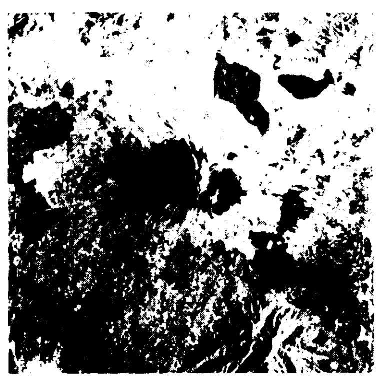
Surface Remote Sensing 4

Balloons, aircraft, rockets, and spacecraft have all been used successfully to acquire images and other data about Earth's surface. The earliest data were gathered more than 100 years ago by photographic cameras mounted on balloons. The advent of the airplane made possible aerial photography and the accumulation of historic archives of panchromatic (black and white) photographs to document surface features and their changes. Eventually, experimenters discovered that images acquired in several different regions of the electromagnetic spectrum yielded additional valuable information about surface features, including likely mineral or oil and gas-bearing deposits, or the health of crops. The Department of Agriculture, for example, has routinely used infrared photography to monitor the extent of planted fields and the conditions of crops, because, compared to many other surface features, vegetation reflects infrared radiation strongly. Airborne microwave radar has demonstrated its utility for piercing clouds, and for detecting the shape and condition of the soil beneath vegetation.

The ability to transmit images of Earth via radio waves made the use of satellites for remote sensing Earth practical. These images, acquired by electro-optical sensors that convert light to electronic signals,[1] can be transmitted to Earth as the satellite passes over a ground station or they can be stored for later broadcast. Placing remote sensing satellites in a near-polar orbit at an altitude that allows them to pass over the equator at the same



[1] A video camera is one example of an instrument that employs an electro-optical sensor.

time each day makes it possible to collect images of Earth's surface with nearly the same viewing conditions from day to day,[2] enabling users of the data easily to compare images acquired on different days. Multispectral sensors enable users to acquire data on surface spectral characteristics. Other, non-polar orbits can be selected to maximize the accumulation of data over certain latitudes. For example, scientists who designed TOPEX/Poseidon, a scientific satellite designed to collect topographic data on the oceans, chose a mid-latitude orbit, optimizing the orbit to travel above the world's oceans, and allowing the satellite to monitor the effects of tidal changes on ocean topography.

THE LANDSAT PROGRAM

NASA initiated the Landsat program in the late 1960s as an experimental research program to investigate the utility of acquiring multispectral, moderate resolution data about Earth's surface (plate 4). Since then the Landsat system has evolved into a technically successful system that routinely supplies data of 30 meter (m) g-round resolution in six spectral bands[3] to users around the world (box 4-A). A wide variety of government agencies at the local, State, and Federal levels, academia, and industry make use of Landsat data.

From a programmatic standpoint, however, the Landsat program has proved much less successful and has several times teetered on the brink of extinction. As the experience of the past decade has demonstrated, the utility of these data for serving both public and private needs has made it difficult to arrive at policies for support of Landsat that satisfy all interests well. After an 8-year trial, Congress and other observers have concluded that the experiment to commercialize the Landsat system has met with only limited success.[4]

Landsat 7

As noted earlier, continuity in the delivery of remotely sensed data, in many cases, is critical to their effective use. Many Landsat data users have long warned that a loss of continuity in the delivery of data from the Landsat satellites would severely threaten their usefulness. Timely and continuous data delivery are important for global change research, but apply equally well to other projects, including those designed to use Landsat data for managing natural resources in regions that lack other sources of data, or for urban planning. Landsat data are extremely important for detecting change in the conditions of forests, range, and croplands over local, regional, and global scales. They can also be used for monitoring changes in hydrologic patterns. Hence, continuity in the delivery of data from Landsat is an important component of environmental research and monitoring.

In 1992, agreeing that maintenance of data continuity was of crucial importance, members of the House and Senate introduced legislation (H.R. 3614 and S. 2297) to establish a new land remote sensing policy. The Land Remote Sensing Policy Act of 1992[5] transfers control of Landsat from the Department of Commerce to DoD and NASA, to be managed jointly. According to the Administration Landsat Management Plan, DoD has responsibility for procuring Landsat 7, planned

[2] The sun's angle with respect to the surface varies somewhat throughout the year, depending on the sun's apparent position with respect to the equator.

[3] Band 6, the thermal band, senses data at a resolution of 120 meters.

[4] See U.S. Congress, Office of Technology Assessment *Remotely Sensed Data From Space: Distribution, Pricing, and Applications* (Washington DC: Office of Technology Assessment July 1992), pp. 3-4. U.S. House of Representatives, report to accompany H.R. 3614, the Land Remote Sensing Policy Act of 1992, May 1992.

[5] H.R. 3614 was passed by the House on June 9, 1992. After lengthy debate, differences between the two bills were resolved in H.R. 6613, which was passed by the House in late September and by the Senate in early October. The Act was signed by President Bush on Oct. 29, 1992.

Box 4-A—The Landsat Program

The United States initiated the Landsat program in 1969 as a research activity. NASA launched Landsat 1 in 1972.[1] Data from the Landsat system soon proved capable of serving a wide variety of government and private sector needs for spatial information about the land surface and coastal areas. NASA designed, built, and operated Landsats 1-3. The perceived potential economic value of Landsat imagery led the Carter administration to consider commercial operation of the system and begin transferring control of Landsat operations and data distribution from NASA to the private sector. The first step in the transition gave operational control of the Landsat system to NOAA in 1981, because of NOAA's extensive experience in operating remote sensing satellites for weather and climate observations. Landsat 4 was launched in 1982; Landsat 5[2] became operational in 1984.[3]

In late 1983, the Reagan administration took steps to speed transfer operation of Landsat 4 and 5 to private hands because it did not want to continue public funding for the system. A few proponents of commercialization expected that industry could soon build a sufficient data market to support a land remote sensing system.[4] Soon thereafter, Congress began consideration of the Land Remote Sensing Commercialization Act of 1984, which was intended to provide legislative authority for the transfer processs. Public Law 98-365 was signed into law on July 17, 1984. During deliberations over the Landsat Act, the administration issued a request for proposal (RFP) for industry to operate Landsat and any follow-on satellite system. After competitive bidding,[5] NOAA transferred control of operations and marketing of data to EOSAT in 1985.[6] At present, EOSAT operates Landsats 4 and 5 under contract to the Department of Commerce,[7] and manages distribution and sales of data from Landsats 1-5. EOSAT will operate Landsat 6, which is scheduled for launch in the summer of 1993. The U.S. Government has paid for the Landsat 6 satellite and the launch. EOSAT will operate the satellite at its expense.

