

# Space-Based Remote Sensing of the Earth



**A Report to the Congress  
September 1987**

# **SPACE-BASED REMOTE SENSING OF THE EARTH**

## **A REPORT TO THE CONGRESS**

Prepared by:

**National Oceanic and Atmospheric Administration  
United States Department of Commerce**

**and**

**National Aeronautics and Space Administration**

Contributing Agencies:

Agency for International Development  
Department of Agriculture  
Department of Defense  
Department of Energy  
Department of the Interior  
Department of State  
Department of Transportation  
Environmental Protection Agency  
National Science Foundation

September 1987

**COVER:** This color image of the Earth, taken on September 1, 1985, was derived from the Visible and Infrared Spin Scan Radiometer Atmospheric Sounder (VAS) of NOAA's Geostationary Operational Environmental Satellite (GOES) and was made possible by a processing technique developed by Goddard Space Flight Center.

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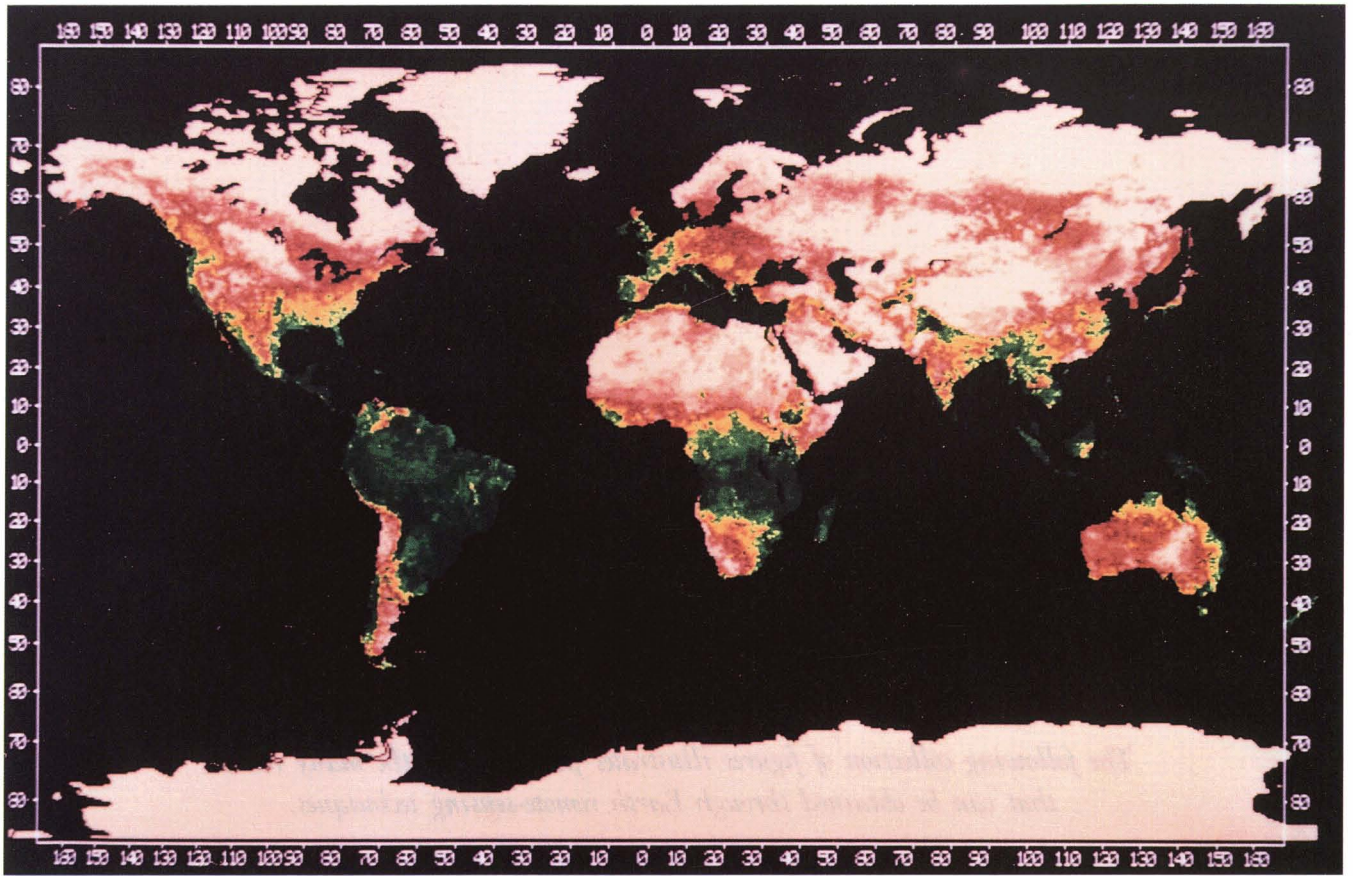
## Abstract

The legislation calling for the commercialization of the Landsat Satellites, Public Law 98-365, requires that the National Oceanic and Atmospheric Administration (NOAA) and the National Aeronautics and Space Administration (NASA) jointly prepare and submit to the Congress a biennial series of reports on remote-sensing research and development applied to the Earth and its atmosphere. This report responds to the 1985 and 1987 Congressional reporting requirements and reviews ongoing Federal research programs in the remote sensing of land, oceans, and atmosphere. The report discusses objectives, progress, and accomplishments as of May 1, 1987. It identifies major gaps in our knowledge of the Earth and its atmosphere and derives a series of space-based measurement objectives. The near-term (approximately through 1992) space observations programs of the United States and other countries are detailed. The report represents the start of the planning process to develop an integrated national program for research and development in Earth remote sensing for the remainder of this century and describes the many existing and proposed satellite and sensor systems that the program may include. NASA and NOAA have been the primary authors; other agencies have provided information on remote-sensing applications that their missions require, and they have reviewed this version of the report. In the future, an even more interactive process will be established to ensure that the national plan continues to represent agency, private sector, and academic needs. This document is designed for agency-level planning purposes and does not represent the Administration's approval or support of any program not included in the President's budget request. Programs discussed in this document are subject to budget constraints and Administration approval.

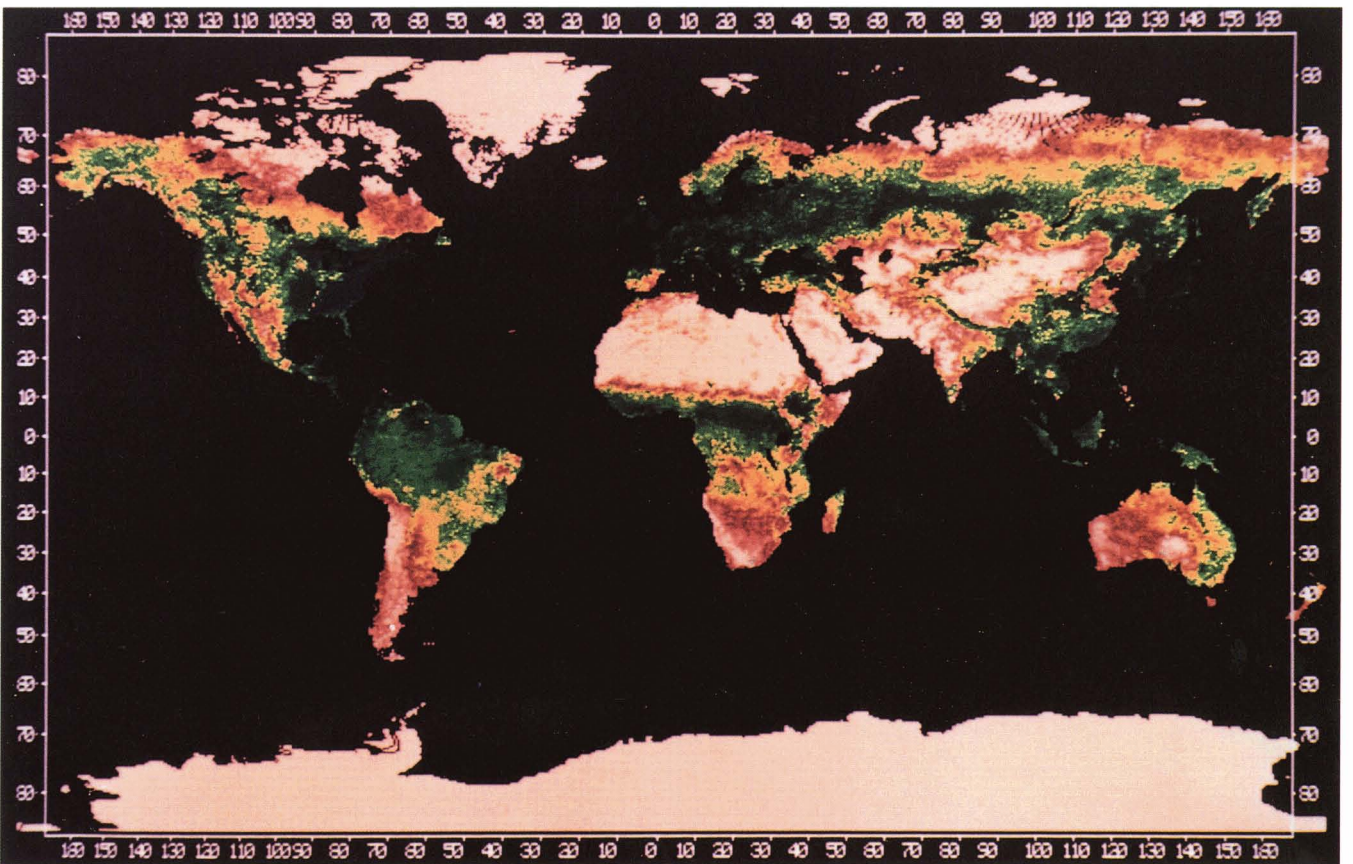




*The following collection of figures illustrates just a few of the many results that can be obtained through Earth remote-sensing techniques.*



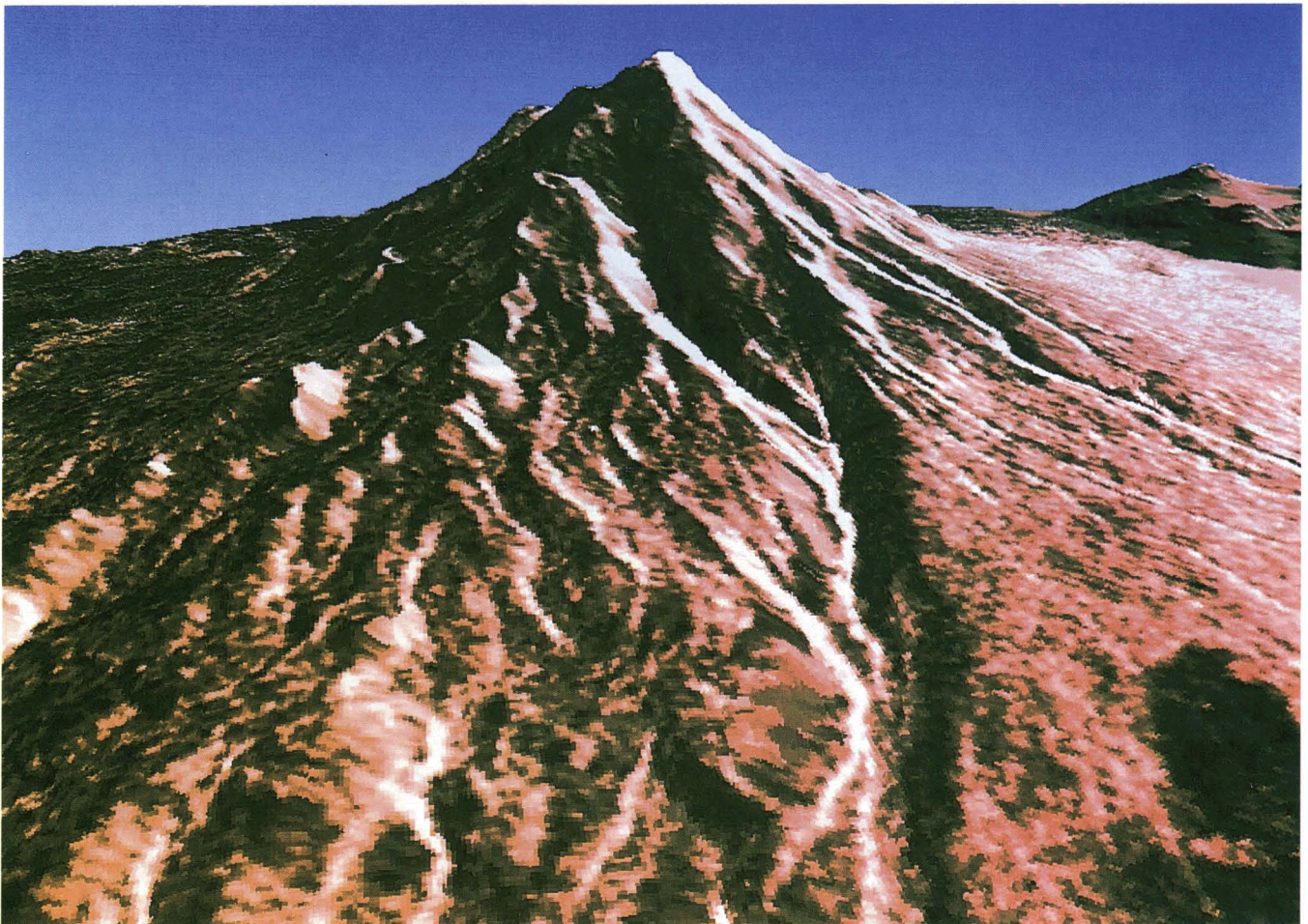
(a)



(b)

FIGURE 1. (a and b) The differential reflectance of green vegetation between the visible and reflected infrared wavelengths measured by instruments aboard NOAA's operational polar-orbiting satellites enable global generation of vegetation index images. The daily maps are composited over several days, saving the maximum index value, to minimize the effects of cloudiness. The two parts of this figure contrast the vegetation conditions for March and June 1983. Regions with dense vegetation appear dark green; deserts and nonvegetated areas are light beige. Note the increased greenness of the Northern Hemisphere at the beginning of the summer in June, in contrast with that at the end of the winter in March.

FIGURE 2. Perspective view generated from SIR-B data of Mt. Shasta, one of the Cascade volcanoes located in northern California. Two stereo SIR-B images of the 14,000-foot mountain were combined to create a digital topographic map, which was then used to reproject one of the images into the scene that would have been seen by a camera located in an aircraft at 20,000 feet. Colors in the picture are proportional to radar brightness, from dark green (radar dark), through pink, to white (radar bright). The relief has been exaggerated by 50 percent in this view. This is a significant result because this image was generated entirely from information contained in the two radar images. SIR-B was the first spaceborne radar that acquired images that made this type of image processing possible.



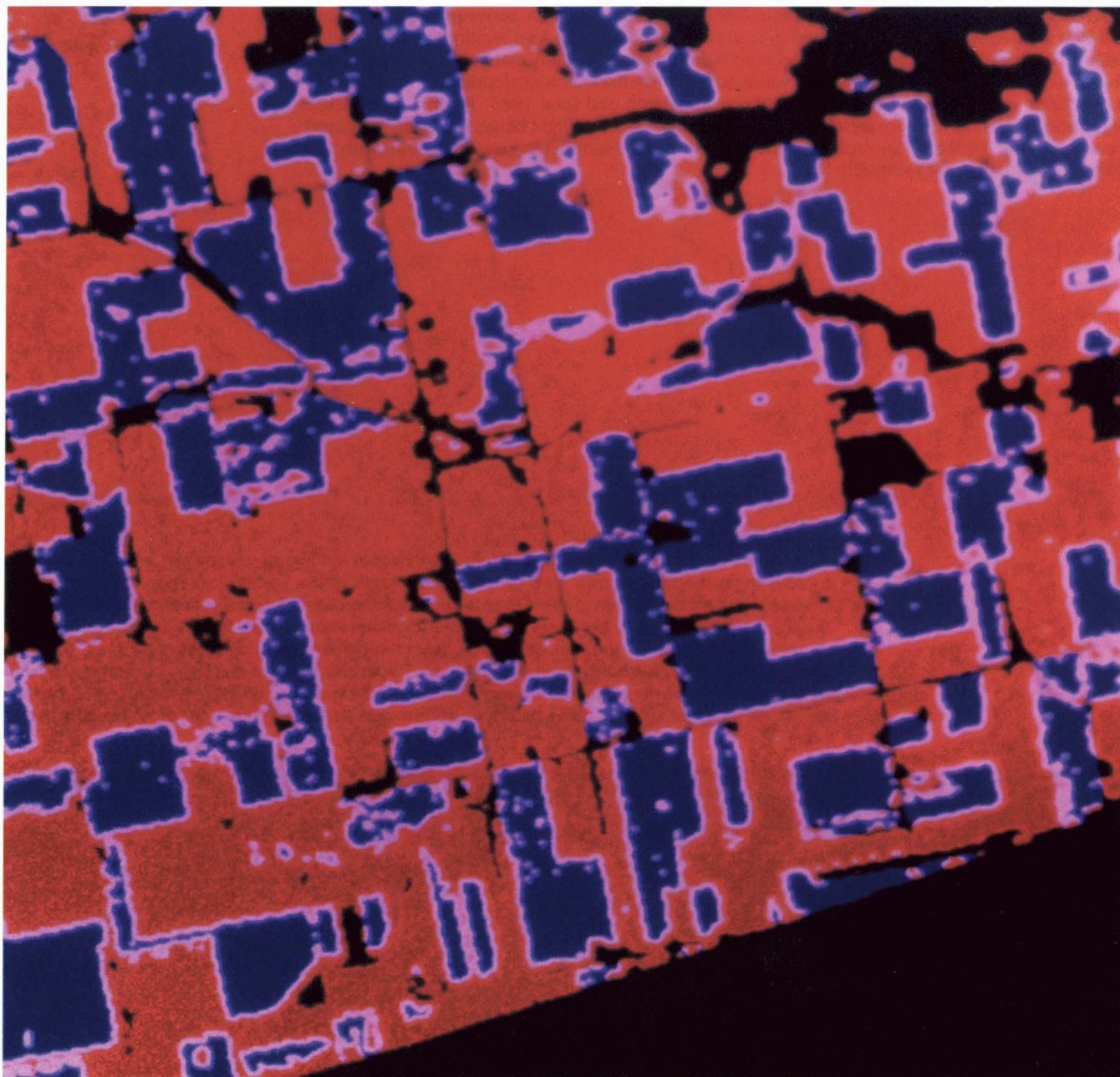
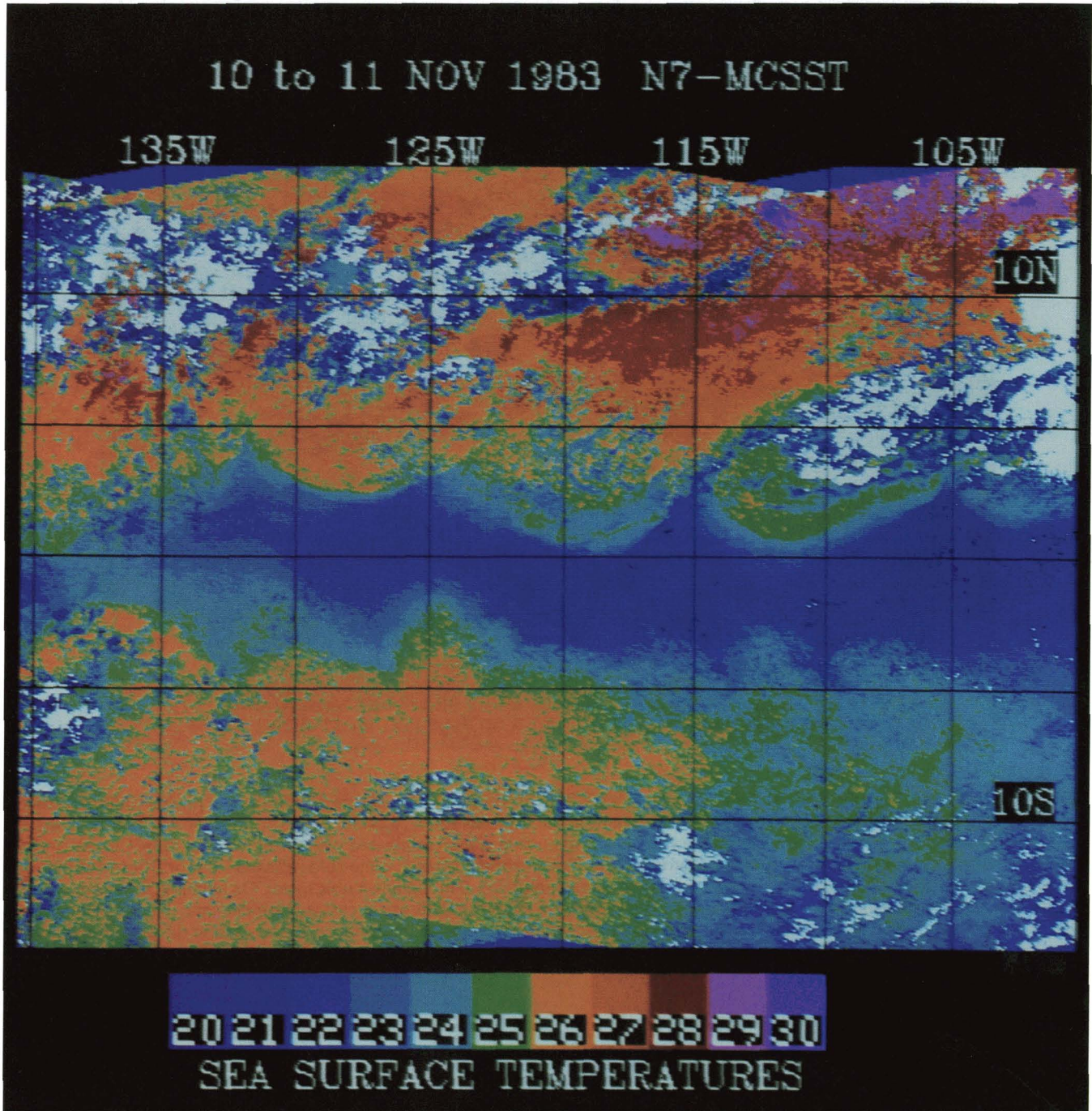


FIGURE 3. The Landsat Thematic Mapper (TM), with ground resolutions as fine as 30 meters and seven channels in the visible, near-infrared, and infrared, collects crop data that can be classified into land cover categories based on the spectral signatures of the crops. The figure shows a color-coded vegetation classification map of a TM zone (7 miles wide) of Webster County, Iowa. The red areas are corn, the blue areas are soybeans, and the black areas (within the colored part of the illustration) are other vegetation types. The large black area at the bottom lower right corner of the illustration is the edge of the print and not a part of the other crops classification.

FIGURE 4. The existence of very long waves in the equatorial Pacific Ocean was first revealed in analyses of sea surface temperatures measured by the Advanced Very High Resolution Radiometer (AVHRR) of NOAA's polar-orbiting satellites. These waves appear seasonally at the equatorial sea surface temperature front. The waves are about 1000 kilometers (km) long and move westward at 40 km per day. The waves signify that relatively strong currents are advecting cold water to the west along the equator. Disappearance of the waves occurs every 4-6 years during equatorial warming events (El Niño).



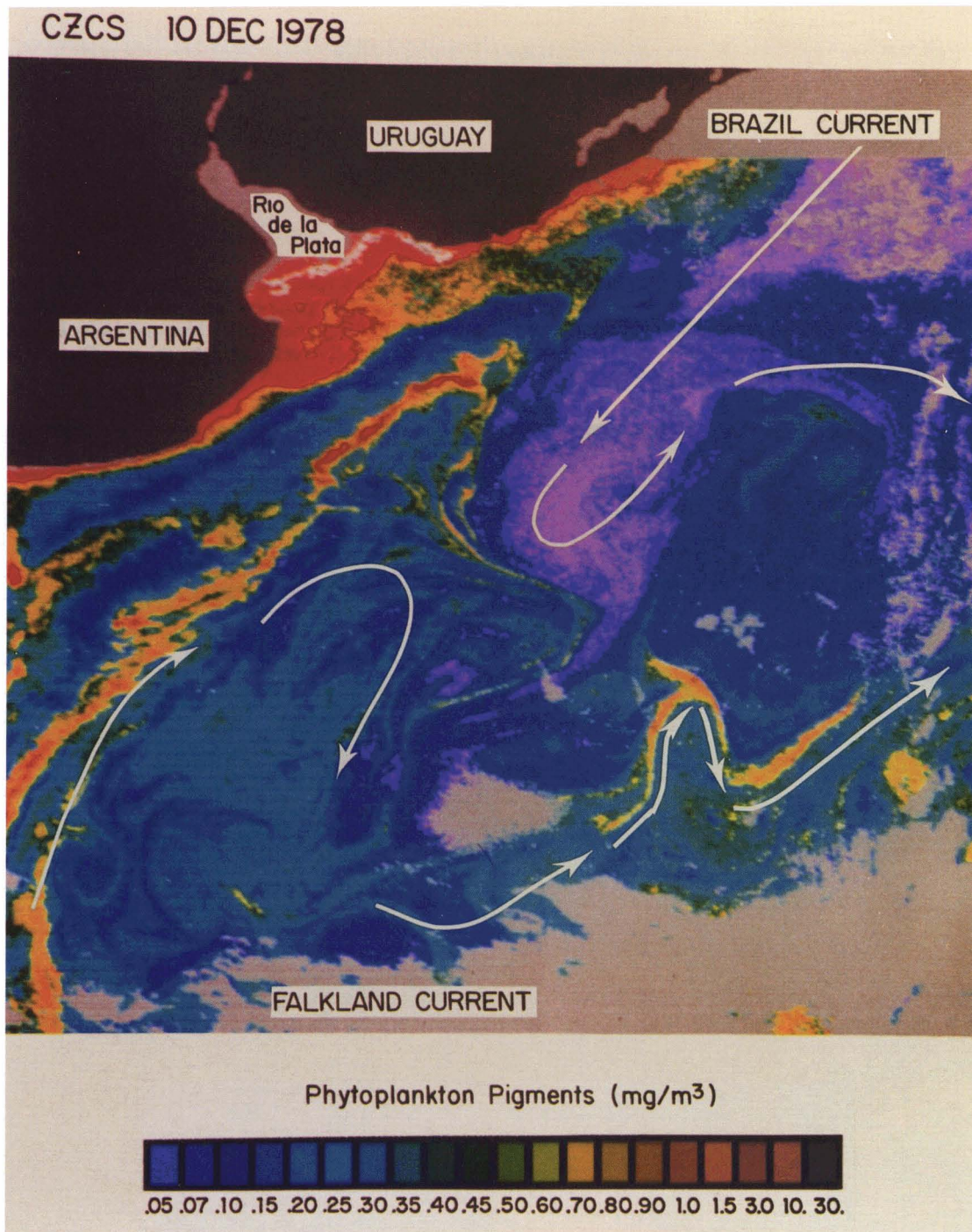


FIGURE 5. This image, from the Coastal Zone Color Scanner (CZCS) of Nimbus-7, depicts the distributions of phytoplankton pigments associated with the confluence of two major current systems in the Western South Atlantic. At the north is the warm Brazil Current, flowing to the south at 1-2 knots. The waters associated with this current system originated with the South Equatorial Current and are poor in nutrients, resulting in very low biological productivity. Flowing from the south is the cold Falkland Current. These nutrient-rich waters support high rates of productivity with concentrations reaching 1.5-3.0 milligrams/cubic meter. On meeting, these two currents swing to the east, forming the South Atlantic Current. Measurements of productivity are necessary to understand the role of the oceans in biogeochemical cycles, such as the carbon dioxide cycle, which is of critical importance to the carbon dioxide-climate issue.

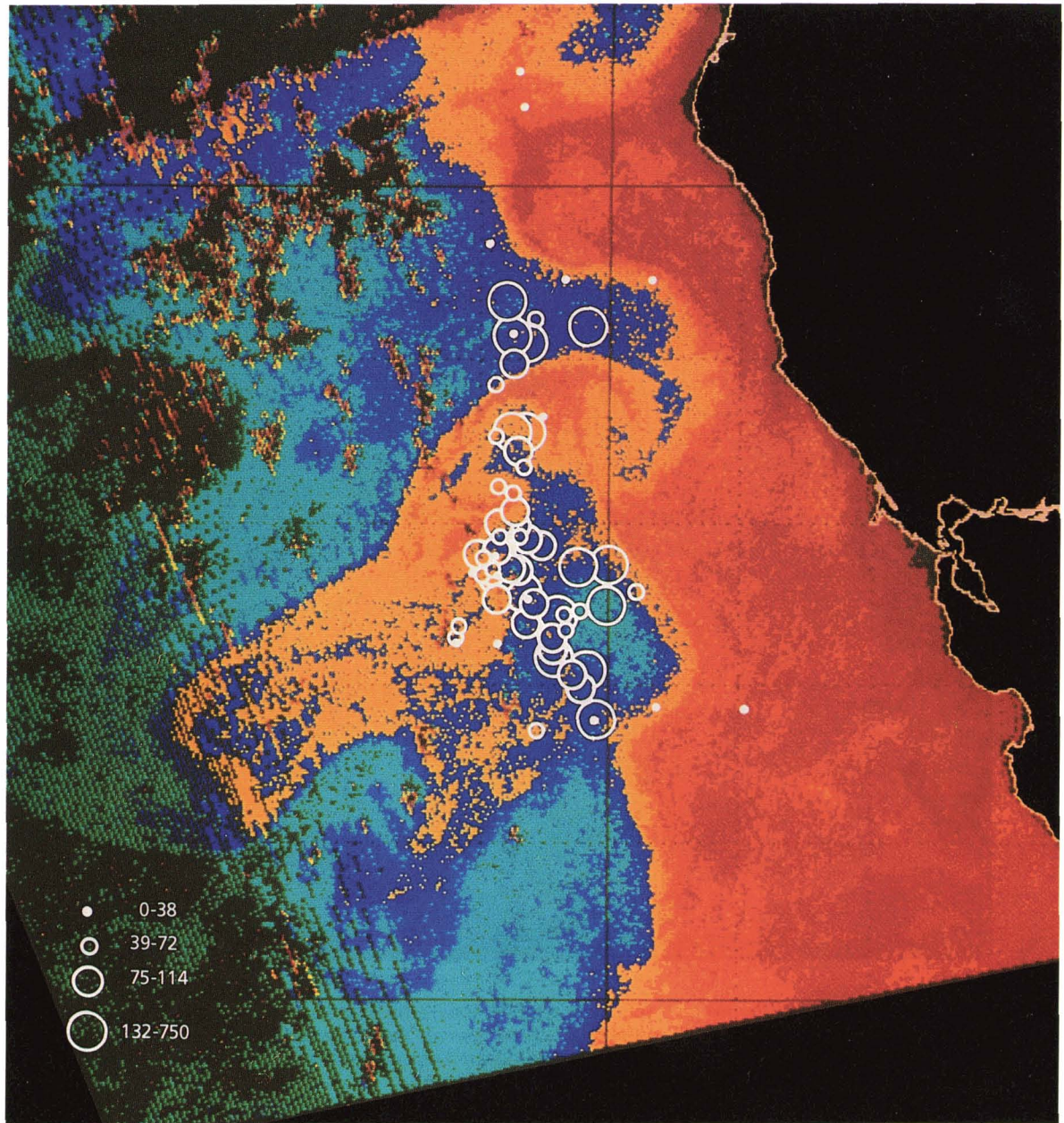


FIGURE 6. The image shows gradations in ocean color off central California, with locations of albacore tuna catches superimposed. The ocean color data were obtained on September 21, 1981 with the Coastal Zone Color Scanner (CZCS) on board NASA's Nimbus-7 satellite. The CZCS data were enhanced to reveal oceanic features and show a transition from coastal waters (red, orange) to offshore regions (blue). The superimposed circles show the size and location of albacore tuna catches from September 19-24, 1981. A comparison of ocean color variations with fish catch data indicates that most of the albacore were caught along the seaward side of the boundary between offshore and coastal waters. At NOAA's Southwest Fisheries Center, CZCS data are used to produce charts showing the locations of favorable fishing areas, widely used by tuna fishermen.



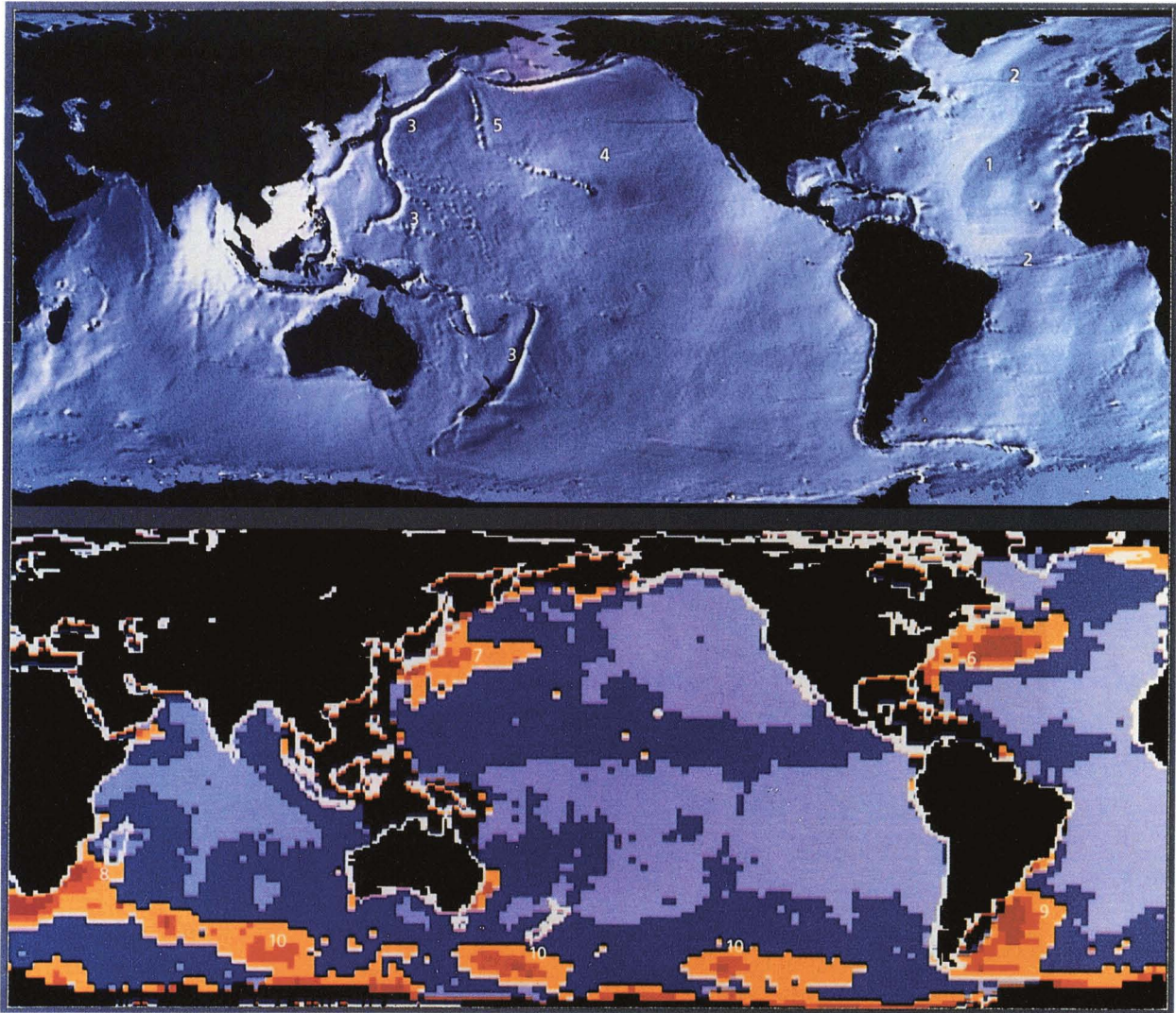
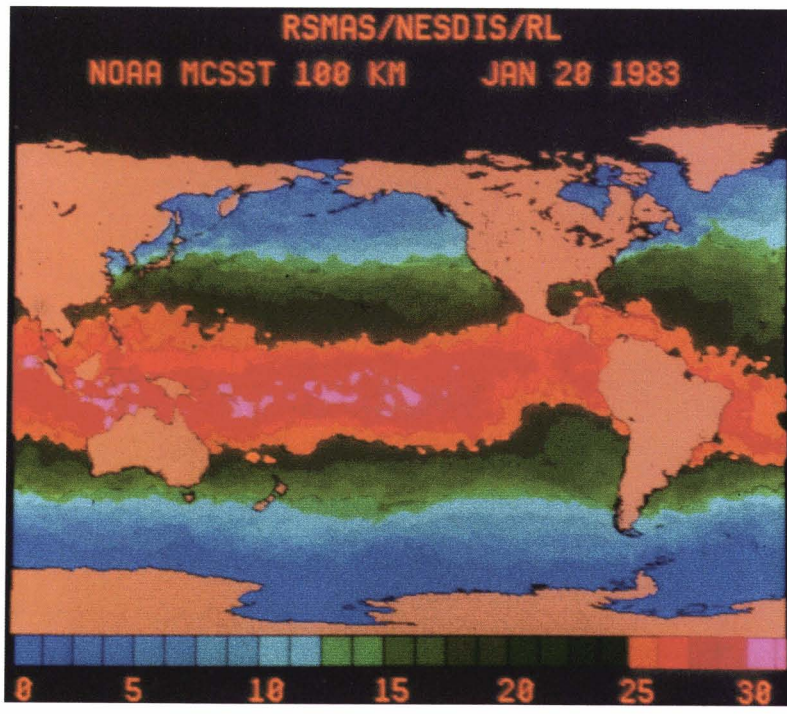


FIGURE 7. This map of the average sea surface topography—the marine geoid—was produced from 70 days of Seasat altimeter data. The results clearly show the relationship between the ocean surface and the changes in gravity caused by the underlying ocean-bottom topography. Because the ocean surface predominantly follows the Earth's geoid, this dramatic image is especially useful for charting poorly surveyed areas.

Sea Surface Topography (top): This image, which has a spatial resolution of about 50 kilometers (31 miles), was computer generated and the changes are revealed as if the map were illuminated from the northwest. Characteristic features of the ocean floor are evident: the mid-ocean ridges, trenches, fracture zones, and seamount chains. Clearly visible are the mid-Atlantic ridge (1) and associated fracture zones (2), the trenches along the west and northwest margins of the Pacific (3), the volcanic Hawaiian Island arc (4), and the Emperor seamount chain (5).

Ocean Currents (bottom): Shown here is a global map of the variability of the sea surface topography about the mean for 1 month during September and October 1978. The largest deviations (10-25 centimeters, or 4-10 inches) are associated with the strong western boundary currents (yellow and orange). These currents include the Gulf Stream (6), the Kuroshio Current (7), the Agulhas Current (8), and the Brazil Falkland Confluence (9). Large variations also occur in the West Wind Drift Current around Antarctica (10). An important revelation from Seasat's mission is the relatively small variability (light blue) over most of the oceans during this month of altimeter measurements.



(a)

(b)

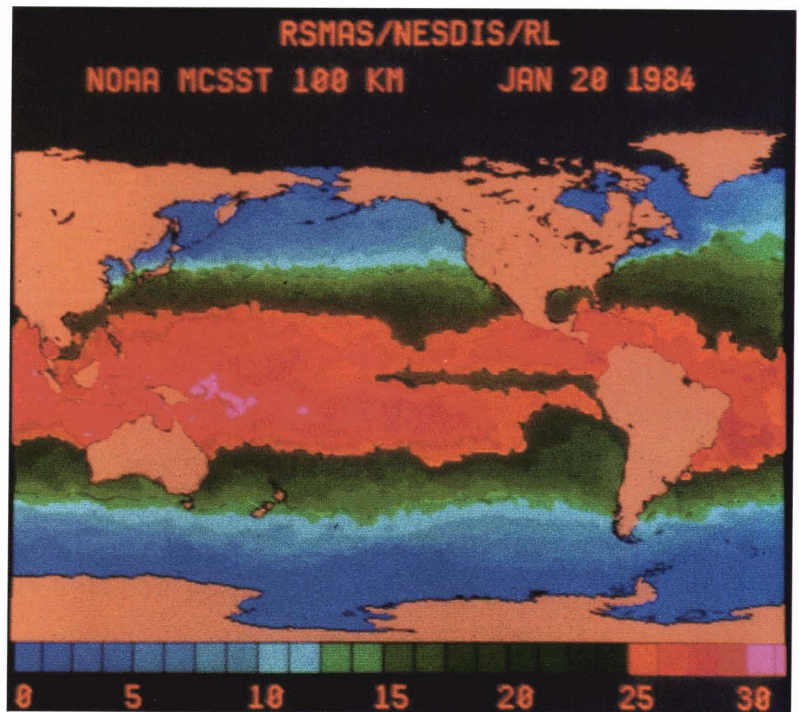


FIGURE 8. (a and b) The distributions of sea surface temperatures (SST) in the Pacific Ocean illustrate the warming that occurred in the equatorial region during the 1982-83 El Niño phenomenon. One year later, the cooler water returned in the eastern equatorial Pacific because of wind-forced upwelling and the westward advection of the Peru Current. The SSTs are derived daily from the Advanced Very High Resolution Radiometer (AVHRR) of NOAA's polar-orbiting satellites. Such anomalous warmings of the Equatorial Pacific lead to various regional climatic fluctuations in the months following El Niño.



# SUMMARY

## Introduction

In April 1960, the United States successfully launched the Television and Infrared Observation Satellite (TIROS), the first satellite for remote sensing of the Earth. This initial remote-sensing effort was significant because it enabled Earth scientists to view our planet from a new perspective: space. For the first time, with the use of instruments flying on Earth-observing satellites, scientists were able to continuously view the entire globe.

Today, the study of the Earth, which includes studying the land, oceans, atmosphere, and their interactions, is advancing because of the continuous regional and global observations provided by satellite remote sensing. Space-based remote sensing is the process of obtaining information about the Earth from instruments flying on Earth-observing satellites rather than by direct in situ observations. As a result of monitoring regional and global variability, Earth scientists have a better understanding of daily weather fluctuations, climate variations, vegetation cover, continental drifts, ocean biological productivity, and ocean circulation. In the future, the data acquired from Earth remote-sensing satellites could enable researchers to understand the causes of natural Earth changes and lead to predictions of such phenomena as volcanic eruptions, earthquakes, and the effects of human activities.

The capabilities and applications of satellite remote sensing have developed tremendously since TIROS' first crude cloud pictures. Today, the U.S. civil space agencies, led by the National Aeronautics and Space Administration (NASA) and the National Oceanic and Atmospheric Administration (NOAA), operate numerous geostationary, sun-synchronous, and polar-orbiting satellites that provide extensive operational and research capabilities. For example, NOAA's Advanced TIROS-N (ATN) series provide data for weather analysis, numerical weather prediction models, climate studies, ozone monitoring, agricultural studies, and hydrological analysis. NOAA's Geostationary Operational Environmental Satellites (GOES), by continuously monitoring cloud development and movements, enable meteorologists to forecast short-term severe weather conditions and provide wind information for longer term weather prediction. Local storm analysis and prediction benefit from the frequent high-density temperature and humidity soundings of the GOES.

NASA's research satellites—particularly those of the Nimbus series—have served as a test bed for much of the instrumentation currently flown on NOAA satellites. The Nimbus series, initiated with the launch of Nimbus-1 in 1964, has provided data used for a variety of scientific research and applications. Ozone layer monitoring is accomplished through stratospheric temperature and composition information. Scientists can now assess the climatic effects of volcanic eruptions through measuring stratospheric aerosols. The changes and chemical composition of the stratosphere are also being analyzed as a result of Nimbus data.

In the field of oceanography, NASA's Nimbus, Geodynamic Experimental Ocean Satellite (GEOS-3), and Seasat research satellites have demonstrated a remarkable ability to measure ocean variables critical to climate and to other national concerns, including fisheries, transportation, defense, and waste disposal. Different types of sensors have provided the research community with measurements that broaden our knowledge of oceanic processes and are expected to prove economically valuable to ocean-related industries. Ship routing, for example, has benefited from ocean wave height measurements. Fish habitats can be inferred from combinations of sea surface temperature and ocean color data, which indicate biological productivity. Knowledge of ocean circulation patterns also has been improved as a result of sea surface wind data. Ocean surface topography has aided in broadening knowledge of ocean currents and the shape of the ocean floor. Sea surface temperature and rainfall estimates in all weather conditions have been used in weather and climate studies. Ocean operations and climate studies have benefited from sea ice concentration measurements. By analyzing ice sheet evaluation data, scientists can also determine whether polar ice caps are growing or melting.

The data provided by the first U.S. experimental land remote-sensing satellite, Landsat, has had worldwide application. The Landsat satellites, with resolution capabilities as fine as 30 meters (approximately 98 feet), have demonstrated the power of space observations in a variety of land science applications. Specifically, Landsat data have been used to detect pollution and to determine vegetation amount, type, and health for agricultural and forestry applications. As a result of monitoring land cover, researchers can determine the effect of human populations on the environment. The Agency for International Development (AID) has used Landsat data for monitoring deforestation in Thailand. Landsat observations, coupled

with aerial photography, were used in the Philippine Government's Forest Inventory Project. Water resources assessments are developed from measurements of snow, lake, and flood extents. In the area of geology, Landsat-provided land surface structure and rock types information are used in assessing mineral and petroleum resources.

In response to the heightened interest in space observations of the Earth, several countries have launched or are planning to launch their own ocean- and land-observing satellites. The United States and the Soviet Union are no longer the only spacefaring nations. Today, the Earth is encircled at the equator by a set of geostationary weather satellites operated by the United States, the European Space Agency, Japan, and India. During the next few years, Canada, France, Japan, India, and the European Space Agency are considering deploying ocean- and land-observing satellites. Japan and France have already launched MOS-1 (Marine Observation Satellite) and SPOT (Système Probatoire d'Observation de la Terre).

There is a growing international interest in global Earth variations, both natural and anthropogenic. Examples of the former include the El Niño phenomenon and its effects on global climate and the intense, long-lasting droughts of the Sahel region of Africa. Anthropogenic concerns include the effects of man-made chemicals on the Earth's climate and ecology and human impact on deforestation and desertification. Nations worldwide are currently embarking on two broad international, interdisciplinary, decadal programs to investigate global processes. The World Climate Research Programme seeks to determine to what extent climate can be predicted and the extent of human influence on climate. The objective of the Global Change Program (formerly the International Geosphere-Biosphere Program) is to understand global changes in the terrestrial environment and its living systems. Space-based observations are expected to play a major role in both programs.

In addition, several far-reaching activities related to the future of Earth science and applications in the United States are currently underway. The Earth System Sciences Committee (ESSC) is reviewing the national scientific objectives for the study of the Earth as a total system and devising and implementing strategies for achieving these objectives. The Office of Science and Technology Policy reviewed and suggested the goals and missions of the various agencies in Earth science research. NASA is studying an Earth Observing System (Eos) for meeting the scientific needs for Earth remote sensing. NOAA's Envirostat-2000 reports support a long-term concept for environmental satellite services. Several committees of the National Academy of Sciences have recently finished, or are currently developing, plans and strategies for Earth science and applications.

Of further significance, on July 17, 1984, the Senate and the House of Representatives of the United States of America enacted Public Law 98-365, the Land Remote Sensing Commercialization Act of 1984. As outlined in the legislation, the purposes of this Act were to

- guide the Federal Government in achieving proper involvement of the private sector by providing a framework for phased commercialization of land remote sensing and by assuring continuous data availability to the Federal Government;
- maintain the United States worldwide leadership in civil remote sensing, preserve its national security, and fulfill its international obligations;
- minimize the duration and amount of further Federal investment necessary to assure data continuity while achieving commercialization of civil land remote sensing;
- provide for a comprehensive civilian program of research, development, and demonstration to enhance both the United States capabilities for remote sensing from space and the application and utilization of such capabilities; and
- prohibit commercialization of meteorological satellites at this time.

Responsibility for continued operation and marketing of the Landsat system has been transferred to the Earth Observation Satellite Company (EOSAT). EOSAT is now responsible for Landsat operation, data distribution, and marketing functions. To enhance present social and economic uses of Landsat data, oil companies, farmers, and Federal agencies will now acquire Landsat data from EOSAT.

The intent of Title V is to require the Federal Government to define a set of research and development goals:

The Secretary and the Administrator of the National Aeronautics and Space Administration shall, within one year after the date of enactment of this Act and biennially thereafter, jointly develop and transmit to the Congress a report which includes (1) a unified national plan for remote-sensing research and development applied to the Earth and its atmosphere; (2) a compilation of progress in the relevant ongoing research and development activities of the Federal agencies; and (3) an assessment of the state of our knowledge of the Earth and its atmosphere, the needs for additional research (including research related to operational Federal remote-sensing space programs), and opportunities available for further progress.

To respond to these specific reporting requirements, representatives for NASA, NOAA, and the other Federal agencies involved in Earth remote sensing have initiated the process of preparing a national plan for research and development in Earth remote sensing. These agencies

contributed material to this report, in particular the missions and the compendium of ongoing research and development activities. For this submission, NASA and NOAA have been the primary authors, with input from other agencies on their specific use of remote sensing for achieving their respective responsibilities.

This report is the result of the first two planning years and is responsive to the 1985 and 1987 Congressional requirements. It marks the beginning of the process of preparing a national plan for research and development in Earth remote sensing, contains a summary of the remote-sensing missions of the Federal agencies; a discussion of the relationship between NASA and NOAA, the two agencies that operate civil remote-sensing satellites; and a compendium of ongoing research and development in Earth remote sensing at these agencies. Also presented in this report is a discussion of the state of our knowledge of the Earth, gaps in our scientific understanding, and current limitations to our applications of remote sensing; a summary of measurement objectives from space that would help to fill these gaps; and the plans for future Earth remote-sensing missions of NASA and NOAA. The report represents the start of the planning process to develop an integrated national program for research and development in Earth remote sensing.

## **Institutional Relationships**

Since the 1960 launch of TIROS, the technology of remote sensing for science, social benefit, and economic gain has evolved to such a mature state of the art that it has become a recognized tool for helping to meet all of these purposes. With this growing reliance on information regarding the physical, chemical, and biological processes, there has also been a growth in the complexity of the user community and information systems needed to satisfy these users. This growth has resulted in a variety of institutional relationships between government, the private sector, and international organizations.

Generally, remote sensing has been recognized as a valuable tool in accomplishing elements of missions of the various governmental agencies. These agencies now use remote sensing from space as key data for such diverse operational responsibilities as the following:

- Land use analyses of cultivation, forestation, and irrigation;
- Water resources management for studies of such phenomena as flood potential and drought;
- Geological mapping; and
- Crop yield and crop stress assessments.

Remotely sensed data from Earth orbit is also of key importance to the research communities participating in the National Science Foundation (NSF) programs for the Earth sciences.

The roles and responsibilities of NOAA and NASA in remote sensing of the Earth have received considerable attention as the maturing of remote-sensing technology and utilization has evolved. In the early stages, NASA's program emphasized the development of remote-sensing technology and Earth-orbiting satellites to determine applicability and usefulness of this capability to the understanding, prediction, and in some cases, management of the Earth's dynamic systems. NOAA's role in satellite remote sensing stemmed mainly from the direct attempt to use this information for operational weather forecasting and to ensure that there was distinct separation of the research and development organization from the primarily operational environment.

In the environment of the 1980s, the NASA/NOAA relationship has changed considerably. The primary objective of NOAA's program is to provide data for the weather and oceanic services and to manage satellite data for land observations. However, there is a growing recognition of the importance of these data to the scientific community in its study of global processes and long-term variability. In response to this expanding use of satellite data, NOAA is examining mechanisms to accommodate the needs of the scientific community for this purpose, including archiving of data sets and calibration of sensors.

NASA's program objectives have also shifted to emphasize the need for structuring a program that provides data to understand the physical, chemical, and biological processes occurring on the Earth. By first establishing the priority needs of the science disciplines, programs for supporting research and technology development can be defined that will contribute to scientific understanding. In general, the program philosophy has emphasized a science lead in ensuring an understanding of the data being acquired. Because instruments developed for the broader range of scientific needs are generally more complex, technology for applications-specific programs will be available for use by industry in developing systems to meet unique needs of a market segment.

To define this evolving basis for the NASA/NOAA relationship, a new "Basic Agreement" between the two agencies has been formulated. The philosophical basis for this new agreement recognizes NOAA's Earth remote-sensing program as an operational, service function with associated research activities that enhance its ability to perform its key function. NASA's role in Earth remote sensing is oriented toward the scientific understanding of the processes occurring on and in the Earth and to the development of instrument and satellite technology and model development that will contribute to the research and operations needs for new and improved data.

The commercialization of land remote sensing has led to additional questions of roles and responsibilities in the public and private sector. Although NASA and NOAA have begun the commercialization process with EOSAT, many complex issues remain whose resolution will require more time. Key issues receiving specific attention at this time are as follows:

- Technology development for new and improved sensors;
- Effect of product cost on ongoing research;
- Competition of research-generated data with commercially acquired data;
- Responsibility for development of new value-added products; and
- Disposition of responsibility for oceanography from space.

These issues are not only being considered by the key participants, but responses are also being solicited from the National Research Council Space Applications Board and from key advisory committees. The elements of this relationship are crucial to the future of land remote sensing and must be carefully implemented if we are to succeed in this new venture.

In keeping with this intent to promote commercialization of space activities, NASA has initiated a new concept for an institutional arrangement that unites the resources of the government, industry, and academia. This program is devised to establish and foster Centers for the Commercial Development of Space that will serve as catalysts for the growth of commercial products from space. NASA has selected the Institute for Technology Development at Hancock County, Mississippi, to perform this function for remote-sensing applications and a second center at Ohio State University for real-time satellite mapping. Competition for a third center is planned. This approach should provide a resource base that will be complementary to the commercialization of land remote sensing. Again, the form and function of this institution will require iterative development as it evolves into an effective contributor.

Of key importance to the success of the commercial land remote-sensing program will be its ability to compete in the international market. The French SPOT satellite, launched in February 1986, is designed specifically for economic profit and is a major competitor to EOSAT or any other private-sector firm that elects to operate a land remote-sensing system. There are other land- and ocean-observing satellites in various stages of development from the European Space Agency, Japan, India, Canada, and other nations. These new systems will offer additional data products that will be of commercial value. To ensure that opportunities for U.S. commercial interests in these new fields are fostered, an appropriate institutional approach must be structured. The involved agencies are

working internally and with advisory boards and committees to establish policies in these areas, dealing with both national and international issues.

## State of Our Knowledge of the Earth and Its Atmosphere

The applications of space techniques to studies of the Earth, together with advances in theory and computer technology, have led to increased knowledge of the three main components of the Earth—the land, the atmosphere, and the oceans—as well as the interdisciplinary areas of climate, biogeochemical cycles, and the hydrological cycle. There is a growing emphasis in the science community on the need for studying the Earth as a total system and the interaction between its three main components. Satellites will play a critical role in these studies.

### Land

*Agriculture and Renewable Resources.* It is clear that a broad range of applications of data obtained from space platforms in agriculture, renewable resources, and the environment is technically feasible.

Briefly, it has been demonstrated that data from satellite and other space platforms can be used on a global, regional, and subregional basis to accomplish the following:

- Delineate, identify, and measure the areas of major vegetation and land use;
- Qualitatively assess the condition (e.g., moisture stress) of major vegetation types;
- Identify, delineate, and measure the area of major crops and assess qualitatively (in some instances quantitative assessments are possible) the condition of the crops affected by weather, disease, or insects;
- Assess progress of planting, plant growth, cultivation, and harvesting of crops;
- Locate, identify, delineate, and measure areas of renewable resources (e.g., forests and wooded areas, rangelands, soils, water) and qualitatively assess their condition; and
- Locate and delineate land areas affected by flooding, fires, and other disasters, both natural and anthropogenic.

Major questions in agricultural and renewable resources include the following:

- What is the quantitative relationship between satellite vegetation indices and vegetation on the surface of the Earth?

- Can satellite estimates of precipitation, temperature, and sunlight be made with sufficient accuracy to permit their use in crop yield prediction models and long-term agricultural planning?
- What is the exact nature of the interaction between sunlight and plants and soil?
- How can the effects of weather, soils, fertilizer, pests, and other factors on crop yields be quantified?
- How can changes in the amount and quality of soil and water resources be assessed?
- What are the best sampling strategies to utilize data more effectively from all sensors?
- Can we develop an all-weather crop monitoring system?

**Geology and Nonrenewable Resources.** The history of the Earth's geological development is largely recorded by the characteristics of the rocks that comprise the continental crust. Consequently, a key to achieving a better understanding of how the solid Earth changes is to map and study the continental crustal rock units. Furthermore, because most of the Earth's nonrenewable resources occur within the continental crust, such investigations improve our ability to discover new mineral and hydrocarbon deposits.

Vast areas of the Earth's continental rock units have not been adequately mapped and studied. Land remote sensing has demonstrated the potential for such mapping. This capability has far-reaching implications for characterizing rock and soil compositions, unraveling the formational history of sedimentary basins, and identifying mineral and hydrocarbon deposits. For example, the technology now exists for detecting specific minerals on the Earth from space sensors.

Major questions in geology and nonrenewable resources include the following:

- What are the dominant lithologic and structural geologic characteristics of the poorly mapped or unmapped regions of the Earth?
- What are the detailed lithologic, mineralogical, and structural geologic characteristics of various geologic settings favorable to the occurrence of mineral and hydrocarbon resources?
- How do weather and other climatic and natural processes modify the composition of rocks exposed on the Earth's surface? What are the relationships between these modifications and original rock composition?
- How are soil formation and degradation affected by climate, topography, vegetation, and geologic substrata?

- What relationships exist between the characteristics of vegetative cover and underlying geologic conditions for different climatic regions of the Earth?
- What are the relationships between surface topography and morphology and the surface and interior processes that have influenced development of existing geomorphological conditions?
- How have global tectonic processes influenced the distribution, geometry, and composition of continental rock units?
- What are the roles and relationships of global and regional tectonic processes in the formation of mineral and hydrocarbon deposits?

**Geodynamics.** Geodynamics is the study of the Earth's interior and its gravity and magnetic fields. Recent space observations have led to several important insights about the Earth.

- The nearly rigid blocks or plates that make up the Earth's crust are now known to move slowly—1 to 10 centimeters per year—in response to driving forces from the Earth's interior.
- The rate at which the Earth rotates about its axis varies not only over periods of decades to thousands of years but also over shorter time spans of days to a year.
- Superimposed on the well-known changes on the Earth's magnetic field (about 0.1% per year) are much more rapid changes that appear to be correlated both with climatic variations and rotation rate fluctuations.

Major questions in geodynamics include the following:

- What are the forces that drive the motion of the tectonic plates?
- What constraint does postglacial rebound provide on mantle viscosity and its variation with depth?
- What is the nature and dynamic state of the material in the Earth's mantle (i.e., the details of convection)?
- What is the structure of the Earth's core, and how is the geomagnetic field generated by a core dynamo?
- What are the various causes in excitation of the Earth's rotation?

## Atmosphere

It is the atmospheric area that has seen the greatest practical exploitation of Earth remote sensing. Weather forecasting and supporting modeling research have been the primary beneficiary. The continuous imagery from the geostationary weather satellites enables the growth of small-scale cloud systems into severe storms to be closely



monitored. As a result, more timely and accurate local severe weather and hurricane warnings are possible. Global satellite temperature and cloud observations permit more accurate and longer range weather predictions. One study by the European Center for Medium Range Weather Forecasts has shown that the time span of useful forecasts can be extended by almost a full day using the satellite observations.

Major continuing questions about the physics and chemistry of the atmosphere include the following:

- Can we improve the accuracy of weather forecasting and extend the useful forecast period?
- Can we improve our understanding of small-scale processes to permit better prediction of severe local storms?
- What exactly are the processes that maintain the atmospheric circulation?
- How are the chemical, radiative, and dynamic processes of the atmosphere coupled?
- How are the lower and upper atmospheres coupled?
- What causes ozone variations? What is the effect of anthropogenic perturbations on ozone?
- What are the detailed processes affecting the transfer of visible and infrared radiation through the atmosphere?

## Oceans

Of the planets of the Solar System, the Earth is the only one with oceans. Although our knowledge of the atmosphere has grown substantially over the last 50 years, largely as the result of the establishment of networks of surface and upper air observing stations, and, more recently, weather satellites, our knowledge of the oceans is still meager. Our information is still based primarily on sparse surface measurements by the commercial shipping fleet and a few buoys and occasional high-quality surface and subsurface measurements by research vessels. With the current weather-observing system, we can obtain a good snapshot of the global three-dimensional state of the atmosphere twice each day. Using the entire archive of oceanographic observations, we still have only a very limited knowledge of the three-dimensional state of the world's oceans and its variations.

We do know that because of their large heat capacity, the oceans act to decrease the seasonal temperature extremes of the Earth. They also carry a significant, but still uncertain, amount of heat from low latitudes to high latitudes, thus moderating the climate of the polar regions. The water that evaporates from the oceans condenses in the atmosphere, forming clouds and rain and providing energy to the atmosphere by releasing latent

heat of evaporation. Sea-ice boundaries around the Arctic and Antarctic oceans undergo surprising seasonal and annual expansions and contractions, which exert strong influences on polar weather and climate.

We also know the large-scale distributions of chemical properties and the gross details of the major current systems. These currents are driven by the winds and by density differences associated mainly with the equator-to-pole gradient of solar heating of the ocean. Observations in the past decade have revealed that superimposed on the major global current systems are mesoscale eddies (with horizontal dimensions of about 100 km) that frequently persist for months to years.

These oceanic eddies may be regarded as the oceanographic equivalent of the atmospheric storms, but their exact role in ocean dynamics remains to be determined.

Major questions about the oceans include the following:

- What are the small-scale and large-scale circulations of the oceans and how do they vary?
- What exactly is the role of the oceans in transporting heat from the tropics to polar regions?
- What is the global distribution of heat, water, and momentum exchange between the oceans and the atmosphere?
- What is the response of the upper ocean to thermal and atmospheric forcing? How are physical and biological processes interrelated?
- How are heat and other properties exchanged between the surface and deeper layers?

## Climate

Until fairly recently the science of climatology had been mainly descriptive. It focused on analyzing weather observations to obtain statistical information on the climatic elements (e.g., precipitation, temperature, winds, cloudiness) and their variations with season and geographical location. As a result, a good idea of the distribution of climatic types around the globe and a great deal of detailed information on the climatic conditions of all geographical locations with weather-observing stations. Although it has been known for some time that the Earth's climate undergoes changes and fluctuations, the thrust of climatological work was on the static nature of the system. It is only recently that climatology has been transformed from a descriptive science to a descriptive and theoretical science.

With the aid of powerful computers, sophisticated numerical climate models have been used to simulate the observed climate and the sensitivity of the climate to

changes in such parameters as solar radiation, carbon dioxide content of the atmosphere, sea surface temperatures, and atmospheric aerosols. These models, which are outgrowths of the numerical models used in weather predictions, are also being used to examine the questions of climate predictability. Given accurate observations, a comprehensive numerical model, and high-speed computers, then day-to-day weather variations are in principle predictable up to 2 weeks in advance. However, there is limited knowledge of the predictability of next month's average weather and of longer term climatic variations. Such a capability could have profound economic and social implications.

