on a lidar instrument designed to measure atmospheric pressures and temperature below or above the flight track of the aircraft. A Radar Ocean Wave Spectrometer (ROWS) has been flown in the Electra, and a Raman Lidar Moisture Sounder is planned for atmospheric work in FY 1990.

Lockheed NP-3A

The P-3 supported the Labrador Sea Extreme Waves Experiment (LEWEX) off the coast of Newfoundland in 1987. The aircraft was equipped with the Surface Contouring Radar (SCR), developed to measure and map wave spectra and significant wave heights, and with the ROWS, which also measures wave heights using a radar scattering technique. The experiment collected an ocean wave data set over large waves simultaneously with measurements made by satellite overpasses and two research ships. The data will be used to validate wave prediction models.

From bases in Thule, Greenland, and Spitsbergen, Norway, the P-3 flew the Airborne Oceanographic Lidar (AOL) and a suite of passive microwave radiometers for an expedition to make ice measurements over the central Arctic ice pack. The aircraft subsequently made chlorophyll measurements in the Greenland Sea using the fluorosensing capability of the AOL while en route to Iceland. While in Iceland, the aircraft conducted a volcanic geomorphology study using the experimental laser altimeter in a temporal or terrain mapping mode. A final radiometric data set was obtained over the Greenland ice shield en route to Sondre, Greenland.

The P-3 will continue to support regional and local studies and instrument development work. The experimental laser altimeter will be used for a joint NASA/Navy program called BIOWATT in the Atlantic Ocean between the Wallops Flight Facility (WFF) and Bermuda, and some instrument development work using the new Global Positioning System (GPS), a downlinking Ocean Data Acquisition System (ODAS), and a Navigation and Environmental Monitoring System (NEMS). In 1988 the P-3 data have supported polar atmospheric ozone experiments and lidar development flights, as well as scatterometer test flights.

Short Brothers SC-7 Skyvan

The Skyvan's primary role involves mid-air retrieval of rocket-launched payloads. However, the aircraft is also used to support Earth resources studies and instrument development work and has supported acid rain studies in Vermont. In 1988 the Skyvan will be used for laser altimeter experiments.

Rockwell T-39 Sabreliner

The Sabreliner was acquired to provide Wallops aircraft users with the capability of reaching altitudes nearer to the stratosphere. The aircraft conducted a geomorphological study in Idaho during June 1987. Currently, the aircraft is supporting a laser altimetry program that utilizes a downward-looking port to conduct geoscience studies. The aircraft is also being modified with an upward-looking window for atmospheric research.

Bell UH-1B Helicopter

The helicopter is used as an instrument platform for Earth resources work. For the past 4 years, it has been equipped with small spectrometers for acid rain studies in the state forests of Vermont. During 1987 the same spectrometers, as well as a C-band radar, were installed on a pointable nose-pod designed at Wallops and used in four FIFE field studies in Kansas from May through October 1987.

Gates Lear Jet

The NSTL Earth Resources Laboratory (NSTL/ERL) operates a Lear Jet in support of the ESAD Land Processes Program. The Lear Jet flies two instruments: the Calibrated Airborne Multispectral Scanner (CAMS), used to study coastal geomorphology and evapotranspiration, and the Thermal Infrared Multispectral Scanner (TIMS), used for geology studies and land cover classification.

In FY 1988 the CAMS has been used to study coastal geomorphology in southern Louisiana, with a series of follow-on missions planned. The Lear Jet will also support a tropical forest study in Costa Rica, with both instruments being used to acquire data over the same area. The TIMS is being used for NASA's ongoing geological studies in California, Nevada, and other Western States. In the summer of 1987 the Lear Jet supported TIMS activities of the Ames Research Center C-130B aircraft during FIFE.

C-2

12
Space Flight Programs

Flight Programs of the Earth Science and Applications Division (ESAD) consist of three major activity areas: Mission Operations and Data Analysis, Mission Development, and Advanced Mission Planning. The three activities are carried out in support of the various Earth science disciplines, and of Earth science as a whole, and their respective research priorities.

An active flight development and operations program is continuing, both directly for NASA research and also to support NOAA's operational meteorological program and the joint Navy-NOAA Ice Center. Detailed treatment follows of the status and plans in the following categories: Operational Systems, including the NASA Meteorological Satellite Program and Landsat; Extended Mission Operations; Shuttle Missions and Payloads for flight on the Shuttle and on satellites of opportunity; Satellite Development; and future mission planning, including use of Space Station Program elements. The tentative flight development and operations schedules for key existing and proposed satellites and instruments appear in Figures 12-1A and 12-1B.

Operational Systems

NASA Operational Meteorological Satellite (Metsat) Program

The U.S. Operational Metsat Program is a joint undertaking by both NOAA and NASA. It consists of two separate satellite systems—the NOAA series of polar-orbiting Television Infrared Observing Satellites (TIROS) and the Geostationary Operational Environmental Satellites (GOES). Both the TIROS and GOES systems operate on a replace-as-needed basis.

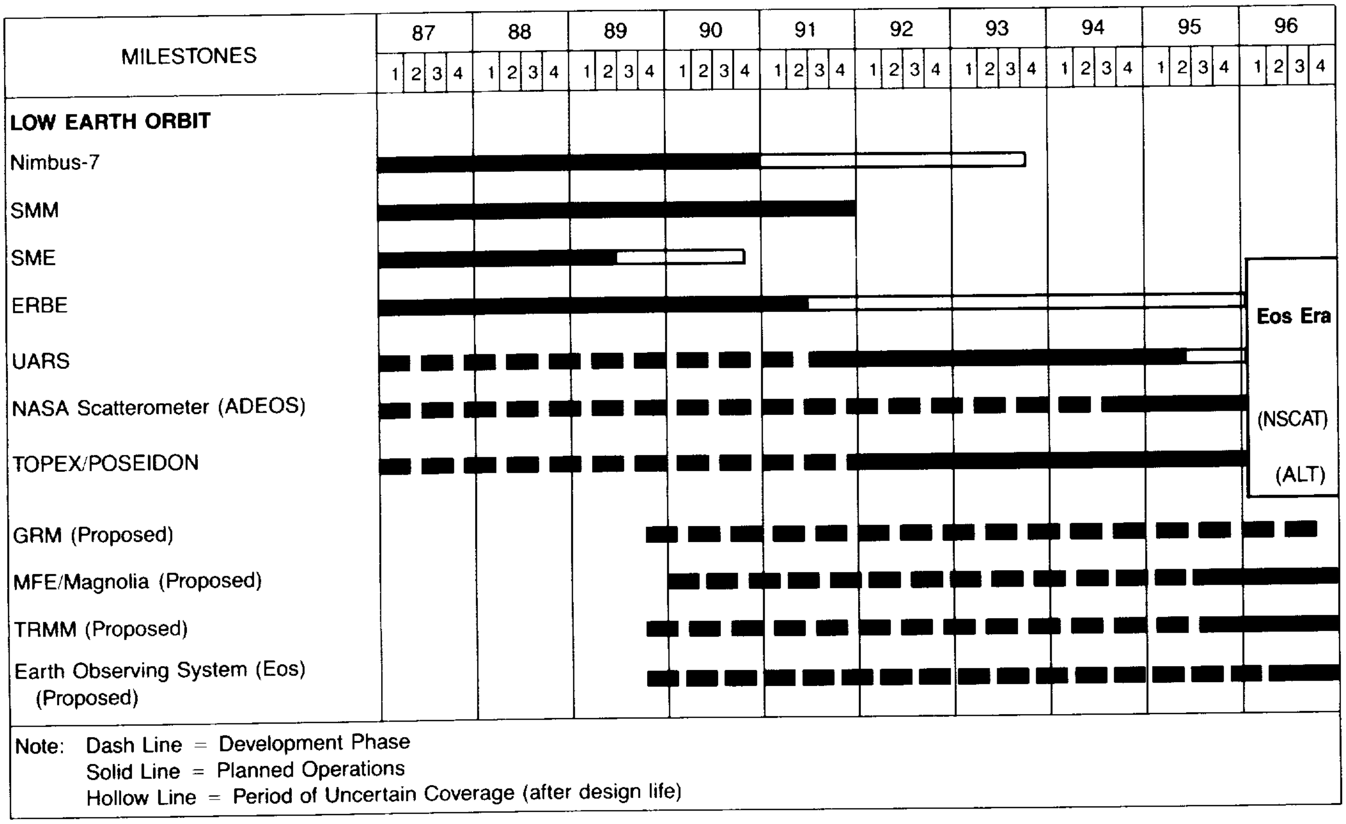
The TIROS morning and afternoon polar-orbiting satellites (labeled NOAA-8, -9, etc. after launch) provide operational coverage of the entire Earth four times each 24-hour day, measuring such variables as atmospheric temperature, humidity, cloud cover, ozone concentration, and energy budget parameters, and also relaying distress messages to rescue forces. The current series is built by GE Aerospace and Defense and launched on Atlas rockets under an agreement with the U.S. Air Force.

GOES satellites provide continuous day and night weather observations, monitor severe storms and other weather events, and measure a number of space environment parameters. A two-satellite system is maintained, providing coverage of the eastern and western halves of the United States. Current GOES satellites are spin-stabilized. They were built by Hughes Aircraft Corporation and launched on Delta expendable vehicles. The next generation of GOES satellites is being built by Ford Aerospace, and will be launched on Atlas/Centaur rockets under a commercial launch services contract with General Dynamics, managed by the Lewis Research Center.

Based on the observational requirements identified by NOAA, and using NOAA reimbursable funding, NASA prepares program implementation plans, issues necessary Requests for Proposals, and oversees the design, engineering, and fabrication of the described spacecraft and/or instruments. NASA oversees the integration of instruments onto the spacecraft, supports launch operations, and examines the satellite after it is in orbit before turning it over to NOAA for operation. Satellites currently in some planning or development phase include NOAA-H, -D, -I, -J, -K, -L, and -M, and GOES-I, -J, -K, -L, and -M. Project implementation is the responsibility of the Metsat Project at the Goddard Space Flight Center (GSFC).

The polar-orbiting satellites carry a number of imaging, atmospheric sounding, and data collection instruments, including the Advanced Very High Resolution Radiometer (AVHRR), High Resolution Infrared Sounder (HIRS), Solar Backscatter Ultraviolet spectrometer (SBUV), Space Environment Monitor (SEM), the French

FIGURE 12–1A. **NASA/ESAD FLIGHT DEVELOPMENT AND OPERATIONS PLAN:** Low Earth Orbit



Argos Data Collection and Platform Location System, and the international Search and Rescue System (S&R).

Current GOES satellites carry a group of imaging, atmospheric sounding, and data collection instruments. These include the Visible and Infrared Spin-Scan Radiometer (VISSR), VISSR Atmospheric Sounder (VAS), SEM, Data Collection System (DCS), Weather Facsimile (WEFAX), and an experimental S&R.

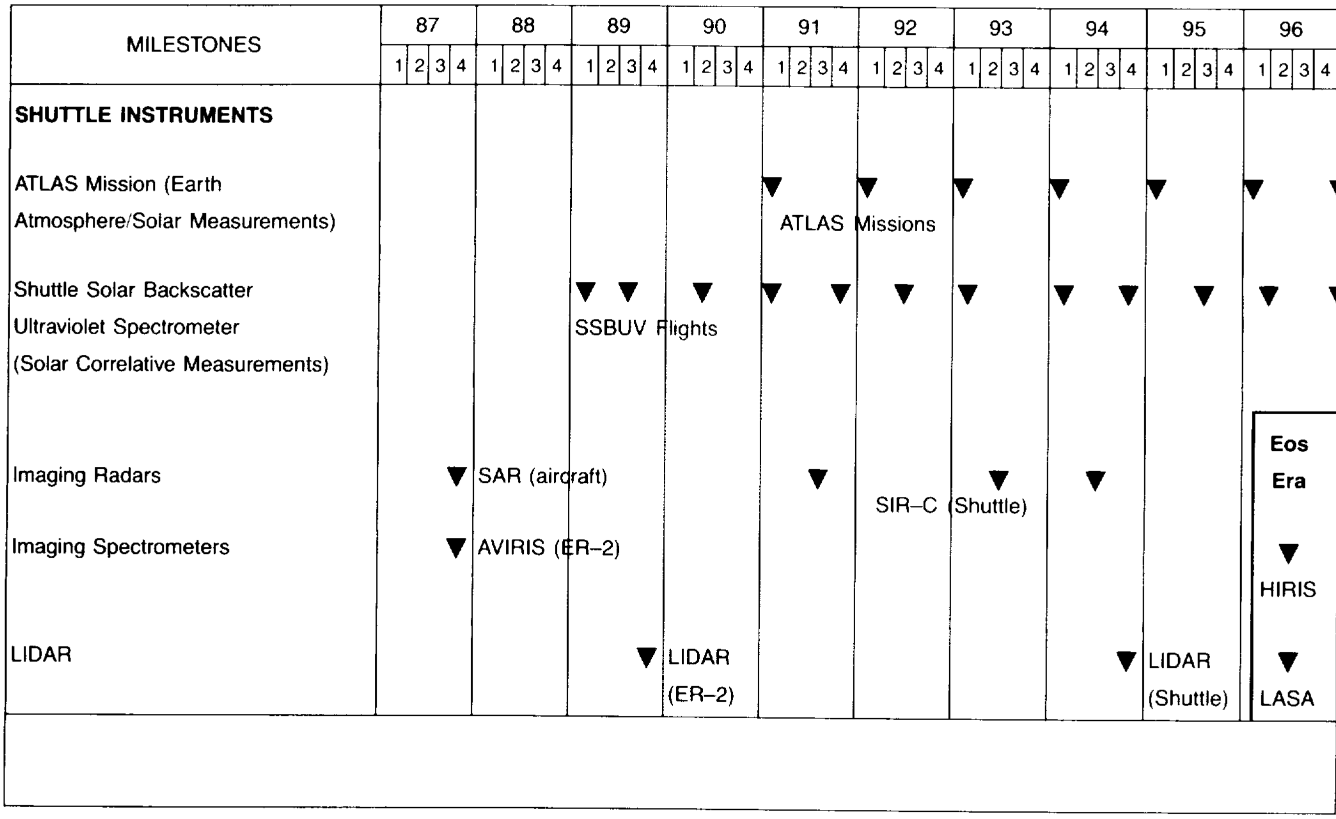
Periodically, NASA experimental instruments are flown on these satellites. The SBUV on the polar satellites is the last of the NASA research and development instruments to be provided under the Operational Satellite Improvement Program (OSIP); the SBUV has now graduated into the operational instrument class. The Earth Radiation Budget Experiment (ERBE) was flown on NOAA-9 and -10 in conjunction with the dedicated Earth Radiation Budget Satellite (ERBS).