Because of concerns over continuity of data collection and delivery, Congress passed the Land Remote Sensing Policy Act of 1992, which transfers control of the Landsat program from NOAA to DoD and NASA. This legislation effectively ends the experiment to privatize the Landsat program. The two agencies will procure and operate Landsat 7.

1 Initially called the Earth Resources Technology Satellite, NASA retroactively changed its name in 1975.

2 Landsats 4 and 5 were designed by NASA and built by GE and Hughes Santa Barbara Research Center.

3 See U.S. Congress, Congressional Research Service, *The Future of Land Remote Sensing Satellite System (Landsat)*, 91-685 SPR (Washington, DC: The Library of Congress, Sept. 16, 1991) for a more complete account of the institutional history of Landsat.

4 However, most analysts were extremely pessimistic about such prospects. See U.S. Congress, congressional Budget Office, *Encouraging Private Investment in Space Activities* (Washington, DC: U.S. Government Printing Office, February 1991), oh. 3.

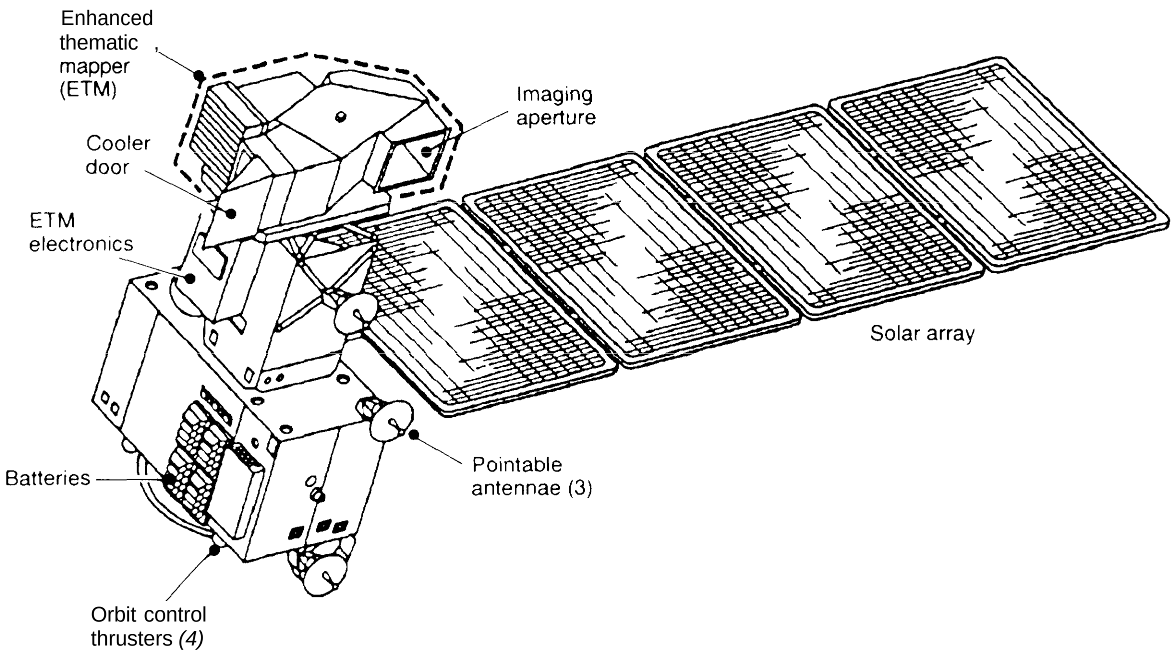
5 Seven firms responded to the RFP, from which two were selected for further negotiations—EOSAT and Kodak/Fairchild. After a series of negotiations, during which the government changed the ground rules of the RFP, Kodak dropped out, leaving EOSAT to negotiate with the Department of Commerce.

6 EOSAT was established as a joint venture by RCA (now part of Martin Marietta Astrospace) and Hughes Space and Communications Group (now part of General Motors) for this purpose.

7 Subsystems in both satellites have failed, but together they function as a nearfy complete satellite system. EOSAT has taken great care to nurse these two satellites along, in order to maintain continuity of data delivery until Landsat 6 is operational.

SOURCE: U.S. Congress, Office of Technology Assessment, *Remotely Sensed Data from Space: Distribution, Pricing, and Applications* (Washington, DC: Office of Technology Assessment, July ?992), pp. 2-3.

Figure 4-1-Landsat 6 Satellite, **Showing the Enhanced Thematic Mapper (ETM)**



SOURCE: EOSAT, 1993.

for launch in late 1997. NASA will manage operation of Landsat 7 and supervise data sales.[6] The agencies will cooperate in developing specifications for possible future Landsat systems and in developing new sensors and satellite technology.