Parallel with the development of the numerical climate models has been a concerted effort to diagnose the observed climatic fluctuations. Because climatic fluctuations are globally interconnected, satellite observations have provided a major input to such studies. A recent major finding is the connection between global climatic fluctuations and large-scale sea surface temperature changes in the tropical oceans, as manifested by the El Niño-Southern Oscillation phenomenon. Anthropogenic impacts on climate, particularly the effects of carbon dioxide, and deforestation and desertification, are a key concern.

Major questions about climate include the following:

- Why does climate vary?
- Are climatic variations predictable?
- What is the extent of man's impact on climate?
- What are the long-term trends in global and regional climate?
- What are the large-scale and low-frequency (month-to-month, year-to-year) variations of the atmospheric variables (wind, pressure, temperature, cloudiness, and precipitation)?
- What are the large-scale and low-frequency variations of the Earth radiation budget and their relationship to cloudiness?
- What are the relationships between the large-scale and low-frequency variations of atmospheric variables and those of sea surface temperatures and current systems?
- How are local and regional climates influenced by land surface evaporation, albedo, and roughness?
- How is the global climate influenced by sea and land ice cover?
- What are the roles of land and oceanic biota as sources or sinks of carbon dioxide and other radiatively important trace gases?

## Biogeochemical Cycles

The study of global biogeochemical cycles is a new field that is receiving increasing attention as a result of the realization that human activity significantly disturbs the natural cycles. Threats to the ozone layer, the increase in atmospheric carbon dioxide and its potential effect on climate, the mysterious rise in atmospheric methane, increases in atmospheric nitrous oxide, and the acid rain problem are a few examples of such disturbances. With water and oxygen, four elements—carbon, nitrogen, phosphorus, and sulfur—are of special interest in the study of the Earth. These elements follow a closed loop involving living matter, the land, the oceans, and the atmosphere. Within the loop are complex interactions of geological, physical, chemical, and biological processes. Understanding global biogeochemistry requires knowledge of the rates of biological processes and the capacities in sizes of various chemical reservoirs. This includes determining the primary biological productivity of oceans and land biomes; the amounts of various compounds carried by rivers; the transfer of different gases both into and out of the atmosphere; and the chemical interactions and transports within the atmosphere. Although some qualitative understanding of these cycles exists, the currently available data are inadequate for quantitative analyses.

An example of the complex interconnections among the components of the Earth system is the sulfur cycle. As recent volcanic eruptions have demonstrated, the primary source of sulfur in the environment at times can be processes relating to degassing of the Earth. Once in the air, sulfur is transformed into sulfuric acid, which can return to the surface through both wet and dry deposition. This acid deposition can potentially alter the acidity of the soil and water and affect both the type and amount of biological activity that occurs in a given region. The acid in the atmosphere is further transformed into particles or aerosols that can significantly alter atmospheric radiative transmission properties. Therefore, understanding of this cycle requires measurements of biological, anthropogenic, and geophysical sources, understanding of atmospheric chemistry, the gas-to-particle conversion process, and the determination of how the Earth's surface interacts with atmospheric sulfur gases and aerosols.

Major questions about biogeochemical cycles include the following:

- What are the details of the processes involved in biogeochemical cycling of carbon, nitrogen, phosphorus, sulfur, and trace metals?
- What is the global distribution of biomass and its variations? What determines its changes and variations?

- What are the detailed processes controlling acid precipitation and deposition?
- What is the rate of transport of sediments and nutrients from the land to inland waters and ocean?
- What are the global distribution, transport rates, and strengths of sources and sinks of tropospheric gases and aerosols?
- Why is the atmospheric methane concentration increasing?
- To what degree is the natural temporal variability of major element dynamics influenced by anthropogenic inputs?

## Hydrological Cycle

The hydrological cycle involves the processes of precipitation, evaporation, evapotranspiration, ice and snow formation and melting, and runoff. A quantification of this cycle is crucial to understanding of climatic processes and as input to hydrologic models used for such diverse purposes as flood forecasting and water resources planning. Until now only crude estimates of the spatial and temporal variations of the principal storage reservoirs of fresh water on the Earth's surface have been possible.

Only about 3 percent of the water on the Earth's surface is freshwater. Approximately 77 percent of this is frozen in the polar ice caps and glaciers, 22 percent is in the form of groundwater, and the remaining 1 percent is partitioned among snow, soil moisture, lakes and rivers, and water vapor. The most variable of these are precipitation, snow, soil moisture, and water vapor. Precipitation is actually measured routinely, but only at widely scattered points on the Earth's surface and not at all over oceans or other vast areas. Even precipitation gauge networks, supplemented by radar and meteorological satellite estimates, enable only crude monthly or annual estimates of global precipitation. Evaporation and evapotranspiration from vegetation generally are calculated from routine measurements of other more directly measured variables, and satellite data have enabled routine weekly charting of surface water temperature and ice cover. Environmental satellite data have enabled a 15-year record of continental and hemispheric snow and pack ice cover (but not depth or water content) to be developed. Satellite techniques exist for obtaining relatively good estimates of the total column water vapor, although layer estimates are not satisfactory. The potential for measuring the amount of soil moisture from space has been demonstrated, but only over large, homogeneous, lightly vegetated areas and not to great depths. There has been limited success in estimating runoff amounts from satellites, and this has been done chiefly with unregulated watersheds. Monitoring water levels in lakes and rivers, except perhaps for the intermit-

tent type, is best done in situ with data relay through satellite data collection and location systems.

Major questions about the hydrological cycle include the following:

- What factors control the global hydrologic cycle?
- What are the distributions of precipitation, evaporation, and runoff over the globe?
- How do sea and land ice influence the global hydrologic cycle?
- Exactly how do vegetation, soil, and topography interact with the components of the hydrologic cycle?
- What are the distributions, capacities, and properties of major freshwater reservoirs? What are the transfer mechanisms between them?

A long-term research effort is needed to derive, study, and understand the Earth observations that are required to answer the above questions. The major components of the required research are as follows:

- Remote-sensing research and development;
- Validation of satellite observations;
- Analysis and interpretation of data;
- Calibration of satellite instruments; and
- Numerical simulation and modeling.

## NASA/NOAA Plans for the Future

Both NASA and NOAA are actively engaged in defining improvements to existing programs and new programs for the future. Potential changes to the programs include advanced sensors; upgraded data processing, archival, and networking systems; and in the case of the Space Station, integrated approaches for operational and research missions. Some of these potential additions are discussed below.

NOAA's proposals include data from a variety of advanced sensors. For data on thermal and moisture structure of the troposphere and atmosphere, NOAA's program includes the development of an Advanced Microwave Sounding Unit (AMSU) for implementation on NOAA-K. AMSU will provide all-weather sounding capability. Temperature and humidity sounding of the atmosphere from geosynchronous altitude was added to the GOES imaging system with the launch of GOES-4 in September 1980. Originally flown as an experimental capability, data from this instrument have proven extremely valuable in determining the genesis and evolution of severe storm conditions. Beginning with GOES-I (GOES-NEXT), the system will be further improved by the separation of

imaging and sounding functions and the addition of the ability to "stare" from a three-axis stabilized spacecraft that will improve the signal-to-noise characteristics.

Given the commercialization of the Landsat remote-sensing system, a viable relationship will be necessary to provide advanced technology for future instrument design and to ensure favorable conditions for continuity of this important resource. The advanced technology for the future passive imaging system is being addressed by NASA's program to develop an imaging spectrometer capable of sensing the visible and infrared spectrum from 0.4 microns to 12.0 microns, at high resolution. With an instrument of this type, the data not only can differentiate among ground types but, with knowledge of specific spectral characteristics, will be able to identify directly the chemical and/or biological makeup of the Earth's surface. The general progress and plans for the instrument are being made available both at the system and subsystem design levels.

NASA has under development a major research mission for understanding the processes occurring in the upper atmosphere. The goal of the Upper Atmosphere Research Satellite (UARS) program is to capitalize on proven instrument technologies and use a specific suite of measurements to improve our ability to understand the interaction of specific chemical, dynamic, and radiative processes of the stratosphere and its interfaces. This ambitious mission will provide a data set that will allow independent investigations of specific constituents, as well as permit analysis of the interdependence of the total system and the key dynamics to the stratosphere.

The most promising opportunity for new operational and research missions is in oceanographic services and scientific study. NASA is developing a scatterometer (NSCAT) for measuring sea surface wind velocity. An Ocean Topography Experiment (TOPEX/Poseidon) will be pursued as a joint mission with France. Also, currently under discussion as a private sector initiative is an ocean color instrument. These flight programs would provide a global picture of sea surface winds, ocean currents, and biological productivity, with wide application to oceanic science and services. This approach reflects future divisions of responsibilities and joint venture collaborations in programs of mutual interest.

NASA is also continuing its development of imaging radar systems. These active microwave systems offer an ability to image the Earth's surface in areas of predominant cloud cover and illuminate and scene independent of sun angle. The Shuttle Imaging Radar (SIR) program has shown considerable promise for studying structural features of the land and ocean surface. As the program evolves, the effects of frequency, look-angle, and polarization are being isolated to assess the utility of these various degrees-of-freedom on the scientific investigation and application of interest. A four-step series of Shuttle flights

has been defined, which should lead to a choice of instrument capabilities for future deployment.

Both NASA and NOAA are examining ways to upgrade their data systems to meet the needs of the research and operational communities. NASA is continuing to develop climate, oceans, and land pilot data systems. These systems are being evaluated for potential integration into a multidisciplinary information system. With the United Nations Environmental Program, NASA is developing a Global Resources Information Database (GRID) that combines remotely sensed and conventional data to facilitate studies of global resources and environmental issues.

NOAA's planned upgrade of its real-time data processing system will integrate ATN, GOES, and DMSP (Defense Meteorological Satellite Program) satellite data on a single, user-accessible, rotating storage system. Also under consideration is the possibility of using a new, inexpensive direct broadcast system (DBS) to transmit satellite images to users. NOAA is examining ways to improve the delivery of archiving services. Some of the efforts being considered are: (1) using data storage devices such as video cassettes and optical disks; (2) decreasing the turnaround time for user requests; and (3) developing a complete computer-based satellite data catalog with image browse and order-taking capabilities.

Currently in Earth science there is growing emphasis on global-scale research questions that span the several disciplines. This, together with the realization that individual remote-sensing instruments can in many cases serve the observational needs of several different disciplines, has resulted in integrated Earth science planning at NASA. As part of this approach, emphasis is being placed on the systematic acquisition of data sets over long time periods to help determine how the Earth as a natural system is changing and why. Eos, the Earth Observing System, is proposed as a research mission to provide scientists with global information.

Eos, as an information system, would help researchers marshal data from the various sources needed to study the large variety of processes and problems confronting them. The information available today and through the upcoming scientific research missions must be extended and augmented with a variety of new remote-sensing capabilities. The closely coordinated use of the full set of space-based measurement capabilities offers considerable synergism in obtaining the geophysical understanding desired. This quantity of space instruments cannot be flown in a coordinated manner on existing satellites; therefore Eos proposes to use the Polar Platform concept under consideration as part of the Space Station. The plans for man-tended servicing would allow an unprecedented observing capability, built up on-orbit over 5 or more years, and yield long-term data sets of a decade or more. Some of the data are already being acquired as part of the NOAA operational program, and additional data sets could be

obtained in this manner with instruments that have or will have been flown before the 1990s. This has led NASA to seek active collaboration with NOAA in the Eos and Polar Platform proposals (see Table 24).

NOAA's proposals for future polar-orbiting systems include several new measurement capabilities. The Space Station Polar Platform concept is one means to attain that capability.

NASA and NOAA have been jointly studying over the past year how they may best collaborate in the Eos and NOAA-NEXT time frames. This collaboration would eliminate duplicate instruments in the payload and allow for the simultaneous acquisition of certain research and operational observations. The different natures of the research and operational tasks dictate that separate data systems be developed for NASA Eos research and NOAA operations, but the two systems can be designed for mutually compatible implementation, and both systems could access each other's data at all levels. This proposal may form the basis on which NASA and NOAA boldly collaborate both to understand the Earth through use of remote sensing and to apply this knowledge and data for immediate benefit to humanity.

NOAA is conducting a 2-year study to determine the feasibility of designing a sensor that will handle the planned civil and military imaging data requirements for the 1990s and beyond. NOAA and DOD have further agreed to use identical instruments in their future respec-

tive weather satellite programs whenever data requirements are the same and engineering and funding constraints permit, to include passive microwave radiometers, atmospheric sounders, and space environment monitors.

## **DOD Plans for the Future**

The Defense Meteorological Satellite Program (DMSP) is a continuing operational program. Upgrades to the spacecraft and sensors will continue to take advantage of developing technology, allowing the system to better meet the validated requirements of the special strategic and Joint-Service missions and the Joint Chiefs of Staff. Ongoing and planned development efforts will be responsive to joint NOAA/DOD requirements where feasible. These planned efforts presently include a microwave water-vapor sounder, the three-phased development of a wind-sensing capability from space, improved tactical data procuring capabilities, improved survivability and autonomous operation capabilities, and the design and development of DMSP Block 6, the follow-on DOD environmental satellite system of the late 1990s. Also, DMSP is studying alternatives to better meet the Navy's oceanographic requirements. The Army is proceeding with plans to develop and use a Defense Environment Support Satellite (DESS) in support of its Air Land Battlefield Environment (ALBE) requirements.

# I. INTRODUCTION

Public Law 98-365, the Land Remote-Sensing Commercialization Act of 1984, requires that the Secretary of the Department of Commerce and the Administrator of the National Aeronautics and Space Administration (NASA) shall, within one year after the date of the Law's enactment and biennially thereafter, jointly develop and transmit to the Congress a report that includes (1) a unified national plan for remote-sensing research and development applied to the Earth and its atmosphere; (2) a compilation of progress in the relevant ongoing research and development activities of Federal agencies; and (3) an assessment of the state of our knowledge of the Earth and its atmosphere, the needs for additional research (including research related to operational Federal remote-sensing space programs), and opportunities available for further progress.

Since the first meteorological satellite, great strides have been made in the field of remote sensing. Temperature soundings of the atmosphere to an accuracy of 2°C are now routinely acquired and used in global forecast models, images of the Earth's surface to a spatial resolution of as low as 30 meters in 7 spectral bands are readily available, active microwave systems have proven their all-weather capability and an ability to penetrate hyperarid sands to the bedrock below, minor atmospheric constituents have been measured from space to an accuracy of 1 ppbv, and ocean winds have been inferred from sea-surface roughness to an accuracy of 2 meters/second. With these advances, however, there have evolved myriad complexities that warrant examination of new issues, identification of potential solutions, and an attempt to put these into a well-formulated, national plan that will enhance and use this technology for the improved adaptation of man and his environment.

The following document addresses this task. Its creation has started the process of getting the participating agencies to work together to produce the mandated national plan for remote-sensing research and development. For this submission, NASA and NOAA have been the primary authors, with input from other agencies on their specific use of remote sensing for achieving their respective responsibilities. In the future, a more interactive process will be established to ensure the responsiveness of the integrated national plan to the needs of these organizations. The present document is a snapshot in time that possibly raises as many issues as it provides solutions. The process of identifying and correctly formulating key issues, however, will clarify the magnitude of needed future

efforts as we seek to identify internationally the needs of the private remote-sensing industry, governmental research and operational agencies, academic researchers in the Earth sciences, and those users of remote-sensing products for direct economic gain.

It is crucial that an integrated set of objectives and approaches be developed that is responsive to the range of needs from the user community and that fosters the U.S. competitive posture in the national and international market for this service. Given the multiple participants in this process, considerable time and detailed assessment will be required to consolidate and unify into one plan the needs and desires of all factions. This document represents the initial results of the start of such a process. It attempts to capture the essence of the governmental programs in remote sensing and their future goals to the extent that they are defined. As the definition of a national plan for remote sensing is further developed, appropriate inter-agency coordinating committees for space-related remote sensing will be involved in the generation, review, and revision process. To establish appropriate mechanisms for identifying and being responsive to the potential user community, NASA and NOAA are working with the National Research Council/National Academy of Sciences.

The plans of the commercial remote-sensing sector are much less explicit primarily because of the uncertainty of the finalization of that process. Initial attempts have been made to identify those areas of the relationship that will require development of coordinated programs to maintain U.S. competitiveness in this market and provide for continuity of these important data.

Several far-reaching activities for defining the future needs of Earth science and applications in the United States are currently underway. NASA has been developing a proposal for an Earth Observing System (Eos) for meeting many of the scientific needs for Earth remote sensing. The Earth System Sciences Committee (ESSC) has reviewed the scientific objectives for the study of the Earth as a system, devising an implementation strategy for meeting these objectives, and defining NASA's role in such a program. The Office of Science and Technology Policy, Executive Office of the President, is now reviewing and defining the goals and missions of the various agencies in Earth sciences research. NOAA has completed its *Envirostat-2000* reports. The National Academy of Sciences' Space Science Board is developing space-based strategies for the study of Earth science and the biosphere. (See the

Academy's publications, *A Strategy for Earth Science from Space in the 1980's. Part I: Solid Earth and Oceans; and A Strategy for Earth Science from Space in the 1980's and 1990's. Part II: Atmosphere and Interactions With the Solid Earth, Oceans, and Biota.*) The Academy's Space Applications Board has published the final report of its Committee on Practical Applications of Remote Sensing. All of these reports will provide significant input to the process of determining goals, objectives, and implementation strategies for the future thrusts of Earth remote sensing. Given the increasing attention to this field from such diverse sources, there should be ample guidance for developing a plan that is responsive to the many users of this technology for the next biennial report to the Congress.

Other reasons make this a particularly appropriate time for the first of these reports to the Congress. The United States and the Soviet Union are no longer the only satellite-launching nations. Today, the Earth is encircled at the equator by a set of geostationary meteorological satellites consisting of the United States' Geostationary Operational Environmental Satellite (GOES), the European Space Agency's (ESA) Meteosat, Japan's Geostationary Meteorological Satellite (GMS), and India's Indian National Satellite (INSAT). France and Japan have launched the polar-orbiting satellites SPOT and MOS-1, respectively. Furthermore, during the next few years, ocean- and land-observing satellites will be launched by Canada, France, Japan, India, and ESA. Within the United States, NASA and NOAA satellites are joined by those of the Department of Defense's Defense Meteorological Satellite Program (DMSP), and the Navy's Geosat (launched in March 1985). This is an appropriate time to assess the implications of the myriad Earth observations that will soon be available and how best to integrate these observations into a dynamic and useful data base.

Meteorological satellites provide vital information required for daily weather forecasting and are a continuing part of the Nation's space program. Scientists believe it is crucial for other kinds of observations to be made on a long-term basis. Such issues as climatic changes resulting from fossil fuel consumption, the sensitivity of stratospheric ozone to trace gases such as fluorocarbons, the rates of deforestation and desertification, the output of the Sun, and an understanding of the interactions between the land, ocean, atmosphere, and biota require a program of long-term, stable, quantitative, global observations of the Earth as a system. Congress has recognized that now is the time for examining the long-term satellite observations that could resolve these issues.

Two international interdisciplinary research programs are looking to satellite observations for major data and information sources. The World Climate Research Programme (WCRP), cosponsored by the International Council of Scientific Unions (ICSU) and the World Mete-

orological Organization (WMO), seeks to determine both the predictability of and human influence on climate. The Global Change Program (GCP, formerly the International Geosphere-Biosphere Program), currently being considered by the ICSU, is a cross-disciplinary effort to quantitatively understand the complicated terrestrial "machine," the functions and interactions of its various parts, and the major geophysical and biochemical cycles by which it is driven.

Chapter II addresses the NASA/NOAA relationship and the roles and responsibilities of both agencies in developing the technology of Earth remote sensing. Also developed are the remote-sensing missions of the user/applications agencies.

Chapter III of this report is a compilation of progress in the relevant ongoing research and development at Federal agencies. For each major component of the Earth—land, atmosphere, and oceans—and for the multidisciplinary areas linking these components—climate, biogeochemical cycles, and hydrological cycles—the major research objectives are summarized and progress is reported.

Chapter IV assesses our knowledge of the Earth and its atmosphere by briefly summarizing our status in each Earth science discipline and by identifying the major gaps in our knowledge and additional research needs. Large-scale national and international research programs currently addressing some of the issues identified in this chapter are also discussed.

Chapter V discusses the emerging foundation of the national plan for remote-sensing research and development as applied to the Earth and its atmosphere. It attempts to fill the gaps in knowledge identified in Chapter IV and to respond to some of the issues raised in this chapter. Finally, it develops research plans for the closing years of this century.

The content of this report contains descriptions of ongoing programs and promising new initiatives that are expected to make contributions to the science, operations, and applications community. Of course, standard budget processes of the Congress and the Administration govern the implementation of any particular program.

To ensure responsiveness of the emerging national plan to changing needs and facilitate modification of goals and objectives as research progresses, responsibility for review and revision of the plan is assigned to the Administrator of NASA and the Secretary of Commerce. In the event that an appropriate Federal interagency coordinating committee for space-related remote sensing is established, that committee could be involved in the review and revision process. This emerging national plan is designed for agency-level planning and the programs discussed are subject to budget considerations and Administrative approval.

# Operational Earth Observation Satellites

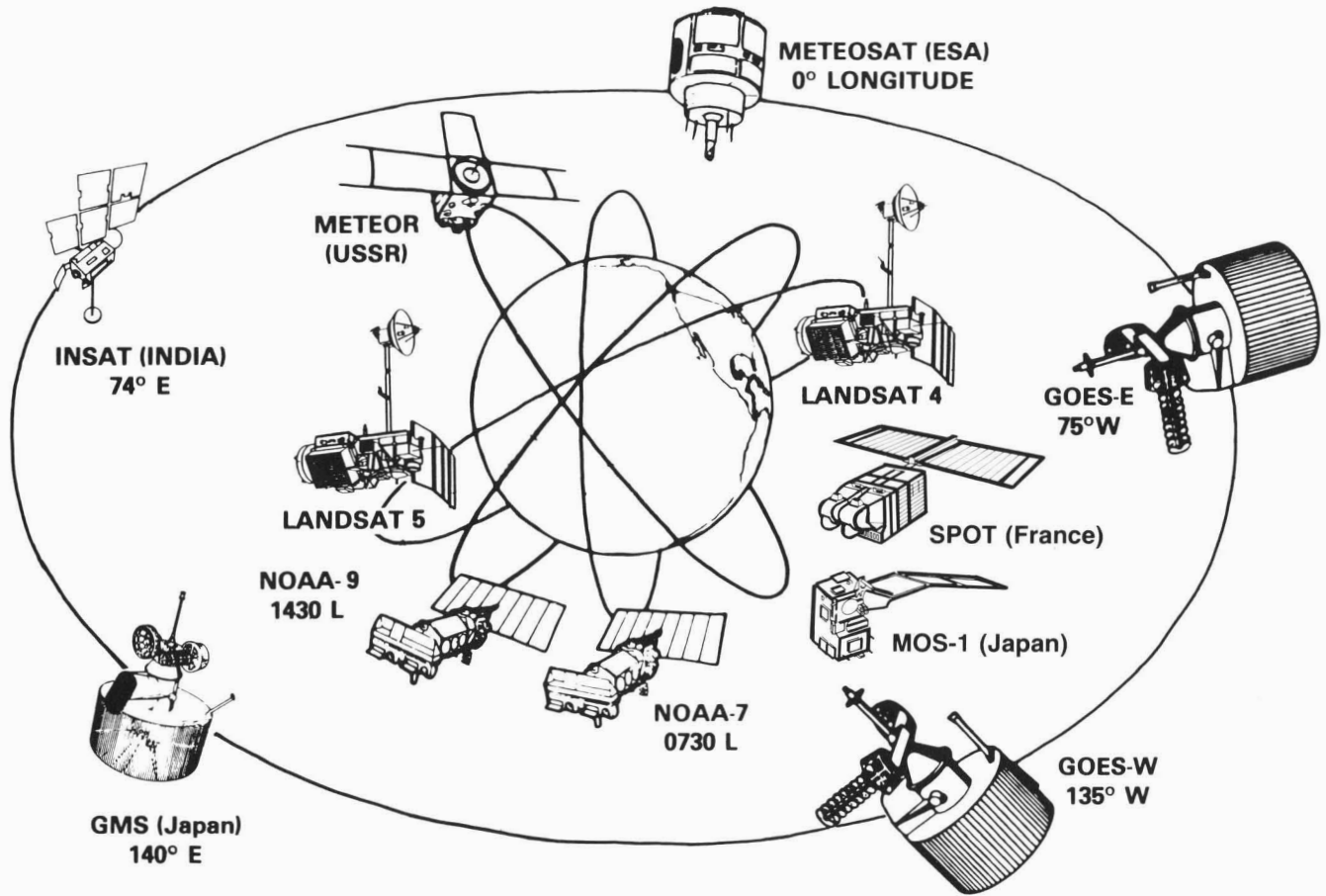


FIGURE 9. The current civil operational environmental satellite system includes satellites from five different countries and the European Space Agency. The diagram shows the longitudinal location of each of the geostationary satellites, which view the Earth continually from altitudes of 22,500 nautical miles, and the paths of the low-altitude polar-orbiting satellites.



## II. REMOTE-SENSING MISSIONS OF THE FEDERAL AGENCIES

Earth remote sensing from satellites has experienced enormous advances in data acquisition, processing capability, and utilization since the initial launch of TIROS-1 on April 1, 1960. Concurrently, there has been an equivalent increase in the use of this technology for its economic value, for its benefit in prediction of life-threatening situations, and for scientific research to better understand the processes controlling the stability of the Earth's physical, chemical, and biological systems. This rapid growth has increased the capability and use of remote-sensing products. Further, it has had far-reaching implications for the roles and responsibilities involved in the definition of information needs, the development of data acquisition and processing systems, and the maintenance and operation of reliable operational systems. The following discussion addresses the key roles, responsibilities, and relationship of the major participants, NASA and NOAA, in the development and use of remote-sensing techniques; it also focuses on the increasing emphasis on remote sensing as a tool for accomplishing the missions of other agencies.

### A. The NASA and NOAA Relationship: Roles and Responsibilities

Evolution and refinement of the roles and responsibilities of NASA and NOAA in the research, development, and operation of satellite systems has dictated that a partnership exist between these two sister agencies to capitalize on the strengths of each agency and to integrate a unified program responsive to the various user needs with minimal duplication. The complementary aspects of roles and programs have led to a working relationship that matches the best attributes of each organization for implementing a total program for the application of remote sensing to Earth science research. There have been several past agreements between NASA and NOAA that have formalized a basis for continued working arrangements. As expected, these agreements have seen many modifications as the agencies' roles and missions have evolved and as the technology of doing business in space has matured. With the advent of an operational Space Transportation System, the planning for the manned Space Station, and the transition of land remote sensing from Government to the private sector, NOAA and NASA have recognized the need to update the agreement governing their relationship.

The philosophical basis for this new agreement recognizes NOAA's Earth remote-sensing program as an operational, service function with associated research activities that enhance its ability to perform its key function. NASA's role in Earth remote sensing, however, is oriented toward the scientific understanding of the processes occurring on and in the Earth and to the development of instrument and satellite technology that will contribute to the research and operations needs for new and improved data. Major elements of each agency's mission and roles have been delineated as follows.

- NASA is responsible for advanced research and development activities to preserve U.S. preeminence in the exploration and exploitation of space. These responsibilities include the following:

*Conducting research and development in advanced space technology and systems;*

*Developing the Space Transportation System to ensure routine, cost-effective access to space;*

*Developing a permanently manned Space Station, and associated platforms, which includes planning for effective utilization of the facility;*

*Conducting research and experimentation to expand through space technology our understanding of the Earth and its environment;*

*Establishing an active, long-term Earth science program at NASA in coordination with other Federal programs; and*

*Providing for archiving and access to data acquired through NASA-supported research in remote sensing and Earth sciences.*

- NOAA is responsible for environmental science applications and service programs to monitor the oceans, atmosphere, and land. NOAA also is responsible for developing and administering ocean and coastal resources management and regulatory programs. These responsibilities include the following:

*Managing the U.S. civil operational spaceborne systems for observing and monitoring the land, oceans, atmosphere, and near-Earth space environment and for assisting search and rescue activities for victims of air and sea disasters;*

*Aggregating Federal requirements and identifying needed research objectives for these civil operational remote-sensing systems;*

*Providing and operating data information management systems for collecting, cataloging, retaining, and dis-*

*seminating environmental data and information in a timely manner and in useful forms to real-time and retrospective users; and*

*Conducting research and development in Earth and environmental sciences and remote sensing with emphasis on applications.*

The structure of this updated agreement is designed to recognize and explicitly treat the unique relationship between NASA and NOAA in the development, launch, and operation of the environmental satellites and to establish a basis for continuing collaboration in advanced operational satellite systems, sensor and spacecraft development, Earth science research, and data management. This agreement, then, will reflect the results of the intense coordination between the two agencies and review comments from external organizations interested in the NASA/NOAA relationship.

## **B. Private Sector Integration**

With the passage of the Landsat Commercialization Act of 1984, a new approach to the implementation of remote sensing from space was initiated. This new approach offers the opportunity to develop a new industry with national and international markets, but creates a complexity requiring delicate treatment if the goals of increased efficiency and reduced Government involvement are to be met. This will require that NASA, NOAA, and the private sector establish working relationships that offer the utmost opportunity for private industry to enter the marketplace and compete nationally and internationally. Issues such as technology development for new and improved sensors, effect of product cost on ongoing research, competition of research-generated data with commercially acquired data, monopolistic advantage, research and development leading to new value-added products, and the effect on U.S. policies and treaties will all need to be addressed in the near future to clarify our relationships.

A range of issues must be addressed to determine approaches for achieving a mutually understood basis for commercialization. It is anticipated that a formal understanding will be needed between NASA, NOAA, and EOSAT (Earth Observation Satellite Company) and appropriate processes and mechanisms to achieve this are being identified. In identifying the issues and potential approaches, the assistance of the NASA Advisory Council's Space and Applications Advisory Committee and the Space Applications Board of the National Research Council has been enlisted. This combination of operating organizations and advisory boards should lead to the establishment of a partnership between government, industry,

and academia that will provide ample opportunity for success in this venture.

NASA has embarked on a new strategy to facilitate the commercialization of space through the establishment of Centers for the Commercial Development of Space. This program is intended to combine the resources of government, industry, and academia to convert high technology research into commercial products, capitalizing on the unique attributes of space. It is expected that this research will eventually lead to the development of new products that either have commercial potential or will contribute to possible new commercial ventures.

In August 1985, NASA announced the selection of five of these Centers for the Commercial Development of Space. One of these centers will be dedicated to remote-sensing technology and will be led by the Institute for Technology Development, located at the National Space Technology Laboratories (NSTL) in Hancock County, Mississippi. The group selected has developed a strong relationship with the university community and the value-added industry and is developing EOSAT participation. It is expected that collaboration will foster the development of economically valuable products for use throughout the globe.

## **C. Remote-Sensing Missions of the User/ Applications Agencies**

Other agencies of the Federal Government have recognized the value of Earth remote sensing in accomplishing their mission objectives. These uses range from the scientific research needs of the National Science Foundation to the data input for construction site planning of the Corps of Engineers. These diverse needs represent design and operations requirements for delivery of remote-sensing information. Brief statements of how remote sensing is incorporated into the missions of the primary user agencies are provided below.

### **Department of the Interior (DOI)**

DOI is one of the U.S. Government's largest users of satellite remotely sensed data. Through its various bureaus and offices, DOI has direct administrative responsibilities for more than 500 million acres, or roughly 40 percent, of the total land and Continental Shelf areas of the United States. DOI also has mapping and resource appraisal responsibilities for the entire country and responsibilities in the Trust Territories of the United States, in Antarctica, and for studies in other countries in cooperation with foreign governments. The vastness of the territories involved in the inventorying, monitoring, mapping, and

management activities requires efficient and effective acquisition of many types of information. Satellite remotely sensed data represent one such source of information that has been and will be increasingly applied in various ways by DOI bureaus and offices. Remote-sensing research and development, conducted by DOI bureaus and offices and spanning a broad range of topics, will continue to be important in advancing the utility of remotely sensed data for Departmental programs.

DOI, through the U.S. Geological Survey EROS Data Center (EDC), also has played an important historic role as the world's principal archive and public source for Landsat and other satellite remotely sensed data. Currently, EDC continues to process, reproduce, and distribute Landsat data in cooperation with NOAA and EOSAT, and will do so until EOSAT implements similar capabilities of its own. Recent initiatives, in cooperation with NOAA, to collocate an Advanced Very High Resolution Radiometer (AVHRR) data reception and processing facility and to locate the National Satellite Land Remote Sensing Data Archive, both at EDC, continues DOI's involvement in remote-sensing data handling.

#### **U.S. Department of Agriculture (USDA)**

USDA administers a range of operational and research programs and activities related to agriculture, renewable resources, and the environment. An extensive remote-sensing research program explores potential applications in agricultural productivity; effective management of soil, forest, water, and range resources; protection and enhancement of the environment; and informed decision-making in carrying out its missions.

The new Remote Sensing Research Laboratory, established as a part of the Agricultural Systems Research Institute, Agricultural Research Service (ARS), has become a focal point for remote-sensing applications research in ARS and the Department. Located at the Beltsville Agricultural Research Center, Maryland, and in existence for slightly more than a year, the Remote Sensing Research Laboratory has as its primary mission basic and applied remote-sensing research to serve Department programs.

#### **Department of Defense (DOD)**

DOD missions require capabilities to conduct operations anywhere in the world. Support of global operations requires a full spectrum of meteorological, oceanographic, topographic, and space-environmental observations, provided by systems that are secure, survivable, and responsive to changing needs. Satellite-based data collection and dissemination systems are key sources of the needed information. Combat-critical environmental data

are normally provided by dedicated military satellite systems (including platforms, sensors, communications, processing, and dissemination subsystems) that can be tailored to meet unique requirements.

DOD relies on elements of the Defense Meteorological Satellite Program (DMSP) to satisfy critical combat-related requirements. These systems cannot meet the full range of environmental-sensing needs of DOD; therefore, some elements of the DOD environmental support system rely upon data or services from NOAA. Specifically, DOD uses NOAA data or services as a backup and/or supplement to DMSP in all cases in which data are available, when it is cost-effective, and when the security limitations, survivability, and responsiveness can or must be accepted.

#### **U.S. Army Corps of Engineers (CE)**

CE applies environmental satellite observations to its Environmental Sciences and Civil Works program, which seeks to

- Support the defense of the United States by maintaining an experienced engineer organization immediately available for defense needs;
- Develop tactical decision aids to provide the field commander with real-time decision support concerning the effects of the environment on friendly and threat weapons and on combat operations.
- Promote the quality of life by reflecting society's preferences for attaining the objectives of (1) enhancing national economic and social development by increasing the value of the Nation's output of goods and services and improving national economic efficiency and (2) protecting the quality of the environment by the management, conservation, preservation, creation, restoration, or improvement of the quality of certain natural and cultural resources and ecological systems; and
- Determine the appropriate role of water resources in solving current and emerging problems.

#### **National Science Foundation (NSF)**

NSF initiates and supports basic and applied scientific research and programs to strengthen the Nation's scientific research potential. Within this broad mandate, NSF emphasizes support of basic research in the Nation's colleges and universities. The Foundation sponsors a wide range of basic research programs in Earth, atmospheric, biological, and oceanic sciences. NSF also has formal coordinating responsibilities for polar sciences in both the Arctic and Antarctic regions.

### **Agency for International Development (AID)**

AID is involved in environmental remote sensing through its goals to

- Understand the environmental impacts of its development activities; and
- Exercise technological leadership in making U.S. space technology available to developing countries.

Future thrusts in AID, which will utilize remote sensing, are

- Food security (food and early warning system), primarily for Africa;
- Monitoring of tropical forests; and
- Conservation of biological diversity.

### **Department of Transportation (DOT)**

Under the Commercial Space Launch Act, DOT is responsible for promoting, encouraging, and facilitating commercial space launches by the private sector. To the extent that the U.S. private sector launch industry will seek to launch commercial remote-sensing satellites, DOT is responsible for licensing those operations.

### **Department of Energy (DOE)**

DOE conducts a variety of research and development activities. The goals are to

- Help ensure adequate supplies of energy at a reasonable cost;
- Help provide for the national defense through the design and test of nuclear weapons and the production of special nuclear materials; and

- Increase understanding of the fundamental constituents of matter and of the health and environmental effects associated with energy production and use.

Many of the individual projects involve use of satellite observations or other remote-sensing techniques.

### **Department of State (DOS)**

DOS (Bureau of Oceans and International Environmental and Scientific Affairs) provides foreign policy/foreign relations oversight, guidance, and assistance to mission-responsible agencies seeking international agreements in environmental remote-sensing research data exchange, and systems/sensor development.

### **Environmental Protection Agency (EPA)**

EPA protects the health and welfare of the American people by controlling pollution hazards. EPA endeavors to abate and control pollution systematically, by proper integration of a variety of research, monitoring, standard setting, and enforcement activities. Remote sensing is an important part of these activities, providing cost-effective monitoring methodologies.

Aerial photography is used to monitor hazardous waste facilities, to document incursions into wetlands, to map non-point pollution sources, and to support the Spill Contingency and Countermeasures Program. Airborne and satellite multispectral scanners are used for large-area monitoring problems such as acid deposition effects studies, global climate studies, and water quality monitoring. Laser-based systems, such as Light Detection and Ranging (LIDAR) and laser fluoro-sensing, are used to support air and water quality mapping.

### III. ONGOING RESEARCH AND DEVELOPMENT IN EARTH REMOTE SENSING AT FEDERAL AGENCIES

This chapter is an overview of current research and development in remote sensing at Federal agencies. Discussions will be grouped by the major components of the Earth—land, atmosphere, and oceans—and by the three interdisciplinary areas linking these components—climate, biogeochemical cycles, and hydrological cycles. The missions, objectives, progress, and achievements of current programs and research are summarized for each agency.

#### A. Land Programs

Land remote sensing includes applications to agriculture and renewable resources, geology and nonrenewable resources, geodetic mapping, geodynamics, and economy and land processes. Of all the Earth sciences components described in this report, the land component has the broadest agency participation. The principal Federal agencies with land remote-sensing programs are NASA, NOAA, DOI, USDA, DOD, CE, NSF, AID, EPA, and DOE.

##### National Aeronautics and Space Administration (NASA)

*Land Processes Program.* This program comprises three interdisciplinary efforts that seek to better understand the state of the Earth's surface, its variation with time, and the processes that control the variations. The program emphasizes the interactions between the land surface, the atmosphere, and to a lesser extent, the oceans. The disciplinary areas, called elements, are terrestrial ecosystems, geology, and hydrology. In addition, research is conducted in remote-sensing science, leading to a better understanding of the relationship between remotely sensed radiances and biological, physical, and geological properties of the Earth's surface.

*Terrestrial Ecosystems Element.* The goal of this element is an improved understanding of the state of the Earth's biological land cover and the role of terrestrial biota in global processes.

The current program extensively uses Landsat sensors and the NOAA operational satellite sensors. Data from several experimental airborne sensors are also being evaluated.

NOAA Advanced Very High Resolution Radiometer (AVHRR) data are being used to explore the time-dependent variations in surface spectral characteristics that result from seasonal vegetation cycles, weather events, and anthropogenic disturbances. Variations in vegetation phenological patterns can be related to biome productivity, especially in grasslands and savannahs, and can be used to objectively define ecosystem boundaries. Future studies to extend this approach to other ecosystems may require major ground-truth activities and coupling with data from the higher resolution Landsat sensors.

Accurate estimation of productivity in boreal and tropical forests, with their high leaf area indices and extensive woody accumulations, requires new techniques. The merger of active and passive microwave and active optical (laser) measurements with currently used passive optical measurements seems promising in this area. Experimental and theoretical activities to develop these techniques are underway.

Remote-sensing driven ecosystem models of forest productivity and biogeochemical cycling also are being developed. Within the next 3 to 5 years, more sophisticated ecosystem models should be partially validated and available for predictive modeling of ecosystem responses to external forcings.

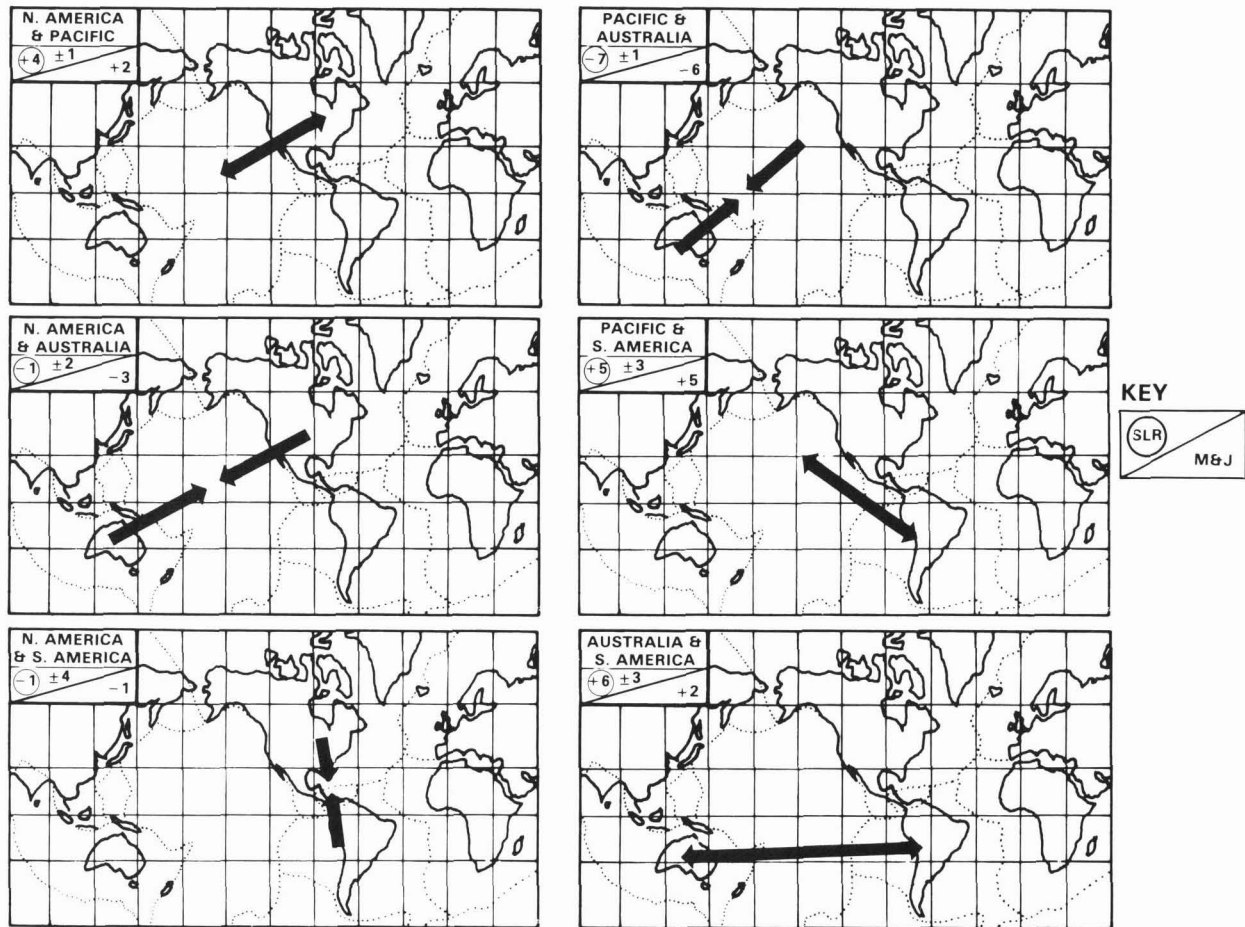
Additional activities include wetland productivity studies, assessment of forest decline because of suspected acid deposition, determination of the relationship between geographic factors and deforestation, delineation of soil types, examination of the thermal emittance properties of vegetation, and laboratory and field studies of the high spectral resolution reflectance characteristics of plants and their constituent chemical compounds.

*Geology Program Element.* This element's goal is to gain an understanding of the tectonic and climatic controls that continuously modify the Earth's surface. The structural and paleoclimatic history of the Earth provides a long-term record of surficial and climatic changes. This can be used with the findings of both the Terrestrial Ecosystems and Hydrologic Processes Elements (see Section E) to make more comprehensive predictive models for the future evolution of the Earth's surface and climate.

The current program makes extensive use of Landsat Thematic Mapper (TM) and Shuttle Imaging Radar (SIR) data for lithologic, structural, and geobotanical analyses. Several experimental aircraft sensors are also being used

# INTER-PLATE DEFORMATIONS OBSERVED BY SLR

## AVERAGED ELLIPSOIDAL CHORD RATES VS. RATES GIVEN BY MINSTER & JORDAN (cm/yr.)



NASA HQ EE84-1781(1)  
7-6-84

FIGURE 10. The above diagrams show average tectonic plate motion for six regions of the world. The measured rates of motion are 1-6 centimeters per year (cm/yr). Such slow motion is impossible to measure by conventional geodetic ground surveying because of the accumulation of errors over large distances and the presence of oceanic boundaries. Instead, NASA has used extraterrestrial methods of laser ranging to satellites equipped with cube corner retroreflectors (including those placed on the Moon), and Very Long Baseline Microwave Interferometry (VLBI), a technique developed by radio astronomers.

The observed rates of motion (in cm/yr) are circled, above the diagonal line in the insets. Numbers are positive where spreading (divergence) at the indicated boundaries is measured and negative where convergence is detected. Below the diagonal line in the insets are the predicted motions, based on geological data averaging these motions over the past few million years. Standard error of measurements are shown to the right of the measured motions, above the diagonal line. There is very good agreement between the satellite measurements and the geological data.

for detailed characterization of rock and vegetation types and analyses of chemical and physical rock weathering.

Much of the current work has been focused on semiarid regions in the western United States where it has been possible to do relative age dating of glacial moraines and alluvial fan deposits using remote-sensing data. This capability enables the modeling of the paleoclimatic history of the region and to infer the timing of events such as the

onset of ice ages and pluvial periods. In addition, studies of the Wind River Basin in Wyoming have shown that remote-sensing measurements can be used to map variations in sedimentary rocks that record such events as transgressions and regressions of oceans and changes in flow regimes of fluvial networks.

In most geologic provinces, a tectonic history is superimposed on the climatic history of the region. These two

components must be unraveled to understand the long-term environmental record. Toward this goal, work is ongoing to model the structural history of the Wind River Basin and the paleoclimatic history. Structural models are being developed based on the results of structural mapping and on input from the global-scale tectonic models developed under the Geodynamics Program.

The major new direction of the Geology Program Element toward global-scale investigations requires expansion of our mapping capabilities to additional geologic provinces and climatic regimes. Several studies are extending our capabilities to vegetated terrains where work is ongoing to determine the relationships between rock types and vegetation species and distribution. Preliminary analyses of TM images show that the data provide direct and useful information about soils and bedrock in forested areas. However, more work is required to exploit the geobotanical and textural information in TM and radar images for lithologic mapping in heavily vegetated regions, such as the tropics, and areas with difficult access, such as the polar regions.

**Geodynamics Program.** Geodynamics is the branch of Earth sciences dealing with the forces and processes (both internal and external) that affect the solid Earth. Geodynamics includes the study of the structure, composition, evolution, and deformation of the solid Earth; the Earth's magnetic and gravity fields and the processes that generate them; the solid Earth and ocean tides; and time variations in the Earth's rotation and the orientation of its rotational axis.

The objectives of the NASA Geodynamics Program are (1) to contribute to our understanding of the processes that move and deform the tectonic plates and (2) to improve measurements of the Earth's rotational dynamics and its gravity and magnetic fields to better understand the internal dynamics of the Earth. The program uses laser ranging to satellites and to the moon, radio transmissions from satellites, and microwave interferometry for precise (centimeter-level) position measurements; it also uses satellite tracking and in situ measurements to map the Earth's global gravity and magnetic fields.

The Geodynamics Program is subdivided into three elements: Earth dynamics, crustal motion, and geopotential research.

**Earth Dynamics Element.** The objectives of this element are to develop models of polar motion and Earth rotation and to relate studies of global plate motion to the dynamics of the Earth's interior. This program is expected to lead to significantly improved understanding of the global structure of the Earth and the evolution of the crust and lithosphere. Research conducted includes studies of the dynamic interaction between different regions of the Earth's interior and its relationship to crustal magnetization, gravity anomalies, and tectonic features.

**Crustal Motion Element.** Field measurements and modeling studies of crustal deformation in various tectonic settings are the primary objectives of the crustal motion program element. These activities provide measurements, analyses, and models describing the accumulation and release of crustal strain and the crustal motion between and within the tectonic plates, particularly the North American, Pacific, Eurasian, South American, and Australian plates. Activities include development of quantitative descriptions of the geophysical and geological constraints on the motion models and block-tectonic models of the western United States. The investigations also compare the geologically determined motion vectors between sites with the geodetically determined values to test the predictions of geological models.

**Geopotential Research Element.** This element uses space and ground measurements to construct gravity and magnetic field models and to investigate data analysis techniques and software systems. Research on the Lageos orbit and the orbits of near-Earth satellites are directed toward advancing gravity field studies. Gravity field data are derived from satellite altimetry, satellite-to-satellite tracking, and gradiometry; magnetic field data are obtained from satellite magnetometers; and ancillary data are used in constructing the models.

## National Oceanic and Atmospheric Administration (NOAA)

The NOAA research program in land remote sensing is currently devoted to the development and practical application of techniques for land surface observations from (primarily) meteorological satellites. The main areas of application are (1) agriculture and renewable resources and (2) geology and nonrenewable resources.

**Agriculture.** NOAA participated in the Agricultural and Resources Inventory Surveys Through Aerospace Remote Sensing (AgRISTARS) project, a national program of research, testing, and evaluation of space remote sensing to meet the needs of USDA. NOAA is currently developing the uses of operational environmental satellite data for agriculture. The goals of the NOAA program are to develop algorithms for producing agriculturally useful products from the satellite data and to test those algorithms in an operational environment. Quantities of interest for agricultural monitoring include vegetation indices, solar radiation, maximum/minimum temperature, and precipitation.

**Vegetation Monitoring.** The differential reflectance of green vegetation between the visible and near-infrared wavelengths allows instruments on the NOAA polar-orbiters to directly observe vegetation. Mathematical

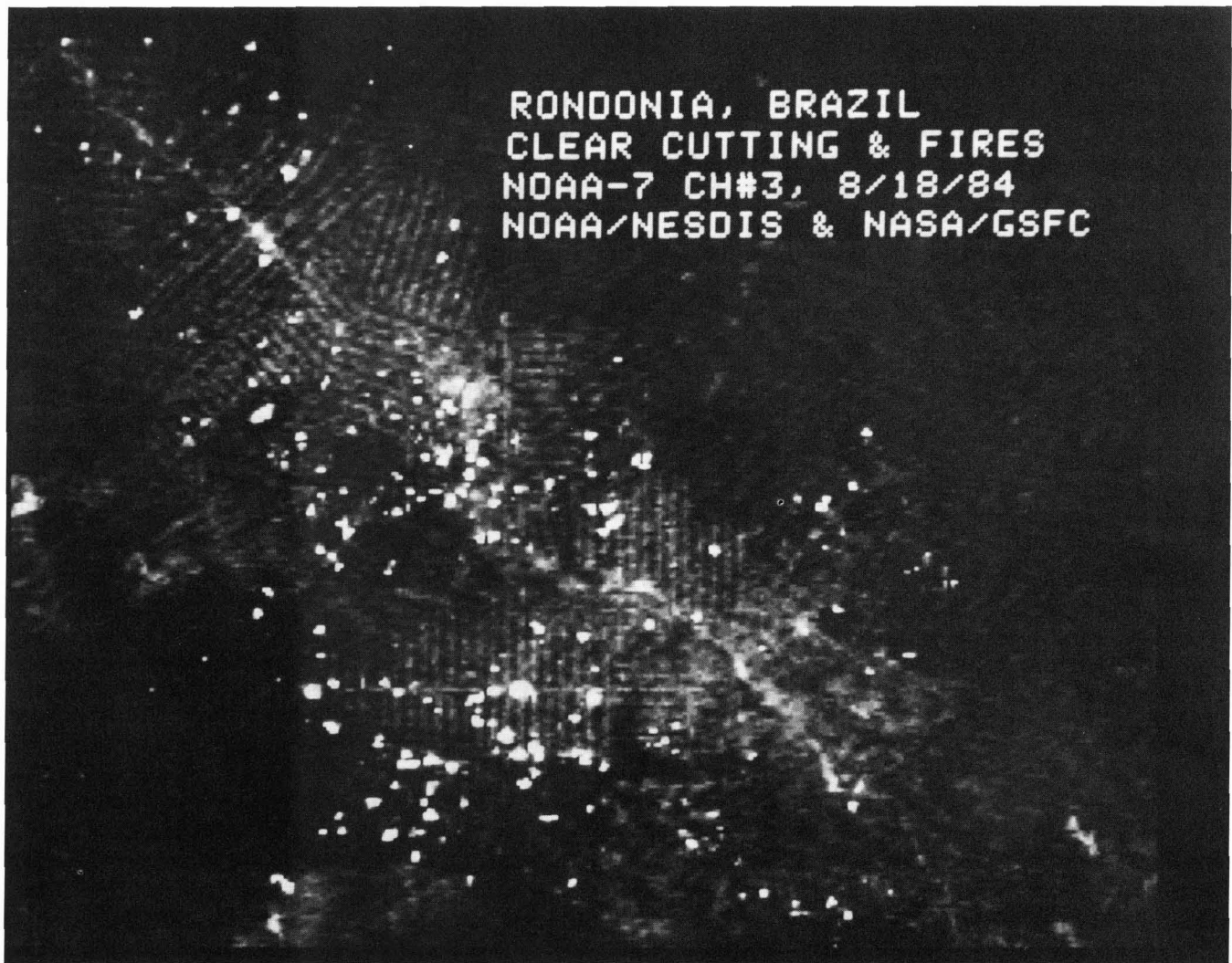


FIGURE 11. This is a NOAA-7 computer-enhanced 3.8 micrometer thermal infrared satellite image of the Rondonia, Brazil area. The image was taken on August 18, 1984 at 19:47 Greenwich Mean Time (GMT) and the resolution is 1.1 kilometers (km). The gray linear features are clear-cut swaths of forest, some more than 80 km long, about 4 km apart, and 600-800 meters wide. The clear-cut area is bisected by highway BR-364. The white areas are fires associated with the clear cutting and slash and burn agricultural activities. The large-scale (100 × 400 km) primary forest disturbance shown in the image is a Government-planned colonization project. Images such as these demonstrate the potential of remote sensing for monitoring deforestation and forest fires.

combinations of the two channels are indicators of the presence and amount of green vegetation.

The NOAA series satellites have two advantages and several disadvantages when compared with Landsat for vegetation monitoring. The advantages are their more frequent repeat time and their wider-area coverage. If the area of interest is cloudy, large gaps occur in the Landsat coverage. The two key disadvantages occur when information is required on the scale of individual fields, in which case Landsat has higher spatial resolution; and when details on the type of vegetation are required, Landsat has better spectral resolution.

Vegetation index images are produced on a global scale using 4-kilometer resolution AVHRR data. The daily

maps are composited over a 7-day period by saving the maximum vegetation index calculated for each map location over the compositing period. This type of maximum value compositing eliminates clouds from the image except for areas that were cloudy during the entire week in daylight hours (or at times of satellite overpasses). Vegetation indices computed from NOAA satellite data are being used by foreign and Federal agencies for operational and experimental purposes.

*Solar Radiation.* The primary source of energy for growing vegetation is solar radiation (insolation) incident on the plant canopy. A method has been developed that uses hourly Geostationary Operational Environmental Satellite (GOES) visible data to estimate hourly insolation. The



technique involves regression against observed target brightness, as measured by GOES, and known brightness of the target under clear conditions. The difference between these two quantities is a measure of cloudiness, the most important factor affecting insolation. Daily insolation estimates are being made and archived for all of the United States and agriculturally important areas of Mexico.

*Maximum/Minimum Temperature.* Air temperature significantly affects crop development. Current operational crop and soil moisture models require daily maximum and minimum air temperature and dew point temperature or relative humidity. Regression techniques have been developed to estimate air temperature from NOAA TIROS Operational Vertical Sounder (TOVS) soundings and radiances and to estimate daily maximum and minimum temperatures from air temperature at a specific time. These regression methods are applied daily to the National Environmental Satellite, Data, and Information Service (NESDIS) satellite temperature retrievals and daily air and maximum/minimum temperatures are estimated.

*Precipitation.* The amount of precipitation determines soil moisture and the moisture available to vegetation. The distribution of precipitation within the growing season may be as important as the total amount. Current research is focused on the continued development of techniques using visible and infrared satellite data. These techniques attempt to relate precipitation rates to the appearance and development of clouds in visible and infrared satellite imagery. Microwave observations, more directly related to the presence of waterdrops in the atmosphere, show greater promise for precipitation determinations.

*Geology and Land Use.* Thermal anomalies, whether naturally occurring or man-made, are often of major concern. Volcanoes, forest fires, and anthropogenic activities produce thermal signatures detectable from satellites. NOAA research is developing means to monitor these phenomena, with the eventual result of operational products.

*Volcanoes.* Satellite remote visible and infrared sensors have been used since at least 1976 to detect and monitor volcanic activity around the globe, particularly in tracking ash clouds. The best documented observations are those taken by the GOES satellite of El Chicon, which erupted in Mexico in late March and early April of 1982.

*Forest Fires.* Environmental satellites such as the NOAA polar-orbiter series, with large swath widths, day/night coverage, and fire-detecting infrared sensors (operating in the 3- to 5-, especially 3.8, micron portion of the spectrum), offer a potential efficient and economical detection and monitoring of fires in large areas. Through daily use of this satellite method in the western United

States during the late summer and early fall of 1981, over 175 fires were observed.

*Urban Heat Islands.* Since 1940, increased urbanization and industrialization in many cities have intensified the associated positive thermal anomalies commonly termed urban heat islands. Satellite data can provide information on the extent and thermal structure of these urban heat islands.

## Department of the Interior (DOI)

Most DOI bureaus and offices have used aerial photography for many years to meet their administrative and program responsibilities. However, during the past 14 years, increasing efforts have been made throughout DOI to realize the advantages offered by space observation through the application of Landsat, NOAA AVHRR, and other satellite remotely sensed data. Current DOI uses of these data can be categorized as operational, pilot/evaluation, and research/study.

*Operational Uses.* Development of operational uses of satellite remotely sensed data by DOI has been facilitated by research and development programs of the Department and other organizations. Consequently, these operational uses provide a measure not only of current capabilities but also of the progress and success of previous and ongoing research and development programs. Several DOI bureaus and offices, most notably the Bureau of Land Management (BLM), the Bureau of Reclamation (BOR), the National Park Service (NPS), and the United States Geological Survey (USGS), routinely apply Landsat multispectral scanner (MSS) and thematic mapper (TM) data in their operational programs. The following list serves to illustrate the types of operational uses of remotely sensed data being made within DOI currently and/or in the recent past.

- USGS uses Landsat MSS data for mapping irrigated lands in an eight-state area of the High Plains to determine water consumption by crops and pumping stress on groundwater resources.
- USGS uses Landsat MSS and TM data for hydrothermal alteration detection and mapping as a part of the Conterminous U.S. Mineral Appraisal Program.
- USGS uses Landsat MSS and TM data in its geological mapping programs.
- Bureau of Indian Affairs (BIA) uses Landsat MSS data for determining woodland strata for noncommercial forest inventories on Indian lands.
- BLM uses Landsat MSS data to identify and monitor unauthorized mineral activities on Federal lands in the eastern United States.

- BLM and NPS use Landsat MSS data to map forest and rangeland resources in the western United States and Alaska for inventory and for characterizing wild-life habitat.
- NPS and BLM use Landsat MSS and NOAA AVHRR data to map vegetation type and biomass accumulation for use with other data in the Geographical Information System (GIS) to develop fire fuel models. Large areas of the western United States and Alaska have been characterized with a fire fuel hazard rating as a result of these programs.
- NPS uses Landsat MSS and TM data with digital terrain data to develop land cover maps and digital data bases for selected parks in Alaska and the lower 48 states.
- BOR uses Landsat MSS and TM data to produce land use and crop inventory maps of irrigated lands for determining consumptive use of irrigation water in the western United States.
- BOR uses Landsat MSS and TM data to inventory surface water accumulations to determine water volumes and evapotranspiration losses for areas of the western United States.
- BOR uses Landsat MSS and TM data for lineament mapping and analysis for dam safety and construction site evaluations in the western United States.
- BOR uses Landsat MSS and TM data to map and monitor snow cover in the western United States for runoff predictions.
- BOR uses Landsat MSS and TM data for measuring chlorophyll A concentrations and turbidity to determine the trophic state of reservoirs in the western United States.
- BOR uses GOES imagery for analysis of cloud type, water vapor, and cloud motion to predict precipitation volumes in the western United States.
- BOR uses GOES Data Collection Platform (DCP) systems to relay a wide range of meteorologic and hydrologic data.

A new effort to use AVHRR data began when NOAA and USGS initiated a joint effort in 1986 to install, at the EROS Data Center (EDC), an AVHRR reception and processing system designed to provide AVHRR data products, optimized for land Earth science applications, to meet Federal research program requirements and DOI operational program needs in a timely fashion. The system, which achieved operational status in May 1987, has the capability to acquire, by direct reception, data from all passes over the conterminous United States. Acquired data can be fully processed and available for distribution in

digital form at full radiometric resolution (10 bits) within 24 to 48 hours following acquisition. Processing includes screening for clouds and geographically registering the data to a user-specified map projection.

*Pilot/Evaluation.* DOI bureaus and offices are continually seeking new operational uses of satellite-sensed data. This process typically involves various degrees of research and development followed by pilot applications projects to evaluate the efficiency and effectiveness of specific applications. DOI pilot/evaluation uses of satellite remotely sensed data include the following:

- Monitoring rangeland for assessment of drought and other forms of stress;
- Monitoring effects of irrigation on water use and groundwater recharge;
- Monitoring forest defoliation and other stages of vegetation stress;
- Classification of flood plain vegetation;
- Flood mapping;
- Monitoring Arctic sea-ice conditions for offshore operations and transportation route suitability;
- Monitoring surface mining and mine reclamation activities;
- Detecting and monitoring oil slicks;
- Base map updating;
- Image map production;
- Regional environmental surveys for preparation of environmental impact statements;
- Environmental assessment of pipeline corridors;
- Mapping forest and rangeland fire scars and monitoring rates of revegetation;
- Monitoring coastal shoreline changes; and
- Assessing flood and other natural disaster impacts.