Current Status. The meteorological satellites constitute an operational system with instruments that are upgraded over time. As we move from the current GOES G-H series to GOES I-M (planned for launch starting in 1990), we will be providing additional channels, improved pointing, and independent imaging and sounding. Beginning with NOAA-K, an Advanced Microwave Sounding Unit (AMSU) will replace the Microwave Sounding Unit (MSU) and Stratospheric Sounding Unit (SSU) flown on earlier missions. The AMSU will be used for temperature sounding through clouds and storm systems.

NOAA-9 and -10 are currently providing afternoon and morning polar orbit coverage, respectively. NOAA-9, which has already exceeded its 2-year design life by over a year, is scheduled for replacement by NOAA-H in the fall of 1988. With the failure of GOES-5 in mid-1984, only GOES-6 was available to provide geostationary satellite coverage of the U.S., but the nominal two-satellite system was reestablished with the successful launch of GOES-7 in February 1987. GOES-I, the intended replacement for GOES-6, will not be available for launch until July 1990. It is likely that the GOES-6 satellite will fail in the latter half of 1988, once again necessitating a one-satellite configuration until the GOES-I launch.

Plans for FY 1988 and FY 1989. With the launch of NOAA-J in 1991, the last of the Atlas-E rockets will be used. During FY 1988 we have been working with the Air Force and industry to develop a launch service arrange-

Figure 12–1B. **POTENTIAL NASA/ESAD FLIGHT DEVELOPMENT AND OPERATIONS PLAN: SHUTTLE INSTRUMENTS**



ment for the NOAA-K, -L, and -M satellites. After NOAA-M in late 1995, we currently plan to move from free-flyer polar weather satellites to flying a suite of operational weather instruments on both the polar platforms of the U.S. Space Station and the ESA Columbus Programs. The groundwork for this transition will be developed during FY 1988 and FY 1989.

Tentative launch dates for the Metsat Program include the following:

Polar-Orbiting Satellites		GOES Weather Satellites	
NOAA-D	5/89 (am)	GOES-I	7/90
NOAA-I	9/90 (pm)	GOES-J	11/91
NOAA-J	12/91 (am)	GOES-K	5/92
NOAA-K	4/93 (pm)	GOES-L	2/96
NOAA-L	7/94 (am)	GOES-M	12/97
NOAA-M	11/95 (pm)		

Landsat

On July 23, 1987, NASA marked the fifteenth anniversary of the first flight of Landsat-1 with a ceremony in Washington, D.C., held in conjunction with NOAA, U.S. Geological Survey and the Earth Observation Satellite Co. (EOSAT). The Landsat-4 and -5 spacecraft, operated by EOSAT under contract to NOAA, have remained stable over the past year except for continuity anomalies in the Ku-band transmission system on Landsat-5. Landsat-4 exceeded its 3-year design lifetime in July 1985, and Landsat-5 exceeded its 3-year design lifetime on March 1, 1987.

Current Status. Congressional action in March 1988 approved a revised one-satellite Landsat commercialization system providing for Landsat-6. In 1987, the Department of Commerce issued a Request for Proposals on new Landsat concepts and in April 1988 selected three projects for advanced concept studies over a 6-month period, before further evaluation of the program later in the year.

Amendments have now been made to the Land Remote-Sensing Commercialization Act of 1984 to facilitate the Federal Government's procurement of imagery for research and development purposes. These changes allow for the negotiation of a price reduction on Landsat data used exclusively for research purposes, in recognition of the contribution of research to future expansion of the commercial use of data.

NASA continues to support Landsat-4 and -5 operations through the use of the Tracking and Data Relay Satellite System as a reimbursable service to NOAA (EOSAT). We are also providing facilities at GSFC for the operation of Landsat-4 and -5. EOSAT is responsible for marketing of all Landsat imagery and all data requests should be made to EOSAT, 4300 Forbes Boulevard, Lanham, Maryland 20706, telephone (301) 552-0565.

In support of the investigations recently selected in response to the NRA for the Remote-Sensing Applications/Commercialization Program (see Chapter 10), a Memorandum of Understanding has been negotiated with EOSAT for the company to provide data at no charge to NASA for use by individual researchers under a "Data Grants" program. The manager of the Applications Program within ESAD has been designated as the point of contact for collecting Principal Investigator data requirements on an annual basis.

An agreement has been negotiated with the French Centre National d'Etudes Spatiales (CNES) and U.S. Government agencies for a special price on a limited amount of SPOT-1 data, to be used only for research and development purposes. NASA investigators have been requested to make their requirements known through the Chief, Land Processes Branch, NASA Earth Science and Applications Division.

Future Plans. As of March 1988, Landsat-6 has been approved for launch in 1991 and will carry a multispectral scanner and thematic mapper for collecting land use data. In addition, in a joint EOSAT/NASA endeavor, a Sea-Wide Field Sensor (Sea-WiFS) is planned for flight onboard. Under an Agreement in Principle, NASA would share the cost of the sensor, have the right to distribute data free of cost to researchers, and would develop a global data processing system and archive in support of the Global Ocean Flux Study (GOFS) and other science programs. EOSAT would retain the right to sell data to commercial enterprises.

The future of Landsat-7 or an advanced Landsat remote-sensing system is currently being evaluated. These steps do point to the continuing involvement of the U.S. in Landsat remote-sensing activities, although a serious data gap between the eventual demise of Landsats-4 and -5 and the launch of the new Landsat-6 satellite is still likely to occur.

Extended Mission Operations

After NASA research satellites complete the basic operations approved as part of the original project (an initial period of 1-3 years), responsibility for managing and budgeting the satellites is transferred to Extended Mission Operations (Mission Operation and Data Analysis). This program provides for ongoing operations, data processing, validation, and data analysis, and now includes Nimbus-7, the Earth Radiation Budget Experiment (ERBE), and the Solar Mesosphere Explorer (SME). As part of the Extended Missions Operations program, correlative measurement efforts are conducted to aid in the calibration of the satellite instruments, including instruments on NOAA's operational satellites, (i.e. SBUV/2, balloons, rockets, etc).

Satellites

Nimbus. Nimbus-7, the last in this series of multidisciplinary research demonstration satellites, continues to provide significant quantities of global data on sea-ice coverage, atmospheric temperature, atmospheric chemistry (i.e. ozone distribution), the Earth's radiation budget, and sea surface temperature. Of its seven instruments, three still operate: the Solar Backscatter Ultraviolet/Total Ozone Mapping Spectrometer (SBUV/TOMS), the Stratospheric Aerosol Measurement II (SAM II), and the Earth Radiation Budget (ERB) instrument. Nimbus instruments have proven so valuable for science and applications that second-generation models have been built, and are now flying, except for the Coastal Zone Color Scanner (CZCS) however, where a Sea-WiFS instrument is being implemented for flight on Landsat-6 as a joint NASA/EOSAT endeavor, as noted above.

Processing and analysis of the Nimbus-7 data are continuing. Strong demand exists for historical and current data on the radiation budget, atmospheric dynamics, and trace constituent concentrations and distributions. These data are used for global weather trend studies, severe storm analysis and prediction, improved numerical forecast models, ozone concentration trend analysis, and Earth climate studies.

The TOMS instrument on Nimbus-7, providing important data relative to atmospheric ozone, has been operating since 1978. In recognition of the long-term requirements for comprehensive daily total column ozone measurements, other future approaches are now being investigated. One option is to launch a new TOMS on the Scout mission around 1992; another is to put an instrument on the Japanese Advanced Earth Observing Satellite (ADEOS) for launch in the 1993-1994 time frame. Discussions are under way with the Soviets on the third possibility, that of attaching TOMS to a USSR sun-synchronous polar orbiter in the near future. The new TOMS instrument will obtain almost global daily maps, taking some 200,000 measurements each day, of all sunlit areas. Only those areas experiencing polar night will not be observed.

Earth Radiation Budget Experiment (ERBE). This experiment measures temporal and spatial variations in the Earth's radiation budget in order to gain basic insight into the causes of climatic fluctuations. Sampling studies based on experimental ERB instruments flown on Nimbus satellites showed that adequate global coverage requires a multiple-satellite system. Improved calibration of sensors and measurements covering at least one full cycle of seasons is required. A combined team of scientists from NASA, NOAA, universities, and industry, as well as the international community, developed scientific goals and measurement requirements for the program.

To provide adequate and meaningful coverage, the experiment consists of three identical radiation budget instrument packages fabricated for the NOAA-F and -G satellites and for a dedicated NASA observatory called the Earth Radiation Budget Satellite (ERBS) in a much different orbit from the NOAA operational satellites. In addition to the ERBE scanners, the ERBS carries the Stratospheric Aerosol and Gas Experiment (SAGE II), which provides measurement data on ozone, water vapor, nitrogen dioxide, and aerosols. The ERBS observatory was launched by Shuttle in October 1984 to an altitude of 300 km, and then propelled by an auxiliary onboard propulsion system to a 57-degree orbit at the operational altitude of 610 km. The NOAA-F launch occurred in December 1984 and NOAA-G in August 1986.

Solar Mesosphere Explorer (SME). The SME, designed to operate for 1 year, was launched in 1981 to provide major input into our overall atmospheric parameter data base. The satellite was proposed, designed, developed, and is operated by a core group of professionals and students at the University of Colorado.

The SME payload consists of three Earth atmospheric measurement instruments and one solar ultraviolet instrument. Because of instrument deterioration on SME and budget reductions in the Office of Space Science and Applications, the three atmospheric instruments have been turned off. However, the solar ultraviolet instrument continues to collect valuable solar UV data for the planetary and solar physics communities.

The simultaneous measurements from SME during short periods of time over some portions of the Earth contributed to understanding of some of the complex chemical processes taking place in the mesosphere, including measurements of ozone and nitrogen dioxide. Processing, analysis, and archiving of the measurements from the atmospheric instruments will be completed before 1989.

Early SME data suggest that many mesospheric properties have short-term magnitude variations that are greater than expected. Information from this satellite is proving helpful for studying the response of ozone to fluctuations in solar activity and seasonal shifts in atmospheric circulation.

Correlative Measurements

In measuring ozone changes in the atmosphere, instruments need to be very precisely calibrated because of the small percentage changes involved. It is important that we be able to separate the variations caused by inaccuracies or changes in the instruments from the short-term temporal and true long-term geophysical changes. For example, our correlative measurements program compares and aids in correcting ozone data being gathered by Nimbus, SME, SAGE II, and the NOAA operational meteorological satellites. Such correlation is necessary because the instruments on satellites cannot be serviced or recalibrated after launch, and degradation does occur over time.

The Rocket Ozone (ROCOZ) and balloon correlative measurement program involves short flights by rockets and balloons with instruments that are precisely calibrated. The data are then put in archives where correlations can be made with the satellite instrument data. Rocket flights are launched from Wallops Flight Facility in Virginia and, in one case, from Natal, Brazil; balloons are launched from both locations. A campaign from the west coast of the U.S. is planned for the fall of 1988 and a second Natal campaign of ROCOZ launches is planned for the spring of 1989.

The rocket portion of the ozone correlative measurements program will soon be augmented by the Shuttle Solar Backscatter Ultraviolet spectrometer (SSBUV). The SSBUV will fly on the Shuttle at 8- to 12-month intervals. This carefully calibrated instrument will underfly the NOAA spacecraft and others that measure ozone, so that satellite ozone data can be compared and corrections can be made to the instruments. The first flight of the SSBUV on the Shuttle is currently scheduled for 1989.

Shuttle Missions and Payloads

The Shuttle system offers a unique opportunity for frequent, short-duration instrument flights and calibration flights. The programs in solid Earth and environmental observations take advantage of this capability through developing Shuttle or Spacelab payloads to:

- Conduct early testing and checkout of remote-sensing instruments being designed for long-term, free-flying missions
- Gather short-term atmospheric and environmental data for basic research and analysis when long-term observations are impractical
- Establish the accuracy of instruments on long-term operational satellites with instruments precisely calibrated before and after short-term Shuttle flights

Atmospheric Laboratory for Applications and Science (ATLAS)

The ATLAS is a series of missions that will be flown on the Space Shuttle utilizing Spacelab pallets to measure solar radiation and upper atmosphere properties. Currently, seven U.S. instruments in various combinations have either been flown on Spacelab or are under development for Shuttle flight. These instruments, combined with several European models, have been pulled together for the ATLAS series of flights (this series was originally called the Earth Observation Mission [EOM]). One or more of the ATLAS missions will underfly the Upper Atmosphere Research Satellite (UARS) to make correlative measurements.

The ATLAS-1 payload consists of two full Spacelab pallets of instruments that will fly on a dedicated Shuttle mission in the fall of 1990. ATLAS-2 is planned as one full pallet of instruments and possibly the German Cyrogenic Infrared Spectrometer and Telescope for the Atmosphere (CRISTA) experiment and will be the mission that underflies UARS. Starting with ATLAS-3, one full pallet of instruments is planned for Shuttle mixed-cargo flights. The ATLAS flight series has been approved for Shuttle flight approximately once a year so that, among other objectives, the 11-year solar cycle can be monitored.

Atmosphere Trace Molecules Observed by Spectroscopy (ATMOS). This instrument measures key trace species in the Earth's atmosphere by high resolution infrared absorption spectroscopy. The data will help determine the compositional structure of the upper atmosphere (10 to 80 km) including those species important in the photochemistry of the ozone layer and the spatial variability on a global scale.

The ATMOS, combined with four solar instruments, makes up the core payload of ATLAS. While Shuttle flights are suspended, an important ground observation program is being conducted with ATMOS from the Jet Propulsion Laboratory (JPL) Table Mountain Observatory.