Because data continuity is important to many users, program managers specified that Landsat 7 should at a minimum duplicate the format and other characteristics of data from Landsat 6. Landsat 7 will therefore carry an Enhanced Thematic Mapper (ETM) sensor very similar to the one on Landsat 6 (figure 4- 1). NASA and DoD are currently designing an additional sensor for Landsat, called the High Resolution Multispectral Stereo Imager (HRMSI), If funded, HRMSI would greatly improve the ability of Landsat 7 to gather data about Earth's surface. As currently envisioned, HRMSI would have much higher surface resolution than the ETM (5 m black and white; 10 m in four visible and infrared bands), and would be capable of acquiring stereo images.[7] Combined, these capabilities would allow the Defense Mapping Agency and the U.S. Geological Survey, among others, to use Landsat data in creating multispectral topographic maps. In addition, HRMSI would have the ability to acquire data on either side of its surface track, allowing the instrument to improve its revisit time from Landsat's current 16 days to only 3 days. This capability would markedly increase the utility of Landsat data for a variety of applications, such as detection of military targets and agricultural monitoring, where timeliness is an important factor. **If Congress wishes to improve the ability of U.S. agencies to use remotely sensed data in carrying out their legislatively mandated missions, it may wish to fund HRMSI or a sensor with similar capabilities.**

6 A commercial entity may well be chosen to market Landsat data.

7 Stereo images make possible the creation cf topographic maps.

NASA and DoD estimate that procuring and operating Landsat 7 with only the ETM sensor through the end of its planned 5-year lifetime will cost about $880 million (in 1992 dollars)--$4lO from NASA and $470 from DoD, About $398 million will be needed in the first few years to purchase the satellite with the ETM. An additional $403 million will be needed between 1994 and the projected end of Landsat 7's useful life to purchase the HRMSI, enhance the ground system to handle the increased data flow,[8] and operate the satellite. General Electric Corp. and Hughes Santa Barbara Research Center, which built Landsat 6 (table 4-l), were awarded the contract to build Landsat 7 (table 4-2).[9]

Table 4-l—Technical Characteristics of Landsat 6

Orbit and coverage:

LandSat 6 will follow an orbit similar to that of Landsats 4 and 5:

Orbit Altitude: **705 kilometers**

Type: Circular, sun synchronous, one orbit *every* 98.9 **minutes (about 14.5 per day)**

Equatorial crossing time: 9:45 **am**

Repeat *coverage at Equator* **16 days**

Inclination: 98.21

Sensor package:

Landsat 6 will carry a Thematic Mapper Sensor similar to Landsats 4 and 5, but with improved calibration, and an additional, higher resolution black and white (panchromatic) band.

Enhanced Thematic Mapper characteristics:

- **Panchromatic band, 15 meter ground resolution**
- **Six (visible-infrared) multispectral bands, 30 meters resolution**
- **One thermal infrared band, 120 meters.**

SOURCE: Earth Observation Satellite Co., 1992.

Future Landsat Satellites

Planning for a system to replace Landsat 7 after it lives out its useful life is in the very early stages. **Higher spatial resolution, a greater number of spectral bands, and improved sensor calibration are among the most important improvements sought for future Landsat satellites. However, timeliness of data delivery after data acquisition and the revisit time of the satellite[10] also need improvement, especially for monitoring short-term changes such as occur in crop and other renewable resource production.**

If Landsat 7 proceeds as planned, scientists will be able to experiment with the use of high-resolution, stereo images in evaluating ecological change. However, the limited number of spectral bands provided by Landsat 7 may inhibit detailed ecological modeling of land processes. Given the importance of remotely sensed land data to global change research (see chs. 5 and 6), NASA may wish to consider the potential for incorporating some of the enhanced spectral capabilities of the proposed High Resolution Imaging Spectrometer (HIRIS)[11] into the design for a follow-on to Landsat 7. HIRIS designers have dealt with many of the design and operational issues associated with hyperspectral capabilities and could significantly improve the design of a successor to Landsat 7.

Recent technological developments, in, for example, focal plane technology and active cryocoolers, suggest that it may be possible to design, build, and operate a Landsat 8 that would be much more capable than Land sat 7. The Land Remote Sensing Policy Act of 1992 calls for a technology development program to fund new sensors and

8 With the HRMSI sensor, Landsat 7 would have a maximum data transfer rate from the satellite to the ground station of about 300 megabytes per second.

9 Martin Marietta Astrospace, which recently purchased GE Astrospace, is now the prime contractor. Hughes Santa Barbara Research Center built the ETM for Landsat 6, will construct the ETM for Landsat 7. It would also develop HRMSI for Landsat 7. Although several aerospace corporations expressed interest, this team was the only bidder, in part because other companies felt they would not be competitive with the team that had built Landsat 6.

10 Perhaps by doubling the number of satellites in orbit.

11 A high-resolution sensor that had been proposal for the EOS program, but recently canceled. See ch. 5: Global Change Research.

Table 4-2—Technical Characteristics of Landsat 7

Compared to Landsat 6, Landsat 7 will have:

1. *Improved spatial resolution-a* **new sensor with 5 meters resolution in the panchromatic band and 10 meters in 4 visible and near infrared bands.**
2. *Improved Absolute Radiometric Calibration-An* **Enhanced Thematic Mapper Plus will have improved calibration of the sensor to allow for gathering improved science data and improved long-term radiometric stability of the sensors.**
3. *Stereo mapping capability~The 5* **meter sensor will collect stereo image pairs along the satellite track with a ground sample distance of 5 meters and a vertical relative accuracy of 13 meters.**
4. *Cross-track pointing-The* **contractor team will provide the ability to point to locations on either side of the satellite's ground track in order to revisit areas imaged on earlier passes. With a 16-day revisit time, Landsats 4,5, and 6 are not able to provide timely data on surface changes that occur in time periods less than 16 days, such as during critical growing periods in the spring.**
5. */mproved radiormetric* **sensitivity~lmprovements in the range of light intensity over which the Landsat sensors can accurately sense reflected or emitted light.**
6. */reproved satellite position accuracy-Mapping* **applications will be much improved by knowing more accurately the spacecraft's position and attitude in orbit at all times. Landsat 7 will carry a GPS receiver to enable improved position data.**

SOURCE: National Aeronautics and Space Administration, 1993.

spacecraft for future land remote sensing satellites.[12] New technologies introduce a significant element of technological and cost **risk. If Congress wishes to reduce these risks for a future Landsat system, Congress could provide DoD and NASA sufficient funds to support a technology development and testing program for advanced Landsat technology.**

Satellite and sensor designers have suggested a number of improvements for land remote sensing satellites, including some focused on reducing satellite size and weight. However, proving new concepts will require extensive design review and technology development. In addition, constructing a satellite system that is **expected** to last 5 or more years without significant degradation requires extensive testing at both the component and system level.