*Research/Study.* The development of operational uses of satellite remotely sensed data requires research and development to establish basic knowledge and understanding of such things as the relationships between surface materials and their interactions with electromagnetic radiation (EMR), atmospheric effects on EMR transmission, effects of sensor characteristics on the radiometry and geometry of the recorded EMR, fundamental digital processing concepts and capabilities, and data analysis and interpretation methodologies. Various DOI bureaus and offices engage in research/study activities aimed at advancing the science of satellite remote sensing and developing new operational uses of satellite remotely sensed data. Such research commonly uses data collected both by experimental and prototype satellite and airborne remote-

sensing systems and by the existing operational systems. Much of the remote-sensing research conducted by DOI is done by USGS and is supported by advanced capabilities for spectral measurement and sample analysis, digital data processing and image enhancement, and product generation at laboratories in Reston, VA, Flagstaff, AZ, Denver, CO, and at the EROS Data Center near Sioux Falls, SD. Examples of DOI research/study uses of remotely sensed data include the following:

- Investigation of bidirectional reflectance characteristics of surface materials;
- Investigation of physical and chemical properties of plants and of vegetation stress;
- Investigation of diagnostic spectral signatures of mineral, rock, soil, and vegetation types and conditions;
- Investigation of weathering effects on rock mineralogy and spectral characteristics;
- Investigations of spectral mixing;
- Determination of classification accuracies;
- Development of automated drainage and lineament mapping capabilities;
- Development of automated planimetric mapping systems;
- Development of digital terrain models based on satellite-acquired data;
- Development of automated sampling methodologies;
- Detection of mine roof hazards;
- Monitoring of ground movements associated with mining activities;
- Prediction of natural disasters;
- Monitoring of the effects of acid rain;
- Development of techniques for merging and integrating remotely sensed, geophysical, topographic, and other spatially referenced digital data;
- Development of digital georeferenced data information systems; and
- Investigation of digital image enhancement techniques.

## U.S. Department of Agriculture (USDA)

*Goals and Objectives.* For USDA and its agencies, remote sensing is one of the many information sources used in decision-making. Generally, USDA's goal is to improve existing and future information systems, thereby

improving decision-making. Therefore, USDA is now engaged in research and development to determine the usefulness, cost, and extent of integrating remotely sensed data into its information systems.

USDA has long employed aircraft remote-sensing systems to great advantage and use of satellite remote-sensing techniques is recognized as a logical evolution. To gain acceptance and be useful, remotely sensed data from space platforms must complement or provide new cost-effective sources of information for coverage, accuracy, or timeliness.

*Key Thrust and Subelements.* The approach taken by the USDA in determining the utility of data from space platforms is a balanced program of remote-sensing research, development, and testing that addresses commodity production information needs and domestic resource management.

The current research program addresses seven information requirements:

- Early warning of change affecting production and quality of commodities and renewable resources;
- Commodity production forecasts;
- Land use classification and measurement;
- Renewable resources inventory and assessment;
- Land productivity estimates;
- Conservation practices assessment; and
- Pollution detection and impact evaluation.

The first two requirements—early warning and commodity production forecasting—have been emphasized because of the immediate need for better and more timely information on crop conditions and expected production. Budget constraints, resource availability, changes in agency priorities, and research accomplishments during the program have affected the ranking of the remaining requirements.

The structure of the technical research program largely follows the information requirements as outlined. However, several subelements focus on research areas comprising several of the requirements. For example, soil moisture research affects both the early warning and commodity production requirements and other information categories. Development of crop yield models also supports the early warning and commodity forecasting components. Supporting research covers development of remote-sensing technology relevant to all requirements—for example, area estimation, spectral crop appearance, crop stress, and soils.

*Historical Perspective.* In 1974, NASA, NOAA, and USDA began the Large Area Crop Inventory Experiment (LACIE) to research, develop, apply, and test space-based,

remote-sensing technology that was designed to estimate worldwide wheat production, with a goal of improved accuracy and timeliness. Wheat area estimates were based on analysis of Landsat data, and weather effects models were used to estimate wheat yields. LACIE, completed in 1978, demonstrated that this technology met the established goals. The LACIE results also indicated that technology improvements were needed in certain important wheat-growing regions, primarily where field size is close to present satellite resolution limits and where spring wheat is difficult to separate from other small grains such as spring barley.

After several years of small-scale research effort, the National Agricultural Statistics Service completed an experiment in 1977 for using Landsat digital data to improve crop acreage estimates for all major spring-planted crops in Illinois. This experiment, using full-frame classification combined with ground data collected from a probability sample, demonstrated the usefulness of remote-sensing data for estimating domestic crop acreages and for supporting land use estimation activities.

Because of the encouraging results of both the LACIE and National Agricultural Statistics Service experiments, government planners supported additional research for applying remote sensing to other domestic uses and to additional crops in other countries. After a year of planning, a research program, AgRISTARS, was initiated in 1980. The AgRISTARS program was a cooperative effort of the Departments of Agriculture, Commerce (NOAA), and the Interior, and NASA. USDA is now continuing applications research and developmental activities begun under the 6-year program.

Scientists of the Agricultural Research Service participated in a cooperative experiment with scientists from the U.S. Geological Survey and the University of Arizona Maricopa Agricultural Center to study the use of remotely sensed spectral data for large-scale farm management. The potential use of remotely sensed data for operational farm management decisions has not been fully realized because relationships between spectral data and soil and crop properties are not sufficiently understood and documented. A detailed examination of what remotely sensed data can tell about soils and crops is a logical first step toward the goal of developing a farm-oriented remote-sensing system. Such a project is complex because it must examine remotely sensed data at different spectral and spatial resolutions over a variety of crops at different growth stages and under different health conditions.

The experiment at the Maricopa Agricultural Center was conceived with the objective of collecting a comprehensive set of remote and ground-based spectral data over agricultural fields whose agronomic properties were monitored. As the experiment progressed, more research and information needs were identified and the list of participants multiplied. The experiment evolved into an

intensive endeavor in which atmospheric measurements, aircraft-mounted and ground-based radiometer measurements, and numerous soil and plant measurements were made on each day of the Landsat-5 overpass, weather and equipment permitting.

## Department of Defense (DOD)

Space-derived environmental information is used to increase the effectiveness of weapons systems, provide intelligence for tactical and strategic command decisions, protect life and property, assist other military planning and operational activities, and support military research and development. The objectives and efforts identified below either use or are involved in acquiring data that are now, or may in the future be, obtained by space-based acquisition techniques.

**Basic Land Research Objectives.** DOD research can be divided into three areas: Earth dimensions, material characteristics, and transmittance and propagation.

- Earth dimension objectives are to

*Improve models of the Earth's size, shape, and gravity field. Specific efforts are to determine more accurate astronomic latitude, Earth rotation rate, and polar motion, and to analyze and compare inertial, gradiometric, and astrogeodetic techniques for positioning and gravity measurements.*

- Material characteristic objectives are to

*Acquire knowledge of the properties of ice, snow, and frozen ground and assess their interaction with a cold environment; and*

*Increase knowledge of Arctic region ice movement, coastal dynamics, and continental margins by developing ice distribution, ice thickness, and frontal dynamic models.*

- Transmittance and propagation objectives are to

*Increase understanding of seismic and acoustic wave propagation in the Earth's solids, liquids, and gases. Specific efforts are to measure excitation, propagation, and detection of strong ground motion and the effects of earthquake seismic waves on ground facilities and measure the effects of long-period crustal motions on accuracy and precision measurements; and*

*Acquire better methods of sensing, describing, characterizing, and mapping geophysical features of the Earth's surface, subsurface, ocean bottom, and sub-bottom, using both direct and remote-sensing techniques for measurement and survey. Specific efforts are to develop artificial intelligence technology for feature extraction from remotely sensed data, develop decision logic network for terrain analysis, develop schemes for using ground-truth data to optimize use of*

*satellite and airborne data in surveying and mapping surface and subsurface features, and develop real-time remote sensing of the under-ice environment.*

**Applied Land Research Objectives.** DOD land research can be divided into three areas: data sets, combat improvement, and computers.

- Data set measurement objectives are to

*Measure and model the Earth's geometry, gravity field, dynamics, and motions. Specific efforts are to use a balloon-borne gravitometer system for validating gravity measurements and measure atmospheric and surface acoustic environments during rocket launches; and*

*Develop methods and equipment for collecting, processing, and disseminating geodetic, topographic, and geographic data products. Specific efforts are to model ground wave motion and study seismic hazards and compute diffraction effects to determine surface and body wave coupling at crustal transition zones.*

- Combat improvement objectives are to

*Improve combat capability in winter and in extremely cold environments. Specific efforts are to establish methods to determine cold environment impacts on material and performance, establish design criteria for new materials and construction, and establish more economical and effective techniques for operating and maintaining cold region facilities.*

- Computer objectives are to

*Develop data base preparation and format concepts. Specific efforts are to develop data base preparation concepts for computer image generation programs; and*

*Develop software for models, manipulation, overlays, interpretation, and experimentation and development. Specific efforts are to develop software for models of terrain mobility and near-ground visibility, contour manipulation and stereo overlay, and photo interpretation logic networks for artificial intelligence experimentation.*

#### **U.S. Army Corps of Engineers (CE): Civil Works Program**

**Research.** The research objective of the CE Satellite Remote-Sensing Research Program is to provide cost-effective methods of acquiring data for the planning, engineering, design, construction, and maintenance of CE projects. Currently, nine research work units are supporting the following CE functions: (1) real-time data for emergency operations and water control, (2) wildlife habitat studies, (3) land use for hydrologic and environmental studies, (4) updating of flood damage data bases, and (5) coastal engineering. The remote-sensing technologies

being addressed are Landsat-5's TM (with 30-meter resolution), Systeme Probatoire d'Observation de la Terre (SPOT, a French civil land satellite with 20- and 10-meter resolutions), transmission of environmental ground sensor data via satellite communications, and active ground radars.

The objectives of these research tasks are to

- Improve the spatial analysis methodology of remotely sensed data. Develop a methodology and analytical techniques to use remotely sensed soil moisture data in hydrologic modeling;
- Evaluate the use of Landsat-5's TM and MSS and SPOT's High Resolution Visible Range (HVR) instruments data products and future satellite simulation sensor data to address water resources, geology, and cold regions relevant to CE's mission;
- Compare the information content, reliability, and cost factors associated with acquisition and analysis of aerial photography and satellite data for wildlife habitat identification and mapping;
- Develop and demonstrate a capability to provide rapid repetitive coverage of the flood waters over the total Lower Mississippi Valley Division (LMVD) region involved in large Mississippi River floods for use in flood water control and emergency operations;
- Test and evaluate techniques for interfacing state-of-the-art hydrometeorological and environmental sensors to GOES and other data relay systems and demonstrate the utility of data acquisition relay systems on an operational basis;
- Develop and document procedures for using satellite digital data in CE planning, engineering, and operational activities;
- Provide accurate coastal engineering data using remote-sensing techniques. Test and evaluate remote-sensing techniques and systems and demonstrate their cost-effective potential for the collection and analysis of data of the coastal zone. This work will be coordinated with and accomplished by the cooperation of other Federal, private, academic, and foreign institutions, wherever feasible;
- Develop and demonstrate the capability to expedite the delineation of flooded areas as a function of river stage and land use classes and develop timely and economical procedures for establishing and updating land use with Landsat-5 and SPOT satellite data and historical flood data bases with archived Landsat data; and
- Develop, demonstrate, and document a multistage sampling procedure for extracting natural resource, terrain, and hydrographic data from multiple sen-

sors/image types and encoding the data in an integrated digital geographic data base.

**Demonstration.** The initial demonstration projects began with U.S. Army Engineer Division, LMVD, South Atlantic Division, and Waterways Experiment Station using the Flood Analysis Simulation Technology system in the late 1970's. In 1980 the demonstration program was formalized and expanded to include Phase I design studies using Spatial Analysis Methodology (SAM) planning techniques. SAM is composed of a spatially oriented data bank and a family of data management and data analysis computer programs. Remote-sensing technology can provide various data base elements and because of its digital format, is compatible with SAM. In March 1981 a Memorandum of Understanding was signed with NASA. The objective is the joint CE/NASA technology assessment and transfer programs to assess and demonstrate the utility of remotely sensed data and associated technologies in planning studies and projects. Currently the program consists of six completed and seven ongoing studies; there are plans to expand the program to include more engineering and operational studies.

#### National Science Foundation (NSF)

The Foundation's current use of satellite data for "land processes" research is limited but dispersed throughout NSF. At least 12 NSF programs use such data. These programs include traditional Earth sciences disciplines such as geology, ecological studies, anthropology, and engineering. Within most of these programs, NSF funds only one or two projects involving use of satellite observations. Of the Foundation's funding to "land processes" research, less than 2 percent supports projects that use satellite observations. A significantly larger fraction (about 25 percent) supports projects that use satellite communication links, satellite-based positioning systems, or both.

Satellite observations of particular value to NSF-supported research projects have been

- Magnetic field observations (Magsat);
- Gravity field observations, especially satellite radar altimetry (Seasat); and
- Multispectral imagery including conventional photography (Apollo, Skylab, Landsat).

The limited use of satellite data by NSF-sponsored land processes research programs is undoubtedly because of the scarcity of image-processing skills and instrumentation in this community. Because of the high potential utility of satellite data, especially multispectral imagery, and the very broad spectrum of possible users, a significant increase in demand can be expected as the necessary skills

and equipment become more widespread. Many programs project that the use of satellite data will double or triple within a few years.

Future satellite missions of special interest to NSF include the following:

- *Geopotential Research Mission (GRM).* Detailed knowledge of the Earth's magnetic and gravity fields can provide important constraints on the mass-distribution, mineralogy, and thermal state of the Earth's interior. These data are needed to understand the structure of the crust and lithosphere and the dynamics of the convecting mantle.
- *The Ocean Topography Experiment (TOPEX/Poseidon) and Higher Resolution Radar Altimetry Studies.* Seasat altimeter data have proven extremely valuable for mapping the detailed shape of the geoid surface, the topography and extent of polar ice sheets, and some features of ocean bottom topography. Further high-resolution radar altimetry studies, especially with high-latitude coverage, would be very useful.
- *Multispectral Imagery Missions.* The NSF-supported academic community has made relatively little use of these data so far. This is expected to change as the data become more available and as image-processing skills and instrumentation become more widespread.

#### Agency for International Development (AID)

Land processes projects sponsored by AID focus on agriculture and forestry, geology and geography, and hydrology. Whereas institution building is a function of many remote-sensing projects, the building of indigenous capacity is especially significant in the activities of three regional remote-sensing centers funded over the period 1981-85 in East Africa, West Africa, and Asia. AID also supports atmospheric remote sensing related to land processes. In addition, the AID Office of U.S. Foreign Disaster Assistance supports the Global Climatic Impact Assessment project.

**Agriculture.** The most significant research in the application of remote-sensing technology to the agricultural sector has been conducted through Remote Sensing for Agriculture (1979-83). As a result of this project, the Area Sampling Frames (ASF) methodology has been introduced in 12 developing countries. The results obtained in four countries (Ecuador, Morocco, the Philippines, and Sierra Leone) demonstrate that remote-sensing data can be used to support estimations of agricultural production of major crops. Phases 1 and 2 of the project involved the development of land use theme maps, sampling procedures for agricultural data stratification, and field surveys to ascer-

tain the accuracy of crop/land use delineations. Specific applications of the technology are outlined below.

In the Philippines, research conducted on the Pangasinan Province indicated the ASF methodology can be used to survey rice and corn production. Results indicated the superiority of ASF, especially for rice production, over the traditional list frame method, which tended to underestimate production. ASF also allows better control of nonsampling errors at a much lower cost, especially over a period of time. In Morocco, the project produced estimations of production data for most major crop regions. Strata were broken down into irrigated land, nonirrigated land, orchard crops, forest, and three levels of urban/village fringe cultivation. In the Kenema district of Sierra Leone, the shifting agricultural landscape and the methods and shifting patterns of cultivation necessitated extensive field surveys, increasing the expense, time, and error rate. Refined methods are required to implement the methodology in this environment. In Ecuador, an agricultural survey of the Pichincha Province identified 15 crops and land-use strata. Therefore, the 1980 estimates of production for seven out of a total of nine crops were considerably higher using the ASF methodology than the 1979 estimates compiled without the use of ASF methodology.

**Forestry.** One promising application of remote sensing to forestry management was identified as a result of AID's Remote Sensing Grant Program in Peru. The Peruvian Amazon Region offers considerable potential for forest resource development. In particular, the aguaje palm has significant economic potential. However, aguaje forests, although estimated at a total of 2 million hectares, account for only 2 percent of the total region's forests. Aerial photographic coverage of the region is almost nonexistent and the region is inaccessible to ground surveyors. Digital analysis of Landsat data, however, has shown that it is possible to discriminate aguaje and other forest species within the lowland areas of the Peruvian Amazon River.

The role that Landsat data can play in the monitoring of deforestation has been well documented in Thailand. National forestry maps prepared in 1977 using Landsat data were compared to forestry maps prepared in the 1960s using aerial photography. The depletion evident from this comparison led the Thai Government to establish a national policy to preserve forested areas. The 1977 survey inventoried various forest species, including the economically significant teak forests. A more detailed comparison of seven provinces revealed depletion rates and specific locations of depletion. This led to field checks that determined that the reason for annual clearings related to rice and cassava planting. This data resulted in a more realistic national policy on the preservation of forests. Another satellite survey delineated forests that needed to be conserved to serve as river basin catchment areas.

Using Landsat digital tapes, the Philippine Government conducted a Forest Inventory Project. The results indicated that Landsat data, supported by aerial photography, could be used to delineate five types of forest cover: full canopy dipterocarp; partial canopy dipterocarp; mangrove; mossy, high-elevation forests; and clearings and nonforests areas, such as wetlands, marshes, and water bodies. A special survey of mangrove areas determined the development of fishing areas with minimal ecological damage.

**Geology and Geography.** The Mineral, Petroleum, and Groundwater Assessment Project has focused on compiling an indepth inventory of mineral potential in Egypt, especially of those minerals that would attract foreign investment. The major focus is on potash salts in the Gulf of Suez, gypsum deposits along the coastlines, gold deposits, and volcano-sedimentary environments expected to hold sulfide, copper, lead, and zinc deposits.

Landsat data are used to provide reconnaissance information of an area prior to ground mapping. Information provided includes access to areas, key locations for examination of stratigraphic sequences, clues to regional stratigraphic and structural relationships, and broad structural and lithologic features. In addition, Landsat imagery of key mineral potential will be made available to potential investors. This service will encourage private sector involvement in the mineral exploration process.

**Hydrology.** Landsat data used in concert with depth-soundings of Lake Volta provided area measurements of total lake volume and provided necessary information for regional irrigation projects.

**Atmospheric Remote Sensing.** The Agro-Climatic/Environmental Monitoring Project represents an ambitious effort to analyze the interaction of the weather and food production in terms of early identification of seasonal floods, droughts, and storm damage. The capabilities of Landsat and various weather satellites—including Japan's GMS, the U.S.S.R.'s Meteor (Meteorological Satellite), and TIROS (Television Infrared Observation Satellite) satellites—are being used to provide an early warning system, vertical temperature profiles, as well as water vapor and ozone content of three layers of the atmosphere. The Data Collection System (DCS) on board the TIROS satellites provides information related to meteorological and hydrological conditions along the principal river systems.

**Climate Impact Assessment for Less Developed Countries.** AID's Offices of U.S. Foreign Disaster Assistance (OFDA) called for a reliable and cost-effective program to support early warning of natural disasters such as crop failure, drought, and flooding. This resulted in the Early Warning Program developed by the NESDIS Assessment

Information Services Center. The Early Warning Program combines regional rainfall estimates from ground receiving stations with cloud data obtained from NOAA weather satellites to improve accuracy of the estimates. Also, daily satellite data are used to monitor crop conditions for evidence of moisture stress and standing water reserves as potential irrigation sources. Weather data are combined with climatic impact assessment models to predict the effect on crop production.

Biweekly assessments are provided to countries of the Caribbean Basin, Africa, South and Southeast Asia, the South Pacific Islands, Central America, and the Andes countries of South America. Under this same OFDA activity, NOAA's NESDIS is assisting 25 less developed countries in the operational implementation of national climatic impact assessment systems. These systems are primarily based on operational weather data reports. In Southeast Asia, pilot projects to incorporate NOAA's AVHRR satellite analyses have been established with Thailand and Malaysia.

## B. Atmospheric Programs

An understanding of the physical, chemical, and meteorological processes in the atmosphere is critical to improved weather forecasting and serves as the basis for predicting the long-term influences of natural and man-made phenomena in the atmosphere. This discussion concerns the research and operational programs of the principal Federal agencies participating in atmospheric remote sensing.

### National Aeronautics and Space Administration (NASA)

#### *Atmospheric Dynamics and Radiation Program.*

The circulation patterns of Earth's atmosphere range from high-altitude currents circling the Earth to migratory cyclones and anticyclones, hurricanes, thunderstorms, and tornados, to small convective clouds, and finally, to small-scale turbulence. Progress in understanding these atmospheric phenomena is usually measured by an improved ability to predict the state of the atmosphere.

The NASA Atmospheric Dynamics and Radiation Program includes mesoscale atmospheric processes, global-scale atmospheric processes, and climate (discussed in Chapter IIID). The goal of the Mesoscale Atmospheric Processes Research Program (MAPRP) is to improve the scientific understanding of storm/environment interactions, weather system evolutions, interscale energy transition, and moisture/precipitation electrical effects. This can be achieved by using airborne and satellite-borne

remote measurements, advanced numerical modeling, and four-dimensional interactive computer analysis of the sequences of all available simultaneous atmospheric observations. The goal of the Global Atmospheric Research Program (GARP) is to improve capabilities for making global observations of meteorologically important parameters from space. These observations are expected to increase our understanding of the complex processes governing the large-scale behavior of the atmosphere.

Key thrusts of the programs include the following:

- Combined mesoscale, storm-scale, and planetary boundary layer numerical model development to study scale interactions and feedback processes and establish observing requirements;
- Numerical simulation of the forcing mechanisms preceding intense convection;
- Airborne evaluation of Multispectral Atmospheric Monitoring Systems and High Resolution Interferometer Spectrometer (HIS) on high-altitude aircraft;
- Observational studies and numerical modeling of satellite-detectable, storm-top rotation;
- Analysis of Doppler Light Detection and Ranging (LIDAR) data for mountain wave events, profiler intercomparisons, Pacific coast oceanic boundary layer flows, and wind fields around mountain obstacles;
- Preparations for the Satellite Precipitation and Cloud Experiment, which involves multiple Doppler radars, special satellite scans, extra radiosonde observations, and supportive aircraft-based experiments;
- Exploitation of available, remotely sensed observations of the atmosphere to initialize, verify, and improve atmospheric models; diagnose atmospheric processes; and assess the impact of such data on our ability to predict the atmospheric behavior;
- Development of new and improved techniques for retrieving useful parameters from satellite-measured radiances and their interpretation to provide information on the state and dynamics of the atmosphere;
- Development of new and advanced remote-sensing systems that will improve our capability to observe the atmosphere from space; simulate the performance of proposed new sensors to assess their potential; and evaluate the usefulness of available space-sensing systems;
- Development of an airborne LIDAR experiment to determine the global distribution and seasonal variability of 9- and 10-millimeter LIDAR backscatter (these determinations are needed to better define a



future satellite-borne Doppler LIDAR wind profiler);

- Validation of the multispectral techniques used to provide global distribution of atmospheric parameters, and once validated, expand data sets of these parameters to a minimum of 1 year; and
- Completion of the development and vectorization of the high-resolution ( $1.0^\circ \times 1.5^\circ \times 18^\circ$  level) general circulation model, then apply this model in impact assessment studies of advanced satellite observations on circulation model skill and range.

*Atmospheric Chemistry Program.* NASA has comprehensive programs of research, monitoring, and technology development in stratospheric and tropospheric chemistry. The programs are aimed at developing an organized, solid body of knowledge of atmospheric processes while providing, in the near term, assessments of potential global-scale effects of human activities on the atmosphere.

The primary goals of the stratospheric research program are to provide a scientific understanding of the physical, chemical, and meteorological processes that control the concentration and distribution of atmospheric ozone and to establish a basis for predicting the influence of both natural and man-made phenomena on the ozone layer.

The goals of the tropospheric chemistry program are to understand global tropospheric chemistry, particularly its impact on stratospheric chemistry, and assess the susceptibility of the global atmosphere to long-term chemical changes.

There are five major elements of the atmospheric research programs.

*Field Measurements Element.* This element supports a balanced set of in situ and remote measurements of atmospheric composition, solar irradiance, temperature, structure, and dynamics. A wide range of platforms are used, including satellites, rockets, balloon, aircraft, and ground-based instrumentation. Successful satellite missions have included Nimbus-4, -6, and -7, Stratospheric Aerosol and Gas Experiment (SAGE) 1, Solar Mesospheric Explorer (SME), and Earth Radiation Budget Experiment (ERBE)/SAGE 2. In addition, the Measurement of Air Pollution from Shuttle (MAPS) and the Atmospheric Trace Molecules Observed by Spectroscopy (ATMOS) sensors have flown on several Shuttle missions. There have also been many major intercomparison campaigns in which rocket-, balloon-, aircraft-, and ground-based systems have made simultaneous measurements of atmospheric constituents at or near the same location. These intercomparisons have improved understanding of inherent differences among various measurement techniques. The "suborbital" measurement systems have also provided correlative measurements for space-based remote-sensing

experiments. Suborbital platforms, especially balloons and aircraft, have been particularly useful in the testing of preliminary versions of sensors that later flew successfully in space.

*Theory and Data Analysis Element.* This element seeks the development and verification of 1-dimensional (1-D), 2-D, and 3-D models of chemistry, radiation, and dynamics, along with the analysis and interpretation of field measurement and satellite data. The reliable prediction of future stratospheric chemical behavior is dependent on the validity and completeness of the models. In the tropospheric program, this element supports the continued development, refinement, and application of 1- and 2-D photochemical models with parameterized transport to experiment planning and data analysis. It also supports the development of the general circulation model with chemistry included that will be required within the next decade to meet the program goals. Some data analysis activities and science studies for current and past field programs also are funded by this element.

*Laboratory Measurements Element.* Supporting laboratory measurements provide the basic input data for the theoretical models. These data consist primarily of chemical kinetics rate constants, mechanisms, product distributions, and photochemical cross-sections. In addition, laboratory data on the unique spectral signatures of atmospheric gases in the ultraviolet, infrared, and microwave regions are acquired in support of the needs of the field measurements program. Development of advanced sensors and calibration standards is also an important aspect of this program.

*Instrument Development Element.* This element involves and supports, exclusive of deployment costs, the development of new technological ideas, techniques, and instruments for atmospheric research. It includes projects to develop measurement capability for key source, sink, and reactive intermediate molecules in the hydrogen, the nitrogen, and the chlorine oxide families; continued work on remote sensing of ozone and aerosol profiles by differential absorption LIDAR in the ultraviolet; and development of fast flux detectors needed to study tropospheric sources and sinks of atmospheric species and stratosphere-troposphere exchange. The instrumental investigations are done in all cases to meet specific measurement objectives derived from science requirements as developed by atmospheric chemistry working groups.

*Assessments, Coordination, and Program Element.* Activities in this element include periodic assessments of the state of the stratosphere, which are incorporated into reports to the Congress and the Environmental Protection Agency. Findings on the effects of the troposphere on the stratosphere are included in these assessments. Other activities included in this element are coordination of stratospheric research programs between NASA field centers, universities, nonprofit laboratories, and other gov-

ernment agencies; workshops, conference support, facility support, and data evaluation activities; support of the work of National Academy of Sciences/National Research Council Committees and Panels in related science areas; the Resident Research Associate Program; and institutional support associated with manpower utilization at certain NASA centers.

The major research centers around a continuation of the balanced program of these five elements. Specific objectives are as follows:

- Development of the Upper Atmosphere Research Satellite (UARS) Program scheduled for launch in 1991;
- Reflights of MAPS and ATMOS on the Shuttle;
- Continuation of in situ and remote measurements of atmospheric constituents from balloon-based platforms, with increased emphasis on multisensor methods to perform intercomparisons and to obtain complete data sets;
- Further studies of the chemical composition of the lower stratosphere, with increased emphasis on the measurement of the reservoir species such as chlorine nitrate, pernitric acid, and others;
- Accurate assessment of the budget and partitioning of nitric oxides;
- An enhancement of the ground-based program to measure tropospheric source gas concentrations;
- Flux studies of source gases from key ecosystems;
- Application of LIDAR to stratospheric ozone measurement;
- Increased emphasis on the accuracy of satellite ozone measurements, including the development of a shuttle-based Solar Backscatter Ultraviolet Radiometer (SBUV) instrument to calibrate the satellite instruments;
- A series of experiments in the tropics and extratropics with multi-instrumented aircraft to investigate the mechanism of exchange between the stratosphere and the troposphere;
- Use of MST radar systems to study the dynamic processes in the stratosphere;
- Continued model development, including multiple approaches to the interactive 3-D modeling of coupled chemical, radiative, and dynamic approaches;
- The Global Tropospheric Experiment/Chemical Instrument Test and Evaluation 2 (GTE/CITE 2), a nitrogen intercomparison/budget experiment, was conducted aboard an Electra aircraft in 1986. This experiment tested and compared instruments for measurement of concentrations of nitrogen dioxide,

peroxy acetyl nitrate, and nitric acid. A previous experiment provided a comparison and assessment of hydroxyl, nitric oxide, and carbon monoxide instruments;

- Coordinated measurements of other odd nitrogen species to determine the abundances and partitioning of the major reactive nitrogen species in the continental and remote oceanic troposphere;
- The Atmospheric Boundary Layer Experiment (ABLE-2A) of the Global Tropospheric Experiment was an Electra-based experiment conducted in Brazil during 1985; ABLE 2B will be conducted in 1987. This experiment will obtain quantitative information about the sources and sinks for important trace gases and aerosols located in the tropical rain forest and investigate the causes of high carbon monoxide concentrations off the coast of Brazil with a coordinated ground-based, aircraft-based, shuttle sensor experiment;
- Development of a second generation hydroxyl detection instrument with sufficient sensitivity for global measurements from aircraft;
- Enhancements in heterogeneous chemistry in laboratory and field measurements;
- Planning and preparation for a boundary layer experiment over agricultural wetlands (possibly in China) and over tundra; and
- Planning and preparation for a DC-8-based experiment involving second generation instruments with a field mission to explore the effects of the Walker circulation on the distribution of trace gases over the Pacific Ocean (GTE/Transport and Atmospheric Chemistry near the Equator (TRACE)).

#### **National Oceanic and Atmospheric Administration (NOAA)**

The major goal of NOAA's research and development activities in atmospheric remote sensing are to develop satellite data analysis techniques and products that improve weather analysis and forecasting. Also included in this research program are measurement and analysis techniques for monitoring changes in stratospheric ozone. NOAA conducts primarily applied research, which is oriented to the needs of products or data supplied to operational users. NOAA is establishing mechanisms that look at ways to increase private sector involvement in remote-sensing data products.

*Weather Analysis and Forecasting.* NOAA currently maintains a system of Geostationary Operational Environmental Satellites (GOES) and polar-orbiting satellites of

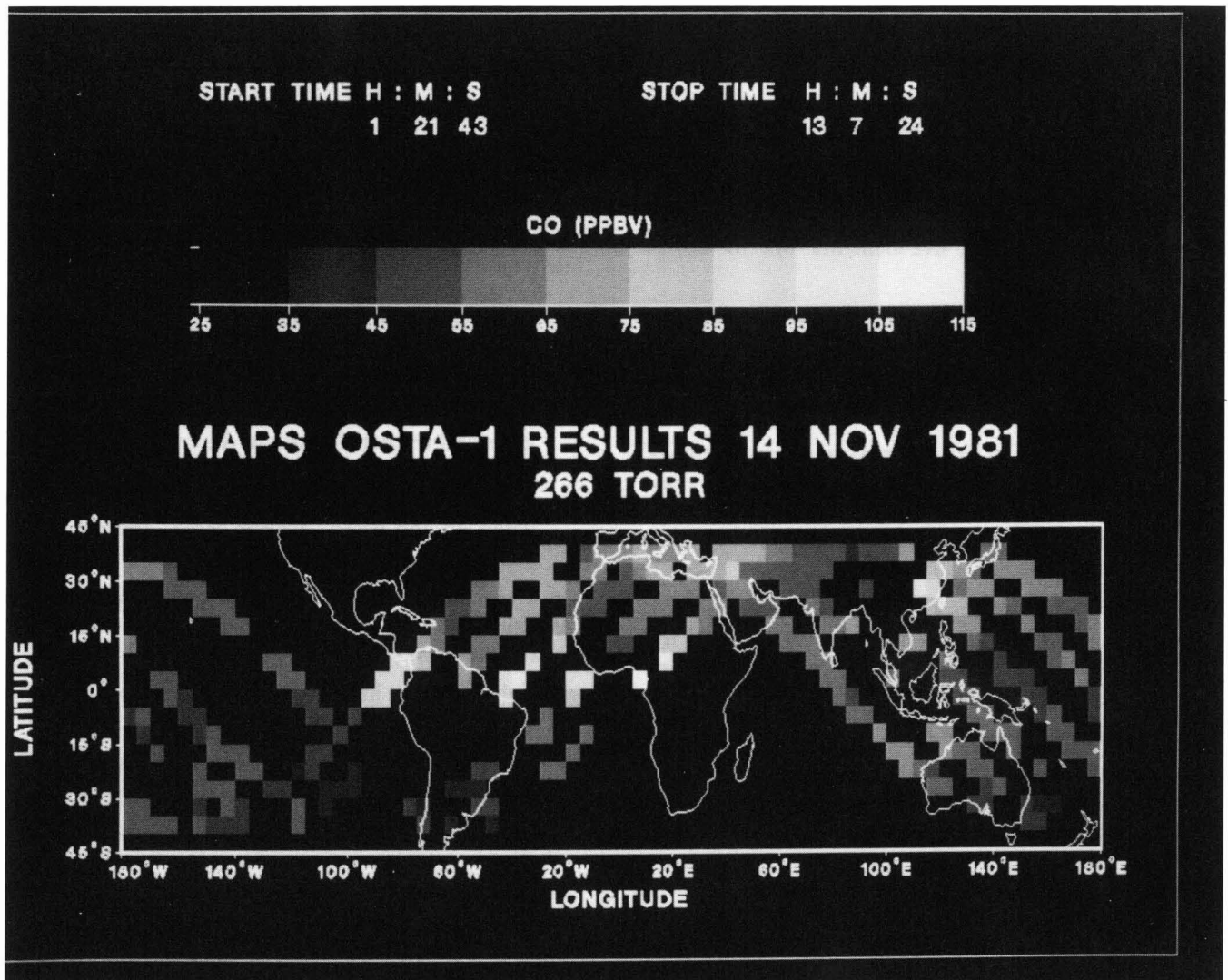


FIGURE 12. The Measurement of Air Pollution from Shuttle (MAPS) experiment that flew as part of the OSTA-1 payload on the second flight of the Space Shuttle during mid-November 1981 acquired about 20,000 individual measurements of middle and upper tropospheric carbon monoxide (CO). The data span the latitude range from 38°N to 38°S over all longitudes. The data showed that the CO was nearly uniformly mixed south of 10°S but that strong gradients existed in the tropics and at northern mid-latitudes. Strong sources are seen to be present in eastern China (the plume from this source is visible nearly to Hawaii) and in the tropics between western South America and eastern Africa. Scientific studies are now being conducted by using these data to estimate source strengths and to track polluted air masses.

the Advanced TIROS-N (ATN/NOAA) series to provide continuous data coverage for regional- and global-scale weather analysis and prediction. Polar-orbiting sensors provide sounding (temperature, humidity) information and sea surface temperature distributions necessary for numerical analysis and forecast models. Sequences of cloud images received from geostationary satellites are used to derive wind estimates at low and high levels using cloud motion vectors. These winds and the sounding information received from the polar-orbiting sensors are being used routinely in numerical models to support weather prediction.

The pictures received from the weather satellites in the early 1960s were immediately used in meteorological analysis to locate fronts and storms. For the first time, meteorologists could observe synoptic-scale cloud formations on a global scale. Over the years, storm development models have been developed based on imagery, which make it possible to track and estimate the strength of tropical and extratropical storms. Satellite data are extremely useful over vast oceanic areas and data-sparse land masses, such as Asia, Africa, and South America. Data and information are used to modify and improve the initial numerical weather analysis. Satellite data can also

be used to estimate atmospheric moisture. Studies have shown that the inclusion of satellite data has extended the useful range of weather forecasts, especially in the Southern Hemisphere where conventional weather observations are sparse.

Satellite data have provided new understanding of convective storm development. Storms on this scale are responsible for tornados, flash floods, and strong winds but are too small to be adequately described and studied using the standard surface observation network. Studies using frequent interval high-resolution geostationary data revealed that thunderstorm occurrence was not random but often resulted from interaction between organized mesoscale circulations. The growth and movement of these cloud systems could be tracked and forecast. Mesoscale Convection Complexes (MCC), which are responsible for many heavy rainfall events, were discovered and studied. Studies of thunderstorm cloud tops revealed distinctive signatures that are associated with heavy rains and downburst winds. These findings have been used at the National Severe Storm Forecast Center (NSSFC) to more accurately pinpoint areas of expected severe weather and to increase the tornado watch lead times.

Currently, the sounding and multichannel data received from the new Visible Infrared Spin Scan Radiometer (VISSR) Atmospheric Sounder (VAS) aboard the GOES are used to study the convective mesoscale phenomena. The distribution of water vapor and stability indices derived from the sounding channels and the high temporal and spatial resolution of these data are deciphering the dynamics of mesoscale storms. The NSSFC of the National Weather Service (NWS) uses the VAS data with other high-density surface observations to analyze and predict severe storms over the United States. VAS data are also being evaluated at both the National Meteorological Center (NMC) in its numerical models and at the National Hurricane Center (NHC) for its impact on analysis and forecasts of hurricanes.

Cloud images received from the GOES are being used to derive precipitation estimates that are useful for flash flood forecasting and agricultural purposes. The rate of cloud growth, cloud height, and other meteorological parameters are used to empirically estimate precipitation. Flash flood predictions incorporating satellite rainfall estimates have been very useful.

The 6.7-micrometer water vapor images are also used in meteorological analysis and aviation application. The sharpness of jet stream boundaries (dry and moist zones) are distinctly identifiable in the 6.7-micrometer images, permitting the identification of zones of potential turbulence.

Current research includes theoretical and numerical studies of the radiative properties of the Earth's atmosphere and their relation to the physical parameters measured by remote sensing. Algorithm development for

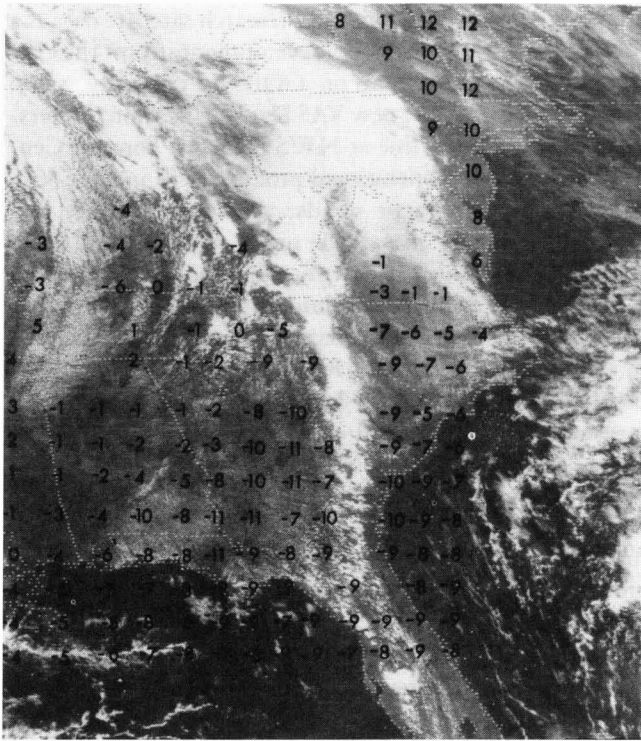
processing both operational and research satellite data is a continuing effort. Product development from the 12-channel VAS instrument on GOES is currently a top priority to support the new VAS Data Utilization Centers, which will come on line at NWS National Forecast Centers in 1988. New operational products will include VAS soundings, water vapor winds, animated stability and moisture imagery, mesoscale severe weather, and flash flood indexes. Studies concerning the effective integration of new observational technology (including VAS) for mesoscale or short-range forecasting are being conducted by the NOAA Program for Regional Observing and Forecasting Services (PROFS). Methods for using microwave measurements for rainfall estimation are being investigated, as are automatic rainfall estimation techniques, which apply cloud growth and tracking algorithms to GOES infrared imagery. Research with animated visible, infrared, and moisture channel imaging continues in order to learn more about the structure and evolution of storm systems and the relationship of the upper air cloud and moisture patterns to the wind fields, turbulence and the tropopause. The results of these studies are now available for NWS forecasters, along with the Satellite Weather Information Systems (SWIS), which will provide animated imagery formatted to NWS forecast offices.

*Stratosphere and Ozone.* NOAA has the responsibility for maintaining and directing the national program for monitoring the stratosphere for early detection of change. NOAA also develops measurement techniques and provides analyses of data for understanding chemical and dynamic processes in the stratosphere.

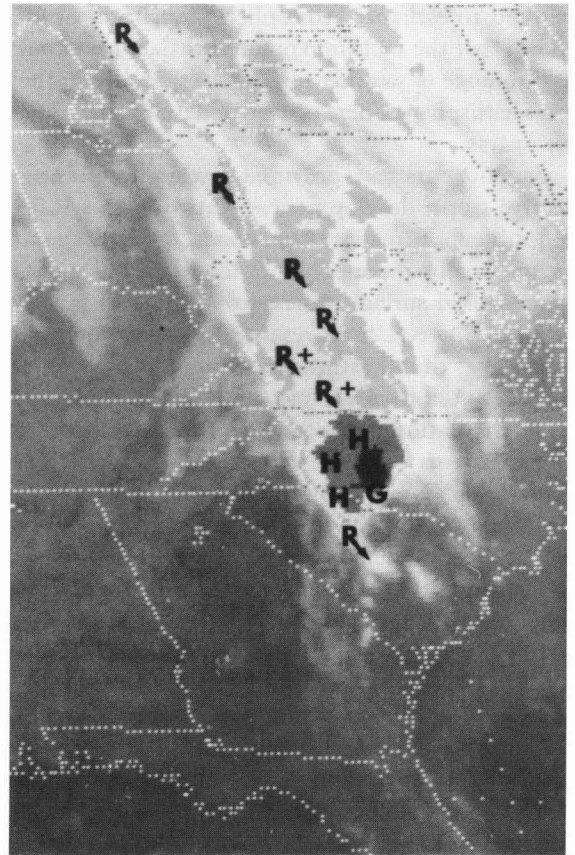
Satellite determinations of stratospheric temperature have been made since the mid-1960s. The first program of long-term ozone measurements used the SBUV technology on the NASA Nimbus satellite series; this continues to the present. The NOAA operational ozone-monitoring system, SBUV/2, was initiated in December 1984 on the NOAA-9 satellite of the ATN series and will continue late into the 1990s. Both instrument systems are based on measurements of backscattered solar ultraviolet radiation. In addition, the operational infrared sounders (TOVS) on the NOAA ATN satellites have yielded global estimates of total ozone since mid-1979.

NOAA also operates a ground-based network under the Geophysical Monitoring for Climatic Change (GMCC) Program for monitoring upper atmospheric ozone by remote-sensing techniques. Vertical ozone distributions are determined from seven or more globally distributed ground sites. This information will be used to study long-term trends in stratospheric ozone and to provide ground-truth support to the operational satellite program.

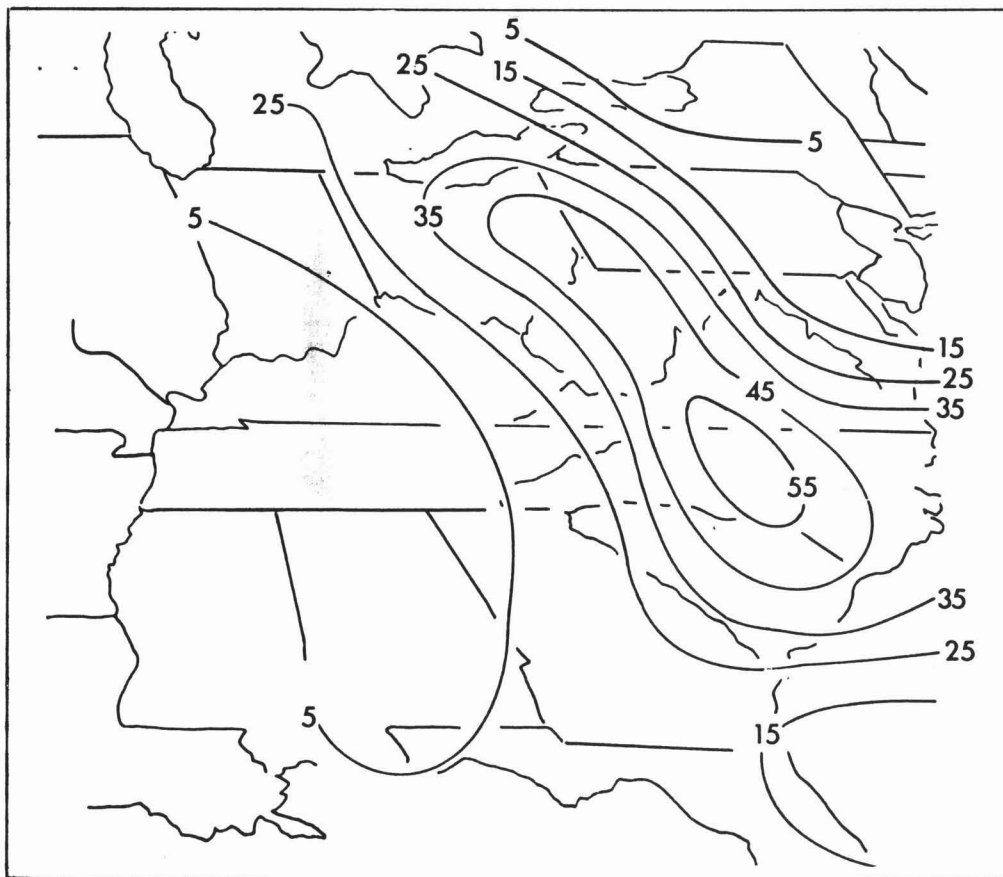
The Climate Analysis Center, NMC/NWS, conducts diagnostic studies and trend analyses with ozone data from both satellites and ground-based platforms. Emphasis has



a



b



c

FIGURE 13. The VISSR Atmospheric Sounder (VAS) instrument on GOES allows meteorologists to analyze areas of potential severe thunderstorms on a 3-hourly basis and to detect where atmospheric instability is increasing. After thunderstorms have developed, visible and infrared imagery are obtained as frequently as every 5 minutes to track severe weather. Indices that measure the stability of the atmosphere can be calculated from the GOES soundings. One of these, the lifted index, is shown plotted on the 3:30 p.m. EDT GOES visible image (a). Generally, the lower the lifted index value, the more unstable the atmosphere; values less than  $-4$  often precede severe thunderstorm development. Note the large area of low lifted indices in the southeast United States. A statistical technique, the Keller Probabilities of Severe Weather, has been developed that relates many atmospheric variables, including the lifted index, to the occurrence of severe thunderstorms. The Keller Probabilities were computed using the GOES soundings of 3:48 p.m. EDT (b), which show an axis of maximum severe weather probability extending from West Virginia southward through central North Carolina. This area is much narrower and better defined than the large area of low lifted indices computed from the raw data. An enhanced infrared image 8 hours later (12:00 a.m. EDT) (c) shows that a second line of severe thunderstorms (R) developed from eastern Ohio through West Virginia and into North Carolina. This enhanced infrared image depicts the cloud top temperatures of the thunderstorms as light grey and dark grey, with the most intense thunderstorms appearing as black. Hail (H) and damaging winds (W) occurred with the largest thunderstorms in central North Carolina near the area the Keller Probabilities showed as having the maximum potential for severe weather.

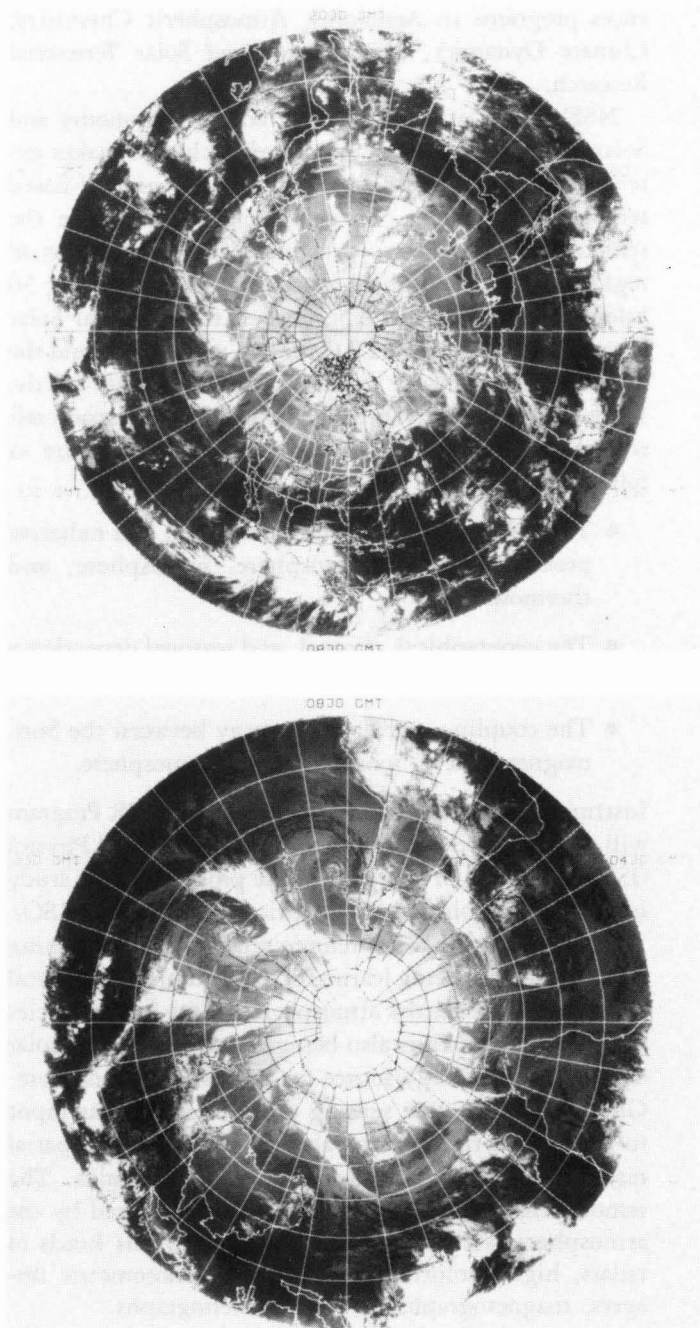


FIGURE 14. These images show the global storm-tracking capability of the polar-orbiting satellites. Twenty-four hours of infrared imagery has been mapped to polar stereographic projections of the Northern and Southern Hemispheres. The Northern Hemisphere image shows six storms in the data-sparse tropical Pacific. These range in intensity from Typhoon Ken, just east of the Philippines, to a tropical depression just forming to the west of Central America. The Southern Hemisphere image shows the spiral cloud formation of an intense high latitude oceanic storm located in the South Pacific between New Zealand and South America. These images demonstrate our ability to continuously monitor the intensity and movement of dangerous ocean storms in regions where few, if any, surface and upper air reports are available.

been on the time variation of the total ozone amount globally integrated from mid-1979 through 1983. Initially the ozone amounts were higher than the average level, then dropped to the average until the winter of 1982-83, when the values dropped to the lowest level. This period is being closely examined to determine the causal events. Diagnostic studies are also being conducted on stratospheric temperatures derived from satellite and rocket measurements for relating temperature to other stratospheric parameters, especially ozone.

The NOAA Aeronomy Laboratory is making long-term measurements of stratospheric nitrogen oxides using ground-based spectroscopic techniques at several North American sites. These measurements are being used to understand the relations between the chemical species and geophysical parameters of the stratosphere. The laboratory has also been engaged since 1981 in cooperative studies of the ozone and other data obtained from instruments on the Solar Mesospheric Explorer (SME) satellite.

### National Science Foundation (NSF)

NSF's Division of Atmospheric Sciences supports atmospheric research ranging from meteorology of the troposphere to atmospheric chemistry, aeronomy, climate dynamics, and solar terrestrial physics. Of the funds currently dedicated to research in atmospheric dynamics, about 5 percent support research that directly uses satellite observations.

Meteorologists use both visual and infrared signatures of clouds in pursuing investigations of synoptic weather systems, the Earth/atmosphere radiation budget, and the radiative environment of clouds. Research projects on global-scale weather processes, such as those of the Global Atmospheric Research Program (GARP), use satellite observations for estimating vertical temperature profiles and (cloud-tracked) winds in the troposphere.

Remote sensing from satellites has played a major role in the scientific advances in mesoscale meteorology during the last several years. Satellite support such as the Research Rapid Scan Days used in the SESAME (Severe Environmental Storms and Mesoscale Experiment) and the CCOPE (Cooperative Convective Precipitation Experiment) are important additions to instrumentation arrays used to study phenomena ranging from individual storms to mesoscale convective complexes. In the future, it is expected that mesoscale research will continue to rely heavily on satellite data support.

The Foundation currently supports limited research in atmospheric chemistry based on satellite operations or data. It is anticipated that NASA's UARS, to be launched in 1991, will provide new opportunities for the atmospheric chemistry research community supported by NSF. The goals of the program are to understand the

mechanisms controlling upper atmospheric structure and processes and to understand and predict the response of the upper atmosphere to natural and man-made perturbations. UARS data should be important in evaluating the extent of ozone depletion caused by human activities and the role of the upper atmosphere processes in climate change. The shuttle-launched satellite, with a payload of 11 scientific instruments, has been designed to obtain global research measurements of temperature, pressure, winds, energy input, ozone, and other trace chemical species in the upper atmosphere. The UARS data will be used for theoretical and experimental research projects being supported by NSF's Division of Atmospheric Sciences programs in Aeronomy, Atmospheric Chemistry, Climate Dynamics, Meteorology, and Solar Terrestrial Research.

NSF's upper atmosphere programs in Aeronomy and Solar-Terrestrial Physics support research that makes extensive use of satellite observations and ground-based remotely sensed data. Various projects investigate the structure, composition, dynamics, and interactions of regions of the atmosphere from an altitude of about 50 kilometers to the Sun. The goal of the National Solar Terrestrial Research (NSTR) Program is to understand the intricate causal chain linking the Sun's events to the Earth's environment. Three areas of study using spacecraft remote sensing and ground-based instruments are as follows:

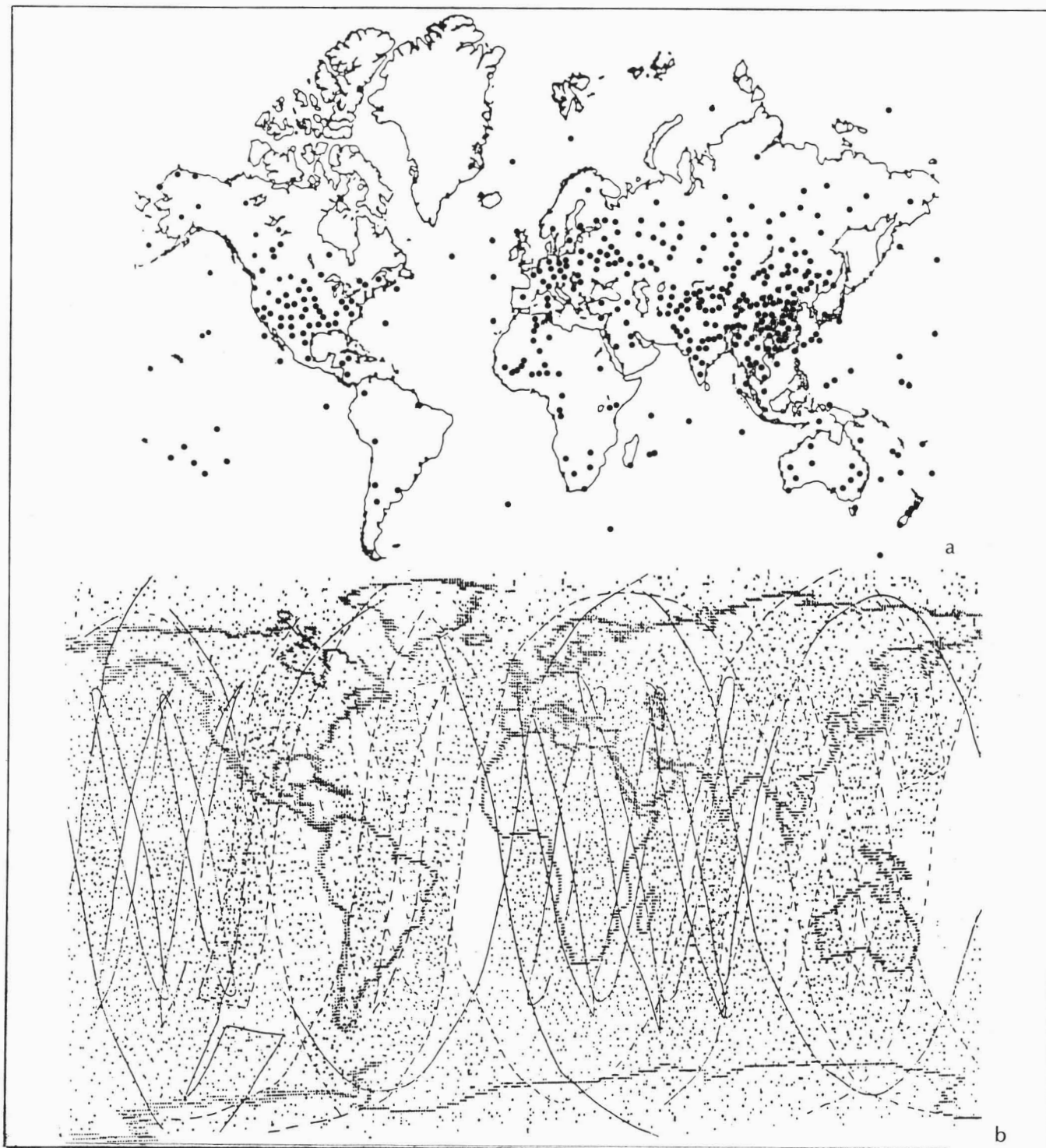
- The interacting dynamical, chemical, and radiative processes in the stratosphere, mesosphere, and thermosphere;
- The geographical, diurnal, and seasonal dependence of these processes; and
- The coupling and flow of energy between the Sun, magnetosphere, ionosphere, and atmosphere.

Instrumentation for remote sensing in the NSTR Program will implement the International Solar Terrestrial Physics (ISTP) Program for space. A future program under study is the High Resolution Solar Optical Telescope (HIRSO).

Because ground-based remote sensing is a continuing activity, much is being learned of the natural and electrical dynamics of the Earth's atmosphere and its minor species composition. Much is also being learned about the solar dynamics, the energy source for the Earth's atmosphere. Ground-based remote sensing provides significant input to these areas through the ability to make high spatial resolution measurements over long time scales. The remote-sensing facilities in place and being used by the atmospheric sciences community are various kinds of radars, high-resolution spectrometers, photometric imagers, magnetographs, and spectroheliographs.

FIGURE 15. (a and b) The top priority of the NOAA polar-orbiter meteorological satellites is to measure the vertical temperature and humidity structure of the atmosphere. Such atmospheric soundings are critical to numerical weather prediction. The conventional means of measuring the vertical temperature and humidity profile is by radiosonde (a), an instrument released at some weather stations and carried aloft by balloon. Radiosonde observing stations are sufficiently numerous for most weather prediction problems only over the United States and Canada, Europe, and eastern Asia. Over the remaining land areas, they are sparse at best. Over ocean areas, just a few island stations exist, so conventional soundings are unavailable over most of the world's oceans.

Part (b) shows the satellite observational coverage of the existing polar-orbiting system for a 24-hour period. Each satellite orbit produces about 600 soundings, each composed of 15-layer mean temperatures, 3-layer precipitable water values, a total ozone value, a cloud cover estimate, and some description of the tropopause.





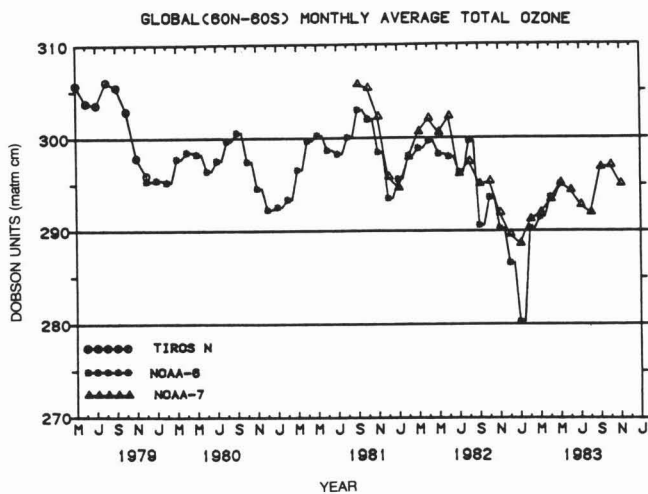


FIGURE 16. Monthly average total ozone values derived from the TIROS Operational Vertical Sounder (TOVS) System on the NOAA polar-orbiters. Values have been integrated over the domain 60°N to 60°S, the general limits of year-round available data, and extend from May 1979 to November 1983. The relationship of the ozone minimum in late 1982-1983 to the El Chichon volcanic event and the highly active El Niño phenomenon is currently under study. Monitoring of long-term trends in global ozone is a key objective of satellite measurements.

### Department of Defense (DOD)

As with land sensing, atmospheric data are used to increase the effectiveness of weapons systems, provide intelligence for tactical and strategic command decisions, protect life and property, assist other military planning and operational activities, and support military research and development. The objectives and efforts identified below either use or are involved in acquiring data that are now or may in the future be obtained by space-based acquisition techniques.

**Basic Atmospheric Research Objectives.** DOD basic research can be divided into three areas: description and modeling, composition and structure, and sensing and measurement.

- Atmospheric description and modeling objectives are to

*Construct validated models of atmospheric behavior. Specific efforts are to predict cyclogenesis and rapid intensification of storms at sea;*

*Improve basic description of the lightning threat to composite aircraft materials and microcircuits; and*

*Improve basic meteorological technology of analysis and forecasting on global, regional, and local scales. Specific efforts are to find techniques for efficient and high-quality signal and image processing.*

- Atmospheric composition and structure objectives are to

*Increase understanding of molecular dynamics and chemistry of the atmosphere;*

*Increase knowledge of transmission and propagation of electromagnetic energy through the atmosphere; and*

*Increase knowledge and map atmospheric composition, structure, behavior, and dynamics. Specific efforts are to measure and describe plume, infrared, marine boundary layer, and marine aerosol processes and interactions with the atmosphere.*

- Atmospheric sensing and measurement objectives are to

*Improve remote sensing of atmospheric conditions. Specific efforts are to use new techniques and new sensors to make quantitative measurements by remote (satellite) sensors;*

*Measure optical and microwave propagation in the presence of fog, clouds, and aerosols in the boundary layer. Specific efforts are to measure transmissivity, scattering, and absorption properties of aerosols, clouds, precipitation, and other atmospheric extinction phenomena, and evaluate, measure, and model their effects on microwave, millimeter-wave, electro-optical, infrared, and other transceiver systems; and*

*Describe remotely sensed atmospheric phenomena in terms of visibility and other weather information. Specific efforts are to explore remote-sensing technology and use multisensor data to derive basic environmental parameters.*

**Applied Atmospheric Research Objectives.** DOD research can be divided into five areas: remote sensing, prediction and climatology, system effects, engineering, and tactical support.