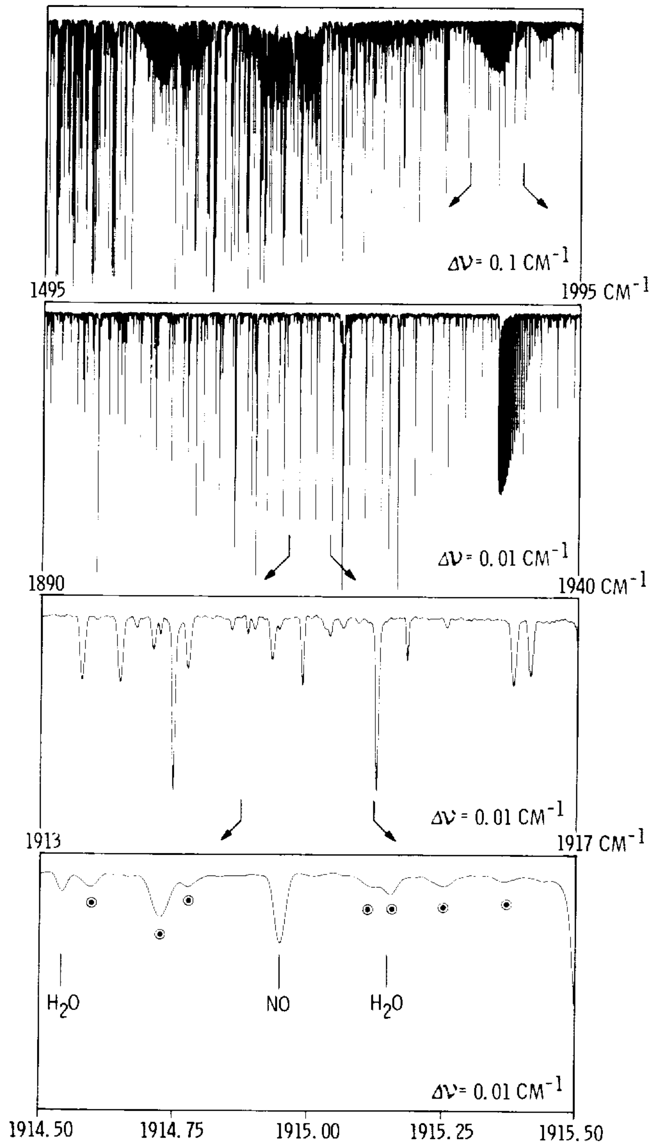
The first flight of ATMOS was on Spacelab (SL)-3 (April 1985); it produced exceptional science results. An international science group analyzed spectra obtained in 16 sunrise and sunset occultations to yield concentration profiles for a wide variety of molecules over extended altitude ranges (see Figure 12-2). This database is a major scientific accomplishment, requiring assembly of spectral parameters for a large number of atmospheric molecules coupled with theoretical models of the composition of the atmosphere. A stunning array of measurements has been produced: minor gases from 5 to 140 km, the entire odd-nitrogen family in the stratosphere, many members of the halogen family, and the first positive observations of such key reservoir species as peroxynitric acid and nitrogen pentoxide. An additional benefit is data on the infrared solar spectrum recorded for the first time from space, which will be of immense value to the solar physics community.

Solar Irradiance Monitoring Program. This program is designed to provide a sustained, long-term solar constant data base with precision adequate for climatological investigations. From this data base, we will try to pursue solar physics implications that may lead to the capability of an improved prediction of solar variability. To carry out this program, a solar constant instrument is flown aboard overlapping satellite missions for continuous solar monitoring. Short-term comparison flight experiments are conducted from rocket and Shuttle flights. Testing and calibration of these instruments is conducted at the JPL Table Mountain Observatory.

The instruments used are long-term satellite Active Cavity Radiometer Irradiance Monitors (ACRIMs). ACRIM-I is in operation aboard the Solar Maximum Mission (SMM). A second, ACRIM-II, is planned for flight on the Upper Atmosphere Research Satellite (UARS). These missions must overlap to provide the continuous data set needed. A highly desirable option—placing the ACRIM instruments aboard the NOAA GOES series—is a long-term objective. The GOES geosynchronous orbit could provide almost 100 percent continuous (duty cycle) solar observation. Accommodation studies for mounting ACRIMs on the GOES satellites have been initiated. In addition, a proposal has been made to the Japanese that ACRIM-II fly aboard ADEOS, due for launch in the 1993-1994 time frame.

The Active Cavity Radiometer (ACR)-1 was developed for flight aboard the Shuttle to provide correlative measurements for the ACRIMs. The ACR-1, first flown aboard SL-1 (1983), is considered a core ATLAS

FIGURE 12-2. **MEASUREMENTS FROM ATMOS ON SPACELAB 3**



WAVENUMBER (CM $^{-1}$) The top trace of this figure shows a 500 cm $^{-1}$ region of spectrum between 1495 and 1995 cm $^{-1}$ recorded with Filter 2. The second trace shows an expanded view of the 1900-1950 cm $^{-1}$ region from the first, the third 4 cm $^{-1}$ similarly expanded from the second in the 1913-1917 cm $^{-1}$ region, and finally 1 cm $^{-1}$ expanded from the third trace centered on 1915 cm $^{-1}$. This one wavenumber region represents one of the selected microwindows for NO.

instrument to be flown once a year on the Shuttle over the 11-year solar cycle.

Measurement of Air Pollution from Satellites (MAPS). MAPS has already flown successfully on two Shuttle flights and will be flown again on the first three Shuttle Radar Laboratories (SRL). In the meantime, data processing and analysis are continuing. MAPS is a gas filter correlation radiometer which measures the levels of tropospheric carbon monoxide and the extent of interhemispheric mass transport in the lower atmosphere. It is approved for four flights, one for each season of the year, to provide the first global measurements of seasonal variation of carbon monoxide in the Earth's atmosphere.

Large Format Camera (LFC)

The LFC, a precision mapping camera capable of producing high-resolution stereophotography, was flown on the Shuttle Orbiter Challenger in October 1984. During this 8-day mission, at an inclination of 57 degrees, photography was acquired by the camera at three different altitudes—200 nm, 147 nm, and 129 nm. The film format is 9 x 18 inches and the ground footprint from a typical Shuttle altitude of 147 nm is 220 nm x 110 nm. The flight film is available for commercial users through Chicago Aerial Survey, Inc., 2140 Wolf Road, Des Plaines, Illinois 60018, (312) 298-1480. Film products for federally funded investigators and related cooperative research programs can be obtained through the EROS Data Center, Sioux Falls, South Dakota 57198, (605) 594-6511. Within NASA, a set of the film is archived at the National Space Science Data Center, located at Goddard Space Flight Center. The government is exploring the possibility of reflights of the camera by the private sector on a reimbursable basis. No additional flights are planned by NASA.

Spaceborne Imaging Radar Program

NASA is working toward the eventual flight of a Synthetic Aperture Radar (SAR) on a polar platform through a series of Spaceborne Imaging Radar (SIR) missions. In 1981 SIR-A acquired L-band radar images at fixed incidence angles of 47 degrees, while the 1984 SIR-B flight explored the use of multiple-look angles (15 to 60 degrees) at a single frequency. The SIR-C missions, the first scheduled for 1991 with second and third flights at about 1-year intervals, will be capable of acquiring digitally processed four-polarization images at selectable incidence angles between 15 and 60 degrees and at two wavelengths (6 cm and 23 cm).

SIR-C will thus provide:

- The first opportunity for simultaneous multifrequency radar imagery from space for geoscientific studies of Earth
- The first spaceborne high-resolution imaging sensor with simultaneous multipolarization capability
- The first multiparameter imaging radar to supply coverage during two different seasons

Agreement has been reached with Italy and the Federal Republic of Germany to enable the incorporation of an X-band system into the structure and data system of the SIR-C, making the SIR-C a three-frequency radar system (L-, C-, and X-band) and an international joint effort. The X-band system being developed by the German/Italian team is called the X-SAR. The Preliminary Design Reviews on the SIR-C antenna, X-band and the system as a whole were completed in late 1987, with Critical Design Reviews scheduled for 1988 and early 1989.

As part of the design effort, an aircraft version of the Synthetic Aperture Radar (SAR) is being developed which both enables testing of the design that will be implemented in the spaceborne SIR-C and also provides an interim sensor capability for gathering scientific data. The aircraft SAR is described in Chapter 11 of this report.

In June 1987, a NASA Research Announcement on SIR-C was issued, simultaneous with release of an announcement for the German/Italian X-SAR, soliciting basic and applied research proposals to conduct scientific investigations using SIR-C. The Science Review Panel met in March 1988 and successful projects were announced July 1988. From the 178 proposals submitted, a total of 49 were successful, with NASA selecting 38 and the German/Italian X-SAR team selecting 11 proposals.

Mission design studies on orbit, inclination and timing, for example, will continue. The X-SAR team is already fabricating and in mid-1990 both instruments will come together for mounting, integration and testing in preparation for a December 1990 delivery prior to a mid-1991 launch.

Imaging Spectrometer Program

The Imaging Spectrometer Program is developing and implementing remote-sensing instruments with high spectral resolution in visible and short-wave infrared portions of the spectrum.

Three instruments are in use or in development: two airborne spectrometers, the Airborne Imaging Spectrometer (AIS) and the Airborne Visible Infrared Imaging Spectrometer (AVIRIS), and the High Resolution Imaging Spectrometer (HIRIS) to be flown as part of the Earth Observing System (Eos). In FY 1988, AIS was replaced by AVIRIS, an instrument designed for long-term aircraft use. By simulating HIRIS data, it will provide useful experience of handling complex data sets in advance of the Eos era. AIS and AVIRIS are described more fully in Chapter 11.

A full design effort is underway on the HIRIS instrument planned for the Eos platform in the mid-1990s. HIRIS is intended as a targeting instrument which acquires data at specified times and places, rather than continuously. Although it will mainly be used to observe the surface, it will also provide valuable information on the atmosphere, including such key attributes as aerosol loading and composition. It will also provide information on cloud characteristics useful for calculating their climatic effects. More details of the HIRIS program can be found in the section describing the Earth Observing System (Eos) below.

Lightning Mapper Sensor (LMS)

The LMS will be capable of measuring lightning flashes during both day and night; it is proposed for flight aboard the NOAA GOES series. The GOES geostationary orbit could provide continuous imaging of the United States, Central America, and the northern part of South America. Estimated to weigh about 15 kg and powered at 30 watts, the LMS will have a data rate of about 64 kbls with a 5-year lifetime. While many scientific opportunities are possible with LMS data, the major thrust will be the study of lightning events in relation to storm evolution and cloud/precipitation development.

Geophysical Fluid Flow Cell (GFFC) Experiment

The Geophysical Fluid Flow Cell (GFFC) instrument was designed to provide for the study of fluid motions in microgravity as a means of understanding fluid flow in oceans, atmospheres, and stars. The GFFC provides data from conditions simulating those associated with the general circulation of planetary atmospheres and the Sun.

The GFFC instrument flew aboard STS 51-B as part of the Spacelab-3 mission, gathering over 50,000 photographic image frames of data during more than 100 hours of instrument operation. Because of the scientific gains realized from the SL-3 mission, GFFC will be flown aboard the International Microgravity Laboratory (IML-1) mission, scheduled for launch in early 1991. Refurbishment and modification of the GFFC for the IML-1 flight are underway. Video camera systems have been added to GFFC to allow Spacelab crew members and investigators on the ground to observe the flow patterns in real time and interact with the experiment parameters.

Research Satellite Development

Upper Atmosphere Research Satellite (UARS)

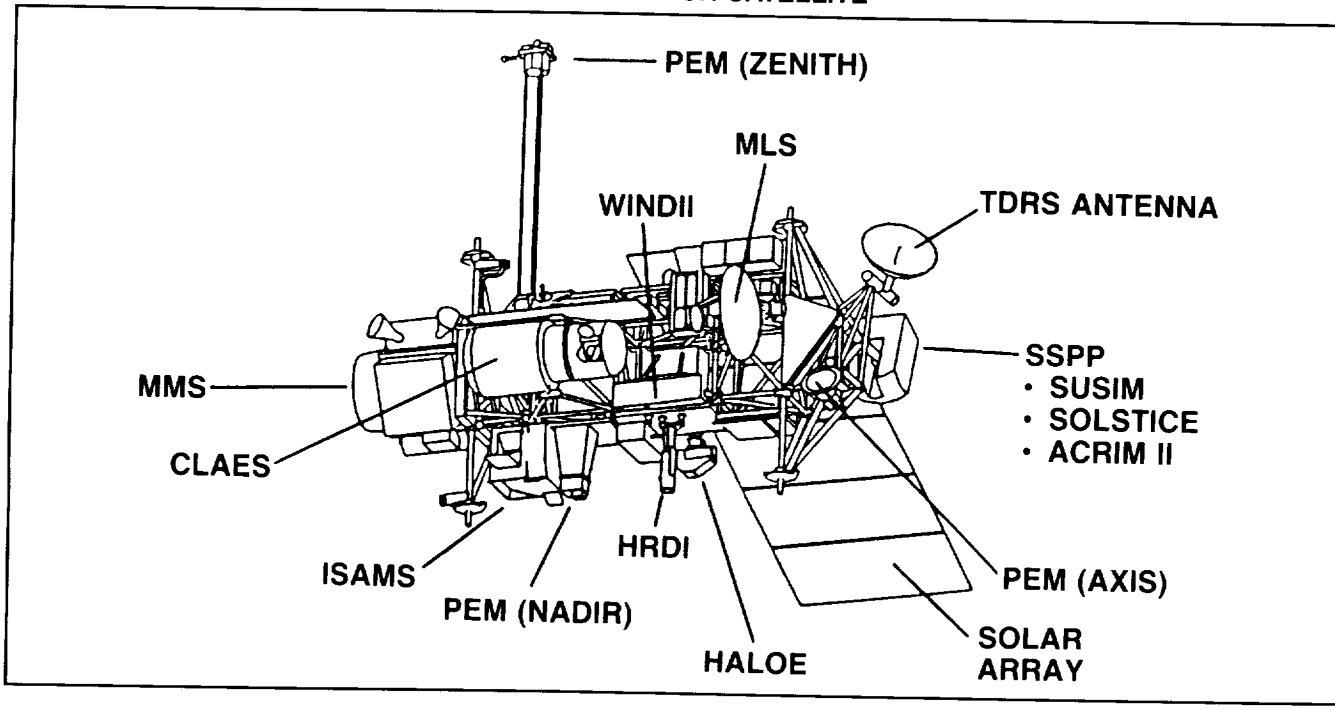
The UARS is essential for understanding the key radiative, chemical, and dynamical processes that control the strength and vulnerability of the ozone layer. The UARS instruments will be making the first integrated global measurements of ozone concentration, most chemical species that affect ozone, solar and energetic particle inputs to the upper atmosphere, temperature, and winds in the stratosphere, mesosphere and lower thermosphere.

UARS (see Figure 12-3) will contribute critical new insights to our overall understanding of the stratospheric ozone layer by providing a rich data set which will be used with numerical models to test our current knowledge and form the basis for assessments of the future of the stratosphere. Improved stratospheric data are also important in designing and implementing long-term monitoring of the ozone layer and in assessing the impact of upper atmospheric changes on climate.

Current Status. The UARS Observatory is scheduled for launch aboard the Shuttle in the fall of 1991. The Shuttle will deliver the spacecraft directly to the operational circular orbit at 600 km inclined 57 degrees to the Equator. The planned operational lifetime of the Cyrogenic Limb Array Etalon Spectrometer (CLAES) instrument is limited by the 15-month lifetime of the solid cryogen used to cool the infrared detectors and optics; however, the design lifetime of the satellite is 36 months. The fall launch, combined with the 15-month CLAES instrument lifetime, will provide coverage of two Northern Hemisphere winters by the entire instrument complement, as recommended by the UARS Science Working Group.