Developing new sensors for programs that have requirements for returning data on a long term, operational basis presents a special challenge to spacecraft designers because these instruments must meet more stringent specifications than those for short-term research missions. Hence, progress in sensor and spacecraft design tends to be incremental, rather than revolutionary. Satellite system experts estimate that the development of a new satellite system for Landsat 8, beginning with concept development and **proceeding through detailed design and construction, could take as long as 8 years. Hence, if Congress wants to increase the chances of maintaining continuity of Landsat data delivery after Landsat 7, it should direct DoD and NASA to start planning in 1993 to specify the design of Landsat 8.**

NON-US. LAND REMOTE SENSING SYSTEMS

Other countries have developed and flown very capable land remote sensing satellites.[13] The following section summarizes the capabilities of these systems.

France

SYSTEME POUR D'OBSERVATION DE LA TERRE (SPOT)

The SPOT-2 satellite, which was designed, built, and is operated by Centre Nationale d'Etudes Spatial (CNES), is the second in a series of SPOT satellites. It achieves a higher spatial resolution than Landsat 6, but has fewer spectral bands. It is capable of acquiring panchromatic data of 10 m resolution, and 20 m resolution data in 3 spectral bands. SPOT's off-nadir viewing yields stereoscopic pairs of images of a given area

12 Public Law 102-555, Title III; 106 STAT. 4174; 15 USC 5631-33.

13 See app. D for more detail on these systems.

by making successive satellite passes. A standard SPOT scene covers an area 60 x 60 kilometers (km). CNES expects to launch SPOT 3 in late 1993.

CNES developed SPOT with the intention of selling data commercially and attempting to develop a self-sustaining enterprise. SPOT Image, S. A., the French company formed to market SPOT data to a global market, is a major competitor to EOSAT in selling remotely sensed land data. Although SPOT Image has been successful in increasing its yearly sales each year, and now makes a modest profit on SPOT operations, it still does not earn sufficient income to support the construction and launch of replacement satellites. The French Government, through CNES, is expected to continue to provide additional satellites through the end of the decade.

During the 1992 and 1993 growing seasons, CNES reactivated SPOT-1 in order to provide more timely coverage of agricultural conditions. Key to the French strategy in building a market for remote sensing data is the CNES plan to assure continuity of data delivery and a series of evolutionary upgrades to the SPOT system. By the end of the century, CNES plans to add the capability of gathering 5 m resolution, panchromatic stereo data. It also plans to add an infrared band to enhance the data's usefulness in agriculture and other applications. The new data policy for Landsat 7 under which "unenhanced data are available to all users at the cost of fulfilling user requests' [14] may pose a problem for SPOT Image, as Landsat data would be sold to private sector users for much less than the current prices. OTA will examine these and other data issues in a future report on remotely sensed data.

India

INDIAN REMOTE SENSING SATELLITE (IRS)

As India's first domestic dedicated Earth resources satellite program, the IRS-series provides continuous coverage of the country. An indigenous ground system network handles data reception, data processing, and data dissemination. India's National Natural Resources Management System (NNRMS) uses IRS data to support a large number of applications projects.

India has orbited two IRS satellites: IRS-1A was launched in March 1988 by a Russian booster; IRS-lB reached space in August 1991, also launched by a Russian vehicle. Each carries two payloads employing Linear Imaging Self-scanning Sensors (LISS). The IRS-series have a 22-day repeat cycle, The LISS-I imaging sensor system consists of a camera operating in four spectral bands, compatible with the output from Landsat-series Thematic Mapper and SPOT HRV instruments. The LISS-IIA & B is comprised of two cameras operating in visible and near infrared wavelengths with a ground resolution of 36.5 m, and swath width of 74.25 km.

As part of the National Remote Sensing Agency's international services, IRS data are available to all countries within the coverage zone of the Indian ground station located at Hyderabad. These countries can purchase the raw/processed data directly from NRSA Data Centre.

India is designing second generation IRS-lC and ID satellites that will incorporate sensors with resolutions of about 20 m in multispectral bands and better than 10 m in the panchromatic band. System designers intend to include a short-wave infrared band with spatial resolution of 70 m. The system will also include a Wide Field Sensor (WiFS) with 180 m spatial resolution and larger swath of about 770 km for monitoring vegetation.

Japan

JAPAN EARTH RESOURCES SATELLITE (JERS-1)

A joint project of the Science and Technology Agency, NASDA, and the Ministry of International Trade and Industry (MITT), JERS-1 was

[14] Public Law 102-55; 106 STAT 4170; 15 USC 5615.

launched by a Japanese H-1 rocket in February 1992. Observations from JERS-1 focus on land use, agriculture, forestry, fishery, environmental preservation, disaster prevention, and coastal zone monitoring. It carries a synthetic aperture radar and an optical multispectral radiometer.

JERS-1 data are received at NASDA'S Earth Observation Center, Saitama, and at the University in Kumamoto Prefecture, the Showa Base in the Antarctica, and the Thailand Marine Observation Satellite station. Under a NASDA-NASA Memorandum of Understanding, the NASA-funded SAR station in Fairbanks, Alaska, also receives JERS-1 data. These data overlap the SAR data from the European ERS-1 mission, and the future Canadian Radarsat mission, planned for launch in 1994.

Japan also operates the Marine Observation Satellite (MOS lb) system that collects data about the land as well as the ocean surface. See below for description.

Russia

RESURS-O

The Resurs-O digital Earth resources satellites are roughly comparable to the U.S. Landsat system and are derived from the Meteor series of polar orbiters. They carry multiple multispectral instruments operating in the visible to thermal infrared. Remote sensing instruments aboard a Resurs-O comprise two 3-band scanners, providing 45 m resolution. A second 5-band scanner senses a 600 km swath at 240 m X 170 m resolution. A 4-band microwave radiometer views a 1,200 km swath at 17 to 90 km resolution. In addition a side-looking synthetic aperture radar provides 100 km coverage at 200 m resolution. The Resurs-O spacecraft can process some data in orbit and relay data directly to ground stations.

Russian scientists are planning a follow-on to this series, which would carry high-resolution optical sensors capable of 15 to 20 m resolution. They have explored the possibility of establishing commercial Resurs-O receiving stations in Sweden, as well as the United Kingdom.