- Remote-sensing objectives are to

*Improve space- and ground-based remote weather detection. Specific efforts are to improve and test analysis techniques, wind and cloud retrieval algorithms, and new dynamic models for exploiting satellite data;*

*Improve observing and measuring capabilities. Specific efforts are to develop engineering tools and methods for LIDAR and LASER technology, automated weather stations, and other observing, measuring, detecting, and acquisition systems; and*

*Improve atmospheric specification/description. Specific efforts are to develop real-time atmospheric specification, target background sensors, data sets and models, and reference atmospheres as a basis for design and operation of new selective (smart) weapon systems.*

- Prediction and climatology objectives are to

*Improve local weather prediction technology. Specific efforts*

*are to develop and evaluate forecasting techniques for point/ local area threshold values, strategic and tactical mission decisions, target planning, and the interface between tropical cyclones and synoptic flow;*

*Improve climatology for system design and testing. Specific efforts are in the areas of electromagnetic attenuation, communications outages, and airframe icing; and*

*Assist hydrologic and flood forecasting. Specific efforts are to develop improved forecasting techniques for clouds and precipitation quantification.*

- System effects objectives are to

*Determine cloud, precipitation, turbulence, atmospheric transmission, and boundary layer effects on military weapons. Specific efforts are to develop models for atmospheric dispersion, infrared transmittance variability, atmospheric visibility (slant and long range), optical turbulence, and cloud cover simulation; and*

*Determine atmospheric effects on other military systems (e.g., LIDAR). Specific efforts are to evaluate and quantify the effects of atmospheric turbulence on infrared sensors, atmospheric effects on electro-optical and electromagnetic systems, atmospheric effects on directed energy systems, and millimeter wave refraction for radar.*

- Engineering objectives are to

*Develop the data base and technology for design and operation of infrared, optical, and laser surveillance and guidance systems under real-world conditions. Specific efforts are to develop System Performance Indicators (SPIs) based on environmental/meteorological factors and conditions; and*

*Build optical and infrared backgrounds.*

- Tactical support objectives are to

*Provide dirty battlefield characterization;*

*Improve assessment and model simulation of the effects of dirty battlefield environments;*

*Develop remote atmospheric sensors and associated processing, algorithms, and display techniques to provide timely tactical environmental intelligence. Specific efforts are to determine ship, weapon, and sensor sensitivities to ship responses induced by ocean waves and winds and the relative sensitivities to performance;*

*Generate tactical decision aids that ensure useful environmental information is available to tactical/battlefield commanders;*

*Provide improved long-range artillery effectiveness. Specific efforts are to prepare weather software for remotely piloted vehicles; and*

*Test feasibility of new numerical modeling concepts.*

## Department of Energy (DOE)

DOE conducts space-related research in the following areas:

- Carbon dioxide
- Geology
- Ecology research

The carbon dioxide research includes exploring the use of data from space for estimating global changes in the carbon in vegetation. A critical unmet need is for instruments that give a reasonably direct measure of vegetative carbon content. The geological research includes work on automated merging of Landsat and topographic data and has led to an important new method for identifying linear features resulting from geological processes. Ecological research being conducted by DOE involves (1) the use of satellite, airborne, and shipborne remote-sensing systems to investigate biological productivity in the oceans and to evaluate transport of energy-related contaminants in coastal areas; and (2) a series of aerial-satellite remote-sensing experiments at watersheds in, for example, Nevada and Alaska.

The bulk of the DOE research involving Earth remote sensing is ground based or aircraft based. Only brief reference will be made to these DOE activities because the principal focus of this report is on remote sensing from space. However, DOE sponsors much research using, for example, seismic and electromagnetic methods for remote sensing. The largest set of projects of this type are associated with detection of nuclear weapons tests. Other seismic and electromagnetic projects are associated with studies of geothermal energy, nuclear waste repositories, and energy plant siting. A Center for Computational Seismology was established recently at Lawrence Berkeley Laboratory in California. Superconducting quantum interference detectors and new remote reference techniques, developed in DOE programs, have greatly enhanced the utility of electromagnetic methods. DOE and its predecessor agencies have pioneered use of tracer methods for study of the Earth and use of aircraft for remote detection of radioactivity. As a final example, a variety of ground-based measurements of insolation and auroral activity are continuing; such studies have resulted in forestalling damage to the Alaska pipeline from the electrical potential gradients developed during periods of high auroral activity.

## C. Oceanic Programs

Research satellites have demonstrated a remarkable ability to measure ocean variables critical to climate and other national concerns, including fisheries, ship routing,

defense, and waste disposal. This section discusses current research and operational activities of Federal agencies in ocean remote sensing.

### National Aeronautics and Space Administration (NASA)

The goals of the Oceanic Remote Sensing Program are to develop spaceborne techniques and evaluate their utility for observing the oceans, to apply these techniques to better understand the behavior of the oceans, and to assist users with the implementation of operational systems. NASA is working closely with the operational oceanographic community because many of the specific issues being addressed by this program will ultimately provide for better use of spaceborne techniques.

The program is organized into four elements: (a) Physical Oceanography, (b) Ocean Productivity, (c) Polar Oceans, and (d) Oceanic Flight Projects.

**Physical Oceanography Element.** This program focuses on the oceanographic utilization of altimetry and scatterometry data. The program emphasizes the development of improved spaceborne techniques to observe and study oceanic and meteorological parameters in both the ocean circulation and air-sea interactions studies.

The ocean circulation studies seek to determine the global oceanic general circulation and its variability, heat content, and thus, horizontal heat flux. The aim is to develop a better understanding of the oceans' role in climate variability. The TOPEX/Poseidon altimetric mission, planned for launch in early 1991, forms the basis of this program. To provide a sound scientific framework for interpretation of the satellite data, emphasis is on theoretical analyses, modeling-based studies aimed at assimilation of satellite and in situ data for research, and the analysis of historical data collected from space.

The goal of the air-sea interaction studies is to determine the winds over the world's oceans accurately enough to advance our understanding of the physical processes occurring in the layers of the oceans and atmosphere close to the sea surface. Specific objectives are to determine surface wind stress, ocean surface waves, air-sea fluxes of momentum and heat, and wind-driven ocean currents. The NASA Scatterometer (NSCAT) is planned for launch in 1990-92.

**Ocean Productivity Element.** The goal of this program is to improve our capability to measure the primary productivity of the oceans, its variability, and how it in turn influences the marine food chain and global carbon dioxide and biogeochemical cycles. Specific objectives are focused on improving determination of phytoplankton abundance and primary productivity based on comple-

mentary satellite, aircraft, ship, and in situ observations. The primary spaceborne measurements are ocean color from the present Nimbus-7 Coastal Zone Color Scanner (CZCS) and the proposed ocean color instrument and sea surface temperature from the NOAA AVHRR. The program further focuses on maximizing the utility of these spaceborne and supporting aircraft measurements. Experiments are closely coordinated with Navy-, NSF-, and DOE-supported shipboard and in situ measurement programs to provide maximum scientific benefit.

**Polar Oceans Element.** The goals of this program are to use spaceborne sensors to determine the characteristics of the polar sea-ice cover, and to understand how sea ice is influenced by, and in turn influences, the atmosphere and ocean. The immediate objective is to improve capability of measuring from space the extent, type, movement, and surface characteristics of the ice cover. This involves detailed analysis of existing data from Seasat and the Nimbus series of spacecraft, airborne testing of new sensors, and collection and analysis of ground-truth data from the ice surface. In addition, modeling programs are supported that address two problems: improvement in understanding of remotely sensed data, and large-scale modeling of sea-ice behavior. A major component of the program is to develop and assess interpretive algorithms for translating passive-microwave data into estimates of sea-ice concentration and surface characteristics. The multi-frequency Scanning Multichannel Microwave Radiometer (SMMR) on Nimbus-7 and Sensor Systems for Microwave Imager (SSM/I) on an upcoming Defense Meteorological Satellite Program (DMSP) mission show greatest promise; data from these sensors will have broad applications in both the scientific and the shipping communities. Consequently, these studies are closely coordinated with associated NOAA and Office of Naval Research (ONR) research and with Canadian investigators. NASA is also working with Synthetic Aperture Radar (SAR) data from Seasat. These provide excellent high-resolution imagery of sea ice, and the next opportunity for acquiring similar data will be from the European Space Agency (ESA) ERS-1 mission, with a planned launch in 1990. In addition, research applications of altimetry data over the ice sheets of Greenland and Antarctica have been investigated.

**Oceanic Flight Element.** The objective of these projects is to develop and evaluate concepts for major flight experiments and supporting instruments that meet the observational requirements of the Oceanic Processes Program. Major projects include The Ocean Topography Experiment (TOPEX), which would support the needs of ocean circulation studies, the NASA Scatterometer, which will support the needs of both the ocean circulation and air-sea interaction studies, and the proposed private-sector

ocean color instrument to support the Ocean Productivity Program.

### National Oceanic and Atmospheric Administration (NOAA)

The role and responsibilities of NOAA are distinct from those of NASA. NASA programs have developed satellite sensors uniquely designed to measure ocean parameters. Over the years, NASA instruments have been flown for limited periods on research satellites to gather data and demonstrate operational feasibility. All NOAA remote-sensing oceanic operational capability is directly traceable to NASA programs. However, the science of Earth observations requires greater input than that permitted by occasional research satellite observations. The goal of NOAA's remote-sensing oceans program, then, is to provide (1) real-time observations of ocean parameters needed to describe the dynamic coupling between the atmosphere and the ocean, especially for routine meteorological forecasts and warnings and (2) long-term systematic observations of key parameters of interest to the climatic and biological research communities. The basis for the first function is the need for global real-time measurements to initialize the numerical forecast models used by NOAA field forecast offices in preparing public forecasts and warnings that enhance the safety of life and property. These same data and products also directly support the U.S. oceanic commerce. The reason for the second function is the need for long-term weather and climate prediction models to incorporate more information about global trends and behavior of the ocean thermal reservoir and its impact on the overlying atmosphere so as to improve long-range forecasting skill. The structure and character of the satellite data collection and ground processing system must necessarily accommodate the priorities of the operational forecast and warning community, while preserving and enhancing the capability to obtain long time series of oceanic observations for use by the research community.

**Oceanic Studies.** NOAA's oceanic studies are discussed in three areas, which include research in sea surface temperature, El Niño, and ocean color.

**Sea Surface Temperature (SST).** SST studies have involved two areas of research: the development of multi-channel sea surface temperature (MCSST) techniques and the generation of AVHRR data bases.

The AVHRR/MCSST method, which has been used operationally since November 1981 to generate global, regional, and local sea surface temperature analyses at weekly intervals and global monthly mean products, has been further refined. The MCSST products have aided

research in physical and biological ocean phenomena, including fisheries research.

Recently, NOAA has developed the AVHRR experimental data base, which generates imagery of atmospherically corrected SST patterns (using the MCSST technique) of the open ocean, coastal, estuarine areas, flooding rivers, and studies of severe weather phenomena such as hurricanes and tornado-producing thunderstorms. Examples are (1) Hurricane Lili, the first December North Atlantic Hurricane to be recorded by an environmental satellite, and (2) computer-generated contoured analyses of environmental parameters such as temperatures or reflectances. Other remotely sensed marine parameters include SSTs of the Sargasso Sea and the Persian Gulf, and turbidity and SST patterns of the Chesapeake Bay and of other estuaries.

**El Niño.** The NOAA-7 AVHRR has been a vital tool for monitoring the 1982-83 El Niño episode in the Pacific Ocean. Developing atypically from past El Niños (such as in 1956, 1966, 1972), it began during the summer of 1982, nearly 6 months out of phase, and was significantly stronger than a typical event. As warming developed in the mid-Pacific, west of the dateline, the satellite's measurement of SST, augmented by ship reports, provided a near-complete record of the El Niño event. The 1982-83 El Niño produced anomalies in warming of the surface waters of 6°-9°C off Peru's and Ecuador's coasts during its peak in early 1983. By summer 1983, the warm waters seemed to lessen their influence on the eastern tropical Pacific.

**Ocean Color Research.** Ocean color research has used the CZCS on Nimbus-7 to develop quantitative techniques for measuring concentrations of plankton and other near-surface material.

Analysis made in 1984 of CZCS data revealed dramatic changes of pigment concentrations around the Galapagos Islands during February and March 1983. These changes were associated with the unusual oceanographic conditions observed during the 1982-83 El Niño from a perspective never before possible. Complete reversals of ocean currents revealed significant changes in the downstream phytoplankton distributions. This redistribution of food resource may have significant causal relationships on the reproductive failure of sea birds, marine mammals, and on primary productivity.

**Fisheries Applications.** At the Southwest Fisheries Center, CZCS and AVHRR data are used to produce charts showing the location of ocean color boundaries or fronts. These charts are used widely by tuna fishermen to locate favorable fishing areas. Studies at the center have shown that the tuna tend to concentrate in the warm, bluish oceanic waters along the fronts. Very few or no tuna are found in the cooler, greenish coastal waters. Recently, satellite information has been particularly useful in locat-

ing fish. Because of the abnormal warming resulting from the El Niño phenomenon, many fish stocks were displaced northward from their usual habitat. The satellite data provided the information required to locate the fish migration areas.

The CZCS imagery also is used by the Southwest Fisheries Center to describe ocean processes related to northern anchovy spawning. Imagery was collected coincident with fine grid oceanographic ship observations. Preliminary results indicate that anchovy avoid areas of low chlorophyll concentrations, presumably because of insufficient food availability. Additionally, CZCS data have been used to investigate distribution and abundance of juvenile salmon off the Oregon-Washington coast.

The Coastal Habitat Fisheries Assessment Research Mensuration (CHARM) Program at the Northeast Fisheries Center is responding to the national goal of zero net loss of wetlands productivity. Wetlands provide and support habitats suitable as spawning, nursery, and feeding areas for 96 percent of the commercial fisheries and 50 percent of the recreational catch. The approach is to use the Landsat data to uniformly classify and monitor wetlands and to integrate the results to determine the effects of fisheries.

Satellite infrared imagery also is used by the Center to delineate the areas affected by sediment plumes from the Chesapeake, Delaware, and Raritan Bays. The plumes contain biostimulants, contaminants, and other materials that can have an adverse effect on fishery resources.

**Oceanic Services.** The international oceanic research community is now advocating establishing several Specialized Ocean Centers, developed at or near major national centers of expertise around the world. One such center is the NOAA Ocean Products Center (OPC). Located with the National Meteorological Center in Washington, D.C., OPC is mapping ocean parameters observed by satellites on a global scale. Satellite observations of surface marine wind fields, significant wave heights, sea surface temperature, sea and Great Lakes ice cover are being analyzed routinely and provided to NOAA field forecast offices as guidance materials. As new satellites come on-line and the oncoming data bases warrant new analysis of sea level anomalies, ocean color and surface currents will be provided. In addition, derived analysis and prediction materials designed to serve as field forecast guidance will be prepared routinely for heat flux to the atmosphere, heat transport by the ocean's current system, ocean circulation, surface currents, and productivity indices for water quality and fisheries applications.

**Other NOAA Activities.** NOAA is considering participation in the collection and dissemination of environmental data now collected by the Navy Geosat program (surface windspeed, significant wave height, sea-ice edge,

fronts, mesoscale oceanic features, and gravitational data). Also under review by NOAA are plans to bring ERS-1 SAR data from NASA's Alaskan receiving facility to the NOAA/NAVY Joint Ice Center in Suitland, MD.

### National Science Foundation (NSF)

Currently, the NSF is supporting a variety of programs in oceanic research that are using data collected by space-based systems. A significant fraction of the research supported in these areas uses satellite communication links, satellite-based positioning systems, satellite imagery (both visual and infrared), and satellite altimetry. These various data sets are invaluable in planning, implementing, and analyzing data collected in field experiments. The Division of Ocean Sciences expects this to increase in the future.

Of the funds the Foundation currently spends on the ocean processes portion of the Earth sciences, including oceanographic research support in physics, chemistry, and biology, as well as oceanographic facilities and ships, approximately 2.3 percent supports individual research projects utilizing satellite observations. A number of these individual awards supply satellite data to large oceanographic research programs that represent a significantly larger fraction of the available resources (perhaps 10-15%).

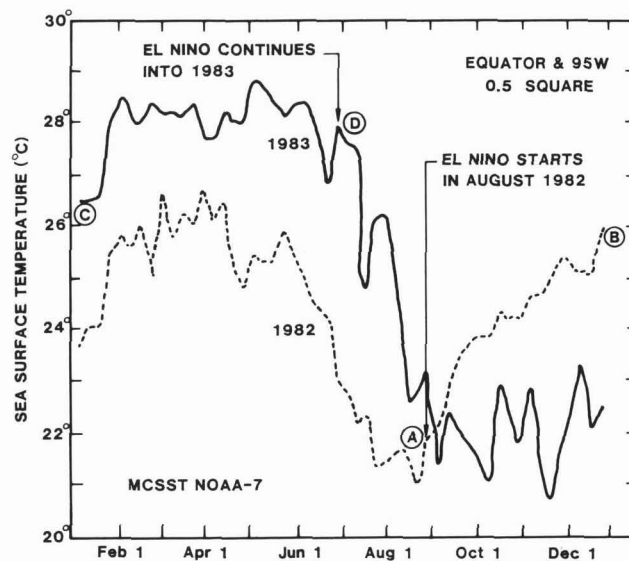
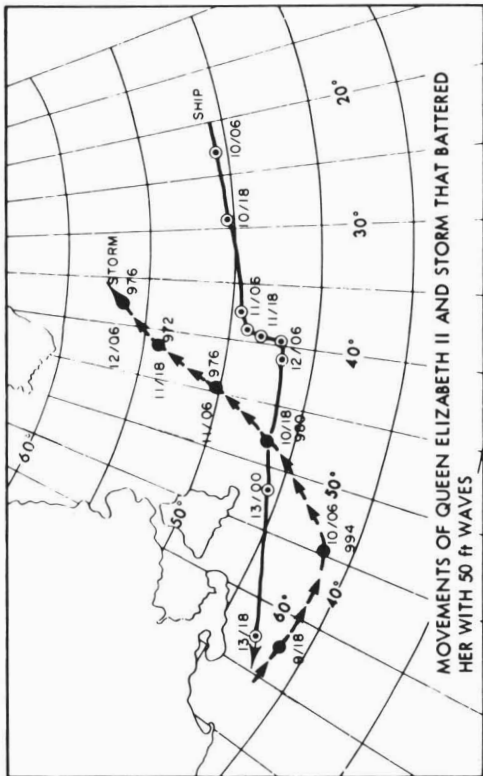
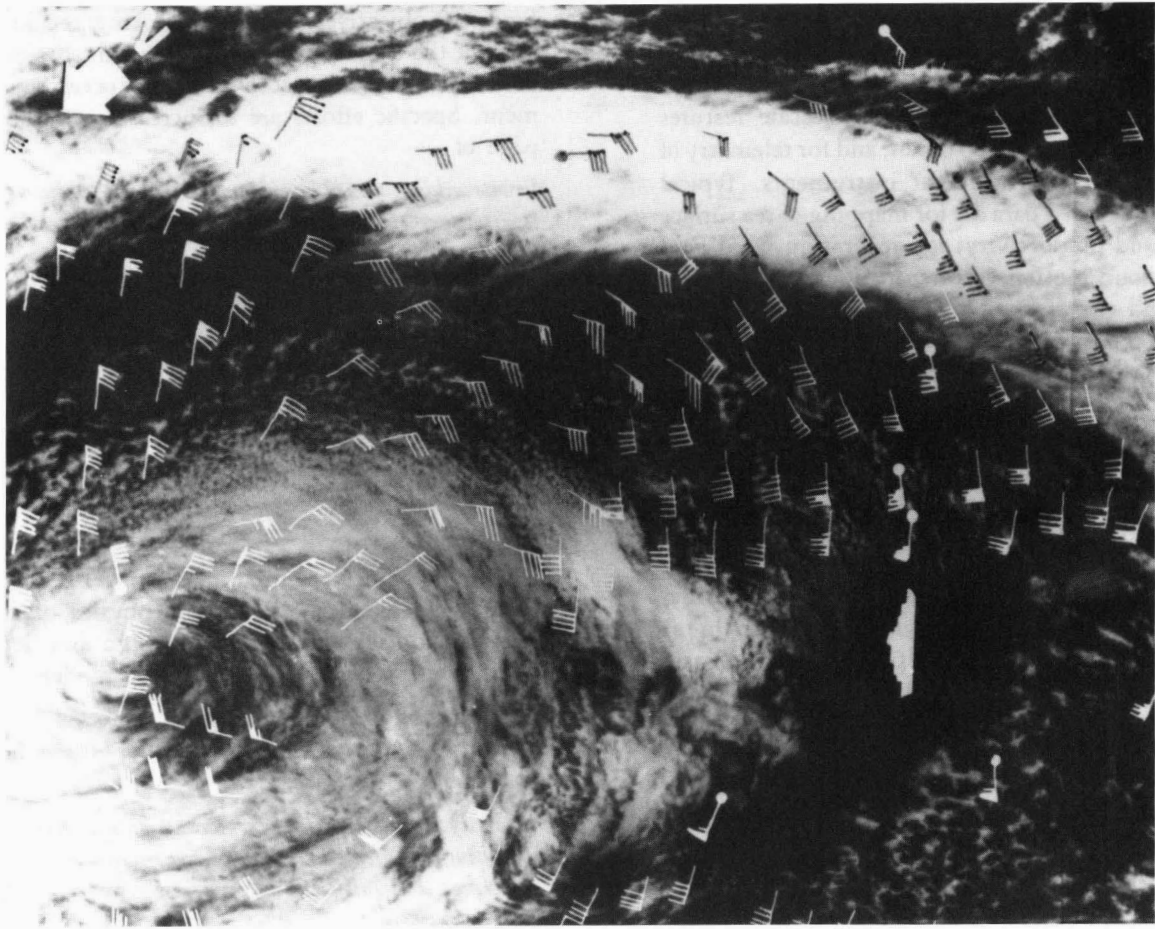


FIGURE 17. The 7-day average satellite sea surface temperature (MCSST) at the equator and longitude 95°W during 1982 and 1983. Onset of El Niño (A) is seen as a sharp rise in sea surface temperature in August 1982. A sharp rise continues into 1983 (B and C) and persists through June 1983 (D), when sea surface temperatures began to fall. The strong El Niño event led to climatic fluctuations in many parts of the world.



a

FIGURE 18. A North Atlantic storm that occurred while the Seasat Scatterometer (SASS) was operational illustrates ocean satellite capability with dangerous open-ocean winds and waves. During September 9-12, 1978, the New York bound Queen Elizabeth II (QE II) was surprised by a severe storm, even though the QE II was in a major North Atlantic shipping lane. Waves higher than 35 feet so severely pounded the ship that she was forced to turn south to avoid more damage. Part (a) illustrates the path of the ship and storm; (b) illustrates SASS-derived winds superimposed on a NOAA-5 image showing the cloud pattern around the storm. This storm is an example of what some scientists call a bomb; an oceanic cyclone that deepens explosively, producing strong winds and dangerous waves. Numerical winds and wave forecasts cannot forecast the onset of such storms in the open ocean. Real-time scatterometer wind fields, however, would considerably improve open ocean forecasts and warnings of such conditions.

Remotely sensed data are necessary for setting the background for some in situ experiments; for monitoring in quasi-real-time major current systems, such as the Gulf Stream and Kuroshio Current, and mesoscale features along the coast and in the deep ocean; and for telemetry of real-time data sets from different instruments. Typical uses of remotely sensed data are for mapping of sea surface temperature and productivity; for generating wind-field maps using cloud motion vectors; for looking at energy fluxes into and out of the sea surface; and for tracking surface drifters to map surface currents. In addition, data from Seasat have shown that for the first time the possibility of globally mapping surface wind fields using scatterometers and the sea surface topography (and therefore the surface current field) using altimeters. These new developments have heightened interest in large programs to study ocean climate and global ocean circulation (see Section E for further discussion).

Large coastal process studies that have used satellite data include Coastal Ocean Dynamics Experiment (CODE), Offshore Persistent Upwelling Structures (OPUS), Microbial Exchanges and Coupling in Coastal Atlantic Systems (MECCAS), and Gulf of California Studies. In the deep ocean, remotely sensed data have been used to support programs looking at mesoscale variability, such as Warm Core Rings, and climate problems such as TROPIC HEAT and the Seasonal Equatorial Atlantic Experiment (SEQUAL).

In summary, remotely sensed data from existing and proposed satellite systems have given the oceanographic community the possibility of obtaining global synoptic data sets of oceanographic variables. These data sets will allow us to look globally at oceans.

## Department of Defense (DOD)

**Introduction.** As with DOD land and atmospheric remote sensing, oceanic observations are used to increase the effectiveness of weapons systems, provide intelligence for tactical and strategic command decisions, protect life and property, assist other military planning and operational activities, and support military research and development.

**Basic Oceanic Research Objectives.** DOD basic research can be divided into two areas: environment and processes. The environment and processes objectives are outlined below.

- Environment objectives include observing, measuring, learning, and understanding the ocean environment. Specific efforts are to improve remote-sensing techniques for oceanic phenomena.

- Processes objectives include increasing the knowledge of the basic processes of the ocean that can be used to enhance man's activities in the ocean environment. Specific efforts are to increase man's knowledge of

*Fronts, eddies, mixed layers, internal waves, phenomena in straits, coastal zones, near shore, and other physical variability in the open ocean;*

*Trace material interactions, photochemistry, ocean biological effects on propagation properties of water environments, and other biofouling phenomena; and*

*Air-sea interaction.*

**Applied Oceanic Research Objectives.** DOD research can be divided into three areas: models, forecasting, and observing.

- Modeling objectives include developing a global ocean model and modeling the physics of sound transmission for use in system design and deployment. Specific efforts are to develop models

*That describe spatial and temporal properties of high-frequency acoustic signals scattered from the bottom, surface, and volume of the ocean;*

*To analyze and predict ocean thermal and current systems including turbulence and mixed layer modeling, numerical modeling, and satellite modeling interaction;*

*For ship sea-keeping performance assessment (spectral wave); and*

*To support sonar performance prediction in the Arctic.*

- Forecasting objectives include improving ocean forecasting and developing real-time Arctic "nowcasting." Specific efforts are to quantify

*Environmental effects on broadband signals over long distances;*

*Atmospheric effects on the transmission of millimeter waves;*

*Environmental dependence and variation of system gains achievable by arrays of geophones implanted in ice;*

*Spatial and temporal characteristics of signal amplitude and phase fluctuations as a function of oceanic variability; and*

*The relationship between spatial and temporal coherence properties of signal and noise fields and the performance of air-deployed arrays.*

- Oceanic-observing objectives include improving remote and in situ sensing techniques, instruments, and the combination of complementary data. Specific efforts are to

*Obtain environmental and related acoustic data to aid in acoustic array design and performance prediction;*

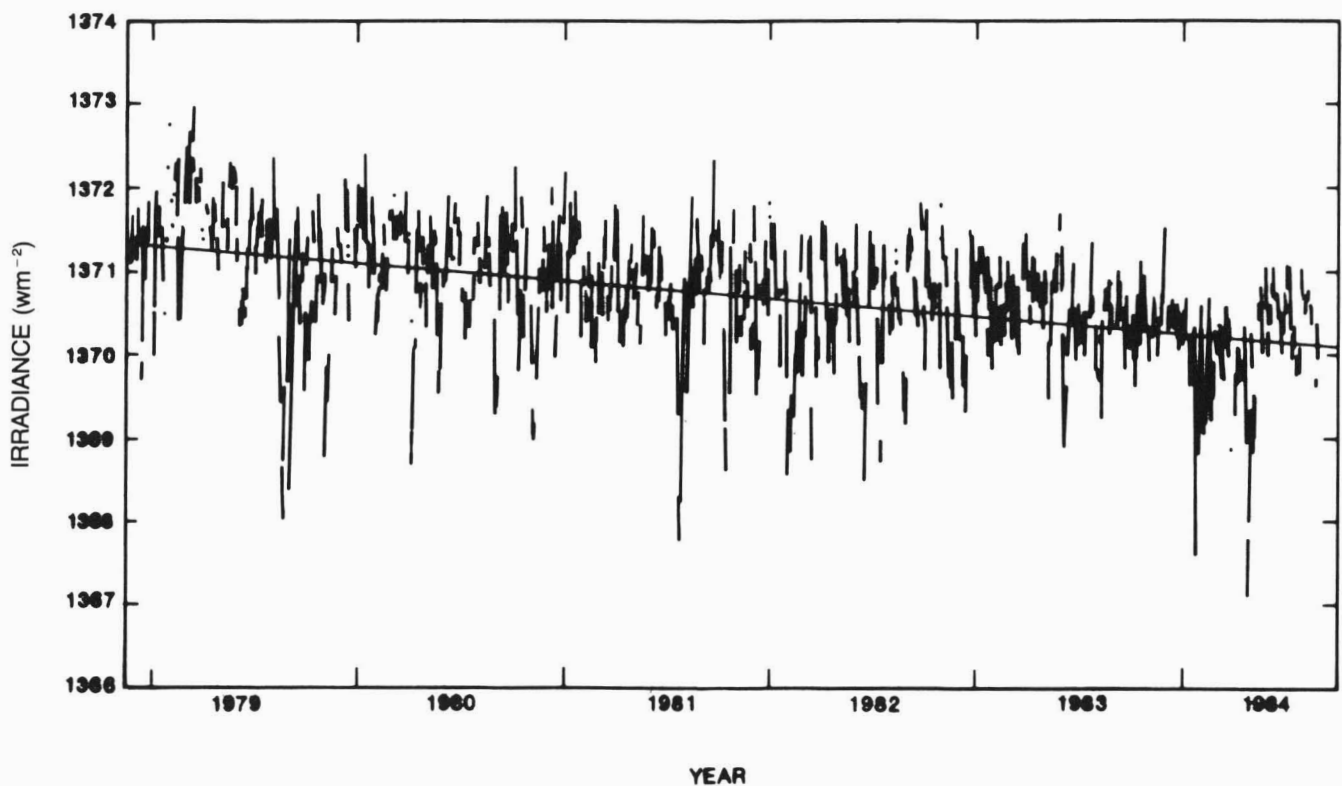


FIGURE 19. Satellites orbiting above the atmosphere provide an ideal platform for monitoring solar radiation. The results of such observations from the Nimbus-7 Earth Radiation Budget Experiment (ERBE) are shown in this figure. There has been a slight downward trend since 1978 (shown by descending line) in solar radiation reaching the Earth's atmosphere. It is presently uncertain whether this is real or just instrument drift. Calculations show that a 1-percent change in the solar output ( $14 \text{ Wm}^{-2}$ ) could, if maintained for a sufficiently long time, lead to a  $2^\circ\text{C}$  shift in average temperatures.

*Assess performance of fiber optic distributed system configurations as a function of environment (air, water, ground); and*

*Develop large aperture arrays with increased bandwidth for the Arctic airborne electromagnetic bathymetric survey system, remote-sensing techniques and mesoscale ocean models to support acoustic models, and techniques for blending high-density satellite data with sparse subsurface thermal data.*

#### D. Climate Programs

Climate is affected by interactions between the atmosphere, oceans, ice, and land. Remote sensing has proven effective in monitoring many climatic variables. NASA, NOAA, and NSF have programs that study changes in the Earth's radiation budget, solar and surface radiation, and cloud and ice variations that may affect climate. These and other programs are discussed below.

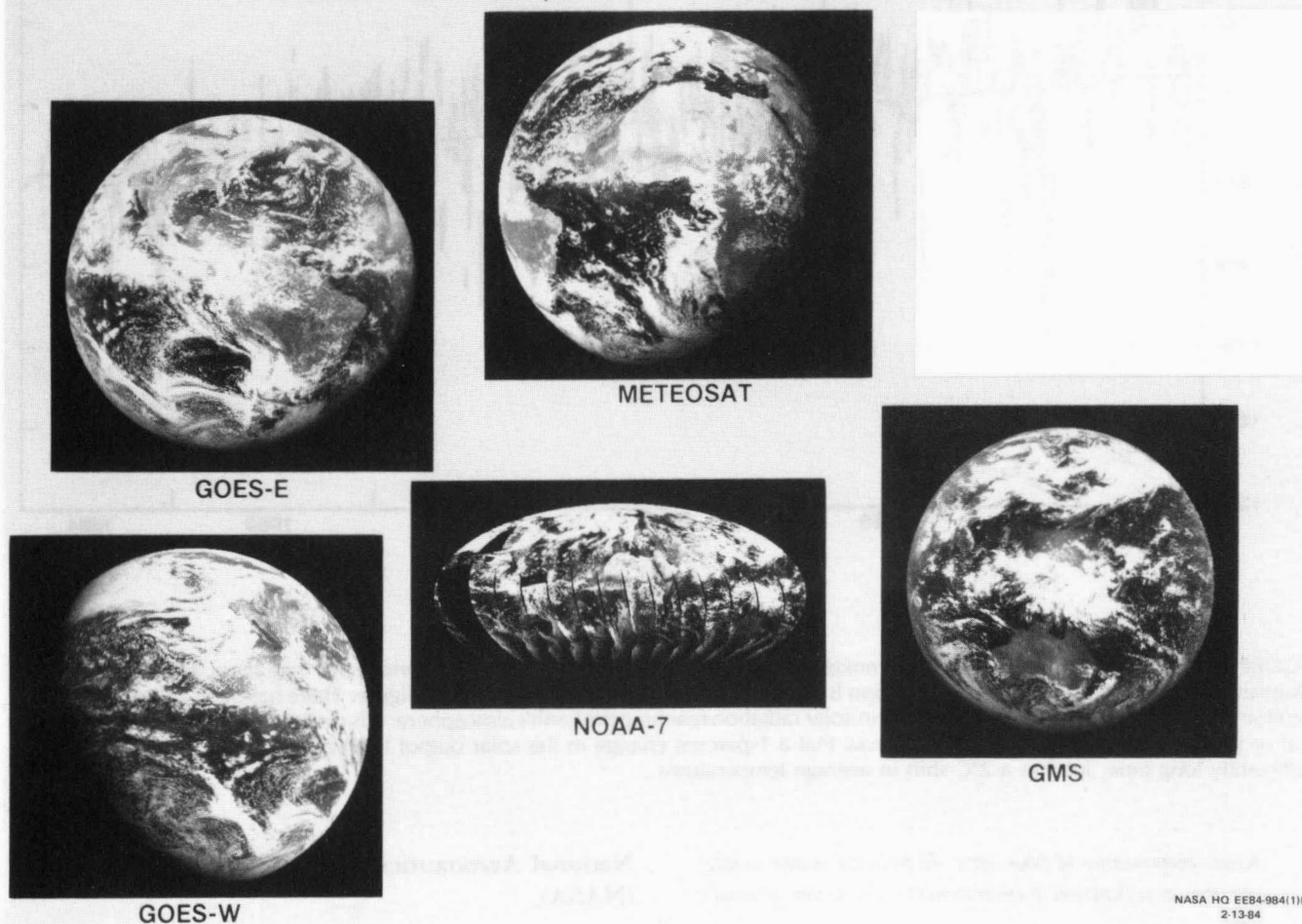
#### National Aeronautics and Space Administration (NASA)

The NASA Climate Research Program currently emphasizes the study of radiation parameters and the components of the Earth's atmospheric system that interact most strongly with the radiation field and the development and improvement of climate models and their application to climate phenomena and predictability. The program comprises three elements: Earth Radiation Budget, Cloud and Radiatively Important Trace Substances, and Climate Modeling. Land Climatology is a fourth research area of climate remote sensing but is formally a part of NASA's Earth Science Research Program (see Chapter IIIA). A major objective is to establish a long-term data set describing the spatial (regional to global) and temporal (monthly) statistics of the atmosphere. These data will be applied to a variety of climate investigations.

*Earth Radiation Budget (ERB) Element.* To understand climate, the global distribution of net energy bal-



INTERNATIONAL SATELLITE CLOUD CLIMATOLOGY  
PROJECT (ISCCP)  
FIRST RESULTS (1 JULY 1983)—VISIBLE (B2)



NASA HQ EE84-984(1)B  
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FIGURE 20. First results from the International Satellite Cloud Climatology Project (ISCCP), the first project of the World Climate Research Programme (WCRP). ISCCP will provide a 5-year global data set of cloudiness parameters for climate research based on the international array of geostationary and polar-orbiting operational satellites shown. (INSAT, which will also participate in this program, had not been launched at the time the project began.)

ance at the top of the atmosphere and at the surface of the Earth must be determined. It is the pattern of sources and sinks of energy that drive the atmosphere and ocean circulation and determine the worldwide distribution of wind, temperature, and humidity.

*Solar Radiation.* Recent evidence suggests there might be climatically significant changes in total solar irradiance occurring on a time scale of months to years. Determining these variations and their significance to climate is the objective of an ongoing NASA solar irradiance monitoring program comprised of experiments on rockets, satellites, and the Shuttle (at some future time). Sounding rocket and Nimbus-ERB measurements began in 1976.

The Solar Maximum Mission/Active Cavity Radiometer Irradiance Monitor (SMM/ACRIM) experiment, launched in 1980, provided the baseline measurements near the peak of the most recent solar cycle. The first STS observation was with an ACRIM I in late 1983 in conjunction with Spacelab I. For long-term continuous monitoring, utilization of operational meteorological satellites or research satellites of opportunity will be explored. This program also calls for monitoring spectral variations and for monitoring the solar diameter and establishing its relationship to solar irradiance.

*Earth Radiation at the Top of the Atmosphere.* The major NASA effort in this area involves the Earth Radiation

Budget Experiment (ERBE). Careful attention is being given to calibration and to improved techniques for converting measurements at satellite altitude to ERB components at the top of the atmosphere. Data from the Nimbus-6 and -7 satellites are being processed to develop a long-term data set. Alternative schemes for post-ERBE measurements will be evaluated, including the reliance on NOAA Earth radiation budget products derived from operational radiometers.

*Surface Radiation.* There is no direct way to globally measure the total surface radiation components from space. The research effort, therefore, involves a combination of observations and calculations based on theoretical and empirical models, which use satellite observations of a wide range of atmospheric and surface parameters. Validation and improvements to the models will be determined from the analysis of direct observations at selected points on the surface. An important aspect of this activity is the improvement of radiative transfer models, which are necessary for a greater understanding of the physical processes responsible for the radiation observed by satellites.

*Clouds and Radiatively Important Trace Substances.* Because clouds generally cause a decrease in both absorbed solar energy and thermal emission to space, the net effect of a particular cloud type can be to increase, decrease, or leave unchanged the net energy in a vertical column. Aerosols and trace gases, such as ozone and carbon dioxide, also can have a significant impact on the energy budget.

*Clouds.* There is an international effort to develop a 5-year global cloud climatology based on imaging radiometer data from as many as five geostationary satellites and two polar-orbiters. The International Satellite Cloud Climatology Project (ISCCP) is jointly sponsored by the World Meteorological Organization (WMO) and the International Council of Scientific Unions (ICSU) as part of the World Climate Research Programme (WCRP); NASA has assumed an important role in this project. Data set development will be backed by research to improve the techniques for remote sensing of cloud parameters, climate sensitivity studies to determine the relative importance and observation requirements for various cloud parameters, and investigations to diagnose and improve the methods for parameterizing clouds in climate models. Because of the need for data at the high resolution associated with cloud formation and dissipation processes, there will be a series of multiplatform regional experiments—using operational satellites, aircraft, balloons, and surface observations—under the aegis of the National Climate Program, designated the First ISCCP Regional Experiment (FIRE).

*Aerosols.* Because the evidence is fairly strong that stratospheric aerosols, such as those induced by major volcanic eruptions, do affect the stratospheric tem-

peratures and the Earth's energy budget, it is important to develop an aerosol climatology and a long-term monitoring plan. The data from Nimbus-7, Stratospheric Aerosol Measurement (SAM II), and the Stratospheric Aerosol and Gas Experiment (SAGE), along with correlative measurements from surface, aircraft, and balloon platforms, will be used to establish the observing requirements for a possible long-term monitoring system. Although tropospheric aerosols also could be important to climate, their impact is not as well established. Because of their heterogeneous nature and short residence times, and the ubiquitous presence of clouds, they are not easily monitored by satellite. The availability of spaceborne LIDAR systems beginning in the 1990s would provide an opportunity to test and evaluate a tropospheric aerosol sensor.

*Trace Gases.* A chemically stable gas that has an important effect on climate is carbon dioxide. The present ground-based network is probably adequate for monitoring its steady increase, which in part is because of the burning of fossil fuels and secondarily to deforestation. For studying sources and sinks, however, it is necessary to monitor the geographical and seasonal variations, which would require a spaceborne monitoring system, but that is not possible with present technology because of the need for very high precision. Spaceborne LIDAR may make it possible to develop such sensors for development in the 1990s.

Ozone, a less stable gas, will be monitored from the operational meteorological satellites, but much more comprehensive observations will require a dedicated satellite mission for monitoring stratospheric temperatures and the trace gases that influence the chemical and thermodynamic structure of the stratosphere. Planning is underway for such a mission, the Upper Atmosphere Research Satellite (UARS) to be launched in 1991. A strong theoretical program will be conducted in parallel, to model the photochemical, dynamic, and thermodynamic processes that govern the structure of the stratosphere, for eventual coupling to a climate model.

*Climate Modeling.* Although climate research as a multidisciplinary endeavor proceeds in many directions and on almost all time and space scales, the emphasis here is on understanding the climate system, its sensitivity to possible or probable anthropogenic changes, and the assessment of its predictability from about 2 weeks to several decades. Because the Earth's climate consists of global phenomena interrelated in space and time, the fundamental strategy is to take maximum advantage of unique space technology to provide the global long-term observations needed for initialization and/or verification of climate models.

SAGE MEASUREMENTS OF STRATOSPHERIC AEROSOL OPTICAL DEPTH FOLLOWING THE ERUPTIONS OF MOUNT ST. HELENS, MAY 1980

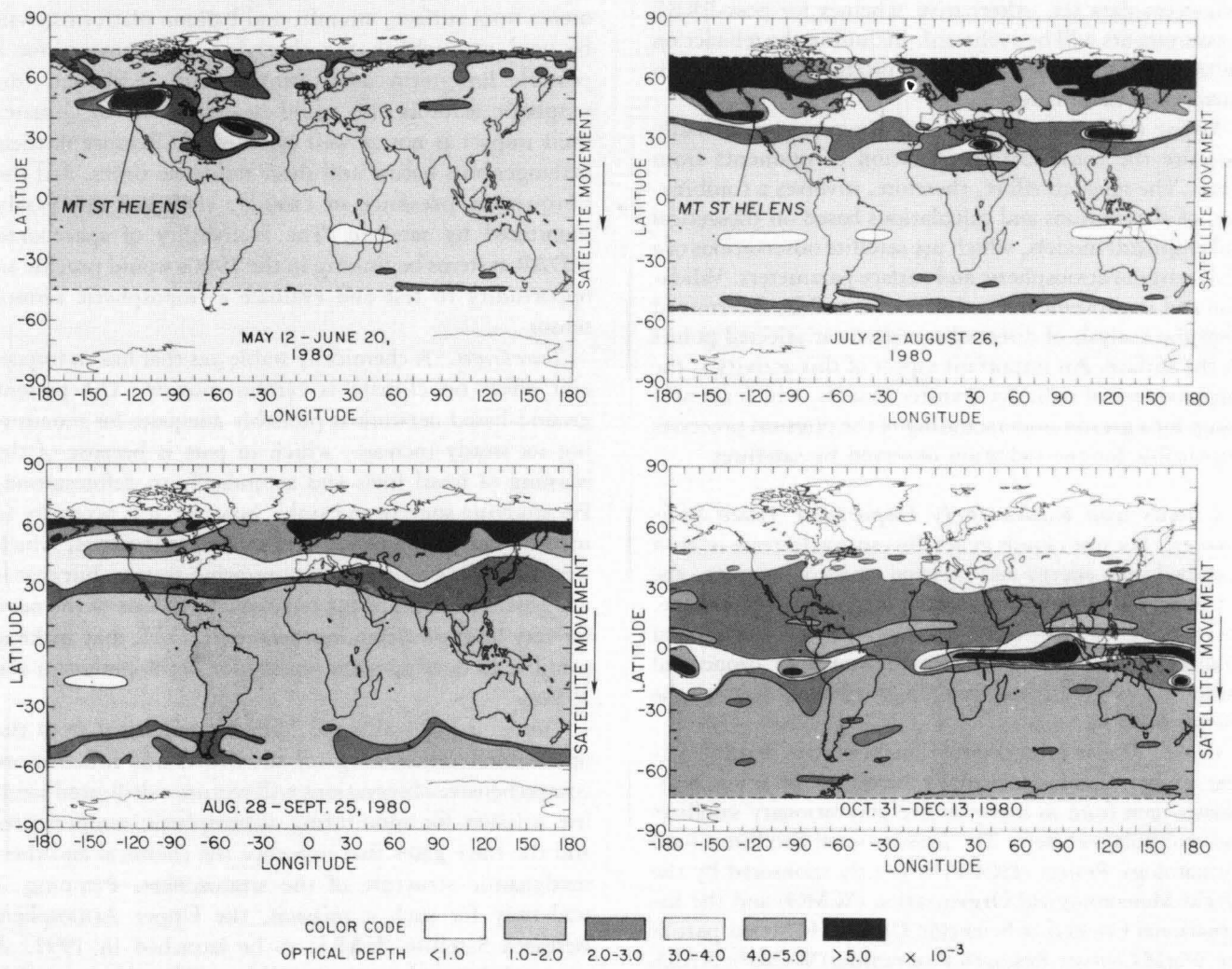


FIGURE 21. SAGE measurements of stratosphere aerosols after the eruptions of Mount St. Helens in May 1980. Successive panels portray the global spreading of the volcanic plume with time. Highest aerosol counts are in the black areas, lowest in the white areas.

National Oceanic and Atmospheric Administration (NOAA)

The NOAA Satellite Climatology Research Program is aimed at obtaining global long-term accurate observation of climate parameters for monitoring, diagnosing, and understanding the behavior of the planetary climate system. Specific research activities include studies of the planetary radiation budget, clouds, aerosols, and land surface climatology. The research uses data from both experimental and operational spacecraft; however, emphasis is on data from the operational spacecraft because this

represents the most probable source of the long-term data sets needed for climate research. NOAA climate research also embraces a variety of other activities, the goal of which is to improve the predictability of the coupled ocean-atmosphere system. Achieving this requires improved observations of the forcing function and response of both fluids and better integrated models. Global observation and modeling requires satellite data and existing and planned ground-based measurement systems.

NOAA research programs include developing seasonal climate predictions, defining the interannual variability of climate, and understanding long-term climate change.

All require observation of the ocean and atmosphere; the long-term program also requires understanding of biogeochemical processes and human influence on them. Examples of programs in each of these areas and their needs for satellite data and telemetry links are given below.

**Earth Radiation Budget (ERB).** Research on the ERB is focused on accurate determination, using operational spacecraft, of the outgoing longwave radiation and albedo and their application in understanding the climate system.

Estimates of albedo and outgoing longwave radiation from operational spacecraft are obtained from narrow spectral interval observations, thus requiring conversions from narrow-to-broadband radiances. Although much progress has been made on the longwave problem, theoretical and empirical studies of narrow-to-broadband relationships will be conducted for the shortwave portion of the spectrum. Such studies will be greatly aided by ERBE observations. Concomitant with the development of narrow-to-broadband relationships is the improvement of the estimates of albedo through application of angular reflectance models and solar zenith angle dependencies derived from the Nimbus-7 of the ERB radiometer.

Other elements of NOAA's research are the application of the long time series of outgoing longwave radiation (OLR) data obtained from NOAA operational satellites to studies of climate anomalies and interannual variability,

the determination of the diurnal variation of the OLR and the validation of climate models. The latter is important because it will help improve radiation parameterization procedures and provide information on the cloud/radiation problem. This problem is also being studied empirically using satellite estimates of the planetary radiation budget and cloudiness.

**Clouds.** NOAA participates in the ISCCP. The National Project Office resides in NOAA and is responsible for coordinating and supporting the efforts of those involved in collecting and processing the data from the U.S. satellites. NOAA's National Environmental Satellite, Data, and Information Service (NESDIS) acts as the Sector Processing Center for collection and processing of the Advanced Very High Resolution Radiometer (AVHRR) visible and infrared radiances. NESDIS also is responsible for collecting special global correlative data sets required for ISCCP processing: vertical temperature and humidity profiles, ozone column amounts, weekly snow and sea-ice cover analyses, and the 3-hourly global collections of surface weather reports. NESDIS will also maintain the ISCCP Central Archive, which will contain condensed radiance data tapes from all satellites participating in the program and final cloud climatology data tapes. NOAA is also participating on a modest level in the First ISCCP Regional Experiment (FIRE) through empirical studies of the cloud and radiation parameterizations of the GCM of NOAA's Geophysical Fluid Dynamics Laboratory

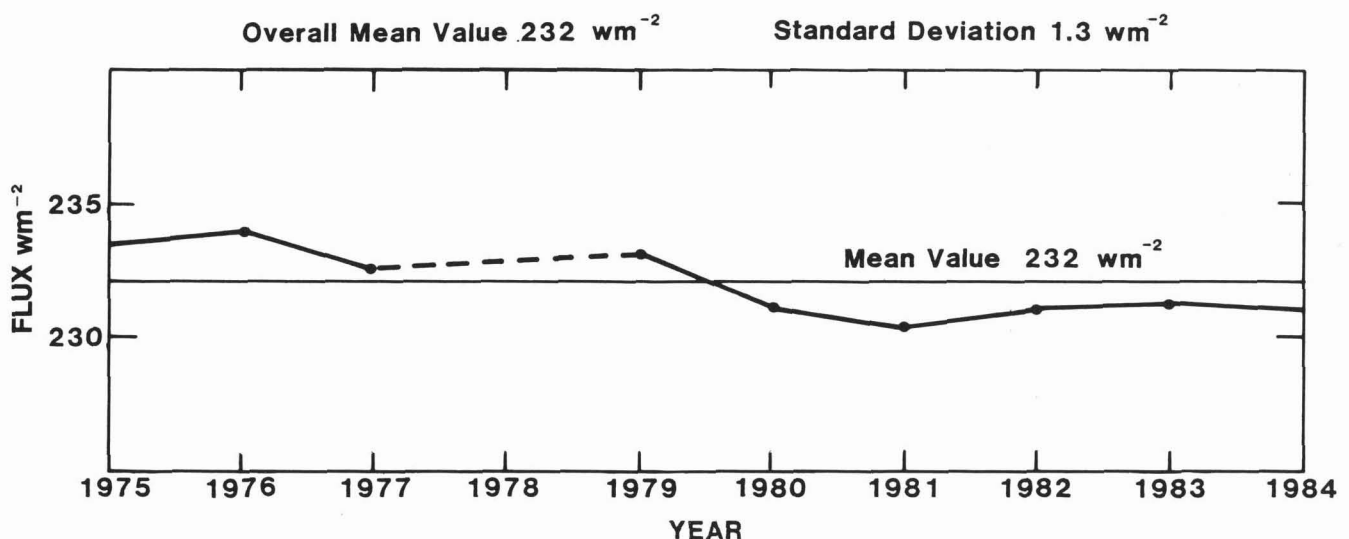


FIGURE 22. Global annual average outgoing longwave radiation estimate from NOAA polar-orbiting satellites. Dashed line represents missing data. The average value of all the years is  $232 w m^{-2}$ , with a standard deviation of  $1.3 w m^{-2}$ . On the average, we expect the absorbed solar energy to balance the loss to space of the longwave radiation, resulting in a net radiation of zero. If the absorbed solar radiation exceeds the outgoing longwave radiation, we can expect warming; if it is less than the outgoing longwave radiation, we can expect cooling. The global annual average outgoing longwave radiation acts like a thermometer reading of the integrated Earth system.

(GFDL), and the sensitivity of the Earth's radiation budget to cloudiness.

A global cloud climatology is being developed from Nimbus-7 Temperature-Humidity Infrared Radiometer and Total Ozone Mapping Spectrometer (TOMS) observations. Originally intended to support the Nimbus-7 ERB effort, the cloud climatology may prove useful for many other purposes. The climatology will contain the statistical properties of low, middle, and high cloud amount, and radiances (altitude) for daily and monthly time scales and 50-500 kilometer spatial scales from April 1979 to the present. The Nimbus-7 cloud climatology will extend the ISCCP cloud climatology, which began in July 1983, back to 1979.

**Aerosols.** The interaction of aerosol particles with incoming solar and outgoing terrestrial radiation can have a significant impact on the Earth's radiation balance. Algorithms have been developed to measure aerosol particle optical thickness over oceans using the visible data from AVHRR. These data will be used with both operational and ERBE estimates of the planetary radiation budget to study the interaction of aerosols and the radiation balance. They will also be used to obtain more accurate sea surface temperatures by correcting for the errors induced by the aerosols.

**Vicarious Calibration of Instruments.** The quantitative use of operational satellite data for determination of climate parameters and for long-term climatic monitoring requires a stable calibrated signal. All the radiometers on NOAA's GOES and Advanced TIROS-N (ATN) satellites are calibrated prior to launch, but only the thermal sensors (i.e., the sensors that measure longwave radiation) have onboard calibrations. Shortwave channels have relied on prelaunch calibrations to infer the stability of the measurements.

NOAA is providing postlaunch calibration of visible channels using a combination of ground-based and high-altitude airborne instrumentation. These aircraft data are taken simultaneously with the satellite measurements from space to provide the desired calibration transfer. Two types of calibration efforts are being conducted. One obtains observations from high-flying aircraft that coincide with satellite observations for time, viewing geometry, spectral response of the radiometer, and spatial resolution at the surface. Measurements are taken over a variety of relatively homogeneous targets, and the well-calibrated instruments on board the aircraft provide the transfer to the satellite instruments. The other method obtains calibrated radiance data from a high-flying aircraft over a fixed target whose properties are known and for which a complete set of surface and atmospheric data are available so that the radiances that should be seen by a passing satellite can be calculated. The aircraft observations are necessary

to develop a diurnal and seasonal albedo atlas of the calibration area (White Sands, NM). Once developed, further aircraft flights will be unnecessary, and spacecraft flights over the target area can be calibrated via an appropriate radiative transfer calculation.

**Land Surface Climatology.** The operational environmental satellites make daily global observations, which provide the data necessary for detecting surface climate change at the surface. The goals of this research are to (1) develop standardized methods for obtaining land surface climatological quantities from satellites on a global basis; (2) monitor climatic and man-made changes in the land surface (desertification, deforestation, drought, snow cover, etc.); and (3) provide remotely sensed boundary conditions for use in climatic models. Algorithms will be developed to convert satellite measured radiances into surface temperature, albedo, estimates of vegetation conditions, soil moisture, snow cover, and surface energy balance.

Future NOAA work in this area may include (1) research in converting satellite data into climatologically useful quantities, (2) collection of specialized coincident satellite and ground data sets for climatic research purposes, and (3) production of satellite products for use in land surface climatic monitoring.

**Seasonal Climate Prediction.** Continued efforts in the Experimental Prediction Program at Geophysical Fluid Dynamics Laboratory seek to improve seasonal climatic forecast models and, in NOAA's WCRP, support use of the First GARP Global Experiment (FGGE) data in extending forecast periods. The primary data requirements, all of which could be supplied by satellite, are cloud amounts, cloud radiation, sea surface temperature, and relative humidity.

**Interannual Variability.** The purpose of the Tropical Ocean Global Atmosphere (TOGA) Program is to observe, understand, and model the coupled variation of events in the tropical ocean and global atmospheric circulation to predict interannual climate variations. This requires long-term (approximately 10-year) observations of the low-frequency, large-scale fields of

- Wind stress
- Sea level
- Tropical precipitation
- Ocean thermal (and density) structure
- Upper air data
- Equatorial circulation
- Sea surface temperature
- Southern Hemisphere atmospheric pressure

Existing and planned satellite missions can contribute to nearly every aspect of this observational requirement. In planning satellite missions, highest priority should be given to measuring wind stress and tropical precipitation for this program. To improve our ability to make useful predictions, we also need to expand our ability to transmit real-time data from in situ sensors (e.g., drifting buoys) and determine their locations.

*Long-term Climate Change.* The purpose of the Global Monitoring for Climate Change (GMCC) and Radiatively Important Trace Substances (RITS) programs is to measure and understand the chemistry of radiatively and chemically reactive oceanic and atmospheric species (including aerosols) that influence climate and determine the chemical health of the atmosphere. Satellite-based measurements of the distribution of ozone, carbon dioxide, aerosols, water vapor, and other chemical species would be extremely valuable to these programs.

#### National Science Foundation (NSF)

NSF has primary responsibility for oceanic heat flux research as a part of the National Climate Program. Within NSF this responsibility has been assumed by the Ocean Sciences Division in close cooperation with the Division of Atmospheric Sciences. The Foundation is cooperating with NOAA and NASA in developing scientific plans and requirements for ocean climate research in the late 1980s.

The Ocean Sciences Division has a long-term commitment to the study of climate-related problems. The ocean and atmosphere are not two separate fluids but rather form the two most important components of a large heat engine that determines climatic fluctuations. Large-scale, ocean-atmosphere interaction was the subject of the North Pacific Experiment (NORPAX), which took place between 1971 and 1980. NORPAX scientists studied equatorial processes and found basin-wide effects associated with El Niño events. The influence of remote atmospheric forcing and the response of the ocean by means of equatorial Kelvin waves was recognized as the prime mechanism for El Niño along the coast of South America. These findings prompted the establishment of a network of sea level stations throughout the tropical Pacific to monitor sea level fluctuations associated with El Niño and with the variability of the equatorial current system in general.

These results led in turn to establishment of the Pacific Equatorial Ocean Dynamics (PEQUOD) Program. The PEQUOD Program attempted to establish a firm dynamical understanding of the El Niño phenomenon. PEQUOD found that low baroclinic-mode equatorial Kelvin waves do describe observed fluctuations. The steady flow consists of a rather broad band of scales centered at a few hundred meters vertically and a hundred kilometers me-

ridionally. The undercurrent, the South Equatorial Current, the subsurface countercurrents, the subsurface intermediate currents, and the deep jets all appear as part of a family that shares even symmetry about the equator and similar scales.

Currently, two projects are being carried out. The TROPIC HEAT Program is a coordinated study to measure and model the seasonal and interannual time-scale evolution of the heat and mass budgets of the central Pacific equatorial ocean. The Western Equatorial Pacific Ocean Circulation Study (WEPOCS) program studies the near equatorial circulation north and east of Papua, New Guinea.

A broad segment of the research community has been developing plans for oceanic, atmospheric, and climatic studies in the next decade as part of the WCRP. Proposed experiments are the WOCE and the TOGA programs. Measurement of sea-surface topography by altimetry (TOPEX/Poseidon Mission) and wind stress by scatterometer (NSCAT {NASA Scatterometer}) are of highest priority as observational systems for these experiments. Proposals are being developed for global primary productivity studies. These experiments would focus on how primary productivity is influenced by oceanic circulation and atmospheric forcing.

#### E. Interdisciplinary Studies

The Interdisciplinary Studies section of this report focuses on two areas: biogeochemical cycles and hydrological cycles. The study of biogeochemical cycles is concerned with the interaction of the physical, chemical, and biological processes taking place on the Earth. The principal Federal agencies conducting research are NASA and NSF.

The hydrological cycle is concerned with the transport of water in all its phases between the land, ocean, and atmosphere and involves the processes of precipitation, evaporation, evapotranspiration, ice and snow formation and melting, and runoff. Current goals for interdisciplinary research using remotely sensed data are discussed below.

#### National Aeronautics and Space Administration (NASA)

Land, atmospheric, oceanic, and biospheric processes are so strongly coupled that to understand the global environment, which is constantly undergoing both natural and man-induced changes, the Earth has to be studied not only from a discipline-specific viewpoint, but also from an integrated perspective. Although scientific under-

standing of global-scale processes is only rudimentary, there is solid evidence that these processes are rapidly changing. The global cycles of the life-sustaining nutrient elements—carbon, nitrogen, sulfur, phosphorus—and elements such as chlorine are currently changing. This is evidenced, for example, by increasing atmospheric concentrations of carbon dioxide, methane, nitrous oxide, the nitric oxides, the sulfur oxides, and chlorine. There is also evidence that the global energy and water cycles are changing. Given these events, NASA is implementing a much-needed comprehensive research program, the Earth Sciences Research Program, to investigate and understand long-term coupled physical, chemical, and biological changes in the Earth's environment.

NASA's approach to implementation of this comprehensive program is to

- Continue relevant ongoing research programs such as upper atmospheric research, atmospheric dynamics, and oceanic processes;
- Expand other relevant programs such as global biology, tropospheric chemistry, and air quality and climate;
- Refocus the current land processes program; and
- Initiate an interdisciplinary research program advancing research in important areas lying between or cutting across existing discipline areas.

NASA's Interdisciplinary Research Program currently consists of studies of the biogeochemical cycling of methane and carbon as well as studies reported in earlier sections on the hydrologic cycle and Land Programs (see Sections A and D, this chapter). These individual components of the program are discussed below.

***Methane Cycle Research.*** The objectives of NASA's current research are to quantitatively understand why the concentration of atmospheric methane is increasing and what the consequences are for the Earth radiation budget (ERB) and atmospheric composition.

Increases in atmospheric methane (for which there is good evidence) could, like carbon dioxide, modify regional and global climate within the next 10-100 years. To understand the causes for, and consequences of, increases in atmospheric methane requires such diverse efforts as (1) flux studies of methane from specific ecosystems (wetlands, tropical forests, arctic tundra); (2) areal extent of ecosystems; (3) atmospheric measurements of methane; (4) atmospheric chemical transformation studies; (5) isotope studies; (6) ice-core sampling; (7) microbial process studies; and (8) models of ecosystem dynamics, atmospheric chemistry, and climate. Individual disciplines (e.g., tropospheric air quality, global biology, climate, and the upper atmospheric research program) will also sponsor research on several of the listed topics.

***Ocean Basin Carbon Fluxes Research.*** NASA is currently seeking to better understand the magnitude and variability of the carbon cycle in the oceans, on an ocean-basin to global scale, and the role of oceanic carbon fluxes in global-scale biogeochemical cycles and climate.

The oceans play a major role in the global carbon cycle, as well as in nitrogen, phosphorus, and sulfur cycles. To better understand that role requires improved estimates of the magnitude and variability of oceanic primary productivity on a basin or global scale and improved large-scale biogeochemical models that relate productivity to physical and chemical processes controlling productivity. Specific areas of research might include, but are not limited to, the following:

- Development of improved algorithms for estimating primary productivity from Coastal Zone Color Scanner (CZCS) measurements;
- Retrospective analysis of existing ship and satellite data to provide the basic observational data sets for an ocean basin-scale study of the mean, seasonal, and interannual variability in oceanic primary productivity;
- Development of improved models for estimating the role of land and oceanic nutrient cycles for controlling ocean productivity;
- Development of mesoscale and basin-scale models that relate primary productivity to wind fields, mixing, and circulation patterns;
- Development of improved global models to examine relationships between interannual variability of ocean productivity and climate and weather; and
- Investigations into the relationships between oceanic primary productivity and biogenic production of atmospheric trace gases and the role of these interactions in weather and climate.