The UARS Observatory will consist of 10 scientific instruments, an instrument module including mission-unique equipment, and the Multimission Modular Spacecraft (MMS). The MMS will be used to provide attitude control, communications and data handling, electrical power storage and regulation, and propulsion. Mission-unique items include the solar array, a high-gain antenna for communication through the Tracking and Data Relay Satellite System (TDRSS), additional attitude sensors, and a solar/stellar pointing platform. The instruments are in the final development stage, with a Critical Design Review (CDR) having been completed

FIGURE 12-3. **THE UPPER ATMOSPHERE RESEARCH SATELLITE**



for 9 of the 10 instruments. The instruments fall into the following categories:

- Energy input—Solar Ultraviolet Spectral Irradiance Monitor (SUSIM); Solar-Stellar Intercomparison Experiment (SOLSTICE); Active Cavity Radiometer Irradiance Monitor (ACRIM); and the Particle Environment Monitor (PEM)
- Species/temperature—Cryogenic Limb Array Etalon Spectrometer (CLAES); Improved Stratospheric and Mesospheric Sounder (ISAMS), a United Kingdom instrument; Microwave Limb Sounder (MLS); and Halogen Occultation Experiment (HALOE)
- Wind measurements/dynamics—High Resolution Doppler Interferometer (HRDI); and Wind Imaging Interferometer (WINDII), a Canadian instrument

Development of the innovative ground data-handling system is also underway at GSFC. The system will permit near real-time, interactive use of the data by all instrument and theoretical investigator teams. Data from the UARS science instruments, as well as from the SBUV on NOAA satellites, will be stored and processed by a central computer, and each principal investigator will have a remote analysis computer connected to the main system for viewing, processing, and correlating the information. Algorithms are now being developed by these investigators. The Phase 1 computer hardware for this ground data-handling system has been delivered.

The UARS instruments are in the final assembly stage in preparation for functional and environmental testing. Following the successful completion of the Observatory Preliminary Design Review in April 1987 and the structure CDR in December 1987, the Observatory structural fabrication processes were verified and fabrication of the structural members was started. The Multipurpose Fixture, which will be used for all Observatory-level ground processing and handling procedures including instrument integration and testing, has been delivered to the new integration and test facility specially designed for UARS by General Electric at the East Windsor, New Jersey, site.

Plans for FY 1988 and FY 1989. CDRs will be held for the Observatory and central data handling facility, and the instruments will complete assembly and functional and environmental testing in FY 1989. Also, the Observatory ground-test equipment and facilities will be ready for the spacecraft integration and test program. The multi-mission modular spacecraft will be delivered to General Electric and readied for integration with the Observatory, and the flight structure fabrication and subassembly process will be completed. The Mechanical Test Model (MTM) will be assembled and the MTM test program completed, and the program of phased instrument delivery will be well underway.

Ocean Topography Experiment (TOPEX/POSEIDON)

The TOPEX/POSEIDON mission (see Figure 12-4) will substantially increase our understanding of global ocean dynamics by making precise, accurate global observations of sea level for at least 3 years. Using a radar altimeter to measure height variations on the sea surface, detailed maps of currents, eddies, and other features of ocean circulation and seafloor geologic structure can be made. The data will help us answer questions pertaining to the effects of ocean circulation on climate, such as understanding the effects of wind, interactions of the atmosphere and ocean, and the exchange of heat across the air-sea interface.

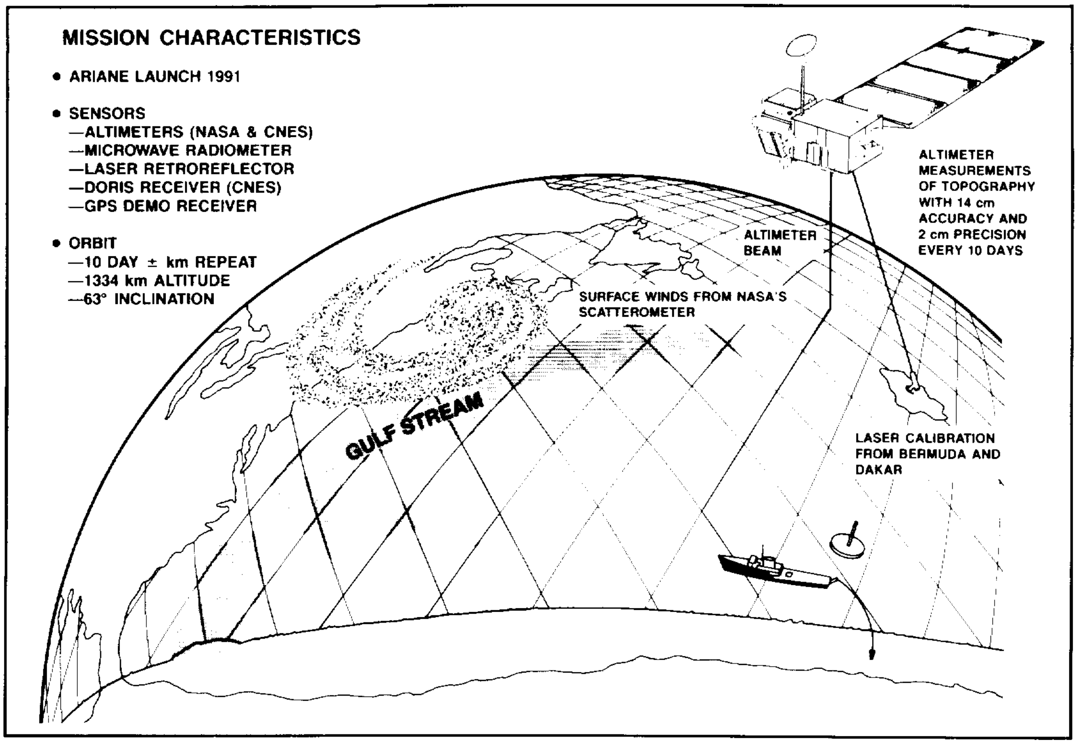
This international effort merges TOPEX with the POSEIDON oceanographic mission of France's Centre National d'Etudes Spatiales (CNES). The U.S. satellite, being developed by the Fairchild Space Company, is scheduled for launch on the French-provided Ariane launch vehicle. It will carry two French instruments in addition to four from the U.S.

Current Status. TOPEX was approved as an FY 1987 new start. With this approval to initiate full-scale development of TOPEX/POSEIDON, launch is currently planned for December 1991. This date coincides with two major international field programs—the World Ocean Circulation Experiment (WOCE) and the Tropical Ocean Global Atmosphere (TOGA) program.

The Memorandum of Understanding between NASA and CNES for the conduct of the joint mission was signed in March 1987, and in July 1986 a NASA Announcement of Opportunity (AO) invited proposals for the TOPEX/POSEIDON program. CNES issued a simultaneous announcement to maximize the participation of the international oceanographic community in this opportunity to conduct fundamental research. Approximately 60 proposals were received by NASA, 25 by CNES, and selection of a Science Definition Team was completed in September 1987. In addition to refining their own plans for specific research investigations with the data, this Team will advise the project on implementation matters crucial to the scientific success of TOPEX/POSEIDON. All other areas of the project are moving ahead similarly.

Plans for FY 1988 and FY 1989. PDRs and CDRs are planned for all major elements of the project, includ-

FIGURE 12-4. **The TOPEX/POSEIDON MISSION:** Ocean Circulation



ing the satellite, sensors, and ground data system. An international team of 38 Principal Investigators has been selected, of which NASA selected 20 projects which will directly contribute to the goals of both the WOCE and TOGA programs.

NASA Scatterometer

The NASA Scatterometer (NSCAT), being built by JPL, is an active microwave radar that will collect detailed global data on near-surface ocean winds. Such winds drive ocean currents, an important contributor to establishing global weather and climate patterns. Although similar in design, NSCAT represents significant improvements over the prototype instrument flown on Seasat in 1978.

Current Status. NSCAT had been planned for flight on the Navy's Remote Ocean Sensing System (N-ROSS) in September 1990. With the Navy's cancellation of N-ROSS in December 1986, and again in March 1988, NASA is proposing to fly NSCAT on Japan's Advanced Earth Observing Satellite (ADEOS), due for launch in the 1993-1994 time frame. Other launch options which have been considered, including the Air Force's Defense Meteorological Satellite Program (DMSP), the Air Force Space Test Program (STP), and TOPEX/POSEIDON itself, will be kept under review.

Plans for FY 1988 and FY 1989. Current program activities are focused on an October 1991 instrument delivery date; the scatterometer would then be ready for integration with the ADEOS satellite system. In addition, development of the ground data system is being continued, as is the refinement of post-launch research and verification plans.

Laser Geodynamics Satellite (LAGEOS)-2

NASA and the Italian Piano Spaziale Nazionale (PSN) are jointly developing the second Laser Geodynamics Satellite (LAGEOS-2), which will be flown as a payload on a test flight of the Italian IRIS upper-stage launch vehicle, to be carried into a 6000-km altitude orbit by the Shuttle in November 1991. The satellite, identical to the LAGEOS-1 launched in May 1976, is entirely passive and is used as an extraterrestrial reference point for precise geodetic positioning using ground-based laser ranging stations. The satellite is an aluminum sphere 60 cm in diameter, the surface of which is covered by 426 isotropically distributed corner-cube retroreflectors designed to reflect laser pulses back to the transmitting telescopes. From the time of flight of the laser pulses and with precise knowledge of the orbit of the satellite, the location of the laser ranging station can be determined to an error less than a few centimeters. The inter-station baseline distances between two or more laser ranging stations operating at the same time can be determined with errors less than 1 centimeter.

The design of LAGEOS-2 and its altitude are identical to LAGEOS-1, but an orbital inclination of 52 degrees instead of 108.8 degrees was chosen to maximize the return of information on the Earth's gravitational field, and solid Earth and ocean tides, from LAGEOS-2 operations. For precise positioning, the availability of LAGEOS-2 will reduce by about 50% the time required to establish the position of a laser ranging station.

LAGEOS-3, another laser ranging satellite which could be placed in an orbit such that information important to relativistic physics could be obtained, in addition to augmenting the complement of satellites available for geodynamical laser ranging, is currently under study.

Plans for FY 1988 and FY 1989. The CDR for LAGEOS-2 was held in April 1988, and the satellite will be delivered by PSN to Goddard Space Flight Center for calibration in March 1989. The satellite will be placed in storage during the remainder of the development of the IRIS vehicle, which is expected to be ready for launch by June 1991.

Earth Probes

A program of Explorer-class missions, called Earth Probes, has been defined, consistent with the recommendations of the Earth System Science Committee (ESSC) Report, *Earth System Science: A Closer View*. These include the Tropical Rainfall Measuring Mission (TRMM), the Geopotential Research Mission (GRM), and the Magnetic Field Explorer (MFE). These are described below.

Tropical Rainfall Measuring Mission (TRMM)

Precipitation measurement is probably the most crucial link in the hydrological cycle. Its large variability makes it a particularly important scientific challenge for modeling the atmospheric circulations and climate, and it is one of the most difficult of all atmospheric variables to measure.

More than two-thirds of global precipitation falls in the tropics and sub-tropics (between 30 degrees north and south) and the latent heat released by this rainfall plays a vital role in driving low-latitude circulation and in the overall global heat budget.

TRMM is a conceptual proposal to measure tropical precipitation from a low-inclination orbit using a combination of active and passive microwave sensors, together with a visible/infrared sensor to overcome many of the previous limitations of remote sensing of precipitation from space. In addition to investigating the role of tropical latent heating in the global atmosphere, the data are important to test the realism of climate models and their ability to simulate and predict accurately on a seasonal time scale. Other scientific issues, such as the effects of El Niño on climate, could be addressed with a reliable, extended time series of tropical rainfall observations.

The passive microwave sensor will provide information on the integrated column precipitation content, its areal distribution, and its intensity. The horizontal resolution will allow the definition and investigation of most rainfall types, including convective cells. The planned active microwave sensor (radar) will define the layer depth of the precipitation and provide information on the intensity of rain reaching the surface, a key factor in determining the latent heat input to the atmosphere. The very high resolving power will also better define the coverage and intensity of rain, and permit the measurement of rain over land, where the passive microwave channels have more difficulty.

The visible/infrared sensors will provide very high resolution information on cloud coverage, type, and top temperatures and will also serve as the link between these data and the long and virtually continuous coverage by the geosynchronous meteorological satellites.

The unique combination of sensor wavelengths, coverages, and resolving powers, combined with the low-altitude, non-Sun-synchronous orbit provides a sampling capability that should yield monthly precipitation amounts to a reasonable accuracy over a 500 km x 500 km grid. Use of these data is also being considered for experiments involving soil moisture and vegetation.

Current Status. Phase A studies have been completed and the TRRM Science Steering Group report has been issued. The mission is feasible within the modest cost of typical Explorer-type missions. If approved in the FY 1990 budget, TRRM could be ready for launch in 1994.

Cooperative efforts now underway with Japan to study precipitation will continue. The Japanese Science and Technology Agency is studying the possibility of participating in a precipitation measuring mission. In March 1988, the cooperative U.S./Japanese feasibility study on TRRM was issued. Once approved, Phase B definition studies could begin as early as July 1988.

Geopotential Research Mission (GRM)

Planning for a low-altitude mission to measure the gravitational and magnetic fields of the Earth was begun in 1978 in response to a determination by the Earth science community that such a mission is of the highest priority for the solid Earth sciences. Such a mission is also needed to measure the oceanic geoid required to satisfy all the objectives of the TOPEX mission, to enable more accurate leveling and surveying measurements, and for more efficient tracking of low Earth orbit satellites.

The design adopted for this mission was for precise Doppler radio measurements between two satellites in identical orbits but separated by a few hundred kilometers. This concept amounts to a long-baseline gravity gradiometer measuring the along-track component of gravity. Long-wavelength gravity components were to be measured by an onboard Global Positioning System (GPS) receiver. The lowest possible altitude was required, determined by the drag coefficient of the satellites and the amount of fuel that could be carried for drag compensation systems on each satellite. With two cylindrical satellites 6 m in diameter and 10 m long, a 6-month mission at 160 km altitude was possible. Phase A and B design studies were complete by 1981, and the Doppler radio link accuracy of 1 micro per second was demonstrated in the laboratory in that year. A two-stage drag compensation system was designed in 1983, in which an inner stage carrying the drag compensation system was magnetically levitated away from the spacecraft bodies.

However, by 1986 it was clear that because of escalating construction costs and the requirement for a Shuttle launch, the original GRM mission would not be a successful new start candidate. Consequently, discussions were begun with the European Space Agency (ESA) on the possibility of a joint geopotential field mapping mission.