RESURS-F

This class of photographic satellite mimics Russian military reconnaissance spacecraft by using a film return capsule, which is deorbited and brought to Earth under parachute. Resurs-Fl and Resurs-F2 spacecraft use the Vostok reentry sphere, earlier used for launching cosmonauts. The Resurs-Fl typically flies at 250km to 400km altitude for a 2-week period and carries a three-channel multispectral system that includes three KATE-200 cameras and two KFA-1OOO cameras. The KATE--200 camera provides for Earth survey in three spectral bands. It can collect stereoscopic imagery having an along-track overlap of 20, 60, or 80 percent.[15] Resolution of the images, according to spectral band and survey altitude, varies from 10 to 30 m over a 180 km swath width. The KFA-1OOO cameras provide stereo images of up to 5 m resolution with a 60 km swath width.

The Resurs-F2 spacecraft normally circuit Earth for as long as 3 to 4 weeks in a variable orbit of 259 to 277 km. Onboard is the MK-4 camera system, which can survey the Earth using a set of four cameras in six spectral channels. Also, 5 to 8 m resolution stereo is possible with a swath width of 120 to 270 km. Imagery provided by Resurs-Fl and F2 spacecraft are being offered commercially through Sojuzkarta.

OCEAN SENSING AND THE ICE CAPS

Because the oceans cover about 70 percent of Earth's surface, they make a significant contribution to Earth's weather and climate. The oceans interact constantly with the atmosphere above them and the land and ice that bound them. Yet scientists know far too little about the details of the oceans' effects on weather and climate, in part because the oceans are monitored only coarsely by ships and buoys. Improving the safety of

15 Reliable stereo requires at least 60 percent overlap.

people at sea and managing the seas' vast natural resources also depend on receiving better and more timely data on ocean phenomena, Satellite remote sensing is one of the principal means of gathering data about the oceans.

Research on Ocean Phenomena

In order to understand the behavior of the oceans and to make more accurate predictions of their future behavior, scientists need to gather data about sea temperature, surface color, wave height, the distribution of wave patterns, surface winds, surface topography, and currents. Fluctuations in ocean temperatures and currents lead to fluctuations in the atmosphere and therefore play a major part in determining weather and climate. For example, El Nino, the midwinter appearance of warm water off the coast of South America every 4 to 10 years, decreases the nutrients in the coastal waters off South America, and therefore the number of fish. However, in 1988, El Nino had a major effect on weather patterns over North America. The warm water was pushed further north than usual, which created severe storms hundreds of miles to the north and shifted the jet stream further north. This blocked the Canadian storm systems, which normally send cool air and moisture south during the summer, and led to an unusual amount of dry, hot weather, precipitating severe drought in the central and eastern United States.[16] The drought, in turn, severely affected U.S. agriculture. The winter 1992-1993 El Nino condition had a major role in producing extremely high levels of rain and snow in the western United States during February 1993. Understanding and predicting these interactions are major goals of climatologists.

The study of other ocean phenomena would enhance scientists' understanding of the structure and dynamics of the ocean. For example, observations of wave conditions are important for modeling ocean dynamics. Because winds create waves, measurements of wind speed and direction over wide areas can lead to estimates of wave height and condition.

Closely observing the color of the ocean surface provides a powerful means of determining ocean productivity. Variations in ocean color are determined primarily by variations in the concentrations of algae and phytoplankton, which are the basis of the marine food chain. Because these microscopic plants absorb blue and red light more readily than green light, regions of high phytoplankton concentration appear greener than those with low concentration. Because fish feed on the photoplankton, regions of high concentration indicate the possibility of greater fish population.

Interest in using satellites to measure ocean phenomena began in the 1960s. In 1978, the polar-orbiting TIROS satellites began to gather data on sea surface temperatures using the AVHRR (plate 5) and microwave sensors. The maps of sea surface temperatures produced form these data demonstrate complex surface temperature patterns that have led to considerable speculation about the physical processes that might cause such patterns. However, it was not until NASA launched Nimbus 7 and Seasat in 1978 that scientists were able to gather comprehensive measurements of the oceans. Nimbus-7 carried a Scanning Multichannel Microwave Radiometer (SMMR) that provided accurate measurements of sea surface temperatures. By measuring the color of the ocean surface, its Coastal Zone Color Seamer (CZCS) provided estimates of ocean biological productivity.

Seasat[17] carried five major instruments-an altimeter, a microwave radiometer, a scatterometer, a visible and infrared radiometer, and a synthetic aperture radar. Scientists used data from these instruments to measure the amplitude and direction of surface winds, absolute and relative

16 D. James Baker, *Planet Earth: The View from Space* (Cambridge, MA: Harvard University Press,1990), pp. 2-3.

17 U.S. Congress, Mice of Technology Assessment, *Technology and Oceanography,* OTA-O-141 (Washington, D. C.: U.S. Government Printing Office, 1981).

surface temperature, the status of ocean features such as islands, shoals, and currents, and the extent and structure of sea ice. Although Seasat operated only 3 months, it returned data of considerable value to ocean scientists and paved the way for the current generation of U.S. and foreign ocean instruments and satellite systems.

Operational Uses of Ocean Satellites

The development and operation of Seasat demonstrated the utility of continuous ocean observations, not only for scientific use, but also for those concerned with navigating the world's oceans and exploiting ocean resources. Its success convinced many that an operational ocean remote sensing satellite would provide significant benefits.[18] The SAR,[19] the scatterometer, and the altimeter all gathered data of considerable utility. Not only do DoD and NOAA have applications for these sensors in an operational mode (i.e., where continuity of data over time is assured and the data formats change only slowly), but so also do private shipping firms and operators of ocean platforms. Knowledge of currents, wind speeds, wave heights, and general wave conditions at a variety of ocean locations is crucial for enhancing the safety of ships at sea, and for ocean platforms. Such data could also decrease costs by allowing ship owners to predict the shortest, safest sea routes.

Over the past decade, the U.S. Government has made two major attempts to develop and fly a dedicated operational ocean satellite carrying sensors similar to those on Seasat. Both attempts failed when the programs were canceled for lack of funding. In 1982, the United States canceled a joint DoD/NOAA/NASA program to develop the National Oceanic Satellite System (NOSS), and in 1988 it canceled a similar satellite that the Navy was attempting to develop, the Navy Remote Ocean Sensing Satellite (N-ROSS). TOPEX/Poseidon, a research satellite, was launched in 1992 for altimetry studies.