***Hydrologic Processes Research.*** The goal of NASA's hydrologic processes research is to develop an improved, quantitative understanding of reservoirs and fluxes of water and energy in the land and across the land-atmosphere and land-ocean boundaries. In contrast to the terrestrial ecosystems program element, which is primarily concerned with the biological and biochemical aspects of vegetated land cover, this program element is concerned with the physical/radiative interaction of the land surface with the climatic system. Much of the focus is on arid and semiarid regions where small perturbations of the boundary conditions may result in large changes in the state of the land cover, which in turn may have a large positive feedback into the atmosphere.

Hydrological models that predict runoff timing and amount have been under development for many years. More recently, these models have used satellite snow cover

observations. These models were previously aimed at near-term agricultural applications, but are now being re-oriented toward longer term studies of the global water balance. Parameters relating snow and water accumulation, land cover, soil properties, and topography have been developed and validated for a variety of watersheds. Current emphasis is on the determination of the hydrological properties of soil and snowpacks and on the modeling of water movement within hill slopes.

The measurement and modeling of evapotranspiration over large (10-500 kilometer) regions, especially as it relates to global climatic processes, is the major new focus of the hydrology program. Investigation of the role of vegetation and land use in the control of regional evapotranspiration are being developed for remotely sensed parameters such as surface temperature, net radiation, soil moisture, soil hydraulic conductivity, leaf area or intercepted, photosynthetically active radiation, and vegetation phenology. An interactive biosphere is being integrated into the NASA Goddard facility and National Center for Atmospheric Research (NCAR) general circulation models, and simulation studies are being conducted to relate land surface changes to monsoonal rains.

**Land Surface Climatology Research.** This research is aimed at determining changes taking place in climatologically important properties of the land surface, physically and biologically quantifying those changes, and determining both the processes that control the changes and the stability of the coupled land-climate system.

Studies are required to improve our understanding of how to relate satellite-measurable parameters to important physical and biological properties of the surface. These studies should be both theoretical and observational, involving properties having spatial scales ranging from a few meters to a hundred or more kilometers.

Linkages need to be established between field measurements of typical homogeneous targets with little atmospheric interference to aircraft and satellite measurements of inhomogeneous targets through an atmosphere of varying properties. Given the present observation intervals, satellite measurements are chronically under-sampled; parameters permitting such data to be used in general theoretical models are needed. Model development is also required to relate atmospheric response at scales of hundreds of kilometers to the aforementioned observations of surface properties. Whereas considerable progress has been made on parameterizing subgrid-scale processes in the atmosphere, little has been done to understand subgrid-scale heterogeneity of land surface properties.

Existing satellite data should be analyzed to determine the degree to which changes in land surface properties are occurring and to gain an understanding of the mecha-

nisms that cause or ameliorate the changes. More than a decade of Landsat data is available, providing repetitive measures of surface composition and surface optical properties. Five years of NOAA imagery from the AVHRR is also available, as is episodic coverage from other satellites (e.g., Seasat, SIR-B). A central data base of space imagery over key sites (e.g., Sahelian Zone of Africa, Sonoran Desert, Southern Great Plains, Central Great Plains, Northern Plains) will be available for investigators choosing to work in those areas.

#### National Oceanic and Atmospheric Administration (NOAA)

NOAA hydrologic research goals are to develop procedures to estimate snow water equivalent, soil moisture, and precipitation from satellite data. Once defined, these procedures will be refined into operational products to provide an improved monitoring and understanding of water resources.

**Snow Cover—Continental and Basin.** Continental and basin snow cover analyses are performed using visible and infrared sensors on the NOAA satellites—Landsat, the Advanced TIROS-N (ATN), and the Geostationary Operational Environmental Satellite (GOES).

Passive microwave radiometers have been available on polar-orbiting satellites since December 1972, including the Electrically Scanning Microwave Radiometer (ESMR) on Nimbus-5, a dual polarization radiometer on Nimbus-6, and the Scanning Multichannel Microwave Radiometer (SMR) on Nimbus-7. The major drawback of these satellite sensors for snow hydrology is relatively poor spatial resolution of about 25 kilometers. However, results from various studies indicate that qualitative monitoring of snowpack buildup and disappearance during the winter appears feasible. In relatively homogeneous, flat areas such as the Canadian high plains and the Russian steppes, a significant relationship between snow depth and microwave brightness temperature can be developed.

**Precipitation.** The GOES satellites, which provide half-hourly coverage, are the primary source of precipitation estimates. For those areas where GOES data are unavailable, techniques using polar-orbiter data are used. The purpose of the precipitation analysis (heavy precipitation, agricultural, or climate) determines the size of the area over which the estimates are computed—small areas for heavy rain, large areas for climate.

**Floods.** Satellite-derived precipitation estimates and 3-hour precipitation trends for convective systems, extratropical cyclones, and tropical cyclones are computed on the NESDIS Interactive Flash Flood Analyzer and trans-



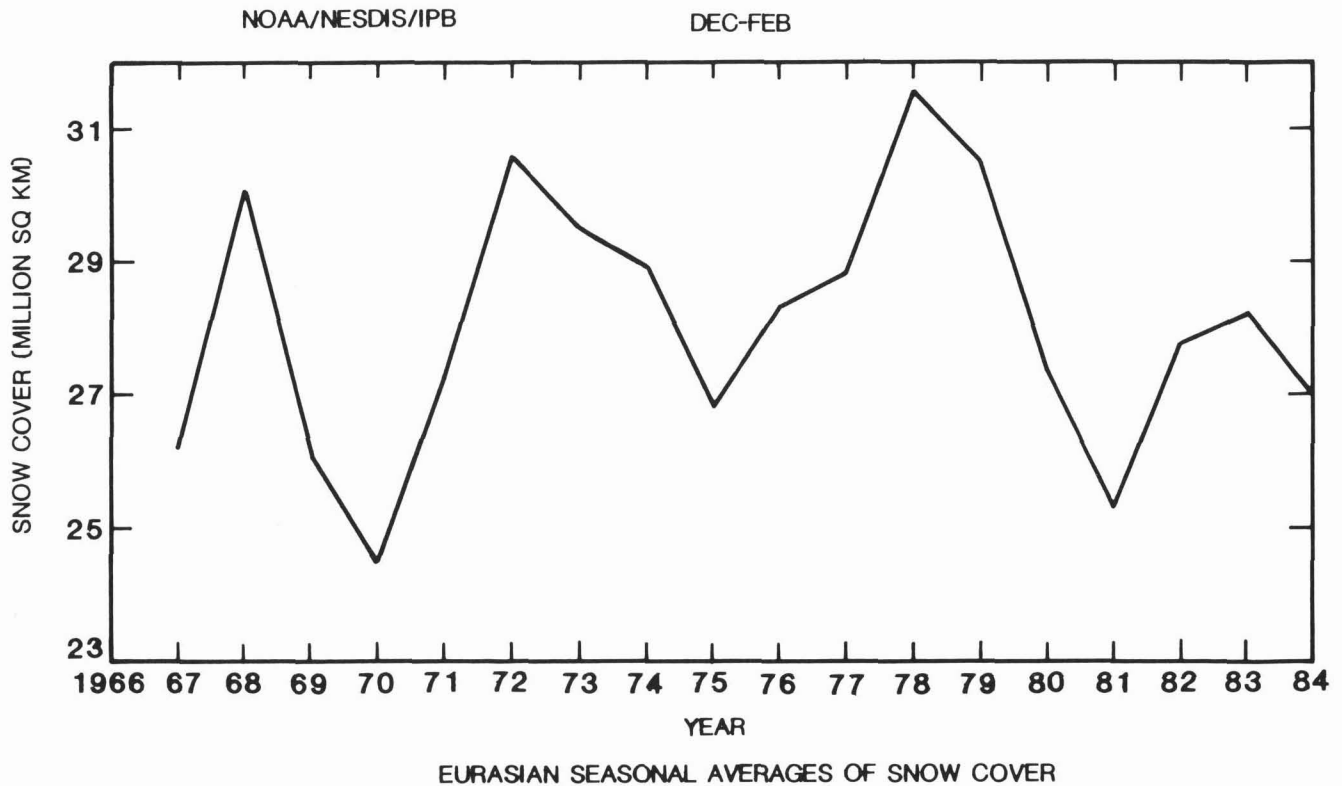


FIGURE 23. Photointerpretation of visible-band imagery from NOAA operational polar satellites has been used for 15 years to generate the Northern Hemisphere Weekly Snow and Ice Cover Charts. Digitization of this product to create a continental snow cover data base has enabled calculation of snow cover frequency and anomaly maps and the monthly and seasonal averages of the amount of snow-covered area on each continent. This is a graph of the Eurasian seasonal (December-February) averages of snow cover from 1966 through 1986 in millions of square kilometers.

mitted via Advanced Field Operations System to National Weather Service (NWS) Forecast Offices, NWS Offices, and River Forecast Centers. Cloud cover permitting, monitoring the satellite imagery over time allows observation of changes in the areal extent of flooding and tracking of the flood wave characteristic of river basins.

**Other Hydrologic Research.** Satellite data from NOAA polar-orbiters and GOES are the main sources of information on ice conditions for safety of Great Lakes shipping and on lake water temperature, which influences development of storms moving over the lakes. Near-infrared sensors on the Landsat MSS detect the enhanced reflections from chlorophyll in floating algal material.

#### National Science Foundation

In 1987 NSF initiated a new Global Geosciences Program to support studies of the Earth as a system of interrelated physical, chemical, and biological processes which regulate the habitability of the planet. This program now contains eight major components: the Global Tropospheric Chemistry Program (GTCP); the Tropical

Ocean and Global Atmosphere (TOGA) Program; World Ocean Circulation Experiment (WOCE); Global Ocean Flux Study (GOFS); Global Ecosystem Dynamics project; studies of Ocean Ridge Crest Processes; Solid Earth Studies; Paleoclimatic Studies from Ice Sheets; and studies of Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR). The TOGA Program has been described under Climate Programs (section D). The other components of the Global Geosciences Program are described briefly below.

#### *Global Tropospheric Chemistry Program (GTCP).*

The GTCP is a coordinated effort to understand the processes that control the composition of the troposphere. The program emphasis is on the study of biological sources of atmospheric species; the chemical processes responsible for creating and destroying atmospheric chemical species; the physical processes responsible for distributing species and removing them from the troposphere; the development of improved atmospheric chemistry models to permit more realistic predictive capabilities; and the advanced methods for measuring concentrations and cycles of trace species through the atmosphere.

**World Ocean Circulation Experiment (WOCE).** The WOCE Program is directed at (1) understanding the general circulation of the global ocean well enough to model its present state and predict its evolution in relation to long-term changes in the atmosphere and (2) developing the scientific basis for the design of an observing system for long-term measurements of the large-scale circulation of the ocean. Planning for WOCE is well underway. The pre-satellite operational phase is just beginning and will last until 1991. It will include global in situ measurements and selected regional programs. The full WOCE operational phase (1991–1996) will couple extensive in situ and satellite observations with numerical models and analysis. These efforts are expected to provide the first comprehensive global survey of physical properties of the ocean.

**Global Ocean Flux Study (GOFS).** The goal of GOFS is to understand the processes governing the production and life span of biogenic materials in the ocean well enough to predict their influences on and responses to global-scale perturbations, whether natural or anthropogenic. This study will seek to link the results of physical processes studies (1) to the emerging understanding of biogeochemical fluxes and (2) to the intensive in situ observations of fluxes of soluble and particulate phases in the oceans.

**Global Ecosystem Dynamics Project.** This project will study the physical and biological processes governing atmospheric composition, climate, and circulation in the biosphere which, in turn, govern the physical structure of the biosphere. The project will include research into the impact of climate change on ecosystems; the processes controlling the flux of biologically mediated atmospheric constituents; the role of ecosystems as material sinks; the biogeochemistry of terrestrial/freshwater environments; the influence of terrestrial environments on ocean productivity; the biological diversity of tropical forests and other habitats; the influence of anthropogenic activities on ecosystem dynamics; and scale-dependent interactions of the biosphere.

**Oceanic Ridge Crest Studies.** The objectives of this program are to examine and quantify the geological,

chemical, and biological processes at sea-floor spreading centers caused by the formation of new oceanic crust. Specific goals are to determine the temporal and spatial scales of volcanic activity; to quantify the chemical flux to seawater which results from hydrothermal circulation in oceanic crust; and to identify the factors that control biological colonization and composition of hydrothermal vent communities.

**Solid Earth Studies.** Observations under this program are intended to improve understanding of the solid Earth, its deep structure and composition, and the active geophysical and geochemical processes that have led over time to the present distribution of oceans and continents. This program will require satellite data for precise geodetic measurements to complement (1) a new global digital seismic network to provide high-resolution imaging of the Earth's interior; and (2) for geological, geochemical, and geophysical studies aimed at recognizing and interpreting events and trends of global significance in the geologic record.

**Paleoclimatic Studies from Ice Sheets.** This global ice core research and analysis program will permit reconstruction of paleoclimatic sequences unavailable from other sources. The first major initiative will be the Greenland Ice Sheet Program, an international collaborative deep-drilling research program designed to obtain a 3200-meter core in central Greenland that would represent a climatic and atmospheric record of 200,000 years, extending into the last glacial period.

**Studies of Coupling, Energetics, and Dynamics of Atmospheric Regions (CEDAR).** This program will study the global middle and upper atmosphere as a coupled entity. The initial step will be to develop state-of-the-art optical facilities (spectrographs, interferometers, monochromatic imagers, and lidars) and upgraded radar facilities (incoherent scatter radar and mesospheric radars). These new systems will permit coordinated multi-instrument studies of vertical and horizontal atmospheric coupling, which will, in turn, establish the nature of such coupling and test and refine global models for these processes.

## IV. EARTH SCIENCE RESEARCH OBJECTIVES AND PROGRAMS

Emphasis in recent years has been increasing on research in externally driven and internally caused (particularly anthropogenic) Earth processes. Researchers now have a global perspective and recognize the interaction of the physical, chemical, and biological systems. This heightened awareness, coupled with the rapid improvements in large-scale computer systems and the relatively routine access to Earth orbit for global observations, has precipitated a virtual revolution in the approach to Earth research.

Motivated by this interest and by related studies of the National Academy of Sciences, NASA, in cooperation with NOAA, asked key members of the scientific research community to participate in an advisory committee, the Earth System Sciences Committee (ESSC). This committee began its deliberations in November 1983 and is preparing recommendations to NASA, NOAA, and the National Science Foundation (NSF) for future goals in Earth science research. These recommendations are expected to help guide our research for the remainder of this century. A published Preview and Overview of the ESSC report have suggested that the goal of an Earth System Science Program should be to obtain an understanding of the Earth as an interdependent, highly interactive system by defining its components and their relationship as a function of time. The Preview poses a specific challenge for the research community to develop the capability of predicting both natural and man-induced changes on the Earth that may occur in the next decade to century. The Overview summarizes key ESSC recommendations.

Critical to the purpose of the present report and future research progress is an assessment of current knowledge and of issues that need to be addressed. This chapter presents a brief summary, then, of the state of knowledge and the major gaps in this knowledge for each of the component and interdisciplinary areas of the Earth sciences.

Measurement objectives from space that specifically address the knowledge gaps are also discussed, as is the supporting research plan that seeks to remedy these gaps. Finally, this chapter discusses the close relationship between remote-sensing research and (1) operational observations of the Earth and (2) international cooperation in Earth science.

### A. Knowledge Gaps and Measurement Objectives

#### Land

*Agriculture and Renewable Resources.* Although Landsat has shown the potential of satellites for monitoring crops on scales as small as fields, and the NOAA Advanced Very High Resolution Radiometer (AVHRR) has demonstrated the possibility of monitoring global vegetation from space, a number of problems remain. In particular, the assessment of vegetation conditions from space is hampered by the lack of appropriate ground-truth data—especially for AVHRR vegetation validations—for comparison with satellite observations.

Some key questions about agriculture and renewable resources are as follows:

- What is the quantitative relationship between satellite vegetation indices and vegetation on the surface of the Earth?
- Can satellite estimates of precipitation, temperature, and insolation be made with sufficient accuracy for use in crop yield prediction models?
- What is the exact nature of the interaction between sunlight and plants and soil?
- How best can the effects of weather, soils, fertilizer, pests, and other factors on crop yields be quantified?
- How best can changes in the amount and quality of soil and water resources be monitored, assessed, and predicted?
- What are the best sampling strategies to utilize data more effectively from all sensors?
- Can an all-weather crop monitoring system be developed?

Measurement objectives for agriculture and renewable resources include the following:

- Monitor and assess global, regional, and local crops and vegetation;
- Measure precipitation, temperature, and insolation for crop yield models; and
- Monitor and assess forests and other renewable resources.

**Geology and Nonrenewable Resources.** The science of modern geology has existed for nearly 200 years. During this time, the science has evolved to include many sub-disciplines, all of which have contributed to knowledge and information not only about the compositional and structural characteristics of the Earth, but also about its formational and deformational history. This history, including the causative processes that have operated through time, is largely recorded by the compositional and textural characteristics, geometry, and age distribution of the rocks comprising the continental crust. Consequently, a key to a better understanding of the Earth's compositional and structural characteristics and its formational and deformational history and processes is to study and map more fully the nature and distribution of the continental crustal rock units. Furthermore, because most of the Earth's nonrenewable resources occur within the continental crust, such investigations are important to advancing knowledge about the genesis and occurrence of these resources and to improving ability to discover new mineral and hydrocarbon deposits.

There is wide variation in the degree to which the Earth's continental rock units have been studied and mapped. Many areas in the United States have been mapped in detail, but vast areas of the Earth, including extensive densely vegetated regions, have been mapped only in a reconnaissance mode or have not been mapped at all. Particularly in sparsely vegetated regions of the world, remotely sensed data from satellites could provide important information allowing significant expansion of current knowledge of the Earth's geologic characteristics, processes, and history.

Key questions that can benefit from or require satellite remotely sensed data include the following:

- What are the dominant lithologic and structural geologic characteristics of the poorly mapped or unmapped regions of the Earth?
- What are the detailed lithologic, mineralogical, and structural geologic characteristics favorable to the presence of mineral and hydrocarbon resources?
- How do weather and other climatic and natural processes modify the composition of rocks exposed on the Earth's surface? What are the relationships between these modifications and original rock composition?
- How are soil formation and degradation affected by climate, topography, vegetation, and geologic substrata?
- What relationships exist between the characteristics of vegetative cover and geologic conditions for different climatic regions of the Earth?
- What are the relationships between surface topography and morphology and the exogenic (surface) and

endogenic (interior) processes that have influenced development of existing geomorphological conditions?

- How have global tectonic processes influenced the distribution, geometry, and composition of continental rock units?
- What are the roles and relationships of global and regional tectonic processes in the formation of mineral and hydrocarbon deposits?

Measurement objectives for geology and nonrenewable resources include the following:

- Map the distribution, geometry, and dominant lithologies of continental rocks;
- Identify constituent mineralogy of soils, rock units, and alteration products;
- Map present and ancient drainage patterns and density;
- Detect and map faults and other fractures in the Earth's surface;
- Measure the sense and amount of motion along active faults;
- Measure and map the topography of the Earth's surface;
- Detect, measure, and map variations in plant type and vigor;
- Locate and measure thermal anomalies on the Earth's surface; and
- Measure the sense and amount of motion of crustal plates.

**Geodynamics.** Recent observations in geodynamics have led to important insights into the solid Earth. The nearly rigid blocks or plates making up the Earth's crust are now known to move slowly (1-10 centimeters per year) in response to driving forces from the Earth's interior. NASA's use of space technology to measure this movement has confirmed this model. Measurements of crustal deformation near seismically active boundaries are also important in earthquake prediction. In addition, the rate of Earth rotation about its axis has been found to vary not only over periods of decades to thousands of years, but also over periods of days to years. These more rapid fluctuations are related to the strength of the westerly winds in the Earth's atmosphere. Superimposed on the well-known changes in the Earth's magnetic field (of the order of 0.1 percent per year) are much more rapid changes that appear to be correlated both with climatic variations and rotation rate fluctuations.

Some key questions about geodynamics are as follows:

- What are the forces driving the motion of the tectonic plates?
- What constraint does postglacial rebound provide on mantle viscosity and its variation with depth?
- What is the nature and dynamic state of the material in the Earth's mantle (i.e., the details of convection)?
- What is the structure of the Earth's core, and how is the geomagnetic field generated by a core dynamo?
- What are the various causes in excitation of the Earth's rotation?

Measurement objectives for geodynamics include the following:

- Determine the relative velocities of the major tectonic plates;
- Map crustal deformation of plate boundaries; and
- Update and improve global measurements of the Earth's gravity and magnetic fields.

## Atmosphere

The atmosphere is the most variable part of the Earth system. Atmospheric scientists deal with its physics, chemistry, and dynamics. Satellites are providing a global, four-dimensional picture of atmospheric state, composition, and structure, primarily by filling in the gaps of conventional observations made over the oceans and in the stratosphere and mesosphere, but also by providing observations for which there are no conventional counterparts. Measurements of atmospheric composition currently are much less comprehensive than those of clouds, temperature, and winds.

In the more general areas of atmospheric science, there are several major gaps in knowledge. Little understanding of mesoscale phenomena exists—for example, how severe storms, like tornados, develop. On the synoptic scale, phenomena such as blocking—in which a particular weather pattern remains stationary for a long period—are poorly understood. In atmospheric chemistry, there is strong evidence of increasing concentrations of chlorofluorocarbons, methylchloroform, carbon dioxide, nitrous oxide, and methane. However, realistic scenarios for future atmospheric concentrations, especially for methane, are difficult to deduce because of an inadequate understanding of the sources and sinks of these substances. Major uncertainties in the future evolution of the ozone layer arise from the uncertain future concentrations of atmospheric methane and from inadequate knowledge of the distribution of several stratospheric constituents, such as water vapor. The exchange mechanism between the stratosphere, with its long residence times, and the tro-

posphere, with its short residence times, is incompletely understood.

Some of the key questions about the atmosphere are the following:

- Can weather forecasting accuracy be improved and the useful forecast period extended?
- Can the understanding of mesoscale processes for better prediction of severe local storms be improved?
- What exactly are the processes maintaining the atmospheric circulation?
- How are the chemical, radiative, and dynamic processes of the atmosphere coupled?
- How are the lower and upper atmosphere coupled?
- What causes ozone variations, and what is the effect of anthropogenic perturbations on ozone?
- What are the quantified attenuation processes and parameters for optical and infrared transmissivity in the atmosphere?

Measurement objectives for atmospheric science include the following:

- Observe global distribution of wind, temperature, moisture, and surface temperature on an all-weather basis;
- Determine global distributions of surface moisture, cloud cover, radiation budget, surface heat and moisture fluxes, precipitation, snow and ice cover;
- Observe with high-frequency and spatial resolution the mesoscale features of wind, temperature, humidity, surface temperature, surface moisture, cloud properties, and precipitation for selected areas;
- Observe global distribution of stratospheric constituents, winds, and temperatures; and
- Implement proper calibration techniques to monitor the stability of long-term measurements of climate parameters.

## Oceans

Because of their ability to globally and continuously transport energy and substances, the atmosphere and the oceans are the main integrators of the Earth system—the pathway through which most of the interactions of the other components proceed. Although knowledge of the atmosphere has grown substantially over the last few decades, knowledge of the oceans is still meager. Information is still largely based on sparse measurements of surface winds, waves, currents, and water temperatures of the commercial shipping fleet, surface observations by a few drifting and fixed buoys, and occasional high-quality observations of surface and subsurface conditions by re-

search vessels. With the current weather-observing system, a good concept of the global three-dimensional state and circulation of the atmosphere is obtained twice each day. Using the entire archive of oceanographic observations, only a very limited knowledge exists of the three-dimensional state and circulation of the world's oceans and their variations. Some of the key questions about oceans are as follows:

- What are the mesoscale and large-scale circulations of the oceans and how do they vary?
- Exactly what is the role of the oceans in transporting heat from the tropics to polar regions?
- What is the global distribution of heat, water, and momentum exchange between the oceans and the atmosphere?
- What are the processes that control sea ice and its interaction with the underlying water?
- What is the response of the upper ocean to thermal and atmospheric forcing? How are physical and biological processes interrelated?
- What are the exchange processes between the surface and deeper layers?

Measurement objectives for oceanic research include the following:

- Observe the time-dependent sea surface elevation, wind stress, near-surface chlorophyll concentration, sea surface temperature, and significant wave height; and
- Determine the time-independent sea surface elevation relative to the geoid, global wind stress, and distribution of mesoscale eddies, and measure directly the near surface circulation and subsurface ocean properties.

## Climate

Until fairly recently the science of climatology had been mainly descriptive, focusing on analyzing weather observations to obtain statistical information on the climatic elements and their variations with season and geography. Although it has been known for some time that the Earth's climate undergoes changes and fluctuations, the thrust of climatological work was on the static nature of the system. It is only recently that climatology has been transformed from a descriptive science to a descriptive and theoretical science.

Climatology now focuses on the dynamics of climate—how is the climate varying, what are the causes of climatic variations, and are climatic variations predictable? To address these questions, it is not sufficient to study only the atmosphere. The Earth's climate and its variations are

determined by the energy received from the Sun and the interactions of the four components of the Earth: the atmosphere, the land, the oceans, and the cryosphere.

With the dynamics of the system as a focus, there has been an enormous increase in scientific activity. Powerful computers have aided sophisticated climate models—three-dimensional numerical models that attempt to include equations for the physical and dynamical processes controlling the climate. These models, which are outgrowths of the numerical models used in weather prediction, are also being used to examine the question of climate predictability. Given accurate observations, a comprehensive numerical model, and high-speed computers, day-to-day weather variations are, in principle, predictable up to 2 weeks in advance. Knowledge of the predictability of next month's average weather and of longer term climatic variations are limited. Recent observational studies of the El Niño-Southern Oscillation phenomenon suggest that a potential for such predictability does exist. Such a capability, depending on how much predictability is actually achieved, could have profound economic and social implications.

Parallel with the development of the numerical climate models has been a concerted effort to diagnose the observed climatic fluctuations. Because climatic fluctuations are globally interconnected, satellite observations have provided a major input to such studies.

Anthropogenic effects on climate, particularly the effects of carbon dioxide and other greenhouse gases, are also a key concern. Although numerical climatic simulation models have advanced, they are still deficient in their treatment of physical processes in the atmosphere (for example, the development of clouds and precipitation and the interaction between clouds and radiation, and climatic processes involving the land, oceans, and cryosphere). Satellites offer the potential of providing the climate system observations required to (1) improve the boundary/initial conditions and the treatment of the various physical processes in the numerical climate models; (2) validate climate model predictions; and (3) detect early indications of a global climate change because of increased carbon dioxide concentrations.

Critical for monitoring of the Earth's climate and for explaining variations are observations of the Earth radiation budget (ERB)—the balance between absorbed solar radiation and emitted longwave Earth radiation. For climate monitoring, a continuous series of well-calibrated, exact observations of the ERB is required.

Key questions about climate are as follows:

- Why does the climate vary?
- Are climatic variations predictable?
- What is the extent of man's impact on climate?

- What are the long-term trends in global and regional climate?
- What are the large-scale and low-frequency (month-to-month, year-to-year) variations of the atmospheric variables (wind, pressure, temperature, cloudiness, and precipitation)?
- What are the large-scale and low-frequency variations of the ERB and their relationship to cloudiness?
- What are the relationships between the large-scale and low-frequency variations of atmospheric variables and those of sea surface temperatures and current systems?
- How are local and regional climates influenced by land surface evaporation, albedo, and roughness?
- How is the global climate influenced by sea and land ice cover?
- What are the roles of land biota as sources or sinks of carbon dioxide and other radiatively important trace gases?

Measurement objectives for climate research include the following:

- Resolve and observe trends in forcing at
  - Top of the atmosphere—insolation, albedo, longwave radiation*
  - Surface—latent heat flux, albedo, vegetation cover, soil moisture, ice extent*
  - Atmosphere—trace gases (carbon dioxide, ozone, water, and chlorofluoromethanes), aerosol opacity, cloud cover, cloud type, cloud height and temperature;*
- Observe global and regional changes in climate: surface temperature, temperature, precipitation, water vapor, snow cover, sea-ice extent and thickness, cloud properties, surface stress, surface ocean currents, mixed layer depth;
- Observe snow cover: extent, depth, density, water equivalent, grain size, albedo;
- Observe sea-ice extent and properties: wind velocity, boundaries, concentration, type, motion, thickness, leads, roughness, surface temperature, wind velocity, ice islands, icebergs; and
- Observe glacial ice: surface elevation, elevation change, boundary thickness, albedo, accumulation rate, surface temperature, surface velocity, internal properties, strain rates, condition at rock interface, and iceberg discharge.

## Biogeochemical Cycles

The study of biogeochemical cycles is a new field of study that is receiving increasing attention because of

threats to the ozone layer, the increase in atmospheric carbon dioxide and its potential effect on climate, the mysterious increase in atmospheric methane, the acid rain problem, and a number of other concerns. All of these problems involve complex interactions of geological, physical, chemical, and biological processes. Understanding the biogeochemistry of the Earth requires knowledge of the rates of biological processes and the capacities and sizes of various chemical reservoirs. This includes determination of the primary biological productivity of oceans and land biomes, the amounts of various compounds carried by rivers, the fluxes of different gases both into and out of the atmosphere, and the chemical interactions and transports within the atmosphere. The currently available data are inadequate.

Some of the key questions on biogeochemical cycles are as follows:

- What are the details of the process involved in biogeochemical cycling of carbon, nitrogen, phosphorus, sulfur, and trace metals?
- What is the global distribution of biomass and its variations? What determines its changes and variations?
- What are the detailed processes controlling acid precipitation and deposition?
- What is the rate of transport of sediments and nutrients from the land to inland waters and ocean?
- What are the global distribution, transport rates, and strengths of sources and sinks of tropospheric gases and aerosols?
- Why is the atmospheric methane concentration increasing?
- To what degree is the natural temporal variability of major element dynamics influenced by manmade inputs?

Measurement objectives for biogeochemical cycles include the following:

- Determine the global distribution of biomass and its variations;
- Determine the global distribution of gross primary production and respiration by autotrophic and heterotrophic organisms;
- Determine the transport of sediments and nutrients from the land to the sea; and
- Determine the global distribution and transport of tropospheric gases and aerosols.

## Hydrological Cycles

The hydrological cycle involves the processes of precipitation, evaporation, evapotranspiration, ice and snow

formation and melting, and runoff. A quantification of this cycle is crucial to understanding climatic processes and as input to hydrologic models. Until now only crude estimates of the spatial and temporal variations of the principal storage reservoirs of fresh water on the Earth's surface have been possible.

Only about 3 percent of the water on the Earth's surface is fresh water. Approximately 77 percent of this is frozen in the polar ice caps and glaciers, 22 percent is in the form of groundwater, and the remaining 1 percent is partitioned among snow, soil moisture, lakes and rivers, and water vapor. The most variable of these water elements are precipitation, snow, soil moisture, and water vapor. Precipitation is measured routinely, but only at widely scattered points on the Earth's surface and not at all over oceans or other vast areas. Even precipitation gauge networks, supplemented by radar and meteorological satellite estimates, enable only crude monthly or annual estimates of global precipitation. Evaporation and evapotranspiration generally are calculated from routine measurements of other more directly measured variables. Satellite data have enabled routine weekly charting of surface water temperature and ice cover. Environmental satellite data have enabled a 15-year record of continental and hemispheric snow and pack ice cover (but not depth or water content) to be developed on a coarse spatial scale. Satellite techniques exist for obtaining relatively good estimates of the total column water vapor, although layer estimates are not yet satisfactory. The potential for measuring the amount of soil moisture from space has been demonstrated, but only over large, homogeneous, lightly vegetated areas and not to great depths. There has been limited success in estimating runoff amounts from satellites, and this has been done chiefly with unregulated watersheds. Monitoring water level in lakes and rivers, except for perhaps the intermittent type, is best done in situ with data relay through satellite data collection and location systems.

Some of the key questions in hydrology are as follows:

- What factors control the global hydrologic cycle?
- What are the distributions of precipitation, evaporation, and runoff over the globe?
- How do sea and land ice influence the global hydrologic cycle?
- Exactly how do vegetation, soil, and topography interact with the components of the hydrologic cycle?
- What are the distributions, capacities, and properties of major freshwater reservoirs, and what are the transfer mechanisms between them?

Measurement objectives for hydrological cycles include the following:

#### *Fresh Water*

- Observe runoff, storage, precipitation, and evaporation;
- Determine land characteristics that control response; and
- Determine past states of hydroclimate, surface water areal extent, floods, floodplains, groundwater drainage, basin area, channels, cover, slope evapotranspiration, soil moisture, precipitation.

#### *Snow Cover*

- Determine extent, depth, density, water equivalent, grain size, albedo.

#### *Sea Ice*

- Determine extent and properties; and
- Resolve and observe boundaries, concentration, type, motion, thickness, leads, roughness, surface temperature, wind velocity, ice islands, icebergs.

#### *Glacial Ice*

- Determine topography, thickness, temperature, albedo, internal structure; and
- Observe surface velocities, strain rates, iceberg discharge surface elevation, elevation change, boundaries, thickness, accumulation rate, surface temperature, surface velocity, internal properties, conditions at rock interfaces, iceberg discharge.

## **B. Supporting Research Plan**

### **General Principles**

The objective of the emerging national plan is both to improve understanding of the Earth as a system and to upgrade existing operational remote-sensing development. Deployment of satellites and associated instrumentation will consume most of the capital investment. However, a substantial fraction of the total resources must be devoted to supporting research.

A long-term research effort is needed to derive, study, and understand the time series of Earth observations required by the proposed national plan. This effort requires the following:

- Sufficient personnel must be available to derive, assimilate, and understand these data sets. This includes both use of established Earth scientists familiar with remote sensing and training programs for graduate students and others unfamiliar with remote sensing. New intellectual talent must be attracted to this activity.



- Sufficient continual funding must be maintained for long-term research programs and data sets.
- Individual Earth sciences disciplines should be kept strong for effective collaboration.
- Researchers should have easy, timely, and inexpensive access to the data sets.

The major components of the required research effort are the following:

- Remote-sensing research and development;
- Validation of satellite observations;
- Analysis and interpretation;
- Calibration; and
- Numerical simulation and modeling.

### Remote-Sensing Research and Development

Current remote-sensing capabilities, including existing and future data collection systems and current data handling, data processing, and data analysis and interpretation capabilities, can accomplish some of the defined measurement objectives and answer certain questions. However, these capabilities fall short of accomplishing all the measurement objectives or answering all of the questions. Extensive and varied remote-sensing research and development are required to realize such capabilities and the potential of space remote sensing for advancing current knowledge.

Remote-sensing research and development encompasses a broad spectrum of relevant and related, but varied, topics. Remote-sensing research and development can be divided into four areas: fundamental, sensor, data systems, and applications. Capabilities in all of these areas must advance if the potential benefits offered by satellite remote sensing are to be realized.

**Fundamental Research and Development.** The basis for the science of remote sensing lies in the relationships among land, ocean, and atmospheric conditions, in their materials and processes, and in the factors controlling the ability to remotely sense these variables. Much remains to be learned about the physical bases of observation. Research and development on topics such as spectral theory, surface and particulate reflectance phenomena, atmospheric interactions, penetrations phenomena, spectral mixing, and many others are required to fully interpret remotely sensed data.

Remote sensing requires satellite instruments that can measure Earth system variables indirectly by their effect on electromagnetic radiation. The conversion of a satellite observation of radiation into a geophysical variable re-

quires a mathematical model commonly called an algorithm. In general, such algorithms are complex, because a satellite radiation observation is usually not uniquely related to a single geophysical variable. Algorithms are constantly being refined as satellite determinations are compared with conventional observations and other forms of ground truth.

In the past, algorithms have been applied to single instruments, generally designed to measure only one, perhaps two, geophysical parameters. The multispectral sensor systems that would be available under the emerging national plan offer the opportunity to develop unified algorithms in which many geophysical variables could be determined simultaneously. This approach requires that teams of algorithm scientists, each representing a particular area of expertise, cooperatively develop unified processing algorithms.

**Sensor Research and Development.** Major advances in sensor and detector technology have been made in recent years. These advances must now meet more stringent requirements pertaining to spatial resolution and the radiometric, geometric, and accuracy characteristics of satellite remotely sensed data. Additional advances in sensor and detector systems must produce more effective sensor packages for future space remote-sensing systems. Such advances will be needed for visible and near infrared sensors, thermal infrared sensors, microwave systems, laser systems, submillimeter instruments, advanced radars, and perhaps even spaceborne gravimeters and magnetometers. The servicing concept being endorsed for long-term observations also offers the opportunity to introduce new technology to the payload through instrument charge out and upgrade.

**Data Systems Research and Development.** Future satellite systems will collect twice as much data as existing remote-sensing systems. Capabilities must be developed to efficiently and effectively transmit, record, and process these large data volumes. Research and development is also required to advance capabilities for processing and enhancing remotely sensed data and for producing products that allow the user to efficiently extract the maximum amount of data required for a specific application. For example, requirements exist for more accurate and reliable image classification capabilities, reliable data compression techniques, better radiometric correction methodologies, automated geometric rectification capabilities, and for many other improvements in current data processing and enhancement capabilities.

**Applications Research and Development.** The value of remotely sensed data lies in their ability to solve real operational and research problems, whether these be calculating the surface area of lakes in Minnesota or mapping

faults to characterize the tectonic framework of earthquake-prone areas. The goal of applications research and development is to establish new operational uses for the data and to improve existing uses. Efforts may include fundamental research, data processing and enhancement research, and development of data analysis and interpretation methodologies. This typically requires extensive field checking and cross-correlation with other data to test and establish validity of results. The scope of applications research and development embraces all Earth science disciplines. Consequently, such research offers great potential for improving the quality of human life through the development of many new scientific, social, and economic uses for satellite remotely sensed data.

### Validation of Satellite Observations

To evaluate the accuracy of remote observations requires some form of surface-truth program. For meteorological observations this has been relatively simple, because conventional weather observations have been available. For example, satellite determinations of atmospheric temperature profiles could be compared with simultaneous, colocated conventional radiosonde observations. For variables for which there are no conventional observing networks, the problem is more complex. For such variables, special surface-truth, field-observing programs are required to validate the satellite determinations. In such programs, in situ measurements are obtained with surface and airborne instruments over the area matching the "footprint" of the satellite.

### Analysis and Interpretation

An enhanced effort in data analysis will be required to analyze and interpret the myriad Earth system observations that will result from the emerging national plan. Special efforts will be required for analysis of data related to multidisciplinary areas, such as biogeochemical cycles, and for high bit-rate image data. For the former, new modes of scientific research, involving intensive cooperative projects among varied discipline scientists, must be established. For the latter, scientists must have the necessary computer and image-processing equipment to manipulate vast quantities of data. Satellite observations offer one source of information for a problem. Other sources of information, such as other observations, laboratory experiments, and theoretical work, must be integrated with these satellite observations. Researchers unfamiliar with remote-sensing methods must be trained so that such data can be fully exploited in Earth science problems.

### Calibration

Space technology can provide unprecedented global synoptic coverage with a uniform instrument system. But special steps must be taken to ensure that the instruments' responses or calibrations are known at all times. Once in space, satellite instruments tend to drift from their pre-launch calibrations. Proper calibration has not been essential for many of the instruments that have been flown thus far. Even in research measurements where quantitative information was required, small changes or drifts in sensor response did not affect the analyses, because the objective was to detect the large-amplitude diurnal, interdiurnal, seasonal, or geographical variations of a geophysical variable. Such information will also be required in the future; a major goal of the Earth observations system, however, will be the detection of subtle, long-term trends in geophysical variables. This requires maintenance of calibration information for the duration of the mission. Pre-launch calibration is relatively simple. Postlaunch calibration requires either inflight calibration or vicarious calibration in which high-flying aircraft (or the Space Shuttle), with instruments identical to those on the satellite, view the same scenes at the same times and viewing angles as the satellite sensors. It is also important to ensure that there are no artificial discontinuities when replacement instruments or improved instruments are flown. Some overlap of flight time for the old and new versions would be sufficient to correct for such artificial discontinuities and maintain the integrity of the time series.

### Numerical Simulation and Modeling

The physical, chemical, and biological processes at work in the Earth system interact and function in complex ways. The quantitative understanding of this system is only expressed in large numerical models that combine the remote-sensing data with the fundamental laws governing the behavior of the system. This synthesis allows predictions of future behavior and additional system observations. These in turn provide the theses and predictions that determine the validity of the models.

## C. Integration of Research and Operations

This discussion shows how remote-sensing research and operational observations are closely integrated in Earth science and applications.

Although a distinction is usually made between operational satellites and research satellites, categorizing Earth remote-sensing satellites has always been somewhat artificial. Research often paves the way for new operational

sensors, and operational data reveal new pathways for research. Future platforms will be able simultaneously to carry instruments serving both communities, and the economics of large platforms will mandate such a combination. Thus, the distinction between operational and research missions, difficult to make in the past, will be even more obscured in the future.

The laboratory of the Earth scientist is the Earth. The global observations gathered and used for a particular day's weather forecast represent part of a continuous series of instrumental observations measuring the state of the Earth and its changes. These measurements are the counterpart of the physicist's or chemist's laboratory measurements. However, they serve two broad user communities—the operational community, which in the specific case quoted above is interested in making weather forecasts, and the scientific community, which in this case is interested in improving the understanding of atmospheric behavior. Thus, as far as the “operational” satellite data are concerned, it is quite clear that they also constitute research data.

In addition to their contributions to myriad individual Earth science research projects, operational satellite observations make vital contributions to many specific large-scale scientific research programs. Some of these programs are summarized below.

***Eastern Pacific Ocean Climate Study (EPOCS).*** This is an ongoing NOAA program to investigate the circulation, currents, and air-sea interaction in the midlatitude Pacific Ocean. Satellite sea surface temperature measurements, at frequent intervals (24-48 hours), are critical for this program.

***Seasonal Equatorial Atlantic (SEQUAL) Experiment.*** SEQUAL was an ongoing NSF study of the response of the equatorial Atlantic Ocean temperature and current fields to the seasonally varying surface winds. The operational satellites provided the sea surface temperature fields for this program carried out in late 1984.

***Marginal Ice Zone Experiment (MIZEX).*** MIZEX, an international study, focuses on meteorological forcing caused by air flow off ice shelves over water. Data from NOAA's polar-orbiting satellites are crucial for large-scale mapping of the sea ice.

***Genesis of Atlantic Lows Experiment (GALE).*** The objective of GALE, a joint venture of NASA, NOAA, the National Center for Atmospheric Research (NCAR), and four universities, was to study the genesis of cyclones in the coastal and offshore East Coast region to better forecast these dangerous storms. NOAA's geostationary and polar-orbiting satellites provided cloud imagery, atmospheric temperature and moisture profiles, cloud vector winds, sea

surface temperatures, and ozone maps for this field program during 1985-86.

***Satellite Precipitation and Cloud Experiment (SPACE) and Microbursts in Severe Thunderstorms (MIST).*** SPACE is a NASA study of the techniques for estimating precipitation by using satellite data to infer cloud dynamics. MIST is a NASA program to investigate thunderstorm “downbursts” in a wet environment. Both programs took place in 1986 in the southeastern United States and will utilize GOES sounding and rapid scan imaging data, and Advanced TIROS-N (ATN) AVHRR and TIROS Operational Vertical Sounder (TOVS) data in the ongoing analysis phase.

***Storm Scale Operational and Research Meteorology (STORM) Program.*** Currently under consideration, STORM is a 10-15 year multiagency U.S. program to seek further insight into severe storms with the ultimate objective of developing advanced techniques for improved forecasts/warnings. Of major importance to STORM will be the ready availability of rapid interval, high-resolution, and concurrent visible and infrared imagery and soundings from NOAA's GOES, the AVHRR, and, possibly, microwave imagery from NOAA's polar-orbiting satellite systems.

The past mode of research satellite operation has been to propose a new instrument for a particular Earth observation and then one or more principal investigators would carry the program through to publication of results. This mode also covered the flying of a highly exploratory new instrument, when neither its capabilities nor likely results were well understood. The scientific requirements needed to observe, understand, and improve capability for predicting the Earth system's land, oceans, ice, and atmosphere mandate a research satellite system with continuing, long-term, stable, global capabilities. Such a system would have characteristics—if not instrumentation—indistinguishable from those of an operational satellite. It might be argued that “operational” systems must have performance reliabilities approaching 100 percent. However, it could also be argued that research satellites should have high reliabilities to prevent gaps in the data record, which represent irretrievable losses. There will still be a need to test new instruments in orbit and for single short-term observations, but such measurements will be complementary to the main research objective of keeping the Earth under constant surveillance.

Research and operations are intertwined in yet another way. In administering their responsibilities, the Departments of the Interior, Agriculture, Defense, and Commerce have many operational requirements for satellite observations. Near-term and long-term space programs of the United States must meet the key operational data needs of the departments and, if possible, avoid forcing

them to rely on foreign satellite systems to meet these principal operational requirements.

The Department of the Interior has geological and land use mapping requirements; the Department of Agriculture has crop inventory and production forecast requirements; and the Departments of Defense and Commerce have weather and ocean prediction requirements. Although the requirements are operational, the remote-sensing methods and analysis techniques are constantly changing. Each new technology is applied in a continual learning process. The extraction of meaningful information from remote sensing is not as simple as reading a thermometer. Research and development are constantly being performed to improve methods for converting remotely sensed observations of radiant energy into geophysical parameters of operational interest. Thus, even the so-called operational applications of remote sensing have a large component of research associated with them. The departments involved with these operational applications, therefore, must assume major responsibility for research and development programs aimed at expanding existing applications and developing new operational and research applications of remotely sensed satellite data.

## D. International Cooperation

### Examples of International Cooperation in Earth Science

Some of the most magnificent examples of international cooperation in science come from the Earth sciences. As long ago as the first and second Polar Years, 1882-83 and 1932-33, respectively, scientists from many countries participated in special observations of the Earth's polar regions. This was followed by the International Geophysical Year (IGY) of 1957-58, which consisted of an intensive, coordinated, observational program covering a broad spectrum of the Earth science disciplines, and led to the launching of the first artificial Earth-orbiting satellite.

The tradition of free exchange of weather data among the countries of the world is another outstanding example of international cooperation. In return for taking and transmitting weather observations from its own territory, each country receives timely weather observations from its region, hemisphere, and, in some cases, the entire globe. It has long been realized that the value of weather information is not diminished by being shared; in fact, it is greatly enhanced. A somewhat similar system for distributing the oceanic observations of the commercial shipping fleet is also in operation. Data from U.S. remote-sensing satellites and instruments are available on a nondiscriminatory basis to users worldwide. U.S. agencies are actively encouraging the development of similar policies of open data

dissemination by many foreign agencies planning to develop and operate remote-sensing satellites.

In the decade of the 1970s, the world meteorological community organized and conducted a Global Weather Experiment (also known as the First GARP Global Experiment, or FGGE) in which intensive, global atmospheric observations were made for an entire year. The observing system consisted of satellites, surface weather stations, radiosonde stations, aircraft, ships, constant level balloons, dropsondes, and ocean buoys; this system provided a complete data set for studying the predictability of weather phenomena. This same community, joined by scientists of other disciplines, is currently embarking upon another major program of international scientific cooperation: the World Climate Research Programme (WCRP). The major objectives of the multiyear WCRP are to determine

- The extent to which climate can be predicted; and
- The extent of man's influence on climate.

In the area of observations, the WCRP's highest priority is for consistent, relatively long time series of global data describing the variability of the components—atmosphere, oceans, land surface, and cryosphere—of the climate system and their interaction. For this reason, the WCRP will rely heavily on operational observing systems but will also require new observing systems, such as experimental oceanographic satellites, for its implementation.

The WCRP has identified several elements for research on climate. Each of these requires satellite observations; these elements are described in the following paragraphs.

**Cloud-Radiation Interaction.** The feedback effects between clouds and radiation represent a major stumbling block in climate prediction and understanding. Recognizing this and the inadequacy of available cloud climatologies, the WCRP initiated the International Satellite Cloud Climatology Project (ISCCP). The objective of the ISCCP is to gather a 5-year global data set of satellite radiances (visible and infrared) from the five geostationary satellites (operated by the United States, Japan, India, and the European Space Agency [ESA]) and the polar-orbiting satellites (the NOAA ATNs). The satellite radiances will be averaged and sampled into reduced global data sets every 3 hours and then transformed to cloud climatological statistics. The observing program began in July 1983. As part of the ISCCP, there are planned national programs to gather detailed observations on radiation and clouds for specific cloud types. In the United States, the First ISCCP Regional Experiment (FIRE) will concentrate on cirriform clouds and marine stratus, both of which have significant effects on the Earth's radiation budget and are poorly simulated in climate models.

**Ocean Atmosphere Coupling.** The controlling effect of the oceans on the climate system has been identified as another critical element of climate research.

The Tropical Ocean Global Atmosphere (TOGA) research project is an international program consisting of observations and modeling research to advance our understanding of the atmospheric and oceanic variations occurring over months to years. The motivation stems from the growing evidence that global atmospheric circulation and sea surface temperatures in the tropics are correlated on interannual time scales. A 10-year program began on January 1, 1985.

The proposed World Ocean Circulation Experiment (WOCE) has as its objectives:

- Collection of the data to develop and test ocean models that can predict climate changes; and
- Determination of how representative the specific WOCE data sets are for predicting the long-term behavior of the ocean, as well as development of methods for determining long-term changes in the ocean circulation.

A major element of WOCE would be an oceanographic satellite observation system, including (1) at least one altimetric satellite mission for measuring the ocean surface topography with appropriate accuracy for a minimum of 3 years, and (2) one satellite for measuring surface wind or wind stress for a minimum of 1 year during the same period. WOCE is proposed to begin in the 1990s.

**Land Surface Processes.** The hydrological cycle and the interaction between the land surface and the atmosphere at their common interface are the subjects of this program. In particular, there is a need to develop mathematical parameters of the exchange processes at this interface to be incorporated into climate models. The International Satellite Land Surface Climatology Project (ISLSCP), initiated by the United Nations Environmental Program (UNEP) to develop methods for detecting land surface changes due to climatic fluctuations, will play a major role in providing the required satellite observations.

Summaries of the satellite data requirements for these World Climate Research Programme elements may be found in NOAA's *Envirosat-2000* technical reports.

The Global Change Program (GCP), an international endeavor currently proposed under the aegis of the International Council of Scientific Unions (ICSU), would have profound implications for global satellite observations. The GCP would be a multiyear, cross-disciplinary effort to obtain a comprehensive, quantitative understanding of the complicated terrestrial "machine," the functions and interactions of its various parts, and the major geophysical and biochemical cycles by which it is driven. An important aim of the program would be the development of a knowledge base through a sharply focused aggregate of

research programs sharing a global view of the interconnected Earth system. Such a program should help assess trends and anticipate natural and manmade change over a 50- to 100-year period. Two concurrent modes of experimental research would be required: the reconstruction of major natural changes that took place in the past; and the measurement of current change on a global scale. One of the main purposes of the GCP would be to develop further the use of space techniques for observation of the Earth and the changes that occur on a global scale in the processes coupling the geophysical and biological systems.

### Mechanisms for International Cooperation

The mechanisms for international cooperation are varied. Exchange of observational data is a necessary first step. NASA's policy on space observations has always been directed toward the widest possible data dissemination and international science participation in payload investigations. NOAA's meteorological satellites have continuous direct transmission capabilities, so that anyone with ground-receiving systems can tune in on the transmissions while the satellite is overhead. The weather satellites of the ESA, Japan, and the U.S.S.R. have similar direct broadcast systems, although India's INSAT currently beams its data only to an Indian receiving station. (Negotiations are taking place to explore various possibilities for the real-time distribution of INSAT observations to the global community.) Landsat data (current and retrospective) are being marketed by the Earth Observation Satellite Co. (EOSAT).

The Agency for International Development (AID) also has several programs to further international cooperation in understanding land processes through remote sensing. Most land remote-sensing activities are carried out in the tropics where the U.S. knowledge base regarding landforms and vegetation is minimal. For example, AID and host country projects dealing with rainforests in Thailand, Bangladesh, and Peru entail research in physical processes, such as stratification of the spectral properties of rainforest species (mangrove, teak, aguaje palm), as well as sociological research into man's interaction with the rainforest (market road penetration into tropical forests). Many of these activities in highland jungle, arid, and semiarid savannah are contributing to the knowledge pool of how land processes affect human development.

Another mode of international cooperation is one in which countries or groups of countries make special observations, provide instrumentation for special observing systems, or provide other types of observing support. This mode is exemplified by the NOAA ATN system for which (1) France provides "blind orbit" telemetry and tracking support to NOAA, (2) France also supplies the ARGOS data collection and platform location system, (3) France

and Canada provide the hardware for the satellite-aided search and rescue system, and (4) the United Kingdom currently provides the Stratospheric Sounding Unit and will supply for the NOAA-K to -M series an Advanced Microwave Sounding Unit (AMSU) for water vapor determinations. Scientists from other countries also provide ground-truth knowledge and expertise for interpreting satellite observations.

Several international coordination groups for environmental satellite programs are currently in existence. They are as follows.

*The International Polar-Orbiting Meteorological Satellite (IPOMS) Group.* This group was formed under the auspices of the Economic Summit of Industrialized Nations. It was founded to discuss technical, financial, administrative, and legal issues regarding international contributions to the U.S. polar-orbiting environmental satellite system or an internationally developed system. Membership is limited to those countries that participate in the Economic Summit and countries that are current, or potential, contributors to the future U.S. polar-orbiting meteorological system.

*Coordination of Geostationary Meteorological Satellites (CGMS).* Participation in this group is limited to those countries that have initiated development of, or are presently operating, geostationary meteorological satellites. This currently includes the United States, ESA, India, and Japan as operators, and the U.S.S.R. as having initiated development. The function of the group is to serve as a forum through which individual plans for geostationary meteorological satellites can be informally nationalized and harmonized so that participating agencies can develop complementary and compatible space segments.

*Committee on Earth Observations Satellites (CEOS).* The objective of this multilateral committee is to enhance the benefits of spaceborne observations of the oceans and the land for members and the international user community. CEOS serves as a forum for the exchange of technical information to encourage complementarity and compatibility among spaceborne Earth observations systems that are currently in service or development. Improved complementarity and compatibility is obtained through cooperation in mission planning and the development of compatible data products, services, and applications. Membership is open to international, national, or regional organizations responsible for a spaceborne Earth observations program that is currently operating, or at least in Phase B or an equivalent stage of development.

*International Forum on Earth Observations Using Space Station Elements (IFEOS).* This multilateral

group provides a forum for discussing planned use of the polar platform as well as other elements of the Space Station for Earth observations, both operational and research. It also offers an opportunity for international dialogue between representatives of Earth observation agencies and the Space Station developers; such dialogue aims to examine what characteristics will be required for the polar platform to accommodate planned Earth observations use. Membership is open to countries planning to use the Space Station polar platform for Earth observations.

*Coordination Group of Space Station Partners on the Use of Polar Platforms for Earth Observations.* This informal group brings together representatives of the Earth observation divisions of agencies in the Space Station partner countries and organizations, namely Canada, ESA, Japan, and the United States (NASA and NOAA). Discussions focus on payload development and selection processes for the polar platform and on planning for platform operation.

*International and Regional Organizations.* Coordination of satellite activities also occurs within the framework of existing international organizations such as the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC), and the International Council of Scientific Unions (ICSU), and through such groups as the Committee for Space Research (COSPAR).

By the post-1990 era, Brazil, Canada, ESA, the Federal Republic of Germany, France, India, Japan, and others will have demonstrated varying degrees of skill in Earth observation systems. All of these countries and many more will have a requirement for continued Earth observations data. The combination of capability and need is an ideal beginning for international cooperation. When this combination is integrated with the concept of cost effectiveness for a global observation system, the argument for international cooperation is indeed compelling.

Several regional organizations of developing countries have evolved in the past 8 years to share in land remote-sensing activities and data interchange. The African Remote Sensing Council has 23 country signatories to its constitution, and oversees the activities of two regional remote-sensing user assistance and training centers supported by U.S. donors and African states. The Society of Latin American Specialists in Remote Sensing (SELPAR) meets biannually to share experiences in remote-sensing research and applications and to formulate plans for data reception stations. The Asian Society for Remote Sensing is active and works well with both the Asian Regional Remote Sensing Center and the UNESCAP Regional Remote Sensing Program to further project activities in southeast Asia. All of these activities involve AID as a

participant and/or sponsor. U.S. participation in remote sensing in developing countries has reached high levels and was reported on at three economic summits held at the following locations:

- London, United Kingdom, 1984;
- Bonn, West Germany, 1985; and
- Kyoto, Japan, 1986.

Several meetings to discuss the topic have been convened and a large meeting was held in Berlin in 1986. At a recent meeting in Rome, Italy, a working group on remote sensing for development was tentatively planned. If ap-

proved, AID would represent the United States as a member.

There is good reason to be optimistic in seeking international cooperation in Earth observations. Precedents have been established by several foreign countries for the contribution of hardware to operational weather satellites. International coordinating bodies are in place to serve as forums to advance these ideas. By the 1990s, many countries will have demonstrated their ability to place Earth observing instruments into space. International specialists in remote sensing and their parent agencies are prepared to discuss these issues in depth.

## V. OPERATIONAL AND RESEARCH MISSION PLANNING FOR THE FUTURE

### A. Introduction

This chapter delineates the development and planning activities ongoing within NASA and NOAA for advances in Earth remote sensing. These activities are treated in three components: flight systems planning; data systems planning; and the Space Station Polar Platform opportunities. Although some of the issues identified in the previous chapter may be answered through current applications of satellite remote sensing, most solutions must be based on comprehensive research programs that integrate satellite remote sensing with in situ studies of the land, ocean, ice, and atmosphere; theoretical and modeling studies; and laboratory-based analytical programs.

Both the flight and the data systems planning sections primarily focus on endeavors scheduled to occur between now and the mid 1990s. Because they offer an additional source of research and operational data, DOD and foreign satellite mission plans for this period are also discussed. These two sections also address questions of data continuity, access, acquisition, and information systems. Because of the long lead-time needed for developing satellite instruments and for procuring and launching the satellites, many of the missions described have already begun.

The major new thrust in flight systems will be in oceanic observations. Already in orbit is the Navy's Geosat altimeter, and in 1987 a four-channel microwave imager (SSM/I) will be launched by the Defense Meteorological Satellite Program (DMSP). NASA plans to fly a scatterometer (NSCAT) for measuring sea surface winds and is proceeding to implement the Ocean Topography Experiment (TOPEX/Poseidon) for launch in 1991. Also, preliminary definition of a Geopotential Research Mission (GRM) is currently under study. EOSAT, the private sector operator of Landsat, is considering various designs and the marketability of an ocean color instrument. Japan has recently launched its Marine Observation Satellite (MOS-1) with a scanning visible and infrared radiometer and plans to launch its Earth Resources Satellite (ERS-1) in 1991 carrying a Synthetic Aperture Radar (SAR) instrument. The European Space Agency (ESA) is planning an ocean satellite, Earth Remote Sensing Satellite (ERS-1), in 1990 which will carry an altimeter, scatterometer, and a SAR.

The operational atmospheric and land-observing satellites will be improved during the next 5 years and are

being joined by land-observing satellites from France, Japan, and India.

Both NASA and NOAA are upgrading their data systems to meet the needs of the research and operational communities. Concerned mainly with research data, which are usually used in a retrospective or non-real-time mode, NASA will (1) continue its development of the climate, oceans, and land pilot data systems; (2) integrate these systems into a multidisciplinary information system, the proposed Earth Observing System Data and Information System (EOSDIS), which would facilitate access to environmental data sets held by NASA and other agencies and institutions; and (3) jointly, with the United Nations Environmental Program (UNEP), develop a Global Resources Information Database (GRID) that combines remote-sensing and conventional data to improve the study of global resource and environmental issues.

NOAA's data systems should accommodate the requirements of operational users for real-time data as well as those of the research community for retrospective studies. NOAA also makes data available to the private sector for further enhancement. NOAA's planned upgrade of its real-time data processing system will (1) integrate satellite observations and conventional meteorological data in weather office workstations; (2) integrate data from the ATN, GOES, and DMSP satellites on a rotating 240-hour, 40-million byte disk storage system with direct user access via remote terminals; and (3) permit governmental and private users to receive satellite images via a new, inexpensive Direct Broadcast System (DBS) that uses a commercial communications satellite rather than dedicated telephone lines. NOAA is also improving its satellite data archive service, the Data Management and User Services (DAMUS) Satellite Archive System (DSAS). These improvements will permit more efficient and economical data storage by recording GOES digital data on videocassettes, storing ATN data on IBM cassettes, and, over the next 4-6 years, introducing an optical archive system. Improvements will also allow users to access a complete satellite data catalog, browse reduced resolution/precision data, and place orders for data. Planned upgrades will increase the speed of filling user requests for data.

The discussion in the final section focuses on the exciting possibilities offered for Earth observations by the proposed Polar Platform concept of the manned Space



Station. Such a concept would dramatically increase spacecraft capability and serviceability and could provide the simultaneous, synergistic operation and research observations necessary to achieve objectives of the Earth observing program. Included in this section are current NASA plans for using the Polar Platform for research through the proposed Earth Observing System of the 1990s, NOAA's proposals for using the Polar Platform for operational observations, and NASA and NOAA proposals for data management.

## B. Flight Systems Planning

This section will describe by agency the state-of-the-art systems that have been successfully flown and those activities showing promise for improvement or breakthroughs in the near future. Satellite missions supporting atmospheric, oceanic, and land operations and research are incorporated into systems discussions as appropriate. Tables 1-23 (see Appendix A) provide comprehensive candidate payload and orbit characteristics of the various missions.

### NOAA's Operational Satellite Systems

These two systems are NOAA's Advanced TIROS-N (ATN) and Geostationary Operational Environmental Satellite (GOES) series. NOAA's operational progress with these two series has evolved—and will continue to evolve—from NASA's remote sensing research. Both the ATN and GOES systems provide high-quality information. Their capabilities are now briefly discussed.

*Advanced TIROS-N (ATN) Polar-Orbiting Spacecraft.* The ATN satellites have meteorological observations as their objective, but only as the first rather than the exclusive objective. The instruments that provide meteorological observations also provide measurements of sea surface temperature, sea ice, snow cover, and an assessment of the condition of the Earth's vegetation. The satellites also serve as the home for the search and rescue system that directs aid to crashed aircraft and ships in distress.