In 1985 ESA had two candidates for their intended "solid earth mission"—one flying a French-designed gravity gradiometer called GRADIO (derived from precise accelerometers previously flown on the Cactus mission), and a second to put into orbit a precise radio locating system called Popsat. A joint ESA/NASA study began in 1985 on the possibility of combining GRADIO/Popsat with GRM. The Popsat option was soon dropped and it was also found that adding a GRADIO instrument to one of the GRM spacecraft would neither improve the mission science nor reduce the cost to NASA.

However, a very attractive approach to achieving the science objectives of GRM emerged with the possibility of flying only one GRM spacecraft that would determine gravity by means of the GRADIO instrument to almost the same accuracy and resolution as the original GRM design (3-5 milligal accuracy at 100 km resolution) and the short-wavelength magnetic field by means of the original GRM magnetometers mounted on a boom. The attitude rate control requirements for GRADIO, however, exceeded previously tested technological capabilities.

The ESA preference was to launch the GRADIO instrument without GPS receiver or magnetometers on the ERS-2 Ariane launch vehicle rather than a Delta-II vehicle. Consequent space and payload weight constraints and concern over the attitude rate control problem led NASA to decline to cooperate in this mission.

Plans for FY 1988 and FY 1989. ESA will complete a Phase B design study on the GRADIO mission in mid-1988. NASA's offer to cooperate in a Delta-II launch of the full geopotential mission, without time constraint, is still open. Discussions are now taking place with CNES for a bilateral NASA-CNES geopotential mission flying the GRADIO instrument, GPS receiver, and both French and U.S. magnetometers. It is expected that all these options will be resolved by the end of 1988.

Superconducting Gravity Gradiometer Mission (SGGM)

In 1983 NASA began support of the development of a superconducting gravity gradiometer at the University of Maryland. This instrument would be capable of an accuracy of 10^{4} Eötvös (10^{9} sec^{1}), roughly a thousand times greater than the accuracy of GRADIO. Such an instrument would be an attractive payload instrument for orbital flights about other planetary bodies in the solar system, and would be capable of measuring quantities of interest to the relativistic physics community. Laboratory operation of this instrument, for example, would be capable of measuring possible deviations from the inverse square law of gravitation to unprecedented accuracy.

Formidable design problems exist in designing such an instrument and planning its space flight. A 15-year design and planning period was anticipated when NASA became involved in this project, and at present it appears that this schedule should be met. An interagency study team has been formed for the SGGM, and a Phase A study will be completed in mid-1988 by a team led by Marshall Space Flight Center.

In the meantime, the Gravity Probe-B (GP-B) project being conducted by the Astrophysics Division of NASA is being studied for ways of obtaining gravity information from that project by inclusion of a GPS receiver and possibly corner-cube retroreflectors on the GP-B spacecraft, and by sharing technology with the GP-B project.

Magnetic Field Explorer (MFE)

In addition to the low-altitude magnetic field measurements planned for GRM and its possible successor geopotential research missions, there is a strong scientific rationale for flying a magnetic field satellite at higher altitude but for much longer duration: only in this way can the secular changes of the geomagnetic field be measured—data which is regarded as vital for the construction of models of the dynamo action in the Earth's core which is responsible for the existence of the geomagnetic field. Ideally, a succession of satellites could be flown, so that vector and scalar magnetometers could be in orbit continuously for a period of decades. In order to separate the internal geomagnetic field from fields externally generated (in the magnetosphere, for example), it is also desirable to have two or more magnetic field satellites in different orbit at the same time. By adding additional instruments to such satellites, e.g., electric field instruments and particle wave detectors, their measurements can be usefully applied to studies of ionospheric and magnetospheric physics.

To meet these requirements, NASA is now considering several missions. One is a small Scout-launched Explorer mission in which the magnetometers would be copies of those carried by Magsat-A in 1979 in addition to the magnetospheric physics instruments. Another is a joint project of the NASA Magnetic Field Explorer and the CNES Magnolia mission, MFE/Magnolia. This spacecraft would carry both French and American magnetometers, and be launched together with a SPOT satellite, on an Ariane launch vehicle in about 1994. Magnetospheric physics instruments would also be carried on this flight.

Mission to Planet Earth

Earth Observing System (Eos)

Eos combines concepts and elements of previous NASA flight programs to address the broad range of scientific challenges which we must meet in order to better understand our world and how it is changing. Eos is designed as a long-term, interdisciplinary and multidisciplinary, interagency research mission which is international in scope. Emphasis is put on the study of global-scale processes that shape and influence the Earth as a system. Eos will carry a comprehensive set of instruments in low Earth orbit (LEO) to measure the Earth's atmosphere, oceans, land surface, and interior. Observations made from four platforms in low Earth orbit will provide global coverage of these phenomena with sampling frequencies ranging from 6 hours to 5 days. (See Figure 12-5 for one Eos conceptual payload scenario, courtesy of JPL.)

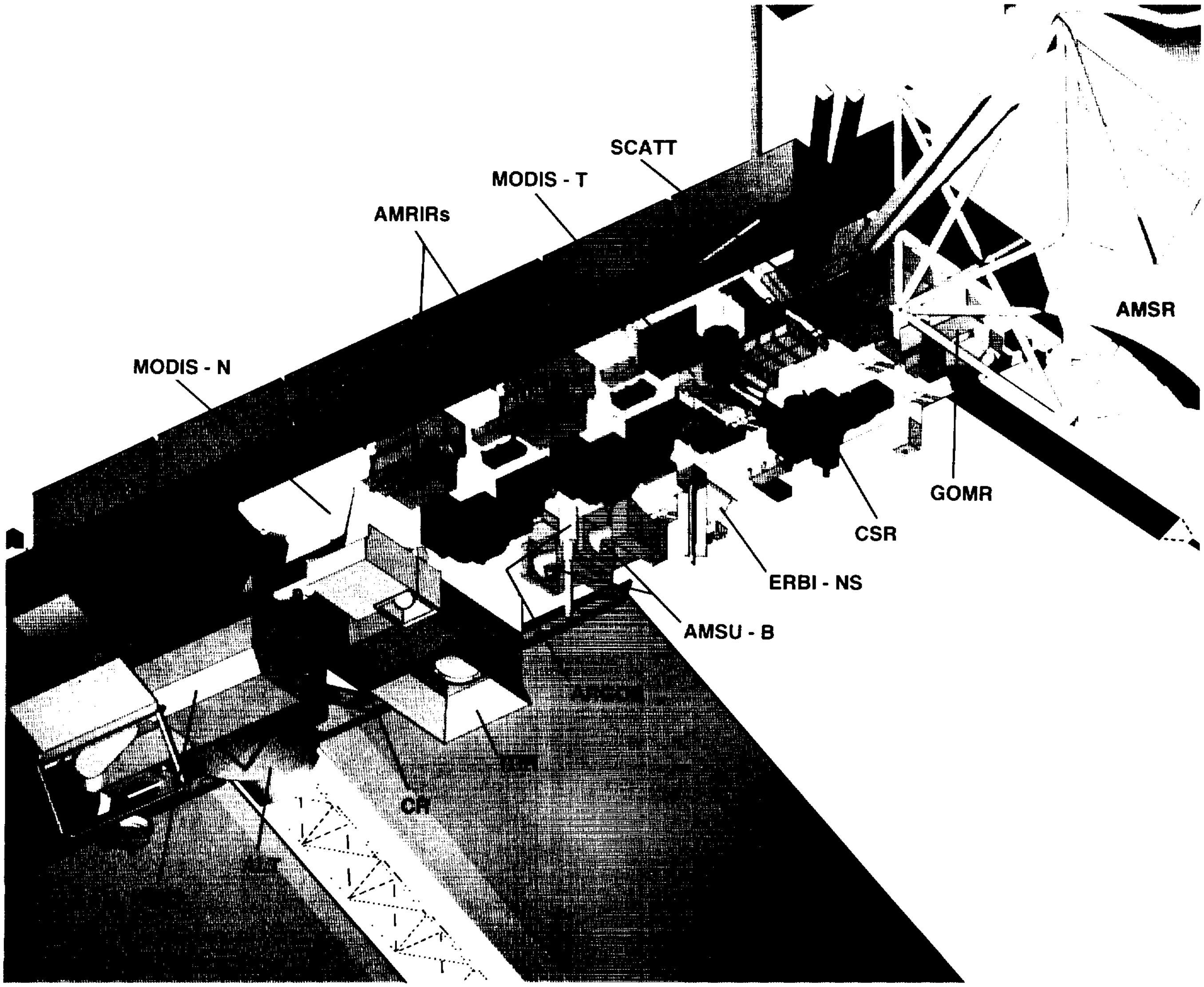
Eos must be thought of not as a collection of hardware, but as a complete research information system capable of acquiring and maintaining long-term, calibrated, self-consistent, time-series data bases of Earth observations and of providing access to non-Eos data and research results obtained using Eos data.

The Eos concept advances our capacity for observing the Earth by providing a number of long-term platforms in space from which to do scientific research. It is an evolutionary program with an observing capability to be built up over time. Eos will be maintained for up to 15 years to provide the long-term data base required to understand the Earth, and the global changes taking place upon it, with sensors and/or parts of sensors and platform subsystems being robotically replaced as needed. Current plans call for the launch of two instrumented, Space Station-derived, polar-orbiting platforms, one in late 1996 (NASA) and another in 1997 (ESA). Both will orbit at 824 km. Also in 1997 a second NASA platform is planned for earliest-possible launch in the same orbit as the first NASA platform. A Japanese platform is planned for launch in 1998. The platforms will be shared by research and operational instruments. In addition, certain Eos payload elements may make use of the 28.5 degree-inclination, low-altitude orbit (335-460 km) opportunity being provided by the manned Space Station. A key feature of the platform design will be the provision for servicing in orbit. Both the space platforms and most sensors will be designed in modular fashion to permit replacement of major subsystems. This will allow updating of the instrumentation and the use of the Eos platforms to fulfill a broad range of scientific requirements over an extended lifetime.

The Eos mission is starting a 2-year Phase B study in anticipation of an FY 1991 new start. As part of the completion of Phase A during the past year or so, a series of reports from seven working committees has been published. These include:

- The Eos Mission Implementation Report, *Pattern to Process: The Strategy of the Earth Observing System*, takes the earlier two-volume Science and Mission Requirements Working Group Report *Earth Observing System*, which identifies the mission's generic science requirements, and converts its recommendations into actual flight mission scenarios and more specific plans for sensors and mission implementation.

FIGURE 12-5. **EOS CONCEPTUAL PAYLOAD SCENARIO** (courtesy of JPL)



- Reports of six Instrument Panels, made up of NASA and non-NASA scientists, who have studied the specific characteristics of the following instrument concepts: Moderate Resolution Imaging Spectrometer (MODIS), LIDAR Atmospheric Sounder and Altimeter (LASA), High Resolution Multifrequency Microwave Radiometer (HMMR), High Resolution Imaging Spectrometer (HIRIS), Synthetic Aperture Radar (SAR) and Laser Atmospheric Wind Sounder (LAWS). The panels converted the generic science specifications completed earlier into quantitative instrument requirements.
- The Altimetric System Panel Report, which defines a complete altimetric system capable of perpetuating the data set to be derived from TOPEX/POSEIDON, thus enabling key scientific questions (both discipline-specific and multidisciplinary) to be addressed.
- The Report of the Panel on Eos Data System Characteristics, which studied how to deal with the vast amount of data that will be generated by Eos, both in terms of transmittal to the ground and of the manipulation needed to make it accessible to researchers.

In January 1988 a NASA Announcement of Opportunity was released inviting proposals for instrument investigations for flight on the polar platforms and/or manned Space Station including secondary science payloads for flight on the polar platforms; Research

Facility instrument team member and team leader investigations for the six NASA Research Facility instruments; and Interdisciplinary Investigations for data analysis and modeling, preparing for and using Eos. Proposals are also solicited for scientific investigations which involve either Earth observing instruments for flight as attached payloads on the manned Space Station or non-Earth observing instruments to fly in polar orbit with Eos, as secondary science payloads. Coordinated Announcements of Opportunity were also released by Japan's Science and Technology Agency (STA) and the European Space Agency (ESA).

The NASA Research Facility instruments expected to be included in the Eos payloads are the Moderate Resolution Imaging Spectrometer (MODIS); the High Resolution Imaging Spectrometer (HIRIS); the Synthetic Aperture Radar (SAR); the Geodynamics Laser Ranging System (GLRS); the Laser Atmospheric Wind Sounder (LAWS); and the Atmospheric Infrared Sounder (AIRS).

In addition, NOAA and other operational entities plan to provide a set of Operational Facility instruments comprising the Advanced Microwave Sounding Unit (AMSU) for measuring atmospheric temperature and humidity; the Advanced Medium Resolution Imaging Radiometer (AMRIR): the Global Ozone Monitoring Radiometer (GOMR); the Space Environmental Monitor (SEM); the Earth Radiation Budget Instrument (ERBI); a Scatterometer (SCATT-1) and an Altimeter (ALT-1).

The Japanese research instruments to be flown are the Advanced Microwave Scanning Radiometer (AMSR) and the Intermediate Thermal Infrared Radiometer (ITIR). ESA will fly the Moderate Resolution Imaging Spectrometer (MERIS); the High Resolution Imaging Spectrometer (HRIS); an Atmospheric Lidar (ATLID); a Scatterometer (SCATT-2); an Altimeter (ALT-2); and a C-band Synthetic Aperture Radar (SAR-C).

The key to the success of the Eos mission lies in the successful implementation of the Eos Data and Information System (EosDIS). The EosDIS will:

- Provide for the command and control of the space elements of the mission
- Receive, process, analyze, and store all data from the mission and the detailed results of research conducted using the data
- Provide for the distribution of data to the selected investigators, the exchange of research results among selected investigators, and the information services necessary to conduct the science
- Provide access for the Earth science and applications research community to all Eos data and, as a precondition of data access, to the results of research making use of this data.

Thus, a fully realized EosDis will provide the data-handling infrastructure for space-based Earth science research in the 1990s, and will be central to the dissemination of Eos data across the Earth science community.