Data from the SeaWiFS instrument aboard the privately developed SeaStar satellite, will provide ocean color information, which could have considerable operational use.[20] Although NASA's EOS will include ocean sensors to support research on issues concerning the oceans and ocean-atmospheric interactions, no instruments devoted to operational uses are planned.

Observations of Sea Ice

Because sea ice covers about 13 percent of the world's oceans, it has a marked effect on weather and climate. Thus, measurements of its thickness, extent, and composition help scientists understand and predict changes in weather and climate. Until satellite measurements were available, the difficulties of tracking these characteristics were a major impediment to understanding the behavior of sea ice, especially its seasonal and yearly variations.

The AVHRR visible and infrared sensors aboard the NOAA POES have been used to follow the large-scale variations in the Arctic and Antarctic ice packs. Because they can "see through" clouds, synthetic aperture radar instruments are particularly useful in tracking the development and movement of ice packs, which pose threats to shipping, and in finding routes through the ice. Data from ERS-1, Almaz, and JERS-1 (see below) have all been studied to understand their potential for understanding sea ice and its changes. The Canadian Radarsat will be devoted in part to gathering data on the ice

18 Donald Montgomery, "CommercialApplications of Satellite Oceanography," *Oceanus* 24, No. 3, 1981; Joint Oceanographic Institutions, "Oceanography From Space: A Research Strategy for the Decade 1985 -1995," report (Washington, DC: Joint Oceanographic Institutions, 1984).

19 See appendix B, box B-3, for a description of how synthetic aperture molar operates.

m See below for a summary description of SeaStar. See ch. 7 for discussion of the financial arrangements that have made its development possible.

packs to aid shippers, fishing fleets, and other users of the northern oceans. NASA is providing a receiving station in Alaska to collect Radarsat data and make them available to U.S. researchers.

MAJOR EXISTING OR PLANNED OCEAN AND ICE REMOTE SENSING SATELLITES

The separation of satellites into those that view the land or the ocean is highly artificial because instruments used for land features often reveal information about the oceans and vice versa. In addition, because most instruments specifically designed either for land or ocean features can fly on the same satellite, such separations are not required for operational use, Nevertheless, as a result of the division of disciplines and the desire of funding agencies to group instruments designed primarily for investigating land or ocean features on the same satellite bus, satellites generally fall into one category or the other.

Canada

RADARSAT

This satellite, to be launched in 1995 aboard a Delta II launcher, will carry a C-band synthetic aperture radar capable of operating in several different modes and achieving resolutions from 10 to 50 m, depending on the swath width desired. It is designed to gather data for:

1. ice mapping and ship navigation;
2. resource exploration and management;
3. high arctic surveillance;
4. geological exploration;
5. monitoring of crop type and health;
6. forestry management;
7. Antarctic ice mapping.

The satellite will have a repeat cycle of 1 day in the high Arctic, 3 days over Canada, and 24 days over the equatorial regions. The Canadian firm, Radarsat International, will market data collected from the Radarsat system. It will offer contracts to stations around the world that are collecting SPOT and/or Landsat data, enabling them to collect and market Radarsat data.

European Space Agency

EARTH RESOURCES SATELLITE (ERS-1)

The ERS-1 satellite was launched into polar orbit by an Ariane booster in July 1991 and was declared operational 6 months later. Operating from a Sun-synchronous, near-polar orbit, ERS-1 is the largest and most complex of ESA'S Earth observation satellites. It carries several instruments:

1. Along Track Scanning Radiometer and Microwave Sounder, which makes infrared measurements to determine, among other parameters, sea surface temperature, cloud top temperature, sea state, and total water content of the atmosphere.
2. Radar Altimeter, which can function in one of two modes (ocean or ice) and provides data on significant wave height; surface wind speed; sea surface elevation, which relates to ocean currents, the surface geoid and tides; and various parameters over sea ice and ice sheets.
3. Synthetic Aperture radar to study the relationships between the oceans, ice, land, and the atmosphere. The SAR'S all-weather, day-and-night sensing abilities is critical for polar areas that are frequently obscured by clouds, fog, and long periods of darkness.
4. Wind Scatterometer to measure surface winds. By measuring the radar backscatter from the same sea surface, picked up by the three antennas placed at different angles, wind speed and direction can be determined.

The primary objectives of the ERS-1 mission focus on improving understanding of oceans/atmosphere interactions in climatic models; advancing the knowledge of ocean circulation and transfer of energy; providing more reliable estimates of the mass balance of the Arctic and

Antarctic ice sheets; enhancing the monitoring of pollution and dynamic coastal processes (plate 6); and improving the detection and management of land use change.

More specifically, data form ERS-1 are being used to study ocean circulation, global wind/wave relationships; monitor ice and iceberg distribution; determine more accurately the ocean geoid; assist in short and medium-term weather forecasting, including the determination of wind speed and direction, as well as help locate pelagic fish by monitoring ocean temperature fronts. Data from the spacecraft also contribute to the international World Climate Research Program and to the World Ocean Circulation Experiment.

Japan

MARINE OBSERVATION SATELLITE (MOS)

The MOS-1 was Japan's first Earth observation satellite developed domestically. The frost MOS-1 was launched in February 1987 from Tanegashima Space Center by an N-II rocket. Its successor, MOS - lb, with the same performance as MOS-1, was launched by an H-I rocket in February 1990. These spacecraft orbit in sun-synchronous orbits of approximately 909 km and have a 17-day recurrent period, circling the Earth approximately 14 times a day. The two spacecraft can be operated in a simultaneous and/or independent mode.

MOS-1 and MOS-lb are dedicated to the following objectives:

- establishment of fundamental technology for Earth observation satellites;
- experimental observation of the Earth, in particular the oceans, monitoring water turbidity of coastal areas, red tide, ice distribution; development of observation sensors; verification of their functions and performance; and
- basic experiments using the MOS data collection system.