The environmental systems can be categorized conveniently into four functional areas:

- Sounding (profiles of atmospheric temperature and water vapor as a function of altitude) accomplished by the TIROS Operational Vertical Sounder (TOVS);
- Imaging (multispectral measurements of upwelling radiation in image format—whether recorded as an image or in digital form) with the Advanced Very High Resolution Radiometer (AVHRR);

- Data collection (capture of environmental data from in situ sensor systems that transmit to the over-flying spacecraft); and
- Measuring the Earth's near-space radiation environment using the Space Environment Monitor (SEM).

Because of their importance in preparing daily weather forecasts and warnings as well as their other purposes, these instruments must be maintained as permanent Earth-observing systems in orbit for the foreseeable future.

The AVHRR is a five-channel scanning radiometer carried aboard the polar-orbiting operational meteorological satellites (e.g., NOAA's ATN). This instrument continues the heritage of scanning radiometers started with the first meteorological satellites; progressively more advanced models have appeared on all of the subsequent polar-orbiting meteorological satellites. The five channels of the AVHRR detect radiation in the visible, near-infrared, and thermal infrared portions of the spectrum at optical ground resolutions of 4 kilometers and 1 kilometer. Measuring the radiation in the same view, this array of diverse wavelengths, after processing, permits multispectral image analyses to be performed that more precisely define cloud and other meteorologic parameters, as well as hydrologic and oceanographic parameters. The AVHRR is more advanced than previous operational imagers flown on the polar-orbiting series, because it has superior radiometric calibration, greater calibration stability, and higher spatial resolution.

Beginning with NOAA-K, the AVHRR will have changes made in several of its channels. Channels 1 and 2 will be modified to make the visible and near-infrared data more useful for the calculation of a "vegetation index," a data product indicating the "greenness" of the region imaged. Channel 3 will be replaced by a switched channel for sunlight and dark scenes. Channel 3A remains unchanged in spectral content. Channel 3B will enhance the determination of cloud cover versus surface snow and ice cover. For Channels 1 and 2, slight changes are proposed in the onboard processing algorithm to enhance the resolution of brightness in the low-albedo region of the instrument's brightness curve. The change is not expected to be detectable by direct data readout users but it would improve sea surface temperature measurements by making better corrections for aerosols.

NOAA presently relies on a three-instrument complement of sounding sensors to provide operational data from the polar-orbiting satellites to the fine-mesh models for predicting the weather. These instruments are

- The High Resolution Infrared Radiation Sounder (HIRS) to measure scene radiance in 20 spectral bands, permitting the calculation of the vertical temperature profile from the Earth's surface to about 40 kilometers altitude (the HIRS Channel 20 is to be

broadened to enhance its value as a data source for studies of the Earth radiation budget, a change that seeks to compensate researchers for the loss of the experimental Earth Radiation Budget Experiment [ERBE] instrument);

- A four-channel Microwave Sounding Unit (MSU) for all-weather measurement of the temperature profile from 0 to 20 kilometers; and
- A three-channel Stratospheric Sounding Unit (SSU) based on gas-filter techniques for measuring temperature distribution in the upper stratosphere between 25 and 50 kilometers.

With the use of this data, NOAA is able to derive the temperature profile of the atmosphere to approximately 2°C.

Improvements to the microwave sensor are planned for the NOAA-K and subsequent series of polar-orbiting spacecraft through the development of the Advanced Microwave Sounding Unit (AMSU). With the installation of AMSU, HIRS will be retained, but MSU and SSU will be dropped. The AMSU is a 15-channel microwave radiometer system for measuring temperature from the ground to an altitude of approximately 40 kilometers. A complementary instrument consisting of five microwave channels for sounding tropospheric water vapor will be provided by the British Meteorological office. In addition, NASA is supporting AMSU activities through the development of geophysical algorithms to interpret AMSU measurements and through aircraft-based measurements using passive microwave instruments similar to the proposed AMSU system.

Improvements in the infrared sounding capabilities are being studied by two different approaches. The concept behind the proposed Advanced Moisture Temperature Sounder is that an instrument with very high spectral resolution, while maintaining radiometric sensitivity, could provide data from which more accurate soundings of atmospheric temperature and moisture could be made at higher vertical resolutions than by existing instruments. Simulation studies using the projected instrument parameters indicate that this technology will provide the ultimate vertical resolution and accuracy available from a passive infrared satellite sounder. Another concept is to increase spectral resolution through the utilization of high resolution interferometry. A joint NASA/NOAA program has produced an aircraft instrument known as the High Resolution Interferometer Spectrometer (HIS) to provide data that test the accuracy and resolution of this technique. Decisions on future implementation will depend on improvements to the present forecasting capability and availability of resources.

As described later in this chapter, NOAA-9 and NOAA-10 carry two experimental sensors developed by NASA in support of the climate and upper atmospheric

research programs. These two sensors are the Solar Backscatter Ultraviolet Radiometer (SBUV), for ozone measurements, and the Earth Radiation Budget Experiment (ERBE), for studies of Earth's thermal balance process.

In addition, an orbital change is scheduled for NOAA-H and subsequent spacecraft. The time for equatorial crossings is to be advanced from 1430 to 1330 local times. A Sun-synchronous orbit is retained. The planned change requires a thorough redesign of the spacecraft's thermal controls and instrument shades, since the spacecraft will observe the Sun constantly at higher viewing angles during all sunlit flight times. The change is planned to coordinate Eastern Pacific data collection with a change scheduled by the U.S. National Weather Service, to move forward the start-up time of its numerical prediction runs.

A final element to be noted is that the ATN satellites carry subsystems supplied by foreign governments at no cost to the United States (see Chapter IVC).

***Geostationary Operational Environmental Satellite (GOES) Program.*** Geostationary satellites provide an apparently fixed viewpoint for weather observations and data relay to and from all points within the field of view of the spacecraft. A geostationary orbit high above the Earth's equator is also ideal for sensors measuring the energy of particles and high-energy radiation (ultraviolet, X-rays, and so forth) arriving in the vicinity of the planet Earth. Solar high-energy data are used in forecasts of conditions affecting radio communications, aviation, manned space flights, power lines, oil pipelines, and other very large installations.

A new era of meteorological observations began with the launch of the first geostationary spacecraft, Applications Technology Satellite-1 (ATS-1), by NASA in December 1966. ATS-1 allowed meteorologists to see at a glance weather patterns covering almost one-third of the Earth's surface. When later ATS satellites added infrared imaging sensors, weather pattern analysis could be continued into the nighttime hours. Infrared values also disclosed cloud heights. Given this information, sequential ATS images, when analyzed for cloud movement, disclosed wind speeds and directions at the cloud heights. After the flight of three ATS spacecraft (1966-74) and two SMS (Synchronous Meteorological Satellite) spacecraft (1974-75), NASA and NOAA in 1975 began the launch of the series of GOES that continues to the present.

The primary instrument for imaging on the initial GOES series was a two-channel scanning radiometer, known as the Visible and Infrared Spin Scan Radiometer (VISSR), capable of imaging the full Earth disk as an operational product every 30 minutes. The resolution of this radiometer is about 1 kilometer for the visible channel and about 7 kilometers for the infrared channel. The primary contribution made by the VISSR is its ability to track the hourly motion of typhoons, hurricanes, heavy

rain storms, snow, and blizzards. This information is used by the National Weather Service to provide the location of these severe meteorological features and to track their probable path.

With the launch of GOES-4, an additional 10 channels were incorporated into the VISSR, providing for atmospheric sounding. Its name became VISSR Atmospheric Sounder (VAS). This capability promises to be effective in identifying instabilities leading to severe storms, determining wind speed in clear areas by tracing the movement of high-humidity zones, and providing additional data to the short-term forecast models. With the VAS, visible imaging data are provided every 30 minutes by each spacecraft during daylight, and infrared (7-kilometer) imaging data are provided day and night on the same schedule. In the event of severe weather, the imaging schedule goes to every 15 minutes with reduced North-South coverage. Some imaging sequences at 3- to 5-minute intervals have been undertaken for special research projects.

In the GOES-NEXT (1989) specifications, the VAS instrument is to be replaced by separate modules for images and soundings, each with its own radiation-gathering telescopic mirror. Soundings can be scanned simultaneously with and independent of image scans. The stabilized (nonspinning) spacecraft will increase the available scanning time. Detector arrays for the sounder (rather than a single-point detector) could scan swaths of the Earth, and so reduce the time for complete area coverage (while retaining the same size field of view and multichannel spectral data input). The goals for navigation of the data are +1 kilometer for registration of successive images.

**Landsat.** The Landsat program has facilitated the evolution of high-spectral and spatial resolution imaging since its initial deployment in July 1972. The Landsat satellite that was launched on July 23, 1972 proved the viability of Earth resources surveys from space. After 6 months of operation, perceptions of Landsat-1, then known as the Earth Resource Technology Satellite (ERTS-1), were changing. Starting as an experimental system dealing with various parameters relating to Earth resources, ERTS-1 quickly became a system that was taken for granted in providing routine multispectral images over the United States and much of the Earth to domestic and foreign ground stations. Landsats-1, -2, and -3 carried the Multi-Spectral Scanner (MSS) and the Return Beam Vidicon (RBV) cameras as their Earth imaging systems. During their lifetimes, these three Landsat satellites acquired a total of 1,212,700 MSS frames of imagery and a total of 271,596 RBV frames of imagery. Landsat-3, the last of this early series, was deactivated on September 7, 1983.

The Landsat-4 satellite represented a significant step forward in the remote sensing of Earth resources from space. This satellite was launched on July 16, 1982 and carried a new sensor, the Thematic Mapper (TM), in addition to the standard MSS. The TM is significantly more complicated and sophisticated than the MSS. The TM possesses about twice the number of spectral bands and two-and-one-half times greater spatial resolution in the visible and reflective infrared bands. The output signal of the TM detectors is quantified to one of 256 different gray levels as compared to the 64-level gray scale used with the raw MSS data. The full impact of this improved data is still being assessed. NASA has recently embarked on an expanded TM research program to better understand surface conditions and processes on the Earth. This research will build on the results of earlier investigations but will deal with more topical problems that can be addressed in innovative ways through analyses of TM imagery.

Although the Landsat-4 satellite is still operating, it suffered several anomalies that so reduced its capability that the backup Landsat-5 satellite was launched. This was placed into orbit on March 1, 1984 and is identical to Landsat-4. Both satellites are operating and providing operational data under the management of NOAA. The transfer of the Landsat system to a private sector operator was implemented with the award of a contract to the EOSAT Company.

#### *Operational Remote-Sensing Improvements and Augmentations*

*Private Sector Ocean Color Instrument.* The Coastal Zone Color Scanner (CZCS), flown aboard Nimbus-7, has made a significant contribution to studies of ocean productivity and location of nutrients at the ocean surface. One key accomplishment of this instrument was to establish the feasibility of determining chlorophyll concentration from space. A science working group with membership from the academic oceanographic community, NASA, NOAA, and other agencies has recommended the flight of an advanced ocean color instrument to meet the scientific and operational requirements for chlorophyll data. The proposed instrument would be an improved CZCS. It would have eight to ten visible channels. The sensor digitizing would be increased to 10 bits, and a diffuser plate for in-flight instrument radiometer calibration would be provided. In addition, the instrument would provide both high-resolution data in coastal areas and low-resolution data in the open ocean. The ocean color instrument system would transmit ocean color data directly to local users and would dump recorded data to ground stations for processing and distribution to the scientific and operational communities.

The ocean color data would be used operationally to predict fishing locations; visualize the flow of ocean currents and eddies for drilling and mining operations; estimate optical properties and phytoplankton abundance for marine resource and habitat assessment; and provide observations of pollution and sediment inputs to the coastal zone and their effects on the marine food web. For research studies, the ocean color instrument would provide observations to determine ocean productivity estimates for use in understanding the global carbon cycle and the ocean's role in climate.

Because of its commercial applications, the ocean color instrument represents an opportunity for private sector participation. NOAA's policy on the instrument is to have private industry build it, while NOAA would help the builder find a suitable spacecraft.

*Solar Occultation Absorption Spectroscopy.* NOAA has been examining infrared solar occultation, a potential satellite monitoring technique. Solar occultation measurements use absorption spectroscopy of the constituents of the stratosphere. The source of radiation is the Sun. Twice in each orbit the radiation reaching the satellite will pass horizontally through the limb of the Earth's atmosphere. During these events, the Sun will either be rising or setting as seen from a satellite, and the intensity of the incoming radiation will be recorded as a function of altitude in the stratosphere. Ratios of the signals obtained through the atmosphere's limb to those obtained when the Sun is above the atmosphere yield profiles of transmittances versus altitude. The transmittance profiles are the basic data from which we derive profiles of gas concentrations and aerosol extinction versus altitude.

The sensor is a multichannel infrared grating spectrometer operating between 1 and 12 micrometers. Rather than scanning the infrared spectrum, it senses radiation continuously in several spectral intervals, which are located in absorption bands of species of interest. A prototype sensor has been built at the National Environmental Satellite, Data, and Information Service (NESDIS) for use on balloon experiments. It is a spectrometer with eight spectral intervals chosen for measuring concentrations of ozone, water vapor, nitric acid, and Freon-12. A future satellite version would use many more spectral intervals and would be capable of measuring concentrations of the following stratospheric species: ozone, chlorofluorocarbon-12, chlorofluorocarbon-11, nitrous oxide, nitrogen dioxide, carbon monoxide, water, nitric acid aerosols, and perhaps hydrochloric acid.

The solar occultation technique is well suited for long-term monitoring for the following reasons:

- Because of their extreme length, limb paths offer the sensitivity needed for the detection of extremely sparse stratospheric species.

- The sensor does not need extensive cooling, nor does it need sophisticated detector technology. Because the Sun is such an intense source, the signal/noise will be ample, and the spectrometer's optics can be uncooled. If the detectors need to be cooled at all, they can be cooled to liquid nitrogen, rather than liquid helium, temperature.
- The data system requires neither a large dynamic range nor a high data rate.
- Calibration is simple and stable. Because the basic measurements are relative, the instrument does not have to be absolutely calibrated.
- The data reduction is accurate and simple because it does not require radiative transfer calculations and the associated need for accurate prior knowledge of stratospheric temperatures.

The choice of a multichannel grating spectrometer in this application was made for reasons connected with its reliability, simplicity, long lifetime, and low cost, all of which are important in a monitoring program. Its only mechanical motions involve the Sun-tracking mirror and an occasional rotation of the grating. The technology for executing these motions in space is already proven, so they are unlikely to fail. The multichannel spectrometer was selected in preference to a filter radiometer mainly because of its superior spectral purity. It would be difficult, if not impossible, to build a filter instrument at a reasonable cost with the specific, narrow, and accurately known spectral intervals required in this application.

The prototype sensor, built at NESDIS, has been tested in two high-altitude balloon experiments conducted at Palestine, Texas. In both experiments, vertical profiles of ozone, water vapor, and nitric acid were determined in the stratosphere between 22 and 42 kilometers altitude. Those results demonstrated that the infrared occultation technique, as implemented with this type of sensor, does offer the potential for long-term monitoring of many stratospheric compounds. In a third flight, the NESDIS sensor will be accompanied by a high-resolution scanning spectrometer. The objectives are to extend the region of measurement to the lower stratosphere and to confirm the sensor's measurements with detailed atmospheric spectra.

*Light Detection and Ranging (LIDAR).* NOAA and the Institute for Physical Science and Technology (IPST) at the University of Maryland are developing a ground-based LIDAR system. The system is intended to demonstrate that LIDAR systems can be built that will obtain high-quality data on atmospheric variables, and that they can serve as prototypes for potential future space-based systems to make global measurements of these quantities.

A typical LIDAR system designed for studying the atmosphere consists of a laser, a collecting telescope, and a detector mounted together as a single unit. The laser

emits a short pulse of radiation of definite length and frequency. As the pulse travels out from the laser, some of its energy is scattered back toward it by aerosols and molecules in the atmosphere. The returning energy is collected by the telescope and its intensity as a function of time can be used to determine, as a function of distance, the properties of the atmosphere through which it is passing. Atmospheric properties can be measured with a spatial resolution limited only by the length of the laser pulse, which can be as short as a few meters.

*Long-Range Technology Potential.* Certain programs and activities currently initiated or developing that have a long lead-time may affect NOAA during the next 20 years. They include the Wind Satellite (Windsat), satellite-borne radars, the Lightning Mapper, and possibly a geostationary microwave sensor. These sensors offer the potential for improved observations or products.

- *Windsat.* The Windsat concept was developed in the mid-1970s. It proposes to measure global winds using an infrared Doppler LIDAR mounted on a polar-orbiting satellite to provide twice-daily input for global weather forecasts (and to obtain a truer measure of atmospheric dynamics). The Windsat concept uses aerosol backscatter from LIDAR to obtain profiles of wind speed, which are (theoretically) better indicators of atmospheric dynamic conditions than are temperature profiles. These wind profiles are also considered superior to present wind measurements derived from cloud motions (which are limited in height and geographic distribution) and to temperature soundings in the tropics. Data from ground-based and airborne LIDARs are being evaluated as part of a plan for a global backscatter assessment.
- *Satellite-Borne Radars for Rain Measurements.* Spaceborne radar is considered an improvement over ground-based radar for measuring rainfall rates over land areas; it also would be the only source of this information over the oceans. Present research studies envision an airborne meteorological radar, modified to find the minimum detectable rain rates by path attenuation rather than reflectivity, to be used in designing a satellite-borne sensor. Preliminary results indicate this method works best directly beneath the aircraft subpoint track, but there is the potential for further refinement. In conjunction with these studies, a ground-based radar at Wallops Island, Virginia, is being modified to permit measurements of rainfall rates based on differential reflectivity, which will help to serve as ground truth for airborne (and later satellite-borne) radars. NOAA could improve rainfall rate data via such satellite sensors and will continue to monitor developments in this area.

- *Space-Based Lightning Detectors.* NOAA is evaluating the usefulness of lightning detection mapping systems. Current research using experimental ground- and aircraft-based sensors has suggested several potential uses of lightning mapping in severe storm monitoring and warning. A satellite-based lightning detector would be able to cover ocean areas to enhance marine and aviation warning and forecast services; it could augment (but not replace) a projected operational network of ground-based sensors. Lightning monitoring could be done on a large scale for research on the relationship of lightning to storm development, growth rates, precipitation, and wind fields. Present optical technology allows detection of lightning from geosynchronous altitudes during daylight and darkness over nearly the full disk.
- *Geostationary Microwave Sensor.* Despite the substantial improvements expected with the GOES-NEXT sensors, the problem of taking accurate sounding observations in cloudy areas will most certainly remain. NOAA recognizes this as a technological and financial problem. The series of GOES satellites to follow GOES-NEXT is discussed in Section D of this chapter.

## National Aeronautics and Space Administration (NASA)

NASA has maintained an aggressive satellite remote-sensing development program since its inception and has pioneered new techniques for exploiting the electromagnetic spectrum for research in the Earth sciences. NASA's program in sensor systems includes the following instrument categories: passive, including imaging (visible/infrared, microwave, and radiation budget) sensors and sounders (humidity and temperature, atmospheric constituents, and atmospheric dynamics); active, including microwave sensors (altimeters, scatterometers, and synthetic aperture radar) and lasers; and magnetic/gravity sensors. Although these categories entail some overlap, they are treated separately in this section to reflect research emphases.

### *Passive Systems*

*Visible/Infrared Sensors.* NASA's imaging systems technology has advanced to the point where operational digital data of images of the Earth's surface are routinely acquired. These systems range in spectral and spatial resolution from the Advanced Very High Resolution Radiometer (AVHRR) flown on NOAA's polar-orbiting meteorological satellites to the highly complex Thematic Mapper (TM) aboard the Landsat series. This technique has also capitalized on the ability to "stare" from geosynchronous orbit to gather information from the GOES

on short-term phenomena, such as cloud motion, severe storms, and hurricanes.

With the advent of solid-state detector array technology, high spectral and spatial resolution systems can be designed to incorporate "push-broom" scanning and to exploit increased sensor performance in the spatial, spectral, and radiometric characteristics. To effectively use this technology requires the design of focal planes with many individually calibrated detectors. Two approaches are underway to develop this technology for use in future optical remote-sensing systems: (1) a linear array that could be used to build an upgraded TM-type instrument and (2) an area array that would become the focal plane for an imaging spectrometer. In the linear array, we are in the final stages of producing a mercury-cadmium-telluride array operating in the 1- to 2.5-micrometer region. Applications of this technology to the needs of civil and commercial operational remote sensing is expected. NASA is working with NOAA and EOSAT to determine how to incorporate this technology most effectively into their programs.

To capitalize on the promising area of array technology, we have initiated development of the Shuttle Imaging Spectrometer Experiment (SISEX). The SISEX instrument is planned for Shuttle flight in the early 1990s. To support both the technology and scientific techniques required, an Airborne Imaging Spectrometer (AIS) is being used as a test bed for the focal plane development effort and an Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) is being built for investigations of the atmospheric path effects on high spectral resolution remote sensing. The AVIRIS is a 224-band instrument designed for flight aboard the U-2 or ER-2 aircraft. It will be completed in 1986 and operational in 1987. Design factors are being included that will allow minimal modifications for transition of this type instrument onto the Space Station Polar Platform.

Although not a digital system, a Large Format Camera (LFC) was flown on the Shuttle in October 1984 and obtained spectacular imagery of many parts of the Earth. The resultant film product has been acclaimed by the cartographic community. Preliminary analysis strongly indicates that maps at a scale of 1 to 50,000 can be achieved. A total of 2,143 frames of imagery were exposed during the daylight passes of the orbiter. All of the photography was taken in stereo, which will permit stereo interpretation of the imagery for geologic and other investigations of the Earth's surface features. Although the imagery has not yet been widely distributed, it is expected that its value will soon be realized by all scientific disciplines that find a high-resolution perspective from space useful. The imagery is being released to federally funded agencies and cooperating investigators through the EROS Data Center in Sioux Falls, South Dakota. Through the Request for Proposal process, NASA has released the LFC

experimental data to Martel Laboratories of St. Petersburg, Florida. Martel will market the data worldwide on a nondiscriminatory basis. Following the provisions outlined in the Land Remote Sensing Commercialization Act of 1984, the sale of LFC data represents the first example of how experimental data has been marketed.

*Microwave Sensors.* The microwave portion of the spectrum has an added benefit for remote-sensing systems, because radiation is minimally attenuated by cloud cover. By sensing in this region, information can be acquired under nearly all weather conditions on sea surface temperature, ice cover, and other hydrologic features. A series of experimental instruments were flown on Nimbus and Seasat to determine the viability of this approach. The Electrically Scanning Microwave Radiometer (ESMR) was first carried aboard Nimbus-5 and a modified ESMR was later flown on Nimbus-6. The ESMRs were designed to produce a microwave image of the portion of the Earth near the satellite track. The Nimbus-5 ESMR operated at a frequency of 19.35 GHz, whereas the Nimbus-6 ESMR operated at 37.0 GHz. The Scanning Multichannel Microwave Radiometer (SMMR) was first carried aboard Seasat and is currently operating aboard Nimbus-7. The primary contribution of this instrument has been the study of polar ice dynamics. In 1987 DMSP will carry a Sensor System Microwave/Imager (SSM/I) for determining ice properties and the sea-ice edge. The SSM/I is derived from the SMMR.

*Radiation Budget Sensors.* Of key interest to the long-term climate of the Earth are studies of the relative balance between incoming solar radiation and the reflected plus thermal or re-emitted energy from the Earth. Instruments to study this delicate balance have been flown on Nimbus-6, Nimbus-7, and the Solar Maximum Mission. In October 1984, the latest program to provide data on this transfer of energy was initiated. Called the Earth Radiation Budget Experiment (ERBE), it consists of a set of solar radiation measuring instruments and Earth radiation instruments flown on an Earth Radiation Budget Satellite (ERBS) and two NOAA polar-orbiting satellites, NOAA-9 and NOAA-10.

Two classes of radiation detectors have been developed for Earth radiation budget measurements. The first class consists of high absolute accuracy radiometers specifically designed for solar irradiance measurements. These radiometers are designed to absorb all wavelengths equally; they generally respond to the conversion of radiation to heat energy. In this manner, determinations of the so-called solar constant are made. To provide periodic samples of incoming solar flux and as a calibration check on the free-flying instruments, a Shuttle-borne instrument called the Active Cavity Radiometer (ACR) has been flown on Spacelab 1 and will fly on follow-on missions for this purpose.

The second class of radiometers is designed to measure and differentiate the reflected and emitted radiation from the Earth. Separation of different bands of radiation is accomplished by filtering the incoming radiation. Again, the individual channel radiometers are designed to be spectrally flat and to operate by converting sensed radiation into heat energy.

The ERBS and NOAA-9 instruments have been functioning nominally since turn-on in November 1984 and February 1985, respectively. Data are being acquired and processed into appropriate data sets. NOAA-10, launched September 1986, completed the orbital complement for this experiment.

*Temperature and Humidity Sensors.* Temperature and humidity structure of the atmosphere are keys to understanding the stability of the weather system and forecasting short- and long-term changes. Satellite measurements of microwave and infrared radiation emanating from the surface and atmosphere of the Earth have been shown to be very useful in determining the temperature of the surface and the temperature structure of the atmosphere. To determine the temperature of the surface, instruments have been designed to observe the Earth at microwave and infrared wavelengths at which the atmosphere is transparent. To determine the temperature structure of the atmosphere, instruments have been designed to observe the atmosphere at wavelengths in which there is absorption and emission by a uniformly mixed gas. At microwave wavelengths, that gas is molecular oxygen. Infrared observations use wavelengths in which carbon dioxide is absorptive. Recently, techniques have been developed to use radiation emitted by molecules of water vapor to determine the vertical and horizontal structure of moisture in the Earth's atmosphere. Satellite instruments used to remotely probe the temperature and moisture structure of the atmosphere are generally referred to as sounding instruments.

The temperature and moisture structure of the atmosphere are crucial to the generation of weather forecasts. With the incorporation of the Advanced Microwave Sounding Unit (AMSU) into the operational instrument complement, NOAA will have an all-weather (i.e., cloud or clear conditions) capability for these measurements from polar orbit that should approach the state-of-the-art limits of this technology.

*Atmospheric Constituents/Ozone Sensors.* Satellite measurements of the concentration of atmospheric constituents in the troposphere, stratosphere, and mesosphere are made by remotely sensing radiation that is emitted, scattered, or absorbed by the atmosphere. In some cases, infrared or microwave thermal radiation is detected. In others, scattered solar radiation or the absorption of direct solar radiation as the Sun is viewed through the atmosphere is used as the basis for detection. Several such instruments have been flown in the past aboard opera-

tional satellites, such as TIROS, or research satellites, such as Nimbus; these have measured ozone, aerosol content, and other species residing primarily in the stratosphere.

With the advent of the Shuttle, short-duration flights using instruments can acquire survey data of a portion of the electromagnetic spectrum, perform proof-of-concept assessments of new designs, and provide an independent calibration source for similar instruments aboard free-flying spacecraft. The NASA program presently includes four instruments, described below, using this method.

Measurement of Air Pollution from Shuttle (MAPS) is a gas filter correlation instrument that detects the energy emitted by or reflected from the Earth's surface after it has passed through the atmosphere and been partially absorbed by carbon monoxide in the atmosphere. It has been flown twice aboard the Shuttle and has successfully measured the distribution with latitude and longitude of carbon monoxide in the middle free troposphere.

The Imaging Spectrometric Observatory (ISO) is a survey instrument that measures the airglow spectrum in five bands ranging from the extreme ultraviolet to the infrared. Several metastable states of atomic nitrogen and of atomic nitrogen and oxygen ions, molecular nitrogen band systems, metallic trace constituents and their ions, and the global distribution of helium and hydrogen are detectable, in many cases uniquely. The ISO was flown on Spacelab 1.

The Atmospheric Trace Molecules Observed by Spectroscopy (ATMOS) is a high spectral resolution interferometer that detects several trace species by measuring their absorption of infrared radiation from the Sun. This is measured by viewing the Sun in occultation by the atmosphere. The instrument is designed for deployment aboard the Shuttle orbiter and provides high-resolution spectrographs from 2 to 16 micrometers.

The series of Solar Backscatter Ultraviolet Spectrometer (SBUV) instruments to be flown on the NOAA polar-orbiting satellites (e.g., ATN) are to provide a long-term continuous data set of ozone variability. To ensure that the output of the sensor reflects true ozone variability and not degradation of the sensor, a series of underflights of another SBUV onboard the Shuttle will be made for calibration. The data acquired will be used as an input to the NASA/NOAA ozone trend analyses as well as to the scientific analyses to be performed during the Upper Atmosphere Research Satellite (UARS) program.

An advanced Stratospheric Aerosol and Gas Experiment (SAGE-II) is presently orbiting aboard the ERBS, capitalizing on this flight opportunity. A derivation of a Nimbus instrument, SAGE-II uses the occultation of solar radiation by the Earth's limb to derive information about the vertical distribution of atmospheric constituents. The most recent implementation utilized seven spectral bands to obtain ozone, nitrogen dioxide, aerosol,

and total molecular extinction. The vertical resolution is 1 kilometer. The instrument is basically a filtered radiometer, radiatively cooled.

The next major thrust of the NASA program to measure atmospheric constituent concentrations by remote sensing is the UARS, scheduled for launch in the fall of 1991, which will obtain for the first time a global data set on a large number of stratospheric and mesospheric chemical species involved in the complex question of the effects of human activities on the Earth's ozone layer. UARS will measure concentrations of key source and sink species and a major reactive intermediate (chlorine monoxide) involved in the ozone destruction chemistry. Given that the stratospheric and mesospheric chemistry is tightly coupled to the dynamics of the upper atmosphere, and that both are driven by energy input from the Sun (primarily from solar ultraviolet radiation and energetic solar particle bombardment), UARS will also provide direct remote-sensing measurements of upper atmosphere winds and of the solar energy input. The mission is designed to last 2 years and is a precursor to the Earth Observing System's (Eos) efforts to measure upper atmosphere parameters globally in a long time series. The atmospheric constituent remote sensors to be flown on UARS are now described.

ISAMS (Improved Stratospheric and Mesospheric Sounder) is a pressure-modulated radiometer, which is one example of a gas correlation spectrometer in that it uses a gas sample to filter incoming infrared radiation from the Earth's limb. Its predecessor (SAMS) was flown on Nimbus-7. In ISAMS, the pressure in the gas filter cells is modulated, which then modulates the intensity of radiation reaching the detectors and provides a basis for very high sensitivity through phase sensitive detection. ISAMS measures more species than did SAMS, and it includes helium pressure modulators that drive closed Stirling cycle coolers that reduce the detector temperature to 7K. ISAMS is 100 times more sensitive than SAMS. Species that will be measured by ISAMS on UARS include nitrous oxide, nitric oxide, nitrogen dioxide, nitric acid, ozone, water, methane, carbon monoxide, and carbon dioxide.

CLAES (Cryogenic Limb Array Etalon Spectrometer) is an emission radiometer that, like ISAMS, will determine altitude dependence of the concentration of atmospheric constituents in the stratosphere and mesosphere. It uses a combination of filters and tilting etalons to achieve high-resolution spectral selectivity. It measures the same species as ISAMS and will attempt to add members of the chlorine family, notably freons, hydrochloric acid, chlorine monoxide, and chlorine nitrate. The detector temperature will be 11K, the spectrometer temperature will be 20K, and the telescope foreoptics temperature will be 110K. Detectors will be gallium-doped silicon. CLAES will be an instrument of very high sensitivity, which has been used to obtain high resolution through the combina-

tion of filters and tilting etalons (which through their variable angle allow for a spectral scan within the narrow band accepted by the filters).

MLS (Microwave Limb Sounder) measures atmospheric thermal emission from molecular spectral lines at millimeter wavelengths in a limb-viewing geometry. It operates on a pair of lines near 204 GHz to measure pressure between 30 and 60 kilometers; three lines near 204 GHz that detect chlorine monoxide, hydrogen peroxide, and ozone (up to 60 kilometers); and two lines near 183 GHz that detect water vapor and higher altitude ozone (up to 90 kilometers). Like infrared limb sounders, the MLS operates day and night. Vertical resolution of the concentration profile at the limb is 3 kilometers. The instrument will provide the best chance for measurement of the very important chlorine monoxide radical.

HALOE (Halogen Occultation Experiment) is a gas cell correlation instrument that operates in a solar occultation mode. In the correlation mode, it measures the altitude distribution during twilight of hydrochloric acid, nitric oxide, hydrofluoric acid, and methane. It uses broadband filters to detect ozone, water, nitrogen dioxide, and carbon dioxide (for tangent height pressure measurements). It is a particularly effective instrument for detection of key source and sink species involved in stratospheric photochemistry (such as hydrochloric acid, hydrofluoric acid, and methane).

In addition to these instruments, the UARS payload will include two instruments to measure solar ultraviolet energy input with different techniques, an instrument to measure in situ the energetic particles entering the Earth's upper atmosphere, and two instruments for direct, remote-sensing measurements of upper atmosphere winds. These instruments, HRDI (High Resolution Doppler Imager) and WINDII (Wind Imaging Interferometer) measure winds by passive remote sensing of the motion of the atmosphere with respect to the satellite. WINDII will obtain data only in the upper mesosphere and thermosphere, but HRDI will cover the atmosphere from the upper troposphere well into the thermosphere. These passive remote-sensing measurements of winds on UARS complement the active remote-sensing techniques for measurement of tropospheric winds.

Whereas remote sensing of stratospheric constituents are currently emphasized, the early 1990s technological advances could enable global-scale investigations of tropospheric chemical and transport processes with space-based measurements. Any satellite instrument measuring tropospheric species must be able to provide total burden and/or vertical profiles with at least a two-level resolution within the troposphere and the free troposphere. These conditions may be satisfied with either species-specific or spectral survey type instruments. A spectral survey instrument could be an important satellite sensor. This sensor will have a capability for detecting many gases (even some



unsuspected ones) and for providing clues as to the presence of interferents. The system must be capable of spectral resolution of at least 0.1 centimeter. Either an interferometer or grating technique offers potential for meeting this requirement. Such survey instruments are complex and inherently have a large data output. Therefore, appropriate technology advances in sensor components and information processing will be used in the development of this instrument. Using this survey instrument to supplement the data collected by advanced species-specific sensors (e.g., a MAPS descendant), satellite remote sensing of the troposphere could be gaining considerable maturity by the mid-1990s.

### *Active Systems*

*Microwave Altimetry.* An altimeter is a radar that, when operated from low Earth orbit, can accurately measure the height of a satellite above the local ocean surface, thereby creating a "map" of ocean topography. When combined with knowledge of the satellite's position, these data infer the speed and direction of ocean surface currents beneath the satellite. Such information is vital to improving our understanding of the interaction of the atmosphere and the ocean and the associated effect on climatic variations. Fundamentally, altimeters measure height by counting the time it takes for a transmitted pulse to travel to the ocean surface and return to the satellite. Information concerning the local wind and wave conditions can also be derived from the shape and amplitude of the reflected signal.

Altimeters have been flown in space by NASA three times to date, namely on Skylab (1972) as an engineering evaluation/demonstration, on GEOS-3 (1975) to provide data leading to an improved marine geoid, and on Seasat (1978) to demonstrate its oceanographic utility. On each flight, successively improved technology was incorporated such that the height measurement precision improved from 1 to 2 meters RMS (root mean square) on Skylab, to 20 to 50 centimeters on GEOS-3, and finally to 5 to 7 centimeters on Seasat. With the flight and demonstrated performance on Seasat, the door was opened for exploitation of altimetry for routinely monitoring the ocean's surface.

The principal technology developments permitting these improvements were the incorporation of advanced pulse compression techniques, the change from a time domain sampling scheme to a frequency domain approach, and the use of a high-speed microprocessor to control the radar and processing of the reflected signal. Since Seasat, development work has continued by both NASA and the U.S. Navy, in conjunction with the Navy's Geosat (launched in early 1985) program, leading principally to a longer lasting instrument design. Future technology development should include the addition of a

second channel to correct errors introduced by the ionosphere, the development of long-life, solid-state transmitters, and the realization of height measurement performance at the 2-centimeter level. NASA's TOPEX/Poseidon mission, a dedicated, free-flying altimetric satellite scheduled for flight in 1991, is being planned around the availability of this technology; accordingly, the TOPEX program sponsored the development of an Advanced Technology Model to design, implement, and test these features. This unit was completed at the end of 1985 and substantially reduces the risk associated with the TOPEX program. Beyond the TOPEX/Poseidon mission, it appears that the emphasis will be on the development of a multibeam capability that would provide altimetry measurements over a wide swath, thus greatly reducing the time it takes to obtain global coverage and also permitting real-time determination of mesoscale features, such as ocean fronts and eddies.

*Scatterometry.* A scatterometer is an active microwave radar that, when operated from low Earth orbit, can accurately measure the amplitude of energy reflected from the ocean surface, from which the speed and direction of near-surface winds can be inferred. Such information is vital to marine forecasting. When coupled with altimetry data, both the ocean's driving force (winds) and its response (topography changes) can be used to better understand the effect of the ocean/atmosphere interaction concerning climatic variations.

The physical basis for scatterometry is the Bragg scattering of microwave energy from ocean surface wavelets (created by the instantaneous wind field) having wavelengths of a few centimeters. A scatterometer is configured to view the ocean surface at various incidence angles to derive an accurate wind speed and the most likely wind direction.

Scatterometers have flown in space twice, first on Skylab (1972) as an engineering evaluation/demonstration and then on Seasat in 1978 to demonstrate its oceanographic utility. The Seasat scatterometer measured wind speed with an accuracy of about 1.5 meters/second and recovered wind direction with an accuracy of about 20°. Note, however, that wind directions so determined are not unique. Typically there are four possible solutions and picking the correct solution usually requires additional data on local weather patterns. To minimize this problem, NASA's Scatterometer (NSCAT) will carry two additional antennas (Seasat had four) to provide different views of the sea surface, thus greatly simplifying the estimation process. NSCAT will also use digital Doppler filtering for better coregistration of measurement cells and simplification of ground processing. Radarsat, proposed by the Canadians to fly in mid-1991, may also carry a NASA-developed scatterometer similar to NSCAT. Future technology development will be directed toward (1) developing onboard processing techniques; (2) using pulse

compression techniques so that a long-life, low-power, solid-state transmitter can be used; (3) developing a multifrequency capability; and (4) developing microstrip antenna technology.

*Synthetic Aperture Radar (SAR).* The SAR systems have been and will continue to be developed within the context of the Shuttle Imaging Radar (SIR) Program. Through the addition of these imaging systems, we will greatly expand our capability to conduct geoscientific investigations. A high-resolution, two-dimensional radar image can be produced by a SAR and combinations of images can be coregistered to develop increasingly accurate three-dimensional representations of the imaged area.

Imaging radars, both alone and with other sensors, have unique capabilities that are important in addressing Earth science questions. For example, analysis of SIR-A images of Egypt have demonstrated the potential of mapping subsurface features and bedrock with imaging radars in hyperarid regions. Moreover, preliminary studies in the Mojave Desert of California indicate that it may be possible to penetrate alluvial cover and map buried surfaces in more environments than was previously thought. It is estimated that 10 percent of the Earth's land surface is amenable to such investigations.

To date, three SAR systems have been flown in space. The first was on Seasat in 1978, then SIR-A in 1981 and, most recently, SIR-B in October 1984. Each system represents a progressive step toward defining the optimum radar system for the future. The next system, currently entering the design phase, is SIR-C.

The role of SIR-C in reaching the overall science objectives is to provide unique information about surface units and processes that can be obtained through its multipolarization and multifrequency capabilities. For mapping continental geology, this means an increase in the texture and surface-roughness information derivable from remote-sensing data. In renewable resource studies, better estimates can be made of vegetative composition and health because leaf orientation, canopy structure, and soil moisture can be imaged, allowing a better estimate of the response of the surface-to-wind stress and current motion.

The SIR-C Project has additional technical objectives. These are as follows:

- To develop the high-risk, high-payoff technologies required for spaceborne radar systems of the 1990s. These include the development of (a) modular multispectral (L-, C-, and later X-band) sensor hardware, (b) high-power, wide-bandwidth transmitters, (c) large, multifrequency, multipolarization antennas, (d) multiple-beamwidth antennas, (e) real-time digital processors, and (f) postprocessing techniques for data analysis. Some of these technologies are being developed under research tasks; however, SIR-C will

use them in the space environment and under real operating conditions.

- To develop and demonstrate techniques from space that would be more flexible in using the radar sensors for Earth observations. These techniques include squint mode, multilook mode, burst mode, generation of circularly polarized data, and use of the coherent aspect of radar data.

SIR-C will capitalize on the hardware and experience gained from SIR-A and SIR-B. Electronic assemblies will be reflown with minimum refurbishment when practical. A modular approach will allow easy reconfiguration of, and modification to, the basic sensor. The number of frequency-independent modules will be increased so that modifications and additions will involve a minimum number of modules. The use of identical modules for the different channels will also increase the flexibility and reliability of the total system.

On the completion of the SIR-C, NASA plans to upgrade the system to the next generation, SIR-D. Preliminary plans call for studies on the feasibility of additional frequency capability and increased electronic steering functions. The SIR Program, and ultimately SIR-D, will generate a SAR that will be flown on the proposed Space Station Polar Platform as part of the proposed Earth Observing System (Eos).

*Laser Systems.* Laser systems (LIDARs) are radars that operate in the optical or infrared parts of the spectrum. NASA's laser research has emphasized applications for atmospheric measurements that can eventually be space based. Ground-based and aircraft-borne LIDARs have demonstrated measurement techniques for atmospheric phenomena at altitudes ranging from the surface to 90 kilometers. Measurement techniques have covered the entire range of current LIDAR technology, from single and multiple wavelength investigations of atmospheric aerosol spatial distributions and composition to differential absorption and high spectral resolution measurements of water vapor and trace gas concentrations. Differential absorption (DIAL) techniques are also being used to determine temperature and pressure profiles of the atmosphere.

Traditionally, the purpose of conventionally measuring atmospheric temperature and pressure was to infer the horizontal density gradients. These density gradients, together with the Earth's rotation, determine the large-scale motions of the atmosphere. Because of problems in calculating density and atmospheric motions, scientists have sought direct observations of the large-scale motions of the atmosphere because of their higher quality. This is especially true in tropical regions where density gradients are more subtle. In recent years, carbon dioxide lasers operating in the 10.6-micrometer wavelength region have been made stable enough to permit heterodyne detection of the Doppler shift of the backscattered energy. The

Doppler shift then can be used to directly infer the wind velocity. Such carbon dioxide systems have flown on aircraft platforms and successfully measured small-scale atmospheric motions. These observations point to the future application of such coherent systems on space platforms. These satellite-borne systems may utilize the carbon dioxide laser technology that has been evolving for the past decade or use the coherent solid-state sources recently reported. Studies to test a Doppler LIDAR wind profiler on a Shuttle platform are underway. When the technique is feasible from a space platform, it will be a viable system for the proposed Eos platform.

As a precursor to the development of a spaceborne differential absorption system, NASA has initiated the LIDAR Atmosphere Sensing Experiment (LASE) to develop an autonomous differential absorption LIDAR (DIAL) system for operation on the NASA ER-2 high-altitude aircraft; to conduct scientific investigations with the ER-2 DIAL system with emphasis on the troposphere; and to continue the evaluation of DIAL/LIDAR techniques before going to space. The science objectives of the ER-2 DIAL system are to use measured water vapor mixing ratio profiles to conduct meteorological investigations in the middle to lower troposphere and to study troposphere-stratosphere exchange in deep convective events; and to use aerosol and cloud multiple wavelength LIDAR profiles to study atmospheric aerosol distributions and transport, aerosol size distributions and number densities, cloud layer effects on passive remote instruments and radiation budgets, meteorological parameters inferred from aerosol and cloud data, and ice-water discrimination in cirrus clouds.

The NASA Space Shuttle will help advance and demonstrate NASA's space laser systems, and the proposed Space Station Platform would permit further progress. Because a space-qualified laser is required for all future space applications, NASA is developing a Shuttle-borne experiment for flight in 1991 to develop the technology and measurement techniques required to successfully operate a solid-state laser LIDAR system from space and to provide a spaceborne test bed for emerging technology developments. Designated LITE, for Laser In-Space Technology Experiment, the experiment will use existing LIDAR technologies and measurement techniques, and the design will depend heavily on "off-the-shelf" designs and components.

**Magnetic Field.** One of the major questions in Earth and planetary sciences is how planetary magnetic fields are generated. It is now thought that some sort of dynamo operates in an electrically conductive fluid core (i.e., the Earth's) and the outer core, which is known to have suitable properties for existence of a geodynamo. However, global vector measurements of the geomagnetic field only became available after NASA's Magsat mission

in 1979. Understanding the geodynamo also requires measurement of changes in the Earth's geomagnetic field, known as the westward drift of magnetic compasses.

Consequently, both vector and scalar magnetometers will be included on the proposed Geopotential Research Mission (GRM), placed at the end of an isolating boom on one of the spacecraft. The separate scalar measurement is desirable because its accuracy can be made several times better than that of the vector magnetometers. The magnetic field information will meet the needs for studies of inhomogeneities in the Earth's crust. The GRM instruments are essentially reflights of the 1979 Magsat instruments. To follow changes in the multipolar geomagnetic field, it is highly desirable to have missions spaced no more than 10-15 years apart, a criterion satisfied by flying GRM in the early 1990s. As a backup, a much less expensive, simple reflight of the 1979 Magsat-A, the proposed Magnetic Field Explorer (MFE), is being studied; this mission could be flown by 1989. A follow-on joint mission with the French called MFE/Magnolia could be launched in 1992 or later. Both MFE missions are in higher altitude orbits appropriate for Earth core magnetic field monitoring. The GRM is configured to measure the magnetic field associated with the Earth's top layer. The proposed MFE missions would begin a program of long-term measurements of the magnetic field using U.S. and international satellites and the instruments planned for Eos. MFE will be similar to Magsat-A but will be placed in a higher circular orbit to extend its lifetime to 3 years (Magsat-A operated 8 months before re-entry). MFE would carry scalar and vector magnetometers.

**Gravity Field.** The Earth's gravity field provides information on the distribution of mass within the solid Earth, and is one of three ways that the interior of the Earth can be studied (the other two are seismology and electromagnetic waves). Accurate knowledge of the global gravity fields will, in conjunction with other data types, be essential in studying the dynamic state of the solid Earth and is required for other purposes (e.g., providing a reference surface by which ocean heights can be measured via satellite altimetry, and for prediction of satellite ephemerides).

Two major developments are being pursued in satellite gravimetry. GRM will measure the global gravity field to about 1 milligal (one part in  $10^6$  of the value at the surface of the Earth) and the global geoid to 5 centimeters. Both these accuracies represent at least an order of magnitude improvement over the present level of knowledge and, in many regions of the world, will be the first measurements of gravity at all. The gravity field information would meet the needs for studies of mantle convection and the internal structure and composition of the Earth. Because it will provide a much improved geoid, to which sea surface heights are referred, the GRM will allow full realization of the results of the NASA TOPEX/Poseidon mission.

The GRM will perform gravity measurements through observation of the horizontal gradient of the gravity field via a closed Doppler link between two spacecraft in identical orbits at 160 kilometers altitude, with the spacecraft separated by about 150 kilometers. Dynamic compensation for nongravitational forces on the satellites will be accomplished through each of the spacecraft sensing the position of a free-floating ball relative to the spacecraft itself, and activating thrusters to keep the balls moving like miniature satellites unaffected by winds, drag, and radiation pressure. The second major activity oriented toward measurement of the gravity field is development of a gravity gradiometer, which will operate in space as a five-element cluster of uniaxial gradiometers to measure the complete gravity tensor. A one-dimensional gradiometer model is presently being constructed and will be tested under standard gravity conditions. The expected accuracy of this gradiometer is unclear before the tests are conducted, but it is expected to be at least the accuracy of the GRM. The primary rationale for developing the gradiometer is that it can be towed on a tether at very low altitudes where a free-flying spacecraft cannot operate.

**Precise Positioning.** Future developments in precise positioning instruments will concentrate on three areas: improving the accuracy of these measurements to better than 1 centimeter (from the present 3-5 centimeters); developing methods to make these measurements at points on the floor of the deep ocean; and developing cheaper and more rapid measurements of regional crustal deformation in seismically active (earthquake-prone) areas.

The accuracy improvements will be accomplished (1) for Very Long Baseline Interferometry (VLBI) methods, by improvements in data processing, in the atmospheric models used, and in the operation of reliably calibrated water vapor radiometers at observing sites; and (2) for satellite deployment of lasers, by shorter and shorter pulse length (the dominant factor in laser accuracy), by the improvement of satellite ephemerides (due partly to better knowledge of the gravity field through the GRM), and by better knowledge of the effect of atmospheric refraction.

Many scientifically important regions of crustal deformation and tectonic plate motion are in the deep ocean, beneath more than 5 kilometers of ocean water. Future initiatives in space geodynamics must include a search for methods of space measurement in these areas. The major problems are (1) anchoring the reference mark on the ocean floor to the underlying lithospace and (2) fluctuations in the path length between the ocean-bottom reference mark and a platform at the surface of the ocean (the platform communicates with the extraterrestrial fiducial body required for space position measurements). These fluctuations are so large they swamp the expected deformation velocities and must be removed for space methods

to be feasible. Promising studies of different methods for overcoming these difficulties are now being conducted.

For regional deformation measurements, where relative position markers that are 50-500 kilometers apart are adequate (rather than geocentric positions), two new methods are under development. These correspond to the twofold approach to global positioning through radio methods and laser-ranging methods.

First, the Global Positioning System (GPS) navigational satellites being operated by DOD can be used for scientific research in non-real-time. Several different designs for receivers to use GPS signals for centimeter-level relative positioning are presently under development. Because the radio signals generated by GPS satellites are many times brighter than the extragalactic radio sources used by classic VLBI, the GPS receivers are correspondingly small, inexpensive, and highly mobile. The use of GPS for regional deformation measurements will be tested in a prototype research project to measure crustal deformation in California and in the Caribbean, an area with high seismic potential that is important to the United States.

The second method for rapid measurement of regional deformation is based on inverting the now classic satellite laser-ranging procedure, and putting the laser in space and the retroreflectors on the ground. This possibility had been thoroughly studied in the late 1970s, but discarded because refurbishment of lasers in free-flying satellites was too expensive. With the advent of the Eos, however, the method of spaceborne laser ranging (SBLS) is again being considered. Very inexpensive retroreflectors, once emplaced, can make maps of crustal strain as often as scientists require. Unlike the operation of ground-based laser stations or mobile VLBI or GPS receivers, such maps can be made frequently in the event of a major earthquake; this is a scientific necessity for any practical earthquake prediction system.

#### Department of Defense (DOD)—U.S. Air Force

The Defense Meteorological Satellite Program (DMSP) is pursuing a number of spacecraft and sensor upgrades phased into the next century. In addition, DMSP is pursuing several remote-sensing development initiatives to satisfy DOD operational military requirements. These efforts are being accomplished by contractors and the Air Force Geophysics Laboratory (AFGL), funded by DMSP.

DMSP, a joint-Service program with the Air Force as executive agent, is DOD's most important single source of global weather data. This program provides data to DOD strategic and tactical forces. DMSP includes the satellites and sensors; ground command and control; Air Force, Marine Corps, and Navy fixed and mobile tactical ground terminals; and Navy shipboard terminals. DMSP provides visible and infrared cloud cover data and other mete-

orological, oceanographic, and solar-geophysical information. These data are required over the entire surface of the Earth to support strategic and tactical missions. Each operational satellite is required to provide coverage of the Earth twice each 24 hours.

There are five major ongoing efforts, as discussed below.

**DMSP Microwave Imager (SSM/I) Data Analysis.** In 1987 DMSP will launch the S-9 satellite as Flight-8 (F-8) with the first SSM/I. This instrument will provide precipitation, soil moisture, wind speed over the ocean, sea ice morphology, cloud water, and liquid water data. SSM/I data will be processed and used operationally at AFGWC and FNOC. Research objectives are to develop techniques for processing and displaying SSM/I data. These data will be presented in a versatile format so that the geophysical parameters derived from the SSM/I can be verified and used directly with the visible and infrared imagery of DMSP. The tasks are to

- Demonstrate the merging or overlaying of the SSM/I data with DMSP imagery. This will include an assessment of how the SSM/I data products, which might be generated in a Mark IV tactical terminal, would improve weather analysis and prediction;
- Prepare for the analysis of data collected from the SSM/I on the DMSP satellite. A major portion of the development will be to evaluate or verify the geophysical parameters that are derived from the SSM/I data. This effort began in May 1985; and
- Procure a video image workstation as part of the Man-Computer Interactive Data Access System (McIDAS) at AFGL. This workstation will be used to analyze SSM/I data and other types of meteorological data.

**DMSP Microwave Temperature and Water Vapor Sounders (SSM/T and SSM/T-2).** The Sensor System Microwave/Temperature (SSM/T) is operational on DMSP today. In the early 1990s DMSP will fly the first Sensor System Microwave/Water Vapor (SSM/T-2) on Satellite S-13. Microwave sounders provide global all-weather profile data for AFGWC and FNOC. These data are also provided to NOAA. Research goals are to explore techniques for using temperature and moisture soundings in the DMSP Mark IV tactical terminals. One important aspect is to provide a theoretical and technical assessment of 183 GHz multichannel radiometers for estimating water vapor profiles over land. Measurements (183 GHz) from an aircraft will be analyzed and evaluated with theoretical simulations. The tasks are to

- Analyze the 183 GHz multichannel radiometer measurements obtained over land during NASA CV-990

flights, using NOAA-archived radiosonde data that match the times and location of the flights;

- Evaluate the estimated water vapor profiles over a variety of land surfaces and carry out simulations of retrieving water vapor profiles using several combinations of channels near 183 GHz; and
- Evaluate how SSM/T and SSM/T-2 data could be effectively used in Mark IV terminals.

**Development of an Active Satellite Sensor for Meteorological Observations.** This effort's objective is to develop a family of active atmospheric sensors for space. These sensors will include a space-borne LIDAR for measuring aerosol and cloud properties, to be followed by more advanced LIDAR systems to obtain profiles of temperature, moisture, density, minor constituents, and wind. The tasks are to

- Design a LIDAR sounder for DMSP Block 5D-3 spacecraft;
- Design simulation studies for the above-mentioned LIDAR sounder;
- Analyze 1.064-micrometer detector for LIDAR sounder;
- Specify and test critical LIDAR components; and
- Form a technical plan for advanced LIDAR.

After the completion of these preliminary studies, development of the prototype light detection and ranging (LIDAR) sounder for determination of cloud top heights and aerosol content will begin. This effort is slated to fly under the Space Test Program (STP) and is currently ranked as the highest priority Air Force experiment. This is the first phase in a three-phased program that will ultimately lead to the ability to measure global winds from space in the late 1990s. Future studies will also investigate DIAL/LIDAR applications.

**Electron Density Profiles.** Studies are being conducted in conjunction with the Naval Research Laboratory on an ultraviolet sensor to measure ionospheric characteristics.

**DMSP Block 6.** In FY 1988, DMSP will award four competitive concept studies for the follow-on DMSP Block 6 satellites, which will be needed to meet on-orbit requirements in the late 1990s. Objectives include lowering life-cycle cost through a competitive design to cost approach, upgrading 1970s Block 5D technology, and exploring cost-effective opportunities for satisfying military requirements for increased survivability and remote-sensing capability. In FY 1990, DMSP will award two competitive advanced development contracts for Block 6, based on the result of the FY 1988-1989 concept studies.

In 1992 full-scale engineering of the Block 6 satellite will begin, leading to delivery of a prototype satellite available for launch in 1998.

#### Department of Defense (DOD)—U.S. Navy

Naval research and development programs address a wide range of areas that are applicable to environmental remote sensing. The programs include basic research, exploratory development, advanced development, and technique improvement. The areas include materials, structures, components, sensors, algorithms, command and control, orbits, navigation, artificial intelligence, communications, satellite fabrication, end-to-end system design, data processors, and product exploitation and applications. This section characterizes areas of activity that are representative of Navy projects.

Operational Navy requirements for remote-sensing measurements of environmental parameters are frequently more stringent than those of the civilian community, and thus require significant technology research and development.

Naval operations and missions are global and involve ships, aircraft, submarines, satellites, amphibious vehicles, and tanks. Environmental parameters of concern include characterization of land areas, coastal zones, oceans, ice, the atmosphere, and space. Time scales range from the fast-response tactical needs of the Marines and aircraft to the long-term strategic requirement for deployment of forces (minutes to weeks). Similarly, space scales range from feet to thousands of miles.

#### *Naval Developments for Environmental Satellites.*

This discussion will consider only environmental satellite systems and will not address related technologies in communications and navigations (e.g., Fleet Satellite Communications System [FLTSATCOM] and Global Positioning System [GPS]). Neither will this discussion address the related engineering system developments directed toward space-based radar and infrared system definition and design.

Geosat was launched on March 12, 1985 and is performing well with an expected lifetime of 3 years. Geosat is an altimeter-only, polar-orbiting satellite with an anticipated range precision of 3.5 centimeters. This precision will be about twice that of the Seasat altimeter. The orbit will be very similar to that of Seasat, with an altitude of 800 kilometers at an inclination of 108°.

The geodetic-related mission will not be available directly to the civil marine community during the first 18 months, while the orbit is in about a 152-day repeat cycle. This cycle will provide an 18-kilometer grid at the equator, so that about three complete cycles are expected while in this mode. The second 18-month period will use a

repeat cycle of 17 days, which will provide an equatorial grid of about 140-150 kilometers and the data will be available to marine users through NOAA/NESDIS. Geosat objectives are the measurement of the geoid and of the ocean surface slopes as necessary to drive global circulation models.

A microwave imager (SSM/I) has been developed jointly with the Air Force for implementation in 1987. The SSM/I has a nominal resolution of 30 kilometers and operates at 19, 22, 37, and 85 GHz. SSM/I is designed to measure surface water vapor and to provide an estimate of soil moisture under certain conditions.

The Navy is contributing its requirements to performance specifications for DMSP, Block 6.

The Navy is upgrading the Satellite Processing Center (SPC) at Fleet Numerical Oceanographic Center (FNOC), Monterey, California to handle data from all available satellite systems (DMSP, NOAA, Geosat, GOES) in real time. Improved shipboard satellite receivers for major capital ships are being developed. An onboard real-time data processing system, the Tactical Environmental Support System (TESS), is being developed to produce Tactical Decision Aids from satellite data, in situ measurements, and external data fields. TESS will be installed at shore locations and on ships. Communications links and display facilities are being improved.

*Remote Sensor Development.* The Navy is pursuing research and development of instruments that can make remote measurement of environmental parameters. These efforts are in all portions of the electromagnetic spectrum. (Complementary work is being done with acoustics, gravity, magnetics, and the electric field.) Sensor development is considered to include the physics, mathematics, and engineering necessary to derive environmental parameters from instrument measurements. Remote sensors have been and will continue to be used on the surface, on aircraft, and on satellites.

Navy remote sensor development includes the following activities:

- An ultraviolet sensor is being developed for use on DMSP to measure ionosphere characteristics.
- A surface contour radar was developed for NASA Wallops Flight Center to provide an aircraft measurement of ocean wave spectra.
- Support was provided to NASA to upgrade the airborne ocean color scanner.
- Airborne sensors using multispectral scanners and/or lasers are being developed for coastal bathymetry measurement.
- Cooperative and complementary efforts are being made with NASA and NOAA to develop a satellite

sensor for measurement of directional ocean wave energy spectra.

- Experiments are being conducted to develop algorithms for determining oceanic surface wind stress from scatterometers and radiometers.

An aircraft flight facility at the Naval Research Laboratory uses multichannel microwave radiometers to develop new measurement capabilities and develops, tests, and evaluates active (radar and LIDAR) sensors. This facility is also used as a platform for performance validation of new satellite sensors.

Technological exchange and development are being pursued to use LIDAR (Raman and Brillouin scattering) and millimeter-wave radar to measure fine-structured atmospheric profiles of temperature, humidity, winds, turbulence, and aerosols. These profiles are necessary to predict electromagnetic propagation and sustain global prediction models. LIDAR and radar systems are being tested to measure topography and trafficability over land areas.

Radar and millimeter-wave radiometer measurement are being made from aircraft to improve ice characterization algorithms and to improve applications and forecast models. Finally, ocean color scanner data are being used to develop algorithms for water mass identification, measurement of sediment transport and littoral currents, and determination of optical propagation parameters.

## International Efforts

Remote sensing of the Earth is entering a new and more complex era in the late 1980s. No longer is space the exclusive domain of the United States and the Soviet Union. Whereas collaboration from the European countries, both independently and with ESA, with NOAA in operational ventures, and with NASA for research programs, was the primary international involvement prior to the 1980s, today's situation is considerably different. Independent satellite systems are being flown by France, Japan, and India. Other countries such as Canada and Brazil will soon be ready to enter this field. The basis for their entry ranges from economic exploitation of the land remote-sensing market by France's SPOT (launched in 1986) to the traditional systems for national environmental forecasting, such as Japan's Geostationary Meteorological Satellite (GMS), operational for many years.

This new ingredient in international relationships requires new considerations in the technology development of U.S. programs. Although science programs will benefit from the expansion of remote-sensing capabilities and new data availability, an awareness of the effect of certain decisions on the posture of the U.S. remote-sensing indus-

try must be maintained. As stated in Chapter II, NOAA and NASA are working with private industry and major advisory committees of the National Research Council to establish appropriate policies that will serve the needs of U.S. industry in both national and international marketplaces.

Several groups have been established for the international coordination of environmental satellite programs (see Chapter IVD). All members must strive to understand the goals, motivations, and plans of the various international participants in our periodic meetings and to use these meetings as opportunities for communicating our program plans and assessing opportunities for joint collaboration. These meetings have become highly effective vehicles for collaboration on space systems and data exchange.

This discussion briefly introduces foreign satellite missions supporting Earth sciences research and applications. Missions are introduced by discipline; comprehensive payload and orbit characteristics for the various missions are in the respective tables (see Appendix A).

### *Atmospheric Observations*

*Meteosat.* The European Space Agency's (ESA) Meteosat satellite provides continuous coverage of about one-third of the Earth. Meteosat's geosynchronous orbit and its visible and infrared imaging sensors allow meteorologists to see day and night weather patterns that may affect Europe.

*Geostationary Meteorological Satellite (GMS).* The sensors on board Japan's GMS are similar to those flown on the USA's GOES satellites.

*Indian National Satellite (INSAT).* INSAT-I is a multi-purpose geostationary satellite system for domestic telecommunications, meteorology, nationwide direct-use television broadcasting to rural communities, and radio and television program distribution for rebroadcasting/networking.

INSAT-IA, the first in the series, was launched from the United States on April 10, 1982 aboard a Delta vehicle. Because of certain technical deficiencies, the spacecraft was turned off after 147 days of useful in-orbit life. The second satellite in the series, INSAT-IB, was launched by the U.S. Space Shuttle "Challenger" on August 30, 1983 and is currently operational.

The proposed INSAT-II satellites will be a major step toward enhancing self-reliance in INSAT space segment. It eventually will replace the foreign-procured INSAT spacecraft with indigenously designed, developed, tested, and qualified operational satellites with high reliability and long life. The INSAT-II spacecraft are intended as test versions of the second generation INSAT satellites.

*Meteor.* The U.S.S.R.'s complement to NOAA's ATN satellite series is Meteor-2. Flying in a near polar orbit,

Meteor-2 provides observations useful to land, sea, and atmospheric analyses.