Eos Instruments

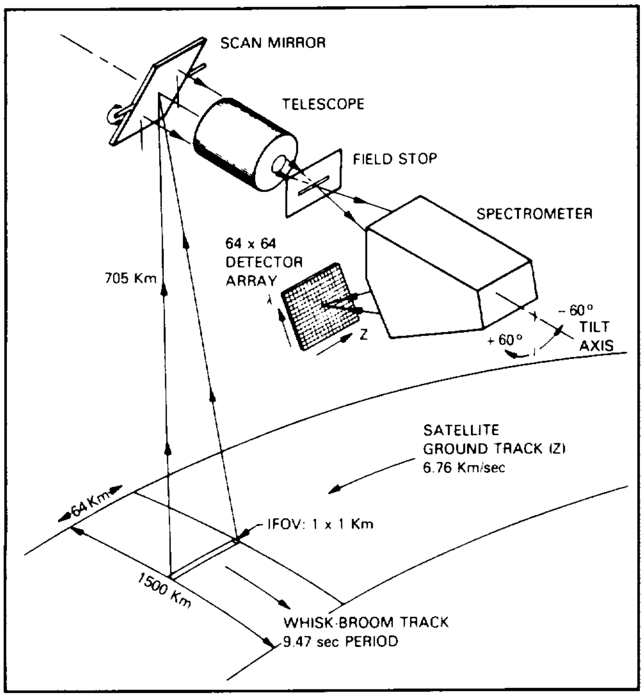
Moderate Resolution Imaging Spectrometer (MODIS). The report of the MODIS Instrument Panel, formed in mid-1984 to further define the scientific requirements and generate a set of sensor parameters, was published in 1986. MODIS, as presently conceived, is a system of two imaging spectroradiometer components, MODIS-N and MODIS-T, designed for the widest possible applicability to research tasks and capable of frequent, long-term, global surveys at spatial resolution of 0.5 to 1 km for studying terrestrial, oceanic and atmospheric properties. The sensor requirements defined by the terrestrial, oceanographic and atmospheric subgroups on the Instrument Panel included:

- A view of 20 to 60 degrees fore and aft of nadir for ocean observations and land bidirectional reflectance studies
- The capability to perform uninterrupted long-term global ocean surveys
- Minimum atmospheric path radiance for routine terrestrial sensing

Because these requirements were incompatible with a single-sensor package, the optical component of the MODIS system will be divided into two packages, MODIS-T (tilt), with a pointing or tilting capability, and MODIS-N (nadir). MODIS-T (see Figure 12-6) would contain visible and near-infrared channels, and be capable of viewing fore and aft relative to nadir. MODIS-N would include all required channels in the visible and near-infrared and also those in the thermal infrared, where cooled detectors are necessary, but fore and aft viewing is not required.

Data from both optical components will be of interest to many, if not all, users and should be considered as a single data set. Complete spatial coverage will be possible during fore-aft tilt operations, which is especially useful along coastlines for both terrestrial and oceanic applications, and will aid in the required intercalibration of the T and N components. The system is preliminary and subject to scientific and technological review and modification, although the basic concept is likely to remain unchanged.

FIGURE 12-6. **MODIS-T SCAN GEOMETRY AND CONCEPTUAL SYSTEM LAYOUT**



Current Status. The MODIS Facility is scheduled for the first Space Station Polar Platform, which has a planned launch date of October 1995. A Request for Proposals on the Phase B Definition Study of MODIS-N was issued in November 1987, to help further define instrument requirements. Five proposals were received in response, of which two are being selected for concurrent Phase B studies over a 1-year period to summer 1989. The two sets of findings will then undergo open synthesis to put together a specification and statement of work for Phases C and D. A Science Team, of about ten U.S. and five international members, will be in place by mid-1989. In-house development at GSFC on MODIS-T Phase B definition is progressing, with detailed design to begin in the fall of 1990. Both instruments are to be delivered by January 1994.

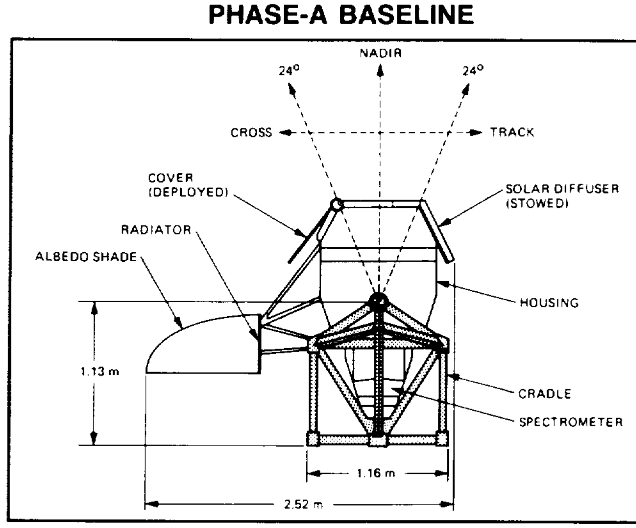
High Resolution Imaging Spectrometer (HIRIS). HIRIS is an Eos sensor developed for high spatial and high spectral resolution. It can acquire more information in the 0.4-2.5 micrometer spectral region than any other sensor yet envisaged, making it an ideal complement to MODIS and AMSR, which are lower resolution sensors designed for repetitive coverage. HIRIS (see Figure 12-7) is intended as a targeting instrument that will acquire data at specified times and places rather than continuously, and offers an intermediate level in a multistage sampling program between in situ field data and global mapping instruments.

Imaging spectrometry enables virtually all information available in the return signal to be extracted. For example, HIRIS observations will allow many minerals to be directly identified; suspended sediments from phytoplankton in near-surface waters to be separated; atmospheric effects over waters with higher concentrations of matter to be removed; and will permit selective mapping of various continental and maritime aerosols over clear water, improving ability to correct for atmospheric effects in near-land scenes. In addition, the characteristics of soils and vegetation can be evaluated separately, and vegetation stress, associated with soil excesses or deficiencies, can be detected. HIRIS can measure key attributes of the atmosphere, such as aerosol loading and composition, and can provide cloud characteristics information useful for calculating their climatic effects. The instrument will also be valuable in analyzing certain snow characteristics.

The large volume of HIRIS data will require a disciplined approach to data processing. The planned data system will allow maximum flexibility in the number of bits and number of bands transmitted to the surface, within constraints imposed by the available data rate. Information-preserving compression schemes are being studied and experience with scientific use of AVIRIS data will allow evaluation of their potential.

Current Status. The HIRIS Instrument Panel report, justifying the need for and describing the basic features of the HIRIS instrument required to meet the needs of the Earth science community, was published in December 1987. Current planning focuses on detailed

FIGURE 12-7. **CONCEPTUAL LAYOUT OF HIRIS, PHASE-A BASELINE**



system design for both the instrument and its data processing system, in preparation for a new start in FY 1990.

Synthetic Aperture Radar (SAR). The SAR sensor recommended by the SAR Instrument Panel report is based on the technology inherited from the Shuttle Imaging Radar-C (SIR-C). It has two fundamental modes of use:

- Large-scale coverage (global coverage every 3 days) at a moderate resolution (a few hundred meters) which complements MODIS for global monitoring
- Multispectral, multipolarization, high-resolution (tens of meters) imaging to study the details of surface processes, which complements HIRIS

The Eos SAR will be the first orbital imaging radar to provide multifrequency, multipolarization, multiple-incidence observations of the entire Earth. It will include L-, C- and X-band frequencies; selectable polarizations for both transmit and receive channels; and selectable incidence angles from 15 to 52 degrees. (The X-band portion of the instrument is to be provided by the Federal Republic of Germany in collaboration with Italy. The German/Italian team is already working on providing the X-band system for the Shuttle instrument SIR-C.) The instrument will have three main viewing modes: a local high-resolution mode with typically 25-m resolution and 50-km swath width; a regional mapping mode with 100-m resolution and up to 200-km swath width; and a global mapping mode with typically 500-m resolution and up to 700-km swath width, this last allowing global coverage in 3 days. SAR provides imagery that characterizes the physical properties (e.g., morphology, roughness, dielectric properties, geometric shapes) of the land, vegetation, snow and ice cover, and the oceans. These observations are acquired independent of cloud or sunlight, thus allowing all-time observation, a key requirement for observing dynamic phenomena.

Laser Atmospheric Wind Sounder (LAWS). The Laser Atmospheric Wind Sounder (LAWS) is also designated a facility instrument in Eos and is under study as an attached payload for the Space Station. It will provide global-scale measurements of wind profiles from the Earth's surface to altitudes of 10-15 km. LAWS will use a pulsed lidar to measure the line-of-sight Doppler shift in the backscattered signal from atmospheric aerosols. The system will be scanned conically about the nadir axis to direct lidar shots from several different angles into a common region. Optimized algorithms will derive profiles of horizontal winds from the line-of-sight velocities and navigation parameters.

The baseline LAWS design contains a CO_2 isotope laser (9.11-micrometer wavelength, with a pulse energy of 10J, variable pulse rate from 1 to 10 Hz, and pulse length of 7 microseconds), a 1.5-m diameter transmit and receive telescope, a nadir angle of 45 degrees and a scan rate of 6 rpm. For a Space Station orbital altitude of 400 km, these system parameters provide a swath width of 827 km, a vertical resolution of 1 km, and a horizontal resolution of 100 km with 16 shots per wind estimate. Data from LAWS will appear as swaths of wind profiles along the satellite ground track. Observing system simulation studies at NASA and elsewhere have shown that these data will be better assimilated into Numerical Weather Prediction (NWP) models than measurements of temperature and pressure, and, furthermore, that inclusion of direct wind measurements will significantly increase NWP forecast skill. These improvements will be important in regions where ageostrophic conditions predominate, particularly in the tropics.

Plans for FY 1988 and 1989. Feasibility and conceptual design phase studies of LAWS have been initiated in FY 1988, utilizing the extensive heritage of lasers applied to atmospheric remote sensing.

Lidar Atmospheric Sounder and Altimeter (LASA). The Lidar Atmospheric Sounder and Altimeter (LASA) is designated a facility instrument as part of the Eos payload. As originally conceived, LASA would provide vertical profiles of several atmospheric constituents (most notable of which is atmospheric water vapor), surface altimetry for a variety of surface types (most notable of which are ice and snow surfaces), and laser ranging to retroreflectors placed for geodynamical investigations. However, the instrument has undergone several modifications. The technological requirements for retroranging were quite different from the requirements for atmospheric sounding, so a separate instrument, to be known as the Geodynamics Laser Ranging System (GLRS), has evolved. (GLRS is described below.) It has also been shown that the GLRS possesses the capability to determine surface altimetry--especially for highly reflective surfaces such as ice or snow. The remaining capability for atmospheric profiling has been focused primarily on that constituent needed to better understand the hydrological cycle, namely high-resolution vertical profiles of atmospheric water vapor and of temperature.

Geodynamics Laser Ranging System (GLRS). As mentioned above, the GLRS facility is being developed for flight on the Eos. The GLRS would provide frequent global coverage of highly seismic areas with a single laser in space ranging sequentially to a large number of corner-cube retroreflectors on the ground, and would respond quickly to assess the extent of crustal deformation following major earthquakes. The variation of crustal strain in highly seismic areas requires frequent mapping of the positions of a large number of locations. Considering all of the major seismic areas in the world, the number of sites which should be monitored at least several times per year amounts to several thousand. The GLRS is seen as a rapid and inexpensive way of measuring deformations related to earthquake hazards, and as a way of involving many Third World countries that have real societal concerns about earthquakes.

Current Status. Conceptual (Phase A) studies are underway at GSFC, and will be followed by the initiation of Phase B studies in FY 1989. Fabrication of the GLRS is planned to begin in FY 1990, with an expected flight date of 1996.

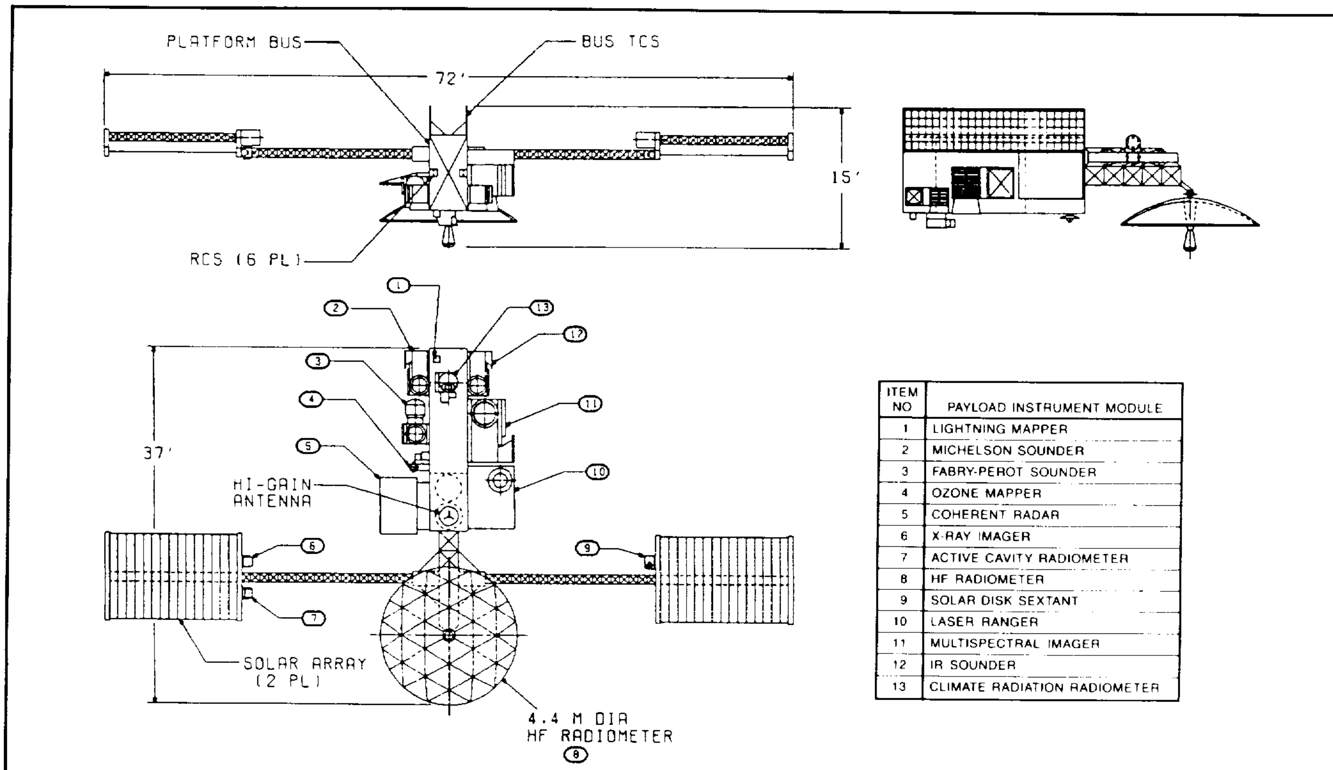
Geostationary Platform

The GEO part of the Space Station complex is planned for flight in 1999. Pre-Phase A study activities are underway for the Earth sciences observations to be made on this platform. The concept of the geostationary platform (see Figure 12-8 for one concept) has undergone some change and participation is now being opened up not only to other agencies of the U.S. Government, but also to commercial organizations and participants from agencies in other countries.