Each of the spacecraft carry three sensors: a Multispectral Electronic Self-seaming Radiometer (MESSR); a Visible and Thermal Infrared Radiometer (VTIR); and a Microwave Scanning Radiometer (MSR). MOS products are available for a fee from the Remote Sensing Technology Center of Japan (RESTEC).

U.S./French

TOPEX/POSEIDON

TOPEX/Poseidon is a research satellite devoted primarily to highly accurate measurements (to an accuracy of about 2 cm) of the height of the oceans. The satellite, which was launched in September 1992 by the European Ariane launcher, also carries a microwave radiometer in order to correct for the effects of water vapor in the atmosphere. France supplied a solid-state altimeter and a radiometric tracking system. The satellite's orbit allows determination of ocean topography from latitudes 63° north to 63° south. The height of the ocean is crucial to understanding patterns of ocean circulation. Accurate altitude measurements could lead to better understanding of ocean topography and dynamics, tides, sea ice position, climate, and seafloor topography, among other ocean-related qualities.[21] Data from TOPEX/Poseidon are distributed to scientists in the United States, France, and other countries in accordance with data policies agreed on between NASA, CNES and other members of CEOS.

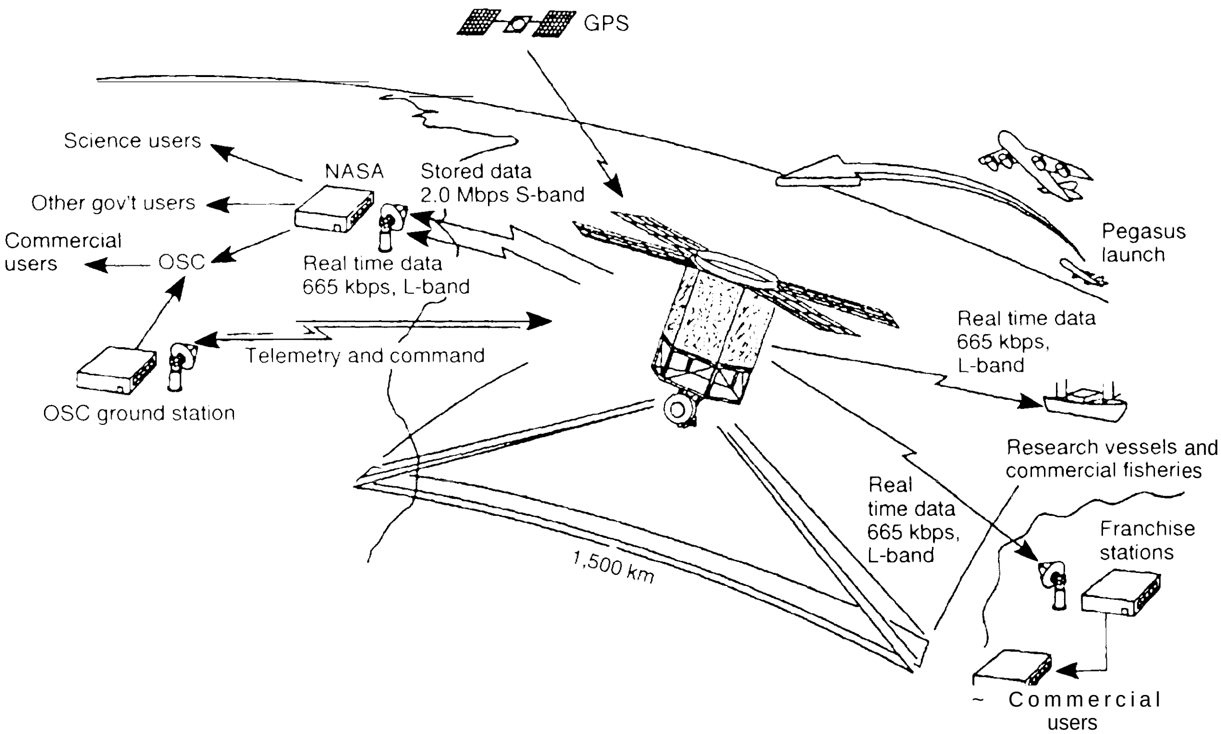
Orbital Sciences Corp.

SEASTAR/SEAWIFS

The Orbital Sciences Corp. (OSC) is constructing the SeaStar satellite, which will carry the Sea-viewing Wide Field of view Sensor (SeaWiFS), an 8-band multispectral imager oper-

21 "Satellite Altimetric Measurements of the Ocean," report of the TOPEX Science Working Group, NASA, JPL 1981; Richard Fifield, "The Shape of Earth from Space," *New Scientist, Nov.* 15, 1984, pp. 46-50.

Figure 4-2—The Orbital Sciences Corporation's SeaStar Ocean Color Satellite System



SOURCE: Orbital Sciences Corp., 1992.

ating in the very near infrared portion of the spectrum.[22] SeaWiFS, which OSC plans to launch in late 1993, will be used to observe chlorophyll, dissolved organic matter, and pigment concentrations in the ocean. The sensor will contribute to monitoring and understanding the health of the ocean and concentration of life forms in the ocean. Data will have significant commercial potential for fishing, ship routing, and aquaculture, and will be important for understanding the effects of changing ocean content and temperatures on the health of aquatic plants and animals.

Under an experimental arrangement with NASA, the company's SeaStar satellite will collect ocean color data for primary users (including NASA), who then have the option to sell both unenhanced and enhanced data to other users (figure 4-2). NASA has agreed to purchase data from orbital Sciences in a so-called anchor tenant arrangement in which NASA has paid OSC $43.5 million up front. This arrangement allowed OSC to seek private financing for design and construction of the satellite.[23]

This experimental data purchase agreement should provide valuable lessons for possible future agreements of a similar character. If it is successful, the Federal Government may purchase quantities of other remotely sensed data from private systems, allowing these firms to earn a profit marketing data to other users.