### *Ocean Observations*

*ERS-1.* ESA's program for oceanic satellites is focused on a 1989 launch of the first ESA Remote-Sensing Satellite, ERS-1. The primary mission of ERS-1 is to increase scientific understanding of global ocean processes and to promote economic and commercial applications. This mission is to be accomplished by a payload consisting of an Active Microwave Instrument (AMI), a radar altimeter, and an infrared Along-Track Scanning Radiometer (ATSR). In addition, a Precise Range and Range-Rate Experiment (PRARE) is being studied to extend the ERS-1 mission to include geodetic and geodynamic applications.

*Radarsat.* Canada is currently evaluating a mission called Radarsat. This mission is targeted at four sets of applications of a SAR: operations in sea ice-covered waters, basic oceanography, renewable resource assessments, and detection of nonrenewable resources. Radarsat, combined with ERS-1, further SIR flights on the Space Shuttle, and a Japanese mission also called ERS-1 (Earth Resources Satellite), will provide ample experimentation to justify the continuation of SAR missions on an operational basis.

*Marine Observation Satellite (MOS).* Japan will launch both ocean- and land-observing satellites during the remainder of this decade and the 1990s. The MOS will have instruments for determining ocean chlorophyll, sea surface temperature, and atmospheric water vapor. MOS-1 was launched in February 1987.

### *Land Observations*

*Système Probatoire d'Observation de la Terre (SPOT).* The French SPOT system, launched in 1986, has characteristics complementing those of Landsats-4 and -5. SPOT has fewer spectral bands but higher spatial resolution than Landsat—and provides offset pointing and stereo capability.

*Japanese Earth Resources Satellite (ERS-1 [Japan]).* The primary objective of ERS-1 is terrestrial mapping of renewable and nonrenewable resources. Scheduled for launch in 1990, it will be in a Sun-synchronous orbit and will carry a Landsat-type visible and near-infrared radiometer and an L-band SAR.

*Indian Remote-Sensing Satellite (IRS).* Specifically tailored to Indian needs, the Indian Remote-Sensing Satellite System will cater to India's resource-management requirements with emphasis on agriculture, water management, forestry, and certain aspects of mineral geology. It is proposed to build the satellite indigenously, based on various elements of technology development that have

been gathered through aircraft sensors, other payloads, and other followup systems.

The 850-kilogram IRS-1A, the first in the IRS satellite series, will be a semioperational satellite scheduled for launch in October 1987. IRS-1B is planned 24 to 30 months after IRS-1A.

*Laser Geodynamics Satellite-2 (LAGEOS-2).* Italy, under agreement with NASA, is developing the LAGEOS-2 for launch by the Space Shuttle in 1993. LAGEOS-2, which will be identical to the LAGEOS-1 (built by NASA and launched in 1976), will be used for crustal motion and Earth orientation studies. LAGEOS-2 will be placed in a 52°, circular, 6000-kilometer orbit.

## **C. Data Systems Planning**

In recognition of the increasing need for a collaborative effort to manage Earth observation data acquired from space- and ground-based sensors, NASA and NOAA have formed a Data Management Working Group. Other agencies with interests in these data are also invited to participate. The working group strives to facilitate the management and access of Earth data collected by the participating agencies involved and to resolve major issues in this area.

### **National Aeronautics and Space Administration (NASA)**

Accessibility and timeliness of data to the researcher or end-user are crucial elements in the establishment and operation of an effective remote-sensing program. Because of the extensive amount of data now being produced daily and the projections for increases in the future, NASA is examining its approaches to the Earth science flight programs and to systems for applying mission- and ground-acquired data to research outside a particular mission. NASA has used as guidelines the recommendations to NASA issued in a 1982 report of the Committee on Data Management and Computation (CODMAC) of the National Academy of Sciences. These recommendations call for a distributed system concept in which the data are geographically dispersed and near to the user community most closely associated with the data. At the same time, to ensure that the system responds to the scientific objectives of the user community, strong science-user participation is encouraged throughout life-cycle development of the entire system.

In defining the flight programs, NASA has stressed the need to ensure a balance of emphasis on the flight segment, data processing distribution and archiving segment, and research analysis. In fact, the Upper



Atmosphere Research Satellite (UARS) program is implementing this approach in its end-to-end data system that provides each of the Principal Investigators with a distributed computational capability and access to a centralized computing facility for integration of a total mission data set. Our definition of TOPEX has also emphasized this approach. TOPEX would include a system responsive to the Principal Investigators and the more extensive research communities. Future missions will ensure that this program approach is effectively addressed.

In 1978, NASA initiated a coordinated, multidisciplinary activity to make satellite data accessible online to the NASA research community and to provide the processing capabilities necessary for global-scale, multidisciplinary research based on multisensor data sets. This activity involved the systematic development of improved techniques for data management, networking, data standards, and advanced processing systems. The task was structured around the development of distinct discipline-focused pilot data systems for land, ocean, and climate research. The successful development of the Pilot Ocean Data System led to the establishment of the operational NASA Ocean Data System in 1986. The development of the Pilot Climate Data System is nearing completion under the technical management of Goddard Space Flight Center (GSFC), while a prototype of the Pilot Land Data System, under definition by GSFC, is expected to be tested in 1987.

To facilitate the evolution of the discipline pilot data systems into an interdisciplinary information system, NASA has conducted studies and workshops on specific technical issues concerning the integration of the pilot data systems. Workshops continue to be planned to address data standards, scientific work stations, networks, and data catalogs, as well as other relevant components of an information system. These studies and workshops will continue in efforts to bring data experts together to address specific elements of global data systems.

Research into the global systems aspects of Earth science will require space-acquired data as well as conventionally acquired and maintained data sets that can provide the detail of classical ground-truth data. To begin to integrate these data sets and to assess the complexity of global systems, NASA agreed in 1984 to participate with the United Nations Environmental Program (UNEP) in the development of a Global Resources Information Database (GRID) within UNEP's Global Environmental Monitoring System (GEMS). This is an international cooperative program to improve the study of global resource and environmental issues.

The approach of this program consists of the development of methodologies for accessing and analyzing data on national, regional, and global scales, using environmental data sets existing within the UNEP system and remote-sensing data provided by NASA and other

sources. GRID will be structured as a globally distributed network of data bases linked by the Intelsat Communications Satellite. NASA is providing data systems hardware and software for the pilot-phase development of these capabilities. As the pilot data systems evolve toward an integrated operational status in concert with other efforts such as GRID, other international global environmental data bases will be incorporated into the full system as dictated by the science needs of the International Geosphere-Biosphere Program (IGBP) and other programs. This comprehensive system will support the Eos objectives and the eventual establishment of the Eos Data and Information System (EOSDIS).

The NASA Associate Administrator for Space Science and Applications requested the National Research Council to identify the critical issues on which NASA must act to ensure that its information systems activities lead to interoperable systems worldwide, with a minimum of disruption. This study, conducted by the Board on Telecommunication and Computer Applications, was completed in 1986. In addition, much of the information systems planning conducted as part of the planning for scientific uses of the Space Station bears directly on the technical issues inherent in a system supporting global-scale research.

In addressing evolving data and information system requirements, future NASA plans focus on the following:

- Continuing the operational development of the Pilot Data Systems;
- Integrating these systems into a pilot multidisciplinary information system which would facilitate access to environmental data sets held by NASA and other agencies and institutions; and
- Contributing to the concept of international access to global data through the UN's Global Resources Information System (GRIS). (GRIS is designed to facilitate integrated research involving worldwide global data sets, potentially available from satellite remote sensing and other conventional sources, in order to address global environmental and resource processes.)

The planning and operation of these systems will serve as useful tools for research and applications but will also provide test beds for the definition of the information system that must accompany the increased capability to be provided in the Space Station era. This new system is being defined to provide a comprehensive data distribution and archiving system capable of integrating data from traditional ground-based sources, from national and international research satellites, and from operational data streams provided by other agencies, such as NOAA.

## National Oceanic and Atmospheric Administration (NOAA)

**Real-Time Processing.** Real-time data processing and centralized computer processing of environmental satellite data are presently being upgraded at NOAA. This will significantly improve the collecting, processing, distributing, and archiving of data from polar-orbiting and geostationary satellites.

**Program for Regional Observing and Forecasting Services.** During the past 5 years, the NOAA Program for Regional Observing and Forecasting Services (PROFS) has accommodated all forms of geostationary satellite data as one of its major operational data sources. In addition to satellite data, the PROFS meteorological workstation allows easy access to many other sources of data: radar (conventional particles per inch [PPI] reflectivity, Doppler reflectivity and velocity), Radiosonde Observation (RAOB) data, a local automated surface network, aircraft pilot reports, and radiometric thermal and wind profiler data. Because of the diverse mix of data types, the workstation offers a unique means for integrating satellite information with other data. When data are mapped into suitable projections, satellite data can be combined with other data in several user-selectable ways. Experience has verified that much more can be understood about atmospheric circulation from viewing combined products than is possible by viewing products created from an individual data source. In addition, one can combine the quantitative data from several sources in a Mesoscale Analysis and Prediction System (MAPS), described below in more detail.

Since 1982, PROFS has had the capability of direct access and display of Visible and Infrared Spin Scan Radiometer (VISSR) data. In late 1983 VISSR Atmospheric Sounder (VAS) data were added, and during 1984 data bases were developed to store retrieved soundings and areal radiance data from the VAS instrument. Both VAS multispectral imagery (MSI) and VAS sounding data now reside on the workstation in real time. The intent is to exploit all new data sources and techniques. This capability has led to a new science: the effective real-time methodology of meteorological data integration and display.

Satellite products fall into two very general categories: qualitative and quantitative. Each can be viewed separately but are more productive when used together. Qualitative displays include satellite and radar images. Quantitative graphics products such as VAS retrieval data, AFOS (Advanced Field Operations Systems) products, MAPS output, and derived radar information may also be displayed with the imagery.

PROFS is developing MAPS for the assimilation of tropospheric data and the generation of short-term forecasts on a 3-hour cycle. PROFS is receiving VAS soundings several times a day from the University of Wisconsin. The objective analysis scheme is multivariate optimal

interpolation, in which observations of wind influence the height analysis and vice versa.

The experience gained during PROFS' and NASA's experience with other interactive systems will serve as the knowledge basis for operational implementation of such systems on a NOAA-wide basis (e.g., the Advanced Weather Interactive Processing System of the 1990s, AWIPS-90).

**NESDIS Central Computer System Upgrade.** Over the past 13 years, the current computer system evolved incrementally from a system containing 12 major hardware vendors, 6 major separate maintenance contracts, 4 different software operating systems, 3 totally different programming environments, and almost no time-sharing capability for development work. Polar and geostationary processing activities were separate and the data resided on different media, ranging from disks to unique mass storage video tapes.

The new system is called the Metsat Data Processing and Services Subsystem (DPSS). It consists of IBM 4300 multiprocessor systems operating in multiprogramming modes, combining computing resources for polar and geostationary ground operations for time-sharing, data base, communications, and batch processing services on a 24-hour basis. The multiprocessor system consists of one IBM 4341 Model 2 and three 4381 Model 1 mainframes with a total of 50 billion bytes of directly addressable data storage. About half of this ground system has been installed. Polar-orbiting operations began in April 1985, and geostationary processing will be integrated into the system in September 1987.

**Central Data Base.** At the center of all this will be a 50-billion byte direct access disk storage subsystem that will provide storage for the Metsat central data base. The central data base will consist of data sets and directories of sensor data collected from NOAA's polar-orbiting and geostationary environmental satellites for a 24-hour period. The following types of sensor data will be resident on the Metsat DPSS data base from the NOAA polar-orbiting series: Advanced Very High Resolution Radiometer (AVHRR), High Resolution Infrared Radiation Sounder (HIRS), Microwave Sounding Unit (MSU), and Stratospheric Sounding Unit (SSU). From the GOES satellites, all full-resolution, 1-kilometer visible data, VAS digital imagery, and dwell sounding data will be included.

The central data base will also contain data and products from DOD's weather satellites in the Defense Meteorological Satellite Program (DMSP). This will be made possible through a cooperative agreement known as Shared Processing. The agencies involved in Shared Processing are NOAA, the U.S. Air Force Air Weather Service, and the U.S. Navy's Naval Oceanography Command. The agreement essentially calls for the exchange of data bases between the Nation's three central weather

satellite processing centers: NOAA/NESDIS at Suitland, Maryland; Air Force Global Weather Central (AFGWC) at Offutt AFB, Omaha, Nebraska; and Fleet Numerical Oceanography Center (FNOC) at Monterey, California. Initial shared-processing operations began in 1986. These operations included a capability for the AFGWC to transmit and NESDIS to receive shared processing data and products. The following DMSP data and products are scheduled for exchange and residency in the Metsat DPSS during implementation of the final operating capability scheduled for October 1988:

- The AFGWC Satellite Global Data Base, a 3-nautical mile visible and infrared image data base;
- The AFGWC Real-Time Nephanalysis, a 25-nautical mile cloud analysis data base that contains both satellite and conventional observations;
- FNOC global sea surface temperature products;
- SSM/I data—a seven-channel microwave imaging radiometer, with a subpoint resolution of 25 kilometers. The Metsat DPSS data base will contain both SSM/I brightness temperature fields and environmental data records (EDRs) such as soil moisture, ocean surface wind speed, and precipitation measurements; and
- SSM/T data—a seven-channel sounding microwave radiometer, with a subpoint resolution of 170 kilometers. The SSM/T will be available in a raw format and will be used by NESDIS to produce atmospheric temperature soundings for subsequent distribution to NMC, AFGWC, and FNOC.

*Data Access.* NOAA is responsible for collecting and distributing environmental data in near-real time as required for operational use, and for retaining select data sets as part of the national archive. These activities are carried out through the joint efforts of the National Ocean Service (NOS), the National Weather Service (NWS), and the National Environmental Satellite, Data, and Information Service (NESDIS). Both the operational and retrospective data management services provided by NESDIS support the NWS and NOS as well as the National Marine Fisheries Service and the Office of Oceanic and Atmospheric Research (OAR). They also support other U.S. and international government agencies, research institutions, and the private sector.

Recent developments in both satellite and ground-based sensory technology have caused the volume of operational data acquired by NOAA to increase by orders of magnitude. The current NOAA AVHRR system, for example, produces a data stream of 6 billion bits per day. Next-generation polar-orbiting instruments have been proposed that will produce over 300 times that amount. Ground-based systems currently being developed, such as the Next-Generation Weather Radar (NEXRAD) and

demonstrations of the Doppler Radar for Wind Profiling (Profiler) will generate data at similar rates of increase.

NOAA's present near-real-time satellite data distribution capability consists of an outdated system of telephone circuits and analog facsimile equipment. For example, the existing system for transmitting sectorized GOES infrared and visible images in analog, facsimile format, via telephone lines through the satellite field service stations, uses equipment that is over 10 years old. Also, dedicated telephone circuits are becoming more expensive. Although the GOES-Tap system continues to be a reliable means of accessing the GOES imagery, today's technology offers more attractive and cost-effective alternatives.

These increases in the volume of operational data also affect the way data are selected and stored in NOAA's historical environmental data base. Projections based on programs already underway show that by 1989, NOAA's data management system, as it now operates, will not be able to handle the volume and complexity of incoming retrospective data. In addition, the data base is not responsive to the increasing number of retrospective data users who need information more quickly.

In response to the challenges presented by increasing data volumes, the opportunities presented by recent advances in data management technologies, and the needs of programs such as those proposed for the Global Change Program, an upgrade to the NOAA data management system is planned, to possibly include operational data distribution and historical data management.

*Near-Real-Time Data Distribution.* Development of a new system (NOAAPORT) to replace currently used telephone circuits with a technologically up-to-date telecommunications system to distribute environmental data and products to the user community, including both government and private sector groups, in near-real time. The system is being planned to receive data from various NOAA and non-NOAA sources, prepare them for distribution, and broadcast them to multiple receiver sites. If fully implemented, NOAAPORT would provide an advanced, near-real-time data distribution capability to support programs now planned by NOAA for operation in the 1990s.

It is anticipated that NOAAPORT would be implemented incrementally. In 1987, NOAA plans to begin partial implementation of Phase I of the system in which data would be distributed to a limited number of NOAA field sites. Phase I would be designed to meet NOAA's immediate near-real-time data distribution needs in three areas.

The NWS communications system is overloaded. As a result, some National Meteorological Center (NMC) guidance and analysis products are now being delayed in their delivery to field forecast offices. The planned Phase I of NOAAPORT would provide a means of directing these

NMC products and guidance materials from the presently overloaded system to a more timely delivery via NOAAPORT.

NOS collects and provides oceanic data, including observations, oceanographic model output, derived products from Geosat, and ice analyses, which are of great value to NOAA's oceanographic user community. Plans for Phase I NOAAPORT include developing an adequate means of distributing these and other NOS data and analyses in near-real time.

OAR does not currently have a means of distributing research data and information from new observing systems such as the Profiler and development analysis systems such as PROFS. The plans for Phase I NOAAPORT provide for the distribution of selected NOAA research data streams to the NWS, to OAR laboratories, and to academic institutions.

Functionally, if implemented, NOAAPORT Phase I would provide a means of delivering NWS, NOS, NESDIS, and OAR data streams from source locations (Suitland, Maryland, Wallops, Virginia, and Boulder, Colorado) to user locations in the United States. Phase II of NOAAPORT is being planned as part of the NWS Advanced Weather Interactive Processing System for the 1990s (AWIPS-90). NOAAPORT requirements have been included in the definition phase of this system and are planned to be part of the development, design, and deployment as well. A major milestone was achieved in this process on December 17, 1986, with the release of the AWIPS-90/NOAAPORT Request for Proposal (RFP) for Definition Phase contracts. Proposals have now been submitted and are being evaluated.

If implemented, Phase I NOAAPORT would remain in service until the AWIPS-90/NOAAPORT system is fully deployed, currently anticipated for the mid-1990s. At that time, NOAAPORT would include virtually all NOAA data and information requiring point-to-multi-point dissemination to users in near-real time, such as full resolution GOES-East and West, Polar-Orbiting Operational Environmental Satellite (POES) global area and local area coverage, AWIPS-90 centrally collected and processed products and guidance, and products from non-NOAA satellites (Meteosat, GMS, ERS-1).

**Retrospective Data Management.** Also under consideration is an upgraded data management system that would take advantage of existing and emerging technological advances to maximize the value of retrospective environmental data. The system upgrade would include a suite of data management and user service capabilities designed to meet the needs of U.S. industry and research through the year 2000. The goal of the system upgrade would be to provide improved data management capabilities in the areas of data management planning, data-

base maintenance, user services, and external data system links.

While NOAA will continue to maintain the national archive for environmental data, it is not practical permanently to archive all levels of all the oceanic and atmospheric data produced by modern, high-tech environmental monitoring systems. The data management planning system being considered would define data base requirements as a primary function.

Plans also include an upgraded retrospective data base maintenance capability designed to handle increasing data volumes through improved data base planning, the use of advanced processor technology, high-density storage, communications, and innovative applications software. If implemented, this would allow improvements in NOAA's capacity to receive, select, process, and quality control the vast amounts of Earth platform (conventional) and space platform (satellite) data that will be generated by NOAA programs planned or being considered for the 1990s (e.g., NEXRAD, Profiler, ASOS, Polar Platform, AWIPS-90, GOES-I/M, and PROFS).

The total NOAA planned data base *would not* be maintained on-line. The data maintenance system would be designed to provide an efficient means of interfacing the primary data base (maintained off-line) to an improved user services function to permit rapid access to data regardless of storage location.

## Department of the Interior

**National Satellite Land Remote Sensing Data Archive.** NOAA and the U.S. Geological Survey signed a Memorandum of Agreement in 1986 to establish and operate the National Satellite Land Remote Sensing Data Archive at the EROS Data Center. This Memorandum was in response to requirements of Public Law 98-365 that direct the Secretary of Commerce to provide long-term preservation and upgrading of a global, land remote sensing data set (termed "the basic data set") for historical, scientific, and technical purposes, including long-term global environmental monitoring.

The basic data set will be used for long-term global monitoring, as well as for remote sensing and Earth resources research and development. It will consist of Landsat and other U.S. satellite data acquired over the past decade, as well as any future data to be acquired by U.S. and foreign, operational and experimental, and commercial and governmental satellite remote sensing systems.

## Data From DOD and Foreign Satellites

Environmental data from Department of Defense (DOD) satellites (Geosat and DMSP) and foreign satellites

(ESA's ERS-1 and Canada's Radarsat) will be jointly processed and shared as follows:

**DOD (Geosat, DMSP).** A number of data processing upgrades have been completed or are underway. In 1986 the interactive Satellite Data Handling System (SDHS) became operational at AFGWC. A three-phased upgrade to SDHS, called the Satellite Data Support System (SDSS) will provide the operational capabilities needed in the future, permit full implementation of the Shared MET-SAT Data Processing Agreement, and feed products to the Air Weather Service Automated Weather Distribution System (AWDS) now in development. Under the shared processing agreement, beginning in 1986, the Navy began to process ocean-related data; the Air Force, polar-orbiting imagery data; and NOAA, atmospheric sounding data. Data exchange among the three will process up to 2 million operational wind reports, 60,000 wave reports, and 50,000 SST reports per day. The Domsat system will also provide for a major increase in processing sea ice, precipitation, soil moisture, and snow cover data. PROFS has provided support to SDSS studies.

**ERS-1 and Radarsat.** Sea-ice data acquired by Synthetic Aperture Radar (SAR) on ERS-1 and Radarsat will be acquired and shared through a NASA ground-receiving station at Fairbanks, Alaska. Wind velocity data from the Radarsat scatterometer (RSCAT) will be at both Fairbanks, Alaska and Wallops Island, Virginia and then forwarded directly to Navy's Fleet Numerical Oceanography Center (FNOC), in Monterey, California for processing under the shared-processing agreement. NOAA is discussing access to data from ERS-1 and Radarsat with ESA and the Canada Centre for Remote Sensing.

**Data Management.** NOAA will provide Level II data (geophysical data located in time and place) in near-real time and retrospectively (archive) through the shared-processing system. The increased data acquisition levels require a national data archive larger than is presently available.

#### **D. Proposed Concept for the Space Station Era**

The Earth is a unique planet, receiving the proper amount of sunlight and having the required surface materials to support many complex processes. Earth scientists have begun to think quantitatively about how the Earth works, including interior, surface, and atmosphere processes. Increased attention is also being given to the Earth as an interrelated system in which processes operate across

the boundaries between the interior, surface, and atmosphere.

A major new capability proposed for Earth remote sensing is the Space Station Polar Platform. This new satellite concept is characterized by a coordinated, interdisciplinary approach involving the synergistic and interchangeable use of a broad array of sensors operating across the electromagnetic spectrum from ultraviolet to microwave. The Space Station Platform could accommodate energy intensive remote-sensing techniques such as Synthetic Aperture Radar (SAR) and LIDAR. It could also support and maintain accurate pointing of colocated instruments, including larger passive optical systems. As currently planned, the Space Station Polar Platform will reside in a near polar orbit and will be designed for shuttle servicing, and instrument augmentation and replacement. The platform's on-orbit servicing would permit larger instrument investments than have been practical in the past because servicing can guarantee their use for a decade or longer. Servicing also may extend the life of the spacecraft system, thus freeing resources for investments in instruments and data systems. A similar improvement in geostationary orbit is also envisioned but not by the end of this century. Therefore, the following discussion of specific operational and research missions for this long-term plan focuses primarily on the Polar Platform as a vehicle for basing remote-sensing instruments. This discussion presents the potential characteristics of a Polar Platform program. The configuration and instrumentation of the Polar Platform are still under review and have not yet been determined.

NOAA and NASA are currently studying how to make their planned missions compatible and capable of sharing the same orbiting resources. NOAA will also conduct joint design studies in 1987 and 1988 for an upgraded visible and infrared radiometer to replace the AVHRR. In conjunction with this design study, NOAA and DOD will jointly assess the cost and technical impacts of designing a common imaging sensor that meets the NOAA and DOD requirements. This will include unique DOD requirements for variable nodal crossing time, constant resolution across image scan, nighttime visible imagery, and survivability.

#### **Flight Systems Planning**

##### **NASA: Eos—The Earth Observing System of the 1990s**

**Overview.** The Earth Observing System (Eos), undergoing preliminary definition by NASA for the 1990s, is intended to provide the observational capabilities and information system needed for understanding the Earth's system and for stressing those global processes that operate at or near the Earth's surface. Concepts for the proposed

system, termed Eos for the Greek goddess of dawn, were developed by an Eos Science and Mission Requirements Working Group. These concepts attempted to reflect the emerging recommendations of the ESSC. The Eos is still in the preliminary definition stage. Inclusion of the Eos platforms, instruments, and information systems are subject to future budget decisions.

NASA's concept for Earth remote sensing in the closing years of the 20th century is based on a new level of sophistication in remote-sensing technologies and an integration of Earth-observing activities. To serve the unifying goal of understanding the Earth as a system and coordinating information about the Earth for human benefit, the proposed plan for the Earth Observing System Data and Information System (EOSDIS) addresses the need for coordinated observation of the land, oceans, and atmosphere. The plan recognizes the complementary roles of research and operational organizations in providing the data needed to accomplish this goal. The plan is based on the continued use of both polar-orbiting and geostationary satellites as bases from which to conduct remote-sensing of the Earth, with an increased emphasis on data processing and distribution and the rapid exchange of scientific analyses and results.

The cutting edge in future Earth research currently appears to lie in the global-scale integration of the physical, chemical, and biological processes. Progress in this arena depends on a balanced program of theoretical modeling, laboratory measurement of fundamental properties, in situ measurements of detailed natural processes, and remote sensing of the globe. The remote-sensing component of this activity will focus on making coordinated observations, using instruments designed to provide an integrated set of measurements of the land, oceans, and atmosphere. The long-term strategy is to achieve global coverage with Sun-synchronous, polar-orbiting satellite observations. Continuous viewing of rapidly changing phenomena will still be obtained through an international set of geostationary satellites, including the U.S. GOES.

*Elements of an Implementation Strategy.* The strategy outlined by the science working group for implementation of Eos has seven elements, which are as follows:

- Implement the Earth science missions currently proposed within NASA. They are the approved Upper Atmosphere Research Satellite (UARS), the Ocean Topography Experiment (TOPEX/Poseidon), and the unapproved Geopotential Research Mission (GRM). Implement the planned series of experimental flights on the Space Shuttle, including the SIR-series synthetic radar measurements and the Shuttle Imaging Spectrometer Experiment (SISEX). These measurements provide a data base that Eos can build on and, in the case of the Shuttle experiments,

mechanisms for focusing instrument development and evaluation.

- Use sustained observational capabilities offered by operational satellites, without waiting for the launch of new missions: specifically ATN, GOES, Landsat, non-U.S. geostationary meteorological satellites, ERS-1, MOS-1, and other ocean-observing satellites (as they are developed).
- Put first priority on developing a system designed to allow user access to mission operations, to Eos data, and to other relevant data sets, and have the required capability functioning prior to putting Eos instrument complements in orbit.
- Deploy the NASA proposed Advanced Data Collection and Location System (ADCLS) as part of Eos to support and aggregate in situ observations. The ADCLS would transmit ground data to satellites for later transmission to convenient receiving stations.
- Put a substantial new observing capability in low Earth orbit for sustained measurements over a decade or longer, with flexibility to capitalize on new technologies.
- Group instruments into synergistic packages that exploit their synergistic capacities to maximize the scientific utility of Eos and minimize the costs of implementation.
- Implement a vigorous program of Eos data analysis, including acquisition of group and other in situ observations, to help interpret the spaceborne data.

The first two elements form a foundation from which Eos can execute the others. The full resolution of the questions posed for the Earth sciences will also require efforts beyond these elements, especially the exploitation of enhanced geostationary observing capabilities as they become available. At present the Eos Science Steering Committee, the follow-on to the Working Group, is considering such orbits.

*Eos Instrument Packages.* Three proposed Eos instrument packages, grouped to maximize the synergy of observations, are now described. Selected components from each package could be placed on a given Platform.

Meeting the instrument requirements associated with the packages requires a continuing program of instrument development. Some of the instruments for Eos can be ready in the 1990s only if their development is begun soon. However, several of the instruments planned for Eos are derivatives of existing instrument programs, such as the SAR from the SIR series on the Shuttle, the HIRIS from the Shuttle Imaging Spectrometer Experiment (SISEX) on the Shuttle, and the upper atmosphere composition instruments from UARS. The time lag between the definition of an instrument concept and the initiation

of successful, continuous operation from space is such that a coordinated, ongoing program of instrument development is needed.

*Surface Imaging and Sounding Package (SISP).* SISP is a proposed package of instruments that includes moderate and high spatial resolution imaging spectrometers, a multifrequency microwave radiometer, and a LIDAR atmospheric sounder and altimeter. Although some of these instruments use proven technology, others are still in the engineering design phase. However, with proper attention and funding, they could be ready for flight in the 1990s.

The proposed SISP will investigate the Earth's fluid and solid surfaces and interactions among the surface, oceans, and atmosphere. Some observations of this class have been and continue to be made, but improvements to these measurements are essential for understanding the biosphere and related physical and chemical processes. In particular, mapping of geological materials and the understanding of biogeochemical cycles, the hydrologic cycle, and the world climate will require the types of new measurements to be provided by SISP. These new data sets will be used to obtain fundamental data on these processes.

SISP will also provide repetitive observations over extended periods. Long time series observations are important in many disciplines. For example, biological systems are highly dynamic and vary on temporal and spatial scales spanning many orders of magnitude. Deciphering such variability is a major research concern that is greatly aided by repetitive, synoptic data. SISP offers a dramatic advance in the examination of such systems because of its excellent spatial, temporal, and spectral resolution. The possibilities of global-scale recognition of individual species or functional groups of organisms and the complex patterns typical of ecosystems will profoundly change ecological study.

*Sensing with Active Microwave (SAM).* SAM is a proposed package that includes instruments using active microwave techniques and requiring high-inclination, near-polar orbits. SAM includes (1) a Synthetic Aperture Radar (SAR), (2) a radar altimeter (ALT), and (3) a radar scatterometer (SCAT). All of these instruments are highly developed, although the multiple-look angle, multiple-frequency imaging radar has yet to be implemented.

A high-inclination SAM mission can meet many objectives in geology, agriculture, forestry, land cover, dynamic oceanography, and the cryospheric sciences. The most demanding instrument in this group is the SAR for power, weight, cost, data rate, and complexity. The ALT, SCAT, and SAR form a particularly synergistic instrument package for ocean and ice applications. The radar altimeter, depending on the choice of frequency, could also be used for measuring land topography, although laser or stereo-

grammetric-imaging techniques are expected to provide significantly better resolution.

The SAM instrument grouping exemplifies the interactive synergistic aspects of the Eos concept: global and local coverage of dynamic and quasi-static phenomena, and a major step in observational and instrumentation capabilities.

*Atmospheric Physical and Chemical Monitor (APACM).* The focus of the proposed APACM package is the chemistry and physics of the atmosphere. APACM will include a Doppler LIDAR, an interferometer for measuring upper atmosphere winds, instruments for determining the chemistry of trace elements and compounds, and instruments for measuring the solar flux and the particle and field environments.

*Summary.* The concept of the NASA-proposed Eos for the 1990s represents a change from past NASA approaches to the Earth sciences. The proposed Eos is an information system that includes spaceborne observations, ground observations, a data collection system, and a program of scientific analysis. To meet Eos science objectives requires establishing a data system to handle Eos data in a geographically distributed environment. The system should also facilitate access to other NASA data and data from other agencies. Data needs to be maintained over a long period to answer some of the major Earth science questions, such as biogeochemical cycling, causes of climatic variations, and others as posed by the ESSC. Thus, existing and planned research and operational satellites should proceed and their data should be available. If Eos is implemented as an information system (i.e., EOSDIS)—including the proposed observing capabilities in the reflected, thermal, and microwave parts of the spectrum that will be enabled by the suggested instrument packages—significant advances can be expected in our understanding of global processes operating on the Earth's surface.

#### ***NOAA: Proposed Space Station Polar Platform Plan***

*Overview.* The NOAA interest in the proposed Polar Platform of the Space Station is based on the potential for improved services and/or reduced costs of procurement of the system. In addition, the proposed instruments offer tremendous advantages for research and operations. For the former interest, there is the advantage of complementary measurements made simultaneously at the same location. For the latter, there is the possibility of research instruments moving directly into operation if the instruments prove operationally useful.

NOAA's interest in the proposed Polar Platform derives from NOAA's operational mission: (1) the Polar Platform could be a major step in operational Earth observations if it is explicitly designed to be such a step from the very outset and (2) the operational payload for the platform is

essentially known today. The operational payloads of the 1990s will be the direct result of the successful flight of operational and research missions of the 1980s. There is no present technical obstacle to developing a useful Polar Platform capable of producing dramatic advances in the practical applications of space systems in the early 1990s. Decisions on whether and when to proceed will depend rather on budget considerations and Space Station priorities.

In the following discussion, the payload refers to the proposed operational payload, not to the accompanying research payload of the NASA Eos component of the national plan. Although some of the proposed instruments discussed below are still in research, it is assumed that they could be ready for operational use in the 1990s.

*Basic Principles.* In presenting the process by which a payload could be selected for an operational Polar Platform, the easiest approach is to divide the operational remote-sensing function into three segments: Atmosphere and Meteorology, Oceans and Ice, and Land. In each segment it is possible to make a brief statement about what can be measured and over what time scale. However, the separation of the remote-sensing function into segments is convenient but highly artificial. There is great synergism among the atmospheric and oceanographic instruments, and their coordinated use should lead to striking insights into ocean-atmosphere processes.

The sensor payload will be categorized first by discipline (atmosphere and meteorology, oceans and ice, and land); within each discipline will be the following instrument categories, as appropriate:

- Radiometers and imagers (visible, infrared, and microwave);
- Sounders (infrared and microwave); and
- Active sensors (altimeters, scatterometers, and SAR).

*Atmosphere and Meteorology.* The principal functions to be performed involve providing quantitative data for numerical weather prediction, quantitative and qualitative imagery data for local readout, environmental data collection from in situ sensors, and measurements related to climatic change. Equator crossing time would be chosen to meet the requirements of the synoptic weather models. There is some flexibility in setting the exact equator crossing times that is a function of ground data processing system capability. Therefore, the needs of users of data in the other two categories can effectively influence the ultimate choice of an equator crossing time within a reasonable range.

Proposed instruments include the following categories: radiometers and imagers, sounders, and active sensors.

*Radiometers and Imagers.* There will be a continuing requirement for an Advanced Medium Resolution Imaging Radiometer (AMRIR) operating in the visible and

infrared. The instrument would be a successor to the AVHRR flown on the NOAA-K through -M series of polar-orbiters. Normal progress in the user community will lead to improving the spatial resolution from the current value of 1 kilometer to a smaller value of only 500 meters. The applications of this sensor exemplify the dangers of using discipline categories, because this sensor spans all of the three categories used here. The applications include weather forecasting (particularly in remote areas and the developing world); precipitation estimation; global radiation balance studies; ice, snow, and frost mapping; sea surface temperature and ocean current mapping (in the absence of clouds); monitoring of hydrologic events; vegetation assessments; and continuation of the worldwide provision of Automatic Picture Transmission (APT) and High Resolution Picture Transmission (HRPT) services.

This sensor can provide daily global coverage, precise radiometric calibration, and multispectral coverage extending from the visible to the far infrared.

In the climate-related area there are two instruments: (1) a global ozone measuring device; and (2) Earth radiation budget radiometer. The Solar Backscatter Ultraviolet (SBUV) instrument was flown on Nimbus-7 and will also be flown on the ATN series into the early 1990s. The device provides data from which global maps of ozone concentration can be made. Long-term ozone trends can be estimated from these maps. The instrument proposed for the Polar Platform would be a follow-on instrument to the SBUV. Canada has expressed an interest in providing this device. It will be referred to below as a Global Ozone Monitoring Radiometer (GOMR). Similarly, the Earth Radiation Budget Experiment (ERBE) can be used as the model for the second instrument. These two instruments require a moderately high Sun angle and would not, therefore, be flown on an orbit with an early morning crossing time.

*Sounders.* The sounding system on the present series of NOAA polar-orbiters (NOAA-E through -J series) consists of the Microwave Sounding Unit (MSU) and the Stratospheric Sounding Unit (SSU) sensors mentioned above and the High Resolution Infrared Radiation Sounder (HIRS). This complement is called the TIROS Operational Vertical Sounder (TOVS). As previously noted, the NOAA-K through -M satellites will have the MSU and SSU sensors replaced by the AMSU. The new vertical sounder system will provide (1) better definition and resolution of the temperature sounding below cloud cover, (2) the capability to identify and quantify precipitation, (3) improved atmospheric water vapor measurements, and (4) an indication of soil moisture and snow or ice cover. The HIRS sensor will continue as an adjunct to the AMSU because it provides improved temperature soundings in the lower troposphere in clear air, it is used for long-wave



Earth radiation budget measurements, and it is also used to cross-calibrate the AMSU measurements.

The overall purpose of the new sounder system is to contribute measurements to the numerical forecast models. In the 1990s, these models will require a measurement spacing between soundings of 10-50 kilometers for regional models, 150 kilometers for global models, and 250 kilometers for global climate studies. These resolutions are accommodated by the AMSU/HIRS combination. The parameters of that combination are consistent with proposals for a Polar Platform. The sounder system will be designated the Advanced TOVS, or ATOVS.

**Active Sensors.** It is not anticipated that active sensors will be available for atmospheric measurements by the early 1990s. The active sensors flown for oceanographic purposes will provide surface wind speed and direction over the ocean. One candidate for later flight would be a coherent infrared laser radar system that is intended to measure the global tropospheric wind field with a horizontal resolution of 1 kilometer. Such a concept is included in NASA's proposal for the Polar Platform.

*Oceans and Ice.* The remarks made about observational frequency for the atmosphere and meteorology also apply to certain ocean and ice measurements. Since a changing fluid medium must be measured frequently enough to predict its behavior, the placing of oceanographic instrumentation on the Polar Platform is under consideration.

The objective of the sensors in this discipline category is to produce a timely, globally synoptic view of the world's oceans and mesoscale analyses of areas of special importance (e.g., the Extended Economic Zone). Sensors would continue the measurements carried out in the latter half of the 1980s by such spacecraft as TOPEX/Poseidon, Geosat, ERS-1, Radarsat, Japan's ERS-1 and MOS-1, and others.

The next few paragraphs will discuss the specific proposed instruments and their characteristics. The sounder category is excluded because no special sounding instruments, beyond those discussed in the preceding discipline category, are required for ocean and ice measurements.

**Radiometers and Imagers.** Two instruments are included: an advanced microwave radiometer, and the private sector ocean color instrument.

The advanced microwave radiometer will produce sea surface temperature measurements with a 25-kilometer spatial resolution and a 1.5K temperature resolution over a 1350-kilometer swath width. Wind speed will be determined over a range of 0 to 50 meters/second, with an accuracy of 2 meters/second or 10 percent, whichever is greater at 17-kilometer resolution. Sea-ice concentration will be measured to within  $\pm 15$  percent at 9-kilometer resolution and classified as new, first-year, or multiyear ice. Total atmospheric water vapor will be measured to within 0.2 gram/centimeters<sup>2</sup> at 9-kilometer horizontal resolution.

It may be desirable to complement the precise all-weather sea surface temperature measurements of the advanced microwave radiometer with the potentially very precise measurements of the Along-Track Scanning Radiometer (ATSR) that will be flown on ESA's ERS-1. This instrument uses an innovative scanning approach to derive an improved atmospheric correction and offers the possibility of providing accuracies near 0.3K.

The proposed private sector ocean color instrument would be an improved version of the CZCS that previously flew on the Nimbus-7 satellite. The characteristics of this instrument have been previously described (see Section A, this chapter).

**Active Sensors.** Three active sensors are proposed for the payload: (1) an altimeter, (2) a scatterometer, and (3) the Sea Synthetic Aperture Radar (SEASAR).

The altimeter would essentially be a duplicate of that flown on the Geosat mission. An alternative approach would be to use a TOPEX-quality altimeter, but that option can be left to a later decision. The Geosat-type altimeter would meet present operational requirements for measurements of significant wave height, surface wind speed, and ocean currents.

Similarly, the scatterometer would continue the measurements of sea surface winds made by NSCAT and use the same basic six-beam design. Again, the characteristics of the NASA scatterometer, NSCAT, are given in the discussion of satellite missions.

The SEASAR would build upon the advances in satellite SAR technology gained from missions beginning with Seasat in 1978 and culminating with SIR-D, anticipated to fly as part of Eos. The SEASAR proposed for the Polar Platform would allow multiparameter observations similar to SIR-D, using combinations of frequencies, polarizations, and incidence angles that work best for ocean monitoring. The key use is monitoring sea ice. Possible applications include observations of surface winds, wave structure, upwelling, currents, fronts, bottom morphology, oil slicks, entrained materials, and coastal refraction.

*Land.* The land measurements would be made principally with two imaging instruments, the Multispectral Linear Array (MLA) and possibly a Geologic Synthetic Aperture Radar (GEOSAR). The MLA is expected to be the instrument selected and operated by the private sector. Unlike the daily global coverage requirements of the meteorological and oceanographic instruments (without the SEASAR), the more limited swath widths of the land instruments would limit their repeat coverage of a given spot—in the absence of off-nadir pointing—to 16 to 18 days. On the assumption of 50-percent average cloud cover, the MLA would provide only monthly coverage of a given spot.

The MLA would be used for agriculture, forestry, range resources, land use and mapping, geology (rock types,

soils, volcanic deposits, and landforms), water resources monitoring, and environmental monitoring (surface mining, reclamation, pollution, and natural disasters). The MLA would be an instrument of the commercial Landsat operator.

The high spatial resolution measurements of the MLA system have only a coarse temporal resolution. MLA measurements will be complemented by land data derived from the medium spatial, but high temporal, resolution meteorological imager and radiometer that will evolve from the current AVHRR.

The GEOSAR would be the same instrument as the SEASAR but would operate with combinations of frequencies, polarization, and incidence angles that are optimum for land remote sensing. The GEOSAR would complement the MLA and be used in cartography, forest monitoring, structural and lithologic mapping, and to study water surfaces, soil moisture, glaciers, crops, and rangelands.

The MLA and the GEOSAR could share space on a platform. Off-nadir pointing would be a likely capability to be included in the MLA to permit more frequent revisits of chosen areas. Again, the high data rate associated with the instrument, and the relatively slowly changing phenomena it would observe, lead to the conclusion that only one GEOSAR is needed in orbit at a time.

*Other Payloads.* Other proposed auxiliary payloads include the Argos Data Collection and Platform Location System, the Search and Rescue Satellite-Aided Tracking (SARSAT) system, and the Space Environment Monitor (SEM).

*Orbits.* In any consideration of combining operational payloads under a Polar Platform concept, the obvious issue is the compatibility of the orbital requirements. The afternoon orbit is relatively inflexible, insofar as moving it farther away from noon. At a 1:00 p.m. crossing time, the orbit is well suited to the meteorological and oceanographic missions, because both perform synoptic analyses; the orbit also meets the high solar elevation angle requirement for the proposed ocean color instrument, GOMR, and ERBE. Further, the high solar angle aids in some agricultural assessments. High-resolution land measurements could use an early morning equator crossing time.

Early morning civil meteorological and oceanographic measurements are somewhat more flexible in the choice of an equator crossing time. In this instance, the Landsats have successfully operated from approximately 8:30 a.m. to 9:30 a.m., whereas the French SPOT system is in a 10:30 a.m. equator crossing time. Some in the geological and mapping community would prefer earlier times; others in the agricultural community would prefer later times.

*Summary of Platform Instrumentation.* From the discussion of past missions and their instruments and this over-

view, it is possible to identify payload candidates for a Polar Platform system. (See Appendix A, Table 24 for the proposed payload.)

*Repair and Servicing Issues.* For the proposed Platform to be permanent and outlive many generations of instruments, it would have to be flexible. Either through provision of excess capacity at the outset or the use of any of several modular construction techniques, the proposed Platform would have to be able to change and evolve.

Flexibility and reliability could lead to a Platform that is a constellation of elements rather than a single large structure. If the cluster approach were used, the segments would co-orbit so closely that they would appear as a single point source to ground radio telemetry stations; a single servicing mission could readily visit all segments.

Reliability also implies redundancy, and redundancy requirements can be related to the time between servicing missions. The time between servicing missions to a Polar Platform is a function of Shuttle capabilities from the west coast and cost.

Successful on-orbit servicing involves other issues than simply designing the equipment for convenient repair and developing astronaut techniques for carrying out the task. The first issue is whether the service person (or possibly robot) goes to the Platform or the Platform must return to Shuttle altitude for servicing. The former seems more reasonable, given the potential burden on the Platform and the need to remove the Platform from service during any altitude change, but does require that either an astronaut or a robot journey 400-500 kilometers above the Shuttle. This is a major technical challenge that would have enormous and very positive ramifications for space exploitation.

*Geostationary Satellites.* In addition to the Space Station Polar Platform Plan, NOAA will continue to develop the Geostationary Observational Environmental Satellite (GOES) Series.

The generation of GOES satellites (GOES-N) to follow the already procured GOES-NEXT series (see Section B of this chapter) represents the future of the U.S. geostationary remote-sensing program. No goal stands higher in NOAA's satellite priorities than improved atmospheric temperature soundings from geostationary platforms. More accurate temperature profiles versus height, from smaller fields of view, would greatly aid "mesoscale" (small area) forecasting and strengthen the hands of severe storm forecasters. A GOES-N sensor candidate is the High Resolution Interferometer Spectrometer (HIS), an instrument able to tune through a spectral band of thermal infrared energy in extremely small steps. The HIS designers hope that scans with the HIS will improve the accuracy of soundings and increase the vertical resolution of the soundings obtained. A laboratory version of the HIS is scheduled for aircraft flight test in 1985-86.

As with all other infrared sounders, the HIS fails when clouds obscure the ground. An alternative is a microwave sounder for GOES deployment. However, because of the required size of the dish antenna to obtain small fields of view at the Earth's surface from a geostationary instrument, the cost of a GOES microwave sounder would be prohibitive. Thus, it is currently not under consideration. Given changes in microwave and space system technology, it may become feasible early in the next century.

Other changes in future GOES spacecraft systems are possible. The Data Collection System (DCS) would be enlarged to include both additional channels (permitting thousands more remote-region sensing platforms) and higher data relay rates.

The economic value of warnings based on solar sunspot activity has led to consideration of deployment on future GOES spacecraft of a sensor to observe the X-ray image of the Sun. The sensor would supplement the existing high-energy SEM detectors. The Air Force and NOAA have completed a cooperative agreement to fly jointly at least one Solar X-Ray Imager on a GOES-NEXT satellite during the early to mid 1990s.

Modifications are also expected to future U.S. geostationary spacecraft to permit sharing of spacecraft with both Europe and Japan for mutual backup. Modification would include carriage of additional transmitter channels and command-recognition capabilities, so that in the event of spacecraft failures, geostationary spacecraft could be relocated and operated by either Japan or Europe. Their spacecraft, in turn, would carry the capability to respond to U.S. commands and transmit on U.S. data frequencies.

**Polar Platform Consolidation.** The objectives, instrumentation, orbital requirements, schedules, data management and transmission needs, and servicing techniques proposed by NOAA and NASA for the Space Station Polar Platform are currently being consolidated. NASA has proposed that data be transmitted over the Tracking and Data Relay Satellite System (TDRSS) as a primary mode of communication and that servicing be accomplished by lowering the platforms to Shuttle-reachable orbits. NOAA requires that some data be directly transmitted to users and that servicing of the Platform be performed with an absolute minimum interruption in operations.

## Data Systems Planning

**NASA: Current Activity.** The Earth Science and Applications Division (ESAD) and the Information Systems Office (ISO) recently implemented the Earth Science and Applications Data System (ESADS) initiative; this is a joint, direct effort at coordinating the data systems activities that support ESAD. A group of about 100 systems

experts, user scientists, and NASA Headquarters Data Systems Managers are participating in developing a plan and identifying specific actions that will move existing data handling facilities toward greater interoperability and greater sharing of resources. This is viewed as the first step in creating the tools needed to support demands for increased data handling capability by interdisciplinary and discipline-oriented scientists and to prepare for the anticipated data handling requirements of future, high data-volume missions, including Eos. The ESADS effort stresses near-term, achievable goals.

The initial focus of ESADS activities took place at a workshop in Easton, Maryland, in late February 1987. ISO is using the actions specified in the resulting ESADS Workshop Report to generate its FY 1988 call for Research and Technology Objectives and Plans (RTOPS) to the NASA centers. Ongoing groups—the ESADS Committee of Science Users and the Headquarters Earth Science and Applications Data Systems Managers—were formed to assure continuity of the process and implementation of the actions, as well as to plan a follow-up ESADS Workshop for early 1988.

The ESADS Committee has identified a subset of the recommended actions for immediate support. The specified actions fall in the areas of: (1) establishment and implementation of network standards; (2) completion of a standard system for labeling data formats to facilitate data exchange; (3) development of guidelines for deliverable flight project and general utility software; (4) collection and distribution of specific information on developing data storage technologies, solving the problems of inputting and exchanging catalog and directory entries among the involved data systems and agreeing upon critical terminology; (5) institution of guidelines for the scope and documentation of archived ancillary data, (6) development of efficient data ingest software, and (7) support for the convergence of user interface elements. Progress in these areas will be assessed during the year.

**NASA: Future Plans.** A vision of the future scientific data handling environment has been described by the Eos Data Panel in its report (NASA Technology Memorandum TM-87777, 1986). This environment involves interdisciplinary, interagency, and international exchange of data and information on a routine basis. Eventually, the concept calls for integrating new data sources, including the Eos science and applications sensors, into a total data system with access to past NASA satellite and associated nonsatellite (e.g., in situ) data sets: NOAA, USGS, the Earth Resources Observation System (EROS) Data Center, and Earth science data from other agencies; the NASA UARS data sets; relevant DMSP data, such as that from the SSM/I; and the European Space Agency's ERS-1 and Japanese MOS data, when available.

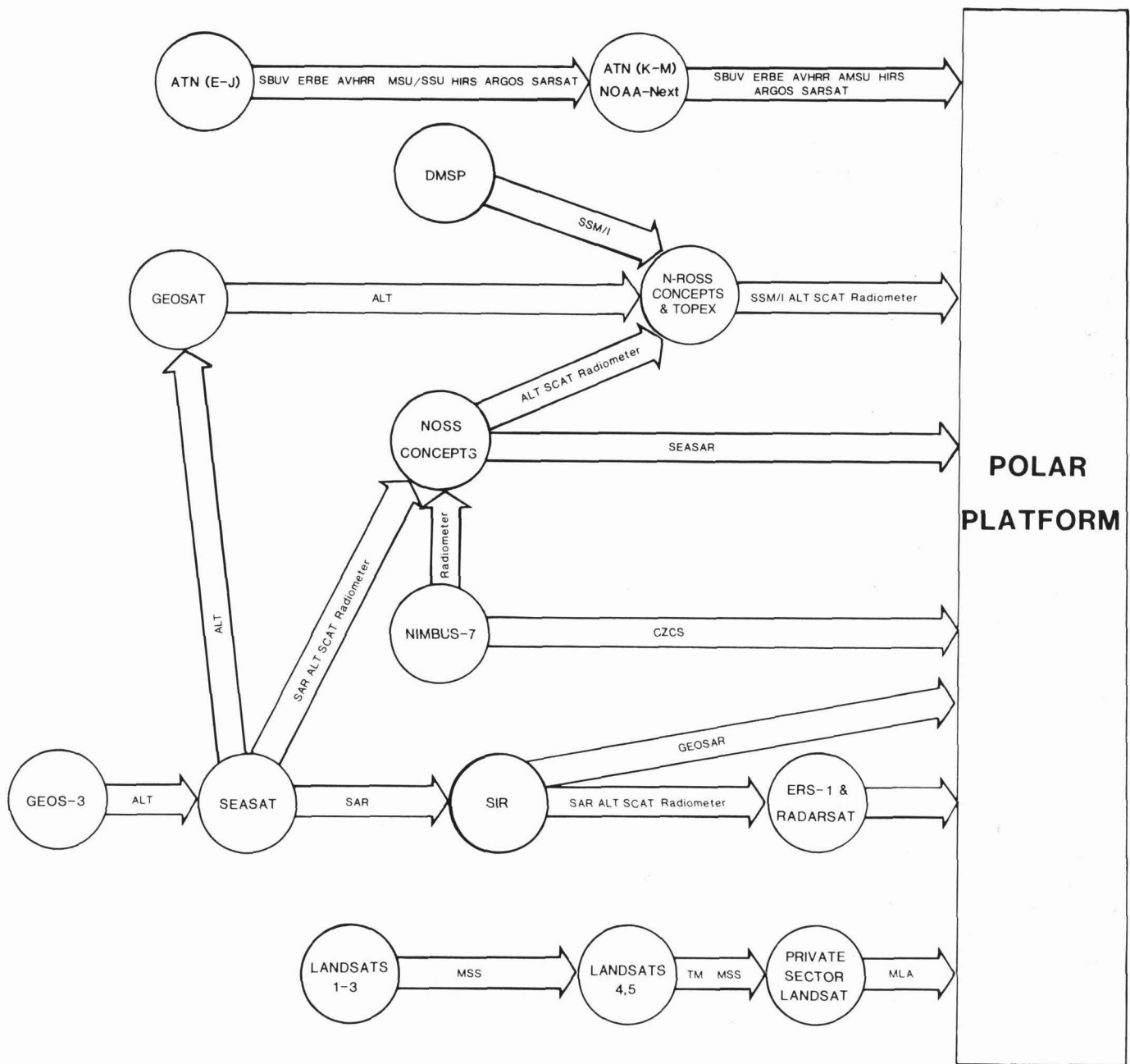


FIGURE 24. Flow of instruments to the Polar Platform.

This system would be internationally accessible, supporting many kinds of computer hardware and would handle all of such routine but important tasks as calibration, registration, and remapping. The system also must facilitate high volume data exchange. Other potential features of this concept are distributed and on-line utility and analysis software, computer bibliographies of relevant engineering and science documents, remote access to super-computers, and an accounting system to ensure appropriate and controlled access. Ultimately, the infor-

mation system should provide reasonably easy and fairly uniform access to extensive holdings of retrospective and recent data located in distributed repositories. Archives will vary in function, size, and longevity; permanent storage facilities providing reasonable access to vast quantities of data will be a part of this environment.

The goals of the ESADS initiative are to begin a process that will contribute directly to the realization of this long-term vision. Initial efforts must include development of the archiving and data processing tools using selected

retrospective data sets. Capabilities must be built incrementally, designed with a layered, modular architecture, and planned with an understanding that elements will need to be updated and modified frequently. It is appreciated that to preserve the flexibility needed to support research, data system development efforts should aim at standardizing interfaces rather than attempting to control the contents of all components.

In the next few years, a detailed plan will be developed to solve the problems of handling large time-series data sets. The plan will add artificial intelligence techniques to the arsenal needed to analyze multistream, multidimensional data flows, will develop rapid communication among distributed data storage and data analysis sites, will explore methods of accessing manageable subsets of vast data sets, and will investigate physical storage of all types of data in reasonably accessible form. With these tools, the scientific challenges of Earth System Science in the 1990s can be addressed successfully.

### *NOAA: Data Management for the Polar Platform*

*Overview.* The greatest challenge associated with the proposed Polar Platform concept is not the development and launch of the Platform or the development of new Earth observation instruments; instead, it is the processing and management of the myriad data streams that would originate on the Platform. Taking advantage of the potential provided by the instrument complement described in this document requires that unprecedented care be devoted to the design of the overall data system associated with the Platform. In this section a brief description will be provided of the issues associated with the data processing and archiving system. Also, the major system elements and their requirements will be outlined.

The key considerations in the design of a data management system for the Polar Platform are as follows:

- The Polar Platform data system must be developed as an integral part of a highly complex environment and not as an independent entity.
- Notably in meteorology and oceanography, but elsewhere also, the timelines for receipt, processing, and the transmission of products are very critical. It is largely true that excessively delayed data are useless data.
- Satellite data must be integrated with other data sets to have utility; there is no possibility for the development of a stand-alone observing system that can dispense with in situ and correlative data.
- Data from a given instrument on the Platform is likely to have multidisciplinary applications, and each discipline may require a different processing timeline and path.

- A given application is likely to require multisensor data sets that are readily accessible and available in a form that facilitates correlative use of the sets.

These requirements influence the principal system elements, which are

- Platform Mission Control Center (PMCC)
- Payload Operations Control Center (POCC)
- National Earth Observations Center (NEOC)

*Platform Mission Control Center (PMCC).* The PMCC would be responsible for the operation of the Platform and their support subsystems.

Telemetry data received at the PMCC would be used to monitor the condition and status of the Platform subsystems. In addition to being used for graphic displays at the consoles for the system controllers, these data would also reside in a System Control Processor, along with the status of various communication links (e.g., Tracking and Data Relay Satellite System [TDRSS], DOMSAT [Domestic Satellite], terrestrial), planned operating schedules, and other aids for the controllers.

The PMCC would also be responsible for scheduling major Platform events such as orbit boost and deboost, subsystem changes, reconfiguration of communication activities, deploying or stowing instruments, reprogramming or reconfiguring onboard computational resources, and commanding nonautomatic backup modes. Because instrument changes requested by the user communities would have to be compatible with current Platform capabilities, the PMCC would have to approve all instrument configuration change requests.

The PMCC would be responsible for generating, scheduling, verifying, and sending all commands to the Platform, irrespective of whether those commands relate to the Platform or its payload. This function includes selection of the appropriate communications path through TDRSS or one of the Command and Data Acquisition (CDA) stations. It would also include a Platform emulator that simulates the response of the Platform to various commands and ensures that an unexpected or unintended response would not endanger their health or disrupt operations.

Finally, the PMCC would extract attitude and ephemeris data and pass them to the Payload Operations Control Center (POCC). This would include processing Global Positioning System (GPS) data.

*Payload Operations Control Center (POCC).* The POCC would perform many of the functions for the payload that the PMCC performs for the Platform. Telemetry data relayed by the PMCC would be used to monitor the operation of each of the instruments in the payload. These data are used for graphic displays for the payload controllers and are stored with other data in the Payload Control Processor (PCP).

The POCC would develop instrument operating schedules for changing user requirements and Platform operating capabilities. These schedules would include turning some instruments off and on at chosen times and adjusting those times as necessary to account for such changes as seasonal scene lighting variations or—on a shorter time scale—the presence or absence of cloud cover over a particular area. The latter would influence selection of a particular sensor or set of sensors.

The POCC would also serve as the interface between the National Earth Observations Center (NEOC) and the PMCC. The POCC would send information needed in data processing to the NEOC system and payload. It would receive from the NEOC the data orders, special operating instructions, and other requests from the user communities.

*National Earth Observations Center (NEOC).* Before reviewing the functions of the proposed NEOC, it is necessary to provide definitions for the various data processing levels that will be used in the discussion. Five levels are used to describe the degree to which a given data stream has been processed.

- Level 0: Raw sensor output data. All raw sensor data plus position and attitude data in block telemetry form.
- Level 1: Preprocessed sensor data output. Sensor data Earth-located (latitude, longitude) and in engineering units. Data are time ordered, time tagged, and internal calibration and corrections have been applied. Data are “reversible” and in the Sensor Data Record (SDR) format.
- Level 2: Geophysical data output. Sensor-measured quantities converted to geophysical units. Instrument transfer function and environmental effects removed. Data are time-ordered, time-tagged, Earth-located (latitude, longitude), and in the Geophysical Data Record (GDR) format. Some external data are required to conduct processing.
- Level 3: Integrated sensor data outputs. Sensor-measured quantities processed into integrated geophysical data sets. These sets will vary with grid resolutions and geographic coverage. Processing will be automated if possible and may involve non-reversible smoothing, interpolation, and information blending with spatial and temporal averaging. External data may be required for processing and quality control.
- Level 4: Conclusionary extrapolations made from integrated sensor data and numerical pre-

dition models. These outputs include agricultural, meteorological, and oceanographic forecasts, advisories, and warnings. In situ and correlative data sets are likely to be required for this level of processing.

NOAA will encourage having the Level 3 and 4 processing (particularly some of the specialized services performed in Level 4) done by the private sector.

With these definitions in mind, it is now possible to discuss the overall data processing task that must be accomplished in conjunction with the Polar Platform system. Levels 0 and 1 data will flow through processing channels defined for each of the 17 operational sensors and be converted by Level 2 processing to GDRs. Most of the GDRs are employed in several Level 3 processing chains because many of the sensors have multidisciplinary applications. In addition, the multisensor data needs of many of the applications require that several GDRs be used to create a single Level 3 product.

A further aggregation occurs in the next stage of processing, in which several Level 3 products are used to develop forecasts or advisory information. In most instances, this is the first point where the nonspecialist or the general public is presented with results stemming from the remote-sensing system. All of the forecasts produced by Level 4 processing require in situ data as well as satellite observations.

The next step in examining the data system requirements is to derive the daily Level 0 processing load that the Polar Platform concept would accept. The low data rate stream could produce an average of 0.1 Mbps yielding about 9 gigabits of data per day. These are the data most important for forecasting models for the ocean and atmosphere and are also the data that have the most critical timelines. They must be processed in real or near-real time to meet deadlines.

The potential high data-rate stream is 500 Mbps. This corresponds to a daily collection of about 8500 gigabits (8.5 terabits) of data. In general, most of these data are intended for applications having a more relaxed timeline than the data intended for numerical forecasting models. Even here, however, substantial data backlogs would not be acceptable, because they are something from which it is not possible to recover.

Therefore, it is essential that the data system be designed for little or no buffering of the data in the low data-rate streams and for a zero backlog in the high data-rate channels over some brief period of time, neglecting the delay between making the measurement on the satellite and relaying it to a ground station. Whether that brief period is 24 or 48 hours, or some other period, must await a more detailed analysis of the data system than can be provided here.

Although the data rates and volumes appear high, they are not remarkably higher than the data volumes that are accommodated in the current operational system. A typical day sees the collection of 200 scenes from the Landsat Multispectral Scanner (MSS) and 50 scenes from its companion Thematic Mapper (TM). This represents about 128 gigabits of data. During the same period, about 96 images are taken by the geostationary operational weather satellites, yielding another 133 gigabits of data. The 28 daily orbits of the two polar-orbiting weather satellites produce another 35 gigabits of data. The sum of these is about 300 gigabits per day. Of these data sets, only the TM processing system has a sizable backlog; this is the result of an undersized data system rather than technology limitations.

The corresponding sum of the streams from the two Platforms plus the continuing data from the geostationary weather satellites would be about 13,000 gigabits (or 13 terabits) per day, less than 50 times the current rate of data collection. By segregating some of the processing chains and devoting them exclusively to a single sensor or set of sensors, and assuming only modest increases in data system technology over the next decade, there seems to be no reason to believe that the required data system would be beyond reach.

Because the proposed Platform concept would provide service to more than 100 countries and millions of people, rather than simply discretionary research data to a few dozen investigators, no compromise can be made in assuring reliability of operation and continuity of data from the core operational instruments. The design requirements for the PMCC, POCC, and NEOC must be developed with this view firmly in mind.