An Earth sciences working group on the geostationary platform, composed of scientists representing each of the Earth science disciplines, as well as representatives from NOAA and ESA, has been organized to define and articulate the science requirements for GEO-Eos. In June 1988 the working group selected some six facility instruments which best complemented suggested Eos instruments and best met the multidisciplinary requirements of the GEO mission. The vast quantity of data expected from Eos also suggests that the platform should offer a broadband communications system and data networking option for Eos data. This also implies that the geostationary platform should be launched within the same time frame as Eos.

As a result of these efforts, a report will be issued later in 1988 describing the science objectives and observational requirements. Subsequently, an AO will be issued for scientific participation and instrument development pertaining to the Earth sciences portion of the geostationary platform. Other instruments may be incorporated into the program at that time.

FIGURE 12-8. **ONE GEOSTATIONARY PLATFORM CONCEPT - BUS AND PAYLOAD ARRANGEMENT**



ITEM NO	PAYLOAD INSTRUMENT MODULE
1	LIGHTNING MAPPER
2	MICHELSON SOUNDER
3	FABRY-PEROT SOUNDER
4	OZONE MAPPER
5	COHERENT RADAR
6	X-RAY IMAGER
7	ACTIVE CAVITY RADIOMETER
8	HF RADIOMETER
9	SOLAR DISK SEXTANT
10	LASER RANGER
11	MULTISPECTRAL IMAGER
12	IR SOUNDER
13	CLIMATE RADIATION RADIOMETER

TABLE 12-1. **EOS INITIAL OPERATIONAL CONFIGURATION: INSTRUMENTS AND OBJECTIVES**

Part 1. Eos Baseline Deployment Scenario: Initial Operational Configuration (IOC)

Instrument Classification	Platform 1 Launch 1996	Platform 2 Launch 1997-98	Platform 3 Launch 1996
Research	MODIS MERIS HIRIS ITIR AMSR CR MAG MPD	SAR SUB-MM IR-RAD F/P-INT MLS SUSIM MAG MPD PEM	SAR-C HRIS ATLID AMIR GLRS MAG MPD
Operational	AMSU (2) AMRIR (2) SEM		AMSU (2) AMRIR (2) SEM
Current Research/ Projected Operational	ALT ERBI SCATT GOMR		ALT ATSR ERBI SCATT
Other	ARGOS + DB P/L-EX PPS-PODS S&R	DB P/L-EX	ARGOS + DB PPS-PODS S&R

NOTE: A fourth Eos platform, projected for launch in 1997-98, has recently been included in the NASDA (Japan) long-range plan.

Part 2. Eos Instruments: Initial Operational Configuration (IOC)

Instrument	Source/Platform	Objectives
ALT: Radar Altimeter	NOAA/1;ESA/3	Ocean circulation, surface topography
AMIR: Advanced Microwave Imaging Radiometer	Europe/3	Snow and ice extent and character, sea surface winds, atmospheric water vapor, surface temperature
AMRIR: Advanced Medium Resolution Imagery Radiometer[a]	NOAA/1,3	Surface temperature, snow and ice extent, cloud properties, atmospheric temperature and water content
AMSR: Advanced Microwave Scanning Radiometer	Japan/1	Precipitation rate, snow and ice extent and character, sea surface winds, atmospheric water vapor, surface temperature
AMSU: Advanced Microwave Sounding Unit[a]	NOAA-U.K/1,3	Surface temperature, atmospheric water content, atmospheric temperature
ARGOS + : French satellite-borne data relay and platform location system[b]	France/1,3	Data relay and location of ground-based measurement platforms
ATLID: Atmospheric Lidar	ESA/3	Aerosols and atmospheric parameters
ATSR: Along Track ScanningRadiometer	U.K.-Australia/3	Sea surface temperature, atmospheric corrections
CR: Correlation Radiometer	PI/1	Tropospheric composition (carbon monoxide)
DB: Direct Broadcast	NOAA/1,2,3	Communications and data distribution
ERBI: Earth Radiation Budget Instrument	NOAA/1,3	Earth radiation budget on regional, zonal, and global scales
F/P-INT: Fabry-Perot Interferometer	PI/2	Upper atmosphere wind velocities

Part 2. Eos Instruments: Initial Operational Configuration (IOC)—(Continued)

Instrument	Source/Platform	Objectives
GOMR-Global Ozone Monitoring Radiometer	NOAA/1	Total ozone column content and profile
HIRIS: High Resolution Imaging Spectrometer	NASA/1	Biological activity, land surface composition
HRIS: High Resolution Imaging Spectrometer	ESA/3	Biological activity, land surface composition
IR-RAD: Infrared Radiometer	PI/2	Composition of upper atmosphere, aerosols
ITIR: Imaging Thermal Infrared[c]	Japan/1	Surface temperature, surface composition, biological activity
MAG: Magnetosphere Current/Fields	PI/1,2,3	Measurements of magnetospheric currents and fields
MERIS: Medium Resolution Imaging Spectrometer[d]	ESA/1	Ocean biological activity, land surface composition and biological activity, total aerosol column content, cloud properties
MLS: Microwave Limb Sounder	PI/2	Upper atmosphere composition and pressure
MODIS: Moderate Resolution Imaging Spectrometer[e]	NASA/1	Biological activity, land surface composition, snow and ice extent, aerosols, cloud properties, surface temperature, atmospheric temperature profiles
P/L-EX: Payload Executive	NASA/1,2	Optimization of instrument use, support of Direct Broadcast
PEM: Particle Environment Monitor	PI/2	Magnetospheric energy input into the atmosphere
PPS-PODS: Precise Position System-Precise Orbit Determination System	PI/1,3	Precise determinations of position and orbit
S&R: Search and Rescue	NOAA/1,3	Search and rescue operations
SAR: Synthetic Aperture Radar	NASA-FRG/2	Land surface composition, topography, snow and ice extent and character, sea-ice extent and character, ocean waves, wetlands extent, soil moisture
SAR-C: Synthetic Aperture Radar-C Band	ESA/3	Sea-ice extent and character, snow and ice extent and character, ocean waves, wetlands extent, soil moisture, topography, land surface composition
SCATT: Scatterometer	NOAA/1:ESA/3	Sea surface wind velocities
SEM: Space Environment Monitor	NOAA/1,3	Monitoring of particles and fields environment
SUB-MM: Submillimeter Spectrometer	PI/2	Composition of upper atmosphere
SUSIM: Solar Ultraviolet Spectral Irradiance Monitor	PI/2	Solar spectral irradiance

(a) The AMRIR, AMSU instrument pair supersedes the current AVHRR, HIRS operational instruments
(b) The French ARGOS + system supersedes the U.S. Advanced Data Collection and Location System
(c) The Japanese ITIR instrument supersedes the U.S. Thermal Imaging Spectrometer (TIMS) instrument
(d) The European Space Agency's MERIS instrument is essentially similar to and could replace the U.S. MODIS-Tilt instrument
(e) The MODIS instrument listed here includes the MODIS-Nadir and MODIS-Tilt instruments

Part 3. Eos Instrument Candidates, Post-IOC

Instrument	Source	Objectives
CIS: Cryogenic Interferometer/ Spectrometer	U.S.-International	Composition of upper atmosphere
ESTAR: Electronically Steered Thinned Array Radiometer	U.S.-International	Surface soil moisture
LASA: Laser Atmospheric Sounder and Altimeter	NASA	Tropospheric state and composition, atmospheric temperature, atmospheric moisture, cloud-top properties, surface vegetation
LAWS: Laser Atmospheric Wind Sounder	NASA	Tropospheric winds
NCIS: Nadir Climate Interferometer/ Spectrometer	U.S.-International	Tropospheric composition
SAR-X: Synthetic Aperture Radar-X Band	Japan	Land surface composition, topography, snow and ice extent and character, sea-ice extent and character, ocean waves, wetlands extent, soil moisture
VIS-UV: Visible/Ultraviolet Spectrometer	U.S.-International	Composition of upper atmosphere

Appendices

Appendix A.

Earth Science and Applications Division Budget Summaries
FY 1984 — FY 1989

PROGRAM	FY 1984	FY 1985	FY 1986	FY 1987	FY 1988+ (a)	FY 1988+ (b)	FY 1989+ (a)	FY 1989+ (b)
ERBE	15.5	8.1	1.9	—	—	—	—	—
UARS	20.0	55.7	114.0	113.8	95.4	89.6	100.0	103.9
Scatterometer	—	12.0	14.0	32.9	22.7	22.7	16.0	15.8
TOPEX	—	—	—	18.9	90.0	75.0	98.0	97.8
Global Geospace Science	—	—	—	—	25.0	—	102.0	—
PAYLOADS								
Solid Earth Observations	17.0	12.1	21.8	21.4	21.1	20.8	25.6	25.3
Environmental Observations	7.6	7.8	5.3	4.7	4.1	4.1	4.8	5.2
Collaborative Solar-Terrestrial (COSTR)	—	—	—	5.0	15.0	—	44.0	—
Tether Payloads	—	0.9	1.6	5.5	3.4	—	3.7	—
OPERATING SATELLITES								
Mission Operations & Data Analysis:								
Earth Science	12.6	11.0	16.7	19.5	14.8	14.8	18.5	18.5
Space Plasma Physics	14.8	18.5	18.3	14.1	12.0	—	8.5	—
RESEARCH AND ANALYSES								
Upper Atmosphere	28.4	31.0	31.1	32.7	34.4	32.7	35.8	34.0
Oceanic Processes	18.2	19.4	17.4	18.0	21.5	20.2	22.2	21.6
Atmospheric Dynamics/Radiation	27.5	28.5	28.7	31.3	32.9	31.4	34.3	32.8
Space Plasma Physics	16.8	16.7	16.8	20.8	21.5	—	23.0	—
Interdisciplinary Research	—	1.0	1.0	1.1	1.1	1.1	1.2	1.2
Geodynamics	28.0	29.9	21.9	23.2	24.2	23.6	25.3	24.7
Land Processes	14.6	15.6	19.1	19.4	22.6	21.1	23.7	22.9
Eos	—	—	—	—	—	—	15.0	14.5
Airborne Science	—	—	—	—	—	21.9	—	23.0
Laser Network Operations	—	—	8.1	8.4	8.9	8.8	9.4	9.2
TOTAL (Dollars In Millions)	221.0	268.2	335.8	390.7	470.6	387.8	611.0	450.4
ESTIMATED REIMBURSABLE SATELLITE DEVELOPMENT FUNDS								
NOAA	50.0	95.0	65.0	50.0	25.0	25.0	90.0	90.0
GOES	60.0	95.0	145.0	115.0	120.0	120.0	210.0	210.0
TOTAL (Dollars in Millions)	110.0	190.0	210.0	165.0	145.0	145.0	300.0	300.0

+ Presidential Request

(a) Prior to the reorganization of the Earth Science and Application Division, October 1987, and prior to Appropriation Realignment.

(b) Post-reorganization of the Division, and post-Appropriation Realignment.

Appendix B.

Acronyms List

ABLE	Atmospheric Boundary Layer Experiment
ACMOWG	Aircraft Science Management and Operations Working Group
ACN	Applications/Commercialization Notice
ACR-I	Active Cavity Radiometer-I
ACRIM	Active Cavity Radiometer Irradiance Monitor
ADEOS	Advanced Earth Observing Satellite (Japan)
AEM-2	Atmosphere Explorer Mission
AFGWC	Air Force Global Weather Center
AIS	Airborne Imaging Spectrometer
AIRS	Atmospheric Infrared Sounder
ALT-2	Altimeter (ESA)
AMAC	Aerospace Medicine Advisory Committee
AMMS	Advanced Microwave Moisture Sensor
AMPR	Advanced Microwave Precipitation Radiometer
AMPTE	Active Magnetospheric Particle Tracer Explorers
AMSR	Advanced Microwave Scanning Radiometer
AMSU	Advanced Microwave Sounding Unit
AO	Announcement of Opportunity
AOL	Airborne Oceanographic LIDAR
AOS	Archive and Operations System
APT	Automatic Picture Transmission
ARC	Ames Research Center
ARMAR	Airborne Rain Mapping Radar
ASAS	Advanced Solid State Array Spectrometer
ASF	Alaskan SAR Facility
ATLAS	Atmospheric Laboratory for Applications and Science
ATLID	Atmospheric Lidar
ATMOS	Atmospheric Trace Molecules Observed by Spectroscopy
AVHRR	Advanced Very High Resolution Radiometer
AVIRIS	Airborne Visible Infrared Imaging Spectrometer
BASD	Ball Aerospace Systems Division
BMFT	West German Ministry for Research and Technology (Bundesministerium für Forschung und Technologie)
BRESEX	Brazilian Remote-Sensing Experiment
CAMS	Calibrated Airborne Multispectral Scanner
CCDS	Centers for Commercial Development of Space
CCE	Charge Composition Explorer
CDHF	Central Data-Handling Facility (UARS)
CDP	Crustal Dynamics Project
CEOS	Committee on Earth Observing Systems
CISD	Communications and Information Systems Division
CITE	Chemical Instrumentation Test and Evaluation
CLAES	Cryogenic Limb Array Etalon Spectrometer
CLS	Cloud Lidar System
CNES	French National Center for Space Studies (Centre National d'Etudes Spatiales)
CNR	National Research Council of Italy (Consiglio Nazionale delle Recerche)
CRRES	Combined Release and Radiation Effects Satellite
C-SAR	C-Band Synthetic Aperture Radar
CS	Color Scanner
CTS	Cloud Top Scanner
CZCS	Coastal Zone Color Scanner
DCS	Data Collection System
DE	Dynamics Explorer
DMSP	Defense Meteorological Satellite Program
DoD	Department of Defense
DOE	Department of Energy
EOIS	Earth Observing Information System
EOM	Earth Observation Mission
Eos	Earth Observing Satellite
EOSAT	Earth Observation Satellite Co.
EosDIS	Eos Data and Information System
ERB	Earth Radiation Budget Instrument
ERBE	Earth Radiation Budget Experiment
ERBS	Earth Radiation Budget Satellite