22 Built by Hughes Santa Barbara Research Center.

23 See ch. 7: The *Private* Sector, for a more detailed discussion of this arrangement.

Box 4-B-System Tradeoffs

Remote sensing instrumentation can be launched into space in a variety of orbital altitudes and inclinations; instruments can be flown on endo-atmospheric systems-aircraft, balloon, and remotely piloted aircraft; or they can be sited on the ground. The selection of a particular "system architecture" for a given mission typically involves many compromises and tradeoffs among both platforms and sensors. For imaging missions based on satellites, the most important factors indetermining overall system architecture include the required geographical coverage, ground resolution, and sampling time-intervals. These affect platform altitude, numbers of platforms, and a host of sensor design parameters. Each remote sensing mission will have unique requirements for spatial, spectral, radiometric, and temporal resolution. A number of practical considerations also arise, including system development costs; the technical maturity of a particular design; and power, weight volume, and data rate requirements.

Spectral *resolution* refers to the capability of a sensor to categorize electromagnetic signals by their wavelength. *Radiometric resolution* refers to the accuracy with which the intensities of these signals can be recorded. Finally, *ternporal resolution* refers to the frequency with which remote sensed data are acquired. it is also possible to categorize the "coverage" of three of the instruments' four resolutions: spatial coverage is a function of sensor field of view; spectral coverage refers to the minimum and maximum wavelengths that can be sensed; and radiometric coverage refers to the range of intensities that can be categorized. The required measurement intervals vary widely with mission. For example, data on wind conditions might be required on time scales of minutes; data on crop growth might be needed on time scales of a week or more; and data on changes in land use are needed on time scales of a **year or more.**

Sensor design requires tradeoffs among the four "resolutions" because each can be improved only at the expense of another. Practical considerations also force tradeoffs; for example, on Landsat, multispectral and spatial data compete for on-board storage space and fixed bandwidth data communication channels to ground stations. For a given swath width, the required data rate is inversely proportional to the square of the spatial resolution and directly proportional to the number of spectral bands and the swath width. For example, improving the resolution of Landsat from 30 m to 5 m would raise the data rate by a factor of 36. Adding more bands to Landsat would also increase the required data rate. Changing the width of coverage can increase or decrease the required data rate proportional to the change in swath width. The baseline design for a proposed high-resolution imaging spectrometer (HIRIS) sensor would have 192 contiguous narrow spectral bands and a spatial resolution of 30 m.[1] To accommodate these requirements, designers chose to limit the ground coverage and thereby reduce the swath width of the sensor. HIRIS would have been used as a "targeting" instrument and would not acquire data continuously.

Spatial resolution drives the data rate because of its inverse square scaling. One way to reduce the data rate requirements without sacrificing spatial resolution is to reduce the field of view of the sensor.[2] Designing multispectral sensors that allow ground controllers to select a limited subset of visible and infrared bands from a larger number of available bands is another option to lower data rates?

1 HIRIS was eliminated as an EOS instrument during the restructuring of EOS (see ch. 5: Global Change Research).

2 The different resolutions can be traded against ground coverage. For example, the French SPOT satellite offers 10 m resolution in black and white, but its ground swath width is 60 km versus Landsat 5's 185 km.

3 Data compression is another option to reduce data rates. A lossless compression would allow the full set of raw data to be recovered; reductions in data rates of approximately a factor of two might be gained implementing these algorithms. Most researchers prefer this to a data set that has been pre-processed in away that destroys some data (but reduces data rate requirements) because "one person's ndse can prove to be another person's signal."

SOURCE: 19S3 Landsat Short Course, University of California Santa Barbara and Hughes SBRC; Office of Technology Assesemen$ 1993.

United States

GEODESY SATELLITE (GEOSAT)

Launched in 1985, this satellite carried an improved version of the altimeter that flew on Seasat. Designed by the U.S. Navy primarily for collecting precise measurements of ocean topography for military use, the satellite was initially placed into a 108° orbit. The data from this part of the mission were classified but have recently been released for scientific use. The satellite was later maneuvered into a different orbit in order to collect data that would allow oceanographers to determine changes in ocean topography. Geosat operated until 1989. The Navy plans to replace it with Geosat Follow On (GFO), which would fly in an orbit that is 1800 out of phase with the orbit of Geosat, Current plans call for a 1995 launch of GFO.

Russia

ALMAZ

From March 1991 until November 1992, Alrnaz-1, a large spacecraft equipped with synthetic aperture radar (SAR), provided radar images of the oceans and Earth's surface.[24] Almaz (Russian meaning "diamond") orbited Earth in a 300 km-high orbit, providing coverage of designated regions at intervals of 1 to 3 days. Imagery was recorded by onboard tape recorders, then transmitted in digital form to a relay satellite that, in turn, transmitted the data to a Moscow-based receiving facility. The imagery formed a hologram recorded on high-density tape for later processing as a photograph. Alternatively, a digital tape can be processed. Hughes STX Corp. of Lanham, Maryland, is the exclusive worldwide commercial marketer, distributor, processor, and licenser of data from the Almaz-1 spacecraft.[25] A second Almaz satellite is available for launch if the funds can be found to launch and operate it. Although the cost of such an operation is reported to be extremely low compared to other SAR satellites, NPO Machinostroyenia, the satellite builder, has not yet found an investor.

Sensor Design and Selection

Each remote sensing mission has unique requirements for spatial, spectral, radiometric, and temporal resolution. A number of practical considerations also arise in the design process, including system development and operational costs; the technical maturity of a particular design; and power, weight, volume, and data rate requirements. Because it is extremely expensive, or perhaps impossible, to gather data with all the characteristics a user might want, the selection of sensors or satellite subsystems for a mission involving several tasks generally involves compromises (box 4-B).

Sensor performance may be measured by spatial and spectral resolution, geographical coverage, and repeat frequency. In general, tradeoffs have to be made among these characteristics. For example, sensors with very high spatial resolution are typically limited in geographical coverage. Appendix B provides a detailed discussion of these technical issues. It also discusses many technical and programmatic concerns in the development of advanced technology for remote sensors and satellite systems.

[24] Cosmos-1870, a similar bus-sized, radar-equipped prototype spacecraft was launched in 1987. Cosmos-1870 operated for 2 years, producing radar imagery of 25-30 m resolution.

[25] Earlier, Almaz Corp. was formed to stimulate commercial use of the satellite data.