*Data Archives.* The intent of the following discussion on archives is to open issues for discussion, rather than to provide definitive answers. In NASA, NOAA, USGS, and elsewhere, the data archives have been the subject of intense debate. Unresolved issues include what data are to be archived, the format to be used, the accessibility requirements, the cost-recovery practices under which the archive is to be managed, the time frame for mandated depositing of data, the ancillary information to accompany the data, and many other considerations.

These are not issues that any one agency can resolve. A major interagency study is required with extensive input from the private sector, state and local governments, and the academic community. No one agency, company, or group of investigators has the breadth of view necessary unilaterally to establish national policy in this area. One small example may serve to illustrate the unusual directions that a study of data archives can take. NOAA's National Climatic Data Center is the country's repository for weather and climate records. The Center operates on a partial cost-recovery basis. If asked to predict what user group represents the largest paying customer of the facili-

ty, one might reasonably say that the largest customers would be professional climatologists or operators of weather-dependent activities (e.g., trucking firms, builders) or researchers or, maybe, architects. Each of these is indeed a data purchaser, but not the largest; attorneys are the largest single user group, representing 20 percent of the data sales. Not too far down the list are insurance claims adjusters, representing 8.2 percent of sales. The purpose in giving this example is simply to note that a wide spectrum of possible uses for data must be considered when data archives are designed, and that the motivations and requirements of the various users may be quite different. A start toward an interagency study of archiving requirements for the Space Station era has been made, however, with the NASA/NOAA Memorandum of Understanding, which contains guidelines for satellite data management systems.

The use of in situ data is inherent in the interpretation of satellite observations. The integration of conventional and satellite data is inherent in the production of a forecast of atmospheric, oceanic, or other phenomena. Unravelling problems in the Earth sciences requires that a retrospective user of a data archive have ready access to both satellite-derived and conventional data sets. These and other considerations lead to the conclusion that a geophysical data archive must provide for the storage and access to records stemming from satellites, other remote sensing systems, and in situ measurements.

Each of NOAA's data centers would receive appropriate data from the instruments on the proposed Polar Platform. The centers are currently linked by the Data Management and User Services (DAMUS) system that is intended to maximize the value of their environmental holdings to all users. Such networks will, of necessity, expand greatly to meet the needs of the information system described in this section.

The brief comments above illustrate the complexity of the data environment into which data from the proposed Polar Platform would have to fit, but even these comments provide only a hint of that environment's extent. For example, no mention has been made of the U.S. Geological Survey's EROS Data Center (EDC), with its large collection of satellite and aircraft imagery and its changing relationship with the private sector. Indeed, the private sector has been neglected entirely in this discussion and with it the very difficult issue of determining what data taken by private entities have long-term national interest warranting government support for its preservation, even though its market value would not warrant its upkeep. No mention was made of the Survey's National Cartographic Information Center (NCIC) either. These are only some of the largest and most obvious omissions. They illustrate, however, that a major interagency study on data archiving must be carried out to help the remote-sensing community cope with a Polar Platform potentially producing more than 10 terabits of data per day.

## **APPENDIX A**

### **Payload and Orbit Characteristics of the Various Missions**





Table 1A. **NOAA Advanced TIROS-N (ATN) Weather Satellites (E-J)**  
**1983-91 Launches—U.S.A.**

**Objectives of Mission:** Meteorological observations; measurements of sea surface temperature, sea ice, and snow cover; assessment of condition of vegetation

**Orbit Characteristics:** Polar, 833-870 km altitude, 7 a.m. and 2 p.m. equator crossing times

**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
AVHRR/2 (Advanced Very High Resolution Radiometer)	Cloud Temp., Sea Surface Temp., Land Temp., Vegetation Index	5	0.58–12.5 $\mu\text{m}$	1.1 km at Nadir 4 km at Edge of Scan	2,700 km
HIRS/2 (High Resolution Infrared Sounder)	Temp. and Moisture Profiles	20	3.8–15.0 $\mu\text{m}$	17.4 km	2,240 km
SSU (Stratospheric Sounding Unit)	Atmospheric Sounding, Temp. Profiles	3	14.7 $\mu\text{m}$ (Centered)	147 km	736 km
MSU (Microwave Sounding Unit)	Atmospheric Sounding	4	50.3–57.05 GHz	109 km	2,347 km
DCS (Argos) (Data Collection System)	Random Access from Buoys, Balloons, and Platforms	N/A	136.77 MHz 137.77 MHz	N/A	N/A
SAR (Search and Rescue)	Search and Rescue Operations	N/A	121.5 MHz 243.0 MHz 406.0 MHz	N/A	N/A
SBUV* (Solar Backscatter UV Experiment)	Solar Spectrum, Ozone Profiles, Earth Radiance Spectrum	12	252.0–339.8 nm	169.3 km	Nadir Viewing
ERBE (Earth Radiation Budget Experiment)	Determine Earth's Radiation Loss and Gain	8	0.2–50.0 $\mu\text{m}$	67.5 km	Horizon to Horizon
SEM (Space Environment Monitor)	Measurements of Solar Protons, Alpha Particles, "e" Flux Density	N/A	N/A	N/A	N/A

Note: N/A means not applicable.

\*P.M. satellite only

Table 1B. **NOAA Advanced TIROS-N (ATN) Weather Satellites (K-L-M)**  
**1992-95 Launches—U.S.A.**

**Objectives of Mission:** Meteorological observations; measurements of sea surface temperature, sea ice, and snow cover; assessment of condition of vegetation

**Orbit Characteristics:** Polar, 833-870 km altitude, 7 a.m. and 2 p.m. equator crossing times

**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
AVHRR/3* (Advanced Very High Resolution Radiometer)	Cloud Temp., Sea Surface Temp., Land Temp., Vegetation Index	6	0.58–12.5 μm	1.1 km at Nadir 4 km at Edge of Scan	Limb to Limb
HIRS/3 (High Resolution Infrared Sounder)	Temp. and Moisture Profiles, Radiation Budget	20	0.2–15.0 μm	17.4 km	2,240 km
DCS (Argos) (Data Collection System)	Random Access from Buoys, Balloons, and Platforms	N/A	136.77 MHz 137.77 MHz	N/A	N/A
SAR (Search and Rescue)	Search and Rescue Operations	N/A	121.5 MHz 243.0 MHz 406.0 MHz	N/A	N/A
SBUV† (Solar Backscatter UV Experiment)	Solar Spectrum, Ozone Profiles, Earth Radiance Spectrum	12	252.0–339.8 nm	169.3 km	Nadir Viewing
SEM (Space Environment Monitor)	Measurements of Solar Protons, Alpha Particles, "e" Flux Density	N/A	N/A	N/A	N/A
AMSU-A (Advanced Microwave Sounding Unit-A)	All-weather Temp. Profiles	15	23.0–90.0 GHz	40 km	2,240 km
AMSU-B (Advanced Microwave Sounding Unit-B)	All-weather Atmospheric Profiles (Water Vapor, Precipitation, and Ice)	5	90.0–183.0 GHz	15 km	2,240 km

Note: N/A means not applicable.

\*Channels 3a and 3b are time shared during day and night.

†P.M. satellite only

Table 2A. **Geostationary Operational Environmental Satellite (GOES)  
1985-87 Launches—U.S.A.**

**Objectives of Mission:** Operational weather data, cloud cover, temperature profiles, real-time storm monitoring, severe storm warning, sea surface temperature

**Orbit Characteristics:** Geostationary at east and west longitudes

**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
VAS (Visible and Infrared Spin Scan Radiometer)	Imaging—Day/Night Cloud Cover	5	0.55–0.7 $\mu\text{m}$ 3.90–14.7 $\mu\text{m}$	1 km—Vis 8 km—IR	Limb to Limb
[VISSR] Atmospheric Sounder)	Sounding—Temp. and Water Content	12	3.90–14.7 $\mu\text{m}$	7–14 km	Limb to Limb
DCS (Data Collection System)	Random Access from Buoys, Balloons, and Platforms	N/A	136.77 MHz 137.77 MHz	N/A	N/A
SEM (Space Environment Monitor)	Measurements of Solar Protons, Alpha Particles, "e" Flux Density	N/A	N/A	N/A	N/A
SAR (Search and Rescue)	Search and Rescue Operations	N/A	406.0 MHz	N/A	N/A

Note: N/A means not applicable.

Table 2B. **Geostationary Operational Environmental Satellite (GOES)  
1989-2000 Launches—U.S.A.**

**Objectives of Mission:** Operational weather data, cloud cover, temperature profiles, real-time storm monitoring, severe storm warning, sea surface temperature

**Orbit Characteristics:** Geostationary at east and west longitudes

**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
Imager	Imaging	5	0.55–12.5 $\mu\text{m}$	1 km—Vis 4 or 8 km—IR	Selectable Areas
Sounder	Atmospheric Sounding Temp. and Moisture Profiles	19	3.7–14.7 $\mu\text{m}$	4–8 km	Selectable Areas
DCS (Data Collection System)	Random Access from Buoys, Balloons, and Platforms	N/A	136.77 MHz 137.77 MHz	N/A	N/A
SEM (Space Environment Monitor)	Measurements of Solar Protons, Alpha Particles, "e" Flux Density	N/A	N/A	N/A	N/A
SAR (Search and Rescue)	Search and Rescue Operations	N/A	406.0 MHz	N/A	N/A

Note: N/A means not applicable.

Table 3A. **Landsat**  
**Launched 1972-85—U.S.A.**

**Objectives of Mission:** Operational and commercial data, land use inventory, geological/mineralogical exploration, crop and forestry assessment, cartography

**Orbit Characteristics:** Sun-synchronous, 705 km altitude, 98.22 degree inclination, 9:30 a.m. equator crossing time, 16-day repeat cycle

**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
MSS (Multi-Spectral Scanner)	Land Use, Urban Planning, Mapping, Agriculture, Forestry, Water Resources, Geology, Mineral Resources	4	0.5–12.6 $\mu\text{m}$	80 m	185 km
RBV (Return Beam Vidicon)	Same as Above	1	0.5–0.75 $\mu\text{m}$	40 m	185 km
TM (Thematic Mapper)	Same as Above	7	0.45–12.5 $\mu\text{m}$	30 m—Vis/IR 120 m—Thermal-IR	185 km

Table 3B. **Landsat 6**  
**Earth Observation Satellite Company (EOSAT)**  
**1989-92 Launches—U.S.A.**

**Objectives of Mission:** Operational and commercial data, land use inventory, geological/mineralogical exploration, crop and forestry assessment, cartography

**Orbit Characteristics:** Sun-synchronous, 705 km altitude, 98.21 degree inclination, 9:45 a.m. equator crossing time, 16-day repeat cycle

**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
ETM (Enhanced Thematic Mapper)	Land Use, Urban Planning, Mapping, Agriculture, Forestry, Water Resources, Geology	8	0.45–12.5 $\mu\text{m}$	15 m—Panchromatic 30 m—Vis/Near-IR 30 m—Shortwave-IR 120 m—Thermal-IR	185 km

Table 4. **Nimbus-7**  
**Launched 1978—U.S.A.**

**Objectives of Mission:** Monitor atmospheric pollutants, ocean chlorophyll concentrations, weather, and climate

**Orbit Characteristics:** Sun-synchronous, 955 km altitude, 99.29 degree inclination, equator crossing time at noon and midnight

**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
THIR* (Temperature Humidity Infrared Radiometer)	Map Global Cloudiness	2	6.5–7.0 $\mu\text{m}$ 10.5–12.5 $\mu\text{m}$	20.0 km 6.7 km	2,610 km
CZCS* (Coastal Zone Color Scanner)	Map Ocean Chlorophyll Concentrations	6	0.433–12.5 $\mu\text{m}$	0.8 km	1,600 km
SMMR (Scanning Multi-Channel Microwave Radiometer)	Sea Surface Temp., Near Surface Winds, Sea Ice, Snow, Rainfall, Soil Moisture, Water Vapor	5	6.6–37.0 GHz	25–150 km	780 km
ERB (Earth Radiation Budget)	Earth Radiation Budget on Synoptic and Planetary Scales, Solar Irradiance	22	0.2–50+ $\mu\text{m}$	1500 km—WFOV <sup>†</sup> 150 km—NFOV <sup>‡</sup> Solar—Disk	Horizon to Horizon
LIMS* (Limb Infrared Monitor of the Stratosphere)	Vertical Distribution of Temp., O <sub>3</sub> , NO <sub>2</sub> , HNO <sub>3</sub> , and H <sub>2</sub> O From Lower Stratosphere to Lower Mesosphere	6	6.1–17.2 $\mu\text{m}$	2 km Vertical	10–65 km Vertical
SAMS* (Stratospheric and Mesospheric Sounder)	Vertical Distribution of Temp., N <sub>2</sub> O, CH <sub>4</sub> , CO, and NO in the Stratosphere and Mesosphere	12	4.1–100.0 $\mu\text{m}$	10 km Vertical	10–70 km Vertical
SAM II (Stratospheric Aerosol Measurement II)	Vertical Distribution of Stratospheric Aerosols in Polar Regions	1	0.98–1.02 $\mu\text{m}$	1 km Vertical	5–40 km Vertical
SBUV/TOMS (Solar Backscatter Ultraviolet and Total Ozone Mapping Spectrometer)	Ozone Profiles, Total Atmospheric Ozone, Incident Solar UV Irradiance, and Backscattered UV Radiance	12—SBUV Fixed	250–340 nm	11.3 deg.	200 km
		1—SBUV Continuous	160–400 nm	11.3 deg.	200 km
		6—TOMS Fixed	312–340 nm	3.0 deg.	2,700 km

\*Not operational

<sup>†</sup>WFOV is wide field of view.

<sup>‡</sup>NFOV is narrow field of view.

Table 5. **Earth Radiation Budget Satellite (ERBS)**  
**Launched 1984—U.S.A.**

**Objectives of Mission:** Provide observation of the Earth's radiation budget

**Orbit Characteristics:** 610 km, non-Sun-synchronous, circular orbit,  
 inclined 56 degrees to the equator

**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
ERBE Non-Scanner (Earth Radiation Budget Experiment)	Measurements Across the Shortwave Band, Total Radiation, Total Output of Radiant Heat and Light from the Sun	1-4	0.2-3.5 $\mu\text{m}$ 0.2-50.0 $\mu\text{m}$	1,000 km along line of swath width	Limb to Limb— WFOV* 1,000 km—MFOV†
		5	0.2-50.0 $\mu\text{m}$	Full Solar Disc	N/A
ERBE Scanner	Reflected Solar Radiation, Earth Emitted Radiation	3	0.2-50.0 $\mu\text{m}$	40 km	40 km Scans Limb to Limb
SAGE II (Stratospheric Aerosol and Gas Experiment)	Stratospheric Aerosols, O <sub>3</sub> , NO <sub>2</sub> , Water Vapor	7	0.385-1.02 $\mu\text{m}$	0.5 km	N/A

Note: N/A means not applicable.

\*WFOV is wide field of view.

†MFOV is medium field of view.



Table 6. **Upper Atmosphere Research Satellite (UARS)**  
1991 Launch—U.S.A.

**Objectives of Mission:** Coordinated measurement of major upper atmospheric parameters

**Orbit Characteristics:** 57 degree inclination, 600 km altitude

**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Coverage
CLAES (Cryogenic Limb Array Etalon Spectrometer)	Global Synoptic Measurement of Nitrogen and Chlorine Ozone Destructive Species, Minor Constituents Temperature	8 Spectrally Scanned Channels	3.5–12.7 $\mu\text{m}$	2.8 km (Limb) 0.25 $\text{cm}^{-1}$ (Spectral)	50.7 km (Vertical Limb Coverage)
HALOE (Halogen Occultation Experiment)	Stratospheric Gas Species Concentrations	8 Fixed Channels	2.4–10.3 $\mu\text{m}$	2 km (Limb) (Gas filter-spectral)	6–150 km (Vertical Limb Coverage)
HRDI (High Resolution Doppler Imager)	Middle Atmospheric Winds	1 Spectrally Scanned Channel	400–800 nm	4 km (Limb) 0.001 nm (Spectral)	5–100 km (Vertical Coverage)
ISAMS (Improved Stratospheric and Mesospheric Sounder)	Atmospheric Temp. and Species Concentration	8 Spectrally Scanned Channels	4.6–16.6 $\mu\text{m}$	2.6 km (Limb) (Pressure Modulator-Spectral)	65 km (Vertical Limb Coverage)
MLS (Microwave Limb Sounder)	Vertical Profiles of Ozone and Oxygen, Wind Measurements, Inferred Pressure	3 Spectrally Scanned Channels	63–206 GHz	3 km (Limb) 50 mHz (Spectral)	15–85 km (Vertical Limb Coverage)
PEM (Particle Environment Monitor)	Precipitating Charged Particle Entry Measurements for Atmosphere	4 Measure- ments (Electrons, Protons, X-Rays, Magnetic Field)	1 eV–5 MeV (Electrons) 1 eV–150 MeV (Protons)	N/A	In Situ
SOLSTICE (Solar/Stellar Irradiance Comparison Experiment)	Solar Spectral Irradiance	3 Spectrally Scanned Channels	115–430 nm	Solar—0.12 and 0.25 nm Stellar—0.5 and 0.10 nm	Solar/Stellar Pointing
SUSIM (Solar-UV Spectral Irradiance Monitor)	Solar Flux Changes	7 Fixed and Spectrally Scanned Channels	120–400 nm	0.1 nm 1.0 nm 5.0 nm	Solar Pointing
WINDII (Wind Imaging Interferometer)	Doppler Shift of Energy, Upper Atmospheric Winds	1 Spectrally Scanned Channel	550–780 nm	4 km (Limb) 1 nm (Spectral)	70–310 km (Vertical Limb Coverage)
ACRIM II (Active Cavity Radiometer Irradiance Monitor)	Total Solar Irradiance	3 Fixed Channels	0.001–1,000 $\mu\text{m}$	Broadband	Solar Pointing

Note: N/A means not applicable.

Table 7. **Ocean Topography Experiment (TOPEX)/Poseidon\*  
1991 Launch—U.S.A.**

**Objectives of Mission:** Ocean topography, ocean current signatures

**Orbit Characteristics:** 1,334 km, 63.1 degree inclination, nominally circular orbit, 10-day repeat within  $\pm 1$  km

**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
ALT (Dual Frequency Altimeter)	Sea Surface Topography, Wave Height, Scalar Wind Speed, Content of Electron Ionosphere	2	13.6 GHz 5.3 GHz	1–3 cm (Vertical) 20 km $\times$ (2–10 km) (Horizontal) (Depending on Sea State)	2–10 km (Depending on Sea State)
Nonscanning Microwave Radiometer	Water Vapor Correction for Altimeter	3	18 GHz 21 GHz 37 GHz	42 km 35 km 22 km	42 km 35 km 22 km
Laser Retroreflector Array	Tracking by Ground Based Lasers for Precision Orbit Determination	N/A (Passive)	N/A	N/A	N/A
TRANET Doppler Beacon	Tracking by Ground Based Receivers for Precision Orbit Determination	2	150 mHz 400 mHz	N/A	N/A
GPS Demonstration Receiver	Tracking to GPS Satellites	2 (Passive)	1,227 mHz 1,575 mHz	N/A	N/A
Solid State Altimeter	Sea Surface Topography, Wave Height, Scalar Wind Speed	1	13.65 GHz $\pm 165$ MHz	<10cm (Vertical) 7 km $\times$ (2–10 km) (Horizontal) (Depending on Sea State)	2–10 km (Depending on Sea State)
Dual Doppler Receiver (Doris)	Tracking by Ground Based Transmitters for Precise Orbit Determination	2	401.25 mHz 2,036.25 mHz	N/A	N/A

Note: N/A means not applicable.

\*Potential involvement with France

Table 8. **Geopotential Research Mission (GRM)\*\*  
1994 Launch—U.S.A.**

**Objectives of Mission:** Measure gravity and magnetic fields for tectonophysics; mantle convection; internal structure and composition; crustal magnetic anomalies; and main magnetic field models

**Orbit Characteristics:** 160 km circular, polar, 90 degree inclination

**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
Doppler Tracking System	Satellite-to-Satellite Tracking	2	420 GHz 91 GHz	100 km	N/A
DISCOS (Disturbance Compensation System)	Drag-Free Orbit	N/A	N/A	N/A	N/A
Magnetometers (Scalar and Vector)	Magnetic Field Measurements	TBD	TBD	100 km	TBD

Note: N/A means not applicable; TBD means to be decided.

\*NASA is exploring the possibility of forming a joint mission with the European Space Agency.

†Not included in the President's FY88 budget.

Table 9. **Magnetic Field Explorer (MFE)\*\*  
Mid-1990s Launch—U.S.A.**

**Objectives of Mission:** Measurement of Earth's main magnetic field

**Orbit Characteristics:** 600 km circular, 97 degree inclination

**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
Scalar Magnetometer	Measurements of Earth's Surface and Interior Magnetic Fields	TBD	TBD	50 km	N/A
Vector Magnetometer	Measurements of Earth's Surface and Interior Magnetic Fields	TBD	TBD	50 km	N/A

Note: N/A means not applicable; TBD means to be decided.

\*NASA is exploring the possibility of forming a joint mission with the European Space Agency.

†Not included in the President's FY88 budget.

Table 10. **Defense Meteorological Satellite Program (DMSP)  
Continuing Program—U.S.A.**

**Objectives of Mission:** Operational weather data for DOD

**Orbit Characteristics:** Circular, Sun-synchronous, 833 km altitude, 98.7 degree inclination, current equator crossing times 0620 and 1010 ascending, period of 101 minutes

**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
OLS (Operational Linescan System)	Global Cloud Cover, Cloud Top Temperature, Sea Surface Temperature, Auroral Imagery	3	0.4–0.95 $\mu\text{m}^*$ 0.4–1.1 $\mu\text{m}$ 10.2–12.8 $\mu\text{m}$	0.62 km	2,963 km
SSM/T (Sensor System Microwave/Temperature)	Temperature Profiles	7	50–60 GHz	172 km at Nadir 296 km at Edge of Scan	1,595 km
SESS (Space Environment Sensor Suite)	Precipitating Electrons & Protons, Ambient Electron/Ion Temperature and Density, Plasma Drift, Scintillation, Geomagnetic Field Fluctuations	N/A	N/A	N/A	N/A
SESS includes: SSIE/S—Ionospheric Plasma and Scintillation Monitor SSJ/4—Precipitating Electron/Proton Spectrometer SSJ*—Dosimeter SSM—Triaxial Magnetometer					
SSM/I (Sensor System Microwave/Imager)	Precipitation, Soil Moisture, Wind Speed Over Ocean, Sea Ice Morphology, Cloud, Water, Liquid Water	7	19.3 GHz 22.2 GHz 38.0 GHz 85.5 GHz	50 km 25 km—Precip. Over Land, and Cloud Liquid Water Over Land	1,290 km
SSM/T-2 <sup>†</sup> (Sensor System Microwave/Water Vapor)	Moisture Profiles	9	91.5–183 GHz	40 km	1,596 km
SSB/A (Gamma and X-Ray Spectrometer)	Gamma and X-Ray Detector	4	15–120 KeV	102 km Along Track 204 km Across Track	2,778 km
SSB/S (Gamma Ray Spectrometer)	Gamma and X-Ray Detector	4	45–165 KeV	102 km Along Track 204 km Across Track	2,778 km
SSB/X	Gamma and X-Ray Detector	3	60–375 KeV	102 km Across Track 204 km Across Track	2,778 km

Note: N/A means not applicable.

\*Low light visible down to one-quarter full moon illumination

<sup>†</sup>First flight on satellite S-13

Table 11. **Geosat**  
**Launched 1985—U.S.A.**

**Objectives of Mission:** Gravitational measurements, oceanic data on windspeed, significant wave height, sea ice edge, fronts, detection of mesoscale features

**Orbit Characteristics:** 800 km altitude, 108 degree inclination, 152-day repeat cycle first 18 months, 17-day repeat cycle second 18 months

**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
ALT (Altimeter)	Surface Windspeed, Significant Wave Height, Sea Ice Edge	1	13.5 GHz	3.5 cm (Vertical) 1.8–8.1 km (Horizontal) (Depending on Sea State)	1.8–8.1 km (Depending on Sea State)

Table 12. **Meteosat 1-3**  
**Launched 1977–87—European Space Agency (ESA)**

**Objectives of Mission:** Operational weather data, cloud cover, water vapor imagery

**Orbit Characteristics:** Geostationary at 0 degrees longitude

**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
Visible and Infrared Radiometer	Day/Night Cloud Cover, Earth/Cloud Radiance Temp. Measurements	3	0.4–1.1 $\mu\text{m}$ —Vis 5.7–7.1 $\mu\text{m}$ —IR 10.5–12.5 $\mu\text{m}$ —IR	2.5 km or 5.0 km 5.0 km—IR	Limb to Limb
DCS (Data Collection System)	Random Access from Buoys, Balloons, and Platforms	N/A	N/A	N/A	N/A

Note: N/A means not applicable.

Table 13. **Geostationary Meteorological Satellite (GMS)**  
**Launched 1984—Japan**

**Objectives of Mission:** Operational weather data, cloud cover, temperature profiles, real-time storm monitoring, severe storm warning

**Orbit Characteristics:** Geostationary at 140 degrees E longitude

**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
Visible and Infrared Radiometer	Cloud Cover, Earth/Cloud Radiance Temp. Measurements	2	0.55–.75 $\mu\text{m}$ —Vis 10.50–12.50 $\mu\text{m}$ —IR	1.25 km 5.0 km	Limb to Limb
SEM (Space Environment Monitor)	Measurements of Solar Protons, Alpha Particles, "e" Flux Density	N/A	N/A	N/A	N/A
DCS (Data Collection System)	Random Access from Buoys, Balloons, and Platforms	N/A	N/A	N/A	N/A

Note: N/A means not applicable.

Table 14. **Indian National Satellite System (INSAT-I and -II)**  
**Launched 1983 with Follow-ons—India**

**Objectives of Mission:** Domestic telecommunications, meteorology, nationwide direct TV broadcasting to rural communities, and radio and TV program distribution for rebroadcasting/networking

**Orbit Characteristics:** Geostationary at 74 degrees east longitude, altitude 35,800 km

**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
VHRR (Very High Resolution Radiometer)	Day/Night Cloud Cover, Earth/Cloud Radiance Temp. Measurements	2	0.55–0.75 $\mu\text{m}$ —Vis 10.50–12.50 $\mu\text{m}$ —IR	2.75 km—Vis 11.0 km—IR	Limb to Limb
DCS (Data Collection System)	Random Access from Buoys, Balloons, and Platforms	N/A	402.75 MHz 4.0 GHz	N/A	N/A

Note: N/A means not applicable.

Table 15. **METEOR-2**  
**Launched 1977—U.S.S.R.**

**Objectives of Mission:** Meteorological observations; measurement of sea surface temperatures, sea ice, and snow cover; assessment of condition of vegetation

**Orbit Characteristics:** Near polar, 900 km altitude, 81.2 degree inclination

**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
Scanning Telephotometer (for direct imaging)	?	?	0.5–0.7 $\mu\text{m}$	2 km	2,100 km
Scanning Telephotometer (for global coverage)	?	?	0.5–0.7 $\mu\text{m}$	1 km	2,400 km
Scanning IR-Radiometer (for global coverage)	?	?	8.0–12.0 $\mu\text{m}$	2 km	2,600 km
Scanning IR-Spectrometer	?	8	11.0–18.0 $\mu\text{m}$	30 km	1,000 km
Radiometric Complex	?	N/A	Protons, Electrons, 0.15–90 MeV	N/A	2–4 Space Angle

Note: N/A means not applicable.

Table 16. **ESA Earth Remote Sensing Satellite (ERS-1)**  
**1989 Launch with Follow-ons—European Space Agency (ESA)**

**Objectives of Mission:** Provide all-weather imagery of oceans, coastal water, ice fields, and land areas  
**Orbit Characteristics:** Sun-synchronous, 777 km altitude, 10:30 a.m. equator crossing time, 3-day repeat cycle  
**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
AMI—SAR Mode (Active Microwave Instrument—Synthetic Aperture Radar)	Ice Topography, Geologic Structures, Wind Fields, Wave Spectra	1	5.3 GHz	30 m	100 km
AMI—Wave Mode (Wave Spectrometer)	Wave Direction, Wave Length	1	5.3 GHz	25 m	5 km × 5 km (Every 100 km)
AMI—Wind Mode (Active Microwave Instrument—Wind Scatterometer)	Surface Winds	1	5.3 GHz	50 km	500 km
ATSR—M Radiometer (Along Track Scanning Radiometer)	Sea Surface Temperature, Atmospheric Water Vapor Content	3	3.7–12.0 μm	1 km	500 km
ATSR—M Sounder (Along Track Scanning Radiometer with Microwave Sounder)	Atmospheric Profiles	2	23.8 GHz 36.5 GHz	22 km	500 km
PRARE (Precise Range and Range Rate Equipment)	Precise Orbit Determination	3	2.25 GHz 7.2 GHz 8.4 GHz	N/A	N/A
ALT (Radar Altimeter)	Sea Surface Topography	1	13.5 GHz	0.5 m (Wave Height)	Nadir Viewing

Note: N/A means not applicable.

Table 17. **Radarsat**  
**1992 Launch—Canada**

**Objectives of Mission:** High-resolution studies of arctic area, agriculture, forestry, and water resource management; ocean studies  
**Orbit Characteristics:** Sun-synchronous, 1,000 km altitude, 99.48 degree inclination, 3-day repeat cycle  
**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
SAR (Synthetic Aperture Radar)	Ice Topography	1	C or L Band	15–30 m	100 km
AVHRR* (Advanced Very High Resolution Radiometer)	Sea Surface Temp.	5	0.58–12.5 μm	1.1 km	2,940 km
RSCAT* (Radarsat Scatterometer)	Ocean Surface Wind Speed and Direction	1	14 GHz	25 km	600 km (Each Side)
Optical Sensor	TBD	TBD	TBD	TBD	TBD

Note: TBD means to be decided.

\*Proposed NOAA contributions



Table 18. **Marine Observation Satellite (MOS)**  
**Launched 1987 with Follow-ons—Japan\***

**Objectives of Mission:** Observation of the state of sea surface and atmosphere  
**Orbit Characteristics:** Sun-synchronous, 909 km altitude, between 10 a.m. and 11 a.m. equator crossing times, 99.1 degree inclination, 17-day repeat cycle

**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
MESSR (Multispectral Electronic Self-Scanning Radiometer)	Sea Surface Color	4	0.5–1.1 $\mu\text{m}$	50 m	100 km
VTIR (Visible and Thermal Infrared Radiometer)	Sea Surface Temperature	4	0.5–0.7 $\mu\text{m}$ 6.0–7.0 $\mu\text{m}$ 10.5–12.5 $\mu\text{m}$	0.9 km—Vis 2.7 km—IR	1,500 km
MSR (Microwave Scanning Radiometer)	Water Content of Atmosphere	2	23.8 GHz 31.4 GHz	32 km 23 km	317 km

\*MOS-1 Launched February 1987.

Table 19. **Systeme Probatoire d'Observation de la Terre (SPOT)**  
**Launched 1986—France**

**Objectives of Mission:** Operational land use and inventory monitoring system  
**Orbit Characteristics:** Sun-synchronous, 832 km, 98.7 degree inclination, 10:30 a.m. equator crossing time, 26-day repeat cycle  
**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
HRV (High Resolution Visible Range Instruments)	Land Use, Urban Planning, Mapping, Agriculture, Forestry, Water Resources, Geology	4	0.5–0.9 $\mu\text{m}$ (Multispectral Mode)	20 m	60 km
			0.5–0.73 $\mu\text{m}$ (Panchromatic Mode)	10 m	60 km

Table 20. **Earth Resources Satellite (ERS-1)**  
1991 Launch—Japan

**Objectives of Mission:** Global exploration of mineral and energy resources, management of agricultural and forestry resources, environmental monitoring and land use planning

**Orbit Characteristics:** Sun-synchronous, 560 km altitude

**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
VNIR (Visible and Near Infrared Radiometer)	Land Use, Mapping, Agriculture, Forestry, Geology, Mineral Resources	TBD	TBD	25 m	150 km
SAR (Synthetic Aperture Radar)	Ice Topography	1	1.2 GHz	25 m	75 km

Note: TBD means to be decided.

Table 21. **Indian Remote Sensing Satellite (IRS)**  
1987 Launch with Follow-ons—India

**Objectives of Mission:** Provide agricultural, geological, and hydrological data for survey and management of natural resources

**Orbit Characteristics:** Sun-synchronous, 904 km altitude, 22-day repeat cycle

**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
LISS-I (Linear Imaging Self- Scanner Sensor)	Land Use, Urban Planning, Mapping, Agriculture, Forestry, Water Resources, Geology, Mineral Resources	4	0.45–0.86 $\mu\text{m}$	73 m	148 km
LISS-II	Same as Above	4	0.45–0.86 $\mu\text{m}$	3.6 m	148 km

Table 22. **Laser Geodynamics Satellite-2 (LAGEOS-2)**  
1993 Launch—Italy

**Objectives of Mission:** Measure changes in plate tectonic motions

**Orbit Characteristics:** Circular orbit with 52 degrees inclination, 600 km altitude

**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
Passive Laser Cornucube Reflectors	Measure Range to Satellite	N/A	N/A	N/A	N/A

Note: N/A means not applicable.

Table 23A. **Space Station Polar Platform NASA Earth Observing System (Eos) Candidate Instruments 1994 Launch—U.S.A.**

**Objectives of Mission:** Provide Earth observation capability in the atmospheric, oceanographic, and land sciences, and in solar terrestrial research

**Orbit Characteristics:** 824 km altitude, 1-1:30 p.m. and 9:30 a.m. equator crossing time, ascending node 2-day repeat cycle

**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
MODIS-N (Moderate Resolution Imaging Spectrometer—Nadir)	Surface (Land) and Cloud Imaging	36	0.4–14.2 $\mu\text{m}$	0.5–1.0 km	1,500 km at 824 km altitude
MODIS-T (Moderate Resolution Imaging Spectrometer—Tilt)	Surface (Ocean) and Cloud Imaging	64	0.4–1.1 $\mu\text{m}$	1 km	1,500 km at 824 km altitude
HIRIS (High Resolution Imaging Spectrometer)	Surface Imaging	196	0.4–2.2 $\mu\text{m}$	30 m	26 km
LASA (LIDAR Atmospheric Sounder and Altimeter—First Phase of the Laser Instrument Initiative)	Altimetry, Cloud Top Height, Planetary Boundary Layer, Stratospheric and Tropospheric Aerosols, and Cloud Parameters	Multiple	UV, Vis, and Near-IR	Vertical Profiles to better than 2 km	Nadir Only
LASA-MOD (LIDAR Atmospheric Sounder and Altimeter—Second Phase of the Laser Instrument Initiative)	Water Vapor Column Content, Ozone Column Content, Water Vapor Profiles, Ozone Profiles	Multiple	UV, Vis, and Near-IR	Vertical Profiles to better than 2 km	TBD
GLRS (Geodynamic Laser Ranging System)	Geological Drift	1	Vis	cm-level accuracy	Pointable
SAR (Synthetic Aperture Radar)	Land, Ice, and Ocean Images	3	5.3 GHz (C Band) 9.6 GHz (X Band) 1.25 GHz (L Band)	30 m	25–100 km
Radar Altimeter	Ocean and Ice Topography	1	5.3 GHz 13.5 GHz	< 3 cm RMS Precision Height	63 km 24 km
Scatterometer	Vector Wind Field	1	13.995 GHz	2 m/s Wind Speed 10% Angular Resolution	120–700 km from subsatellite point
LAWS (Laser Atmospheric Wind Sounder)	Tropospheric Winds	1	9–11 $\mu\text{m}$	1 m/s	300 km

Note: Eos information is subject to change based on ongoing studies.

Table 23A. (cont.) **Space Station Polar Platform NASA Earth Observing System (Eos) Candidate Instruments 1994 Launch—U.S.A.**

**Objectives of Mission:** Provide Earth observation capability in the atmospheric, oceanographic, and land sciences, and in solar terrestrial research

**Orbit Characteristics:** 824 km altitude, 1-1:30 p.m. and 9:30 a.m. equator crossing time, ascending node 2-day repeat cycle

**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
NCIS (Nadir Climate Interferometer Spectrometer)	Tropospheric Composition of CH <sub>4</sub> , H <sub>2</sub> O, NO <sub>3</sub>	Multiple	6–40 μm	Total Column Density to 1 km; 0.1° to 1° horizontal	Nadir TBD
CR (Correlation Radiometer)	Tropospheric Composition of CO	2	4.66 μm	Total Column Density to 1 km; 0.1° to 1° horizontal	4.4° field of view ±5° to Nadir
TIMS (Thermal Infrared Imaging Spectrometer)	Surface Imaging	2	3–14 μm	30 m	25 km
MLS (Microwave Limb Sounder)	Upper Atmospheric Composition of ClO, O <sub>3</sub> , and many others	17	63–240 GHz	3 km vertical	Limb
F/P-INT (Fabry-Perot Interferometer)	Upper Atmospheric Winds	20	0.3–0.8 μm	3 km vertical	Limb
AMSR (Advanced Microwave Scanning Radiometer)	Precipitation, Snow and Ice, Sea Surface Temperature, Water Vapor	12	6–40 GHz	5 to 20 km Ground Resolution	1,500 km at 824 km Altitude
ESTAR (Electronically Steered Thinned Array Radiometer)	Soil Moisture	Multiple	1.4–6 GHz	10 km Ground Resolution at Nadir	1,000 km
IR Radiometer	Upper Atmosphere Composition of O <sub>3</sub> , N <sub>2</sub> O, Temp., and Wind	Multiple	8–25 μm	TBD	Limb 100 × 1.9° Field of View
PMR (Pressure Modulated Radiometer)	Upper Atmosphere Composition of CO, H <sub>2</sub> O, CH <sub>4</sub> , NO, NO <sub>2</sub> , N <sub>2</sub> O, CO <sub>2</sub> , HNO <sub>3</sub> , O <sub>3</sub> , Temp., Aerosols	5	4.6 μm 16.7 μm	2.6 km Vertical at Limb	Limb
Submillimeter Spectrometer	Upper Atmosphere Composition of OH, HCl, etc.	Multiple	0.05–0.1 cm	TBD	Limb 1.6 × 60° Field of View

Note: Eos information is subject to change based on ongoing studies. TBD means to be decided.

Table 23A. (cont.) **Space Station Polar Platform NASA Earth Observing System (Eos) Candidate Instruments 1994 Launch—U.S.A.**

**Objectives of Mission:** Provide Earth observation capability in the atmospheric, oceanographic, and land sciences, and in solar terrestrial research

**Orbit Characteristics:** 824 km altitude, 1-1:30 p.m. and 9:30 a.m. equator crossing time, ascending node 2-day repeat cycle

**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
Vis/UV (UV Visible Spectrometer)	Upper Atmosphere Neutral and Ionized Atoms	Multiple	300–1,200Å	TBD	Limb 30° Cone Angle
CIS (Cryogenic Interferometer/Spectrometer)	Upper Atmosphere Winds and Oxygen Thermal Emissions	Multiple	2.5 μm–1 mm	Horizontal 80 km × 300 km Vertical 3.5 km	Limb 20–150 km
ERBI (Earth Radiation Budget Instrument)	Radiation Monitor	5	0.2–50 μm	N/A	Limb to Limb
PEM (Particle Environment Monitor)	Magnetospheric Energy Input to Atmosphere	Multiple	N/A Multiple Energy Ranges for Electrons, Protons, X-Rays, and Magnetic Field	N/A	N/A
SUSIM (Solar Ultraviolet Spectral Irradiance Monitor)	Solar Irradiance	8	Variable	N/A	N/A
ADCLS (Argos +) Advanced Data Collection and Location System	Random Access from Buoys, Balloons, and Platforms	N/A	N/A	Location to 1 km Velocity to .3 m/s	N/A

Note: Eos information is subject to change based on ongoing studies; N/A means not applicable; TBD means to be decided.

Table 23B. Space Station Polar Platform NOAA Operational Payload/Candidate Instruments  
1994 Launch—U.S.A.

**Objectives of Mission:** Provide Earth observation capability in the operational atmospheric, and meteorological solar, terrestrial, and oceanic applications

**Orbit Characteristics:** 850 km circular Sun-synchronous orbit, 9 a.m. or 1:30 p.m. equator crossing times

**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
MRIR (Medium Resolution Imaging Radiometer)	Precipitation, Cloud Patterns, Earth Radiation Balance, Sea Surface Temperature, Currents and Circulation, Sea Ice, Coastal/ Estuarine Sediments, Vegetation Classification and Condition, Land Use, Pollution	10	.45–12.5 $\mu\text{m}$	250 m	2,940 km
AMSU-A (Advanced Microwave Sounding Unit-A)	Atmospheric Temperature Sounding	15	23.8–89 GHz	40 km	2,230 km
AMSU-B (Advanced Microwave Sounding Unit-B)	Atmospheric Water Vapor Sounding	5	89–183 GHz	15 km	2,230 km
HIRS/3 (High Resolution Infrared Sounder)	Atmospheric Temp. and Water Vapor Profiles	13	3.76–14.49 $\text{cm}^{-1}$	10 km	2,230 km
ATSR (Infrared SST)	Sea-Surface Temperature	3	3.7, 11, 12 $\mu\text{m}$	1 km	500 km
AMSR (Advanced Microwave Scanning Radiometer)	Cloud Moisture Content, Precipitation, All-Weather Sea Surface Temperature, Sea Surface Winds and Waves, Soil Moisture	12	6–90 GHz	20 km—at 6 GHz 2 km—at 90 GHz	120° Centered on Satellite Ground Track
Scatterometer	Sea Surface Winds and Waves, Currents and Circulation	1	13.995 GHz	25 km	600 km to Each Side Beginning 175 km from Nadir
Altimeter	Sea Surface Winds and Waves, Significant Wave Height, Currents and Circulation, Sea Ice	1	13.5 GHz	2.1° Beam Width	Nadir-Pointing
MEPED (Medium Energy Proton and Electron Detector)	Protons, Electrons, and Ions	N/A	30–80 KeV	N/A	N/A
Precipitating Electron, Proton, and Cumulative-Dose Spectrometer	Electron and Proton Dose	8	e—1–10 MeV p—20–75 MeV 30eV–30 KeV (cum. dose)	N/A	N/A
Ionospheric Plasma Monitor	Ambient Electron and Ion Density and Temperature	N/A	N/A	N/A	N/A

Table 23B.(cont.) **Space Station Polar Platform NOAA Operational Payload/Candidate Instruments  
1994 Launch—U.S.A.**

**Objectives of Mission:** Provide Earth observation capability in the operational atmospheric, and meteorological solar, terrestrial, and oceanic applications

**Orbit Characteristics:** 850 km circular Sun-synchronous orbit, 9 a.m. or 1:30 p.m. equator crossing times

**Payload Characteristics:**

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
Scanning Gamma and X-ray Sensor	X-ray Intensity as a Function of Energy	N/A	2 KeV—<100 KeV	N/A	N/A
X-ray Energy Detector	Energy	N/A	25–115 KeV	N/A	N/A
GOMR (Global Ozone Monitoring Radiometer)	Global Ozone	13	339.8–380 nm	169 km	169 km
ERBI (Earth Radiation Budget Instrument)	Earth Radiation Balance	8	0.2–50 $\mu$ m	68 km	3,000 km
Argos DCPL (Data Collection and Platform Location)	Random Access from Buoys, Balloons, and Platforms	1	401.65 MHz	N/A	N/A
SARSAT (Search and Rescue Satellite-Aided Tracking)	Search and Rescue	3	121.5 MHz 243 MHz 406.025 MHz	N/A	N/A
TED (Total Energy Detector)	Total Energy of Precipitating Magnetospheric Electrons and Protons	N/A	0.3–20 KeV	N/A	N/A

Note: N/A means not applicable.

Table 24. **European Polar-Orbiting Platform  
1995 Launch**

**Objectives of Mission:** Long-term comprehensive research, operational, and commercial Earth observations

**Orbit Characteristics:** Sun-synchronous, 850 km. ( $\pm 25$  km), 9:30-10:30 a.m. equator crossing time, descending node

**Payload Characteristics:\***

Sensor	Applications	No. of Channels/ Frequencies	Spectral Range/ Frequency Range	Resolution	Swath Width
AMSU-A (Advanced Microwave Sounding Unit-A)	Atmospheric Temperature Profiles	15	23-89 GHz	50 km	2,250 km
AMSU-B (Advanced Microwave Sounding Unit-B)	Atmospheric Water Vapor Profiles	5	89-183 GHz	15 km	2,250 km
AOCM (Advanced Ocean Color Monitor)	Observe Optical Parameters of the Oceans	8	Visible and near infrared	250 m	1,140 km
ARA (Advanced Radar Altimeter)	Measure Wave Height, Wind Speed, Sea Surface Topography, and Shape of the Geoid	TBD	13.8 GHz	20 km (Nadir)	TBD
ARGOS	Data Collection and Location	N/A	401 MHz	N/A	N/A
ATLID (Atmospheric Lidar)	Atmospheric Parameters in the Middle and Lower Atmosphere	TBD	1.06 or 1.53 $\mu\text{m}$	10-50 km (Horizontal) 0.5 km (Vertical)	TBD
AVHRR (Advanced Very High Resolution Radiometer)	Cloud Temperature, Sea Surface Temperature, Land Temperature, Vegetation Index	6	0.63 and 12.0 $\mu\text{m}$	1.1 km	2,900 km (Crosstrack)
CCR (Corner Cube Reflector)	Orbit Determination	N/A	N/A	N/A	N/A
DF SAR (Dual Frequency SAR)	High Resolution Imaging of Land, Ice, and Coastal Zones	2	5.3 GHz and L or X band	TBD	200 km
HIRS-2 (High Resolution Infrared Radiation Sounder)	Vertical Temperature and Humidity Profiles of the Lower Atmosphere	20	3.8-14.5 $\mu\text{m}$	10 km	2,300 km (Crosstrack)
HRIS (High Resolution Imaging Spectrometer)	Surface Imaging	10	0.4-1.0 $\mu\text{m}$	20 m	60 km
HROI (High Resolution Optical Imager)	Land Applications	4	0.45-0.90 $\mu\text{m}$ 1.6 and 2.1 $\mu\text{m}$	25 m	200 km
PPS (Precise Positioning Systems)	Orbit Determination	TBD	TBD	N/A	N/A
WINDSCAT (Wind Scatterometer)	Sea Surface Wind Speed and Direction	2	14 GHz 5.3 GHz	25 km	1,000 km

Note: N/A means not applicable; TBD means to be decided.

\*This table represents the initial orbit configuration required for the European Polar-Orbiting Platform as given in the ESA report on Earth Observation Requirements for the Polar Orbiting Platform Elements of the International Space Station, 1986, p. 36. European Polar Platform payload groupings are subject to change based on ongoing studies, changes in requirements, and priorities.





## **APPENDIX B**

### **Glossary of Common Terms**



ABLE	Atmospheric Boundary Layer Experiment	BIA	Bureau of Indian Affairs
ACR	Active Cavity Radiometer	BLM	Bureau of Land Management
ACRIM I	Active Cavity Radiometer Irradiance Monitor	BOR	Bureau of Reclamation
ADCLS	Advanced Data Collection and Location System	CCOPE	Cooperative Convective Precipitation Experiment
ADP	Atmospheric Dynamics Program	CCT	Computer Compatible Tapes
AFB	Air Force Base	CDA	Command and Data Acquisition
AFGL	Air Force Geophysics Laboratory	CE	(U.S. Army) Corps of Engineers
AFGWC	Air Force Global Weather Central	CEOS	Committee on Earth Observations Satellites
AFOS	Advanced Field Operations Systems	CGMS	Coordination of Geostationary Meteorological Satellites
AgRISTARS	Agricultural and Resources Inventory Surveys Through Aerospace Remote Sensing	CHARM	Coastal Habitat Fisheries Assessment Research Mensuration
AID	Agency for International Development	CLAES	Cryogenic Limb Array Etalon Spectrometer
AIS	Airborne Imaging Spectrometer	CNO	Chief of Naval Operations
AISC	Assessment Information Services Center	CODE	Coastal Ocean Dynamics Experiment
ALBE	Air/Land Battlefield Environment	CODMAC	Committee on Data Management and Computation
ALT	Altimeter	COSPAR	Committee for Space Research
AMI	Active Microwave Instrument	CV-990	Convair-990
AMRIR	Advanced Medium Resolution Imaging Radiometer	CZCS	Coastal Zone Color Scanner
AMSU	Advanced Microwave Sounding Unit	DAMUS	Data Management and User Services
APACM	Atmospheric Physical and Chemical Monitor	DARPA	Defense Advanced Research Project Agency
APT	Automatic Picture Transmission	DBS	Direct Broadcast System
ARS	Agricultural Research Service	DCP	Data Collection Platform
ASF	Area Sampling Frames	DCS	Data Collection System
ATMOS	Atmospheric Trace Molecules Observed by Spectroscopy	DIAL	Differential Absorption LIDAR
ATN	Advanced TIROS-N	DMSP	Defense Meteorological Satellite Program
ATOVS	Advanced TOVS	DOD	Department of Defense
ATS-1	Applications Technology Satellite-1	DOE	Department of Energy
ATSR	Along-Track Scanning Radiometer	DOI	Department of the Interior
AVHRR	Advanced Very High Resolution Radiometer	DOT	Department of Transportation
AVIRIS	Airborne Visible/Infrared Imaging Spectrometer	DOMSAT	Domestic Satellite
AWDS	Air Weather Service Automated Weather Distribution Service	DOS	Department of State
AWIPS-90	Advanced Weather Interactive Processing System of the 1990s	DPSS	(Metsat) Data Processing and Services Subsystem
		DSAS	DAMUS Satellite Archive System
		DSB	Direct Sound Broadcast (or Sounder)
		EDC	EROS Data Center

<b>EDR</b>	Environmental Data Records	<b>GMCC</b>	Global Monitoring for Climatic Change
<b>EDT</b>	Eastern Daylight Time	<b>GMS</b>	Geostationary Meteorological Satellite
<b>EMR</b>	Electromagnetic Radiation	<b>GMT</b>	Greenwich Mean Time
<b>EOSDIS</b>	Earth Observing System Data and Information System	<b>GOES</b>	Geostationary Operational Environmental Satellite
<b>Eos</b>	Earth Observing System	<b>GOFS</b>	Global Ocean Flux Study
<b>EOSAT</b>	Earth Observation Satellite Company	<b>GOMR</b>	Global Ozone Monitoring Radiometer
<b>EPA</b>	Environmental Protection Agency	<b>GPS</b>	Global Positioning System
<b>EPOCS</b>	Eastern Pacific Ocean Climate Study	<b>GRID</b>	Global Resources Information Database
<b>ERB</b>	Earth Radiation Budget	<b>GRIS</b>	Global Resources Information System
<b>ERBE</b>	Earth Radiation Budget Experiment	<b>GRM</b>	Geopotential Research Mission
<b>ERBI</b>	Earth Radiation Budget Instrument	<b>GSFC</b>	Goddard Space Flight Center
<b>ERBS</b>	Earth Radiation Budget Satellite	<b>GTCP</b>	Global Tropospheric Chemistry Program
<b>EROS</b>	Earth Resources Observation System	<b>GTE</b>	Global Tropospheric Experiment
<b>ERS</b>	Earth Remote-Sensing Satellite (ERS)	<b>HALOE</b>	Halogen Occultation Experiment
<b>ERS</b>	Earth Resources Satellite (Japan)	<b>HIRIS</b>	High Resolution Imaging Spectrometer
<b>ERTS</b>	Earth Resource Technology Satellite	<b>HIRS</b>	High Resolution Infrared Radiation Sounder
<b>ESA</b>	European Space Agency	<b>HIRSO</b>	High Resolution Solar Optical Telescope
<b>ESAD</b>	Earth Science and Applications Division	<b>HIS</b>	High Resolution Interferometer Spectrometer
<b>ESADS</b>	Earth Science and Applications Data System	<b>HRDI</b>	High Resolution Doppler Imager
<b>ESMR</b>	Electrically Scanning Microwave Radiometer	<b>HRPT</b>	High Resolution Picture Transmission
<b>ESSC</b>	Earth System Sciences Committee	<b>HVR</b>	High Resolution Visible Range
<b>FGGE</b>	First GARP Global Experiment	<b>ICSU</b>	International Council of Scientific Unions
<b>FIRE</b>	First ISCCP Regional Experiment	<b>IFEOS</b>	International Forum on Earth Observations Using Space Station Elements
<b>FLTSATCOM</b>	Fleet Satellite Communications System	<b>IFFA</b>	Interactive Flash Flood Analyzer
<b>FNOC</b>	Fleet Numerical Oceanography Center	<b>IGBP</b>	International Geosphere-Biosphere Program
<b>FY</b>	Fiscal Year	<b>IGY</b>	International Geophysical Year
<b>GALE</b>	Genesis of Atlantic Lows Experiment	<b>INSAT</b>	Indian National Satellite
<b>GARP</b>	Global Atmospheric Research Program	<b>IOC</b>	Intergovernmental Oceanographic Commission
<b>GCP</b>	Global Change Program	<b>IPOMS</b>	International Polar-Orbiting Meteorological Satellite Group
<b>GDR</b>	Geophysical Data Record	<b>IPST</b>	Institute for Physical Science and Technology, University of Maryland
<b>GEMS</b>	Global Environmental Monitoring System		
<b>GEOS</b>	Geodynamics Experimental Ocean Satellite		
<b>GEOSAR</b>	Geologic Synthetic Aperture Radar		
<b>Geosat</b>	Geodetic Satellite		
<b>GFDL</b>	Geophysical Fluid Dynamics Laboratory		
<b>GIS</b>	Geographical Information System		

<b>IRS</b>	Indian Remote-Sensing Satellite	<b>MIST</b>	Microbursts in Severe Thunderstorms
<b>ISAMS</b>	Improved Stratospheric and Mesospheric Sounder	<b>MIZEX</b>	Marginal Ice Zone Experiment
<b>ISCCP</b>	International Satellite Cloud Climatology Project	<b>MLA</b>	Multispectral Linear Array
<b>ISLSCP</b>	International Satellite Land Surface Climatology Project	<b>MLS</b>	Microwave Limb Sounder
<b>ISO</b>	Imaging Spectrometric Observatory	<b>MOS</b>	Marine Observation Satellite
<b>ISO</b>	Information Systems Office	<b>MRIR</b>	Medium Resolution Imaging Radiometer
<b>ISTP</b>	International Solar-Terrestrial Physics	<b>MSI</b>	Multi-Spectral Imagery
<b>LACIE</b>	Large Area Crop Inventory Experiment	<b>MSS</b>	Multispectral Scanner
<b>LAGEOS</b>	Laser Geodynamics Satellite	<b>MSU</b>	Microwave Sounding Unit
<b>LAIRTS</b>	Large Aperture Infrared Telescope Systems	<b>N-ROSS</b>	Navy Remote Ocean Sensing System
<b>LAMMR</b>	Large Antenna Multichannel Microwave Radiometer	<b>NASA</b>	National Aeronautics and Space Administration
<b>Landsat</b>	Land Remote-Sensing Satellite	<b>NCAR</b>	National Center for Atmospheric Research
<b>LASA</b>	LIDAR Atmospheric Sounder and Altimeter	<b>NCDC</b>	National Climate Data Center
<b>LASE</b>	LIDAR Atmosphere Sensing Experiment	<b>NCIC</b>	National Cartographic Information Center
<b>LFC</b>	Large Format Camera	<b>NEDRES</b>	National Environmental Data Referral System
<b>LFMR</b>	Low-Frequency Microwave Radiometer	<b>NEOC</b>	National Earth Observations Center
<b>LIDAR</b>	Light Detection and Ranging	<b>NESDIS</b>	National Environmental Satellite, Data, and Information Service
<b>LITE</b>	Laser In-Space Technology Experiment	<b>NEXRAD</b>	Next-Generation Weather Radar
<b>LMVD</b>	Lower Mississippi Valley Division	<b>NGDC</b>	National Geophysical Data Center
<b>Magsat</b>	Magnetic Field Satellite	<b>NMC</b>	National Meteorological Center
<b>MAPRP</b>	Mesoscale Atmospheric Processes Research Program	<b>NOAA</b>	National Oceanic and Atmospheric Administration
<b>MAPS</b>	Measurement of Air Pollution from Shuttle	<b>NOADN</b>	National Oceanic and Atmospheric Data Network
<b>MAPS</b>	Mesoscale Analysis and Prediction System	<b>NODC</b>	National Oceanographic Data Center
<b>MCC</b>	Mesoscale Convection Complexes	<b>NORPAX</b>	North Pacific Experiment
<b>McIDAS</b>	Man-Computer Interactive Data Access System	<b>NOS</b>	National Ocean Service
<b>MCSST</b>	Multi-Channel Sea Surface Temperature	<b>NOSS</b>	National Oceanic Satellite System
<b>MECCAS</b>	Microbial Exchanges and Coupling in Coastal Atlantic Systems	<b>NPS</b>	National Park Service
<b>METEOR</b>	Meteorological Satellite (U.S.S.R.)	<b>NSCAT</b>	NASA Scatterometer
<b>Meteosat</b>	Meteorological Satellite (ESA)	<b>NSF</b>	National Science Foundation
<b>Metsat</b>	Meteorological Satellite	<b>NSSEC</b>	National Severe Storm Forecast Center
<b>MFE</b>	Magnetic Field Explorer	<b>NSTL</b>	National Space Technology Laboratories
		<b>NSTR</b>	National Solar Terrestrial Research Program
		<b>NWS</b>	National Weather Service

<b>OAR</b>	Office of Oceanic and Atmospheric Research	<b>SCAT</b>	Scatterometer
<b>OFDA</b>	Office of (U.S.) Foreign Disaster Assistance	<b>SDHS</b>	Satellite Data Handling System
<b>OLR</b>	Outgoing Longwave Radiation	<b>SDR</b>	Sensor Data Record
<b>ONR</b>	Office of Naval Research	<b>SDSD</b>	Satellite Data Services Division
<b>OPC</b>	Office Products Center	<b>SDSS</b>	Satellite Data Support System
<b>OPUS</b>	Offshore Persistent Upwelling Structures	<b>SEASAR</b>	Sea Synthetic Aperture Radar
<b>PEQUOD</b>	Pacific Equatorial Ocean Dynamics Program	<b>Seasat</b>	Sea Satellite
<b>Pilot-OLUS</b>	Pilot Online Users Service	<b>SELPER</b>	Society of Latin American Specialists in Remote Sensing
<b>PCP</b>	Payload Control Processor	<b>SEM</b>	Space Environment Monitor
<b>PMCC</b>	Platform Mission Control Center	<b>SEQUAL</b>	Seasonal Equatorial Atlantic Experiment
<b>POCC</b>	Payload Operations Control Center	<b>SESAME</b>	Severe Environmental Storms and Mesoscale Experiment
<b>POES</b>	Polar-Orbiting Environmental Satellite	<b>SIR</b>	Shuttle Imaging Radar
<b>PPI</b>	Particles Per Inch	<b>SISEX</b>	Shuttle Imaging Spectrometer Experiment
<b>PRARE</b>	Precise Range and Range-Rate Experiment	<b>SISP</b>	Surface Imaging and Sounding Package
<b>Profiler</b>	Doppler Radar for Wind Profiling	<b>SME</b>	Solar Mesospheric Explorer Satellite
<b>PROFS</b>	Program for Regional Observing and Forecasting Services	<b>SMM</b>	Scanning Multichannel Microwave Radiometer
<b>Radarsat</b>	Radar Satellite	<b>SMM/ACRIM</b>	Solar Maximum Mission/Active Cavity Radiometer Irradiance Monitor
<b>RAOB</b>	Radiosonde Observation	<b>SMMR</b>	Scanning Multichannel Microwave Radiometer
<b>RBV</b>	Return Beam Vidicon	<b>SMS</b>	Synchronous Meteorological Satellite
<b>RDMS</b>	Retrospective Data Management System	<b>SOT</b>	Solar Optics Telescope
<b>RITS</b>	Radiatively Important Trace Substances	<b>SPACE</b>	Satellite Precipitation and Cloud Experiment
<b>RSCAT</b>	Radarsat Scatterometer	<b>SPC</b>	Satellite Processing Center
<b>RTOPS</b>	Research and Technology Objectives and Plans	<b>SPIs</b>	System Performance Indicators
<b>SAGE</b>	Stratospheric Aerosol and Gas Experiment	<b>SPOT</b>	Systeme Probatoire d'Observation de la Terre
<b>SAM</b>	Sensing with Active Microwave	<b>SSEC</b>	Space Science and Engineering Center
<b>SAM II</b>	Stratospheric Aerosol Measurement II	<b>SSM/I</b>	Sensor System Microwave/Imager
<b>SAMS</b>	Stratospheric and Mesospheric Sounder	<b>SSM/T</b>	Sensor System Microwave/Temperature
<b>SAR</b>	Synthetic Aperture Radar	<b>SSM/T-2</b>	Sensor System Microwave/Water Vapor
<b>SARSAT</b>	Search and Rescue Satellite-Aided Tracking	<b>SST</b>	Sea Surface Temperature
<b>SASS</b>	Seasat-A Satellite Scatterometer	<b>SSU</b>	Stratospheric Sounding Unit
<b>SBLs</b>	Spaceborne Laser Ranging	<b>STORM</b>	Storm Scale Operational and Research Meteorology Program
<b>SBUV</b>	Solar Backscatter Ultraviolet Radiometer	<b>STP</b>	Space Test Program
		<b>SWIS</b>	Satellite Weather Information Systems
		<b>TBM</b>	Terabit Memory

<b>TDA</b>	Tactical Decision Aids	<b>UNEP</b>	United Nations Environmental Program
<b>TDRSS</b>	Tracking and Data Relay Satellite System	<b>UNESCAP</b>	United Nations Economic and Social Commission for Asia and the Pacific
<b>TESS</b>	Tactical Environmental Support System	<b>UOS</b>	Ultraviolet Ozone Spectrometer
<b>TIMS</b>	Thermal Infrared Multispectral Scanner	<b>USDA</b>	United States Department of Agriculture
<b>TIROS</b>	Television and Infrared Observation Satellite	<b>USGS</b>	United States Geological Survey
<b>TM</b>	Thematic Mapper	<b>VAS</b>	VISSR Atmospheric Sounder
<b>TOGA</b>	Tropical Ocean Global Atmosphere Program	<b>VISSR</b>	Visible and Infrared Spin Scan Radiometer
<b>TOMS</b>	Total Ozone Mapping Spectrometer	<b>VLBI</b>	Very Long Baseline Interferometry
<b>TOPEX</b>	Ocean Topography Experiment	<b>WCRP</b>	World Climate Research Programme
<b>TOVS</b>	TIROS Operational Vertical Sounder	<b>WINDII</b>	Wind Imaging Interferometer
<b>TRACE</b>	Transport and Atmospheric Chemistry near the Equator	<b>Windsat</b>	Wind Satellite
<b>UARS</b>	Upper Atmosphere Research Satellite	<b>WMO</b>	World Meteorological Organization
		<b>WOCE</b>	World Ocean Circulation Experiment