EROS	Earth Resources Observation System
ERS-1	Earth Remote Sensing Satellite (ESA)
ESA	European Space Agency
ESAD	Earth Science and Applications Division
ESMR	Electrically Scanning Microwave Radiometer
ESN	Earth Science Net
ESSC	Earth System Sciences Committee
FAA	Federal Aviation Administration
FASINEX	Frontal Air-Sea Interaction Experiment
FIFE	First ISLSCP Field Experiment
FIRE	First ISCCP Regional Experiment
FNOC	Fleet Numerical Oceanography Center
GARP	Global Atmospheric Research Program
GEMS	Global Environment Monitoring System
GEO	Geosynchronous Orbit
GEOS	Geodynamics Experimental Ocean Satellite
Geosat	Navy Geodetic Satellite
GFFC	Geophysical Fluid Flow Cell
GGM	Gravity Gradiometer Mission
GGS	Global Geospace Science Program
GISS	Goddard Institute for Space Studies
GLOBE	Global Backscatter Experiment
GLRS	Geodynamics Laser Ranging System
GOES	Geostationary Operational Environmental Satellite
GOFS	Global Ocean Flux Study
GOLD	Global On-Line Data
GOMR	Global Ozone Monitoring Radiometer
GPS	Global Positioning Satellite System
GRADIO	French Gravity Gradiometer
GRID	Global Resources Information Database
GRIS	Global Resources Information System
GRM	Geopotential Research Mission
GSFC	Goddard Space Flight Center
GTE	Global Tropospheric Experiment
GTO	Geosynchronous Transfer Orbit
HALOE	Halogen Occultation Experiment
HAPEX	Hydrological Atmospheric Pilot Experiment
HCMM	Heat Capacity Mapping Mission
HIRIS	High Resolution Imaging Spectrometer
HIRS	High Resolution Infrared Sounder
HIS	High Resolution Interferometer Sounder
HMMR	High Resolution Multifrequency Microwave Radiometer
HRDI	High Resolution Doppler Interferometer
IACG	Interagency Consultative Group for Space Science
IAU	International Astronomical Union
ICE	International Cometary Explorer
ICSU	International Council of Scientific Unions
IDFS	Ice Data and Forecasting System
IERS	International Earth Rotation Service
IFEOS	International Forum for Earth Observation Using Space Station Elements
IGBP	International Geosphere-Biosphere Program
IML	International Microgravity Laboratory
IMP	Interplanetary Monitoring Platform
IOC	Intergovernmental Oceanic Commission
IPAR	Intercepted Photosynthetically Active Radiation
IPOMS	International Polar-Orbiting Meteorological Satellite
IR	Infrared
IRAP	ISLSCP Retrospective Analysis Program
IRIS	Italian Research Interim Stage
IRM	Ion Release Module (German)
ISAMS	Improved Stratospheric and Mesospheric Sounder (United Kingdom)
ISAS	Institute of Space and Astronautical Sciences (Japan)
ISCCP	International Satellite Cloud Climatology Project
ISEE	International Sun-Earth Explorer
ISLSCP	International Satellite Land Surface Climatology Project
ISO	Information Systems Office
ISTP	International Solar-Terrestrial Physics Program
IUGG	International Union of Geodesy and Geophysics
IUGS	International Union of Geophysical Sciences
IWGDMGC	Interagency Working Group on Data Management for Global Change

JERS-1	Japan's Earth Resources Satellite
JOI	Joint Oceanographic Institutions Inc.
JPL	Jet Propulsion Laboratory
LAGEOS	Laser Geodynamics Satellite
Landsat	Land Remote Sensing Satellite
LASA	LIDAR Atmospheric Sounder and Altimeter
LASE	Laser Atmospheric Sensing Experiment
LAWS	Laser Atmospheric Wind Sounder
LBPMR	L-Band Pushbroom Microwave Radiometer
LEO	Low Earth Orbit
LEWEX	Labrador Sea Extreme Waves Experiment
LFC	Large Format Camera
LIDAR	Light Detection and Ranging
LIMS	Limb Infrared Monitor of the Stratosphere
LLR	Lunar Laser Ranging
LMS	Lightning Mapper Sensor
LSAC	Life Sciences Advisory Committee
LTER	Long Term Ecological Research Site
Magsat	Magnetic Field Satellite
MAMS	Multispectral Atmospheric Mapping Sensor
MAPS	Measurement of Air Pollution from Satellites
McIDAS	Man-Computer Interactive Data Access System
MCR	Microwave Cloud Radiometer
METSAT	Meteorological Satellite
MFE	Magnetic Field Explorer
MIDDS	Meteorological Interactive Data Display System
MIST	Microbursts in Severe Thunderstorms
MIZEX	Marginal Ice Zone Experiment
MLS	Microwave Limb Sounder
MMS	Multimission Modular Spacecraft
MOCS	Multichannel Ocean Color Scanner
MODIS	Moderate Resolution Imaging Spectrometer
MOS	Marine Observation Satellite
MPR	Microwave Precipitation Sounder
MR	Microwave Radiometer
MSFC	Marshall Space Flight Center
MSS	Multispectral Scanner
MSU	Microwave Sounding Unit
MTE	Mesosphere-Thermosphere Explorer
MTS	Microwave Temperature Sounder
NAC	NASA Advisory Committee
NASA	National Aeronautics and Space Administration
NASDA	Japan National Space Agency
NCAR	National Center for Atmospheric Research
NDVI	Normalized Difference Vegetation Index
NEMS	Navigation and Environmental Monitoring System
NEOS	National Earth Orientation Service
NERC	National Environmental Research Centre (United Kingdom)
NESDIS	National Environmental Satellite, Data, and Information Service
NMC	National Meteorology Center
NMD	NASA Master Directory
NOAA	National Oceanographic and Atmospheric Administration
NODC	National Oceanography Data Center
NODS	NASA Ocean Data System
NOSS	National Oceanic Satellite System
NPSS	NASA Packet Switched System
NRA	NASA Research Announcement
NRC	National Research Council
N-ROSS	Navy Remote Ocean Sensing System
NSCAT	NASA Scatterometer
NSF	National Science Foundation
NSI	NASA Science Internet
NSIDC	National Snow and Ice Data Center
NSN	NASA Science Network
NSSDC	National Space Science Data Center
NSTL	National Space Technology Laboratories
NWP	Numerical Weather Prediction
OCI	Ocean Color Imager
OCS	Ocean Color Scanner
ODAS	Oceanographic Data Acquisition System
OMB	Office of Management and Budget
ONR	Office of Naval Research

OSIP	Operational Satellite Improvement Program
OSSA	Office of Space Science and Applications
OTSR	Optimum Track Ship Routing
PDMP	Project Data Management Plan
PEM	Particle Environment Monitor
PIDAS	Portable Instant Display and Analysis Spectrometer
PIMS	Plasma Interations Monitor System
PIPOR	Programme for International Polar Oceans Research
PLDS	Pilot Land Data System
PODS	Pilot Ocean Data System
POES	Polar-Orbiting Operational Environmental Satellite
PROMIS	Polar Region and Outer Magnetosphere International Study
PSCN	Program Support Communications Net
PSN	Piano Spaziale Nationale (Italy)
Radarsat	Radar Satellite (Canada)
RGS	Receiving Ground Station
ROCOZ	Rocket Ozone Correlation Program
ROWS	Radar Ocean Wave Spectrometer
RTOP	Research and Technology Objectives and Plans
S&R	Search & Rescue System
SAAC	Space Applications Advisory Committee
SAGE	Stratospheric Aerosol and Gas Experiment
SAIS	Science and Applications Information System
SAM II	Stratospheric Aerosol Measurement II
SAMS	Stratospheric and Mesospheric Sounder
SAR	Synthetic Aperture Radar
SBUV	Solar Backscatter Ultraviolet Spectrometer
SCATHA	Space Charge at High Altitude
SCOSTEP	Scientific Committee on Solar-Terrestrial Physics
SCR	Surface Contouring Radar
Seasat	Sea Satellite
Sea-WiFS	Sea-Wide Field Sensor
SEM	Space Environment Monitor
SESAC	Space and Earth Science Advisory Committee
SGG	Supercooled Gravity Gradiometer
SGGE	Supercooled Gravity Gradiometer Experiment
SGGM	Supercooled Gravity Gradiometer Mission
SIR	Spaceborne Imaging Radar
SISEX	Shuttle Imaging Spectrometer Experiment
SLR	Satellite Laser Ranging
SME	Solar Mesosphere Explorer
SMM	Solar Maximum Mission
SMMR	Scanning Multispectral Microwave Radiometer
SODSSWG	Satellite Ocean Data System Science Working Group
SOHO	Solar and Heliospheric Observatory (ESA)
SOLSTICE	Solar-Stellar Intercomparison Experiment
SPACE	Satellite Precipitation and Cloud Experiment
SPAN	Space Physics Analysis Network
SPOT	Systeme Probatoire d'Observation de la Terre (France)
SRB	Surface Radiation Budget
SRL	Shuttle Radar Lab
SSAAC	Space Science and Applications Advisory Committee
SSBUV	Shuttle Solar Backscatter Ultraviolet spectrometer
SSEC	Space Science and Engineering Center
SSM/I	Special Sensor Microwave Imager
SST	Sea Surface Temperature
SSU	Stratospheric Sounding Unit
STA	Science and Technology Agency (Japan)
STEP	Solar-Terrestrial Energy Program
STEP	Stratosphere-Troposphere Exchange Project
STO	Solar-Terrestrial Observatory
STORM	Storm Scale Operational and Research Meteorology
STP	Space Test Program
STS	Shuttle Transportation System
SUSIM	Solar Ultraviolet Spectral Irradiance Monitor
SVI	Spectral Vegetation Index

SWADE	Surface Wave Dynamics Experiment
TDRSS	Tracking and Data Relay Satellite System
TEA	Transverse Excited Atmospheric Pressure Laser
THEP	TOGA Heat Exchange Program
TIMS	Thermal Infrared Multispectral Scanner
TIROS	Television Infrared Observing Satellite
TM	Thematic Mapper
TMS	Thematic Mapper Simulator
TOGA	Tropical Ocean Global Atmosphere Program
TOMS	Total Ozone Mapping Spectrometer
TOPEX	Ocean Topography Experiment
TRACE	Transport and Chemistry near the Equator Program
TRMM	Tropical Rainfall Measuring Mission
TSS	Tethered Satellite System
TSWG	Topography Science Working Group
TWT	Traveling Wave Tube
UN	United Nations
UARP	Upper Atmosphere Research Program
UARS	Upper Atmosphere Research Satellite
UNEP	United Nations Environment Program
UNESCO	United Nations Educational, Scientific, & Cultural Organization
UNIDATA	University Data Broadcast Project
USDA	U.S. Department of Agriculture
USFS	U.S. Forest Service
USGS	U.S. Geological Survey
VAS	VISSR Atmospheric Sounder
VISSR	Visible and Infrared Spin-Scan Radiometer
VLBI	Very Long Baseline Interferometry
WCRP	World Climate Research Program
WEFAX	Weather Facsimile
WEGENER	Working Group of European Geoscientists for the Establishment of Networks for Earthquake Research
WFF	Wallops Flight Facility
WINDII	Wind Imaging Interferometer (Canada)
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment
WWW	World Weather Watch
X-SAR	X-Band Synthetic Aperture Radar

Appendix C

Bibliography

Committee on Earth Sciences of the Space Science Board, National Research Council. 1982. *A Strategy for Earth Science from Space in the 1980's, Part I: Solid Earth and Oceans*. National Academy Press, Washington, D.C.

Committee on Earth Sciences of the Space Science Board, National Research Council. 1985. *A Strategy for Earth Science from Space in the 1980's, Part II: Atmosphere and Interactions with the Solid Earth, Oceans, and Biota*. National Academy Press, Washington, D.C.

Committee on Planetary Biology of the Space Science Board, National Research Council. 1986. *Towards a Science of the Biosphere*. National Academy Press, Washington, D.C.

Earth System Sciences Committee of the NASA Advisory Council. 1986. *Earth System Science Overview: A Program for Global Change*. National Aeronautics and Space Administration, Washington, D.C.

Earth System Science Committee of the NASA Advisory Council. 1988. *Earth System Science: A Closer View*. National Aeronautics and Space Administration, Washington, D.C.

Earth Observing System (Eos) Reports. National Aeronautics and Space Administration, Washington, D.C.

Vol. I *Science and Mission Requirements Working Group Report*, 1984

Vol. II *From Pattern to Process: The Strategy of the Earth Observing System*. Science Steering Committee Report.

Vol. IIa *Data and Information System*. Data Panel Report, 1986.

Vol. IIb *MODIS. Moderate-Resolution Imaging Spectrometer*. Instrument Panel Report, 1986.

Vol. IIc *HIRIS & SISEX. High-Resolution Imaging Spectrometry: Science Opportunities for the 1990s*. Instrument Panel Report, 1987.

Vol. IId *LASA. Lidar Atmospheric Sounder and Altimeter*. Instrument Panel Report, 1987.

Vol. IIe *HMMR. High-Resolution Multifrequency Microwave Radiometer*. Instrument Panel Report, 1987.

Vol. IIf *SAR. Synthetic Aperture Radar*. Instrument Panel Report, 1987.

Vol. IIg *LAWS. Laser Atmospheric Wind Sounder*. Instrument Panel Report, 1987.

Vol. IIh *Altimetric System*. Panel Report, 1987.

Global Tropospheric Chemistry Panel, Board of Atmospheric Sciences and Climate of the Commission on Physical Sciences, Mathematics, and Resources, National Research Council. 1984. *Global Tropospheric Chemistry: A Plan for Action*. National Academy Press, Washington, D.C.

Jet Propulsion Laboratory, California Institute of Technology. 1982. *Global Change: Impacts on Habitability, A Scientific Basis for Assessment*. California Institute of Technology, Pasadena, California.

National Oceanic and Atmospheric Administration, U.S. Department of Commerce, and National Aeronautics and Space Administration. 1987. *Space-Based Remote Sensing of the Earth and Its Atmosphere: A Report to the Congress*. U.S. Government Printing Office, Washington, D.C.

Office of Science and Technology Policy of the Executive Office of the President. 1985. *Earth Sciences Research in the Civil Space Program*. Washington, D.C.

Satellite Planning Committee of the Joint Oceanographic Institutions Incorporated (JOI). 1984. *Oceanography from Space: A Research Strategy for the Decade 1985-1995*. JOI, Washington, D.C.

Space and Earth Science Advisory Committee, NASA Advisory Council. 1986. *The Crisis in Space and Earth Science: A Time for a New Commitment*. NASA Advisory Council, Washington, D.C.

Space Applications Board, Commission on Engineering and Technical Systems of the National Research Council. 1985. *Remote Sensing of the Earth from Space: A Program in Crisis*. National Academy Press, Washington, D.C.

U.S. Committee for an International Geosphere-Biosphere Program of the Commission on Physical Sciences, Mathematics, and Resources, National Research Council. 1986. *Global Change in the Geosphere-Biosphere: Initial Priorities for an IGBP*. National Academy Press, Washington, D.C.

World Meteorological Organization, Global Ozone Research and Monitoring Project, Report No. 16. *Atmospheric Ozone 1985: Assessment of our Understanding of the Processes Controlling its Present Distribution and Change*. 3 vols. 1985.